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# Crystal phase content-dependent functionality of dual phase SnO<sub>2</sub>–WO<sub>3</sub> nanocomposite films via cosputtering crystal growth†

Yuan-Chang Liang \* and Yu Chao

In this study, crystalline SnO<sub>2</sub>–WO<sub>3</sub> nanocomposite thin films were grown through radio-frequency cosputtering of metallic Sn and ceramic WO<sub>3</sub> targets. The W content in the SnO<sub>2</sub> matrix was varied from 5.4 at% to 12.3 at% by changing the WO<sub>3</sub> sputtering power during thin-film growth. Structural analyses showed that increased WO<sub>3</sub> phase content in the nanocomposite films reduced the degree of crystallization of the SnO<sub>2</sub> matrix. Moreover, the size of the composite films' surface crystallites increased with WO<sub>3</sub> phase content, and the large surface crystallites were composed of numerous nanograins. Addition of WO<sub>3</sub> crystals to the SnO<sub>2</sub> matrix to form a composite film improved its light harvesting ability. The SnO<sub>2</sub>–WO<sub>3</sub> nanocomposite films exhibited improved photodegradation ability for Rhodamine B dyes compared with their individual constituents (*i.e.*, SnO<sub>2</sub> and WO<sub>3</sub> thin films), which is attributable to the suitable type II band alignment between the SnO<sub>2</sub> and WO<sub>3</sub>. Moreover, an optimal WO<sub>3</sub> phase content (W content: 5.4 at%) in the SnO<sub>2</sub> matrix substantially enhanced the ethanol gas-sensing response of the SnO<sub>2</sub> thin film. This suggested that the heterojunctions at the SnO<sub>2</sub>/WO<sub>3</sub> interface regions in the nanocomposite film considerably affected its ethanol gas-sensing behavior.

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## Introduction

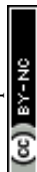
SnO<sub>2</sub> is an n-type semiconductor with a wide bandgap that can be used in numerous applications, such as gas sensor materials and photocatalysts.<sup>1–3</sup> A thin-film structure is a commonly used morphology for wide bandgap oxides in various technological applications. SnO<sub>2</sub> thin films have been prepared through various methods such as sputtering, chemical solution deposition, spray pyrolysis deposition, and the sol–gel process.<sup>4–6</sup> Of these methods, sputtering has the potential to synthesize oxide thin films with precise thickness control, tunable crystallinity, and large-area deposition. Sputtering SnO<sub>2</sub> thin films is therefore of potential interest for gas sensor and photocatalyst applications. However, improving the gas-sensing and photocatalytic properties of SnO<sub>2</sub> thin films to meet the requirements of such practical applications remains highly desirable. Doping impurity atoms into the SnO<sub>2</sub> matrix is a commonly used method for enhancing the gas-sensing and photodegradation properties of SnO<sub>2</sub> films. For example, Ce-doped SnO<sub>2</sub> thin films exhibit a superior ethanol gas-sensing response to that of pure SnO<sub>2</sub> thin films.<sup>1</sup> Ag-doped SnO<sub>2</sub> thin films have been synthesized through spray pyrolysis, demonstrating enhanced H<sub>2</sub>S gas detection ability compared with that of pure SnO<sub>2</sub> thin films.<sup>7</sup>

Doping impurity atoms into SnO<sub>2</sub> lattices affects the crystal defects and surface morphology of SnO<sub>2</sub> thin films, thereby changing its gas-sensing ability. Furthermore, Fe- and Ni-codoped SnO<sub>2</sub> sol–gel-derived thin films exhibit enhanced photocatalytic properties for organic dyes. The dopant modifies the optical bandgap of the SnO<sub>2</sub> thin film and enhances its light-harvesting and photocatalytic activity. However, research on a composite film structure containing a different phase in the SnO<sub>2</sub> matrix to improve gas-sensing and photodegradation properties for organic dyes has been limited. A SnO<sub>2</sub>-based composite structure combining SnO<sub>2</sub> with another phase has been widely used in one-dimensional and sphere/particle morphologies to improve gas-sensing properties and dye photodegradation ability.<sup>8,9</sup> However, due to complex synthesis methods, such two-phase structures in thin films have seldom been reported. SnO–SnO<sub>2</sub> composite thin films have been shown to possess superior NO<sub>2</sub> sensing ability, and the formation of the SnO–SnO<sub>2</sub> junctions at the thin-film surface dominates their gas-sensing ability.<sup>10</sup> Sol–gel-derived SnO<sub>2</sub>–TiO<sub>2</sub> composite thin films exhibit improved photodegradation ability for methyl orange, with an optimal phase content ratio.<sup>11</sup> Therefore, incorporating other oxide phases into the SnO<sub>2</sub> matrix to form SnO<sub>2</sub>-based composite films for enhanced gas-sensing and photodegradation seems promising.

WO<sub>3</sub> is also an n-type semiconductor with a wide bandgap of approximately 2.6–3.6 eV that has been used in gas sensor and catalytic materials.<sup>12,13</sup> WO<sub>3</sub> thin films are usually prepared through sputtering methods.<sup>14</sup> The band alignment between

*Institute of Materials Engineering, National Taiwan Ocean University, Keelung 20224, Taiwan. E-mail: yuanvictory@gmail.com*

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SnO<sub>2</sub> and WO<sub>3</sub> crystals exhibits a type II band heterojunction, and this composite system is reportedly beneficial in reducing the recombination rate of photogenerated carriers in films.<sup>15</sup> Additionally, hydrothermally derived WO<sub>3</sub>-SnO<sub>2</sub> composite particles demonstrate superior sensing behavior toward various volatile organic compounds, compared with the constituent counterparts.<sup>16</sup> Similarly, hydrothermally derived WO<sub>3</sub>-SnO<sub>2</sub> nanosheet composites exhibit better acetone gas-sensing behavior than their counterparts.<sup>17</sup> Developing a SnO<sub>2</sub>-WO<sub>3</sub> two-phase composite film therefore has the potential to enhance gas-sensing responses and organic dye photodegradation abilities. However, several literatures report the synthesis of SnO<sub>2</sub>-WO<sub>3</sub> composite films through thermal evaporation and pulsed laser deposition with a fixed Sn/W composition source.<sup>18,19</sup> These are disadvantageous to modulate the relative phase contents in the composite thin film through a one-step process and are not good strategies to find optimal photodegradation and gas-sensing properties of the composite films associated with the phase content-dependent factors. Developing a single composite film with a SnO<sub>2</sub>-WO<sub>3</sub> two-phase structure through a suitable method therefore has the potential to design and enhance gas-sensing responses and organic dye photodegradation abilities. In this study, SnO<sub>2</sub>-WO<sub>3</sub> composite films with various WO<sub>3</sub> phase contents were prepared using dual-gun cosputtering. The advantage of the cosputtering method provides *in situ* modulation of the relative SnO<sub>2</sub>/WO<sub>3</sub> phase contents during the synthesis of a single composite film. By adjusting sputtering power of the target, varying phase contents of the SnO<sub>2</sub> and WO<sub>3</sub> are designed and obtained in a single composite film. The effects of WO<sub>3</sub> phase content in the SnO<sub>2</sub> matrix on the microstructures and optical properties of composite films were investigated. The gas-sensing behavior and photodegradation rate of the nano-composite films were correlated with the WO<sub>3</sub> phase content-dependent microstructures and optical properties.

## Experiments

SnO<sub>2</sub>-WO<sub>3</sub> composite films with various WO<sub>3</sub> crystal contents were fabricated onto the glass and 300 nm-thick SiO<sub>2</sub>/Si substrates using dual-gun sputtering system. Sn metallic disc and WO<sub>3</sub> ceramic disc with a size of 2 inches were used as sputtering targets to prepare SnO<sub>2</sub>-WO<sub>3</sub> composite films. During growth of SnO<sub>2</sub>-WO<sub>3</sub> composite films, the DC sputtering power of Sn target was fixed at 20 W; moreover, the radio-frequency (rf) sputtering power of WO<sub>3</sub> target varied from 35 to 65 W. The thin-films growth temperature was maintained at 500 °C with an Ar/O<sub>2</sub> ratio of 2 : 1; the gas pressure during thin-film deposition was fixed at 1.33 Pa. The distance between the target and substrate is fixed at 7 cm. The rotation speed of the sample holder is fixed at 5 rpm. The sputtering duration for the composite films was fixed at 20 min. The sputtering guns are set to an incline angle of 60° over the sample surface.

