

# STUDY OF THE STRUCTURAL AND ELECTRONIC CHARACTERISTICS OF ZnO AND Cu-DOPED ZnO PELLETS AS ALTERNATIVE THERMOELECTRIC GENERATOR ELEMENT

Prastika Ramadhani, Autia Nurul Pujianti, Akbar Sujiwa, Nur Aini Fauziyah\*

*Department of Physics, Engineering and Science of Faculty, Universitas Pembangunan Nasional "Veteran" Jawa Timur, Indonesia*

*{ Received: 13<sup>th</sup> December 2025; Revised: 11<sup>th</sup> May 2026; Accepted: 19<sup>th</sup> Juny 2026 }*

## ABSTRACT

In this study, a flexible thermoelectric generator (FTEG) based on ZnO was developed, employing an intrinsically n-type ZnO and Cu-doped ZnO, which is expected to modify the electrical properties of ZnO toward p-type behavior. The ZnO:Cu samples were synthesized using the sol-gel method and subsequently characterized using X-Ray Diffraction (XRD), UV-Vis spectroscopy, and electrical measurement. The UV-Vis result shows a reduction in band gap energy from 3.28 eV for ZnO to 3.12 eV for ZnO:Cu. This decrease indicates successful doping, which reduces the band gap energy and facilitates electron excitation from the valence band to the conduction band at room temperature. Electrical measurements reveal that ZnO:Cu pellets generate higher voltages compared to pure ZnO, suggesting that Cu doping effectively improves the electrical sensitivity of the material. In addition, the polishing process also affects the electrical output, where polished pellets exhibit higher voltage values than unpolished ones. Overall, the results indicate that Cu doping enhances the electrical properties of ZnO-based thermoelectric materials, highlighting their potential application as constituent materials in FTEG devices.

**Keywords:** ZnO; Cu-doped ZnO; Thermoelectric; Semiconductor; Band gap

## Introduction

Energy, one of humanity's primary needs, continues to increase alongside population growth.<sup>1</sup> To date, most energy is still produced from non-renewable resources, which contribute to greenhouse gas emissions and global warming.<sup>2</sup> Renewable Energy (RE) has emerged as a solution to these issues, especially considering Indonesia's abundant natural resources, which provide strong potential for the development of renewable technologies. However, the utilization of RE in Indonesia currently accounts for only 4% of the total national energy mix. Several renewable sources, such as solar energy, hydropower, industrial waste, and livestock waste, are already being harnessed, yet remain limited in scale.<sup>3</sup>

Energy is not only sourced from the environment but can also be harvested from the human body, such as through physical

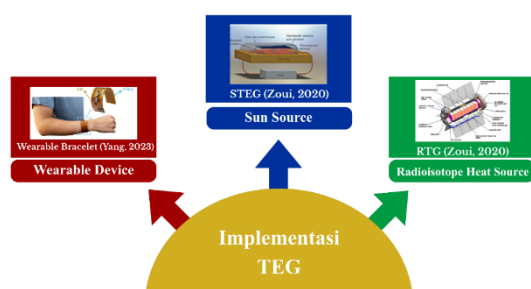
movements and body heat. In a resting state, the human body generates approximately 60 to 180 W of heat, which is released through convection and radiation.<sup>4</sup> This wasted heat has the potential to be converted into electrical energy for wearable devices. However, much of this thermal energy still dissipates into the environment, while current body-temperature, heart-rate, and oxygen-level sensors function solely as detectors without integrated mechanisms for energy storage or conversion.

The Seebeck effect provides a means to convert thermal energy into electrical power by utilizing the temperature difference between two metallic materials. A larger temperature gradient results in a higher output voltage. This energy conversion mechanism can be implemented by exploiting the temperature difference between the human body and the surrounding environment using a thermoelectric generator

\*Corresponding author.

E-Mail: nur.aini.fisika@upnjatim.ac.id

(TEG).<sup>5</sup> Thermoelectric generators have been utilized in various applications (Figure 1). For example, Yang<sup>6</sup> developed a flexible thermoelectric generator for wearable bracelets by harnessing the temperature difference between the human body and the surrounding environment. TEGs have also been advanced into Solar Thermoelectric Generators (STEGs), which are designed to recover heat from solar radiation and convert it into electricity. In addition, TEG technology is employed in Radioisotope Thermoelectric Generators (RTGs), which serve as power sources for spacecraft.<sup>7</sup>



**Figure 1.** Applications of TEG Technology

A Thermoelectric Generator (TEG) is a device capable of producing a stable and consistent DC voltage by utilizing the temperature difference between its two sides. One of the key advantages of TEGs is their ability to operate continuously and reliably without requiring complex environmental conditions or an external energy supply, making them highly suitable for wearable devices such as smartwatches, health sensors, and other portable technologies.<sup>8</sup> Thermoelectric generators operate based on three fundamental effects: the Seebeck, Peltier, and Thomson effects, which enable the direct conversion of temperature gradients into electrical energy.<sup>9</sup> However, most conventional TEGs remain rigid, bulky, and difficult to shape, making them less ideal for integration onto flexible surfaces. Meanwhile, wearable devices require materials that are lightweight and flexible.

