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# Influence of Morphology on the Thermoelectric Performance of Aluminum-Doped Zinc Oxide (AZO) on Diverse Substrate Material

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ABSTRACT

*Aluminum-doped zinc oxide (AZO) thin films for thermoelectric solar energy conversion are investigated in this work. It examines how different substrates and sputtering powers affect the morphology and thermoelectric characteristics of AZO thin films. Polyimide, quartz, and fused silica were selected as substrates to explore this interaction. Utilizing radiofrequency (RF) magnetron sputtering, AZO thin films were deposited onto the substrates. The impact of the sputtering power on the films was examined by varying it between 200 W, 250 W, and 300 W. The distance between the target and substrate was kept at 5 cm, the argon gas flow rate was kept at 10 sccm, and the sputtering period was fixed at one hour. All other deposition parameters were kept constant. The SEM study showed that thicker AZO thin films and a rougher surface texture were the outcomes of increasing the sputtering power. On the other hand, the EDS analysis confirmed that all predicted components were consistently present in the AZO composition for every substrate that was examined. In addition, the Seebeck coefficient, electrical conductivity, and thermoelectric power factor (PF) were measured using a specially designed experimental setup to characterize the thermoelectric properties. The results revealed that the substrate material significantly influenced the morphology of the AZO thin film, which subsequently impacted their thermoelectric properties. Fused silica yielded the most promising results, achieving a power factor of 9.362 nW/mK², conductivity of 2.817 S/m, and Seebeck coefficient of -56.58 µV/K at 150° C and a sputtering power of 300 W. The study highlights the critical role that substrate selection and deposition parameters play in optimizing the thermoelectric performance of oxide-based thin films. Higher sputtering power generally improved film thickness and conductivity but also introduced surface roughness that varied depending on substrate smoothness. Polyimide, due to its naturally rougher surface, exhibited more irregular AZO film growth compared to quartz and fused silica. These structural differences translated into noticeable variations in the thermoelectric behavior. The findings suggest that optimizing both deposition power and substrate type can enhance the efficiency of AZO thin films in solar-thermal energy harvesting applications. This work contributes to ongoing efforts to develop cost-effective, non-toxic, and stable thermoelectric materials suitable for integration in flexible and transparent energy systems.*

*Keywords: Aluminum Zinc Oxide thin film; fused silica; quartz; polyimide; power factor (PF)*

## INTRODUCTION

Thin film thermoelectrics are gaining favor for solar energy conversion due to their flexibility, enabling integration on diverse substrates. Their lightweight design makes them ideal for weight-critical applications, and various deposition techniques allow for large-scale, cost-effective production of these materials. These advantages position thin-film thermoelectrics as a promising choice for next-generation solar energy technologies (Mulla, Jones, & Dunnill 2021). Power factor (PF) plays a critical role in assessing a material's suitability for thermoelectric applications. The power factor is a direct reflection of a material's capacity to convert thermal energy into electricity, and it is defined as the product of the Seebeck coefficient (S) and electrical conductivity (σ):

$$PF = S^2\sigma \tag{1}$$

Radio Frequency (RF) magnetron sputtering was chosen for AZO thin film deposition due to its speed, low operating temperature, and minimal damage to the material (Praveen & Khoobchandani 2018). Furthermore, fused silica, quartz, and polyimide were chosen as substrates for the AZO thin films. Fused silica and quartz offer excellent thermal conductivity (Deng, Shi, & Yuan 2020, Fatemeh Molaei & Hossein Siavoshi 2020), while polyimide provide flexibility and smooth surface (Joseph, 2021), making them suitable for various potential application.

Materials with a higher power factor exhibit greater efficiency in generating electricity from a temperature difference (Liu et al. 2016). This study investigates Aluminum-doped Zinc Oxide (AZO) thin films as potential thermoelectric materials for solar energy conversion. AZO is a promising candidate due to its high transparency, low cost, good chemical stability and tunable electrical conductivity through Aluminum doping (R. Bandorf Sittinger, & G. Bräuer, 2014).