Sample crystal structures were investigated by X-ray diffraction (XRD; Bruker D2 PHASER) using Cu K $\alpha$  radiation. The surface morphology of various thin films was investigated by scanning electron microscopy (SEM; Hitachi S-4800). The

microstructures of the thin-film samples were characterized by high-resolution transmission electron microscopy (HRTEM; JEOL JEM-2100F). The TEM samples are prepared by dual-beam focused ion beam (FIB; FEI Nova NanoLab 200). The sputtering of top Au layer was performed using Cressington 108 sputter coater. The operating current is set as 40 mA and sputtering time is 15 s. The target and substrate distance is 3 cm; the working pressure is  $6 \times 10^{-2}$  mbar. The absorption spectra of thin-film samples were conducted by ultraviolet-visible spectroscopy (UV-Vis; Jasco V-750). X-ray photoelectron spectroscopy (XPS; PHI 5000 VersaProbe) analysis was used to determine the chemical compositions of various thin-film samples. The contact angle measurements were performed in atmospheric air at room temperature using a commercial contact angle meter with  $\pm 1^\circ$  accuracy (CA; SEO Phoenix 300). To measure gas-sensing properties, the silver paste was coated onto the surface of the thin-film samples to form electrodes for gas-sensing measurements. The gas sensors made from various thin-film samples were placed in a closed vacuum chamber, and various concentrations of ethanol vapor (100, 250, 500, 750, and 1000 ppm) were introduced into the test chamber, using synthetic air as the carrier gas. The gas sensing response of the thin-film sensors to ethanol vapor is defined as the  $R_a/R_g$ .  $R_a$  is the sensor electrical resistance in the absence of target gas and  $R_g$  is that in the target gas. Photodegradation tests were performed by comparing the degradation of aqueous solution of Rhodamine B (RhB;  $10^{-6}$  M) containing various thin-film samples under solar light irradiation excited from the 100 W Xe arc lamp. The solution volume of RhB is 20 ml and the sample size for photodegradation tests has a fixed coverage area of 1.5 cm  $\times$  1.5 cm.

## Results and discussion

The XRD patterns of SnO<sub>2</sub> and composite SnO<sub>2</sub>-WO<sub>3</sub> films prepared under various WO<sub>3</sub> sputtering powers are shown in Fig. 1(a)-(d). From Fig. 1(a), the Bragg reflections are ascribed to crystallographic planes of (110), (101), (200), (211) and (220) of tetragonal SnO<sub>2</sub> (JCPDS no. 00-002-1337). The sharp and distinct Bragg reflections originated from SnO<sub>2</sub> revealed that the as-deposited SnO<sub>2</sub> thin film is well crystalline and is in a polycrystalline structure. The SnO<sub>2</sub>-WO<sub>3</sub> composite films grown under various WO<sub>3</sub> sputtering powers of 35-65 W exhibited a Bragg reflection centered at approximately 33° and is ascribed to monoclinic WO<sub>3</sub> (022) (JCPDS no. 01-089-4476). No other distinct Bragg reflection from impurity phase was observed, indicating that the composite films are composed of SnO<sub>2</sub> and WO<sub>3</sub> phases. Upon increasing the WO<sub>3</sub> sputtering power, the intensity of WO<sub>3</sub> (022) peak was gradually increased. Notably, the relative peak intensity of SnO<sub>2</sub> (110) is still more intense than that of WO<sub>3</sub> (022), showing that the SnO<sub>2</sub> is a dominant phase in the composite film. Well crystalline composite films were successfully prepared herein. The crystallite sizes of SnO<sub>2</sub> and WO<sub>3</sub> are further calculated by using Debye-Scherrer equation.<sup>20</sup> The SnO<sub>2</sub> film has an average crystallite size of approximately 20 nm. Notably, the average SnO<sub>2</sub> and WO<sub>3</sub> crystallite sizes decreased during the cosputtering



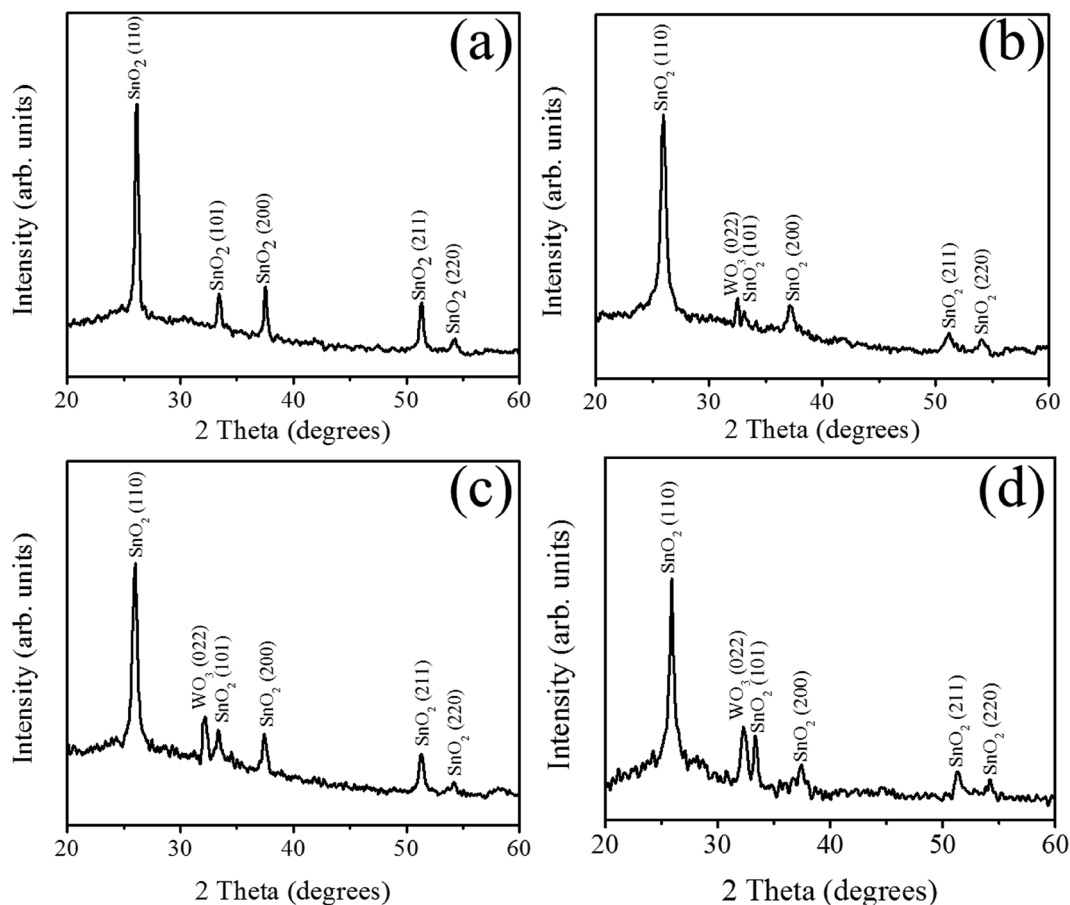


Fig. 1 (a) XRD pattern of the  $\text{SnO}_2$  film and XRD patterns of  $\text{SnO}_2$ - $\text{WO}_3$  composite films prepared at various  $\text{WO}_3$  sputtering powers: (b) 35 W, (c) 50 W, (d) 65 W.

growth of the composite films with an increased sputtering power of  $\text{WO}_3$ . The average  $\text{SnO}_2$  crystallite size was decreased from 20 nm in the  $\text{SnO}_2$  film to 8 nm in the composite film prepared at a  $\text{WO}_3$  sputtering power of 65 W. Moreover, the  $\text{WO}_3$  crystallite size in the composite films decreased from 15 to 11 nm when the sputtering power of  $\text{WO}_3$  was increased from 35 W to 65 W, respectively. The decreased crystallite size of  $\text{SnO}_2$  and  $\text{WO}_3$  in the composite films might be associated with the restricted crystal growth of each  $\text{SnO}_2$  and  $\text{WO}_3$  crystallites during *in situ* cosputtering growth of the two-phase structure in the composite film.

