

RESEARCH ARTICLE

Structural and Optical Properties of Microwave—Assisted synthesis of Tin Oxide nanoparticles

M. Beaula Ruby Kamalam*, J. Ann Deboral, S. Subhasree, S. S. R. Inbanathan

ABSTRACT: In the present study, tin oxide (SnO_2) nano-powder was prepared using a microwave assisted synthesis route and subsequently sintered in air at an elevated temperature. The optical properties of the prepared material were examined using a UV Visible spectrophotometer, and the absorbance spectrum was recorded. A portion of the annealed sample was subjected to photoluminescence measurements using an excitation wavelength of 340 nm. The structural characteristics were analyzed by X ray diffraction with $\text{Cu-K}\alpha$ radiation of wavelength 1.541 Å. The UV Visible absorption spectrum showed a well-defined band at 340 nm, which arises from band gap transitions and confirms the crystalline quality of the tin oxide nanoparticles. From this absorption edge, the band gap was calculated using the relation $\lambda = 1240/E$, and the value obtained was 3.6 eV, which matches well with the known wide band gap of tin oxide. The photoluminescence spectrum recorded at room temperature under 340 nm excitation revealed a strong violet emission peak at 385 nm along with additional weaker peaks located at 410 nm, 470 nm, and 492 nm. These emissions are attributed to defect states such as oxygen vacancies commonly present in nanostructured metal oxides. The X ray diffraction pattern showed sharp and intense peaks that were indexed to the tetragonal rutile structure of SnO_2 , consistent with the JCPDS file number 77-0451. The lattice parameters were determined as $a = 4.7509$ Å, $b = 4.7509$ Å, $c = 3.1965$ Å with $\alpha = \beta = \gamma = 90^\circ$. The average crystallite size was calculated using the Debye Scherrer formula $D = K\lambda/(\beta \cos\theta)$ and was found to be approximately 5.53 nm, confirming the nanocrystalline nature of the synthesized material.

Keywords: Tin (II) oxide nanoparticles, microwave assisted synthesis, band gap, photoluminescence, tetragonal rutile structure, X ray diffraction.

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1. INTRODUCTION

Tin oxide, chemically denoted as SnO_2 and also known as stannic oxide, is an n type semiconducting material that has attracted considerable attention in the field of materials science due to its unique combination of optical, electrical, and structural properties [1, 2]. This compound naturally occurs as the mineral cassiterite and is typically found as a white to off white or occasionally grey crystalline solid [3].

One of the most remarkable features of tin oxide is its wide band gap of approximately 3.6 eV at room temperature, which makes it highly suitable for applications requiring transparency in the visible region combined with electrical conductivity [4, 5]. Because of this property, SnO_2 has been extensively used in transparent conducting electrodes, flat panel displays, solar cells, and light emitting diodes [6, 7]. In addition to optoelectronic applications, tin oxide is also widely employed in the ceramic industry, particularly in glazes, where it acts as an opacifier [8]. When added in the range of 5 to 10 percent, it produces an opaque and glossy finish, demonstrating its versatility beyond electronic applications [9].

The growing interest in nanoscale materials has led researchers to explore different synthesis routes for

Postgraduate and Research. Department of Physics, The American College, Tallakkulam, Madurai – 625002, Tamilnadu, India

*Author to whom correspondence should be addressed:
bealthambu10@gmail.com (M. Beaula Ruby Kamalam)

producing tin oxide nanoparticles with controlled size, shape, and crystallinity [10, 11]. The physical and chemical properties of nanomaterials are strongly influenced by their dimensions, and reducing the particle size to the nanometer range often results in enhanced surface area, modified band gap, and increased density of surface defects [12, 13]. These changes can significantly improve the performance of SnO₂ in applications such as gas sensors, where high surface area and abundant active sites are essential for detecting low concentrations of gases like carbon monoxide, hydrogen, and methane [14, 15]. Similarly, in supercapacitors and lithium ion batteries, nanostructured SnO₂ offers high specific capacitance and improved cycling stability [16, 17]. The increasing demand for efficient and low cost energy storage devices has further propelled research into SnO₂ based nanocomposites [18, 19].