## METHODOLOGY

Thin film aluminum-doped zinc oxide (AZO) was deposited onto fused silica, quartz, and polyimide substrates via RF magnetron sputtering. (Praveen & Khoobchandani, 2018). Three distinct levels: 200 W, 250 W, and 300 W of sputtering power was adjusted. Prior to deposition, the substrates were cut and cleaned. After drying, they were placed on the target holder within the chamber. The AZO target was then mounted in the sputter gun, maintaining a constant 5 cm distance from the substrates. To ensure a clean deposition environment, the chamber was purged with Argon gas for 30 minutes. Sputtering occurs at room temperature for one hour. Following deposition, the physical properties of the AZO thin films were analyzed using Scanning Electron Microscopy (SEM) to evaluate the surface morphology and Energy-dispersive X-ray Spectroscopy (EDS) to assess the surface morphology to confirm the presence and distribution of aluminum, zinc, and oxygen within the AZO layer. The thermoelectric properties were then evaluated by Seebeck coefficient measurement (Figure 1) and four-point probe testing (Figure 2). The power factor of each AZO thin film was calculated by combining the results of the Seebeck coefficient and electrical resistivity measurements, representing the material's efficiency in converting thermal energy into electrical power.

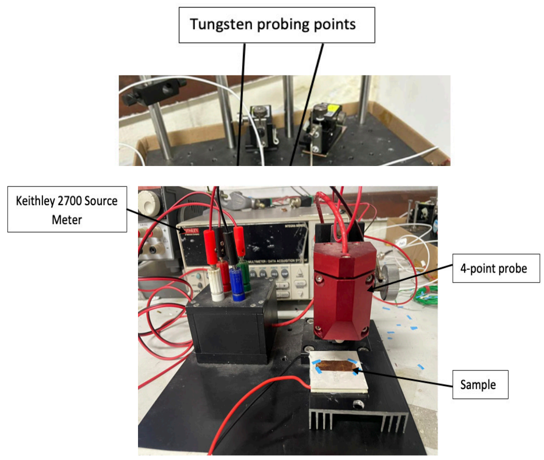



FIGURE 2. Four-point probe setup

## RESULTS AND DISCUSSION

### PHYSICAL PROPERTIES CHARACTERIZATION

### SCANNING ELECTRON MICROSCOPY (SEM) IMAGE - MORPHOLOGY OF AZO THIN FILM

Figures 3, 4, and 5 showed the microstructure of thin film Aluminum-doped zinc oxide (AZO) sputtered onto fused silica, quartz, and polyimide substrates at powers of 200 W, 250 W, and 300 W, captured using SEM at a magnification of x5000. The SEM analysis in all figures revealed a clear trend: higher sputtering power led to rougher AZO thin films on all substrates. This aligns with the previous research where higher sputtering power leads to rougher AZO thin films can be attributed to enhanced kinetic energy of the adatoms, increased nucleation rates, and decreased surface diffusion. Substrate properties also play a role for the deposition of the AZO thin film acts as a physical and chemical template that governs film nucleation, growth, and final structure. Variations in surface energy, thermal stability, and mechanical properties lead to distinct AZO film morphologies across different substrates, validating the observed differences in roughness and crystallinity. (Spadoni & Addonizio, 2015). Quartz, fused silica, and polyimide distinct surface properties that can affect nucleation and growth of AZO films. Quartz and fused silica both feature smooth surfaces with minimal variation in roughness. Polyimide, on the other hand, has a naturally higher roughness, leading to a rougher AZO film (typically 8–20 nm RMS), which leads to a rougher AZO film compared to smoother substrates like glass (<1 nm RMS) or PET (2–5 nm RMS). This elevated roughness promotes non-uniform nucleation during sputtering, resulting in increased AZO surface roughness and reduced film compactness (Kim & Park 2021). This aligns with prior research suggesting that the intrinsic roughness of a substrate can influence the morphology of the deposited thin film (Lin, Hsu, & Huang 2006).

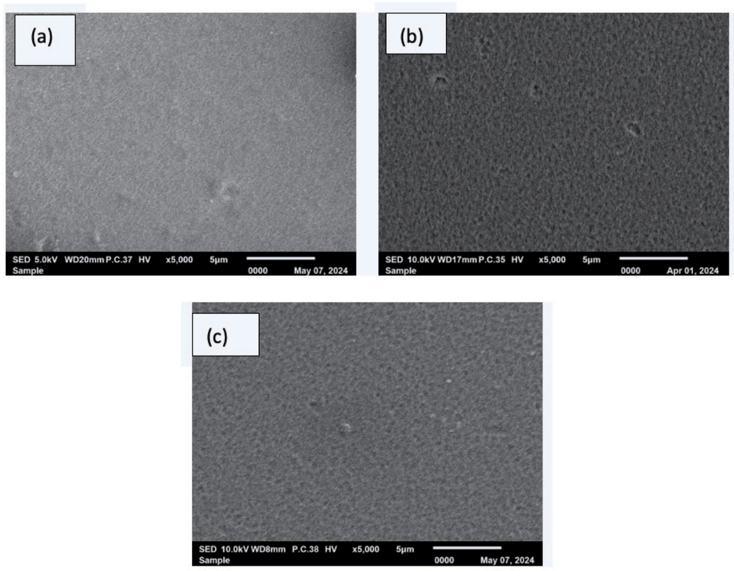



FIGURE 3. AZO thin film microstructure on Fused Silica substrate for sputtering power at (a) 200 W, (b) 250 W and (c) 300 W at a magnification of x5000