Fig. 2(a)–(d) show SEM micrographs of the surface morphologies of the  $\text{SnO}_2$  film and  $\text{SnO}_2$ - $\text{WO}_3$  composite films grown under various  $\text{WO}_3$  sputtering powers. In Fig. 2(a)–(d), all the films display a homogenous crack-free appearance. From Fig. 2(a), the surface micrograph of the  $\text{SnO}_2$  thin film shows the film composed of tiny, irregular crystallites; the film surface had a uniform and dense crystalline form. The surface morphology of the  $\text{SnO}_2$ - $\text{WO}_3$  composite film grown under a  $\text{WO}_3$  sputtering power of 35 W is similar to that of the  $\text{SnO}_2$  film (Fig. 2(b)); this might be associated with the trace content of  $\text{WO}_3$  phase in the  $\text{SnO}_2$ - $\text{WO}_3$  composite film. Notably, the surface crystallites of the composite films prepared at the higher sputtering powers of

$\text{WO}_3$  (50 and 65 W) are the clusters composed of crystallites with different sizes. This surface feature is similar to the reported surface structure of the  $\text{MnO}_2$ - $\text{WO}_3$  composite films.<sup>21</sup> The agglomeration of the nanograins forms large surface clusters and are tightly packed in the composite films with the higher  $\text{WO}_3$  sputtering power. The surface cluster feature coarsened with an increasing content of  $\text{WO}_3$  phase in the  $\text{SnO}_2$ - $\text{WO}_3$  composite films are clearly demonstrated in the SEM micrographs. The average surface cluster sizes of the  $\text{SnO}_2$ - $\text{WO}_3$  composite films prepared at 50 W and 65 W sputtering power of  $\text{WO}_3$  are 49 and 58 nm, respectively.

TEM was also used in this study to investigate the microstructures of  $\text{SnO}_2$ - $\text{WO}_3$  composite films prepared at the lowest and highest  $\text{WO}_3$  sputtering powers. Fig. 3(a) shows a low-magnification cross-section TEM image of an  $\text{SnO}_2$ - $\text{WO}_3$  composite film grown with a  $\text{WO}_3$  sputtering power of 35 W, which was composed of distinct columnar grains with diameters of 23–31 nm; no pores were visible on the film surface. Fig. 3(b) displays the selected-area electron diffraction (SAED) pattern from the  $\text{SnO}_2$ - $\text{WO}_3$  composite film. The presence of concentric rings that could be indexed to the (110), (200), (211), and (220) planes of tetragonal  $\text{SnO}_2$  and the (022) plane of monoclinic  $\text{WO}_3$  revealed that the composite film was of



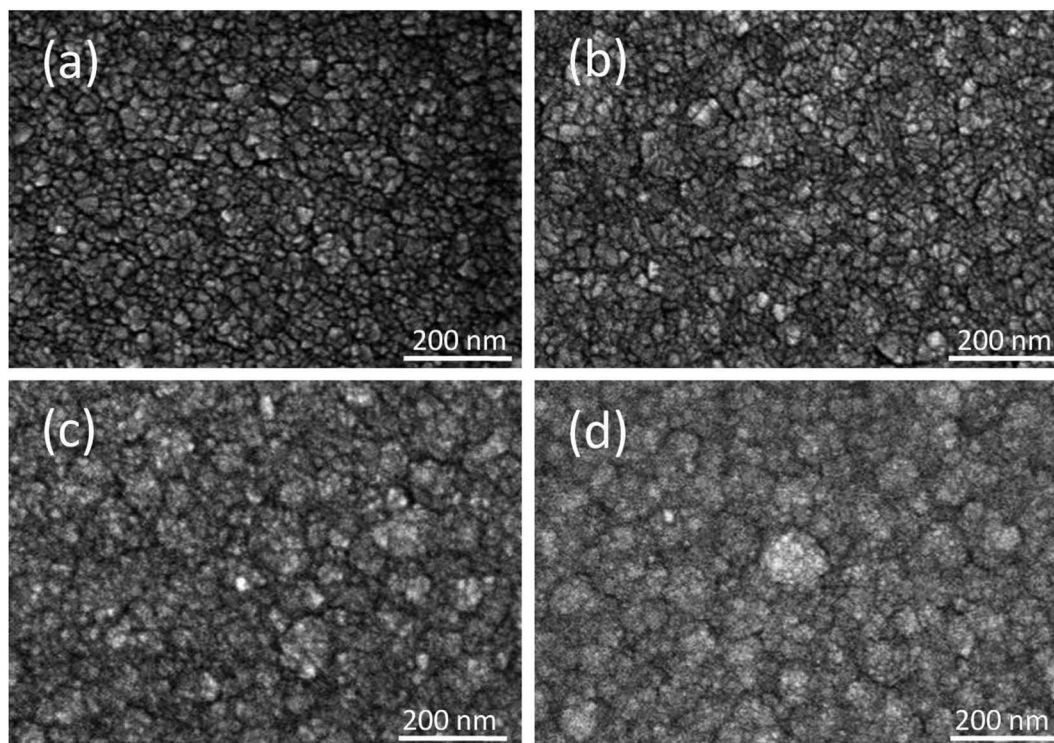


Fig. 2 (a) SEM image of the SnO<sub>2</sub> film. SEM images of SnO<sub>2</sub>-WO<sub>3</sub> composite films prepared at various WO<sub>3</sub> sputtering powers: (b) 35 W, (c) 50 W, (d) 65 W.

a polycrystalline structure. A high-magnification image of a local region in the SnO<sub>2</sub>-WO<sub>3</sub> composite film is shown in Fig. 3(c); the film had a thickness of approximately 100 nm, and grain boundaries between the columnar grains were visible. High-resolution (HR) TEM images from local regions of the composite film are also displayed in the insets of Fig. 3(c), with ordered and pronounced lattice fringes demonstrating that the composite film was highly crystalline. The long-range distributed lattice spacing of approximately 0.33 nm corresponded to the interplanar spacing of tetragonal SnO<sub>2</sub> (110). Moreover, some small regions with ordered lattice fringes had a lattice spacing of approximately 0.27 nm, which corresponded to the interplanar spacing of monoclinic WO<sub>3</sub> (022), revealing that SnO<sub>2</sub> constituted the major phase in the composite film. Fig. 3(d) shows energy-dispersive X-ray spectroscopy (EDS) spectra obtained from the SnO<sub>2</sub>-WO<sub>3</sub> composite film, verifying that Sn, W, and O were the major elemental components of the sample. The W content in the composite film was estimated at approximately 5.1 at%.

Fig. 4(a) shows a low-magnification cross-section TEM image of the SnO<sub>2</sub>-WO<sub>3</sub> composite film prepared with a WO<sub>3</sub> sputtering power of 65 W. The composite film was dense and homogeneously thick throughout the cross-section; the film thickness was approximately 95 nm. Fig. 4(b) shows this composite film's SAED pattern, to which various crystallographic planes of tetragonal SnO<sub>2</sub> and monoclinic WO<sub>3</sub> (022) were indexed; these crystallographic planes were consistent with the XRD result. The high-magnification TEM image in

Fig. 4(c) reveals that the boundary between adjacent columnar grains was less pronounced than that observed in the composite film prepared at a WO<sub>3</sub> sputtering power of 35 W, indicating that the major SnO<sub>2</sub> crystalline film structure might slightly deteriorate with increasing WO<sub>3</sub> phase content in the composite film. HR images from local regions of the composite film exhibit the ordered lattice fringes of tetragonal SnO<sub>2</sub> (110) and monoclinic WO<sub>3</sub> (022). The EDS spectra in Fig. 4(d) show that the W content of the SnO<sub>2</sub>-WO<sub>3</sub> composite film increased to approximately 12.1 at% at a WO<sub>3</sub> sputtering power of 65 W. The W content of composite films prepared at various WO<sub>3</sub> sputtering powers was also evaluated using XPS spectra, as illustrated in Table S1 and Fig. S1,† revealing that the composite films' W content evaluated using TEM-EDS was similar to that determined using XPS results.

