

Fabrication and Performance Analysis of Bi_2Te_3 and Sb_2Te_3 Thin Film Thermoelectric Generator for Waste Heat Recovery

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Abstract: Hybridizing thermoelectric generators (TEGs) with renewable energy systems offers a promising route to enhance energy efficiency. However, conventional bulk TEG modules are bulky and impractical for applications requiring lightweight and flexible designs, such as building-integrated systems. This study addresses this limitation by developing a thin film TEG using stoichiometric bismuth telluride (Bi_2Te_3) and antimony telluride (Sb_2Te_3) deposited on a glass substrate via radio frequency magnetron sputtering. The structural, morphological, and thermoelectric properties of the films were analyzed using XRD, FESEM, EDX, Hall effect, and Seebeck coefficient measurements, confirming their suitability for device fabrication. The fabricated TEG, consisting of 6 n-type Bi_2Te_3 and p-type Sb_2Te_3 pairs, achieved a maximum open-circuit voltage of 208.55 mV and power output of 0.54 μW at a temperature difference of 125 K, with a maximum power per unit active planar area of 0.1 $\mu\text{W cm}^{-2}$. These results demonstrate the feasibility of thin film TEGs for integration into lightweight and compact energy-harvesting systems, highlighting their potential in renewable energy applications.

Keywords: thermoelectric generator (TEG); thin film; Bi_2Te_3 ; Sb_2Te_3 ; sputtering

1. Introduction

The global shift towards renewable energy is essential for achieving a sustainable, low-carbon future. However, as the deployment of renewable energy systems increases, so does the challenge of maximizing their efficiency due to fluctuating conditions. For instance, solar photovoltaic (PV) systems capture sunlight to generate electricity, yet only 5–20% of the sun rays are transformed into electricity while the remaining radiation is either transmitted backward or absorbed in the form of heat by the panel (Dwivedi et al., 2020). The heat absorbed by the panel increases its temperature causing irreversible degradation of its electric output power (Parthiban & Ponnambalam, 2022; Shaker et al., 2024). This waste heat can be repurposed and turned into valuable energy using an energy conversion device such as a thermoelectric generator (TEG), which can be integrated with the PV system to increase the overall power output. This integration enhances the overall power output of the system by generating additional electricity from the thermal energy. Instead of allowing the excess heat to dissipate, which could reduce PV efficiency, the TEGs transform it into a secondary energy source, improving the total system efficiency. Such hybrid systems are beneficial in applications where maximizing energy output is crucial, particularly in regions with high solar irradiance.

Thermoelectric (TE) materials have garnered significant attention in recent years due to their unique ability to directly convert heat into electrical energy via the Seebeck effect (Ochieng et al., 2022; Qasim



et al., 2022). Given the current fast-growing demand for efficient energy conversion technologies, this feature makes them a promising solution for waste heat recovery and renewable energy applications. Among the various classes of TE materials, bismuth telluride (Bi_2Te_3) and antimony telluride (Sb_2Te_3) have emerged as frontrunners, owing to their exceptional TE properties at near-room temperatures (Pei et al., 2020; Soleimani et al., 2020). TE performance of a material is evaluated using the dimensionless figure of merit, $ZT = S^2\sigma T/\kappa$. In this equation, S represents the Seebeck coefficient (V/K), σ denotes electrical conductivity ($\Omega\cdot\text{m}^{-1}$), κ indicates thermal conductivity (W/m.K), and T refers to the absolute temperature (K). For a TE material to have a good efficiency, it needs S and σ values to be as high as possible, and the κ value to be as low as possible.

The increasing interest in TE materials has led to a surge in research focused on enhancing their performance through various means, including nanostructuring (Bo et al., 2019; Jaldurgam et al., 2021; Kul'bachinskii, 2019) and alloying (Adam et al., 2020; Saberi & Sajjadi, 2022; Witting et al., 2020). Among the possible TEG configurations, thin film-based devices have shown considerable promise, including reduced thermal conductivity due to quantum confinement effects (Chen et al., 2020; Syafiq et al., 2022), better retention of the thermal gradient (Isram et al., 2023; Karthikeyan et al., 2020), and the potential for integration into micro- and nanoscale electronic devices (Yang et al., 2022; Zeng et al., 2020). Additionally, thin films enable the exploration of novel material combinations and structures that are not feasible in bulk form, potentially leading to enhanced TE performance. In particular, Bi_2Te_3 and Sb_2Te_3 have demonstrated remarkable potential to be fabricated as thin film TEG, with Bi_2Te_3 typically acting as an n-type semiconductor and Sb_2Te_3 as a p-type semiconductor (Musri et al., 2024; Vieira et al., 2019; Witting et al., 2019).

The performance of the TEG is heavily dependent on the quality of the thin films, which is influenced by factors such as film stoichiometry (Rogacheva et al., 2019; Sun et al., 2022), thickness (Andzane et al., 2021; Wanarattikan et al., 2019a), crystallinity (Amirghasemi & Kassegne, 2021; Z. hao Zheng et al., 2020), and the fabrication method used (Ma et al., 2021; Zhu et al., 2021). One of the primary challenges in the fabrication of Bi_2Te_3 and Sb_2Te_3 thin films is the precise control of film composition and thickness. Variation in stoichiometry can lead to significant changes in the electronic and thermal of the films, thereby affecting their overall thermoelectric performance (Kim et al., 2023). A study done by Yonezawa et al., 2020 shows that the carrier concentration of the film sample was significantly affected by the change in atomic composition, where Bi_2Te_3 changed to Bi_1Te_1 due to annealing. Their highest power factor was still less than that of well-established corresponding bulk alloys, due to the slightly deviated composition that included a certain number of defects such as vacancies and antisites caused by the evaporation of Te atoms. Therefore, the fabrication process must be carefully executed and optimized to produce high-quality, defect-free thin films for high-efficiency TEG.

