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A Novel Approach to Determine the Type of Conductivity in Semiconductors Using a Combined Seebeck and Peltier Effects

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Abstract

This study presents a novel thermoelectric system that integrates the Seebeck and Peltier effects to determine the conductivity type of semiconductors with high precision and improved energy efficiency. Traditional Seebeck measurement setups typically require high-power resistive heaters and bulky cooling systems, consuming up to 500W of electrical power. In contrast, the proposed system employs Peltier modules as both heating and cooling sources, significantly reducing energy consumption while enabling sustainable, solar-powered operation. The system was validated through a series of controlled laboratory experiments conducted on silicon semiconductor samples. The results demonstrated that the device effectively identified the conductivity type by analyzing voltage generation under controlled thermal gradients. The p-type samples exhibited a Seebeck coefficient of -0.0477 V/K at a temperature differential of 48.2°C, generating a maximum voltage of -2.3V, while the n-type samples displayed a coefficient of 0.00037 V/K at a 50°C temperature difference, producing a stable voltage output. The system rapidly reached thermal equilibrium within 36 minutes, confirming its efficiency in thermoelectric testing. The integration of Peltier elements not only enhances precision and thermal stability but also reduces operational costs and environmental impact. This innovative approach offers a more sustainable, compact, and energy-efficient alternative to conventional Seebeck and Hall Effect systems, making it highly suitable for semiconductor characterization, renewable energy applications, and portable thermoelectric testing solutions.

1. Introduction

Semiconductor characterization plays a crucial role in electronic and energy applications, where determining the type of conductivity is fundamental to device performance [1]. Various techniques exist for this purpose, including Hall Effect measurements, thermoelectric assessments, and optical analysis. Among these, thermoelectric-based methods have gained increasing attention due to their simplicity, cost-effectiveness, and ability to operate without an external magnetic field [2].

The Seebeck effect, a well-established thermoelectric phenomenon, generates an electric potential in response to a temperature gradient across a material, providing valuable insights into charge carrier behavior [3]. Traditional Seebeck systems have been widely used to determine semiconductor conductivity types, but they often require complex heating and cooling mechanisms that consume significant electrical power [4]. Recent advancements in thermoelectric technologies have introduced alternative approaches, such as the use of Peltier modules for thermal control, which enhance energy efficiency and sustainability [5].

Several studies have explored thermoelectric principles in semiconductor characterization. Snyder (2006) developed a device utilizing the Seebeck effect to measure the thermoelectric power of various samples [6]. Similarly, Kidia et al. (2008) designed an electrothermal system to analyze electron transport properties in doped zinc oxide [7]. More recently, Mimoun et al. (2020) investigated the integration of Peltier elements with solar energy, demonstrating the feasibility of sustainable thermoelectric systems [8].

Building upon these advancements, this study aims to develop an energy-efficient Seebeck system that integrates the Peltier effect to determine semiconductor conductivity types. By utilizing Peltier modules as both heating and cooling sources, the proposed system minimizes energy consumption while maintaining accurate and reliable measurements. The system's effectiveness is validated through laboratory experiments on silicon specimens, offering a novel and sustainable approach to semiconductor characterization [9]. The system employs a Peltier device for cooling the cold end, replacing the conventional cooling mechanism in standard Seebeck systems, and another Peltier device for heating the hot end, substituting the typical chiller system. The Peltier electrothermal cooler and heater, model 12706, operates at a voltage of 12V, a maximum continuous current of 6A, and a peak power output of 50Wdc. During field testing, the device functioned using solar energy, powered by a solar panel and batteries.

1.1. A Patented Novel Approach

This study presents an alternative to conventional Seebeck systems, which typically require substantial electrical power up to 500W due to their reliance on electric heaters and chiller systems. It also serves as an alternative to the Hall Effect System, which utilizes a high magnetic flux magnet and a chiller system. The technology developed in this research has already been patented by our center (the Renewable Energy and Environment Research Center) under the Central Organization for Standardization and Quality Control (COSQC) [10].