TEGs are composed of thermoelectric materials typically made from semiconductors, polymers, or ceramics. Among these categories, semiconductors are the most commonly used materials for thermoelectric cells. The

semiconductor components consist of p-type and n-type materials.<sup>10</sup> Semiconductors are preferred for thermoelectric applications because they generally exhibit high Seebeck coefficients, typically above  $100 \mu\text{V}/^\circ\text{C}$ . Bismuth telluride ( $\text{Bi}_2\text{Te}_3$ ) is one of the most widely used thermoelectric semiconductors due to its high atomic mass.<sup>11</sup> However, according to Guo,<sup>12</sup> tellurium is toxic and environmentally unsafe for long-term use, prompting research into alternative semiconductor materials that can replace tellurium.

Zinc oxide (ZnO) is one of the most extensively studied semiconductor materials due to its diverse functional properties, abundant availability, and relatively low cost. ZnO exhibits a Seebeck coefficient in the range of  $-350$  to  $-430 \mu\text{V}/\text{K}$ .<sup>13</sup> indicating its potential for thermoelectric applications. In general, ZnO is classified as an n-type semiconductor with a wide band gap of approximately  $3.33 \text{ eV}$ .<sup>14</sup> The band gap refers to the energy difference between the valence band and the conduction band, which determines the amount of energy required for electrons to transition from the valence band to the conduction band. In general, semiconductor band gaps range from  $0$  to  $4 \text{ eV}$ , where smaller band gaps allow electrons to transition more easily, resulting in more efficient electrical current generation.<sup>15</sup> The relatively large band gap of ZnO contributes to its strong photocatalytic activity. However, this wide band gap also poses limitations for certain applications, particularly those requiring enhanced n-type semiconductor performance.<sup>16</sup> To overcome this limitation, material modification through a doping process using other elements is required. Copper (Cu) is one of the commonly used dopants for this purpose.<sup>17</sup> Cu doping in ZnO has been reported to reduce the band gap value and enhance its electrical conductivity, thereby improving the electronic characteristics and charge transport properties of the material.<sup>18</sup> According to previous research,<sup>19</sup> Cu doping in ZnO is reported to induce p-type behavior due to the formation of acceptor defects and hole carriers. Therefore, Cu-doped ZnO exhibits significant potential as a semiconductor material for the development of Flexible Thermoelectric Generator (FTEGs).

Several previous studies have explored the development of Thermoelectric Generators (TEGs) using semiconductor materials. For instance, Feng<sup>16</sup> fabricated thermoelectric semiconductor materials using BiCuSeO as the n-type component and Sb-doped BiCuSeO as the p-type component, where the band gap of BiCuSeO was 0.478 eV and that of SbCuSeO was 0.329 eV. This reduction in band gap indicates that electrons can be more easily excited from the valence band to the conduction band, increasing intrinsic carrier concentration and improving electrical transport properties. Additionally, Muntini<sup>17</sup> successfully fabricated a Thermoelectric Generator module using antimony telluride ( $\text{Sb}_2\text{Te}_3$ ) as the p-type semiconductor and bismuth telluride ( $\text{Bi}_2\text{Te}_3$ ) as the n-type semiconductor. Furthermore, Yang<sup>6</sup> advanced TEG technology by developing a Flexible Thermoelectric Generator (FTEG) that utilizes the temperature gradient between body heat and the surrounding environment as its energy source. In another study, Xu<sup>18</sup> reconfigured FTEG devices using TE chips fabricated from MXene/ $\text{Bi}_2\text{Te}_3$  composite films. However, tellurium is known to be toxic and environmentally hazardous for long-term use, prompting research into alternative semiconductors that can replace tellurium. Guo<sup>12</sup> addressed this issue by developing a Flexible Thermoelectric Generator using  $\text{Ag}_2\text{Se}$  as the n-type material and a combination of PEDOT:PSS polymer and CNTs as the p-type material. This material combination enables FTEG devices to become thinner, lighter, and more flexible while maintaining strong thermoelectric performance. Despite these advances, few TEG or FTEG studies have utilized ZnO and Cu-doped ZnO as semiconductor materials. In fact, environmentally friendly, non-toxic, easy-to-synthesize, and low-cost materials are urgently needed for the continued development of FTEG technology.

Based on the above discussion, it is important to evaluate the initial characteristics of each semiconductor component before its implementation in an FTEG device by measuring the sample properties before

thermal treatment. This study focuses on a preliminary investigation of ZnO-based semiconductor materials for FTEG applications, including intrinsically n-type ZnO and Cu-doped ZnO, which is expected to modify the electrical properties of ZnO toward p-type behavior. The output voltage and band gap energy of each sample were measured as initial parameters to assess the potential of the materials' electrical properties as candidates for FTEG components.