Fig. 5(a)-(e) illustrates changes in the water contact angle on the surface of SnO<sub>2</sub>, WO<sub>3</sub>, and composite SnO<sub>2</sub>-WO<sub>3</sub> films with varying WO<sub>3</sub> content. Fig. 5(a) shows that the contact angle of the SnO<sub>2</sub> thin film was measured at approximately 87°, whereas Fig. 5(b) demonstrates that the WO<sub>3</sub> thin film exhibited a contact angle of approximately 69°. The morphology of the solid films could affect their measured contact angle. In this study, the WO<sub>3</sub> film was more hydrophilic than the SnO<sub>2</sub> film. Incorporation of the WO<sub>3</sub> phase into the SnO<sub>2</sub> matrix should cause SnO<sub>2</sub>-WO<sub>3</sub> composite films to exhibit a smaller contact angle than that of the pure SnO<sub>2</sub> film,<sup>22</sup> as shown in Fig. 5(c)-(e). Moreover, the contact angle of the composite film decreased from 61° to 46° as the WO<sub>3</sub> sputtering power increased from 35



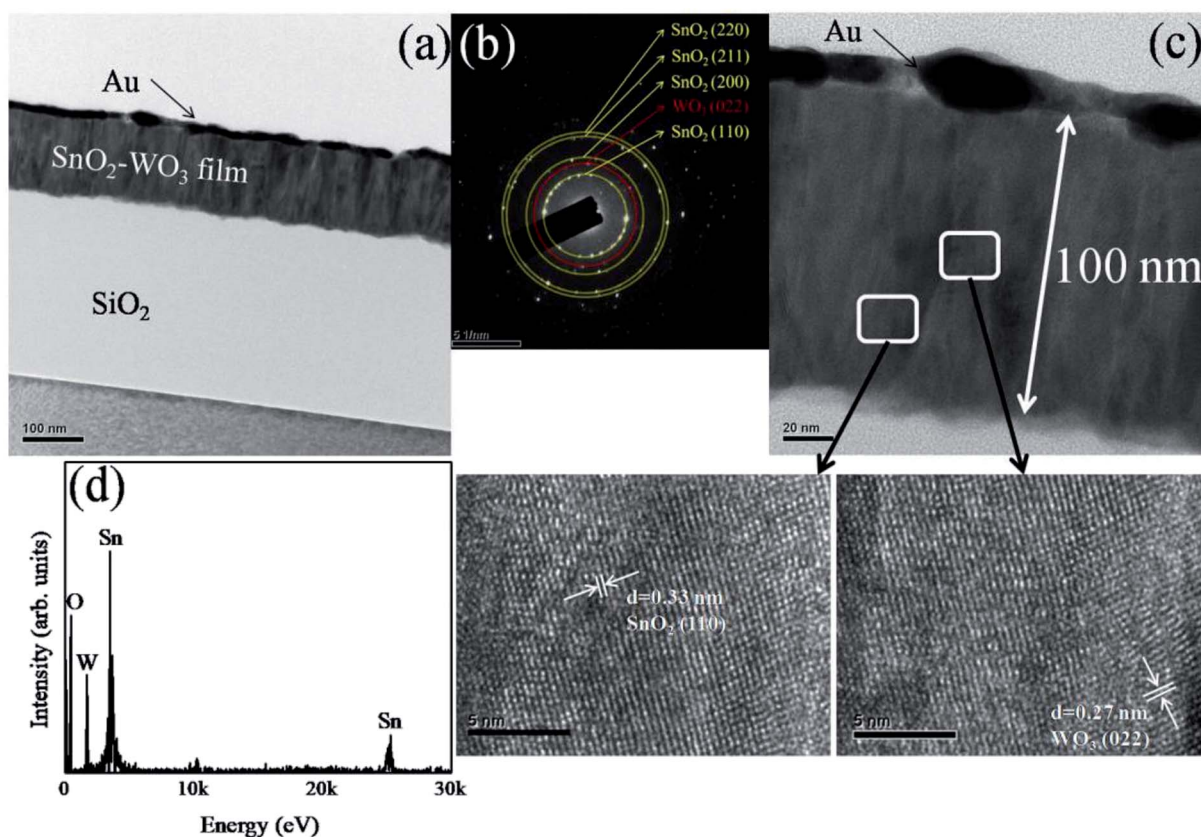


Fig. 3 TEM analyses of the  $\text{SnO}_2\text{-WO}_3$  composite film prepared at the  $\text{WO}_3$  sputtering power of 35 W: (a) low-magnification TEM image. (b) SAED pattern. (c) High-magnification image. The HRTEM images taken from the local regions of the film are shown in the insets. (d) EDS spectra of Sn, W, and O elements taken from the film.

to 65 W, respectively. Fig. 5(d) and (e) shows that the contact angles were substantially smaller than that of  $\text{WO}_3$  film. A pronounced surface morphology difference between the  $\text{WO}_3$  film and the  $\text{SnO}_2\text{-WO}_3$  composite films with higher  $\text{WO}_3$  content, prepared at  $\text{WO}_3$  sputtering powers of 50 and 65 W, might account for this result. A nanograin agglomeration forming large surface clusters was observed on the  $\text{SnO}_2\text{-WO}_3$  composite films with high  $\text{WO}_3$  sputtering powers (50 and 65 W), which differed considerably from the surface of the  $\text{WO}_3$  film. The numerous nanograins on the surface clusters of the composite films enhanced their ability to retain absorbed water, resulting in increased hydroxyl content of these films. The nanocomposite films prepared at  $\text{WO}_3$  sputtering powers of 50 and 65 W thus exhibited increased hydrophilicity compared with the pure  $\text{WO}_3$  film. A similar surface feature-dependent change in hydrophilicity was reported in Ti anodic oxidation formation of  $\text{TiO}_2$ , consistent with the prediction of the Wenzel theoretical model.<sup>23</sup>

Fig. 6(a) presents a comparison of optical absorbance curves for the  $\text{SnO}_2$ ,  $\text{WO}_3$ , and composite  $\text{SnO}_2\text{-WO}_3$  films. Because of the wide bandgap energies of  $\text{SnO}_2$  and  $\text{WO}_3$  in the UV region, the optical absorbance edges of these films were located in that region. The bandgap values of the synthesized  $\text{SnO}_2$  and  $\text{WO}_3$  thin films were evaluated using the Tauc plots in Fig. 6(b) and (c),<sup>24</sup> respectively. The  $\text{SnO}_2$  thin film's bandgap was

approximately 3.61 eV, whereas that of the  $\text{WO}_3$  thin film had a relatively small bandgap of 3.49 eV. Coupling of the  $\text{SnO}_2$  matrix with the  $\text{WO}_3$  phase in the composite film might account for the narrower optical bandgap of the composite films, as shown in Fig. 6(a). As the  $\text{WO}_3$  phase content in the composite thin films increased, a larger degree of redshift in their optical absorbance edge was observed, indicating that the light-harvesting ability of the  $\text{SnO}_2$  thin film was enhanced by incorporating the  $\text{WO}_3$  phase.

Absorbance spectra of the RhB solution after 30, 60, 90, and 120 min of irradiation in the presence of  $\text{SnO}_2$ ,  $\text{WO}_3$ , and different composite  $\text{SnO}_2\text{-WO}_3$  films are shown in Fig. 7(a)–(d). RhB has a characteristic absorption band at approximately 551 nm. The absorbance spectra intensity of the RhB solution containing various thin-film samples decreased with an increased duration of irradiation. The degradation percentage of RhB absorbance spectra intensity *versus* the irradiation duration for the RhB solution containing various thin-film samples is shown in Fig. 7(e). Notably, after 120 min, degradation reached approximately 75–90% for the  $\text{SnO}_2\text{-WO}_3$  composite films, highlighting their superior photodegradation ability compared with the  $\text{SnO}_2$  and  $\text{WO}_3$  films. Moreover, as the  $\text{WO}_3$  content in  $\text{SnO}_2\text{-WO}_3$  composite films increased, the degradation rate significantly improved. The separation efficiency of photoexcited carriers in the  $\text{SnO}_2$ ,  $\text{WO}_3$ , and composite