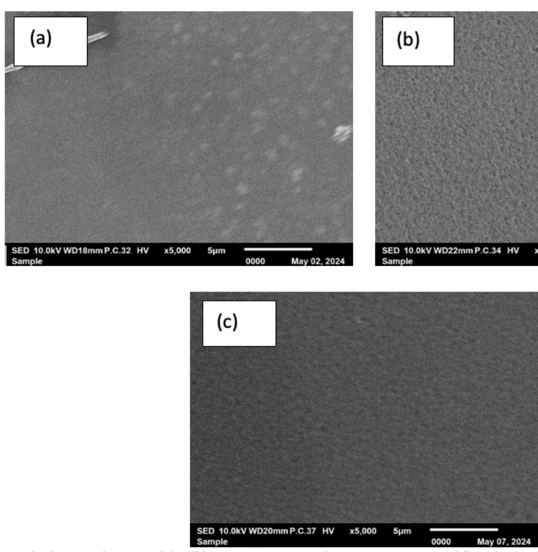



FIGURE 4. AZO thin film microstructure on Quartz substrate for sputtering power at (a) 200 W, (b) 250 W and (c) 300 W at a magnification of x5000

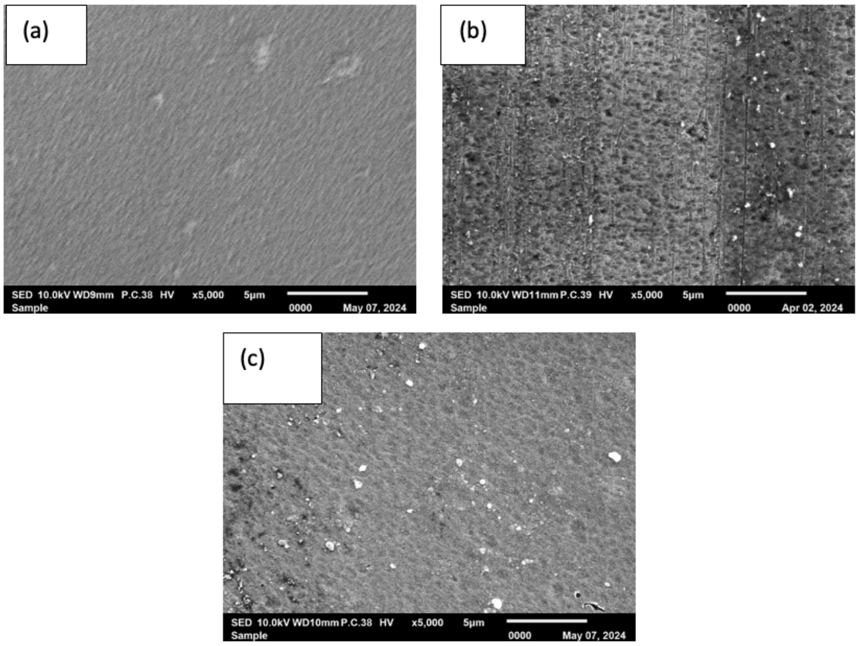



FIGURE 5. AZO thin film microstructure on Polyimide substrate for sputtering power at (a) 200 W, (b) 250 W and (c) 300 W at a magnification of x5000