## Methods

The equipment used in this study included a centrifuge, mesh sieve, digital thermometer, oven, high-temperature furnace, hydraulic press, and pellet mold. The materials employed were zinc acetate dihydrate  $\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$  (SAP), copper(II) acetate monohydrate  $\text{Cu}(\text{CH}_3\text{COO})_2 \cdot \text{H}_2\text{O}$  (Merck), isopropanol (Merck 1.09634.2500, 2.5 L), distilled water, and monoethanolamine (MEA) for the synthesis of Cu-doped ZnO (ZnO:Cu) semiconductors. Distilled water was used for washing residues during the wet-chemical synthesis process. For pellet fabrication, commercial zinc oxide powder (SAP), polyvinyl alcohol (PVA; Danka Poval), and 70% ethanol were utilized. Characterization was carried out on both the furnace-treated Cu-doped ZnO powder and the pure ZnO powder. The tests performed included X-ray Diffraction (XRD, Phillips) to identify the phase composition, UV-Vis spectroscopy (Phillips) to determine the band gap energy, and electrical voltage measurements.

ZnO and Cu-doped ZnO were synthesized using the sol-gel method. Zinc acetate dihydrate (2.74 g) was dissolved in 50 mL of isopropanol and stirred at 350 rpm and 50°C for 40 minutes. This concentration was selected based in previous research,<sup>14</sup> which demonstrated superior doping properties. Separately, copper(II) acetate (0.089 g) was dissolved in 2.976 mL of distilled water, then added dropwise into the zinc acetate solution and stirred for another 40 minutes at room temperature. Monoethanolamine (MEA, 1.4 mL) was added, and the mixture was stirred



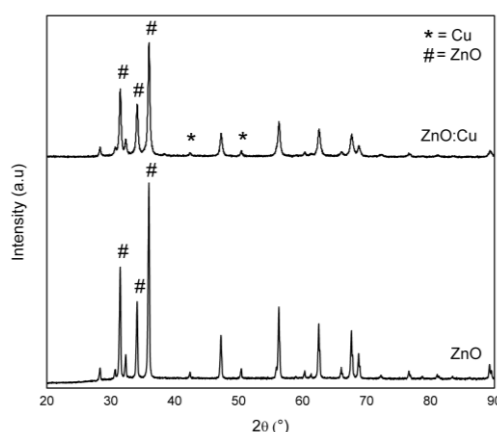
for 90 minutes until a sol was formed, followed by aging for approximately 48 hours to allow precipitation. The precipitate was filtered, washed, centrifuged, dried at 110°C for 1 hour. The dried powder was then ground using a mortar and calcined at 500°C for 2 hours to induce phase transformation in the doped sample. Pellet fabrication was carried out by mixing ZnO or ZnO:Cu powder (0.9 g) with PVA (0.1 g) and 70% ethanol (3.33 mL), followed by grinding for 15 minutes and heating at 80°C until dry. The dried powder was sieved and placed into a die set coated with zinc stearate, followed by hydraulic pressing at a pressure of 86 MPa for approximately 3 minutes to form pellets. The pellets were subsequently sintered at 1000°C for 2 hours to reduce porosity. Furthermore, phase composition and band gap analyses were performed on both ZnO and Cu-doped ZnO samples as part of the initial structural and electronic characterization of the materials.

## Result and Discussion

### a. X-Ray Diffraction Measurement Spectrum

XRD characterization was carried out to determine the phase purity and crystallinity of the samples. The diffraction patterns were recorded within the  $2\theta$  range of 20°-90°. Figure 2 shows the diffraction profiles of the pure ZnO and Cu-doped ZnO samples. For the pure ZnO sample, the main diffraction peaks appeared at  $2\theta = 31.73^\circ$ ,  $34.39^\circ$ , and  $36.21^\circ$ , corresponding to the [100], [002], and [101] planes of the hexagonal structure, in agreement with COD data number 2300112. These results are consistent with the findings of Maddu,<sup>19</sup> who reported similar peak positions for ZnO. After Cu doping, these three peaks exhibited slight shifts to  $31.83^\circ$ ,  $34.42^\circ$ , and  $36.28^\circ$ . Such shifts indicate lattice distortion due to the substitution of  $\text{Zn}^{2+}$  by  $\text{Cu}^{2+}$ , whose smaller ionic radius leads to a slight lattice contraction. This distortion suggests that a portion of Cu was successfully incorporated into the ZnO lattice. In addition to the peak shifts, additional peaks were observed at  $2\theta = 43.10^\circ$  and  $50.03^\circ$ , which

correspond to metallic Cu. This observation is consistent with the results reported by Alatawi,<sup>20</sup> who also found peak shifts in Cu-doped ZnO along with secondary peaks near these angles. Using MAU analysis, the crystal sizes of ZnO and ZnO:Cu were determined to be 135,87 nm and 138,45 nm, respectively. The presence of these extra peaks indicates that not all Cu ions were substituted into the ZnO lattice; instead, excess Cu formed a secondary Cu phase, implying an overdoping condition.