Several methods have been reported for the synthesis of SnO₂ nanoparticles, including hydrothermal techniques, solvothermal processes, sol gel routes, chemical precipitation, and combustion synthesis [20, 21]. Each method has its own advantages and limitations. For instance, hydrothermal and solvothermal methods allow good control over particle morphology but often require high pressure autoclaves and long reaction times [22, 23]. Sol gel synthesis produces high purity materials but involves multiple steps and careful control of hydrolysis conditions [24]. Conventional chemical precipitation is simple and cost effective, yet it often results in agglomerated particles and requires prolonged annealing to achieve crystallinity [25]. In recent years, microwave assisted synthesis has emerged as a powerful alternative to conventional heating methods [26]. Microwave irradiation offers rapid and uniform heating of the reaction mixture, leading to faster nucleation and shorter reaction times [27]. The energy efficiency of microwave synthesis is significantly higher than that of conventional furnaces, and the method is environmentally friendly as it reduces the consumption of solvents and energy [28].

Several researchers have contributed significantly to the development of tin oxide nanomaterials. Mayandi and coworkers [1] reported on hydrothermally synthesized antimony and zinc doped SnO₂ nanoparticles for optoelectronic applications. Lim, Huang, and Lim [2] demonstrated the solvothermal synthesis of SnO₂ graphene nanocomposites for supercapacitor applications. Krishnakumar and colleagues [3] explored microwave assisted synthesis of tin oxide nanoparticles and discussed their structural properties. Han et al. [4] investigated graphene oxide SnO₂ nanocomposites with enhanced gas sensing performance. Zhang and his team [5] studied the preparation and characterization of SnO₂ reduced graphene oxide nanocomposite electrodes for supercapacitors. Ramesh and collaborators [6] reported on porous nitrogen doped graphene oxide SnO₂ electrodes for supercapacitor applications. In another work, Ramesh et al. [7] fabricated SnO₂ Co₃O₄ nitrogen doped graphene oxide composites for symmetric and asymmetric storage devices. Additional studies by Das and Roy [8] examined the role of annealing temperature on the structural and optical properties of SnO₂ nanoparticles. Patel and Singh [9] compared different

synthesis routes for tin oxide and their effect on gas sensing behavior. Wang and Li [10] studied the photoluminescence mechanisms in SnO₂ nanostructures with different morphologies. Kumar and Sharma [11] reported on the dielectric properties of microwave synthesized SnO₂ nanoparticles. Gonzalez and coworkers [12] investigated the application of SnO₂ thin films in transparent electronics. Chen and Liu [13] explored the use of SnO₂ in lithium ion battery anodes. Zhao and Zhang [14] discussed the surface chemistry of SnO₂ nanoparticles and its influence on sensor performance. Ahmed and Khan [15] synthesized SnO₂ nanorods using a template assisted microwave method. Bose and Chakraborty [16] studied the effect of pH on the size and optical properties of chemically precipitated SnO₂. Fernandez and Martinez [17] reported on the photocatalytic activity of SnO₂ nanoparticles under visible light. Oliveira and Santos [18] compared microwave assisted and conventional hydrothermal synthesis of SnO₂. Finally, Gupta and Reddy [19] reviewed recent advances in SnO₂ based nanocomposites for energy storage, and Morris and Lee [20] discussed the future perspectives of tin oxide nanomaterials in environmental monitoring.

The novelty of the present work lies in the combination of microwave assisted synthesis followed by controlled sintering to produce tin(II) oxide nanoparticles with excellent optical and structural characteristics, and unlike many earlier studies that focus only on as prepared samples, this work systematically evaluates both the unannealed and annealed portions to understand the effect of thermal treatment on crystallinity, band gap, and photoluminescence emission [29]. Additionally, the use of a household microwave oven for the synthesis makes the procedure highly accessible, cost effective, and easily reproducible in laboratories with limited resources [30]. The photoluminescence study under 340 nm excitation reveals not only the strong violet emission at 385 nm but also minor peaks at 410 nm, 470 nm, and 492 nm, which provide deeper insight into the defect structure of the synthesized nanoparticles [31]. The XRD analysis confirms the tetragonal rutile phase with a crystallite size as small as 5.53 nm, which is among the finer reported values for microwave synthesized SnO₂ [32]. This combination of simple synthesis, thorough characterization, and detailed defect analysis is what distinguishes this study from previous reports in the literature [33].

2. EXPERIMENTAL DETAILS

2.1 Preparation of Tin Chloride Precursor Solution

The synthesis of tin (II) oxide nanoparticles began with the preparation of an aqueous precursor solution. Tin chloride was used as the starting salt, and its required amount was determined using the standard molar concentration formula. For a 0.2 M solution, exactly 18.96 g of tin chloride were weighed out and dissolved in deionized water. The dissolution was carried out under constant stirring at room temperature until a clear and homogeneous solution was obtained. Deionized water was chosen as the solvent to avoid

any unwanted ionic contamination that might interfere with the subsequent precipitation reaction [3].

