Highly Efficient MoS$_2$/Cs$_x$WO$_3$ Nanocomposite Hydrogen Gas Sensors

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Hydrogen gas sensors are important because of the significant use of hydrogen in industrial and commercial applications. In this study, we synthesized a novel Cs$_x$WO$_3$/MoS$_2$ nanocomposite using a solvothermal method. The samples were spin-coated on Si/SiO$_2$ substrates, and the sensors were fabricated with interdigital electrodes. The hydrogen gas sensing properties of the sensor were investigated. Cs$_x$WO$_3$/MoS$_2$ exhibited an outstanding hydrogen gas sensing ability at room temperature. In particular, the nanocomposite comprising 15 wt.% MoS$_2$ (15% Cs$_x$WO$_3$/MoS$_2$) showed a 51% response to hydrogen gas at room temperature. Further, it exhibited an excellent cyclic stability for hydrogen gas sensing, which is crucial for practical applications. Therefore, this study facilitates the development of effective and efficient hydrogen gas sensors operable at room temperature.

Keywords: Cs$_x$WO$_3$/MoS$_2$ nanocomposites, hydrogen gas, room temperature, sensors, metal oxide gas sensor

INTRODUCTION

A polluted atmosphere endangers the health of living organisms. It comprises various gases that exist in nature and those released from industries (Masteghin et al., 2019; Pisarkiewicz et al., 2020; Duc et al., 2020; Kim et al., 2021). These odorless, tasteless, colorless gases are toxic when they exceed the safe limits (Ha et al., 2018; Miglietta et al., 2020; Pisarkiewicz et al., 2020). Hydrogen (H$_2$), carbon dioxide (CO$_2$), carbon monoxide (CO), and ammonia (NH$_3$) present in the environment have adverse effects on human health when their concentrations exceed the permissible levels (Annanouch et al., 2021; Hübert et al., 2014; Saravanan et al., 2017). Therefore, the amount of these gases in the environment must be monitored, and the development of effective and efficient detection methods is essential.

Hydrogen is one of the most hazardous gas and regulating its concentration with adequate monitoring devices is crucial (Hübert et al., 2014). Currently it is extensively used as a major ecological energy source and is used in semiconductor processing, chemical industry, nuclear reactors, and petroleum extraction. Hydrogen is a potential candidate for next-generation energy requirements in power plants, automobile transportation, and aerospace industries. However, the storage and regulated supply of hydrogen are challenging owing to the potential dangers of leakage (Saravanan et al., 2017). Therefore, developing long-lasting and cost-effective hydrogen sensing devices that are highly reliable for the accurate detection of the hazardous hydrogen gas is compelling (Hienuki et al., 2021; Liang et al., 2021; Sridhar et al., 2021).

In recent years, tungsten-based materials have gained a lot of interest owing to their nanostructures and unique chemical and physical properties (Chala et al., 2017; Motora and...
Because of their good selectivity and stability, they are the most suitable for fabricating high-grade sensors. In particular, tungsten trioxide has been extensively used in sensors for the detection of hazardous gases, such as hydrogen, ammonia, nitrous oxide, and hydrogen sulfide (Wang et al., 2000; Rydosz et al., 2014; Castillo et al., 2020; Dong et al., 2020). However, most of the WO₃-based gas sensors function at high temperatures or have high response/recovery times, which hinder their practical application (Estándiar et al., 2014; Chang et al., 2020). Therefore, the development of tungsten oxide-based gas sensor materials that can circumvent these limitations is important. In our previous study, we proposed a new tungsten bronze material-cesium tungsten oxide (CsₓWO₃) for hydrogen gas sensors, which exhibited significant hydrogen gas sensing properties at room temperature owing to its mixed-valence state and unique properties (Wu et al., 2021). However, its sensor response and response time need to be enhanced to detect hydrogen gas within a short duration, which are crucial for practical applications. Therefore, to circumvent this limitation, a suitable sensor material should be selected.