This study aims to explore advanced deposition techniques for the fabrication of Bi_2Te_3 and Sb_2Te_3 thin films, followed by a comprehensive performance analysis of these films when integrated into a TEG. This work reports on the deposition and characterization of the Bi_2Te_3 and Sb_2Te_3 thin film on soda lime glass substrates along with performance analysis of the complete thin film TEG. The films were deposited via radio frequency (RF) magnetron sputtering technique with a top-down configuration, where the cathode was mounted at an angle to the substrate normal, leading to a more concentrated and convergent plasma to the substrate. By correlating the fabrication conditions with the resulting material properties and device performance, this research seeks to provide valuable insights into the fabrication of thin film TEGs in pursuit of a more sustainable energy generation.

1.1. Materials and Method

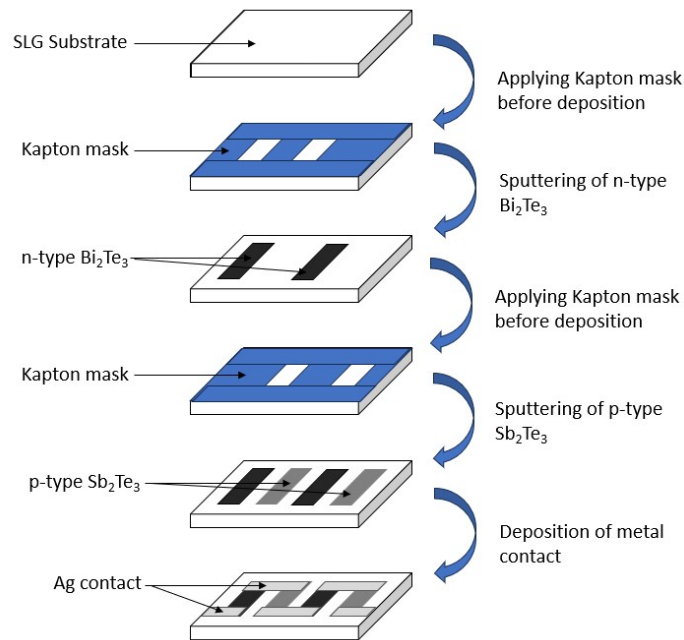
1.1.1. Deposition of Bi_2Te_3 and Sb_2Te_3 Thin Films

Bi_2Te_3 and Sb_2Te_3 thin films were deposited using RF magnetron sputtering on soda lime glass (SLG) substrates that were ultrasonically cleaned with methanol, acetone, ethanol, and deionized water for 10 mins to effectively remove organic contaminants and particulates. Nitrogen gas, hot plate, and UV ozone cleaner were also used to eliminate residues from the substrates. UV ozone treatment further eliminates residual hydrocarbons and introduces surface oxygen functional groups, enhancing surface energy and promoting strong interfacial bonding (Zhang et al., 2019). A sputter target of Bi_2Te_3 (diameter 50.8 mm, thickness 4.25 mm, 99.999% purity), Sb_2Te_3 (diameter 50.8 mm, thickness 6.35 mm, 99.999% purity), with argon gas (99.99% purity) were used for the sputter coating. The samples were deposited without substrate heating using RF power of 75 W for Bi_2Te_3 and 30 W for Sb_2Te_3 at the same deposition time of 60 mins. The parameters were chosen based on the optimised parameters obtained from our previous work (Musri et al., 2024) where the details of the deposition protocol were also extensively discussed. Different RF powers were used to compensate for variations in sputtering yield, atomic mass, and target density, ensuring comparable deposition rates and maintaining film stoichiometry.

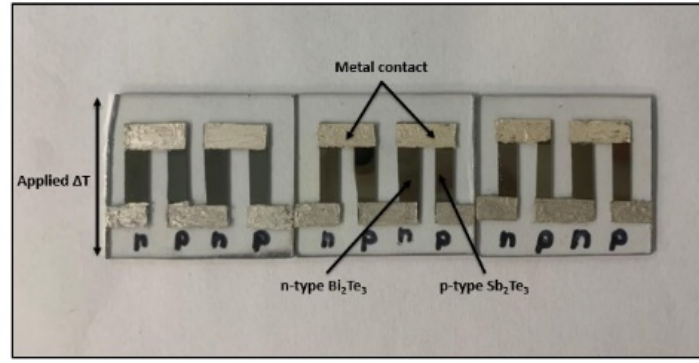
The phase formation of the thin films was analyzed using an X'pert-pro PANalytical X-ray diffractometer with Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$). The lattice parameters a and c were derived from Rietveld refinement of the experimental X-ray diffraction (XRD) data obtained from the as-deposited thin films. Structural reference files for Bi₂Te₃ (PDF 00-015-0863) and Sb₂Te₃ (PDF 01-071-0393) served as input data. Surface microstructure and film thickness were evaluated through topographic and cross-sectional images obtained by Field Emission Scanning Electron Microscopy (FESEM/JEOL, JSM7800F, operating at 3.0 kV). The film composition was confirmed via energy dispersive X-ray spectroscopy (EDX) attached to the FESEM. Hall voltage measurements were conducted using HMS ECOPIA 3000 with a fixed magnetic field of 0.57 T and probe currents of 10 mA and 0.8 mA for Bi₂Te₃ and Sb₂Te₃, respectively, to determine carrier concentration and conductivity. The Seebeck coefficient was measured in-plane using a Linseis LSR-3, with rectangular samples (about 2 cm $\times$ 1.25 cm) mounted for measurement. The absolute Seebeck coefficient was determined in a two-contact configuration relative to a Pt standard, applying a temperature gradient of approximately 25 °C.

