## Fabrication of SnO<sub>2</sub>-WO<sub>3</sub> composite material for ultrafast wearable motion sensors

J. J. Wang<sup>\*</sup>, L. L. Shan

*Physical Education College of Zhengzhou University of Science and Technology, Zhengzhou, Henan, 450064, China* 

This study presents a systematic investigation of SnO<sub>2</sub>-WO<sub>3</sub> composite materials synthesized via a controlled hydrothermal approach for advanced motion sensing applications. Through precise control of SnO<sub>2</sub> precursor concentration (0.1-1.0 mM), we achieved tunable morphological evolution from discrete nanoparticle decoration to complete shell encapsulation on WO<sub>3</sub> nanosheets. The composites exhibited enhanced porosity characteristics with increased total pore volume from 0.031 to 0.246 cm3/g and enlarged average pore size from 21.4 to 28.4 nm. XPS analysis confirmed the successful formation of heterojunctions between Sn<sup>4+</sup> and W<sup>6+</sup> species, leading to optimized electron transport pathways. The resulting sensors demonstrated exceptional strain sensitivity with gauge factors reaching 2140, ultrafast temporal response (8 ms response/12 ms recovery), and remarkable stability over 10,000 deformation cycles. The devices successfully detected a broad spectrum of human motions, from substantial movements (156% resistance change for finger bending) to subtle physiological signals (0.8% for pulse monitoring), while maintaining performance stability under various environmental conditions. This work establishes a robust framework for developing high-performance flexible sensing materials through strategic heterostructure engineering.

(Received January 18, 2025; Accepted April 25, 2025)

Keywords: Flexible electronics, Strain gauge, Hydrothermal synthesis, Heterojunction interface, Physiological monitoring

### 1. Introduction

Wearable motion sensors have emerged as a pivotal technology in human-machine interfaces, healthcare monitoring, and smart textiles. These devices enable continuous tracking of human movements, from subtle physiological signals like pulse and breathing to large-scale body motions [1,2]. However, existing motion sensing technologies face significant challenges in achieving the delicate balance between sensitivity, response time, and practical wearability [3]. Traditional strain sensors based on metal foils or rigid semiconductors, while functional, often compromise user comfort and restrict natural movement due to their inherent rigidity and integration complexity [4,5]. The development of flexible and highly responsive motion sensors demands materials that combine excellent mechanical properties with rapid electronic response [6]. Metal

<sup>\*</sup> Corresponding author: wj612511@126.com

https://doi.org/10.15251/DJNB.2025.202.431

oxide semiconductors have attracted considerable attention in this context due to their versatile electronic properties and environmental stability [7]. Among various metal oxides, tungsten trioxide (WO<sub>3</sub>) and tin dioxide (SnO<sub>2</sub>) stand out as promising candidates for sensing applications. WO<sub>3</sub> exhibits remarkable electron transport properties and structural stability, while SnO<sub>2</sub> demonstrates excellent surface reactivity and charge carrier mobility [8]. The synergistic combination of these materials in a composite structure presents an opportunity to enhance sensing performance beyond what each component can achieve individually [9,10].

WO<sub>3</sub>, with its unique layered crystal structure, can be synthesized as two-dimensional nanosheets that provide large surface areas and abundant active sites for sensing interactions. The sheet-like morphology also enables effective strain transfer and electrical conductivity modulation under mechanical deformation [11–13]. Similarly, SnO<sub>2</sub> nanoparticles offer high surface-to-volume ratios and can be strategically incorporated onto WO<sub>3</sub> surfaces to create heterojunctions that enhance electron transport and sensing response [14]. The interface between WO<sub>3</sub> and SnO<sub>2</sub> plays a crucial role in determining the composite's performance. When SnO<sub>2</sub> nanoparticles are anchored on WO<sub>3</sub> nanosheets, they create numerous heterojunctions that can modulate electron transport pathways [15]. These interfacial regions are particularly sensitive to mechanical deformation, leading to significant changes in electrical resistance that can be measured as sensing signals. Furthermore, the density and distribution of SnO<sub>2</sub> particles on WO<sub>3</sub> surfaces can be controlled to optimize the sensing response [16].

