



Development and characterization of SnTe:Al nanostructures for enhanced solar absorption

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SnTe based material is considered a leading lead-free replacement of the PbTe based thermoelectric materials to addressing the global energy crisis. Our findings show that study the effect of Al-doping on electronic and structure properties of SnTe at concentrations of 2 and 4% are obtained with vacuum evaporation. The structures of the poly-crystalline thin film are observed by X-ray diffraction pattern, Grain size increased with Al content. The studied structures are all cubic crystalline structure. The Arrhenius relation is used to determine the activation energy of SnTe nanostructures within the temperature range (313–423 K). The semiconductors nature of the SnTe nanostructures and the carrier concentrations are determined by Hall effect, the SnTe nanostructures shows p-type semiconductors, and the Electrical properties show a rise of the carrier concentration when the Al concentrations increases. We achieved a maximum conversion efficiency of 1.5 at Al 4% nanostructures, which is greater than that of pure SnTe. This work demonstrates that Al -doping can increase grain size, resulting increase in conversion efficiency of the SnTe thin film.

Keywords: SnTe:Al; aluminum; thin film; photovoltaic; XRD; activation energy.

1. INTRODUCTION

The demand for renewable energy sources has led to significant advances in photovoltaic (PV) technology. The transition metal chalcogenides display huge possible for used in conversion the thermal energy to electrical energy and inversely, to convert light into electrical energy, and quantum effects of light on material [1, 2]. They involved a lot of consideration in current periods. The interesting optical, structural, mechanical, and electrical topographies of layered [3,4]. The IV-VI group compounds, for example GeSe, GeS, SnSe, and SnS semiconductors grows massively

considered due to their narrow bandgap and semi-metals characteristics [5]. The IV-VI group compounds raised in acceptance for applications in solar alteration, just above-infrared optoelectronic, and photon detection devices because of its non-toxicity, earth-abundance elements, and chemical stability [6]. Both the systems, bulk and nanostructures, found applications in optoelectronics, electronics, infrared detectors, solar cells [7]. The direct transition optical bandgap obtained for the SnTe nanostructures is 1.20 eV [8]. The properties of these materials can be controlled and optimized through SnTe various synthesis methods such as co-evaporation of elemental tin and tellurium [9] physical vapor deposition [10]. molecular beam epitaxy [11,12]. thermal evaporation [8,13] drop casting method [14] Atomic Layer Deposition [15] SnTe semiconductor materials have received significant attention due to high carrier concentration and p-type characteristics [13, 16] SnTe is cubic structure compound [17].

Among the various materials under investigation for thin-film solar cells, tin telluride (SnTe) has garnered attention due to its promising thermoelectric properties and narrow bandgap [18] of approximately 0.18 eV, making it suitable for efficient absorption of solar radiation. However, the performance of SnTe can be further enhanced by doping with elements Such as Bi and Se elements [19] Mn-Doped SnTe [20] Zn–Mn co-doped nanostructured SnTe [21] SnTe with dilute co-doping of Ag and Cu [22]. The effect of strontium (Sr) doping [23] and Cu-doped [24] on the properties of nanostructures made of tin telluride (SnTe). In this study, we focus on the fabrication and characterization of SnTe: 2& 4% Al nanostructures, exploring the effect of Al doping on the structural, and electrical properties. This paper reviews various fabrication methods and investigates the potential of these films for photovoltaic applications. The aim is to determine the effect of doping on the material's suitability for high-efficiency solar cells. Structural, and electrical properties of SnTe films is controllable by doping Al where the ionic radii of Al being smaller than the Sn, and Te ions. The Al is suitable dopant for SnTe lattice because the lower ionic radii Al (1.25 Å) than Sn (1.45Å), Te (1.4Å) [25].

2. EXPERIMENTAL

The binary compound alloy SnTe is synthesized using high-purity Tin (Sn) and Tellurium (Te) elements (99.99%), 3 g are obtained by weighing using an electronic balance based on the stoichiometric ratio 1:1 ratio, respectively. The elements are sealed in a clean evacuated quartz tube with a length of 20 cm under a pressure of 5×10^{-3} mbar. The capsules are obliquely placed at an angle (45°) in an electrically programmable furnace (Carbolite). The furnace temperature is gradually raised at a rate of 5 K/min until the furnace temperature reached 1060 K, above the melting points of Sn, and Te. The samples are left at this temperature for 5 hours to form a homogenous alloy. Subsequently, the alloy is allowed to cool gradually to room temperature over a period of 24 hours to prevent thermal shock, after which it is ground for 20 min using a mechanical mill to obtain a fine powder. Nanostructures of SnTe with a thickness of 500 nm are deposited onto glass substrates and Si wafer to manufactory (p- SnTe /n-Si) from powder of SnTe alloy placed in a molybdenum boat using the thermal evaporation technique. The deposition process is carried out under a vacuum pressure of approximately 2.5×10^{-5} mbar. Doping of the SnTe nanostructures is performed using the thermal diffusion method. The samples are returned to the evaporation chamber and doped with high-purity aluminum (Al) (99.99%) at concentrations of 2% and 4% by evaporating aluminum onto the film surfaces. The samples are then removed from the chamber and annealed in an electric furnace at a temperature of 473 K for 60 min to complete the diffusion process. To study the structural of SnTe alloy and SnTe films using X-ray diffractometer (LabX XRD-6000, SHIMADZU, Japan) by detailed 2θ from 10° to 80 °with interval of 0.05°. The average crystalline size (C.S) of a polycrystalline film can be calculated by using Debye- Scherer's formula [26,27].

$$C.S = \frac{0.94 \times \lambda_{(x-ray)}}{\beta_{(FWHM)} \cos \theta} \quad (1)$$