1.1.2. Fabrication of Bi₂Te₃/Sb₂Te₃ Thin Film TEG

The thin film TEG was fabricated according to an illustration made by Isotta et al., 2022 with a few adjustments as shown in Figure 1(a). Clean rectangular SLG substrate were used to deposit the TE legs. Kapton mask was applied on the substrate leaving only the space required for sputtering n-type Bi₂Te₃, then Bi₂Te₃ was sputtered on the exposed area. The old Kapton mask was removed and a new one was applied to cover the n-type legs, using paper strips to protect the legs, leaving the area for p-type Sb₂Te₃. After that, Sb₂Te₃ was sputtered and when the mask was removed, the legs were in alternating positioned as shown in Figure 1(a). Finally, Ag paint was utilized to connect all legs in series due to its fast-drying properties and durability, which is crucial for preventing scratches during measurement. Unlike sputtered metal contacts, which may require additional adhesion layers and careful deposition control, Ag paint provides a simple, efficient, and low-contact-resistance solution that adheres well to thermoelectric materials. While contact resistance could influence overall performance, Ag paint forms a sufficiently conductive interface, ensuring stable electrical connections without significantly limiting the efficiency of the TEG. A schematic of the end TEG is visible in Figure 1(a) and the picture of the final thin film TEG is presented in Figure 1(b).



(a)



(b)

Figure 1. (a) Illustration of the steps to fabricate $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ thin film TEG. (b) A scheme of the end thin film TEGs.

1.1.3. Performance Analysis of $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ Thin Film TEG

All performance measurements were conducted under ambient conditions. Open-circuit voltage (V_{oc}) as a function of temperature difference (ΔT) was recorded using a custom setup shown in Figure 2(a). A metal plate served as the heat sink (without active cooling), while a hot plate in contact with the bottom-lateral side of the TEG substrate acted as the heat source. At both ends of the TEG, contacts with springs were affixed, and a Keithley Agilent 34401A voltmeter was used to assess the voltage produced. The temperature of the hot plate was adjusted in increments of 10 °C, ranging from 70 °C to 250 °C. Temperature differences were monitored using a Fluke Ti_{32} thermal camera, as illustrated in Figure 2(a) and Figure 2(b). Current–voltage–power (IVP) characteristics were measured using the setup arranged as shown in the I-V-P schematic in Figure 2(c), with the experimental setup depicted in Figure 2(b). For these measurements, a Keithley Agilent 34401A was used as the voltmeter, a FLUKE 8846A as the ammeter, and a variable resistor. The hot plate temperature was held constant at 250 °C. By recording I-V values across varying resistances, the power curve of the TEG was derived and plotted using $P = VI$.