In contrast, molybdenum disulfide is a transition metal dichalcogenide (TMD), which is used in various applications, such as photocatalysis, sensing, disinfection, contaminant adsorption, and membrane-based separation (Barua et al., 2017; Li et al., 2018; Bello et al., 2020). It has been applied in the field of sensors as photochemical sensors, gas sensors, glucose sensors, photodetectors, electrochemical sensors, and DNA sensors (Zhang et al., 2015; Akbari et al., 2018). Among the different types of gases, MoS₂ nanostructures are usually selective toward NH₃ gas at room temperature, which hinders their applicability as gas sensors. Although MoS₂ is a good sensing material, it has limitations, such as a low structural strength and conductivity (Huaning et al., 2021). However, few studies have shown that its selective behavior can change while forming hybrids with different materials; this can be ascribed to the charge-transfer-based modulation of the channel conductivity of the gas sensor mechanism (Gottam et al., 2020). Therefore, combining MoS₂ with unique material is important for achieving an enhanced sensing performance. For instance, WO₃/MoS₂ composites have been developed, and the nanocomposite exhibits excellent ammonia and hydrogen sulfide sensing properties (Singh et al., 2020, Singh et al., 2021). However, these sensor devices function only at temperatures higher than 200°C. Besides, most of the previously developed hydrogen gas sensor exhibited low sensor response. It is very important to develop hydrogen gas sensor with high sensitivity, selectivity, and stability for practical applications. Therefore, the development of MoS₂ composites with excellent hydrogen sensing performance at room temperature is crucial.

Herein, we developed CsₓWO₃@MoS₂ nanocomposites for application in hydrogen gas sensors through a solvothermal method by taking advantage of the low-temperature sensing properties of CsₓWO₃ and the high sensor response of MoS₂. The hydrogen gas sensing properties of the developed CsₓWO₃@MoS₂ nanocomposite gas sensor at room temperature were systematically investigated. The proposed gas-sensing mechanism of the sensor was also explained.

**MATERIALS AND METHODS**

**Materials**

The tungsten hexachloride (WCl₆), cesium hydroxide (CsOH·H₂O), anhydrous ethanol, and acetic acid were purchased from Kanto Chemical Co., Inc. Molybdenum disulfide powder (<2 μm, 98%) and N,N-dimethylformamide (DMF) were purchased from Sigma Aldrich.

All reagents and chemicals used in this study were of analytical grade and were used without further purification.

**Synthesis of CsₓWO₃ Nanorods**

Tungsten hexachloride (0.2976 g) was added to anhydrous ethanol (40 ml) under intense stirring, resulting in the formation of a yellowish solution. Thereafter, 0.065 g of CsOH·H₂O was introduced into the yellowish solution. After the resultant solution became homogeneous, 10 ml of acetic acid was added. Subsequently, the mixture was transferred into a 100 ml Teflon-lined autoclave, followed by hydrothermal treatment at 240°C for 20 h. Afterward, it was cooled to room temperature naturally, and the blue product was centrifuged, washed with ethanol several times, and finally dried in a vacuum oven at 60°C for 8 h (Wu et al., 2021).

**Exfoliation of MoS₂ Nanosheets**

The MoS₂ nanosheets were exfoliated by ultrasonication according to a previously reported method (Bera and sciences, 2017). Bulk MoS₂ (0.64 g) was added to DMF (20 ml) in a flat-bottomed beaker (100 ml) and ultrasonicated for 60 min. The temperature of the sonication was controlled by a cooling system during ultrasonication. Afterward, the sample was centrifuged, washed, and dried at 60°C for 8 h.