**Figure 2.** X-Ray Diffraction Pattern from ZnO and ZnO:Cu using Cu K- $\alpha$

**Table 1.** Comparison of ZnO and ZnO:Cu

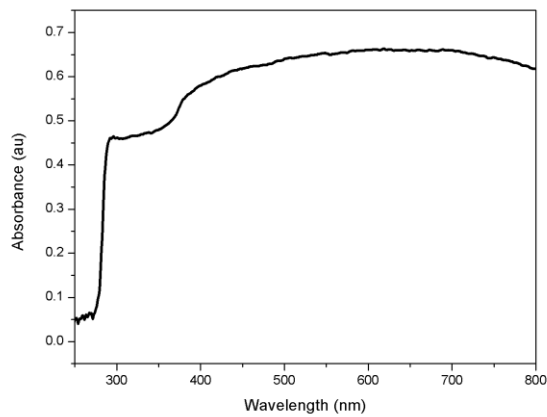
| Sample | ZnO (% mol) | Cu (% mol) |
|--------|-------------|------------|
| ZnO    | 100%        | 0%         |
| ZnO:Cu | 91.8%       | 8.2%       |

In addition, peak broadening was observed in ZnO:Cu after calcination at 500°C, indicating a reduction in crystallite size. According to Das et al. (2017), this phenomenon is attributed to the decrease in crystallite size with increasing Cu concentration.<sup>24</sup>

Table 1 presents the molar composition ratio of ZnO and Cu for the two samples used in this study. The pure ZnO sample consists of 100 mol% ZnO with no dopant added. In contrast, the Cu-doped ZnO sample contains 91.8 mol% ZnO and 8.2 mol% Cu. This composition ratio ensures that Cu acts as a minor dopant in the ZnO matrix rather than as a primary component. The difference in composition also serves as the basis for

analyzing the observed structural changes and the appearance of additional peaks in the XRD results.

### b. UV-Vis Spectroscopy



**Figure 3.** Absorbance Spectrum from ZnO sample

UV-Vis spectrophotometry was carried out to determine the band-gap energy of the samples. The samples were analyzed over a wavelength range of 300-800 nm, and the data were subsequently processed using the Tauc plot method to obtain the band-gap energy based on Equation 1.

$$(\alpha h\nu)^2 = k(h\nu - E_g) \quad (1)$$

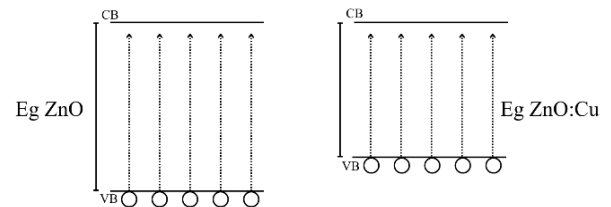
Where  $\alpha$  is the absorption coefficient,  $h\nu$  is the photon energy (in eV),  $n = 2$  is the constant for a direct band-gap semiconductor,  $k$  is a material constant, and  $E_g$  is the band-gap energy. To obtain the band-gap value, a plot is constructed with  $h\nu$  (eV) on the x-axis and  $(\alpha h\nu)^2$  on the y-axis, as illustrated in Figure 3.

**Table 2.** Band-Gap Energy of ZnO and ZnO:Cu

| Sample | Energy Gap (eV) |
|--------|-----------------|
| ZnO    | 3.28            |
| ZnO:Cu | 3.12            |

Fundamentally, ZnO is an n-type semiconductor with a band-gap energy of approximately 3.10-3.37 eV. This band-gap value determines the amount of energy required for electrons to be excited from the valence band (VB) to the conduction band (CB). Based on Table 2, the UV-Vis results

obtained in this study show that the pure ZnO sample has a band gap of 3.28 eV, while the Cu-doped ZnO sample exhibits a reduced band gap of 3.12 eV. This decrease in band-gap energy indicates the successful incorporation of Cu dopants into the ZnO lattice. The band-gap reduction occurs due to the substitution of  $\text{Zn}^{2+}$  sites  $\text{Cu}^{2+}$  ions. Since the ionic radius of  $\text{Cu}^{2+}$  is slightly smaller than that of  $\text{Zn}^{2+}$ , its insertion causes local lattice distortion and introduces additional energy levels near the valence band. The presence of these  $\text{Cu}^{2+}$ -induced states lowers the transition energy required for electrons to move from the VB to the CB, resulting in a smaller measured band gap. The mechanism underlying this band-gap modification is illustrated in Figure 4.



**Figure 4.** Visualization of the Band Gap of ZnO and ZnO:Cu

This reduction in band-gap energy affects the electrical properties of the material. A smaller band gap facilitates the excitation of electrons into the conduction band, thereby enhancing its electrical conductivity. Thus, Cu doping not only modifies the optical characteristics of ZnO but also improves its electrical response through the alteration of its energy-band structure.

Thermoelectric performance cannot be inferred solely from band-gap narrowing. In this study, the observed band-gap reduction is closely related to the substitutional incorporation of Cu ions (~3%) at Zn lattice sites in ZnO, which introduces acceptor-like states and promotes p-type (hole) conductivity. This interpretation is supported by previous research by Joshi & Chaudhri,<sup>25</sup> which confirms p-type behavior in doped samples and reveals that carrier concentration increases significantly with increasing Cu content (3 and 6%), reaching the order of  $10^{15}$

$\text{cm}^{-3}$ , while carrier mobility decreases due to enhanced impurity and defect scattering.