1.2. Thermoelectric Principle

The thermoelectric principle is based on the interrelationship between heat and electricity in materials, primarily governed by three effects: the Seebeck effect, the Peltier effect, and the Thomson effect. These effects form the foundation of thermoelectric generators (TEGs) and thermoelectric cooling devices [11].

The Seebeck effect occurs when a temperature gradient is applied across a conductive or semiconducting material, leading to the generation of an electromotive force (emf). This phenomenon arises due to charge carrier diffusion from the hot side to the cold side, where the electron distribution is affected by thermal excitation. The voltage difference generated (ΔV) is directly proportional to the temperature gradient (ΔT) and is expressed as:

$$\mathbf{S = \frac{V_{hot} - V_{cold}}{T_{hot} - T_{cold}}} \qquad \mathbf{(1)}$$

where S is the Seebeck coefficient (V/K), which depends on the material properties and carrier concentration. The magnitude of the Seebeck coefficient varies significantly among materials, with bismuth telluride (Bi_2Te_3) and lead telluride (PbTe) being among the most efficient thermoelectric materials due to their high Seebeck coefficients and low thermal conductivity [12].

The Peltier effect is the inverse of the Seebeck effect, occurring when an electric current is applied to a junction of two dissimilar conductors, causing heat absorption or release at the junction. The Peltier heat (Q_P) is given by:

$$\mathbf{QP = \Pi \times I} \qquad \textbf{(2)}$$

where Π is the Peltier coefficient (V) and I is the current passing through the material. The direction of heat flow depends on the polarity of the applied voltage, making the Peltier effect useful in solid-state cooling applications, such as thermoelectric refrigerators [13].

The Thomson effect describes the heat absorption or emission when a temperature gradient is applied to a material through which an electric current is flowing. Unlike the Seebeck and Peltier effects, the Thomson effect is distributed along the length of a conductor and depends on the material's electrical resistivity and Seebeck coefficient, expressed as:

$$\mathbf{Q_T = \tau \times I \times \Delta T} \qquad \textbf{(3)}$$

where τ is the Thomson coefficient (V/K). This effect is particularly relevant for optimizing thermoelectric generators [5]. The efficiency of thermoelectric materials is measured using the figure of merit (ZT), defined as:

$$\mathbf{ZT} = \frac{S^2 \sigma T}{k} \qquad \textbf{(4)}$$

where σ is the electrical conductivity, and k is the thermal conductivity. A high ZT value (ZT > 1) indicates superior thermoelectric performance. Recent advancements in nanostructured materials, such as quantum dots and superlattice structures, have improved ZT values in materials like Bi_2Te_3 and skutterudites ($CoSb_3$) [14].

Several studies have explored new thermoelectric materials and device architectures to improve efficiency. Nanostructuring techniques have reduced phonon thermal conductivity, enhancing ZT values [15]. Hybrid thermoelectric systems integrating Peltier modules with solar energy have improved sustainability [16]. Flexible thermoelectric generators (FTEGs) made from polymer-based composites are being developed for wearable applications [17].

Thermoelectric systems offer potential solutions for waste heat recovery in industrial processes, space exploration, and electronic cooling. As material research progresses, the integration of 2D materials like graphene and topological insulators is expected to revolutionize thermoelectric performance [18]. The development of efficient thermoelectric devices has significant implications for renewable energy applications, particularly in converting waste heat into usable electrical power. Emerging research continues to refine thermoelectric materials and system designs, paving the way for more widespread adoption of thermoelectric technology in both industrial and consumer applications [19].

Figure (1) shows a schematic diagram of Seebeck system used to identify the semiconductor conductivity type. As described earlier, the Peltier effect occurs when an electric current flows through dissimilar conductors, causing a slight temperature change at the junction. In contrast, the Peltier effect phenomenon is demonstrated in the diagram of Figure (2), where voltage difference causing temperature difference.