Lattice micro-strain (τ) and dislocation density (δ) can be determined by utilizing X-ray diffraction measurements and using the following equations [28]:

$$\tau = \frac{\beta_{(FWHM)} \times \cos\theta}{4} \quad (2)$$

$$\delta = \frac{1}{(C.S)^2} \quad (3)$$

The surface morphology, surface roughness, and average grain diameter of the SnTe nanostructures are examined using an Atomic Force Microscope (AFM) (Core AFM 2023, Nanosurf AG, Switzerland). Hall effect measurements are performed on both undoped and aluminum-doped SnTe nanostructures at concentrations of 2 and 4%. The measurements are carried out at room temperature using the Van der Pauw method with a Hall measurement system (Ecopia HMS-300). From these measurements, the type of charge carriers, carrier concentration (N_h), Hall coefficient (R_h), and Hall mobility (μ_h) are determined. For most cases of semiconductors, the exponential change in D.C electrical conductivity ($\sigma_{d.c}$) with absolute temperature (T) can be given by the Arrhenius equation [29, 30]

$$\sigma_{d.c} = \sigma_o \exp(-E_a/K_B T) \quad (4)$$

$$E_a(eV) = \text{Slope} \times K_B \quad (5)$$

where (σ_o) is the minimum metallic conductivity, and (E_a) is the activation energy, which is equal to ($E_g/2$) in intrinsic conduction. The slope in the equation (5) represents the relation ($\ln\sigma_{d.c}$) as a function of ($10^3/T$). The current-voltage (I-V) characteristics for heterojunction solar cells under illumination and for forward and reverse bias by exposing them to the light of a halogen lamp type (Philips of 10^3 W) with a power density of (100 mW/cm^2) according to international standards. The maximum current density (J_m), short-circuit current density (J_{sc}) which equal ($I_{sc}/\text{area} (A^*)$), maximum voltage (V_m), and open-circuit voltage (V_{oc}) are calculated. After that, the filling factor (F.F) and conversion efficiency (η) are computed using equations (6) and (7), respectively [31, 32].

$$F.F = \frac{P_m}{V_{oc} I_{sc}} = \frac{V_m I_m}{V_{oc} I_{sc}} \quad (6)$$

$$\eta = \frac{P_m}{P_{in}} = \frac{V_m I_m}{P_{in}} = \frac{F.F V_{oc} I_{sc}}{P_{in}} \times 100 \% \quad (7)$$

3. RESULT AND DISCUSSION

Figure (1) shows the X-ray diffraction (XRD) pattern of the SnTe alloy. The XRD results showed that the SnTe alloy has a polycrystalline structure with cubic symmetry. We observed that the dominant orientation is along the (200) direction; this agrees with the studies [13,14]. It is found that there is very good match for the experimental (d_{hkl}) and (2θ) values with the standard (d_{hkl}) and (2θ) values in the ICDD card with a card number (46-1210), as shown in Table 1.

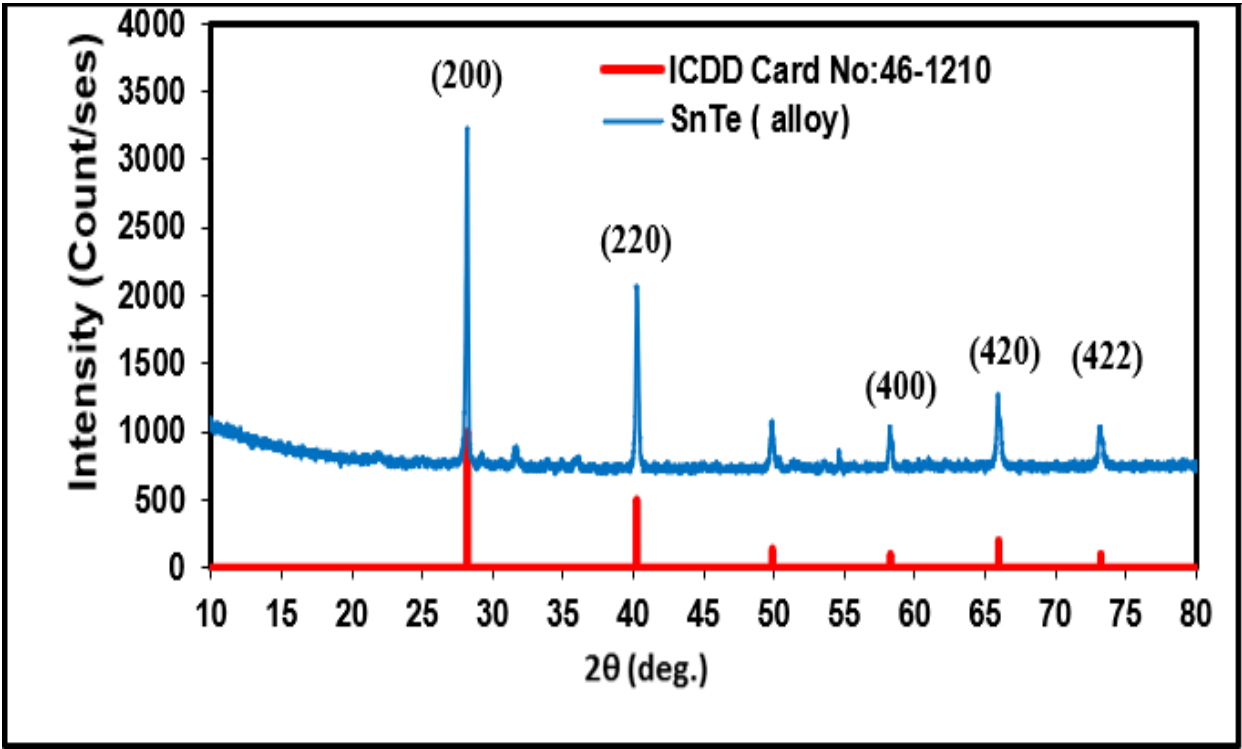


Figure 1 Pattern of XRD for ICDD Card No:46-1210 and alloy SnTe.

Table (1) shows a comparison between the experimentally measured (exp.) values and the standard (stand) values of the interplanar spacing (*d*) and diffraction angles (*2θ*) for the SnTe alloy. All diffraction peaks are consistent with the cubic structure (FCC) similar to the sodium chloride (NaCl)-type structure this agrees with [17]. The identified crystallographic planes (*hkl*) are indexed sequentially as (200), (220), (222), (400), (420), and (422). Good agreement between the standard values and measured is detected, confirmative the phase purity of the crystalline SnTe alloy. The lattice parameter (*a*) is calculated, yielding values of 6.326 Å. This value is very near to the standard lattice constant of the SnTe, reflecting the precision of the measurements and the high crystallinity of the SnTe alloy.

Table 1 XRD data for SnTe alloy.