## THICKNESS OF AZO THIN FILM

Figures 6, 7, and 8 reveal a clear trend showing that as sputtering power increases, the thickness of the AZO films also increases. Research shows that the substrate material be it fused silica, quartz, or polyimide plays a critical role in determining the mechanical, optical, and electrical properties of AZO thin films. The deposition method (e.g., RF sputtering, reactive sputtering, or atomic layer deposition) and the film thickness significantly affect adhesion, surface morphology, transmittance, and conductivity. Thinner films tend to show higher transparency but increased resistivity, while thicker films may offer better conductivity and mechanical robustness. Polyimide substrates often demand flexible film systems due to thermal expansion differences, while quartz and fused silica provide stable, high-temperature-compatible platforms. Spadoni & Addonizio (2015) similarly reported a correlation between sputtering power and film thickness in their studies on aluminum-doped zinc oxide (AZO) films fabricated using RF magnetron sputtering. Other than that, AZO film thickness is also affected by substrate material itself. Due to the similar surface characteristics of fused silica and quartz $SiO_2$ composition, excellent flatness, thermal stability, and inert surface properties, fused silica and quartz provide ideal substrates for uniform thin film growth, they likely exhibit minimal thickness variation. On the other hand, the rougher surface of polyimide facilitates non-uniform nucleation during the early stages of the AZO film, resulting in a thicker film (Lin et al. 2006).

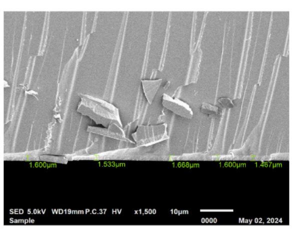
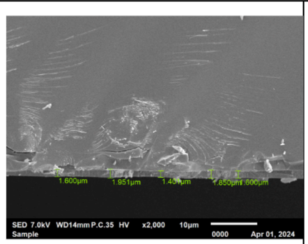
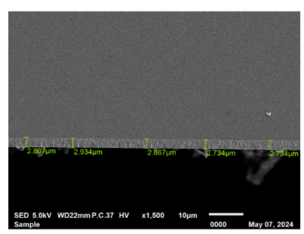
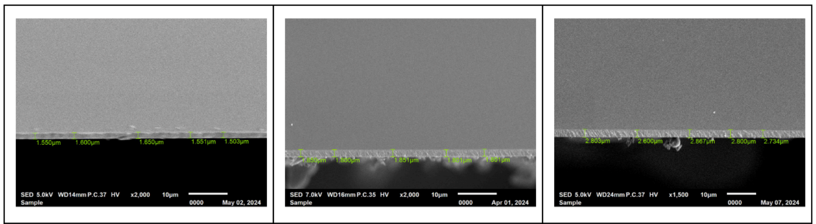
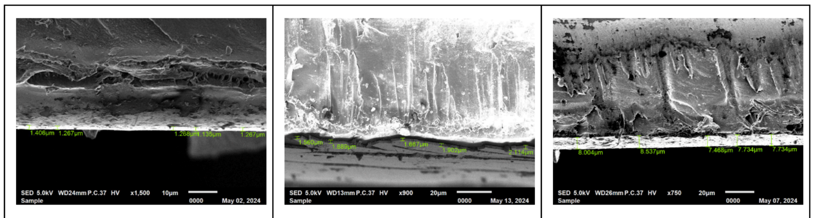
| | | |
|---|---|---|
|  |  |  |
| Sputtering power: 200 W | Sputtering power: 250 W | Sputtering power: 300 W |
| Average thickness: 1.5736 µm | Average thickness: 1.6802 µm | Average thickness: 2.8152 µm |

FIGURE 6. AZO thin film thickness on fused silica at sputtering power of 200 W, 250 W and 300 W



| Sputtering power: 200 W | Sputtering power: 250 W | Sputtering power: 300 W |
|---|---|---|
| Average thickness: 1.5708 µm | Average thickness: 1.8206 µm | Average thickness: 2.7608 µm |

FIGURE 7. AZO thin film thickness on quartz at sputtering power of 200 W, 250 W and 300 W



| Sputtering power: 200 W | Sputtering power: 250 W | Sputtering power: 300 W |
|---|---|---|
| Average thickness: 1.2686 µm | Average thickness: 1.8264 µm | Average thickness: 7.8954 µm |

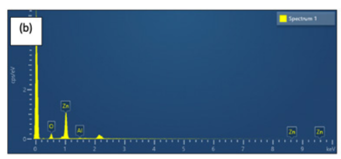
FIGURE 8. AZO thin film thickness on polyimide at sputtering power of 200 W, 250 W and 300 W

## ENERGY DISPERSIVE SPECTROMETER (EDS) ANALYSIS

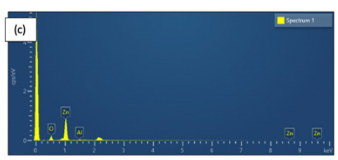
AZO thin films deposited on all substrates was performed using Dispersive X-ray Spectroscopy (EDS) to confirm their elemental composition. The analysis was carried out for each substrate fused silica, quartz, and polyimide under three different sputtering power settings: 200 W, 250 W, and 300 W. The EDS spectra consistently confirmed the presence of the key constituent elements Aluminum (Al), Zinc (Zn), and Oxygen (O) for all deposited films, regardless of the substrate or power level. These results validate the successful incorporation of aluminum dopants into the ZnO matrix, a critical factor for enhancing electrical conductivity in thermoelectric applications.