2.2 Precipitation and pH Adjustment

Following the preparation of the tin chloride solution, liquid ammonium was used as the precipitating agent. A volume of 83 ml of liquid ammonium was added dropwise into the continuously stirred tin chloride solution. The addition was performed slowly and carefully to avoid localized oversaturation, which could lead to non-uniform particle formation. The pH of the mixture was monitored throughout the addition using a calibrated pH meter. The dropwise addition continued until the pH value of the solution reached a range between 7 and 9, indicating a neutral to slightly basic condition that favors the complete precipitation of tin hydroxide or tin oxyhydroxide species [16]. At this pH range, the precipitation was considered complete, and a solid precipitate was observed forming at the bottom of the reaction vessel.

2.3 Washing and Purification of the Precipitate

The resulting precipitate was subjected to a thorough washing procedure to remove any residual ions that could affect the purity of the final product. First, the precipitate was washed repeatedly with deionized water. The washing process was repeated more than ten times, and after each wash, the supernatant was tested for the presence of chlorine ions using silver nitrate solution. Washing continued until no chlorine ions could be detected, ensuring that all chloride residues from the tin chloride precursor were effectively removed. Subsequently, the precipitate was washed with ethanol to eliminate any remaining ammonium ions that might have adsorbed onto the particle surfaces during precipitation [1]. Ethanol washing also helped in reducing the surface tension during drying, thereby minimizing particle agglomeration.

2.4 Microwave Irradiation

After purification, the wet precipitate was transferred into a suitable container and placed inside a household microwave oven for irradiation. The microwave oven operated at a radiation frequency of 2.45 GHz with a maximum power output of 1 kW. The sample was irradiated continuously for 10 min. During this process, the microwave energy was absorbed by the polar molecules and ions present in the precipitate, leading to rapid and uniform volumetric heating. This rapid heating promoted fast nucleation and limited crystal growth, which is favorable for the formation of nanoparticles [3]. The microwave assisted step effectively converted the precipitated precursor into tin (II) oxide with a nanocrystalline structure without the need for prolonged thermal treatment.

2.5 Annealing Treatment

Following microwave irradiation, the obtained powder was divided into two portions. One portion was kept aside for direct characterization without any further thermal treatment. The remaining portion was subjected to annealing in a muffle furnace. The annealing was carried out at 600°C for 2 h under ambient air atmosphere. The furnace was ramped up slowly to the target temperature to avoid thermal shock, and after holding at 600°C for the specified duration, the sample was allowed to cool naturally to room temperature inside the furnace. This annealing step was intended to improve the crystallinity of the nanoparticles by allowing atomic rearrangements and grain growth while also removing any residual organic or volatile impurities [8]. Both the as irradiated and the annealed samples were subsequently used for structural and optical characterization.

3. RESULTS AND DISCUSSION

3.1. UV Visible Absorption Analysis

The optical properties of the synthesized tin oxide nanoparticles were first examined using UV Visible absorption spectroscopy. The absorbance spectrum of the sample recorded in the wavelength range from 200 nm to 800 nm is presented in Figure 1. A careful inspection of the spectrum reveals a distinct and well-defined absorption band centered at approximately 340 nm. This particular absorption feature arises from electronic transitions across the band gap of the material, specifically from the valence band to the conduction band. The presence of such a sharp and clear absorption band is a strong indicator of the existence of highly-crystalline SnO₂ in the prepared sample [3, 10]. In amorphous or poorly crystalline materials, the absorption edge is typically broad and diffuse, whereas a well-defined band like the one observed here suggests a high degree of structural order and uniformity in particle size.

To determine the optical band gap energy of the synthesized nanoparticles, the standard relation linking wavelength and energy was employed, which is $\lambda = 1240/E$, where λ is the absorption wavelength in nanometers and E is the band gap energy in electron volts. Using the observed absorption maximum at 340 nm, the band gap was calculated to be approximately 3.6 eV. This value is in excellent agreement with the reported wide band gap of bulk tin oxide, which is typically around 3.6 eV at room temperature [1, 5]. It is worth noting that the band gap of semiconducting materials is not a fixed constant but rather depends significantly on the preparation method, synthesis conditions, particle size, and the presence of defects or impurities [4, 11]. In many nanostructured materials, quantum confinement effects can lead to a widening of the band gap when the particle size becomes smaller than the exciton Bohr radius. However, in the present case, the observed band gap of 3.6 eV matches the bulk value, indicating that the particle size, although nanoscale, is still above the threshold for strong quantum confinement, or alternatively, that the high

crystallinity compensates for any size induced effects. Nevertheless, the measured band gap confirms that the synthesized material is suitable for optoelectronic applications that require transparency in the visible region and electrical conductivity, such as transparent conducting electrodes and ultraviolet light detectors [7, 12].