Alloy	<i>d</i> _{exp.} (Å)	<i>d</i> _{stand.} (Å)	<i>2θ</i> _{exp.} (deg.)	<i>2θ</i> _{stand.} (deg.)	(<i>hkl</i>)	(<i>a</i>) exp.(Å)	(<i>a</i>) stand. (Å)
SnTe	3.161	3.163	28.193	28.19	(200)	<i>a</i> = 6.326	<i>a</i> = 6.327
	2.238	2.237	40.238	40.238	(220)		
	1.8259	1.826	49.885	49.884	(222)		
	1.58	1.581	58.223	58.278	(400)		
	1.4154	1.414	65.923	65.968	(420)		
	1.291	1.291	73.227	73.222	(422)		

Figure 2 shows the XRD patterns of pure SnTe and Al-doped nanostructures (2% and 4%). It can be observed that doping did not change the crystal structure (the same diffraction peaks are present), but it led to: An increase in peak intensity (especially the main (200) peak) due to improved crystallinity. A slight shift of the peaks toward lower diffraction angles, indicating the incorporation of Al atoms into

the lattice and an increase in the lattice constant. A decrease in dislocation density with increasing Al ratio, leading to a reduction in defects. A decrease in microstrain, indicating improved lattice stability and enhanced crystal structure. This means that aluminum doping improves crystallinity and reduces defects without altering the fundamental crystal structure, which positively reflects on the physical properties of the nanostructures [33]. Table 2: shows the X-ray diffraction (XRD) data for undoped and aluminum-doped SnTe nanostructures with ratios of 2% and 4%. The table displays a good agreement between the measured angle values and the standard values expected for the (200) plane according to the reference ICDD card for SnTe. It is observed that the addition of aluminum does not alter the crystal structure or the preferred (200) orientation of the films. However, there is a slight shift in the position of the diffraction peaks towards lower angles (from 28.193° to 28.182° and then to 28.171°) with increasing aluminum ratio. The table also shows a decrease in the full width at half maximum (FWHM) from 0.207° for the pristine sample to 0.1695° at a 2% ratio and to 0.1602° at a 4% ratio, indicating an improvement in crystallinity and an increase in crystal size as a result of aluminum atoms filling vacancy sites in the crystal lattice and reducing defects [34]. This improvement is also reflected in the slight increase in the interplanar spacing (d) from 3.161 Å to 3.163 Å.

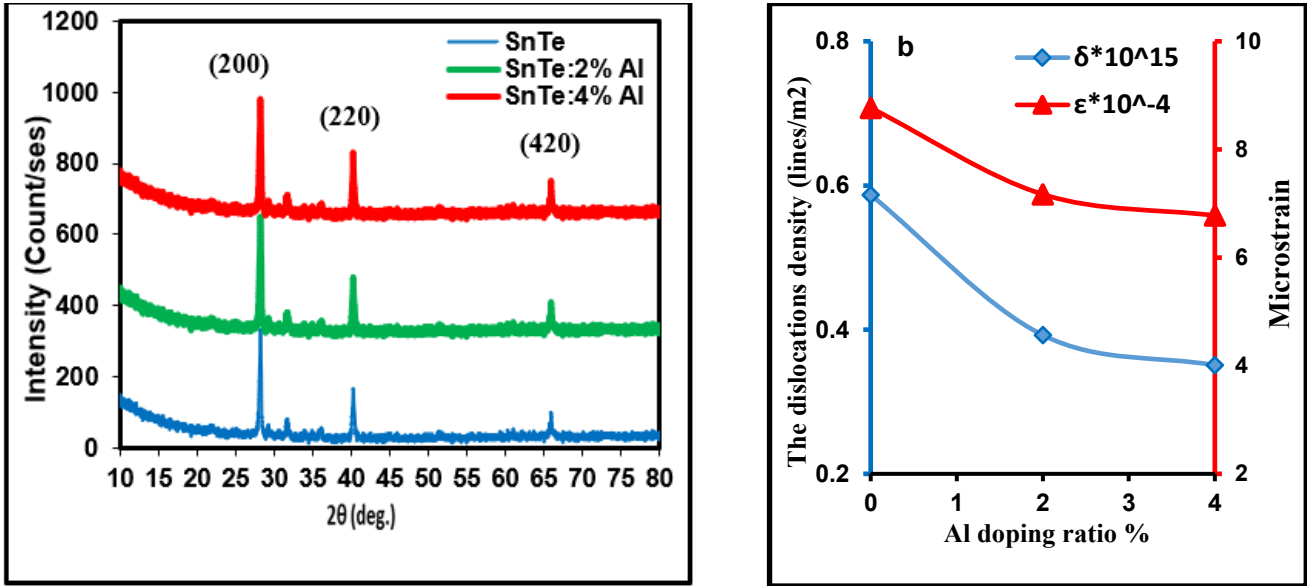


Figure 2 Pattern for XRD of SnTe nanostructures with Al 0, 2% and 4%.

Table 2 Data for XRD of SnTe nanostructures with Al 0, 2% and 4%.

Thin film for hkl (200)	SnTe	SnTe: 2% Al	SnTe: 4% Al
2θ _{exp.} (deg.)	28.193	28.182	28.171
d(exp.) (Å)	3.161	3.162	3.163
β (deg.)	0.207	0.1695	0.1602
C.S (nm)	41.27	50.47	53.40
δ*10 ¹⁵ (lines/m ²)	0.587	0.392	0.350
τ *10 ⁻³	8.7	7.1	6.7

Table 3 displays the average grain diameter, surface roughness, and root mean square (RMS) values of pure and Al-doped SnTe nanostructures with different doping ratios (2% and 4%) at room temperature. The results reveal a clear and systematic increase in all surface parameters with increasing Al doping concentration. The surface roughness of the pure film is (4.23) nm, which increased to (15.37) nm at 2% Al and reached its maximum value of (28.96) nm at 4% Al. Similarly, the average grain diameter increased from (25.24) nm for the pure SnTe film to (30.52) nm at 2% Al, and further to (43.54) nm at 4% Al. In addition, the RMS values showed a significant rise from (5.37) nm for pure SnTe to (19.40) nm at 2% Al, reaching the highest value of (39.95) nm at 4% Al. This gradual increase in surface parameters is attributed to the effect of added Al atoms, which promote greater grain growth and aggregation, leading to an increase in crystallite size and improved crystallinity. Consequently, the surface roughness, average grain diameter, and RMS values increase. These changes in surface morphology are expected to reflect on the optical and electrical properties of the nanostructures due to increased surface scattering effects and modifications in the charge transport mechanism.