Furthermore, the uniformity of elemental distribution across the scanned regions indicated homogeneous film growth, while the absence of foreign peaks suggested minimal contamination during deposition. Variations in peak intensities among different substrates and power levels also hinted at potential differences in film thickness and elemental density, which correlate with earlier SEM findings. Specifically, the EDS profiles for AZO on fused silica displayed slightly stronger Zn and Al signals, likely due to the higher thickness observed at elevated sputtering powers. These consistent spectral confirmations reinforce the reliability of RF magnetron sputtering for fabricating AZO thin films with controlled composition and provide a robust foundation for evaluating the electrical and thermoelectric behavior in subsequent sections. (Jiang et al. 2024).


| Element | Weight % |
|---|---|
| Zn | 84.3 |
| O | 14.0 |
| Al | 1.7 |



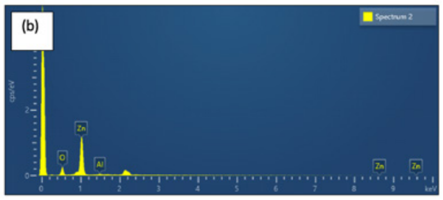

| Element | Weight % |
|---|---|
| Zn | 83.4 |
| O | 14.8 |
| Al | 1.8 |



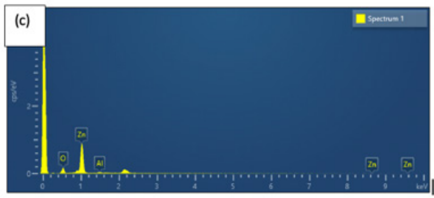

| Element | Weight % |
|---|---|
| Zn | 83.7 |
| O | 14.4 |
| Al | 1.9 |

FIGURE 9. AZO thin film of EDS spectra and weight percentage on fused silica at sputtering power of (a) 200 W, (b) 250 W and (c) 300 W


| Element | Weight % |
|---|---|
| Zn | 73.2 |
| O | 25.0 |
| Al | 1.9 |



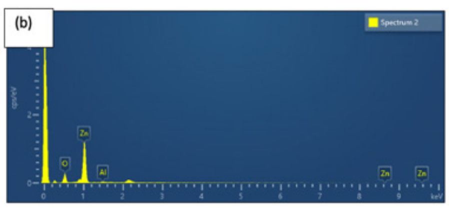

| Element | Weight % |
|---|---|
| Zn | 82.4 |
| O | 15.9 |
| Al | 1.7 |



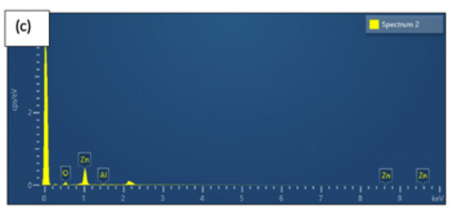

| Element | Weight % |
|---|---|
| Zn | 83.7 |
| O | 14.5 |
| Al | 1.8 |

FIGURE 10. AZO thin film of EDS spectra and weight percentage on quartz at sputtering power of (a) 200 W, (b) 250 W and (c) 300 W


| Element | Weight % |
|---|---|
| Zn | 82.9 |
| O | 15.6 |
| Al | 1.5 |




| Element | Weight % |
|---|---|
| Zn | 81.6 |
| O | 17.0 |
| Al | 1.4 |




| Element | Weight % |
|---|---|
| Zn | 84.9 |
| O | 12.7 |
| Al | 2.5 |

FIGURE 11. AZO thin film of EDS spectra and weight percentage on polyimide at sputtering power of (a) 200 W, (b) 250 W and (c) 300 W

# ANALYSIS OF THERMOELECTRIC PROPERTIES

## SEEBECK COEFFICIENT PROPERTIES: TEMPERATURE GRADIENT AND VOLTAGE EXPERIMENT

Figure 12 presents the measured Seebeck coefficients of AZO thin films deposited under varying sputtering powers and evaluated at elevated temperatures. The AZO thin films exhibit n-type semiconducting behavior as indicated the negative slope in the Seebeck coefficient graph. The data clearly demonstrate that both increased sputtering power and higher measurement temperature contribute to an enhancement in the Seebeck coefficient. This improvement is primarily attributed to the increased charge carrier concentration and mobility in the AZO films. As the sputtering power rises from 200 W to 300 W, more energetic species impact the growing film, enhancing crystallinity and film density. These structural refinements reduce grain boundary scattering and improve charge carrier transport, which positively affects the thermoelectric properties.