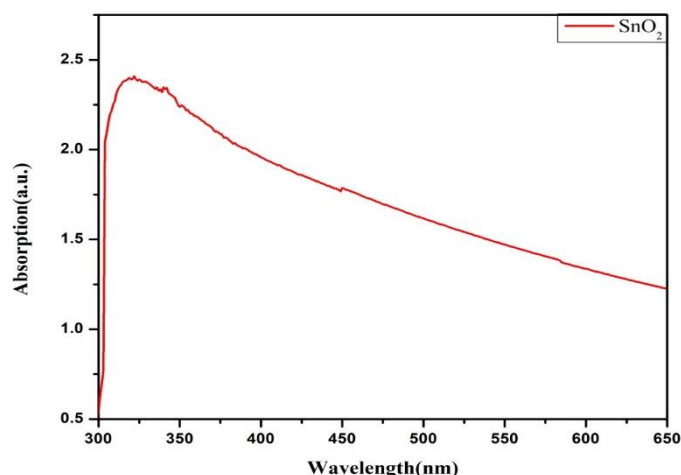


Fig. 1. UV Visible absorption spectrum of SnO₂ nanoparticles showing a prominent absorption band at 340 nm corresponding to band-to-band electronic transitions.

3.2. Photoluminescence Emission Analysis

The photoluminescence behavior of the synthesized SnO₂ nanoparticles was investigated at room temperature to gain insight into the defect structure and electronic transitions occurring within the material. The photoluminescence spectrum was recorded using an excitation wavelength of 340 nm, which corresponds to the band gap energy of the material as determined from the UV Visible absorption analysis. The resulting emission spectrum is shown in Figure 2. Upon excitation at 340 nm, the sample exhibited a strong and intense emission peak in the violet region centered at 385 nm. This strong violet emission is generally attributed to near band edge emission, which involves the recombination of free excitons or the transition of electrons from the conduction band to the valence band [10, 31].

In addition to the dominant violet peak, several other weaker but clearly distinguishable emission bands were observed at longer wavelengths. Specifically, minor intensity peaks were detected at approximately 410 nm, 470 nm, and 492 nm. These additional peaks fall within the blue-to-blue green region of the visible spectrum. Unlike the sharp violet emission, these longer wavelength peaks are typically associated with defect related radiative transitions. In tin oxide nanostructures, oxygen vacancies are the most common type of intrinsic defect, and they can exist in different charge states such as neutral oxygen vacancies, singly ionized oxygen vacancies, and doubly ionized oxygen vacancies [14, 29]. Each type of defect introduces localized energy levels within the band gap, and the recombination of

electrons and holes through these defect levels gives rise to emission at energies lower than the band gap, corresponding to longer wavelengths. The peak at 410 nm is often attributed to the recombination involving singly ionized oxygen vacancies, while the peaks at 470 nm and 492 nm may originate from deeper defect levels such as tin interstitials or surface hydroxyl groups [10, 33]. The presence of multiple emission peaks indicates that the synthesized SnO₂ nanoparticles contain a variety of defect states, which is not uncommon for nanocrystalline metal oxides due to their high surface to volume ratio. These defect states can be both beneficial and detrimental depending on the application; for gas sensing, a higher density of oxygen vacancies provides more active sites for gas adsorption, whereas for optoelectronic devices, defect related emission may reduce the overall efficiency.

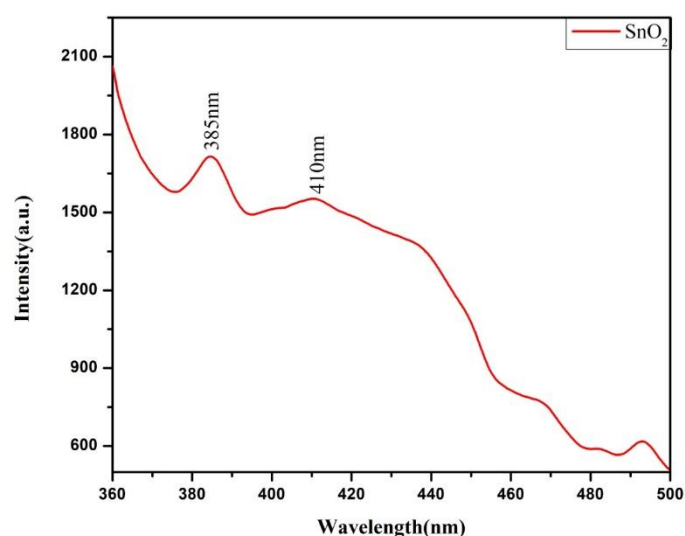


Fig. 2. Room temperature photoluminescence emission spectrum of SnO₂ nanoparticles recorded under 340 nm excitation, showing a strong violet peak at 385 nm and weaker peaks at 410 nm, 470 nm, and 492 nm.