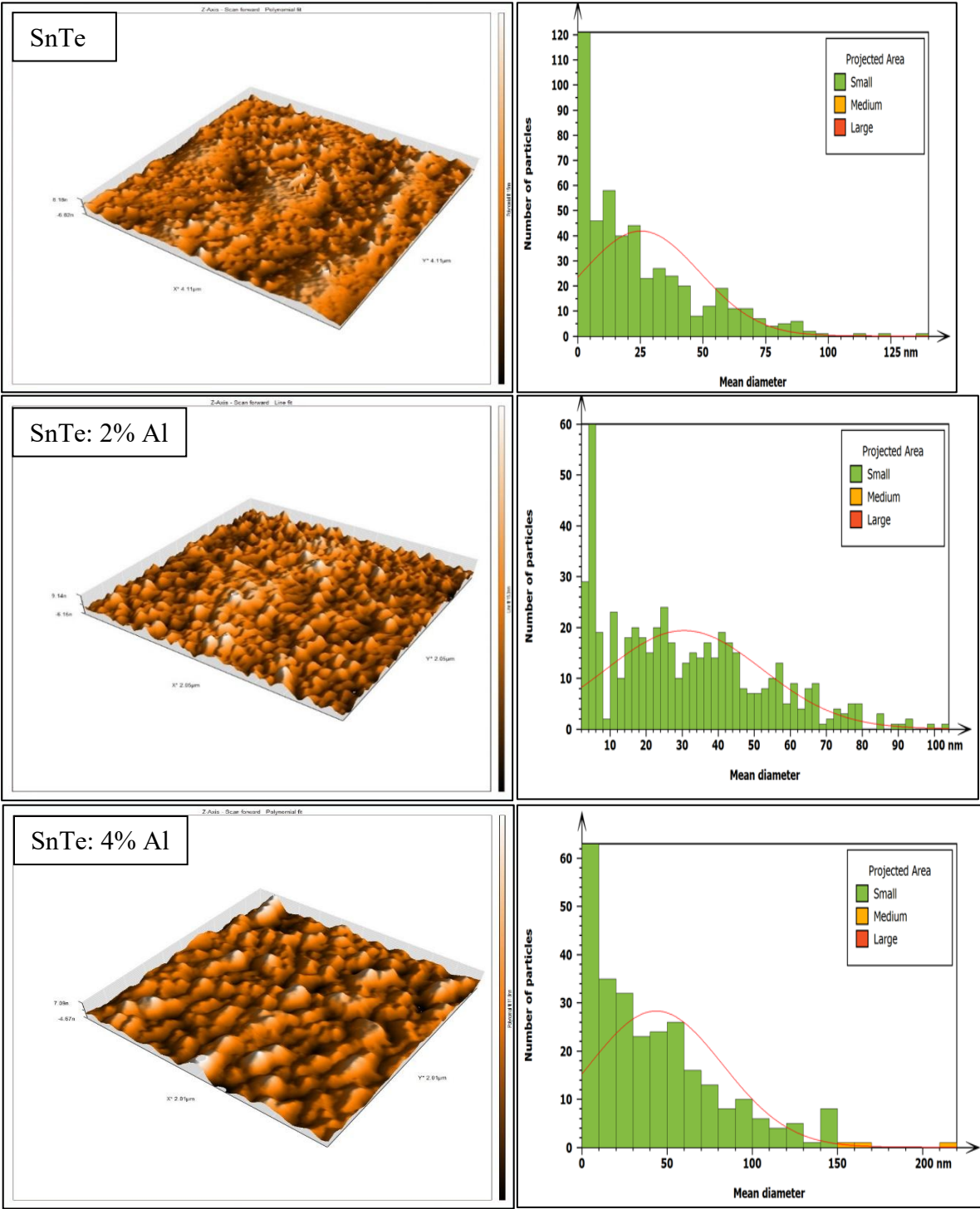


Figure 3 3D (AFM) micrographs of SnTe nanostructures with Al 0, 2% and 4%.

Table 3 Average diameters, surfaces roughness, and r.m.s. for thin film SnTe with Al 0, 2% and 4%.

Nanostructures	Surfaces roughness (nm)	Average diameter (nm)	r.m.s. (nm)
SnTe	4.23	25.24	5.37
SnTe: 2% Al	15.37	30.52	19.40
SnTe: 4% Al	28.96	43.54	39.95

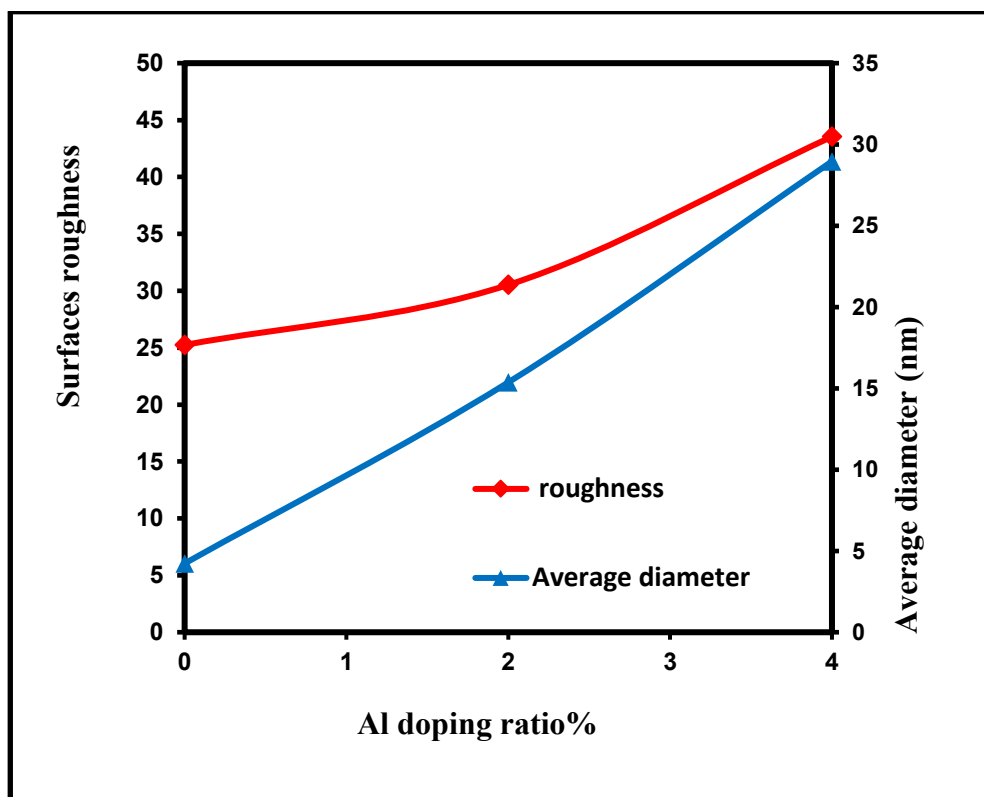


Figure 4 Surfaces roughness and Average diameter of SnTe nanostructures with Al 0, 2% and 4%.