**Preparation of CsₓWO₃/MoS₂ Nanocomposites**

The CsₓWO₃/MoS₂ nanocomposite was prepared using a hydrothermal method. The material required for the synthesis—0.1 M aqueous solution of MoS₂ (30 ml) was stirred for 1 h. Simultaneously, 0.2976 g of tungsten hexachloride was mixed with 40 ml of anhydrous ethanol under intense stirring, which resulted in the formation of a yellowish solution. Thereafter, 0.065 g of CsOH·H₂O was added to the yellowish solution. Subsequently, 10 ml of acetic acid was added to the resultant solution when it became homogeneous. Afterward, different amounts of the prepared MoS₂ solution were added to form composites with different ratios. Subsequently, the mixture was transferred into a 100 ml Teflon-lined autoclave, followed by a hydrothermal process at 240°C for 20 h. The obtained dark blue product was centrifuged, washed with ethanol several times, and finally...
dried in a vacuum oven at 60°C. In this study, three different composites were prepared by changing the amount of MoS2 and labeled as 5%, 15%, and 30%.

Characterization of CsₓWO₃/MoS₂ Nanocomposites
Field emission scanning electron microscopy (FESEM, JSM6500F, JEOL, Tokyo, Japan), transmission electron microscopy (TEM), and high-resolution TEM (TEM, Philips-6500F) were used to study the surface morphologies of the samples. The crystal structures of the CsₓWO₃, MoS₂, and CsₓWO₃/MoS₂ nanocomposites were obtained by X-ray diffraction (XRD; D2 Phaser X-ray diffractometer, Bruker, Karlsruhe, Germany) analysis. The chemical compositions of the prepared samples were determined by Raman spectroscopy using an HR800 instrument (Jobin Yvon, Taipei, Taiwan). The N₂ adsorption/desorption isotherm and Brunauer, Emmett, and Teller (BET) surface area analyses of the samples were conducted at 77 K using a Quanta chrome iQ-MP gas adsorption analyzer (BEL JAPAN, INC.).

Sensor Fabrication and Hydrogen Gas Sensing Measurements
To fabricate the gas sensor, the as-prepared CsₓWO₃, MoS₂, and CsₓWO₃/MoS₂ nanocomposites were diluted with isopropanol (IPA) and spin-coated on Si/SiO₂ substrates, which were then sputtered with multi-finger Pt interdigitated electrodes (Figure 1). The H₂ gas sensing properties of the prepared sensors were measured in a compact vacuum chamber with an H₂ flow of 99.9% (diluted with dry air) via a mass flow controller. The properties were measured systematically from the electrical output response recorded using a Keithley source meter unit (SMU, Keithley 2,400, Tektronix, Beaverton, OR, USA) connected to a computer.

Electrochemical Measurements of the Sensors
The electrochemical properties of the developed sensor materials were investigated by electrochemical impedance spectroscopy (EIS) using a 5,000 electrochemical workstation (Jiehan Technology Corp., Taiwan), wherein a conventional three-electrode configuration was used. In this measurement, 0.1 M aqueous solution of KCl was used as the electrolyte and platinum and Ag/AgCl were used as the counter and reference electrodes, respectively; a titanium substrate was used as the working electrode (Phuruangrat et al., 2009). To prepare the working electrode for EIS measurements, 4 mg of CsₓWO₃, MoS₂, and 15% CsₓWO₃/MoS₂ were added to 80 µL of NaCl solution and 920 µL of absolute ethanol, and the mixture was ultrasonicated for approximately 90 min to obtain a slurry. Thereafter, 40 µL of the slurry was drop-cast onto a 1 × 1 cm² titanium substrate electrode and dried at room temperature.