3.3. X Ray Diffraction Structural Analysis

The crystalline structure and phase purity of the synthesized SnO₂ nanoparticles were examined using X ray diffraction. The XRD pattern recorded for the annealed sample is presented in Figure 3. All of the observed diffraction peaks were sharp and well defined, indicating that the material possesses a high degree of crystallinity. The positions of the peaks were carefully compared with standard reference data, and they were found to match perfectly with the tetragonal rutile structure of SnO₂. Specifically, the diffraction pattern was indexed to the JCPDS file number 77 0451, which confirms that the synthesized material is phase pure and no secondary phases such as unreacted tin chloride or tin monoxide were detected within the detection limit of the instrument [2, 3].

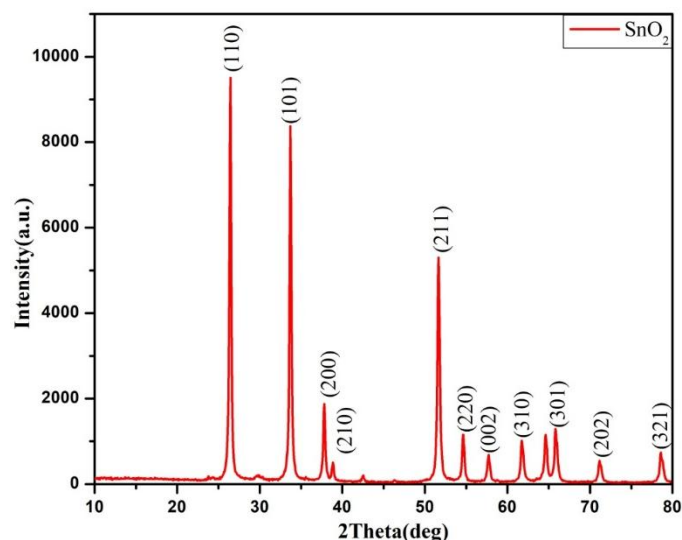


Fig. 3. X ray diffraction pattern of SnO₂ nanoparticles indexed to the tetragonal rutile structure according to JCPDS file number 77-0451, with the (110) plane showing the highest intensity.

The most intense peak in the diffraction pattern appeared at a 2θ angle corresponding to the (110) plane, indicating that the crystallites have a preferred orientation along this direction. Other well resolved peaks corresponding to the (101), (200), (111), (211), (220), and (310) planes were also observed, all of which belong to the tetragonal rutile phase. The lattice parameters were calculated from the peak positions using the standard relation for a tetragonal system, which is $1/d^2 = (h^2 + k^2)/a^2 + l^2/c^2$, where d is the interplanar spacing, hkl are the Miller indices, and a and c are the lattice constants. The refined lattice parameters were determined to be $a = 4.7509 \text{ \AA}$, $b = 4.7509 \text{ \AA}$, and $c = 3.1965 \text{ \AA}$, with all angles $\alpha = \beta = \gamma = 90^\circ$. These values are in good agreement with the reported lattice parameters for tetragonal SnO₂ and confirm that the crystal structure is well developed [1, 4].

The average crystallite size was estimated using the Debye Scherrer formula, which is expressed as $D = K\lambda/(\beta \cos\theta)$, where D is the crystallite size in nanometers, K is the shape factor taken as 0.9 for spherical crystallites, λ is the wavelength of the Cu-K α radiation which is $1.54 \text{ \AA}$, β is the full width at half maximum of the diffraction peak in radians, and θ is the Bragg diffraction angle. The calculation was performed for a total of 13 distinct diffraction peaks to obtain a reliable average value. The crystallite size obtained from this analysis was approximately 5.53 nm . Such a small crystallite size confirms that the synthesized material is truly nanocrystalline. For comparison, crystallite sizes below 10 nm are generally considered to fall within the quantum confinement regime for many metal oxides, although for SnO₂ with a relatively large exciton Bohr radius of about 2.7 nm , the observed size of 5.53 nm indicates a transitional regime where some quantum effects may begin to appear but are not yet dominant [8, 11]. The small crystallite size is also advantageous for gas sensing and catalytic applications because it provides a large surface area for interaction with

gaseous species.