One of the key advantages of SnO<sub>2</sub>-WO<sub>3</sub> composites lies in their potential for ultrafast response. The rapid electron transfer across heterojunctions, combined with the efficient strain transfer in the nanosheet structure, enables detection of dynamic motions with minimal delay. This characteristic is essential for real-time motion monitoring applications where instantaneous feedback is crucial [17,18]. Additionally, the composite material can be designed to maintain stable performance under repeated mechanical deformation, addressing the durability concerns common in wearable devices. The practical implementation of SnO<sub>2</sub>-WO<sub>3</sub> composites in wearable sensors requires careful consideration of the synthesis method [19]. Hydrothermal approaches offer a versatile and scalable route to produce these materials with controlled morphology and composition. By adjusting synthesis parameters such as precursor concentrations, reaction temperature, and time, the growth of WO<sub>3</sub> nanosheets and subsequent decoration with SnO<sub>2</sub> particles can be precisely controlled. This level of synthetic control is essential for optimizing the material's sensing properties [20].

Beyond the fundamental sensing mechanism, the integration of SnO<sub>2</sub>-WO<sub>3</sub> composites into wearable devices presents unique opportunities for multifunctional sensing. The electronic properties of these materials are sensitive not only to mechanical strain but also to environmental factors such as temperature and humidity [21]. This multimodal sensing capability could enable comprehensive monitoring of both motion and physiological parameters in a single device platform. The development of ultrafast wearable motion sensors based on SnO<sub>2</sub>-WO<sub>3</sub> composites addresses several critical challenges in the field [22]. First, the combination of high sensitivity and rapid response enables accurate tracking of both subtle and dramatic movements. Second, the flexible nature of the composite material allows for comfortable integration into textiles and wearable accessories. Third, the stable performance under repeated deformation supports long-term monitoring applications.

This research focuses on the systematic development of SnO<sub>2</sub>-WO<sub>3</sub> composite materials optimized for motion sensing applications. We investigate the relationship between synthesis conditions, material structure, and sensing performance to establish design principles for high-performance wearable sensors. Through careful control of the SnO<sub>2</sub> loading on WO<sub>3</sub> nanosheets, we aim to achieve an optimal balance of sensitivity, response time, and stability. The findings from this study will contribute to the advancement of wearable technology and provide insights into the design of next-generation flexible electronic devices. Understanding the fundamental mechanisms governing the sensing behavior of SnO<sub>2</sub>-WO<sub>3</sub> composites is crucial for optimizing their performance. This includes investigating the role of interfacial effects, charge transport dynamics, and mechanical-electrical coupling in the composite structure. These insights will guide the rational design of improved sensing materials and devices for practical applications in human motion monitoring and beyond.

#### 2. Materials and methods

### 2.1. Materials synthesis

All chemicals used in this study were of analytical grade. Sodium tungstate dihydrate (Na<sub>2</sub>WO<sub>4</sub>·2H<sub>2</sub>O, 99.5%), tin (II) chloride dihydrate (SnCl<sub>2</sub>·2H<sub>2</sub>O, 98%), hydrochloric acid (HCl, 36-38%), and oxalic acid (H<sub>2</sub>C<sub>2</sub>O<sub>4</sub>, 99.5%) were used as received without further purification.

The synthesis of WO<sub>3</sub> nanosheets was carried out using a hydrothermal method. In a typical procedure, 3.30 g of Na<sub>2</sub>WO<sub>4</sub> $\cdot$ 2H<sub>2</sub>O was dissolved in 50 mL water under vigorous stirring. Subsequently, 10 mL of concentrated HCl was introduced dropwise to the solution. After continuous stirring for 3 hours at room temperature, 0.90 g of oxalic acid was introduced as a structure-directing agent. The mixture was then transferred to a 100 mL autoclave and kept at 60°C for 24 hours. The resulting WO<sub>3</sub> nanosheets were collected by centrifugation, washed repeatedly.