RESULTS AND DISCUSSION
Morphological and Structural Properties of CsₓWO₃/MoS₂ Nanocomposites
The surface morphologies of the prepared samples were studied by FESEM, and the FESEM image in Figure 2A shows that MoS₂ has a sheet-like morphology, mostly smaller than 2 µm in size. The FESEM image in Figure 2B depicts that the surface morphology of CsₓWO₃ comprises a nanorod-like structure with an average diameter of 40–50 nm. The FESEM image in Figure 2C shows the coexistence of nanorods and nanosheets, owing to surface morphologies of CsₓWO₃ and MoS₂, confirming the successful synthesis of the intended nanocomposites. Furthermore, the corresponding EDS spectrum confirmed the existence of Mo and S from MoS₂; Cs, O, and W from CsₓWO₃. The actual elemental composition of the 15% CsₓWO₃/MoS₂ nanocomposite
was also investigated and the result as shown in the inset of Figure 2D. It can be seen from the actual mass percentage and theoretical mass percentage of each element in the nanocomposites that they are almost the same. These results reveal that the CsₓWO₃/MoS₂ nanocomposite was successfully prepared.

The FESEM image in Figure 3A and elemental mapping results of the 15% CsₓWO₃/MoS₂ nanocomposites presented in Figures 3B–F show the homogeneous distribution of Mo, S, Cs, O, and W elements in the nanocomposite.

The surface morphology of the synthesized 15% CsₓWO₃/MoS₂ nanocomposite was further studied by TEM and HRTEM. The TEM image of 15% CsₓWO₃/MoS₂ nanocomposite shown in Figure 4A can be ascribed to CsₓWO₃ nanorods and MoS₂ nanosheets. The coexistence of the MoS₂ nanosheets and CsₓWO₃ nanorods can be seen in the HRTEM image of the nanocomposite, as shown in Figure 4B. The lattice spacing of 0.32 nm corresponds to the (002) crystal plane of CsₓWO₃ and that of 0.27 nm corresponds to the (100) crystal plane of MoS₂. The corresponding selected area electron diffraction (SAED) pattern in Figure 4C confirms the combination of both CsₓWO₃ and MoS₂. The dots forming the hexagonal shape are attributed to the MoS₂ nanosheets and those forming the triangle are ascribed to CsₓWO₃ (Ahmadi et al., 2014). However, the SAED dots in Figure 4C form hexagonal and triangular shapes with minimal changes than those of individual CsₓWO₃ and MoS₂. This can be attributed to the nanocomposite formation of CsₓWO₃/MoS₂. These results confirm that the nanocomposite was successfully prepared, and the CsₓWO₃ nanorods and MoS₂ nanosheets were in good contact, which would enhance the gas sensing property.

Figure 5 shows the XRD patterns of the CₓWO₃ nanorods, MoS₂ nanosheets, and their nanocomposites. The XRD pattern of the Cₛ₃ₓWO₃ nanorods can be ascribed to the hexagonal phase of Cₛ₀.₃₃WO₃ (JCPDS No. 83-1334) (Wu et al., 2021). The absence of additional diffraction peaks confirmed the successful synthesis of pure Cₛ₀.₃₃WO₃. The XRD peaks of the MoS₂ nanosheets can be indexed to hexagonal phase of MoS₂ (JCPDS No. 65-1951) (Zhang et al., 2014). The XRD peaks of the CₛₓWO₃/MoS₂ nanocomposites comprise characteristic peaks of both CₛₓWO₃ and MoS₂, confirming the successful preparation of the nanocomposite. In addition, the peak intensity of CₛₓWO₃ at (200) diffraction peak decreases as the MoS₂ content increases. The crystallite size of the CₛₓWO₃ and MoS₂ in the synthesized 15% CₛₓWO₃/MoS₂ nanocomposite was determined by using the Scherrer equation as shown below:

$$D = \frac{0.9\lambda}{\beta \cos \theta} \quad (1)$$

where λ is the wavelength of X-ray used (0.154 nm), β is the full-width at the half maximum of the respective diffraction peak, and θ is the angle at the maximum peak (Bekena et al., 2019). The
finding shows that the crystallite size of Cs_xWO_3 was 2 nm at diffraction peak of (200). While that of the MoS_2 nanocomposite is about 6 nm at (002) diffraction peak.