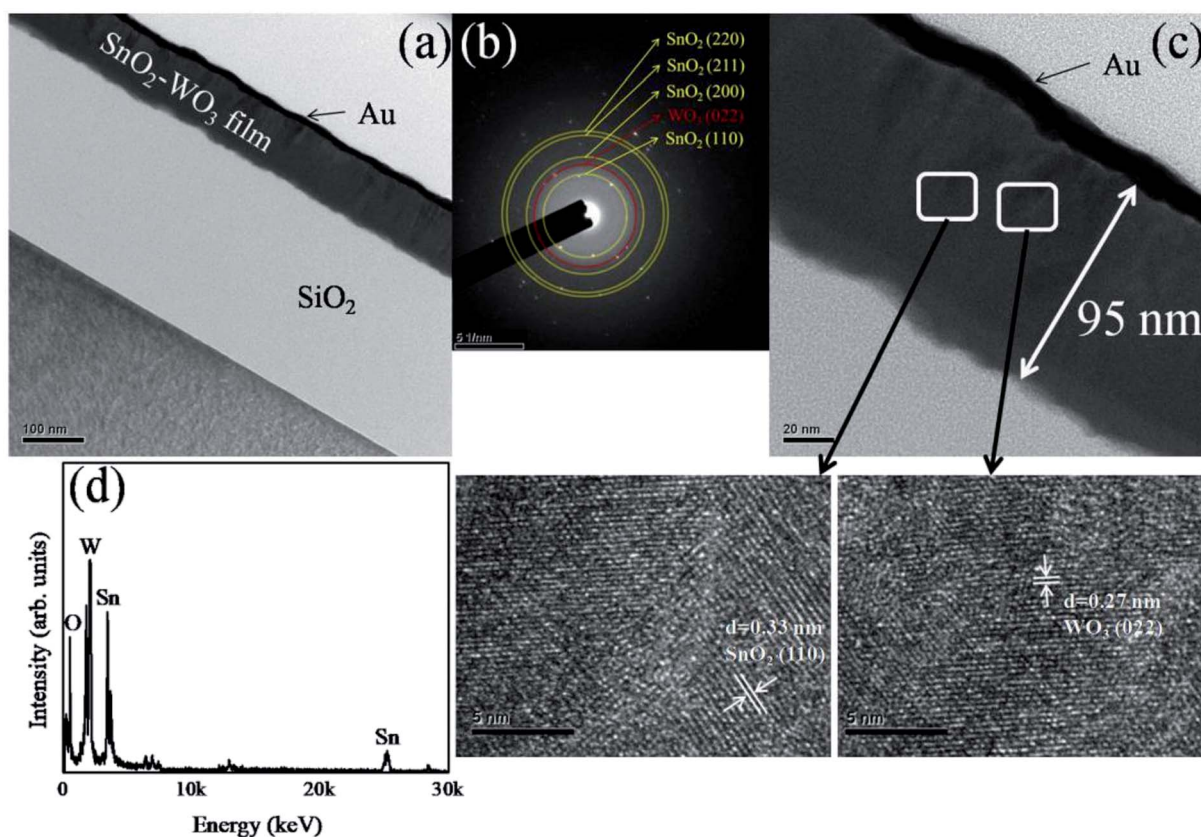


Fig. 4 TEM analyses of the  $\text{SnO}_2\text{-WO}_3$  composite film prepared at the  $\text{WO}_3$  sputtering power of 65 W: (a) low-magnification TEM image. (b) SAED pattern. (c) High-magnification image. The HRTEM images taken from the local regions of the film are shown in the insets. (d) EDS spectra of Sn, W, and O elements taken from the film.

$\text{SnO}_2\text{-WO}_3$  films was a key factor affecting the photo-degradation rate of these thin-film photocatalysts. Formation of a type II band alignment between the  $\text{SnO}_2$  and  $\text{WO}_3$  contact regions in the composite films enhanced photoexcited carrier

separation efficiency relative to the composite film constituents ( $\text{SnO}_2$  and  $\text{WO}_3$ ). This could explain the superior RhB dye photodegradation ability of composite films. A possible mechanism for the improved photodegradation ability of composite

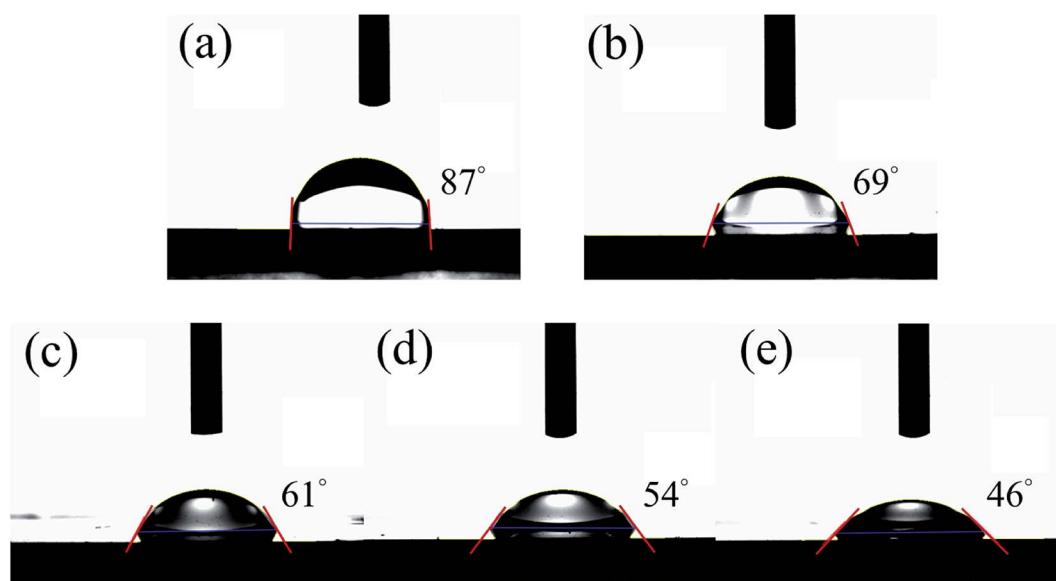


Fig. 5 (a) and (b) are water contact angle results on the  $\text{SnO}_2$  and  $\text{WO}_3$  films, respectively. (c), (d), and (e) are water contact angle results on the  $\text{SnO}_2\text{-WO}_3$  composite films prepared at the  $\text{WO}_3$  sputtering powers of 35, 50, and 65 W, respectively.



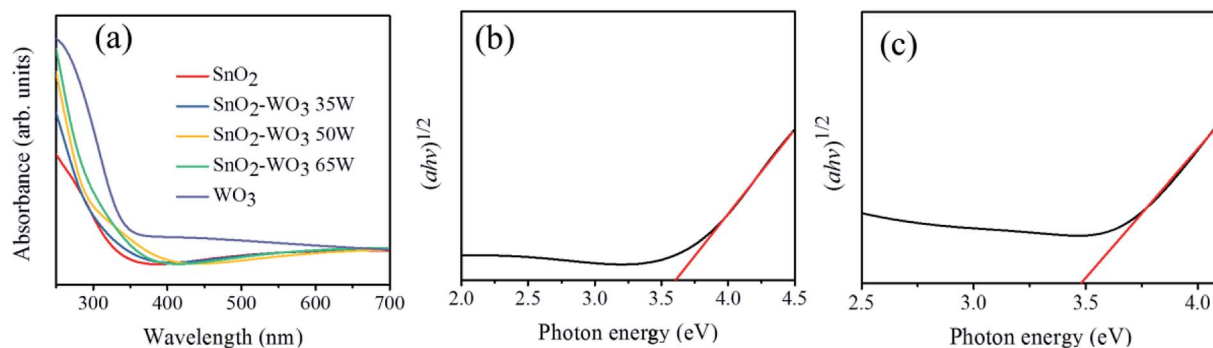
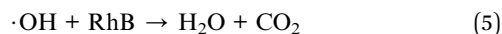
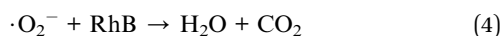
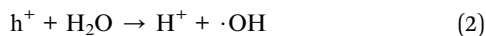


Fig. 6 (a) UV-Vis absorbance spectra of the SnO<sub>2</sub>, WO<sub>3</sub>, and various SnO<sub>2</sub>-WO<sub>3</sub> films. (b) Tauc plot of the SnO<sub>2</sub> film. (c) Tauc plot of the WO<sub>3</sub> film.

films is illustrated in Fig. 8(f). Electrons and holes were generated in both the SnO<sub>2</sub> and WO<sub>3</sub> phases of composite films under irradiation. According to the bandgap energies, the conduction band (CB) edge potential of WO<sub>3</sub> is more negative than that of SnO<sub>2</sub>.<sup>15</sup> Therefore, photogenerated electrons in WO<sub>3</sub> would easily transfer to SnO<sub>2</sub> before recombination, whereas the holes would move in the opposite direction, namely, from the valence band of SnO<sub>2</sub> to WO<sub>3</sub>, resulting in effective charge separation. The greater number of free carriers in the composites than in individual SnO<sub>2</sub> and WO<sub>3</sub> thin films increased the degree of surface reaction to RhB dyes in the thin-film samples under irradiation. Oxygen, which can accept electrons and combine with hydrogen, produced H<sub>2</sub>O on the film surface. The electrons accumulating in the CB of SnO<sub>2</sub> could be transferred to the adsorbed oxygen, thus yielding  $\cdot\text{O}_2^-$ , which then further reacted to finally produce the active  $\cdot\text{OH}$  radical; moreover, the holes transferred to WO<sub>3</sub> oxidized H<sub>2</sub>O molecules to yield hydroxyl radicals, according to the following reactions:



Consequently,  $\cdot\text{O}_2^-$  and  $\cdot\text{OH}$  acted as effective oxidants and reacted with RhB on the surface of the SnO<sub>2</sub>-WO<sub>3</sub> composite films. Similar band alignment effects of decreasing the recombination rate of photogenerated carriers have been demonstrated in SnO<sub>2</sub>-ZnO heterostructured fibers and TiO<sub>2</sub>-WO<sub>3</sub> nanostructures, which improve photodegradation ability toward organic dyes.<sup>25,26</sup> The SnO<sub>2</sub>-WO<sub>3</sub> composite film prepared at a WO<sub>3</sub> sputtering power of 65 W exhibited the highest degradation ability among the composite film samples, which was attributable to several factors. First, composite film prepared at a WO<sub>3</sub> sputtering power of 65 W exhibited a superior hydrophilicity to those prepared at other WO<sub>3</sub> sputtering powers. It has been shown that the higher photocatalytic activity

exhibited in a TiO<sub>2</sub>-SnO<sub>2</sub> composite film, compared with a pure TiO<sub>2</sub> film, was attributable to enhanced hydrophilicity in the composite film.<sup>11</sup> Second, a larger degree of redshift of the SnO<sub>2</sub> matrix adsorption edge with increased WO<sub>3</sub> content was observed. A higher degree of light harvesting and thin film surface hydrophilicity accounted for the superior photodegradation ability of the composite film prepared at a WO<sub>3</sub> sputtering power of 65 W. The photodegradation stability of this composite film under irradiation in the RhB solution was evaluated after its recycling (Fig. 7(g)), and after five test cycles it was found to have maintained relatively consistent activity, without apparent deactivation.