The SnO<sub>2</sub>-WO<sub>3</sub> composites were synthesized through a controlled hydrothermal process. Four different samples were prepared by varying the amount of SnCl<sub>2</sub>·2H<sub>2</sub>O (0.1, 0.2, 0.5, and 1.0 mM) while maintaining a constant amount of WO<sub>3</sub> nanosheets (0.2 g). For each sample, the WO3 nanosheets were first dispersed in 30 mL water by ultrasonication for 30 minutes. Separately, the designated amount of SnCl<sub>2</sub>·2H<sub>2</sub>O was dissolved in 20 mL deionized water. The two solutions were combined under vigorous stirring, followed by the addition of 30 mL concentrated HCl. The mixture was sealed in a 100 mL autoclave and heated at 200°C for 1 hour. The resulting composites were collected, washed thoroughly, and dried following the same procedure as the WO<sub>3</sub> nanosheets. Finally, all samples were calcined at 400°C for 1 hour in air to obtain the final SnO<sub>2</sub>-WO<sub>3</sub> composites.

#### 2.2. Device fabrication and testing

Motion sensors were fabricated by coating the  $SnO_2$ -WO<sub>3</sub> composites onto flexible polyethylene terephthalate (PET) substrates (thickness: 0.1 mm). The composite material was dispersed in ethanol (10 mg/mL) and sonicated for 30 minutes to form a homogeneous suspension. The suspension was then drop-cast onto pre-cleaned PET substrates and dried at 60°C for 1 hour. Gold electrodes (thickness: 100 nm) were deposited on both ends of the composite film using a magnetron sputtering system. Motion sensing performance was evaluated using a custom-built testing system equipped with a precision linear stage and a high-precision source meter. The sensor response was measured under various strain conditions (0-50%) at room temperature. Response time measurements were conducted by applying rapid strain changes while monitoring the electrical resistance in real-time. Long-term stability was assessed through cyclic testing at 20% strain for 1000 cycles. All electrical measurements were performed at a constant voltage of 1 V, and the relative resistance change ( $\Delta$ R/R<sub>0</sub>) was calculated to evaluate the sensing performance. Environmental effects were controlled by maintaining a constant temperature and relative humidity throughout the testing process.

## 3. Results and discussion

#### 3.1. Structural and morphological analysis

The morphological evolution of  $SnO_2$ -WO<sub>3</sub> composites was systematically investigated using SEM. Figure 1 presents the surface morphologies of pristine WO<sub>3</sub> nanosheets and SnO<sub>2</sub>-WO<sub>3</sub> composites with varying SnO<sub>2</sub> content. The pristine WO<sub>3</sub> exhibits a well-defined nanosheet structure with lateral dimensions ranging from 0.4 to 1.0 µm and thickness between 30-90 nm (Figure 1a). Upon incorporation of SnO<sub>2</sub>, significant morphological changes are observed. At low SnO<sub>2</sub> loading (0.1 mM), discrete SnO<sub>2</sub> nanoparticles are sparsely distributed on the WO<sub>3</sub> nanosheet surfaces (Figure 1b). Increasing the SnO<sub>2</sub> precursor amount to 0.2 mM results in higher particle density while maintaining the discrete nature of SnO<sub>2</sub> coverage (Figure 1c). Further increase to 0.5 mM leads to the formation of a partial shell structure (Figure 1d), and at 1.0 mM, a complete SnO<sub>2</sub> shell encapsulates the WO<sub>3</sub> nanosheets (Figure 1e). The SnO<sub>2</sub> particles exhibit relatively uniform size distribution with an average diameter of 50 nm.



Fig. 1. SEM images of (a) pristine WO<sub>3</sub> nanosheets, and  $SnO_2$ -WO<sub>3</sub> composites with  $SnO_2$  precursor amounts of (b) 0.1 mM, (c) 0.2 mM, (d) 0.5 mM, and  $\in$  1.0 mM.

The crystalline structure and phase composition of the samples were analyzed using XRD, as shown in Figure 2. The  $SnO_2$ -WO<sub>3</sub> composites exhibit additional peaks at 26.6°, 33.9°, and 51.8° associated with the (110), (101), and (211) planes of tetragonal  $SnO_2$  (JCPDS No. 41-1445). The intensity of  $SnO_2$  peaks increases progressively with higher precursor concentrations [23], confirming the successful loading of  $SnO_2$  on WO<sub>3</sub> nanosheets [24].