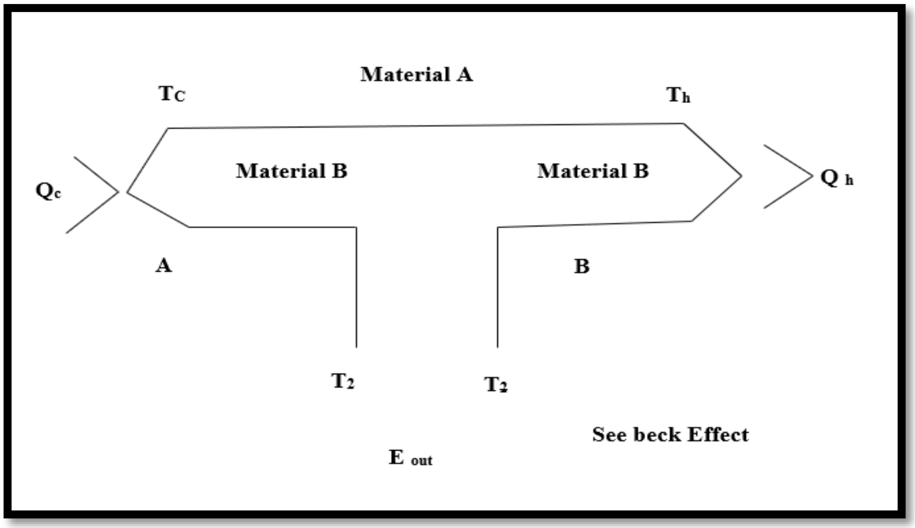

Figure (1): Working principle of Seebeck effect.

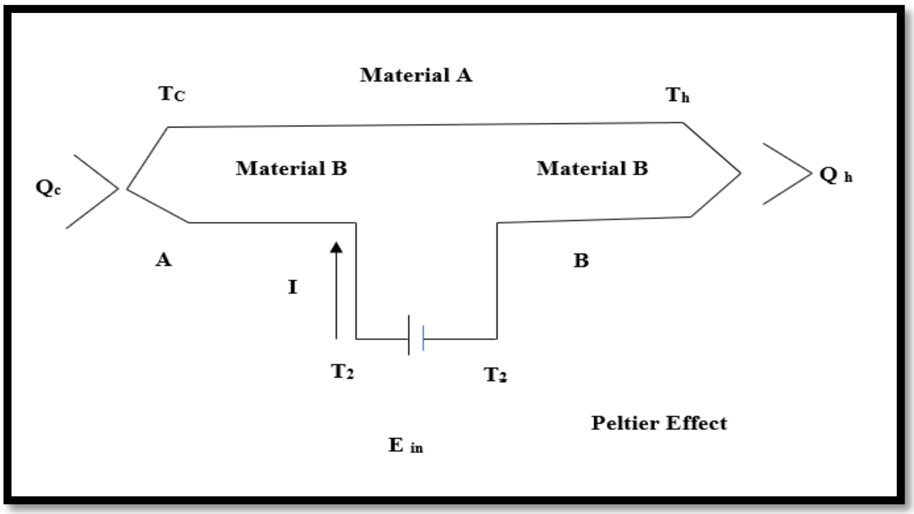

Figure (2): Working principle of Peltier effect.

2. Experimental Procedure

To investigate the thermoelectric properties of semiconductors and determine their conductivity type, a custom-built Seebeck-Peltier system was designed and implemented. This system integrates both Seebeck and Peltier effects to measure the voltage difference induced by a controlled temperature gradient across the sample. The experimental setup consists of a thermoelectric measurement platform with well-calibrated components to ensure high accuracy in data acquisition.

2.1. Experimental Setup

The experimental device comprises:

- **Adjustable Aluminum Ruler:** A precision-machined aluminum ruler facilitates the adjustable positioning of semiconductor samples, ensuring consistent contact with the heating and cooling sources.
- **Thermoelectric Modules (Peltier Model 12706):** Two Peltier modules are employed: one for heating and another for cooling. Each module operates at a rated voltage of 12V, a peak current of 6.4A, and a maximum thermal power output of 50W.
- **Power Supply System:** The device is powered by a regulated 12V DC power supply and can also operate using solar energy. A 100W photovoltaic panel, combined with a charge controller, stabilizes the voltage supply. A 12V, 100Ah Newmax battery ensures continuous operation, even in fluctuating solar conditions.

