

Porous WS₂ Films for Selective and Humidity-robust NO₂ Sensing at Room Temperature

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Summary:

Highly porous WS₂ films were developed for selective NO₂ sensing at room temperature. The films were produced by flame aerosol deposition and dry sulfidation, resulting in a nanostructured porous network. This morphology enabled an enhanced sensor response and much faster response kinetics than compact films. NO₂ was detected down to 1 ppb with excellent discrimination from relevant interferents. The sensor performance remained robust over a wide humidity range and stable during long term testing. The presented sensor is promising for low power air quality monitoring and wearable exposure sensing.

Keywords: nanotechnology, semiconductors, thin films, metal sulfides, environmental monitoring

Background, Motivation and Objective

Nitrogen dioxide (NO₂) is a major atmospheric pollutant emitted by fossil fuel combustion, biomass burning, power generation and industrial activities [1], and both short- and long-term exposure have been linked to adverse respiratory and cardiovascular health effects [2]. In response, the World Health Organization lowered the recommended annual mean exposure limit from 40 to 10 µg/m³, corresponding to about 5 ppb, which increases the need for sensitive monitoring technologies at very low concentrations [4]. Conventional chemiluminescence analyzers are widely used for reference measurements, but they are costly, maintenance intensive and vulnerable to interference from other nitrogen containing compounds [5]. Chemoresistive sensors offer a promising low-cost alternative for distributed and personal monitoring, yet many reported devices still require elevated temperatures or suffer from limited selectivity and humidity dependence [6]. The objective of this work was therefore to develop a room temperature nitrogen dioxide sensor based on porous tungsten disulfide films with improved sensitivity, selectivity and environmental robustness [7].

Description of the New Method or System

A new fabrication route was developed to obtain highly porous tungsten disulfide (WS₂) films for room temperature NO₂ detection. Tungsten trioxide nanoparticles were first deposited directly onto sensor substrates by flame aerosol deposition, forming an open and nanostructured film. These films were then converted by dry sulfidation while preserving the porous architecture. In contrast to compact reference films prepared by

spin coating from the same precursor nanoparticles, the resulting porous films provided much more efficient gas transport and a larger accessible surface area. This method enabled a clear improvement in sensing performance, combining very high sensitivity, fast response, strong selectivity and robustness against humidity variations at room temperature.

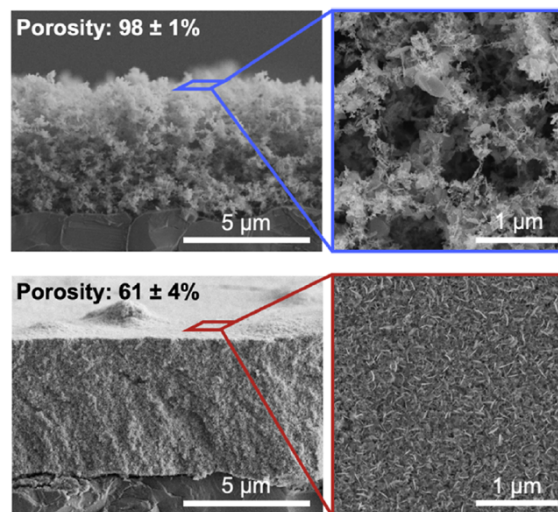


Fig. 1. Cross-sectional and top-view SEM images show the film thickness and film morphology of the flame-aerosol deposited and dry-sulfidized (top) and the spin-coated and dry-sulfidized (bottom) WS₂ films. Reproduced from [7].

Results

Flame aerosol deposition followed by dry sulfidation yielded WS₂ films with a highly open and nanostructured morphology, in clear contrast to the denser spin-coated films (Fig. 1). The porous films consisted of interconnected WS₂

nanosheets arranged in a hierarchical network with pores across multiple length scales, resulting in a porosity of $98 \pm 1\%$. By comparison, the compact films showed a much denser structure with a porosity of $61 \pm 4\%$, with a similar film thickness.