Furthermore, Cu-induced lattice distortion and defect formation are expected to intensify phonon scattering, potentially reducing thermal conductivity, which is advantageous for

improving the figure of merit (ZT). Nevertheless, since ZT arises from the interdependence of the Seebeck coefficient, electrical conductivity, and thermal conductivity, comprehensive transport measurements are necessary for a definitive assessment of thermoelectric performance.<sup>25</sup>

**Table 3.** Measured Voltages of The Pellets

| Pellet Type | Number of Pellets | Pellet Index | Measurement No. | Voltage (mV) | Average (mV) | SD       | $\bar{x} \pm dx$ |
|-------------|-------------------|--------------|-----------------|--------------|--------------|----------|------------------|
| ZnO         | 3                 | 1            | 1               | 1.3          | 1.4          | 0.604152 | $1.4 \pm 0.60$   |
|             |                   |              | 2               | 1.1          |              |          |                  |
|             |                   |              | 3               | 2.4          |              |          |                  |
|             |                   |              | 4               | 1.4          |              |          |                  |
|             |                   |              | 5               | 0.8          |              |          |                  |
|             | 3                 | 2            | 1               | 1.5          | 1.38         | 0.501996 | $1.38 \pm 0.50$  |
|             |                   |              | 2               | 1            |              |          |                  |
|             |                   |              | 3               | 2.2          |              |          |                  |
|             |                   |              | 4               | 1.2          |              |          |                  |
|             |                   |              | 5               | 1            |              |          |                  |
|             | 3                 | 3            | 1               | 1.2          | 1.32         | 0.311448 | $1.32 \pm 0.31$  |
|             |                   |              | 2               | 1.7          |              |          |                  |
|             |                   |              | 3               | 1            |              |          |                  |
|             |                   |              | 4               | 1.1          |              |          |                  |
|             |                   |              | 5               | 1.6          |              |          |                  |
| ZnO:Cu      | 3                 | 1            | 1               | 5.5          | 5.08         | 0.432435 | $5.08 \pm 0.43$  |
|             |                   |              | 2               | 5.4          |              |          |                  |
|             |                   |              | 3               | 5            |              |          |                  |
|             |                   |              | 4               | 5.1          |              |          |                  |
|             |                   |              | 5               | 4.4          |              |          |                  |
|             | 3                 | 2            | 1               | 5.7          | 5.18         | 0.408656 | $5.18 \pm 0.40$  |
|             |                   |              | 2               | 4.7          |              |          |                  |
|             |                   |              | 3               | 5            |              |          |                  |
|             |                   |              | 4               | 5.5          |              |          |                  |
|             |                   |              | 5               | 5            |              |          |                  |
|             | 3                 | 3            | 1               | 5.9          | 5.3          | 0.524404 | $5.13 \pm 0.52$  |
|             |                   |              | 2               | 4.7          |              |          |                  |
|             |                   |              | 3               | 4.8          |              |          |                  |
|             |                   |              | 4               | 5.5          |              |          |                  |
|             |                   |              | 5               | 5.6          |              |          |                  |

### c. Voltage Measurement

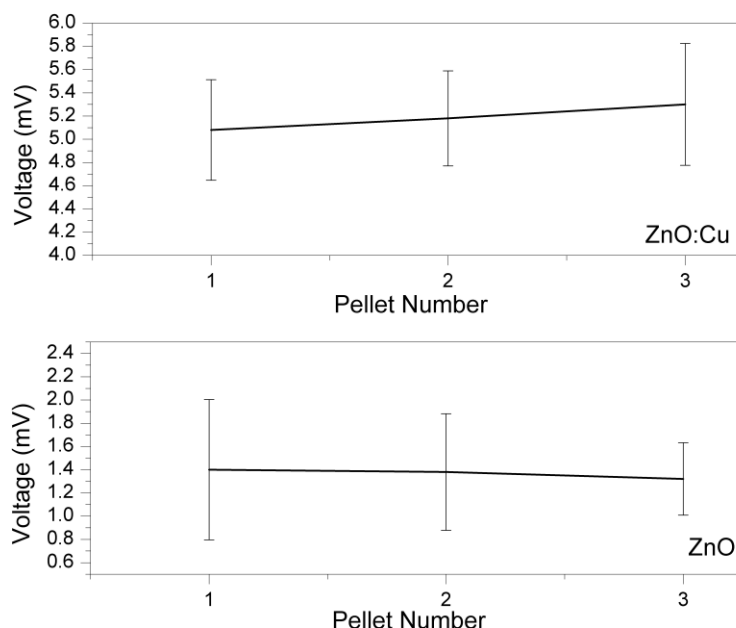
Voltage measurements were performed on two types of pellets fabricated with dimensions of  $3 \times 3$  mm. Each pellet was polished to ensure a smooth and uniform surface, minimizing noise during multimeter readings. Measurements were

conducted on three pellets for each material, with five repetitions per pellet. As presented in Table 3, the pure ZnO pellets produced average voltages in the range of 1.32-1.4 mV, whereas the Cu-doped ZnO pellets exhibited higher average voltages, ranging from 5.08-5.3 mV. Although



the measured voltages remain within the millivolt range, this increase indicates that Cu

doping significantly influences the electrical properties of ZnO.