- **Cooling System:** A water-cooled heat exchanger, aided by a 12V DC water pump, circulates distilled water through a compact reservoir to dissipate excess heat from the Peltier module, ensuring effective thermal management.
- **Measurement Instruments:** A digital voltmeter measures the induced thermoelectric voltage, while a four-channel digital thermometer precisely monitors temperature variations across the sample.

The mechanical and electrical components were assembled following a structured layout. Figures (3 & 4) illustrate the physical construction of the Seebeck-Peltier system, whereas Figure (5) details a flowchart of the connection of the sample to the Peltier modules.

2.2. Experiment Description

The experiment was designed to characterize semiconductor samples by measuring the voltage response due to the Seebeck effect. The methodology involved the following steps:

1. **Sample Preparation:**
   - A semiconductor sample (either p-type or n-type) was selected and its physical properties, such as dimensions and doping concentration, were recorded.
   - The sample was cleaned with isopropyl alcohol to remove surface contaminants and improve thermal and electrical contact.
2. **System Calibration and Setup:**
   - The aluminum ruler was adjusted to match the length of the sample.
   - The sample was securely placed between the hot and cold bases, which were made of hollow aluminum to facilitate thermal exchange.
   - The Peltier module designated for cooling was mounted on one base, while the heating module was placed on the opposite base.
3. **Temperature Gradient Application:**
   - The **hot end** of the sample was gradually heated using the Peltier heater, while the cold end was maintained at a stable temperature through the cooling module.
   - The temperature gradient across the sample was controlled incrementally and monitored using the four-channel thermometer.
4. **Voltage Measurement and Conductivity Determination:**
   - As heat flowed through the semiconductor sample, charge carriers (electrons in n-type and holes in p-type materials) migrated accordingly, generating a voltage due to the Seebeck effect.
   - A **digital voltmeter** was connected across the sample to measure the induced voltage.
   - The polarity of the measured voltage provided a direct indication of the sample's conductivity type:
     - **For n-type semiconductors:** The hot end became positively charged, while the cold end acquired a negative charge.
     - **For p-type semiconductors:** The hot end became negatively charged, while the cold end gained a positive charge.
     - If the voltmeter’s negative terminal was connected to the hot side, a negative reading confirmed an n-type sample, whereas a positive reading indicated a p-type material.
5. **Thermoelectric Performance Analysis:**
   - The voltage response was recorded over time as the temperature gradient was increased in increments.
   - Seebeck coefficient ($S = \Delta V / \Delta T$) was calculated to quantify the thermoelectric properties of each sample.
   - The system was tested under different environmental conditions, including solar-powered operation, to assess energy efficiency and practical applicability.

6. Validation and Data Analysis:

- The voltage-temperature data were compared with theoretical predictions and existing literature values for semiconductor thermoelectric behavior.
- Multiple test cycles were conducted to ensure repeatability and minimize experimental errors.

2.3. Summary of Experimental Conditions

This methodology enables a reliable and energy-efficient approach for semiconductor conductivity classification, eliminating the need for traditional Hall Effect **s**etups and bulky external heating systems. Table (1) summarizes the experimental conditions.

Table (1): Properties of the Thermoelectric (Peltier) Module.

Parameter	Specification
Peltier Module Model	12706
Maximum Power Output	50W
Operating Voltage	12V
Maximum Current	6.4A
Hot End Max Temp	~66°C
Cold End Min Temp	~7°C
Solar Panel Output	100W
Battery Capacity	100Ah
Thermometer Channels	4
Voltage Measurement	Digital Voltmeter

Figure (3): The implemented Seebeck system during testing a sample (p-type silicon).