Fig. 8 illustrates the temperature-dependent ethanol gas-sensing response curves of the SnO<sub>2</sub>, WO<sub>3</sub>, and composite SnO<sub>2</sub>-WO<sub>3</sub> films on exposure to 100 ppm ethanol. The optimal operating temperature of the semiconductors is associated with a resultant equilibrium between surface reaction with ethanol vapor and the diffusion of ethanol vapor to the surface of the materials.<sup>1</sup> An optimal operating temperature of the SnO<sub>2</sub> thin film was 325 °C in this study. Furthermore, the highest ethanol gas-sensing response for the WO<sub>3</sub> thin film was reached at the operating temperature of 350 °C which is the maximum temperature of the measurement system. The high operating temperature of 350 °C for the WO<sub>3</sub> thin film to detect ethanol vapor with a visible response is similar to the previous work.<sup>27</sup> Comparatively, the SnO<sub>2</sub> thin film is more sensitive to detect ethanol vapor at the relatively lower operating temperature. The higher WO<sub>3</sub> phase content in the composite film prepared at the WO<sub>3</sub> sputtering power of 65 W deteriorated the performance of the optimal operating temperature and gas-sensing response compared with the SnO<sub>2</sub> thin-film matrix. By contrast, the composite films prepared at the WO<sub>3</sub> sputtering powers below 50 W exhibited the lower optimal operating temperature at 300 °C. The decreased optimal operating temperature of the composite films prepared at the WO<sub>3</sub> sputtering power below 50 W might be associated with the proper potential barrier numbers in the composite films that decreased the optimal operating temperature and also increased the gas-sensing responses in comparison with those of the SnO<sub>2</sub> thin film.

Fig. 9(a)-(e) shows the typical dynamic gas response curves of the SnO<sub>2</sub>, WO<sub>3</sub>, and composite SnO<sub>2</sub>-WO<sub>3</sub> films for various



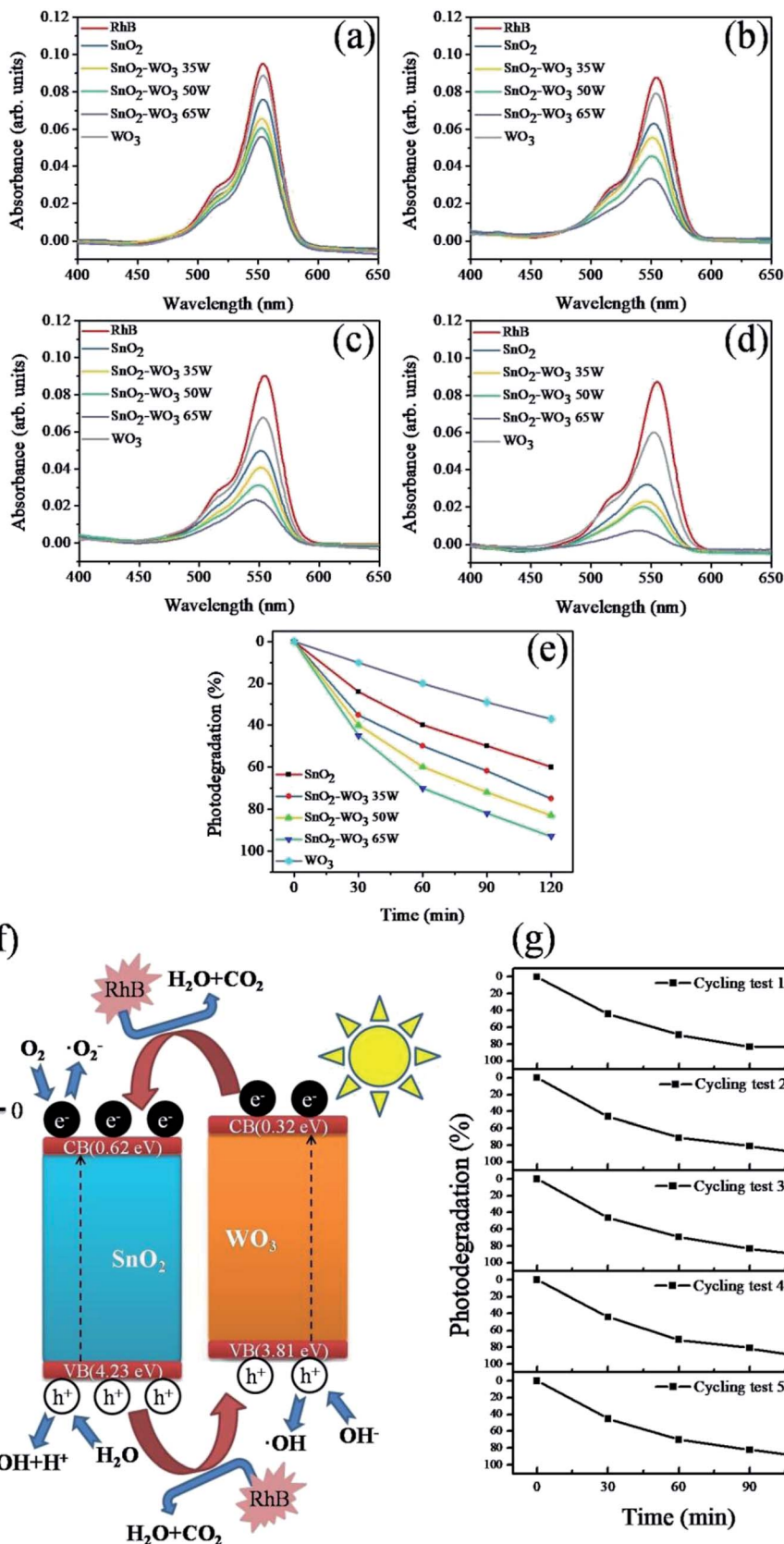


Fig. 7 The absorbance spectra of the RhB solution containing various thin-film samples under different irradiation durations: (a) 30 min. (b) 60 min. (c) 90 min. (d) 120 min. (e) Percentage photodegradation vs. irradiation duration of the RhB solution containing various thin-film samples. (f) Illustration of photodegradation mechanism for the SnO<sub>2</sub>-WO<sub>3</sub> composite film to RhB dyes. (g) Recycled performances in the presence of the SnO<sub>2</sub>-WO<sub>3</sub> film prepared at 65 W sputtering power of WO<sub>3</sub> for photodegrading RhB dyes.