**Figure 5.** Voltage Deviation Plot from ZnO and ZnO:Cu

Figure 5 shows that the voltage error remains relatively high, likely due to the presence of closed porosity within the samples. These closed pores trap air and isolate it from the external environment, thereby affecting the electrical conductivity. This observation is consistent with previous studies by Ijaz<sup>21</sup> and Tristiana,<sup>22</sup> which reported that higher porosity leads to a decrease in the electrical conductivity of a material.

**Table 4.** Voltage of ZnO:Cu Pellets Before and After Polishing

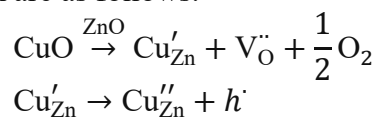
| Pellet Type | Output Voltage Before Polishing (mV) | Output Voltage After Polishing (mV) |
|-------------|--------------------------------------|-------------------------------------|
| ZnO:Cu      | 0.28                                 | 5.08                                |
|             | 0.24                                 | 5.18                                |
|             | 0.34                                 | 5.3                                 |

Voltage measurements were also performed on the ZnO:Cu pellet samples before and after polishing. Table 4 shows that the measured voltage increased significantly after polishing. The voltage of the unpolished pellets ranged from 0.24-0.34 mV, whereas after polishing it increased to 5.08-5.30 mV.

Before polishing, the pellet surface was rough, non-homogeneous, and porous, resulting in a very small contact area between the pellet and the multimeter probes and consequently a high contact resistance. This condition caused the measured voltage to be highly fluctuating and relatively low. After polishing, the pellet surface became smoother and more uniform, reducing contact resistance through improved electron transfer and lower measurement noise. This observation is consistent with the findings of Bishara,<sup>23</sup> who reported that grain boundaries can reduce thermoelectric efficiency, where grain boundary resistivity is strongly dependent on its structural quality. When the grain boundary structure is well-ordered, resistivity decreases; conversely, poorly ordered boundaries lead to increased resistivity. Thus, even if atoms within the crystal lattice are well arranged, disordered atomic arrangements at the boundaries can cause fluctuation in the detected potential. This explains why the polished ZnO:Cu pellets exhibited higher and more stable voltage values compared to the unpolished pellets.

Copper (Cu) doping into the ZnO lattice causes significant structural changes,

indicated by the shift of XRD diffraction peaks due to the substitution of  $\text{Zn}^{2+}$  by  $\text{Cu}^{2+}$ . Since the ionic radius of  $\text{Cu}^{2+}$  (0.73 Å) is smaller than that of  $\text{Zn}^{2+}$  (0.74 Å), this substitution induces distortion and contraction of the crystal lattice. Not all Cu ions are successfully incorporated into the ZnO lattice; excess Cu forms a secondary metallic Cu phase detected at  $2\theta \approx 43.10^\circ$  and  $50.03^\circ$ , indicating an overdoping condition. The defect reactions occurring in Kröger-Vink notation are as follows:



The first reaction indicates the substitution of  $\text{Cu}^{2+}$  at the  $\text{Zn}^{2+}$  site, resulting in an acceptor defect ( $\text{Cu}'_{\text{Zn}}$ ) and oxygen vacancies ( $\text{V}_{\text{O}}^{\bullet\bullet}$ ). The second reaction shows that the acceptor defect  $\text{Cu}'_{\text{Zn}}$  generates holes ( $h^{\bullet}$ ), which are responsible for the p-type behavior in ZnO:Cu.

The impact of Cu doping further affects the electronic properties of the material. The presence of  $\text{Cu}^{2+}$  as an acceptor introduces new energy levels above the valence band, thereby reducing the band gap from 3.28 eV (pure ZnO) to 3.12 eV (ZnO:Cu). This band gap narrowing facilitates electron excitation from the valence band to the conduction band at room temperature, while simultaneously increasing the charge carrier concentration (holes) to the order of  $10^{15} \text{ cm}^{-3}$ . This phenomenon is confirmed by the significant increase in output voltage, from an average of ~1.4 mV in pure ZnO to ~5.2 mV in ZnO:Cu. In addition, lattice distortion caused by doping enhances phonon scattering, which potentially reduces thermal conductivity, an important advantage for improving the figure of merit (ZT) in flexible thermoelectric generator (FTEG) applications.

Intrinsically, ZnO possesses a relatively wide band gap, which makes electron excitation from the valence band to the conduction band more difficult at room temperature. This condition results in very low measured voltages. Doping ZnO with Cu reduces the band gap, allowing electrons to be

more easily excited. This explains why the measured voltage of the Cu-doped ZnO pellets is higher than that of the pure ZnO pellets.