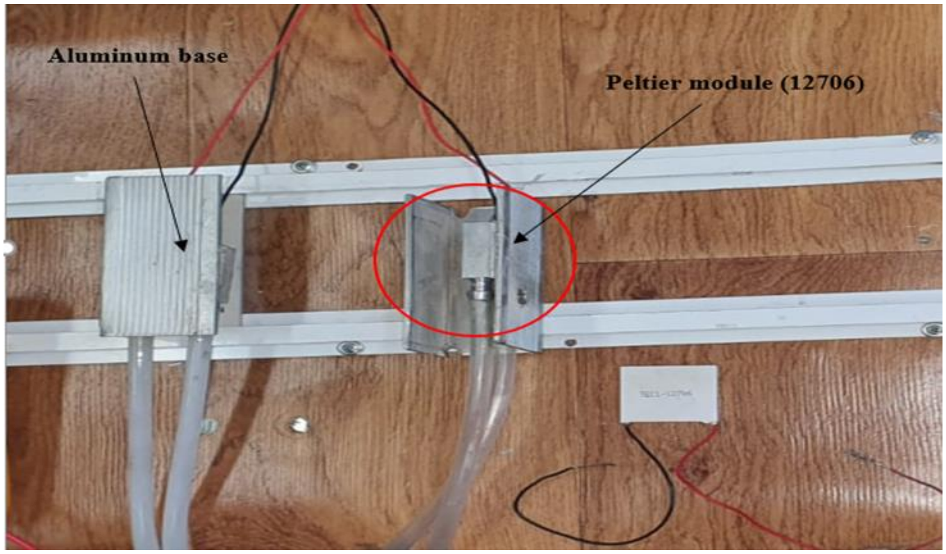

Figure (4): A photograph of Seebeck device construction.

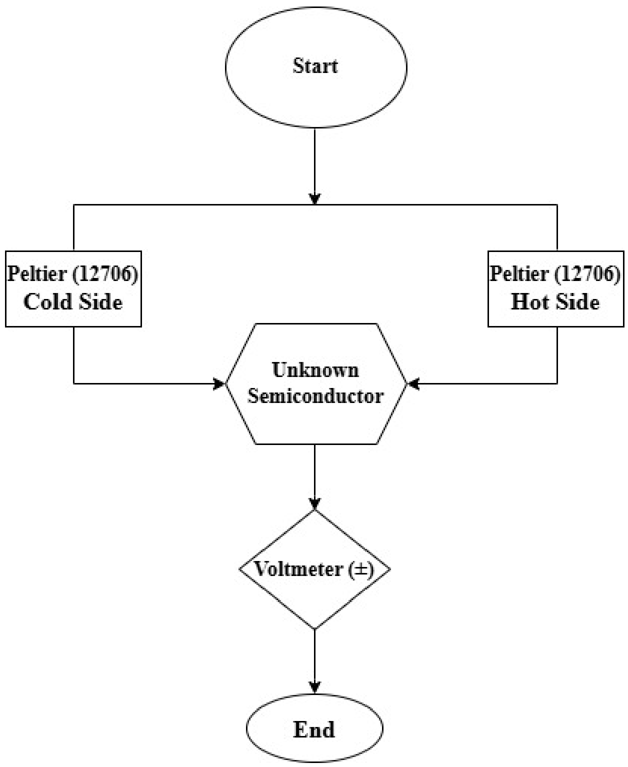

Figure (5): Connecting of Semiconductor with Peltier.

3. Result and Discussion

Figure (6) illustrates the relationship between voltage and temperature differential for the p-type thermoelectric sample, showing the variations caused by the operation of the thermoelectric pump. Initially, the temperature differential decreases to 13°C. Once the heat source is activated, the temperature at the hot end rises to 20°C. At this point, the Seebeck coefficient for the p-type sample is recorded at -0.0011, generating a corresponding voltage of -0.008V.

As the system reaches its peak, the hot end temperature increases further to 48.2°C, while the temperature differential narrows to 5.8°C. At this stage, the Seebeck coefficient reaches -0.0477, and the corresponding voltage for the p-type sample rises to -2.3V, as shown in Figure (6). This behavior indicates a significant increase in voltage output as the temperature gradient becomes more pronounced, emphasizing the sensitivity of the p-type sample to changes in thermal conditions.