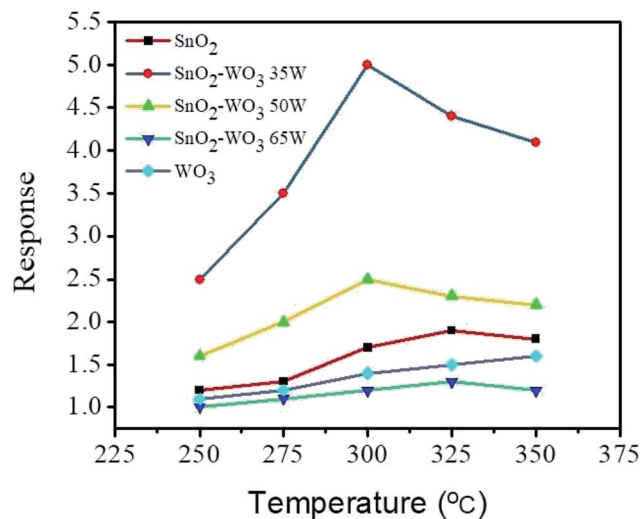


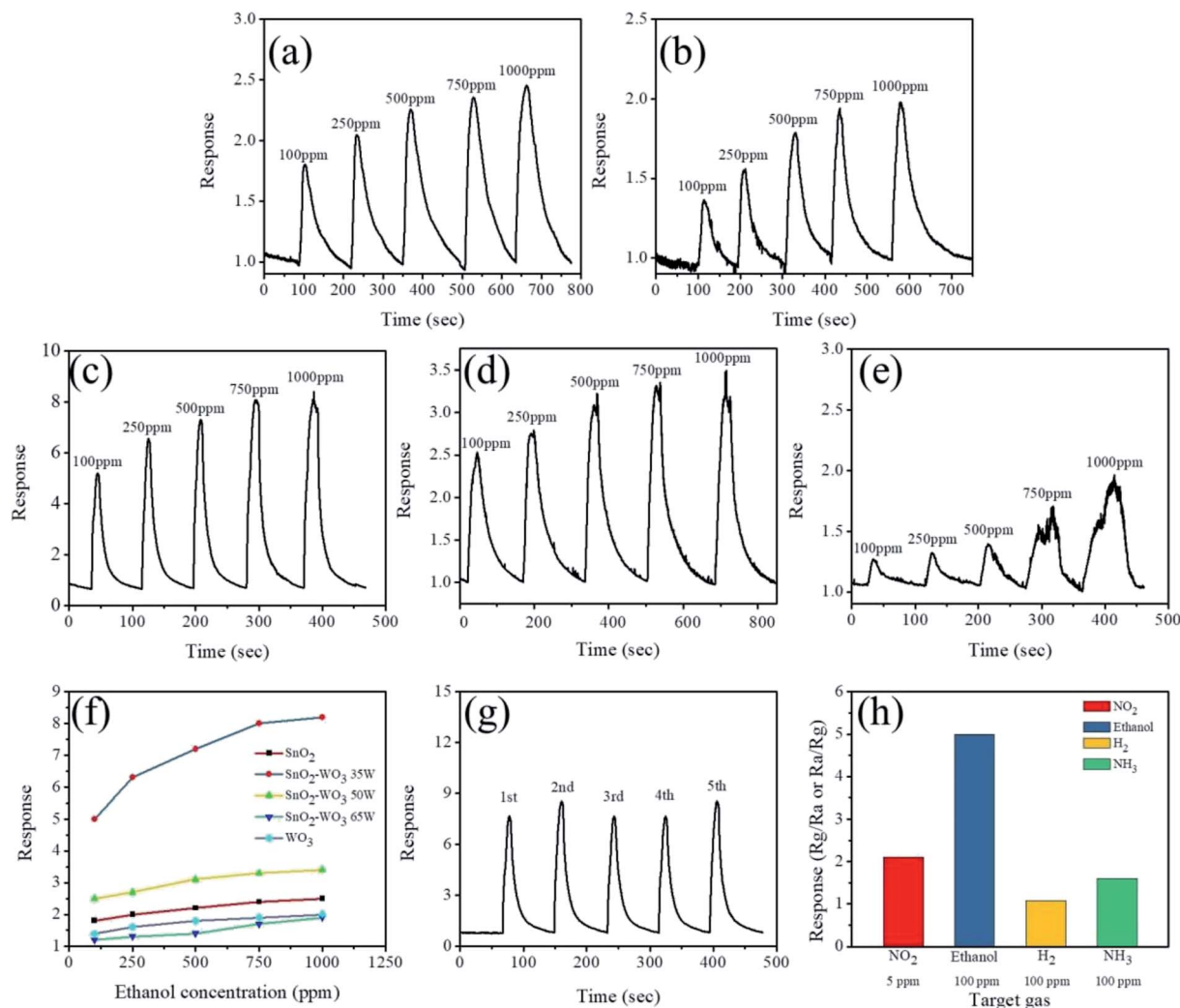
Fig. 8 Temperature-dependent 100 ppm ethanol gas-sensing responses of the SnO<sub>2</sub>-WO<sub>3</sub> composite film prepared at 35 W sputtering power of WO<sub>3</sub>.

concentrations of ethanol vapor (100 to 1000 ppm). The n-type conduction of these oxide films induces oxygen molecules adsorbed on their surface to extract electrons from their CB and became adsorbed oxygen ions on that surface. An electron depletion layer should be formed in the surface region of these films, which increases their electrical resistance. The reaction of ethanol vapor with the adsorbed oxygen ions on n-type oxide films is well documented.<sup>1</sup> When reducing gas molecules such as ethanol vapor are introduced on the film surface, the adsorbed oxygen ions release electrons to the film, further reducing its electrical resistance. Fig. 9(a)–(e) shows that the SnO<sub>2</sub>, WO<sub>3</sub>, and composite SnO<sub>2</sub>-WO<sub>3</sub> films exhibited a concentration-dependent ethanol gas-sensing response; namely, higher ethanol vapor concentrations resulted in a higher gas-sensing response. This is attributable to the fact that more ethanol molecules react with more adsorbed oxygen ions on the film surface, thus producing a higher gas-sensing response. Moreover, the SnO<sub>2</sub>, WO<sub>3</sub>, and composite SnO<sub>2</sub>-WO<sub>3</sub> films demonstrated various degrees of gas-sensing ability to the ethanol vapor, as shown in Fig. 9(a)–(e). The ethanol gas-sensing responses of these films on exposure to various ethanol vapor concentrations are summarized in Fig. 9(f). Notably, the gas-sensing response of the SnO<sub>2</sub> film on exposure to 100–1000 ppm ethanol vapor ranged from 1.8 to 2.5, relative to which the WO<sub>3</sub> film demonstrated a poorer ethanol gas-sensing ability, with responses ranging from 1.4 to 2.0 when exposed to 100–1000 ppm ethanol vapor. The SnO<sub>2</sub>-WO<sub>3</sub> composite films prepared at a WO<sub>3</sub> sputtering power of 35 and 50 W demonstrated enhanced gas-sensing ability compared with their constituent SnO<sub>2</sub> and WO<sub>3</sub> films. Moreover, the highest ethanol gas-sensing response was observed for the SnO<sub>2</sub>-WO<sub>3</sub> composite film prepared at a WO<sub>3</sub> sputtering power of 35 W, attaining gas-sensing responses of 5.1 and 8.3 on exposure to 100 and 1000 ppm of ethanol vapor, respectively. However, as shown in Fig. 9(f), ethanol gas-sensing response rapidly

declined when the SnO<sub>2</sub>-WO<sub>3</sub> composite film was prepared at the highest sputtering power of 65 W. This composite film's gas-sensing response was even poorer than that of the individual SnO<sub>2</sub> and WO<sub>3</sub> films. Comparison of gas-sensing performance demonstrated that a slight increase in WO<sub>3</sub> content (preparation at a WO<sub>3</sub> sputtering power of 35 W) led to a marked improvement in the SnO<sub>2</sub>-WO<sub>3</sub> composite film's gas-sensing response. Partial addition of a WO<sub>3</sub> phase into the SnO<sub>2</sub> matrix caused formation of heterojunctions between SnO<sub>2</sub> and WO<sub>3</sub> crystals. These SnO<sub>2</sub>-WO<sub>3</sub> heterojunctions in turn caused depletion regions to form at heterointerfaces, thereby increasing the number of potential barriers in the composite film. An optimal loading content of ZnO particles in SnO<sub>2</sub> tubes was reported to improve gas-sensing responses. This phenomenon is closely associated with modulation of the local depletion layer in SnO<sub>2</sub>/ZnO contact regions on exposure to target gases.<sup>28</sup> Notably, the ethanol gas-sensing response of the SnO<sub>2</sub>-WO<sub>3</sub> composite film prepared at 35 W sputtering power of WO<sub>3</sub> on exposure to 20 ppm ethanol (the minimum ethanol concentration in the measurement system) was still visible and the response reached 2.1. Additionally, response and recovery times of the SnO<sub>2</sub>-WO<sub>3</sub> composite films were defined as the durations required for occurrence of a 90% change in resistance on exposure to ethanol gas (response) and air (recovery), respectively. Response times for the SnO<sub>2</sub>-WO<sub>3</sub> composite film prepared at a WO<sub>3</sub> sputtering power of 35 W when exposed to various ethanol vapor concentrations (100–1000 ppm) ranged from 6 to 11 s, whereas recovery times ranged from 61 to 71 s. Response times for the composite film prepared at 50 W ranged from 14 to 20 s, whereas those for the composite film prepared at 65 W ranged from 16 to 40 s. Recovery times for the composite films prepared at WO<sub>3</sub> sputtering powers of 50 and 65 W all exceeded 80 s. Notably, response times for the SnO<sub>2</sub> film were in the range of 11–14 s, and recovery times in the range of 72–153 s. The improved sensing speed of the SnO-WO<sub>3</sub> composite film prepared at a WO<sub>3</sub> sputtering power of 35 W was thus evident. Fig. 9(g) shows cyclic gas-sensing test results for the composite film prepared at a WO<sub>3</sub> sputtering power of 35 W when exposed to 750 ppm of ethanol vapor. Stable sensing behavior over five test cycles was observed for this composite film, demonstrating its high stability and reproducibility for ethanol vapor detection. The gas-sensing selectivity of the film was further investigated on exposure to various oxidizing and reducing target gases in Fig. 9(h). The result demonstrated that the SnO<sub>2</sub>-WO<sub>3</sub> composite thin film was more sensitive to detect ethanol vapor in this study. Table 1 summarizes the ethanol gas-sensing performances of the reported SnO<sub>2</sub>-WO<sub>3</sub> composite film and other SnO<sub>2</sub>-based composite films prepared using various methods upon exposure to various ethanol vapor concentrations at the sensor operating temperatures of 300 °C.<sup>29–31</sup> Comparatively, ethanol gas-sensing responses of the SnO<sub>2</sub>-WO<sub>3</sub> composite film prepared at a WO<sub>3</sub> sputtering power of 35 W in this work exhibited a superior gas-sensing response than did those under similar gas-sensing test conditions in previous studies.