## Conclusion

This study demonstrated that Cu doping modifies the structural, optical, and electrical characteristics of ZnO at a preliminary material level. XRD analysis confirmed the partial substitution of  $\text{Zn}^{2+}$  by  $\text{Cu}^{2+}$  within the hexagonal ZnO lattice, evidenced by peak shifts and the emergence of a secondary metallic Cu phase, indicating an overdoping condition. UV-Vis spectroscopy revealed a reduction in band-gap energy from 3.28 eV (pure ZnO) to 3.12 eV (ZnO:Cu), suggesting that Cu incorporation introduces acceptor-like energy states near the valence band, which facilitates electron excitation at room temperature. Electrical measurements showed that Cu-doped ZnO pellets produced higher output voltages (~5.1–5.3 mV) compared to pure ZnO (~1.3–1.4 mV), indicating an improvement in the electrical response of the material. However, it should be noted that these voltage measurements were conducted without an applied temperature gradient; therefore, the results reflect the material's intrinsic electrical sensitivity rather than Seebeck-based thermoelectric performance. Since thermoelectric efficiency depends on the interplay of the Seebeck coefficient, electrical conductivity, and thermal conductivity, comprehensive transport measurements, including Hall effect, four-probe conductivity, and thermal conductivity characterization, are necessary before any conclusion regarding practical TEG suitability can be drawn. Nonetheless, the observed band-gap narrowing and enhanced electrical response collectively suggest that Cu-doped ZnO warrants further investigation as a candidate material for flexible thermoelectric generator (FTEG) applications.

## Acknowledgment

The authors would like to thank the advisors and laboratory staff who provided



guidance and technical support throughout this research. Appreciation is also extended to the institution for providing facilities and financial support. The authors also acknowledge all individuals who contributed to this work, including those who assisted with proofreading, data processing, and material preparation.

## References

1. Kharisma A, Pinandita S, Jayanti AE. Literature Review: Kajian Potensi Energi Surya Alternatif Energi Listrik. *J En Baru & Terbarukan*. 2024;5(2):145–54. doi:10.14710/jebt.2024.23956
2. Setyono JS, Mardiansjah FH, Astuti MFK. POTENSI PENGEMBANGAN ENERGI BARU DAN ENERGI TERBARUKAN DI KOTA SEMARANG. *JURNAL RIPTEK*. 2019;13(2):177–86.
3. Paturu RO, Yulianingrum AV. Urgensi Pengembangan Kebijakan Energi Baru dan Terbarukan Dalam Rangka Ketahanan Energi Nasional. *JIPSI*. 2023;2(2):170–82. doi:10.58540/jipsi.v2i2.376
4. Tabaie Z, Omidvar A. Human body heat-driven thermoelectric generators as a sustainable power supply for wearable electronic devices: Recent advances, challenges, and future perspectives. *Heliyon*. 2023;9(4):1–20. doi:10.1016/j.heliyon.2023.e14707
5. Lapalutu T, Arbie A. KONVERSI ENERGI TERMAL HASIL PEMBAKARAN ECENG GONDOK (EICHHORNIA CRASSIPES) MENJADI ENERGI LISTRIK MENGGUNAKAN SISTEM TERMOELEKTRIK GENERATOR. *Jurnal Inovasi Fisika Indonesia (IFI)*. 2025;14(1):1–12.
6. Yang S, Li Y, Deng L, Tian S, Yao Y, Yang F, et al. Flexible thermoelectric generator and energy management electronics powered by body heat. *Microsyst Nanoeng*. 2023;9(1):106. doi:10.1038/s41378-023-00583-3
7. Zoui MA, Bentouba S, Stocholm JG, Bourouis M. A Review on Thermoelectric Generators: Progress and Applications. *Energies*. 2020;13(14):3606. doi:10.3390/en13143606
8. Rizaldi R, Edahwati L. Analisa Termoelektrik Generator Dan Motor DC + Kipas Dengan Perbedaan Alas Konduktor Dari Sumber Energi Panas. *flywheel*. 2022;13(2):14–22. doi:10.36040/flywheel.v13i2.5853
9. Muharnif M, Umurani K, Nasution FAA. Analisis Termoelektrik Generator (TEG ) Sebagai Pembangkit Listrik Bersekala Kecil Terhadap Perbedaan Temperatur. *Jurnal Rekayasa Material, Manufaktur dan Energi*. 2022;5(1):26–32.
10. Diki M, Hadi CF, Lestari RF, Nalandari R. Pemanfaatan Termoelektrik Sebagai Sumber Energi Terbarukan. *ZTR*. 2022;4(1):23–5. doi:10.36526/ztr.v4i1.1913
11. Isa PC, Arbie A, Setiawan DGE, Demulawa M, Kurniasari S, Yunus M. ANALISIS PEMANFAATAN BIOMASSA LIMBAH BATANG PADI MENJADI ENERGI LISTRIK MENGGUNAKAN SISTEM TERMOELEKTRIK GENERATOR. *BIOCHEPHY:JSE*. 2025;5(1):296–301. doi:10.52562/biochephy.v5i1.1477
12. Guo R, Shi W, Guo R, Yang C, Chen Y, Wang Y, et al. A Novel PDMS-Based Flexible Thermoelectric Generator Fabricated by Ag<sub>2</sub>Se and PEDOT:PSS/Multi-Walled Carbon Nanotubes with High Output Performance Optimized by Embedded Eutectic Gallium–Indium Electrodes. *Nanomaterials*. 2024;14(6):542. doi:10.3390/nano14060542
13. Sulaiman S, Sudin I, Al-Naib UMB, Omar MF. Review of the Nanostructuring and Doping Strategies for High-Performance ZnO Thermoelectric Materials. *Crystals*. 2022;12(8):1076. doi:10.3390/cryst12081076
14. Supu I, Odde NNS, Hala A. SINTESIS SEMIKONDUKTOR ZnO UNDOPE DAN DOPED Cu<sup>2+</sup> DENGAN VARIASI TEMPERATUR KALSINASI MENGGUNAKAN METODE SOL-