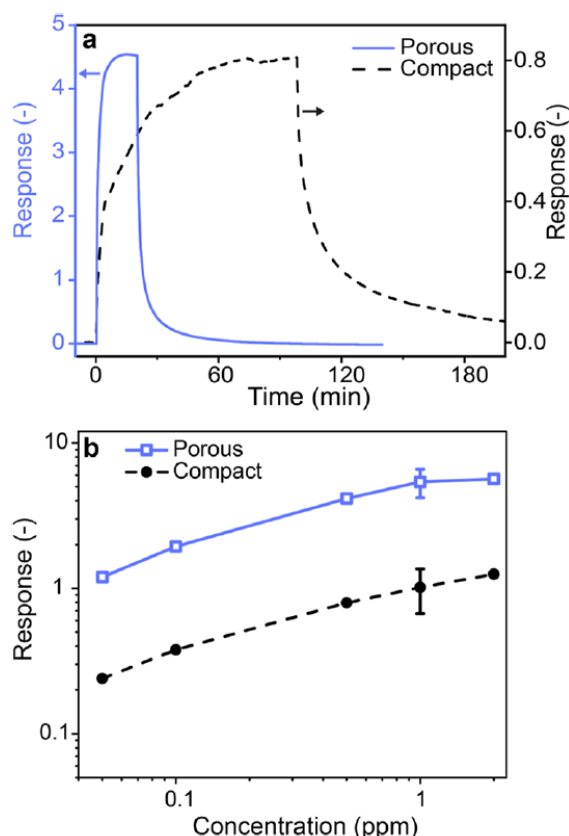


Fig. 2. (a) Response of porous (blue solid line) and compact (black dashed line) WS₂ films to 1 ppm NO₂, shown with different y-axis scales. (b) Sensing response of porous (blue open squares) and compact (black filled circles) WS₂ films exposed to 50–2000 ppb NO₂. At 1000 ppb, the symbols and error bars indicate the mean $\pm$ standard deviation for six porous sensors and two compact sensors fabricated under identical conditions. All measurements were carried out at room temperature and 50% RH. Reproduced from [7].

The porous architecture translated directly into superior NO₂ sensing performance. Upon exposure to 1 ppm NO₂ at room temperature and 50% RH, the porous WS₂ films exhibited a response about five times higher than that of the compact films (Fig. 2a). In addition, the porous sensors showed a much faster response time of 60 s, whereas the compact films required about 31 min under the same conditions. The enhanced performance was also maintained over a wider concentration range from 50 to 2000 ppb (Fig. 2b). This improvement is attributed to the open film structure, which facilitates analyte diffusion and provides a larger accessible surface area with more reactive sites.

Beyond sensitivity and speed, the porous WS₂ films also showed excellent selectivity (Fig. 3)

and environmental robustness. The response to NO₂ was far stronger than that to a range of interfering gases relevant for air-quality monitoring, demonstrating a high preference for the target analyte. Moreover, the sensor response remained stable across varying humidity conditions and during long-term operation. Together, these results show that tailoring WS₂ into a highly porous film architecture is an effective strategy to enhance sensing performance, yielding faster, stronger, and more selective NO₂ detection under practical operating conditions.

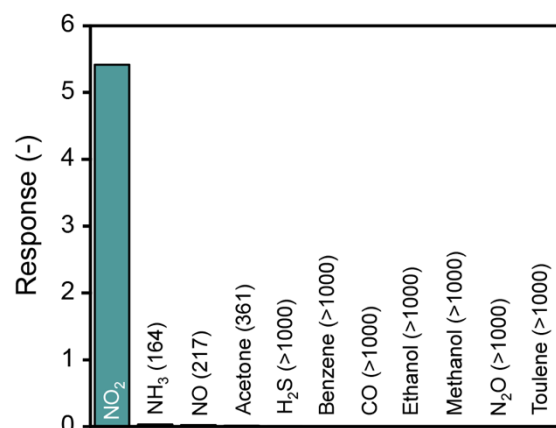


Fig. 3. Sensor response of porous WS₂ film against 1 ppm of air quality-relevant interferents at room temperature and 50% RH. Reproduced from [7].

References

- [1] Jion, M. M. M. F. et al., A critical review and prospect of NO₂ and SO₂ pollution over Asia: Hotspots, trends, and sources. *Sci. Total Environ.* **876**, (2023); doi: 10.1016/j.scitotenv.2023.162851
- [2] Meng, X. et al., Short term associations of ambient nitrogen dioxide with daily total, cardiovascular, and respiratory mortality: Multilocation analysis in 398 cities. *BMJ* **372**, (2021); doi: 10.1136/bmj.n534
- [3] World Health Organisation. WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide, p1–360 (2021).
- [4] Dunlea, E. J. et al., Evaluation of nitrogen dioxide chemiluminescence monitors in a polluted urban environment. *Atmos. Chem. Phys.* **7**, 2691–2704 (2007); doi: 10.5194/acp-7-2691-2007
- [5] Abegg, S., Cerrejon, D. K., Güntner, A. T. & Pratsinis, S. E. Thickness optimization of highly porous flame-aerosol deposited WO₃ films for NO₂ sensing at PPB. *Nanomaterials* **10**, 1–15 (2020); doi: 10.3390/nano10061170
- [6] Hersberger, S., Pereira Martins, M., Fassbind, S. & Güntner, A. T. Selective, Stable and Humidity-Robust NO₂ Sensing at Room Temperature with Porous WS₂ Films. *ACS sensors* **10**, 8596–8605 (2025).