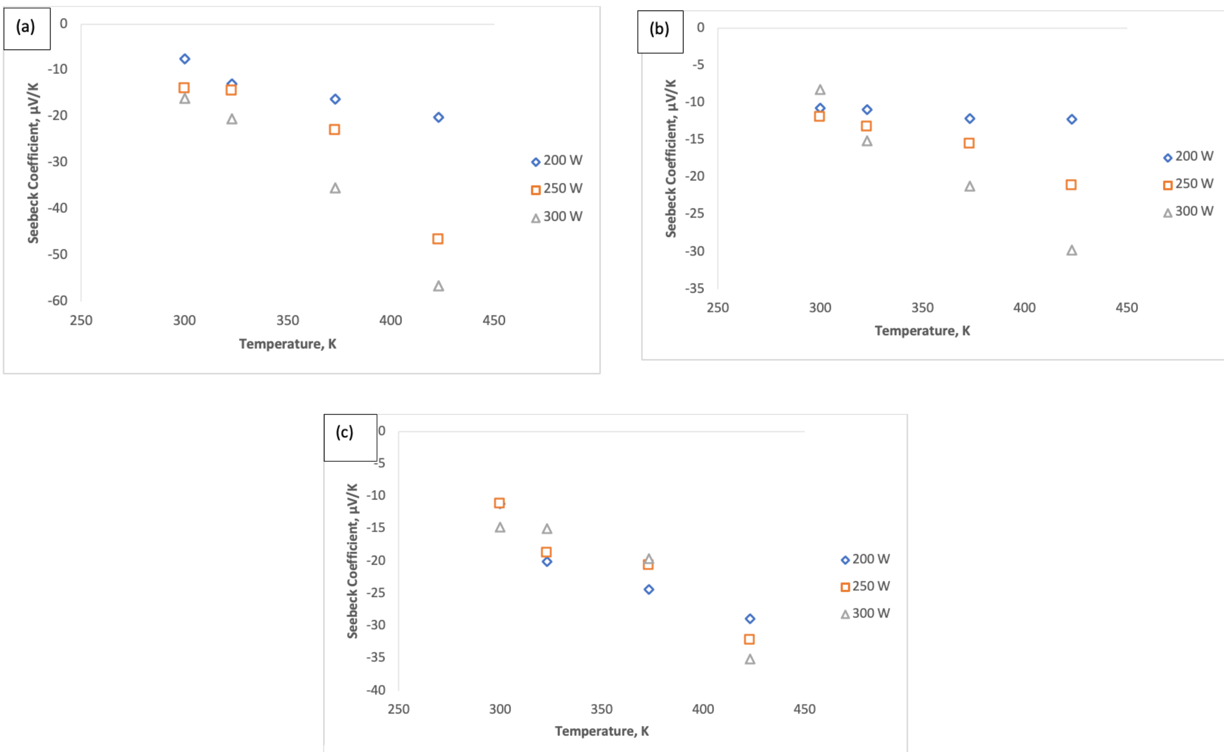



FIGURE 12. Graph shows the Seebeck coefficient as a function of temperature for AZO thin film on (a) fused silica, (b) quartz and (c) polyimide at sputtering power of 200 W, 250 W and 350 W.

Temperature also plays a crucial role in the carrier dynamics. At elevated temperatures, carrier mobility tends to increase due to enhanced phonon activity, allowing for more efficient separation of charge carriers and thus improving the Seebeck coefficient. The influence of the substrate is equally important. Among the tested substrates fused silica, quartz, and polyimide fused silica yielded the highest Seebeck values. This outcome can be attributed to the intrinsic purity and thermal stability of fused silica, which supports the growth of thicker AZO films with more prominent surface roughness. This surface morphology facilitates localized energy filtering and modifies scattering mechanisms, contributing positively to the Seebeck response. (Kiliszkiewicz et al. 2024).