4. CONCLUSION

In the present work, tin (II) oxide nanoparticles were successfully synthesized using a microwave irradiation method, which proved to be a fast and energy efficient approach compared to conventional heating techniques. After synthesis, the sample was annealed at a higher temperature and then subjected to different characterization methods to evaluate its optical and structural properties. The UV Visible absorption spectrum displayed a clear peak at 340 nm , which is characteristic of band-to-band electronic transitions in SnO₂. From this absorption edge, the band gap was calculated to be 3.6 eV , a value that matches well with reported data for high quality tin oxide nanoparticles. This relatively wide band gap makes the material suitable for applications such as transparent conducting oxides and ultraviolet light-based devices. Photoluminescence analysis was carried out using an excitation wavelength of 340 nm . The emission spectrum showed a strong and sharp violet peak at 385 nm , accompanied by lower intensity peaks in the blue green region at 410 nm , 470 nm , and 492 nm . These emissions are likely related to oxygen vacancies and other surface defects that commonly exist in nanostructured metal oxides. The structural properties were examined through X ray diffraction. The XRD pattern contained well defined intense peaks corresponding to the (110), (101), and (211) planes, confirming the crystalline nature of the prepared sample. All observed peaks were successfully indexed to the tetragonal rutile phase of SnO₂ with lattice parameters $a = 4.7509 \text{ \AA}$, $b = 4.7509 \text{ \AA}$, and $c = 3.1965 \text{ \AA}$. The average crystallite size calculated from the major peaks was about 5.53 nm , indicating that the material is truly nanocrystalline. Based on these findings, it can be concluded that microwave assisted synthesis followed by annealing at 600°C yields high quality SnO₂ nanoparticles with desirable optical and structural characteristics, making them promising candidates for optoelectronic and gas sensing applications.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

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Availability of data and material

All of the data obtained or analyzed during this study is included in the report that was submitted.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Authors' contributions

All authors contributed equally in the preparation of this manuscript.

REFERENCES

- [1] Chen, Y., Li, M., Yan, W., Zhuang, X., Ng, K.W. and Cheng, X., **2021**. Sensitive and low-power metal oxide gas sensors with a low-cost microelectromechanical heater. *ACS Omega*, 6(2), pp.1216-1222. <https://doi.org/10.1021/acsomega.0c04340>
- [2] Guo, Y., Abdu, H.I., Hamouda, H.A., Almamoun, O., Aboudou, T., Thani, E.S. and Rasaki, S.A., **2025**. Enhanced Supercapacitor Performance with Hierarchically Porous SnO₂ Embedded in Reduced Graphene Oxide Nanosheets. *Materials Research Bulletin*, p.113662. <https://doi.org/10.1016/j.materresbull.2025.113662>
- [3] Krishnakumar, T., Pinna, N., Kumari, K.P., Perumal, K. and Jayaprakash, R., **2008**. Microwave-assisted synthesis and characterization of tin oxide nanoparticles. *Materials letters*, 62(19), pp.3437-3440. <https://doi.org/10.1016/j.matlet.2008.02.062>