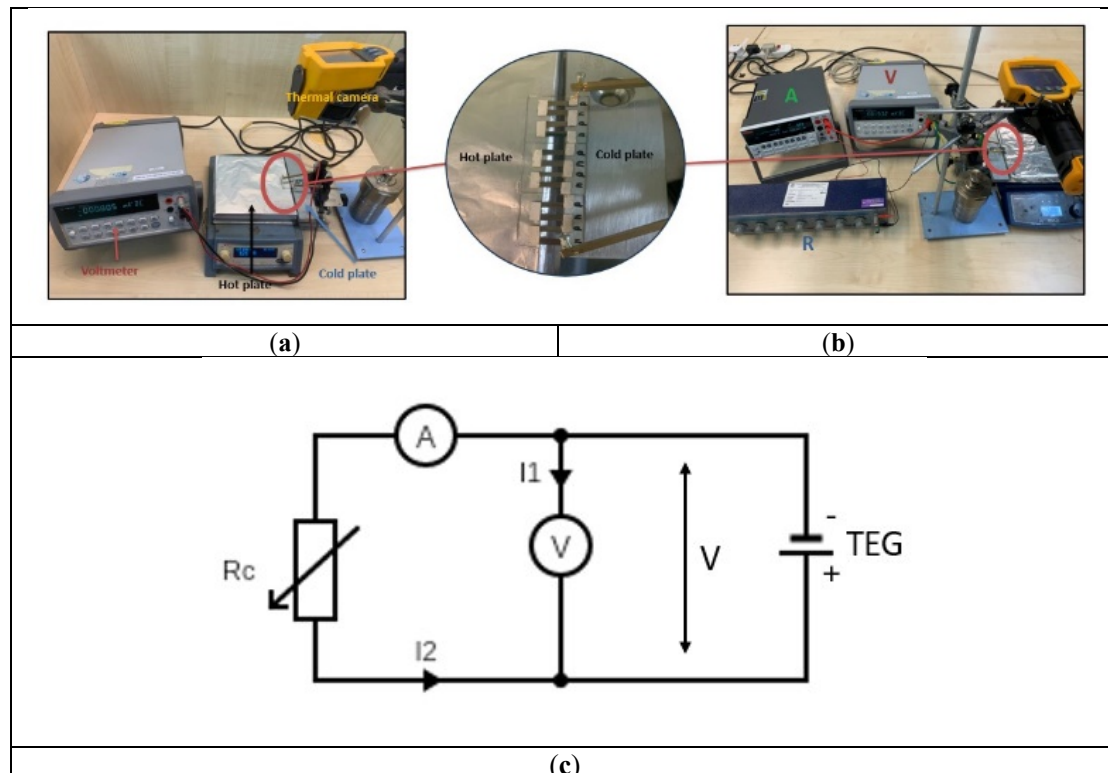


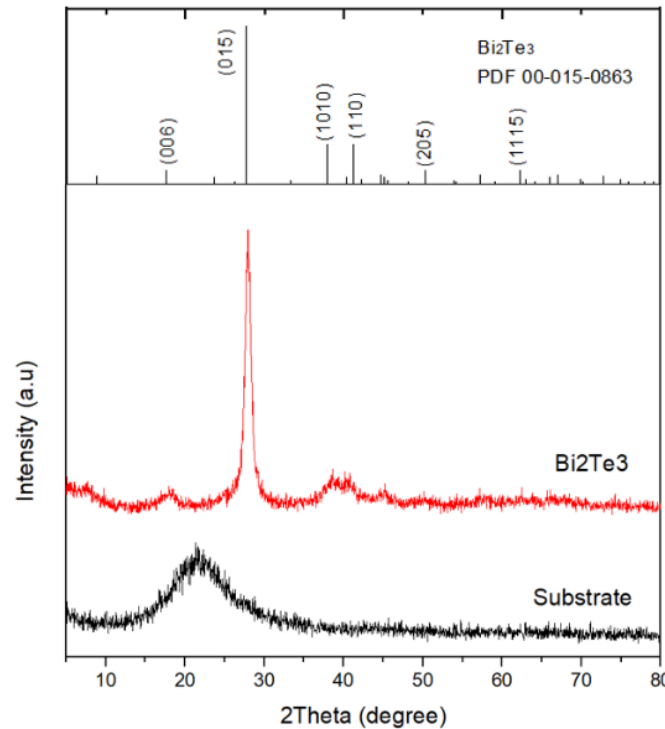
Figure 2. (a) In-house measuring setup for the V_{oc} versus ΔT plot. (b) In-house measuring setup for the I-V-P measurement. (c) Schematic of the setup connection used to measure the I-V-P characteristics.

2. Results and Discussion

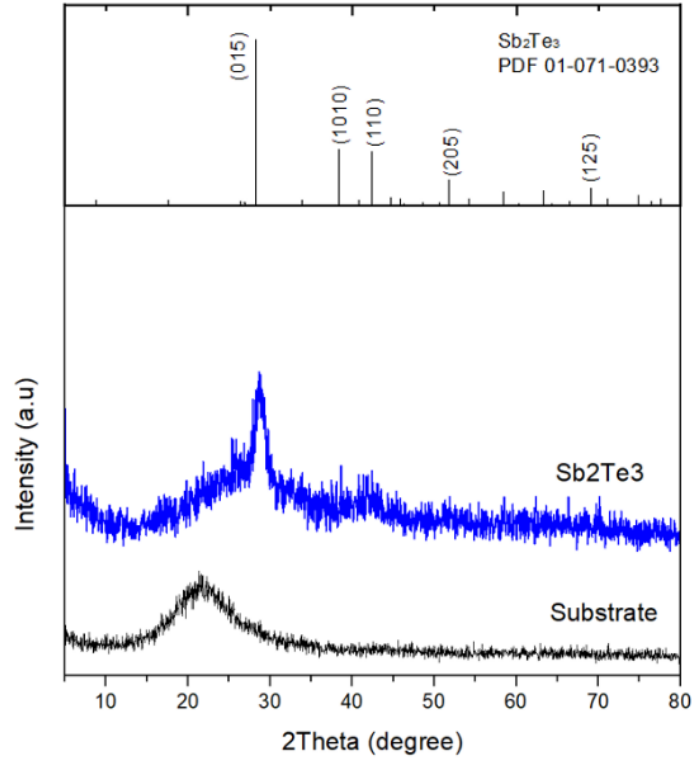
2.1. Structural and Compositional Characterization of the Thin Films

The phase purity and crystallinity of the thin films were measured using X-ray diffraction (XRD) technique. As visible in Figure 3(a),(b) the XRD measurements indicate a good phase purity for both Bi_2Te_3 and Sb_2Te_3 samples, with no measurable trace of secondary phases. The XRD reflections observed for the Bi_2Te_3 and Sb_2Te_3 samples can be indexed with the respective rhombohedral Bi_2Te_3 phase (PDF # 00-015-0863) and Sb_2Te_3 phase (PDF # 01-071-0393) in the space group R-3m (166) with lattice parameters $a = 4.3852 \text{ \AA}$, $c = 30.4830 \text{ \AA}$ for Bi_2Te_3 and $a = 4.2640 \text{ \AA}$, $c = 30.4580 \text{ \AA}$ for Sb_2Te_3 . For the Bi_2Te_3 film, the observed reflections illustrate preferential growth along the c-axis with a sharp dominant peak growing anisotropically along the (0 1 5) direction, indicating a highly crystalline structure with a few small peaks corresponding to (0 0 6), (1 0 10) and (1 1 0) directions. For the Sb_2Te_3 film, a small and broad peak corresponding to the (0 1 5) direction due to the low thickness of the film, as proven by the FESEM cross-section image to be discussed. Overall, both XRD patterns do not show any peaks for secondary phases.