The SnTe usually p-type conductivity because of Sn deficiency and the interpenetration of Te atoms that produces in the valence bands two holes. Consequently, Tin Telluride performs similar to a highly doped degenerate p-type semiconductor [14].

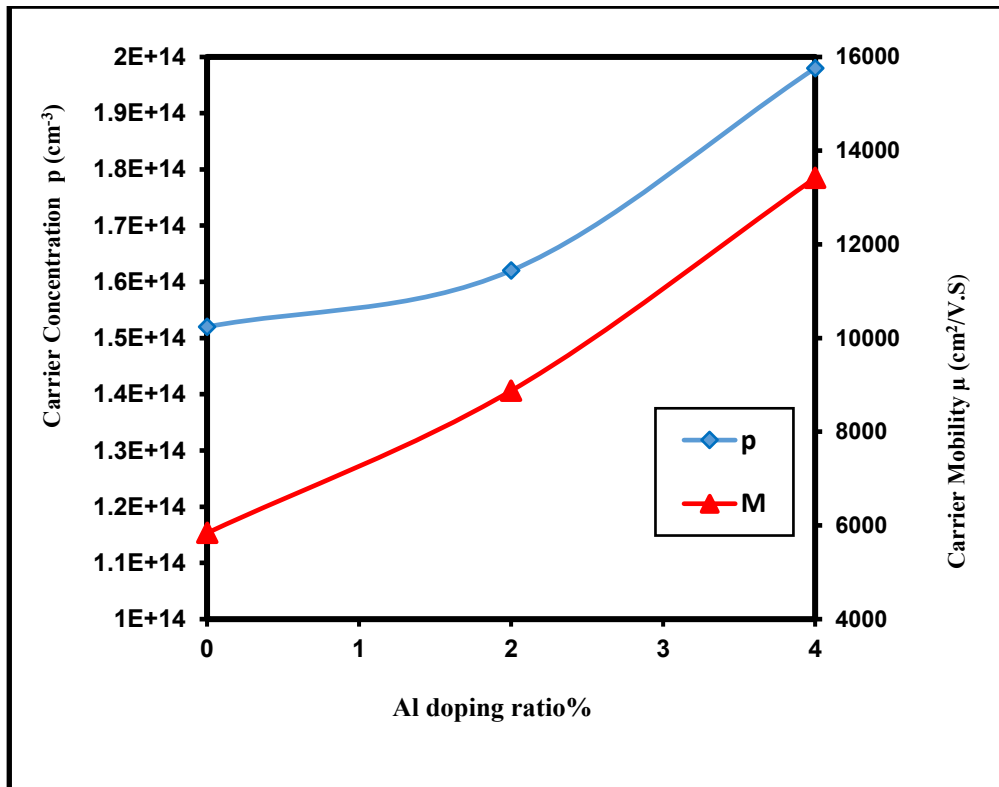


Figure 5 Effect of aluminum doping ratio on the carrier concentration (p) and mobility carrier of SnTe nanostructures with Al 0, 2% and 4%.

Figure (5) and Table (4) Shows a clear increase in both carrier concentration (p) and mobility carrier (μ) with increasing Al doping ratio. This development is credited to the substitutional merger of Al into the SnTe lattice, which adjusts defect states and rises charge carriers. The development in mobility shows reduced scattering centers and improved crystallinity leading to reduced resistivity and enhanced electrical conductivity. Manufacture the doped films more suitable for electronic and thermoelectric applications. The Hall coefficient sign checks that all deposited films exhibition positive charge carriers, representing p -type conductivity where the majority carriers is holes. This performance proposes that the incorporation of Al does not change the conduction type but meaningfully affects the electric transport properties [34].

Table 4 Electrical parameters of SnTe nanostructures with Al 0, 2% and 4%.

Nanostructures	ρ (Ω .cm)	$R_H \times 10^4$ (cm^3/C)	N_A ($1/\text{cm}^3$)	$\mu_H \times 10^4$ ($\text{cm}^2/\text{V.s}$)
SnTe	7.042254	4.11	1.52E+14	5.84
SnTe: 2% Al	4.347826	3.86	1.62E+14	8.87
SnTe: 4% Al	2.352941	3.16	1.98E+14	13.41

Figure (6) displays the change of electrical resistivity (ρ) as a function of temperature for the pure and doped SnTe films. It is obvious that the resistivity reductions with increasing temperature, confirming that the pure and doped SnTe films exhibition a negative temperature coefficient of resistance, which is a typical individual of semiconducting. Furthermore, the lowest resistivity value is recorded for the doped SnTe:4% Al film, this behavior similar to [23]. This confirms that Al doping significantly improves the electrical conductivity of the films by growing the charge carrier density.