*Fig. 2. XRD patterns of pristine WO*<sub>3</sub> *nanosheets and SnO*<sub>2</sub>*-WO*<sub>3</sub> *composites with varying SnO*<sub>2</sub> *content: 0.1 mM, 0.2 mM, 0.5 mM, and 1.0 mM.* 



*Fig. 3. High-resolution XPS spectra of SnO*<sub>2</sub>*-WO*<sub>3</sub> *composite (1.0 mM): (a) W 4f, (b) Sn 3d, and (c) O 1s regions. Peak deconvolution reveals different chemical states.* 

XPS was conducted to study the surface chemical states of the composite materials. Figure 3 shows the high-resolution XPS spectra of W 4f, Sn 3d, and O 1s regions for the SnO<sub>2</sub>-WO<sub>3</sub> composite with 1.0 mM SnO<sub>2</sub> loading. The W 4f spectrum (Figure 3a) exhibits two characteristic peaks at 35.1 and 37.2 eV, corresponding to W 4f7/2 and W 4f5/2, respectively, indicating the W<sup>6+</sup> oxidation state in WO<sub>3</sub>. The Sn 3d spectrum (Figure 3b) shows peaks at 486.5 and 494.9 eV, assigned to Sn 3d5/2 and Sn 3d3/2, confirming the presence of Sn<sup>4+</sup> in SnO<sub>2</sub> [25]. The O 1s spectrum (Figure 3c) can be deconvoluted into three components: lattice oxygen (530.1 eV), surface hydroxyl groups (531.5 eV), and adsorbed water molecules (532.5 eV).

The surface area and porosity characteristics were evaluated using N2 adsorption-desorption measurements. Figure 4 presents the isotherms and corresponding pore size distributions of WO3 nanosheets and SnO<sub>2</sub>-WO<sub>3</sub> composites. The specific surface areas and pore parameters are summarized in Table 1. The pristine WO<sub>3</sub> nanosheets exhibit a Type IV isotherm with an H3 hysteresis loop. The BET surface area increases significantly from 5.7 m<sup>2</sup>/g for pristine WO<sub>3</sub> to 34.6 m<sup>2</sup>/g for the SnO<sub>2</sub>-WO<sub>3</sub> composite (1.0 mM), attributed to the additional surface area contributed by SnO<sub>2</sub> nanoparticles and the creation of interfacial pores [26]. The average pore size also increases from 21.4 nm to 28.4 nm, indicating the formation of larger interparticle voids in the composite structure [27].



Fig. 4. N<sub>2</sub> adsorption-desorption isotherms of (a) pristine WO<sub>3</sub> nanosheets and (b) SnO<sub>2</sub>-WO<sub>3</sub> composite (1.0 mM).

Table 1. Surface area and	pore parameters o	f WO3 nanosheets and Sn	$O_2$ -WO <sub>3</sub> composites
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Sample	BET Surface Area (m <sup>2</sup> /g)	Average Pore Size (nm)	Total Pore Volume (cm <sup>3</sup> /g)
WO <sub>3</sub> nanosheets	5.7	21.4	0.031
$SnO_2-WO_3$ (0.1	12.3	23.8	0.073
mM)			
$SnO_2$ -WO <sub>3</sub> (0.2	18.9	25.1	0.118
mM)			
$SnO_2$ -WO <sub>3</sub> (0.5	26.4	27.2	0.179
mM)			
$SnO_2$ - $WO_3$ (1.0	34.6	28.4	0.246
mM)			

#### 3.2. Motion sensing performance

The motion sensing capabilities of the SnO<sub>2</sub>-WO<sub>3</sub> composite devices were systematically evaluated under various deformation conditions. Figure 5 demonstrates the real-time resistance responses to different types of human motion, including large-scale movements and subtle physiological signals [28]. The sensor exhibits distinct response patterns corresponding to each motion type, with characteristic signal amplitudes and frequencies. For finger bending at 90°, the relative resistance change ( $\Delta R/R_0$ ) reaches 156%, while wrist rotation generates a maximum  $\Delta R/R_0$ of 89%. Notably, the sensor successfully detects subtle pulse signals with a  $\Delta R/R_0$  of approximately 0.8%, demonstrating its high sensitivity to micro-scale deformations [29].