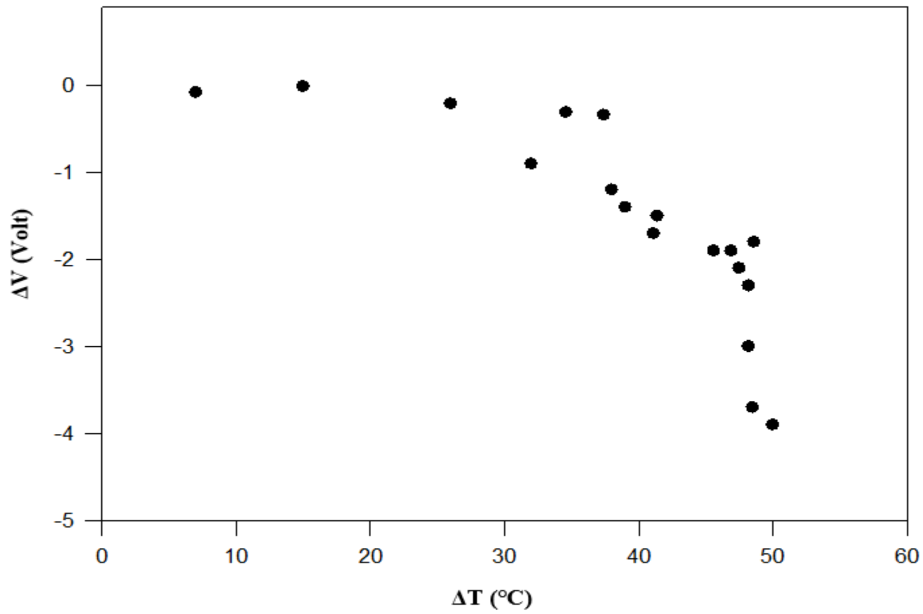

Figure (6): Change in voltage and temperature difference of the p-type sample.

In contrast, the n-type sample behaves differently under similar conditions, as shown in Figure (7). The temperature decrease is more localized, with the temperature at the cold end stabilizing at 0.4°C, while the hot end reaches 50°C. Under these conditions, the generated voltage for the n-type sample is measured at 0.002V, which remains constant until thermal equilibrium is achieved.

As the temperature rises, the Seebeck coefficient for the n-type sample also increases, reaching 0.00037. This increase is attributed to changes in the material's electronic and thermal properties as the system absorbs thermal energy. A key factor driving this behavior is the rise in thermal energy, which excites charge carriers (electrons and holes). This excitation enhances the movement of charge carriers from regions of lower energy (cold end) to regions of higher energy (hot end), thereby generating a larger voltage difference across the sample. Consequently, the Seebeck coefficient increases due to this temperature-induced charge carrier mobility, leading to a greater voltage output at a constant temperature gradient [5].

Both p-type and n-type samples exhibit distinct responses to temperature changes, with the p-type sample showing a more pronounced voltage increase as the temperature differential narrows, while the n-type sample demonstrates a more gradual rise in voltage output as thermal energy excites the charge carriers.