The as-prepared samples were further characterized by Raman spectroscopy, and the Raman spectra are shown in Figure 6A. The spectra show that two major peaks were observed for the MoS_2 nanosheets, which be indexed to the 2H phase of MoS_2 and E_{2g} (308 cm^{-1}) and A_{1g} (408 cm^{-1}) activation modes (Vadivelmurugan et al., 2021). The E_{2g} mode corresponds to the plane vibration of S and Mo atoms, whereas the A_{1g} mode is attributed to the relative vibration of the S atom, which is in the plane direction (Yao et al., 2019). Further, the two weak peaks at 451 and 1599 cm^{-1} indicate E_{1g} and the longitudinal acoustic phonon modes, respectively. In the case of Cs_xWO_3, the Raman peak at 731 cm^{-1} corresponds to monoclinic Gama WO_3 and that at 935 cm^{-1} corresponds to nanocrystalline Cs_xWO_3 (Okada et al., 2019). These peaks in Cs_xWO_3 confirm the nanocrystalline formation of WO_3 with cesium. The characteristic peaks of both MoS_2 and Cs_xWO_3 were observed for Cs_xWO_3/MoS_2 composite, indicating the successful preparation of the nanocomposites. In addition, there is a slight shift in the WO_3 peaks, at 872 and 993 cm^{-1}, which
indicates the presence of different organizations of elemental WO₆ octahedral.

The BET specific surface areas of the materials were investigated by N₂ adsorption analysis, and the results in Figure 6B show that all the samples exhibited N₂ adsorption-desorption isotherms similar to type IV curves according to the Brunauer-Deming-Deming-Teller classification (Wang et al., 2018). The specific surface areas of the pure CsₓWO₃, pure MoS₂, and 15% CsₓWO₃/MoS₂ nanocomposites were calculated from the linear region of the multipoint plot. The BET specific surface areas of CsₓWO₃, MoS₂, and 15% CsₓWO₃/MoS₂ nanocomposites were 31.1, 3.3, and 15.0 m² g⁻¹, respectively. Herein, the surface area of 15% CsₓWO₃/MoS₂ was lower than that of pure CsₓWO₃ because of the encompassing of the nanorods by the MoS₂ nanosheets. Compared to MoS₂ nanosheets, the 15% CsₓWO₃/MoS₂ nanocomposites possessed a larger surface area, which is important for the adsorption of a higher amount of hydrogen gas, and would aid in enhancing the gas sensing properties of the sensor.

Hydrogen Gas Sensing Properties of CsₓWO₃/MoS₂ Composites-Based Gas Sensors
The sensing properties of metal oxide-based gas sensors are usually measured in terms of their sensitivity and repeatability by varying the resistance values of gas and vacuum/air vs. time. The H₂ gas detection properties of the CsₓWO₃/MoS₂ nanocomposites were tested at a gas concentration of 10–500 ppm at 25°C ( ~ 35 RH %). The sensor response of the samples is calculated using Equation 2 for oxidizing gases and vice versa for reducing gases.

\[
S(\%) = \frac{R_g}{R_a} \times 100
\]

where \( R \) is the resistance; \( a \) is the air atmosphere, and \( g \) is the gas atmosphere of the samples.