The FESEM micrograph shows that the as-deposited Bi_2Te_3 and Sb_2Te_3 films covers the entirety of the substrate in a continuous and homogenous manner. As can be seen in Figure 4(a),(d), Bi_2Te_3 films comprise of hexagonal grains, conforming the crystal structure of Bi_2Te_3 . The grains are densely packed with varying sizes, indicating a polycrystalline nature. The surface of the Sb_2Te_3 film exhibits more fine, rounded grains and is consistent in size compared to Bi_2Te_3 film, indicating a nearly amorphous phase resulting in a low and broad peak in XRD. From the cross-sectional view in Figure 4(b),(e), the interface between the film and the substrate looks distinct, with no significant diffusion between the two, suggesting good adhesion properties. From these images, the thickness of the films was estimated, yielding values of around $1.429 \pm 0.01 \text{ \mu m}$ for Bi_2Te_3 thin films and $0.424 \pm 0.01 \text{ \mu m}$ for Sb_2Te_3 thin films. Energy-dispersive X-ray spectroscopy (EDXS) was used to analyze the chemical composition of the films. The composition of the films was calculated from the EDXS spectra in Figure 4(c),(f), giving atomic percent of 41.9% Bi:58.1% Te, 40.0% Sb:60.0% Te. The estimated values show that both films gave a consistent Bi:Te and Sb:Te ratio of 2:3, indicating stoichiometric Bi_2Te_3 and Sb_2Te_3 were successfully fabricated.



(a)



(b)

Figure 3. (a) XRD pattern of Bi_2Te_3 thin film. (b) XRD pattern of Sb_2Te_3 thin film.

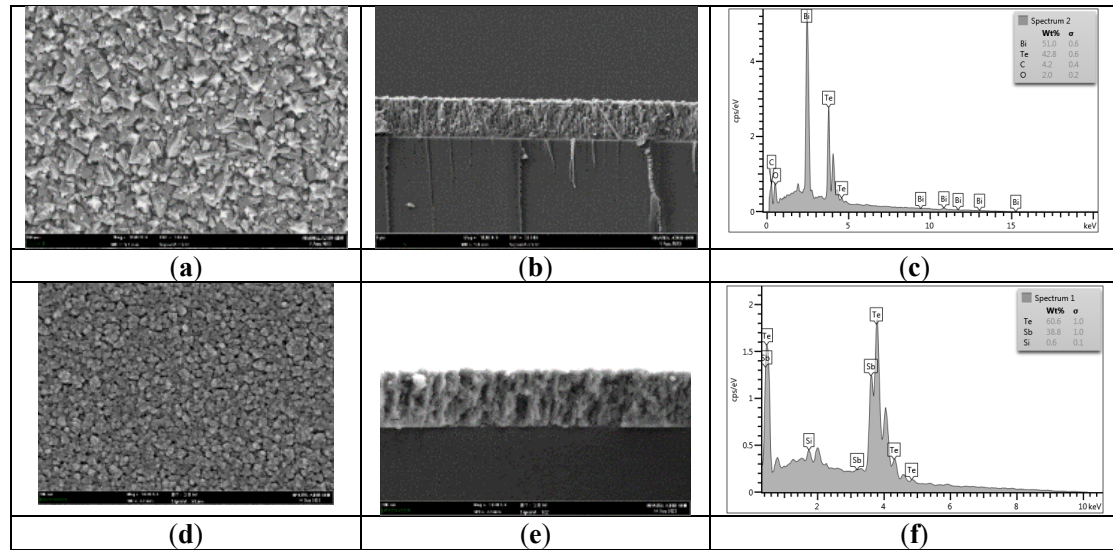


Figure 4. (a,b) FESEM surface and cross-section image of Bi_2Te_3 thin film. (c) EDXS spectra of Bi_2Te_3 thin film. (d,e) FESEM surface and cross-section image of Sb_2Te_3 thin film. (f) EDXS spectra of Sb_2Te_3 thin film.

2.2. Thermoelectric Characterization of the Thin Films

The Seebeck coefficients of the Bi_2Te_3 and Sb_2Te_3 thin films are reported in Figure 5, as a function of temperature in the range of 50–250 °C. The S values for Bi_2Te_3 are negative over the entire temperature range, but shown as an absolute value in the plot, highlighting its n-type behavior. Initially, the S value reached $-72.84 \mu\text{V/K}$ recorded at ~ 50 °C. As the temperature increases, the S value gradually becomes more negative, reaching nearly $-200 \mu\text{V/K}$ at ~ 200 °C. This trend suggests that the thermoelectric performance of Bi_2Te_3 is likely to increase as the temperature rises, which may be attributed to the

annealing effect where grain size and grain boundaries are improved (Zhao et al., 2021), consequently reducing the scattering effect (Zang et al., 2023). In contrast, Sb_2Te_3 displays a positive S across the temperature range, signifying p-type behavior. Starting at $336.11 \mu\text{V/K}$ at $\sim 50^\circ\text{C}$, the S value decreases slightly as the temperature increases, falling to approximately $220 \mu\text{V/K}$ at $\sim 200^\circ\text{C}$. This gradual decline suggests a relatively stable thermoelectric performance for Sb_2Te_3 , although the slight decrease indicates some temperature dependence, possibly due to phase changes in the material (Y. Zheng et al., 2024). The contrasting behaviors of Bi_2Te_3 and Sb_2Te_3 emphasize their suitability for different thermoelectric applications. The measured S aligns with previously reported values for sputtered thin films, where S values for Bi_2Te_3 were in the range of $50\text{--}90 \mu\text{V/K}$, while Sb_2Te_3 in the range of $190\text{--}300 \mu\text{V/K}$ (Junlabhut et al., 2020; Naumochkin et al., 2022; Wanarattikan et al., 2019b). The trends observed where S remains high and relatively stable suggest better performance at elevated temperatures. This information is essential for the development of thermoelectric devices tailored for particular temperature settings, ensuring optimal energy conversion efficiency.