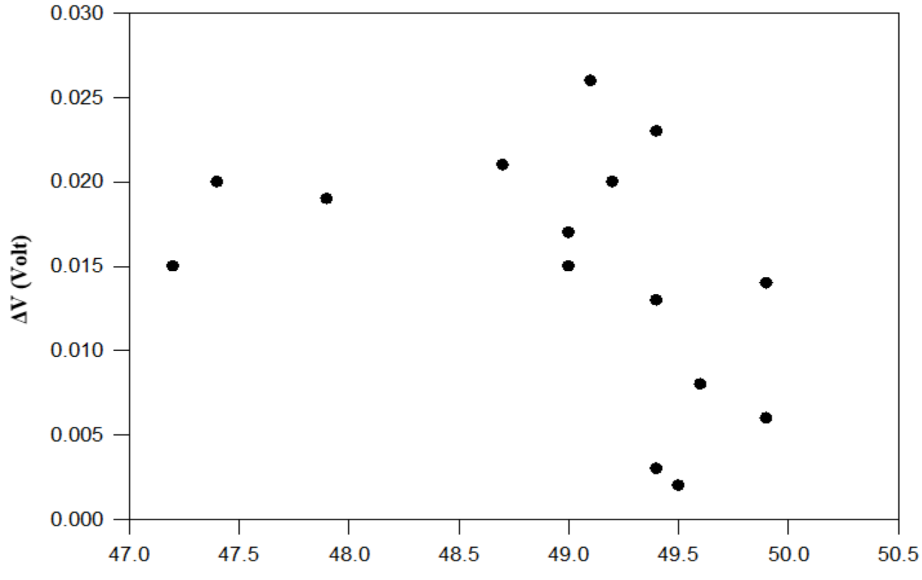

Figure (7): Change in voltage and temperature difference of the n-type sample.

The silicon-based specimen in our investigation generates distinct voltages when subjected to varying temperatures at both ends. This is achieved by utilizing both a cold and a hot source on the Peltier module. Figure (8) illustrates this phenomenon using two silicon wafers of indeterminate conductivity under controlled laboratory conditions. A temperature difference within the sample induces the Seebeck effect, where a greater temperature gradient between the cold and hot ends increases the generated electrical potential until thermal equilibrium is reached, and the charge carriers within the sample equalize. The investigations indicate that the minimum voltage achievable through the thermoelectric effect is -0.08V, with the heat source maintained at 57°C. In addition, we illustrate the direction of current flow within the semiconductor and the resulting polarity inversion. At precisely 36 minutes, the temperature at the device's cooled end reached 7°C, while the Seebeck coefficient was recorded at -0.0078, with a temperature difference of 57°C for the p-type sample test. The observed temperature differences lead to the random motion of charge carriers, causing voltage variations in a nonlinear and unpredictable manner.

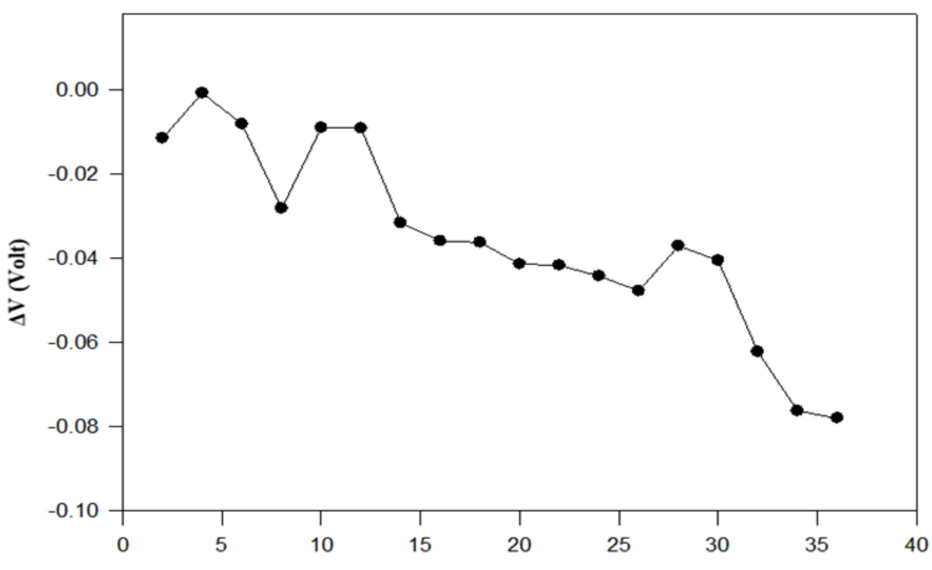

Figure (8): Testing of p-type semiconductor with a positive polarity of the voltmeter connected to the hot side of the sample.

Figure (9) illustrates the relationship between temperature difference and elapsed time for an n-type Peltier device. When a temperature difference of 50°C is achieved across the device, the hot side of the module rapidly stabilizes at approximately 57°C in less than a minute. This rapid response presents the efficiency of Peltier devices in managing temperature gradients.