The gas-sensing performance of a sensor can be determined using the current-voltage (I-V) curve recorded before and after the adsorption of the gas. Herein, we also evaluated the H₂ gas sensing performance of 15% CsₓWO₃/MoS₂ nanocomposites using I-V characteristics before and after the adsorption of hydrogen gas, and the results in Figure 7A show the change in the electrical performance in the presence of H₂ when compared with that of no hydrogen gas. Figure 7B shows the sensor response of the developed 15% CsₓWO₃/MoS₂ nanocomposite gas sensor at different concentrations (500, 250, 100, and 10 ppm) of hydrogen gas. The developed sensor exhibited outstanding H₂ gas sensing properties with a 50.6% sensor response toward 500 ppm of H₂ gas with 60 and 120 s response and recovery time, respectively. These recovery time and
response time are better than that of reported Pd/CNT/Ni H₂ gas sensor that has 312 s response time and 173 s recovery and Ni/Pd-graphene H₂ gas, which has 180 s response time and 720 s recovery time. (Lin and Huang, 2012; Phan and Chung, 2014). This sensor response is superior to that of the H₂ gas sensor of pure CsₓWO₃ (31.3%) (Wu et al., 2021), which indicates that nanocomposite formation has enhanced the sensitivity. Figure 7C presents the sensor response vs. concentration curve, which shows a linear increase in the sensor response with an increase in concentration, revealing that the developed sensor can be applied to detect a wide range of concentrations of H₂ gas. Figure 7D shows that the fabricated 15% CsₓWO₃/MoS₂ nanocomposite H₂ gas sensor demonstrates excellent cyclic stability for the five consecutive cycles that are important for practical applications. These findings reveal the potential applicability of the developed 15% CsₓWO₃/MoS₂ nanocomposite sensor for the detection of H₂ gas.

Long-term stability of sensor is very important for practical application. Herein, the long-term stability of the developed sensor was investigated. The result as shown in Figure 8A shows that it has excellent long-term stability during the 11-days evaluation period. Moreover, selectivity of the fabricated 15% CsₓWO₃/MoS₂ nanocomposite hydrogen gas sensor was also studied. The finding in Figure 8B indicates that the 15% CsₓWO₃/MoS₂ nanocomposite sensor presented excellent selectivity towards hydrogen gas by showing only 4 and 5% sensor response toward ammonia and carbon dioxide, respectively. The sensor response of the developed sensor toward CO₂ and NH₃ is negligible when compared with that of H₂ (50.6%). These findings confirm that developed sensor has potential applicability for real application for H₂ gas sensing. The sensing property of the developed sensor with respect to current versus time was also investigated. As it can be seen in Supplementary Figure S1, the current response of the fabricated sensor increases with increasing H₂ gas concentration, which proves the behavior of the n-type semiconductor sensor (Wisitsoraat et al., 2009; Mohamad et al., 2010). Moreover, the pure CsₓWO₃ and MoS₂ also have the same properties (Saravanan et al., 2019; Wu et al., 2021).

Figure 9 shows the sensor response of CsₓWO₃/MoS₂ nanocomposites against different amount of MoS₂ (5%, 15%, and 30%) added to CsₓWO₃. The sensor response of the nanocomposite initially increased with an increase in the amount of MoS₂ up to 15% MoS₂ addition and then decreased.
till 30% MoS₂ addition. This could be because of the encompassing of Cₓ₇WₓO₃ nanorods by MoS₂ nanosheets with low surface areas, which influences the adsorption of H₂ gas and consequently the sensor response (Supplementary Figure S2).

The photograph of the prepared samples dispersed in IPA shown in Supplementary Figure S3 also confirms that the intensity of the dark color of the nanocomposite increases with an increase in the concentration of MoS₂ nanosheets, which confirms the
presence of the high amount of MoS₂ in 30% MoS₂. Therefore, 15% CsₓWO₃/MoS₂ nanocomposite was selected for further studies.

Possible Hydrogen Gas Sensing Mechanisms of CsₓWO₃/MoS₂ Nanocomposites

Metal oxide-based gas sensors, which sense hydrogen gas, are usually explained based on the variation of the electron depletion layer (EDL) and oxygen adsorption (Sun et al., 2011; Park et al., 2015; Wang et al., 2018). Herein, we propose a sensing mechanism for the developed sensor based on EDL. CsₓWO₃ has oxygen defects in its structure, and MoS₂ is tuned to have a high bandgap after the exfoliation of bulk MoS₂. Therefore, the CsₓWO₃ nanorods in the nanocomposite can adsorb oxygen from the air because of its oxygen vacancies, and the adsorbed oxygen extracts electrons from the conduction band and generates oxygen species and increases the width of the EDL (Figure 10A). In contrast, when the sensor is exposed to H₂ gas, the adsorbed oxygen species react with H₂ gas and produce extra electrons in the conduction band of CsₓWO₃, which increase the electrical performance of the material and consequently the sensing property (Figure 10B).