Table 1 summarized the values of thermoelectric properties recorded at relative ambient temperature. The carrier concentration of the thin films measured using Hall effect measurement exhibits a negative value for Bi_2Te_3 , further confirming the n-type conductivity, and a positive value for Sb_2Te_3 , confirming the p-type conductivity. The electrical conductivity of the thin films was determined to calculate the power factor (PF) of each film. PF becomes a decisive parameter for the selection of thin film materials due to its configuration. A low thermal conductivity is ideal for good efficiency, however, the substrate typically dominates thermal transport in thin film configurations because of the significant difference in thickness (Isotta et al., 2022). The calculated PF was 0.5781 and $0.3451 \mu\text{W/K}^2 \text{cm}$ for Bi_2Te_3 and Sb_2Te_3 thin films, respectively, which were quite low in comparison with other reported values (Tang et al., 2022). The S and σ values greatly influenced the PF of thermoelectric materials, calculated by $PF = S^2\sigma$. However, these two properties exhibit an inverse relationship due to their mutual dependence on carrier concentration, where an increase in one promotes a decrease in the other (Musah et al., 2021).

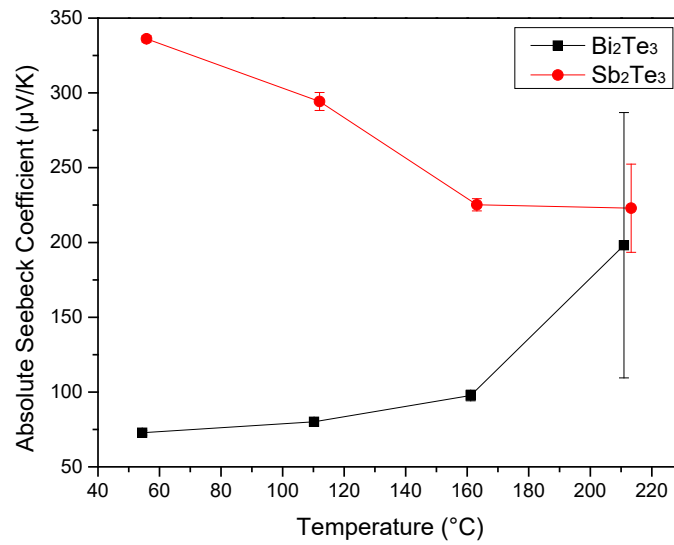


Figure 5. Absolute Seebeck coefficient, S of both Bi_2Te_3 and Sb_2Te_3 films.

Table 1. TE properties of both Bi_2Te_3 and Sb_2Te_3 thin film samples.

Target	RF power, (W)	Thickness ($\pm 0.01 \mu\text{m}$)	Absolute Seebeck coefficient, S ($\mu\text{V K}^{-1}$)	Carrier concentration, N_b (cm^{-3})	Conductivity, σ ($\Omega \text{ cm}$) ⁻¹	Power Factor, PF ($\mu\text{W/K}^2 \text{cm}$)
Bi_2Te_3	75	1.429	-72.84	-5.71×10^{20}	108.96	0.5781
Sb_2Te_3	30	0.424	336.11	1.44×10^{21}	6.05	0.3451

The trade-off between the S and σ in the films is evident from the results in Table 1. Sb_2Te_3 exhibits a significantly high S ($336.11 \mu\text{V/K}$) but suffers from low σ ($6.05 \Omega^{-1} \text{cm}^{-1}$), while Bi_2Te_3 has a lower S

($-72.84 \mu\text{V/K}$) but a much higher σ ($108.96 \Omega^{-1} \text{cm}^{-1}$). This inverse relationship arises due to carrier concentration differences, where Sb_2Te_3 has a higher Nb ($1.44 \times 10^{21} \text{cm}^{-3}$) compared to Bi_2Te_3 ($-5.71 \times 10^{20} \text{cm}^{-3}$), leading to strong phonon scattering that reduces charge carrier mobility and, consequently, conductivity. The observed differences can be understood using the Boltzmann transport equation and the Mott relation (Kumar et al., 2021):

$$S = \frac{\pi^2 k_B^2 T}{3e} \frac{1}{\sigma} \frac{d\sigma(E)}{dE} \bigg|_{E=E_F} \quad (1)$$

This equation shows that S is inversely related to Nb ; when Nb is high, more charge carriers are available for conduction, increasing σ but lowering S . Although a high S benefits thermoelectric voltage generation, the low σ in Sb_2Te_3 results in a reduced power factor ($PF = 0.3451 \mu\text{W/K}^2\text{cm}$), compared to $0.5781 \mu\text{W/K}^2\text{cm}$ for Bi_2Te_3 . This highlights the well-known optimization challenge in thermoelectrics, where increasing carrier concentration can improve σ but typically degrades S , requiring careful doping and nanostructuring strategies to achieve an optimal balance for high efficiency.