In comparison, smoother substrates such as quartz and polyimide limit the thickness and microstructural evolution of the AZO layer, resulting in relatively lower Seebeck coefficients. Therefore, the combined effect of optimized sputtering power, substrate temperature, and material selection provides a robust strategy for enhancing the thermoelectric efficiency of AZO-based thin films.

## ELECTRICAL CONDUCTIVITY: FOUR-POINT PROBE TESTING

The four-point probe method is a widely employed technique for assessing the electrical conductivity of thin films and various materials. This method involves arranging four equidistant probes in a linear configuration on the sample surface. The outer probes deliver a current through the material, whereas the inner probes assess the voltage differential across a defined distance. The segregation of current and voltage probes mitigates the influence of contact resistance and current dispersion at the probe-material interface, hence facilitating a more precise assessment of the material's resistivity. The resistivity (ρ) of the AZO thin films on fused silica, quartz, and polyimide substrates can be computed by applying a known current and measuring the voltage that results. The material's electrical properties are evaluated by determining its conductivity (σ), which is the reciprocal of resistance

TABLE 1. An overview of the sample's resistance, resistivity and conductivity

| Substrates | Fused Silica | | | Quartz | | | Polyimide | | |
|---|---|---|---|---|---|---|---|---|---|
| Sputtering Power | 200 W | 250 W | 300 W | 200 W | 250 W | 300 W | 200 W | 250 W | 300 W |
| R (Ω) | 3.205 | 3.027 | 0.887 | 4.719 | 1.774 | 0.693 | 3.743 | 3.181 | 0.586 |
| ρ (Ωm) | 0.897 | 0.848 | 0.355 | 1.888 | 0.710 | 0.333 | 2.994 | 2.545 | 0.469 |
| σ (S/m) | 1.115 | 1.179 | 2.817 | 0.530 | 1.408 | 3.002 | 0.334 | 0.393 | 2.132 |

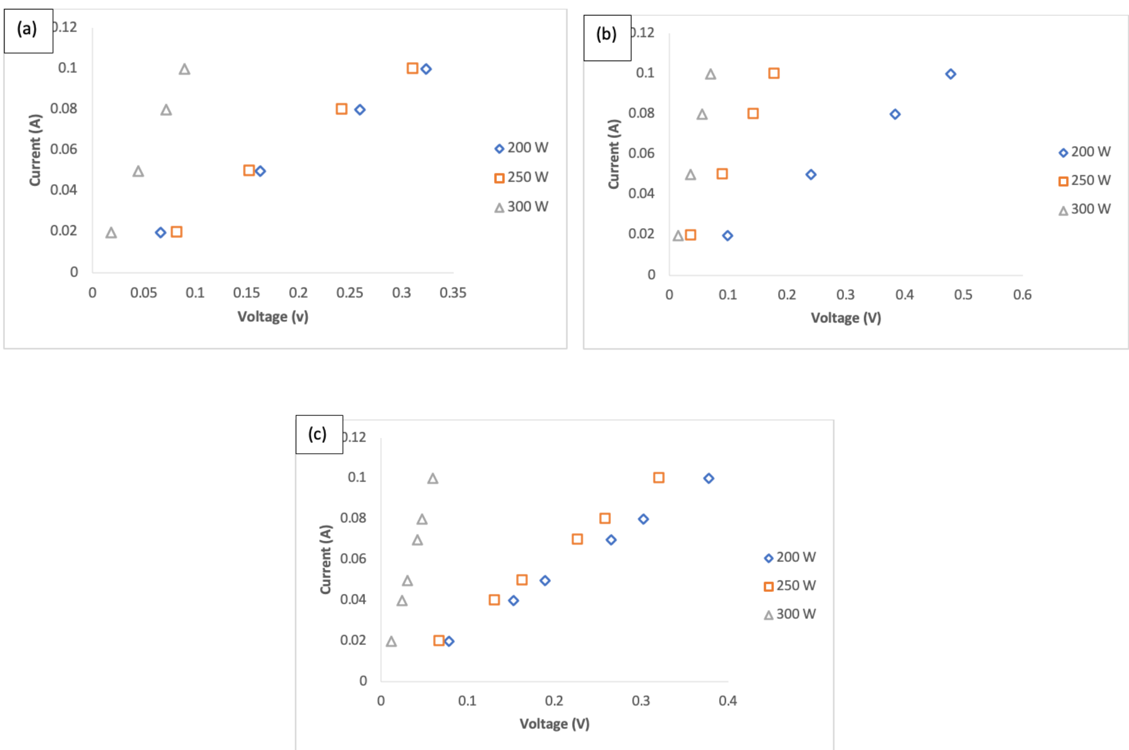



FIGURE 13. Graph shows the current vs voltage of AZO thin film on (a) fused silica, (b) quartz and (c) polyimide at sputtering power of 200 W, 250 W and 300 W