Further, the electrochemical properties of the samples were investigated, and the results in Figure 11 show that the EIS semicircle radius of the 15% CsₓWO₃/MoS₂ nanocomposite is lower than those of pure CsₓWO₃ and pure MoS₂, confirming that the nanocomposite has a higher electrical conductivity than those of pure materials, which contributed to the enhancement in the hydrogen gas sensor response.

The hydrogen gas sensing response of the developed 15% CsₓWO₃/MoS₂ nanocomposite was also compared with those of reported hydrogen gas sensors, and the results in Table 1 indicate...
that the 15% CsxWO3/MoS2 nanocomposite exhibited a higher sensor response than those of other sensors (Esfandiar et al., 2012; Huang and Lin, 2012; Anand et al., 2014; Liu et al., 2015; Yang et al., 2015; Zhang et al., 2018; Sharma and Kim, 2018; Xiao et al., 2018; Wu et al., 2021). Further, some of the reported sensors can only operate at high temperatures. Therefore, the developed 15% CsxWO3/MoS2 nanocomposite H2 gas sensor is a promising candidate for practical application in the detection of hydrogen gas.

CONCLUSION

In this study, CsxWO3/MoS2 nanocomposites were successfully prepared using the solvothermal method. The developed CsxWO3/MoS2 nanocomposite-based sensor exhibited outstanding hydrogen gas sensing properties with 51% response to 500 ppm H2 gas. It also exhibits excellent cyclic stability. Further, the developed 15% CsxWO3/MoS2 nanocomposite demonstrated a superior H2 gas sensing response at room temperature compared to reported H2 gas sensors. The enhanced sensing response could be because of the improved electrical properties of the 15% CsxWO3/MoS2 nanocomposite. Therefore, this study facilitates the development of an effective and efficient H2 gas sensor at room temperature, which will play a crucial role in the detection of hydrogen gas in the environment.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

C-MW: Supervision, conceptualization and reviewing and editing. Shrisha: Methodology, data curation and writing. KM: Review and editing. G-YC: Methodology and data curation. D-HK: Resources. NG: Methodology.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmats.2022.831725/full#supplementary-material

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The following is a Table comparing different metal oxide-based gas sensors:

| Materials | Sensing response (%) | Operating temp. (°C) | H2 conc. (ppm) | References |
|-----------|----------------------|-----------------------|----------------|------------|
| MoS2-Si   | 15.4                 | RT                    | 5,000          | Liu et al. (2015) |
| MoS2 nanosheets | 20.5               | 120                   | 500            | Zhang et al. (2018) |
| rGO–TiO2  | 22                   | 180                   | 500            | Esfandiar et al. (2012) |
| Graphene–Ag-Pt | 9                 | RT                    | 500            | Sharma and Kim, (2018) |
| ZnO–graphene | 3.5                | 150                   | 500            | Anand et al. (2014) |
| ZnO–perovskite | 15               | RT                    | 500            | Huang and Lin, (2012) |
| Cd-doped ZnO nanorods | 1.6         | 80°C                  | 500            | Yang et al. (2015) |
| ZnO nanorods | 20.5                | 350                   | 5,000          | Xiao et al. (2018) |
| CdO nanoparticles | 7.5                 | RT                    | 500            | Wu et al. (2021) |
| Cds–WO3 nanorods | 31.3                | 25                    | 5,000          | Xiao et al. (2018) |
| Cs0.5WO3 films | 27.5               | RT                    | 500            | This work |

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