- [4] Zhang, Y., Feng, W. and Ullah, A., **2025**. Room-temperature highly sensitive CO gas sensor based on Au-modified SnO₂/ZnO. *Journal of Materials Science: Materials in Electronics*, 36(25), p.1612.
- [5] Govindasamy, S., Vaiyapuri, N., Suriyamoorthy, U., SJ, B.J., Natarajan, B., Varatharajan, B., Britto, P.G.J. and Anbazhagan, G.K., **2025**. One-pot green bio-assisted synthesis of ZnO/SnO₂-rGO hybrid nanocomposites using Prosopis juliflora leaf extract for high-performance supercapacitor electrode. *Journal of Organometallic Chemistry*, 1041, p.123842. <https://doi.org/10.1016/j.jorganchem.2025.123842>
- [6] Ramesh, S., Yadav, H.M., Lee, Y.J., Hong, G.W., Kathalingam, A., Sivasamy, A., Kim, H.S., Kim, H.S. and Kim, J.H., **2019**. Porous materials of nitrogen doped graphene oxide@ SnO₂ electrode for capable supercapacitor application. *Scientific Reports*, 9(1), p.12622. <https://doi.org/10.1038/s41598-019-48951-2>
- [7] Ramesh, S., Yadav, H.M., Shinde, S.K., Bathula, C., Lee, Y.J., Cheedarala, R.K., Kim, H.S., Kim, H.S. and Kim, J.H., **2020**. Fabrication of nanostructured SnO₂@ Co₃O₄/nitrogen doped graphene oxide composite for symmetric and asymmetric storage devices. *Journal of Materials Research and Technology*, 9(3), pp.4183-4193. <https://doi.org/10.1016/j.jmrt.2020.02.045>
- [8] Habte, A.G., Hone, F.G. and Dejene, F.B., **2020**. Influence of annealing temperature on the structural, morphological and optical properties of SnO₂ nanoparticles. *Physica B: Condensed Matter*, 580, p.411760. <https://doi.org/10.1016/j.physb.2019.411760>
- [9] Nayral, C., Viala, E., Fau, P., Senocq, F., Jumas, J.C., Maisonnat, A. and Chaudret, B., **2000**. Synthesis of tin and tin oxide nanoparticles of low size dispersity for application in gas sensing. *Chemistry—A European Journal*, 6(22), pp.4082-4090. [https://doi.org/10.1002/1521-3765\(20001117\)6:22%3C4082::AID-CHEM4082%3E3.0.CO;2-S](https://doi.org/10.1002/1521-3765(20001117)6:22%3C4082::AID-CHEM4082%3E3.0.CO;2-S)
- [10] Periyasamy, M. and Kar, A., **2020**. Modulating the properties of SnO₂ nanocrystals: morphological effects on structural, photoluminescence, photocatalytic, electrochemical and gas sensing properties. *Journal of Materials Chemistry C*, 8(14), pp.4604-4635. <https://doi.org/10.1039/C9TC06469A>
- [11] Parthibavarman, M., Vallalperuman, K., Sathishkumar, S., Durairaj, M. and Thavamani, K., **2014**. A novel microwave synthesis of nanocrystalline SnO₂ and its structural optical and dielectric properties. *Journal of Materials Science: Materials in Electronics*, 25(2), pp.730-735.
- [12] Awad, M.A., Abaza, E.R. and Shaaban, E.R., **2025**. Optimizing the conditions to synthesize transparent conductive SnO₂ thin films for optoelectronic applications. *Surfaces and Interfaces*, 69, p.106734. <https://doi.org/10.1016/j.surfin.2025.106734>
- [13] Sunjaya, N.B.P., Yulianti, R.T., Hanifah, A., Fadila, S., Indriyati, I., Priyono, S., Indayaningsih, N., Setiawan, J., Effendi, M. and Yudianti, R., **2026**. Structural and Synergistic Effect of SnO₂-Carbon Interfaces for Improved Lithium-Ion Battery Anode Performance. *Surfaces and Interfaces*, p.108502. <https://doi.org/10.1016/j.surfin.2026.108502>