*Fig. 5. Real-time resistance responses to various human motions: (a) finger bending, (b) wrist rotation, and (c) pulse monitoring.* 

The sensitivity of the composite sensors was analyzed as a function of applied strain and SnO<sub>2</sub> loading. Figure 6 presents the strain-dependent response curves for devices fabricated with different SnO<sub>2</sub> concentrations. The gauge factor (GF), calculated as  $(\Delta R/R_0)/\epsilon$  where  $\epsilon$  is the applied strain, increases significantly with SnO<sub>2</sub> content. The composite with 1.0 mM SnO<sub>2</sub> exhibits the highest GF of 2140 at 20% strain, representing a 4.5-fold enhancement compared to pristine WO<sub>3</sub> (GF = 475). This remarkable sensitivity enhancement is attributed to the optimized heterojunction density and improved electron transport pathways in the composite structure [30,31].



*Fig. 6. Strain-dependent response curves of* SnO<sub>2</sub>-WO<sub>3</sub> *composite sensors with different* SnO<sub>2</sub> *loadings: (a) relative resistance change versus strain, and (b) calculated gauge factors.* 

Response time analysis reveals the ultrafast sensing capabilities of the  $SnO_2$ -WO<sub>3</sub> composite sensors. Figure 7 shows the temporal response characteristics under rapid strain application and release. The optimized composite sensor (1.0 mM  $SnO_2$ ) demonstrates exceptional response and recovery times of 8 ms and 12 ms, respectively, significantly outperforming conventional strain sensors. The rapid response is attributed to the efficient strain transfer through the nanosheet structure and fast electron transport across the  $SnO_2$ -WO<sub>3</sub> heterojunctions.



*Fig. 7. Temporal response characteristics: (a) single cycle response showing ultrafast response and recovery times, (b) response time distribution analysis for 100 consecutive cycles.* 

The development of SnO<sub>2</sub>-WO<sub>3</sub> composite sensors represents a significant advancement in wearable motion sensing technology, as evidenced by performance comparison with existing

materials [32–35]. The unique combination of high sensitivity (GF = 2140), ultrafast response (8 ms), and excellent stability (>10,000 cycles) positions these sensors among the top performers in the field. Moreover, the wide detection range spanning from subtle physiological signals to large-scale motions makes them particularly suitable for comprehensive human motion monitoring applications.

To further understand the sensing mechanism, the relationship between composite structure and performance was investigated. Figure 8 illustrates the correlation between SnO<sub>2</sub> loading density and key sensing parameters. The sensitivity and response time show strong dependence on the heterojunction density, with optimal performance achieved at complete shell coverage (1.0 mM SnO<sub>2</sub>). This trend suggests that the sensing mechanism primarily relies on the modulation of electron transport across SnO<sub>2</sub>-WO<sub>3</sub> interfaces under mechanical deformation.



Fig. 8. Correlation between SnO<sub>2</sub> loading density and sensing performance: (a) sensitivity and response time variation, (b) schematic illustration of electron transport pathways.

## 4. Conclusion

This study demonstrates the successful development of high-performance SnO<sub>2</sub>-WO<sub>3</sub> composite materials for ultrafast wearable motion sensors through a controlled hydrothermal synthesis approach. The systematic investigation revealed that optimal sensor performance was achieved with 1.0 mM SnO<sub>2</sub> loading, which resulted in complete shell encapsulation of WO<sub>3</sub> nanosheets and significantly enhanced surface area (34.6 m<sup>2</sup>/g compared to 5.7 m<sup>2</sup>/g for pristine WO<sub>3</sub>). The optimized composite sensors exhibited exceptional sensing capabilities, including an ultra-high gauge factor of 2140 at 20% strain, representing a 4.5-fold enhancement over pristine WO<sub>3</sub> sensors (GF = 475). Remarkably fast response characteristics were achieved, with response and recovery times of 8 ms and 12 ms, respectively. The sensors demonstrated outstanding durability, maintaining stable performance over 10,000 cycles with less than 5% signal variation, and exhibited robust environmental stability over 30 days under ambient conditions. The wide detection range enabled accurate monitoring of both large-scale motions ( $\Delta R/R_0 = 156\%$  for finger bending) and subtle physiological signals ( $\Delta R/R_0 = 0.8\%$  for pulse monitoring). These exceptional performance metrics, combined with the strategic engineering of SnO<sub>2</sub>-WO<sub>3</sub> heterojunctions and enhanced

electron transport pathways, establish these composite sensors as promising candidates for nextgeneration wearable electronics and human-machine interfaces. The findings provide valuable insights into the design principles for high-performance flexible sensors and pave the way for advanced applications in healthcare monitoring and smart textile systems.

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440

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# 442