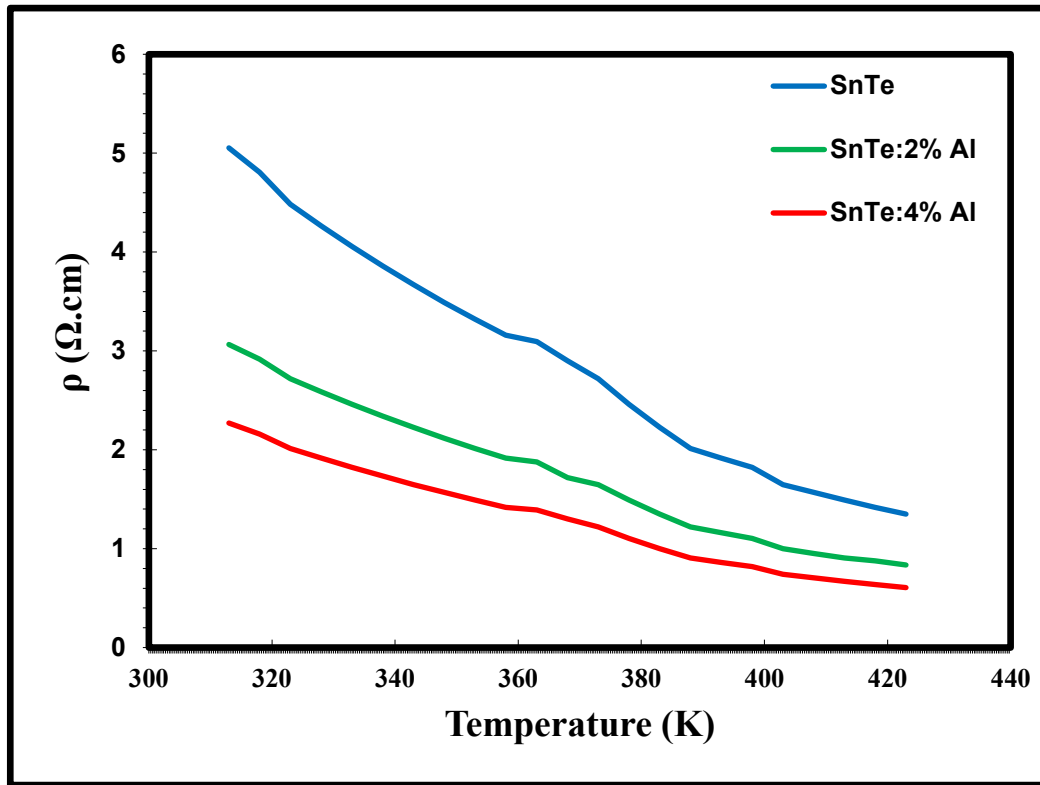


Figure 6 Variation of electrical resistivity (ρ) with temperature for SnTe nanostructures with Al 0, 2% and 4%.

Figure (7) Shows the relationship between $\ln\sigma_{d.c}$ and $(1000/T)$ for pure SnTe and Al-doped SnTe nanostructures (2% and 4%) within the temperature range (313–423 K) follows the Arrhenius relation. It is clearly observed that the values of $\ln\sigma_{d.c}$ growth with growing Al ratios, representing an improvement in the electrical conductivity and, so, a decrease in the electrical resistance. This enhancement is attributed to the increase in charge carrier concentration due to the introduction of localized energy states within the band gap near the conduction band edge. These states facilitate electron transport and reduce the required activation energy [30]. From the $\ln\sigma_{d.c}$ versus $(1000/T)$ plots and Table (5), the activation energy is considered within two discrete temperature regions, indicating the presence of two different conduction mechanisms: First mechanism (low-temperature region: 313–373 K). The activation energy values (E_{a1}) reach to (0.090 eV) presentation a regular decrease with increasing Al ratio. Second mechanism (high-temperature region: 378–423 K) The activation energy values (E_{a2}) reach to (0.168 eV), similarly decreasing with increasing doping ratio. The presence of two activation energies suggests that structure is polycrystalline, these results fall along with the XRD results.

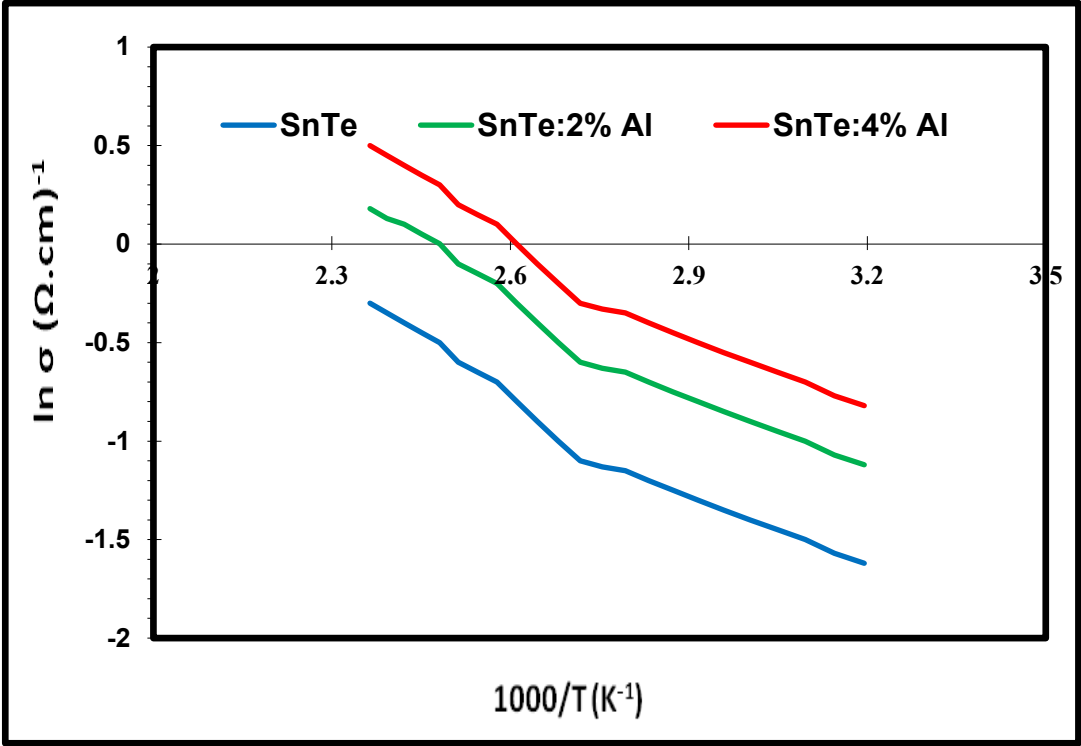


Figure 7 Variation of $\ln \sigma_{d,c}$ with $(1000/T)$ for SnTe and SnTe: Al nanostructures.