- [14] Wang, Z., Zhao, C., Han, T., Zhang, Y., Liu, S., Fei, T., Lu, G. and Zhang, T., **2017**. High-performance reduced graphene oxide-based room-temperature NO₂ sensors: A combined surface modification of SnO₂ nanoparticles and nitrogen doping approach. *Sensors and Actuators B: Chemical*, 242, pp.269-279. <https://doi.org/10.1016/j.snb.2016.10.101>
- [15] Habte, A.G., Hone, F.G. and Dejene, F.B., **2020**. Effect of solution pH on structural, optical and morphological properties of SnO₂ nanoparticles. *Physica B: Condensed Matter*, 580, p.411832. <https://doi.org/10.1016/j.physb.2019.411832>
- [16] Thiruppathi, K.P. and Majumder, S.B., **2025**. Facile Microwave-Assisted Surfactant Free Hydrothermal Synthesis of Nanoporous SnO₂ Nanowire Bundles for Alcohol Detection. *ACS Applied Nano Materials*, 8(31), pp.15652-15661. <https://doi.org/10.1021/acsanm.5c02707>
- [17] Ramanathan, G. and Murali, K.R., **2022**. Photocatalytic activity of SnO₂ nanoparticles. *Journal of Applied Electrochemistry*, 52(5), pp.849-859.
- [18] Mendes, P.G., Moreira, M.L., Tebcherani, S.M., Orlandi, M.O., Andrés, J., Li, M.S., Diaz-Mora, N., Varela, J.A. and Longo, E., **2012**. SnO₂ nanocrystals synthesized by microwave-assisted hydrothermal method: towards a relationship between structural and optical properties. *Journal of Nanoparticle Research*, 14(3), p.750.
- [19] Amuthameena, S., Dhayalini, K., Balraj, B. and Siva, C., **2021**. Enhanced Performance of SnO₂-Noble Metal Composites on Electrical Energy Generation and Storage Devices. *IEEE Transactions on Electron Devices*, 68(10), pp.5291-5297. <https://doi.org/10.1109/TED.2021.3107224>
- [20] Das, S., Sen, B. and Debnath, N., **2015**. Recent trends in nanomaterials applications in environmental monitoring and remediation. *Environmental Science and Pollution Research*, 22(23), pp.18333-18344.
- [21] Karmaoui, M., Jorge, A.B., McMillan, P.F., Aliev, A.E., Pullar, R.C., Labrincha, J.A. and Tobaldi, D.M., **2018**. One-step synthesis, structure, and band gap properties of SnO₂ nanoparticles made by a low temperature nonaqueous sol-gel technique. *ACS omega*, 3(10), pp.13227-13238. <https://doi.org/10.1021/acsomega.8b02122>
- [22] Li, T., Zeng, W., Long, H. and Wang, Z., **2016**. Nanosheet-assembled hierarchical SnO₂ nanostructures for efficient gas-sensing applications. *Sensors and Actuators B: Chemical*, 231, pp.120-128. <https://doi.org/10.1016/j.snb.2016.03.003>
- [23] Xu, C., Tamaki, J., Miura, N. and Yamazoe, N., **1991**. Grain size effects on gas sensitivity of porous SnO₂-based elements. *Sensors and Actuators B: Chemical*, 3(2), pp.147-155. [https://doi.org/10.1016/0925-4005\(91\)80207-Z](https://doi.org/10.1016/0925-4005(91)80207-Z)
- [24] Manificier, J.C., De Murcia, M., Fillard, J.P. and Vicario, E., **1977**. Optical and electrical properties of SnO₂ thin films in relation to their stoichiometric deviation and their crystalline structure. *Thin solid films*, 41(2), pp.127-135. [https://doi.org/10.1016/0040-6090\(77\)90395-9](https://doi.org/10.1016/0040-6090(77)90395-9)
- [25] Becker, T., Ahlers, S., Braunmühl, C.B.V., Müller, G. and Kieseewetter, O., **2001**. Gas sensing properties of thin-and thick-film tin-oxide materials. *Sensors and Actuators B: Chemical*, 77(1-2), pp.55-61. [https://doi.org/10.1016/S0925-4005\(01\)00672-4](https://doi.org/10.1016/S0925-4005(01)00672-4)
- [26] Rao, K.J., Vaidhyanathan, B., Ganguli, M. and Ramakrishnan, P.A., **1999**. Synthesis of inorganic solids using microwaves. *Chemistry of materials*, 11(4), pp.882-895. <https://doi.org/10.1021/cm9803859>
- [27] Yoshimura, M. and Byrappa, K., **2008**. Hydrothermal processing of materials: past, present and future. *Journal of Materials Science*, 43(7), pp.2085-2103. <https://doi.org/10.1007/s10853-007-1853-x>
- [28] Zhu, Y.J. and Chen, F., **2014**. Microwave-assisted preparation of inorganic nanostructures in liquid phase. *Chemical reviews*, 114(12), pp.6462-6555. <https://doi.org/10.1021/cr400366s>
- [29] Kar, A., Kundu, S. and Patra, A., **2011**. Surface defect-related luminescence properties of SnO₂ nanorods and nanoparticles. *The Journal of Physical Chemistry C*, 115(1), pp.118-124. <https://doi.org/10.1021/jp110313b>
- [30] Krishnakumar, T., Jayaprakash, R., Parthibavarman, M., Phani, A.R., Singh, V.N. and Mehta, B.R., **2009**. Microwave-assisted synthesis and investigation of SnO₂ nanoparticles. *Materials Letters*, 63(11), pp.896-898. <https://doi.org/10.1016/j.matlet.2009.01.032>
- [31] Gu, F., Wang, S.F., Lü, M.K., Zhou, G.J., Xu, D. and Yuan, D.R., **2004**. Photoluminescence properties of SnO₂ nanoparticles synthesized by sol-gel method. *The Journal of Physical Chemistry B*, 108(24), pp.8119-8123. <https://doi.org/10.1021/jp036741e>
- [32] Chetri, P. and Choudhury, A., **2013**. Investigation of optical properties of SnO₂ nanoparticles. *Physica E: Low-dimensional Systems and Nanostructures*, 47, pp.257-263. <https://doi.org/10.1016/j.physe.2012.11.011>

- [33] Chen, C., Zhang, W., Li, Y. and Cai, C., **2017**. Defect-related optical bandgap narrowing and visible photoluminescence of hydrothermal-derived SnO₂ nanoparticles. *Journal of Materials Science: Materials in Electronics*, 28(24), pp.18603-18609. <https://doi.org/10.1007/s10854-017-7809-2>.