Table 1 shows that conductivity increased with sputtering power due to improved crystallinity and thickness. This finding is corroborated by previous study from Rana et al. (2021) of deposited AZO thin films, which indicates that higher sputtering power can enhance electrical conduction. Electrical conductivity and the thickness of AZO thin films on different substrates are correlated based on the analysis. The cross-sectional area available for current flow grows in correlation with the film thickness. AZO thin film deposited on fused silica and quartz exhibited the highest conductivity due to their similar properties and thicker films, whereas polyimide had the lowest conductivity despite its thicker film.

## THERMOELECTRIC POWER FACTOR

The thermoelectric power factor (PF) determines a material's ability to generate voltage from heat (Seebeck coefficient) and its ability to conduct electricity (conductivity) as shown in Table 2. It reflects how efficiently a material converts heat into electricity. The Aluminum-doped Zinc Oxide (AZO) thin films deposited on fused silica at 150 °C and under 300 W sputtering power exhibited the highest power factor among the tested conditions.

TABLE 2. Summarization of Seebeck coefficient, electrical conductivity and power factor of the sample

| Substrates | Fused Silica | Quartz | Polyamide |
|---|---|---|---|
| Sputtering Power | 300 W | 300 W | 300 W |
| S (mV/K) (150°C) | -56.58 | -29.76 | -35.07 |
| s (S/m) | 2.817 | 3.003 | 2.132 |
| PF (nW/K$^2$m) | 9.362 | 2.660 | 2.622 |

This result is consistent with its higher Seebeck coefficient, indicating enhanced thermoelectric performance under these optimized deposition parameters. However, when compared to existing literature, particularly the study by Trinh et al. (2016), the power factor observed in this study is significantly lower. Trinh and colleagues reported AZO thin films on glass substrates achieving a power factor in the range of 0.05–0.1 mW/K$^2$·m, which is orders of magnitude greater than the values obtained here (9.362 nW/K$^2$·m).

Several factors may explain this discrepancy. Firstly, the dimensional scale of the deposited thin films in this study could have influenced the measurement accuracy—particularly if the films were too thin or non-uniform, thereby affecting the reliability of the Seebeck voltage and conductivity data. Secondly, the sputtering conditions such as deposition temperature, argon gas flow, chamber pressure, and target-to-substrate distance may vary significantly between studies and can greatly influence the microstructure, crystallinity, and carrier concentration of the AZO films. Any variation in these parameters can drastically alter the electronic and thermal transport properties, leading to a lower power factor.

Furthermore, the difference in substrate types (fused silica versus conventional glass) could also contribute to the variation in film morphology and quality due to differences in thermal conductivity, surface energy, and thermal expansion coefficients, all which impact nucleation and film growth dynamics. Therefore, the combination of material deposition conditions, sample scale, and substrate characteristics may account for the lower thermoelectric performance observed in the present study compared to prior high-performing AZO films reported in the literature. (Luo et al. 2022).

## CONCLUSION

Sputtering powers of range 200 W, 250 W, and 300 W were successfully deposited AZO thin films on fused silica, quartz, and polyimide substrates using. SEM morphology analysis revealed a correlation between higher sputtering power and increased roughness of the AZO thin film. All intended elements were present in the AZO films across all substrates was confirmed from EDS analysis. Also all samples exhibited negative Seebeck coefficients that consistent with the n-type nature of AZO thin film. Particularly, the AZO thin film deposited on fused silica at 300 W demonstrated the highest Seebeck coefficient at 150°C. Four-point probe measurements indicated that the AZO film deposited on quartz had the highest electrical conductivity compared to those on fused silica and polyimide at 300 W sputtering power. The fused silica substrate produced the greatest results, even though the computed thermoelectric power factors for all samples were lower than those documented in the literature, most likely because of differences in film thickness and deposition techniques. At 300 W sputtering power and 150°C, this sample showed a power factor of 9.362 nW/mK$^2$, a conductivity of 2.817 S/m, and a Seebeck coefficient of -56.58 µV/K.

## ACKNOWLEDGEMENT

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## DECLARATION OF COMPETING INTEREST

None

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