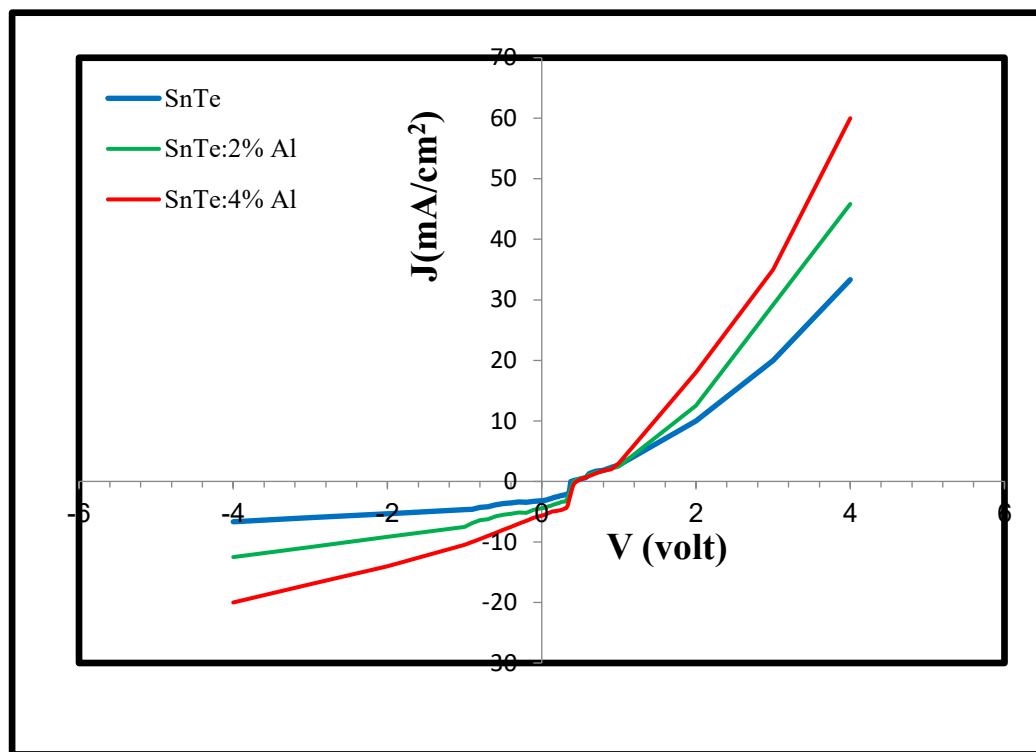
Table 5 Activation energy values for SnTe and SnTe:Al nanostructures.

Nanostructures	$\sigma_{R.T}$ ($\Omega.cm$) ⁻¹	E_{a1} (eV)	Temp. Range (K)	E_{a2} (eV)	Temp. Range (K)
SnTe	1.01005	0.0990955	313-373	0.1800953	378-423
SnTe: 2% Al	2.691234	0.0982338	313-373	0.17234	378-423
SnTe: 4% Al	9.974182	0.0904785	313-373	0.1680315	378-423

Figure (8) illustrates the illuminated current density–voltage (J–V) characteristics of the n-SnTe/p-Si solar cell at room temperature. From the figure, it can be observed that the current density (J) increases with increasing aluminum doping ratio (0%, 2%, and 4%), indicating an improvement in charge transport and an increase in carrier concentration. The values of the open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), voltage and current at the maximum power point (V_m and J_m), fill factor (FF), and conversion efficiency (η) are presented in Table (6). It is clear from the table that all photovoltaic parameters improve with increasing Al content. The value of V_{oc} increases from 0.37576 V to 0.45578 V, while J_{sc} increases from 3.1764 mA/cm² to 5.6 mA/cm², leading to an enhancement in the conversion efficiency from 0.69498% to 1.513%. This improvement is attributed to enhanced optical absorption and improved electrical conductivity as a result of doping, which reduces carrier recombination and improves the junction quality, thereby enhancing the overall solar cell performance [33].

Table 6 I-V parameters under light for the SnTe nanostructures with Al 0, 2% and 4%.

Nanostructures	V _{oc} (Volt)	J _{sc} (mA/cm ²)	V _m (Volt)	J _m (mA/cm ²)	F.F	η %
SnTe	0.37576	3.18	0.3159	2.2	0.5822	0.69498
SnTe: 2% Al	0.41574	4.422	0.33	3.3	0.5930	1.089
SnTe: 4% Al	0.45578	5.6	0.34	4.45	0.5927	1.513

**Figure 8** I-V characteristic under illumination for an n- SnTe /p-Si solar cell with Al 0, 2% and 4%.

4. CONCLUSIONS

Pure and Al-doped SnTe nanostructures (2% and 4%) were successfully prepared by thermal evaporation at room temperature. Structural analysis confirmed a polycrystalline cubic structure for all films, and aluminum doping improved crystallinity, increased crystallite size, and reduced structural defects. Hall measurements revealed p-type conductivity for all films, with decreased resistivity and enhanced carrier concentration and mobility as Al content increased. Reduced in activation energy upon doping. The fabricated p-SnTe/n-Si heterojunction exhibited improved photovoltaic performance. The maximum conversion efficiency (1.513%) was achieved at SnTe: 4% Al, representing that aluminum doping effectively improves the structural, electrical, and photovoltaic properties of SnTe nanostructures for solar cell applications.