2.3. Performance Analysis of $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ Thin Film TEG

Plotting the open circuit voltage (V_{oc}) against temperature differential (ΔT) is an essential tool for evaluating the performance of the TEG. This relationship helps to comprehend how effectively, in different thermal circumstances, a TEG can convert thermal energy into electrical energy. V_{oc} in a TEG is the voltage measured across the terminals of the device when no external load is connected, meaning no current flows through the circuit, and is directly proportional to both the S and ΔT (Al Qubeissi et al., 2020). This measurement also gives information on the maximum voltage that can be generated by the $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ thin film TEG at specific ΔT s. The measurement was done in the temperature range of $70\text{--}250^\circ\text{C}$, with a 10°C increment. A metal plate served as the heat sink, and a hotplate was adjusted to raise the temperature of the hot side while maintaining the cold side at room temperature. However, due to poor heat sink setup and heat dispersion on the hotplate, the measured ΔT s did not fully match the set temperature of T_h and T_c . The metal plate may accumulate heat over time, reducing the ΔT across the thermoelectric legs. To mitigate these issues, active cooling methods, such as fan-assisted or liquid cooling, can enhance heat extraction and maintain a stable ΔT . Figure 6(a) shows that the V_{oc} presents a linear trend of voltage with increasing applied temperature difference, depicting the ideal behavior of TEG (Li et al., 2020). The steep slope indicates high S , meaning the material of the TEG is effective at generating voltage from a given ΔT . The TEG with 6 pairs generated a maximum output voltage of 55 mV at ΔT 38 K .

Figure 6(b) shows the current-voltage IV and the current power IP curve of the $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ thin film TEG. The IV curve represents the voltage as a function of current. The voltage starts at a maximum value when the current is zero, which corresponds to the open circuit voltage. As the current increases, the voltage decreases linearly, indicating that the internal resistance of the device dictates this behavior. The linear decline suggests Ohmic behavior, where the voltage drop is directly proportional to the current flowing through the device (Buchalik et al., 2021). On the other hand, The IP curve exhibits the classical parabolic shape. As the current begins to increase from zero, the power increases because both the current and the voltage contribute positively to the power output. However, as the current continues to increase, the voltage starts to drop significantly due to the internal resistance, leading to a decrease in power. The peak of the curve represents the maximum power point, where the product of current and voltage is maximized. This occurs when the load resistance matches the internal resistance of the device (Al Qubeissi et al., 2020). At this point, the power transferred to the load is at its maximum, and any further increase in current will cause the power to drop due to the decreasing voltage. The $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ thin film TEG produces an impressive maximum power of $0.54 \mu\text{W}$ at 0.005 mA with ΔT 127°C , meaning operating the TEG too far from this point (either at very high or very low currents) leads to suboptimal performance, as indicated by the declining power on either side of the peak. The maximum power per unit active planar area was calculated by dividing the maximum power with the area and number of TE legs, giving the value of $0.1 \mu\text{W cm}^{-2}$.

The measured power output achieved in this study is low compared to commercial bulk Bi_2Te_3 -based TEGs, which typically achieve W/cm^2 -level power densities under similar temperature gradients (Maksymuk et al., 2022; Xu et al., 2022). This gap is primarily due to the intrinsic material differences between thin film and bulk thermoelectric materials. Bulk Bi_2Te_3 modules generally have higher carrier mobility and optimized doping, leading to superior electrical conductivity and power factor. Despite the lower power output, the thin film TEG in this study offer advantages such as flexibility, scalability, and integration into microelectronic devices, deposited with well-established industrial process suitable for real-world applications. Further optimization, such as improving film thickness, carrier concentration

tuning, and advanced thermal engineering, could help bridge the performance gap between thin-film and bulk TEGs.