Peltier modules operate based on the Peltier effect, where an electrical current creates a thermal difference between two sides of the device, one side absorbs heat (cold side), while the other side releases heat (hot side). This characteristic makes them ideal for precise temperature control in various applications, such as cooling electronics or maintaining specific thermal conditions.

During continuous operation, thermal equilibrium is reached when the rate of heat generation within the Peltier module equals the rate at which heat is dissipated into the surrounding environment. Maintaining this balance is crucial for the long-term performance of the device. Without effective heat dissipation, the module's efficiency may degrade due to overheating, potentially leading to thermal saturation and eventual failure.

The experimental results demonstrate the effectiveness of using a water-cooled heat exchanger to enhance the heat dissipation capacity of the Peltier system. Water-cooled systems provide superior heat transfer compared to air-cooled alternatives due to water's higher thermal conductivity and specific heat capacity. This allows for more efficient heat removal from the hot side of the Peltier module, preventing temperature buildup that would otherwise reduce its efficiency.

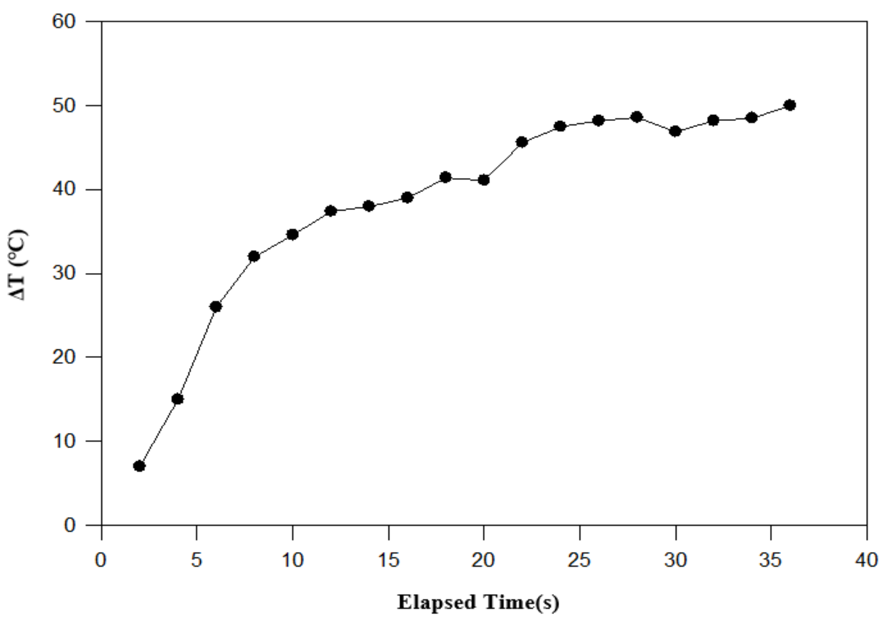

Figure (9): Temperature difference versus elapsed time of n-type sample.

4. Conclusions

This work represents a significant advancement in semiconductor analysis by improving device performance and efficiency. The innovative technology integrates the Seebeck and Peltier effects, enhancing our understanding of thermoelectric phenomena and revolutionizing the approach to identifying semiconductor conductivity types. The system's use of Peltier elements for both cooling and heating marks a major improvement in energy efficiency, reducing operational costs and minimizing environmental impact. Moreover, its capability to operate using solar energy underscores its potential for sustainable and practical applications in the field. The laboratory experiments with silicon samples demonstrate the system's accuracy and reliability in determining semiconductor conductivity types, which is an essential factor in semiconductor research and development, where precise characterization is critical. This technology not only represents progress in thermoelectric research but also contributes to a more sustainable and technologically advanced future.

Conflict of Interest: The authors declare that there are no conflicts of interest associated with this research project. We have no financial or personal relationships that could potentially bias our work or influence the interpretation of the results.

Editorial Transparency: Omar A. Abdulrazzaq is the Editor of the Iraqi Journal of Industrial Research. Despite this role, the peer review process and the final decision were conducted independently, ensuring that his editorial role did not influence the outcome in any way.

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