References

- [1] Zainab Naseer Hasheem, Estabraq Talib Abdullah, Experimental and Theoretical NANOTECHNOLOGY, 9 (2025) 303 <https://doi.org/10.56053/9.S.303>
- [2] Sundus A. Abdullah Albakri, Aya F. Ibrahim, Hawraa A. Hussein, Experimental and Theoretical NANOTECHNOLOGY, 9 (2025) 311 <https://doi.org/10.56053/9.S.311>
- [3] S. Vadaei, H. Faghiehian, Environmental Toxicology and Pharmacology, 58 (2018) 45. <https://doi.org/10.1016/j.etap.2017.12.019>
- [4] D. K. Bhat, U. S. Shenoy, Materials Today Physics, 4 (2018) 12. <https://doi.org/10.1016/j.mtphys.2017.11.003>
- [5] A. Hmood, A. Kadhim, H. A. Hassam, Superlattices and Microstructures, 76 (2014) 36. <https://doi.org/10.1016/j.spmi.2014.09.016>
- [6] G. H. Patel, S. H. Chaki, R. M. Kannaujiya, Z. R. Parekh, A. B. Hirpara, A. J. Khimani, M. P. Deshpande, Physica B: Condensed Matter, 613 (2021) 412987. <https://doi.org/10.1016/j.physb.2021.412987>
- [7] K. C. Kwon, J. H. Baek, K. Hong, S. Y. Kim, H. W. Jang, Nano-Micro Letters, 14 (2022) 58. <https://doi.org/10.1007/s40820-022-00813-8>
- [8] A. K. Singh, B. S. Yadav, A. K. Vishwakarma, S. Kumar, F. Ahmad, P. Kumar, N. Kumar, Journal of Electronic Materials, 52 (2023) 7132. <https://doi.org/10.1007/s11664-023-10624-8>
- [9] A. A. Taskin, F. Yang, S. Sasaki, K. Segawa, Y. Ando, Physical Review B, 89 (2014) 121302. <https://doi.org/10.1103/PhysRevB.89.121302>
- [10] J. Liu, X. Li, H. Wang, G. Yuan, A. Suvorova, S. Gain, W. Lei, ACS Applied Materials & Interfaces, 12 (2020) 31810. <https://doi.org/10.1021/acsami.0c07318>
- [11] T. Jiang, Y. Zang, H. Sun, X. Zheng, Y. Liu, Y. Gong, K. He, Advanced Optical Materials, 5 (2017) 1600727. <https://doi.org/10.1002/adom.201600727>
- [12] K. Tsuboi, N. Su, S. Kobayashi, K. Sugimoto, M. Kobayashi, Journal of Crystal Growth, 597 (2022) 126805. <https://doi.org/10.1016/j.jcrysgro.2022.126805>
- [13] A. Ashfaq, E. A. Shokralla, A. Ali, M. M. Sabugaa, M. A. Fahmy, S. A. M. Abdelmohsen, M. Y. Ali, A. Baig, O. A. Algethami, M. Abboud, Inorganic Chemistry Communications, 153 (2023) 110790. <https://doi.org/10.1016/j.inoche.2023.110790>
- [14] R. M. Kannaujiya, S. H. Chaki, A. J. Khimani, Z. R. Parekh, A. B. Hirpara, S. S. Soni, S. N. Bariya, M. P. Deshpande, Surfaces and Interfaces, 45 (2024) 103788. <https://doi.org/10.1016/j.surfin.2024.103788>
- [15] Y. K. Lee, E. S. Park, C. Yoo, W. Kim, J. W. Jeon, M. Ha, C. S. Hwang, Crystal Growth & Design, 20 (2020) 4649. <https://doi.org/10.1021/acs.cgd.0c00338>
- [16] Z. Weng, S. Ma, H. Zhu, Z. Ye, T. Shu, J. Zhou, X. Wu, H. Wu, Solar Energy Materials and Solar Cells, 179 (2018) 276. <https://doi.org/10.1016/j.solmat.2018.02.020>
- [17] Rusul Adnan Al-wardy, Experimental and Theoretical NANOTECHNOLOGY, 9 (2025) 327 <https://doi.org/10.56053/9.S.327>
- [18] M. Wortmann, B. Bednarz, N. B. Nezafat, K. Viertel, O. Kuschel, J. Schmalhorst, I. Ennen, M. Gärner, N. Frese, G. Jakob, J. Wollschläger, G. Schierning, A. Hütten, T. Kuschel, Applied Surface Science, 713 (2025) 164356. <https://doi.org/10.1016/j.apsusc.2025.164356>
- [19] M. Muthumari, M. Manjula, P. Veluswamy, D. V. Kuznetsov, Journal of Physics and Chemistry of Solids, 176 (2023) 111232. <https://doi.org/10.1016/j.jpcs.2023.111232>
- [20] Z. L. Liu, Z. L. Guo, L. Deng, Inorganic Chemistry, 63 (2024) 5389. <https://doi.org/10.1021/acs.inorgchem.3c04368>
- [21] A. Bugalia, V. Gupta, A. Pandey, Journal of Physics D: Applied Physics, 57 (2024) 195502. <https://doi.org/10.1088/1361-6463/ad2d76>
- [22] G. Jamwal, A. Kumar, M. Warish, S. Chakravarty, S. Muthiah, A. Kandasami, A. Niazi, Journal of Alloys and Compounds, 954 (2023) 170182. <https://doi.org/10.1016/j.jallcom.2023.170182>

- [23] E. A. Shokralla, A. Ashfaq, H. Alqurashi, L. G. Alharbe, E. G. Hanna, M. A. Fahmy, R. R. Macadangdang Jr., S. H. Alrefae, R. S. Almufarij, A. R. Abd-Elwahed, *Ceramics International*, 50 (2024) 34467. <https://doi.org/10.1016/j.ceramint.2024.05.262>
- [24] Ahmed S. Hassan, Jasim H. Kadhum, Sarmad Najah ALSalhy, Osama T. Al-Taai, *Experimental and Theoretical NANOTECHNOLOGY*, 9 (2025) 335 <https://doi.org/10.56053/9.S.335>
- [25] A. Tony, R. Clarison, *Experimental and Theoretical NANOTECHNOLOGY*, 9 (2025) 347 <https://doi.org/10.56053/9.2.347>
- [26] Safa Salah Salman, Asaad T. Al-Douri, Albosale Abbas Hadi, Saeb Jasim Mohammed Alnajm, *Experimental and Theoretical NANOTECHNOLOGY*, 9 (2025) 361 <https://doi.org/10.56053/9.2.361>
- [27] Björn Reetz, Andreas Frehn, Wolfgang Budweiser, William Bishop, *Experimental and Theoretical NANOTECHNOLOGY*, 9 (2025) 465 <https://doi.org/10.56053/9.3.465>
- [28] M. M. Margoni, S. Mathuri, K. Ramamurthi, R. R. Babu, K. Sethuraman, *Thin Solid Films*, 606 (2016) 51. <https://doi.org/10.1016/j.tsf.2016.04.018>
- [29] G. G. Rusu, M. Rusu, *Solid State Communications*, 116 (2000) 363. [https://doi.org/10.1016/S0038-1098\(00\)00376-8](https://doi.org/10.1016/S0038-1098(00)00376-8)
- [30] Maksood Adil Mahmoud Al-Doori, Asaad T. Al-Douri, Nahedh Ayad Faris, *Experimental and Theoretical NANOTECHNOLOGY*, 9 (2025) 489 <https://doi.org/10.56053/9.3.489>
- [31] R. S. Mahmood, et al., *Journal of the Mechanical Behavior of Materials*, 34 (2025) 1. <https://doi.org/10.1515/jmbm-2025-0040>
- [32] H. Kara, M. Upadhyay Kahaly, K. Özdoğan. *Journal of Alloys and Compounds*, 735 (2018) 950 doi.org/10.1016/j.jallcom.2017.11.022
- [33] R. Prakash, G. Kalpana. *RSC Advances*, 13 (2023) 10847 doi.org/10.1039/D3RA00942D
- [34] S. Singh, D. C. Gupta. *Results in Physics*, 13 (2019) 102300 doi.org/10.1016/j.rinp.2019.102300