- GEL. Cokroaminoto Journal of Chemical Science. 2022;4(2):9–13.
15. Anugrah MR, Prayitno TB, Suhendar H. PERBANDINGAN PERFORMA ALGORITMA RANDOM FOREST REGRESSOR DAN XGBOOST REGRESSOR DALAM PREDIKSI BAND GAP MATERIAL SEMIKONDUKTOR SILIKON. PROSIDING SEMINAR NASIONAL FISIKA (E-JOURNAL). 2025;13.
  16. Ningsih SKW. SINTESIS DAN KARAKTERISASI NANOPARTIKEL ZnO DOPED Cu<sup>2+</sup> MELALUI METODA SOL-GEL. EKSAKTA. 2017;18(02):39–51. doi:10.24036/eksakta/vol18-iss02/51
  17. Siagian SM, Khairani S, Chrisna Hs S, Tampubolon FR. SINTESIS DAN KARAKTERISTIK SIFAT OPTIK SEMIKONDUKTOR ZnO DAN ZnO DOPPING Cu. Orb J Pend Ilm Fis. 2022;8(1):79. doi:10.31764/orbita.v8i1.8406
  18. Irsyad A, Sanjaya H. PENGARUH VARIASI KONSENTRASI DOPPING CuO DAN ADITIF MONOETHANOLAMINE (MEA) PADA SINTESIS NANOPARTIKEL ZnO DAN UJI AKTIVITAS FOTOKATALITIKNYA. Journal of Research and Education Chemistry. 2025;7(1):66–74.
  19. Ghahramanifard F, Rouhollahi A, Fazlollahzadeh O. Electrodeposition of Cu-doped p-type ZnO nanorods; effect of Cu doping on structural, optical and photoelectrocatalytic property of ZnO nanostructure. Superlattices and Microstructures. 2018;114:1–14. doi:10.1016/j.spmi.2017.07.019
  20. Feng B, Li G, Hou Y, Zhang C, Jiang C, Hu J, et al. Enhanced thermoelectric properties of Sb-doped BiCuSeO due to decreased band gap. Journal of Alloys and Compounds. 2017;712:386–93. doi:10.1016/j.jallcom.2017.04.121
  21. Muntini MS, Afyanti MM, Oktavianoni FF, Namhongsab W, Ruamruk S, Khottummee N, et al. Fabrikasi Modul Termoelektrik Generator (TEG) menggunakan Semikonduktor Tipe-p SbTe dan Tipe-n BiTe. JFA. 2020;16(1):61. doi:10.12962/j24604682.v16i1.6216
  22. Xu Y, Wu B, Hou C, Li Y, Wang H, Zhang Q. Reconfigurable flexible thermoelectric generators based on all-inorganic MXene/Bi<sub>2</sub>Te<sub>3</sub> composite films. FlexMat. 2024;1(3):248–57. doi:10.1002/flm2.28
  23. Maddu A, Zetria Zikri, Irzaman I. Structure and Morphology of ZnO Nanoparticles Prepared by Sonochemical Method. timeinphys. 2023;1(2):51–8. doi:10.11594/timeinphys.2023.v1i2p51-58
  24. Alatawi NM, Saad LB, Soltane L, Moulahi A, Mjejri I, Sediri F. Enhanced solar photocatalytic performance of Cu-doped nanosized ZnO. Polyhedron. 2021;197:115022. doi:10.1016/j.poly.2021.115022
  25. Das BK, Das T, Parashar K, Parashar SKS. Structural, optical and dielectric study of Cu doped ZnO nanoparticles synthesised by high energy ball milling. Int J Nano and Biomaterials. 2017;7(2):140–9. doi:https://doi.org/10.1504/IJNB.2017.090131
  26. Joshi BC, Chaudhri AK. Sol–Gel-Derived Cu-Doped ZnO Thin Films for Optoelectronic Applications. ACS Omega. 2022;7(25):21877–81. doi:10.1021/acsomega.2c02040
  27. Ijaz U, Siyar M, Park C. The power of pores: review on porous thermoelectric materials. RSC Sustainability. 2024;2(4):852–70. doi:10.1039/D3SU00451A
  28. Tristiana AL, Sembiring S, Simanjuntak W. Struktur Mikro dan Konduktivitas Listrik Keramik Kordierit dengan Penambahan Magnesium Oksida (0, 10, 15 wt %) Berbasis Silika Sekam Padi. Jurnal Teori dan Aplikasi Fisika. 2017;5(1):1–7.
  29. Bishara H, Lee S, Brink T, Ghidelli M, Dehm G. Understanding Grain Boundary Electrical Resistivity in Cu: The Effect of Boundary Structure. ACS Nano. 2021;15(10):16607–15. doi:10.1021/acsnano.1c06367