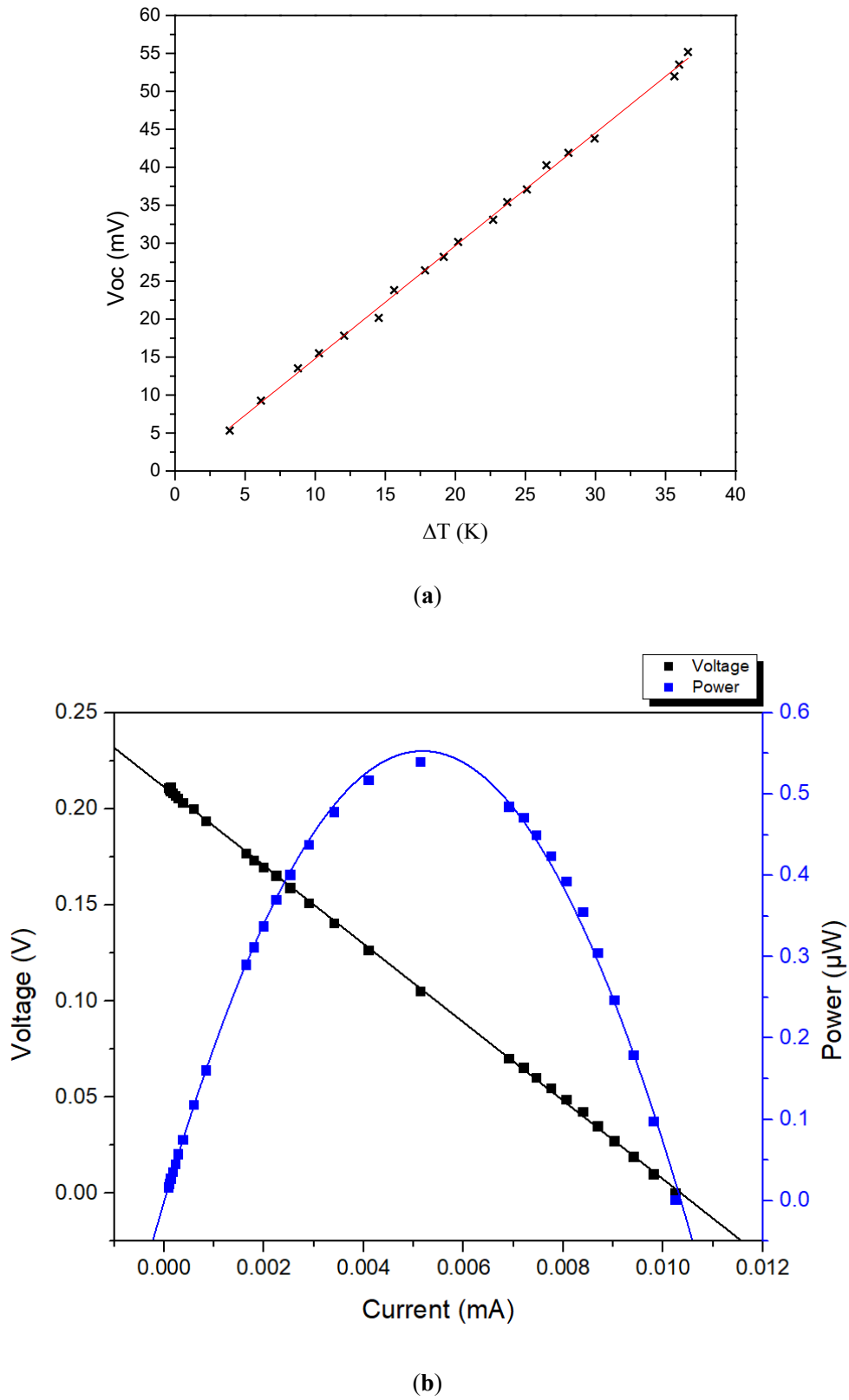


Figure 6. (a) V_{oc} versus ΔT of the $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ thin film TEG. (b) I-V-P curves of the $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ thin film TEG.

Table 2 compares the performance of the fabricated $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ thin-film TEG with previously

reported devices. The high ΔT (127 K) in this study results in a relatively high output voltage (211.6 mV), demonstrating strong thermoelectric response. The present $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ thin-film TEG achieves an output voltage and power that are on par with (or exceed) several comparable devices in the literature, even with a modest number of p–n pairs and relatively compact dimensions. These results indicate that the fabrication approach is effective in producing a thin-film TEG capable of delivering strong performance at moderate temperature differences.

Table 2. Comparison of the performance data of the $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ thin film TEG fabricated in the present work with those of devices published in the literature.

Reference, year	TE units	Device Dimension	ΔT (K)	Output Voltage (mV)	Output Power (μW)
this work, 2025	n-type Bi_2Te_3 p-type Sb_2Te_3	6 pairs; 3 mm $\times$ 15 mm $\times$ 1.429 μm n-type legs 3 mm $\times$ 15 mm $\times$ 0.424 μm p-type legs	127	211.6	0.54
Song et.al., 2024	n-type Bi_2Te_3 p-type $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$	15 pairs; 2 mm $\times$ 2 mm $\times$ 400 nm	11	54.6	0.69
Chang et.al., 2020	n-type $\text{Bi}_2\text{Se}_{0.32}\text{Te}_{2.7}$ p-type $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$	3 pairs; 3.4 mm $\times$ 20 mm $\times$ 0.04 mm	54.9	~ 80	50.0
Kobayashi et.al., 2020	n-type Bi_2Te_3 p-type Sb_2Te_3	16 pairs; 130 mm $\times$ 20 mm $\times$ 125 μm	20	122.9	0.31
Viera et.al., 2019	n-type Bi_2Te_3 p-type Sb_2Te_3	15 pairs; 1 mm $\times$ 8 mm $\times$ 400 nm	35	210	0.70
Kong et.al., 2019	n-type Bi_2Te_3	13 pairs	24	48.9	0.69
Takayama & Takashiri, 2017	n-type Bi_2Te_3 p-type Sb_2Te_3	11 pairs	28	32	0.15
Yang et.al., 2017	n-type Bi_2Te_3 p-type Sb_2Te_3	20 pairs; 0.3 mm $\times$ 6 mm $\times$ 400 nm	30	190	~ 0.15

3. Conclusion

In conclusion, the fabrication and performance analysis of Bi_2Te_3 and Sb_2Te_3 thin film TEG represent a significant advancement in the field of energy conversion technologies. Through careful fabrication technique, this study has demonstrated the potential of Bi_2Te_3 and Sb_2Te_3 thin film to achieve high thermoelectric efficiency. A prototype of thin film TEG with 6 pairs of $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ legs was designed and fabricated, that able to achieve an impressive maximum power of 0.54 μW at ΔT 127 $^\circ\text{C}$. The calculated maximum power per unit active planar area obtained for the TEG was 0.1 $\mu\text{W cm}^{-2}$. The ability to control film composition, thickness, and crystallinity is crucial in enhancing the electrical and thermal properties of these materials. Further optimization of the deposition parameters, film properties, and TEG structure needs to be studied to fully exploit the benefit of thin film configuration. The continued exploration of thin-film thermoelectrics, as exemplified by this study, holds the promise of making significant strides toward more efficient and practical applications of thermoelectric technology in the global quest for energy sustainability.

Authors' contributions

N. A. Musri: Conceptualization, methodology, formal analysis, writing—original draft, U. Syafiq.; supervision, resources, project administration, writing—review and editing, Y. Putthisigamany, P. Chelvanathan, N. A. Ludin, N. M. Yatim; writing—review and editing, project administration, validation. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest Statement

The author(s) has/have no competing interests to declare.

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