The ethanol gas-sensing mechanisms of pure SnO<sub>2</sub> and SnO<sub>2</sub>-WO<sub>3</sub> composites with adequate WO<sub>3</sub> phase content in this study





**Fig. 9** (a) and (b) are ethanol gas-sensing response curves of the  $\text{SnO}_2$  and  $\text{WO}_3$  films, respectively. (c), (d), and (e) are gas-sensing response curves of the  $\text{SnO}_2$ - $\text{WO}_3$  films prepared at  $\text{WO}_3$  sputtering powers of 35, 50, and 65 W, respectively. (f) Gas-sensing response values vs. ethanol vapor concentrations for various thin films. (g) Cyclic gas-sensing response curves for the  $\text{SnO}_2$ - $\text{WO}_3$  film prepared at 35 W sputtering power of  $\text{WO}_3$  on exposure to 750 ppm ethanol vapor. (h) Gas sensing selectivity histogram of the  $\text{SnO}_2$ - $\text{WO}_3$  composite film prepared at 35 W sputtering power of  $\text{WO}_3$  on exposure to 5 ppm  $\text{NO}_2$  and 100 ppm of  $\text{H}_2$  and  $\text{NH}_3$ .

are shown in Fig. 10. Surface depletion regions in  $\text{SnO}_2$  and  $\text{WO}_3$  crystals and  $\text{SnO}_2/\text{WO}_3$  crystal contact regions formed various potential barrier heights. In a gas-sensing test, higher numbers of surface potential barriers may be expected to act with ethanol vapor molecules in the composite film than in the pure  $\text{SnO}_2$  film.

Therefore, a higher degree of resistance variation is observed on exposure to ethanol vapor in the  $\text{SnO}_2$ - $\text{WO}_3$  composite film with adequate  $\text{WO}_3$  phase content. Higher ethanol gas-sensing responses were observed for this composite film than for the pure  $\text{SnO}_2$  film in given gas-sensing test conditions.

**Table 1** Ethanol gas-sensing performance of various  $\text{SnO}_2$ - $\text{WO}_3$  and other  $\text{SnO}_2$ -based composite films prepared using various methods upon exposure to ethanol vapor at the optimal temperature of 300 °C (ref. 29–31)

Composite film	Synthesis method	Optimal temperature (°C)	Concentration (ppm)	Response ( $R_a/R_g$ )	Detection limit (ppm)	Response/recovery time (sec)
$\text{SnO}_2$ - $\text{WO}_3$	Hydrothermal method	300	200	1.39	N/A	180/200
$\text{SnO}_2$ -ZnO	Hydrothermal method	300	200	4.5	20	72/900
<b><math>\text{SnO}_2</math>-<math>\text{WO}_3</math> (this work)</b>	<b>Cosputtering</b>	<b>300</b>	<b>250</b>	<b>6.5</b>	<b>20</b>	<b>7/63</b>
$\text{SnO}_2$ - $\text{CeO}_2$	Sol-gel method	300	800	7.8	30	60/600
<b><math>\text{SnO}_2</math>-<math>\text{WO}_3</math> (this work)</b>	<b>Cosputtering</b>	<b>300</b>	<b>750</b>	<b>8</b>	<b>20</b>	<b>9/67</b>



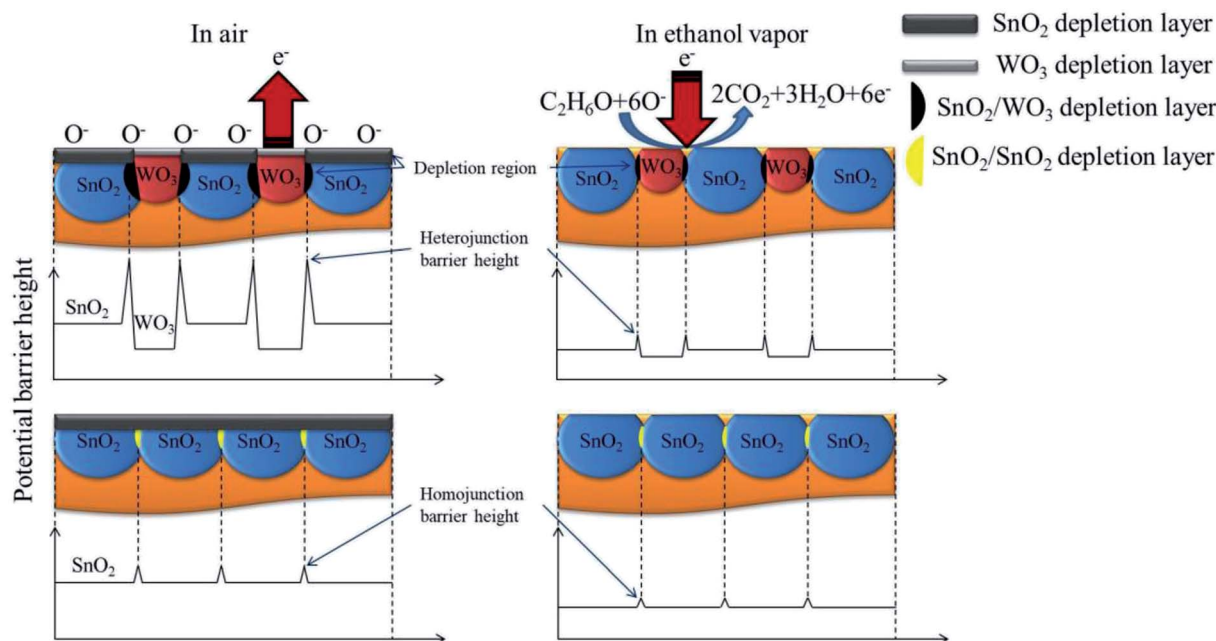


Fig. 10 Schematics of ethanol gas-sensing mechanisms for the SnO<sub>2</sub> and SnO<sub>2</sub>-WO<sub>3</sub> films.

## Conclusions

In this study, SnO<sub>2</sub>-WO<sub>3</sub> nanocomposite films with various WO<sub>3</sub> phase contents were prepared by rf cosputtering metallic Sn and ceramic WO<sub>3</sub> targets. The W content of the resulting SnO<sub>2</sub>-WO<sub>3</sub> composite films was varied from 5.4 at% to 12.3 at% through different WO<sub>3</sub> sputtering powers. Structural analysis indicated that high WO<sub>3</sub> phase content degraded the SnO<sub>2</sub> matrix's crystalline quality in the composite films, with surface crystallites in these films becoming coarser. Moreover, a higher light harvesting ability of the composite films was observed with higher WO<sub>3</sub> phase content. The SnO<sub>2</sub>-WO<sub>3</sub> composite films exhibited superior RhB dye photodegradation ability relative to their constituents. Ethanol gas-sensing tests revealed that the addition of suitable WO<sub>3</sub> crystals (W content of 5.4 at%) to the SnO<sub>2</sub> matrix improved the gas-sensing response. The heterogeneous potential barriers in the composite films play an essential role in their ethanol gas-sensing behavior.

## Conflicts of interest

There are no conflicts to declare.

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