Metal-oxide Semiconductor Based Low Powered Humidity and Gas Sensors at Room Temperature

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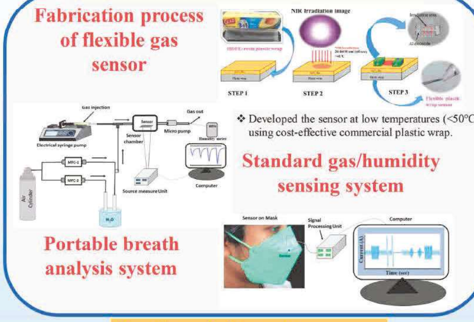
Abstract

- Developed low-power SnO_2 , Au/SnO_2, and TiO_2/SnO_2 -based sensors for relative humidity (RH), H_2S, and NOx detection, respectively, all operating efficiently at room temperature.
- These sensors exhibit exceptional performance, achieving high resolution for RH changes as small as 0.1% and detecting ultra-low gas concentrations, such as 2 ppb (parts-per billion) H_2S and 4 ppb NOx, which are highly challenging benchmarks.
- Furthermore, they are capable of detecting various respiratory and oral diseases, including asthma, pneumonia, and halitosis, by analyzing specific biomarkers in human breath.

SnO_2-based relative humidity/respiratory monitoring sensor

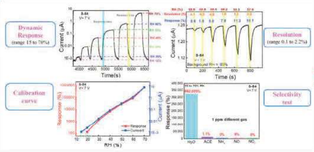
Importance of humidity/respiratory monitoring

Device preparation and sensing system



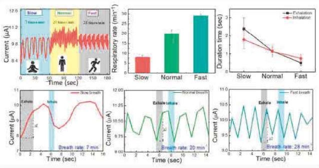
❖ Developed the sensor at low temperatures (<50°C) using cost-effective commercial plastic wrap.

Results and discussions



❖ The sensor can detect RH 15 to 70% with resolution as low as 0.1% RH at room temperature.

❖ Sensor shows highly selectivity towards water molecules.



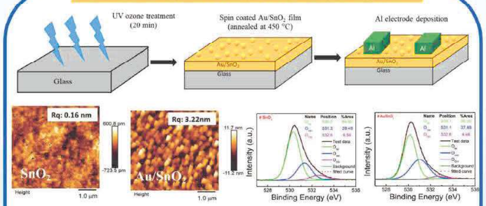
❖ The sensor detects slow, normal, and fast breathing, with a normal rate of 18-22 breaths/min, matching commercial breath analyzers.

Flower petal like nanostructure Au/SnO_2-based H_2S gas sensor

Importance of H_2S gas monitoring

❖ Healthy individuals exhale oral breath with H_2S levels below 50 ppb, while patients with oral diseases like halitosis, periodontitis, or oral squamous cell carcinoma emit over 100 ppb of H_2S.

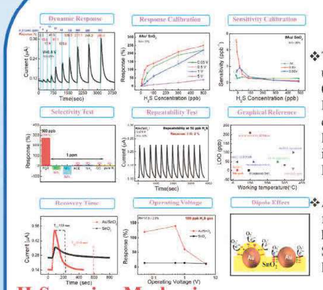
Device structure and Characterization



❖ AFM data reveals that flower-petal-like Au/SnO_2 nanostructures enhance surface area and roughness compared to pure SnO_2. XPS analysis shows higher oxygen vacancies in Au/SnO_2 (37.49%) versus pure SnO_2 (26.49%), contributing to improved gas responsivity.

❖ The standard gas sensing system was used for H_2S gas measurement.

Results and discussions



H_2S sensing Results

❖ The sensor operates at ultra-low voltages (0.05–0.5 V) and reliably detects H_2S at 2 ppb, the lowest concentration reported at low temperatures, as shown in the literature (Graphical Reference).

❖ Au/SnO_2 exhibits 4 fold faster recovery and 5 fold higher response than pure SnO_2, attributed to localized dipole effects.

H_2S sensing Mechanism

Reaction: $2H_2S\,(gas) + 3O_2^-\,(ads) \leftrightarrow 2H_2O\,(ads) + 2SO_2 + 3e^-$

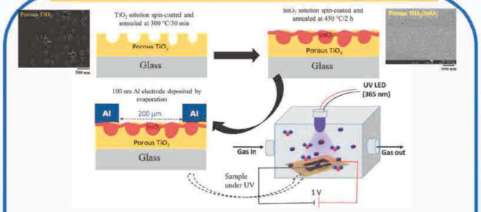
❖ The Au/SnO_2 sensor provides more oxygen vacancy sites than pure SnO_2 , enhancing adsorbed oxygen (O_2^-) sites and boosting H_2S gas response.

Nanoporous TiO_2/SnO_2-based NO and NO_2 gas sensor

Importance of NOx gas monitoring

❖ Breath NO diagnosis requires ultra-ppb level detection, with exhaled NO levels <15 ppb for healthy individuals, >20 ppb for COPD patients, and >40 ppb for asthma patients.

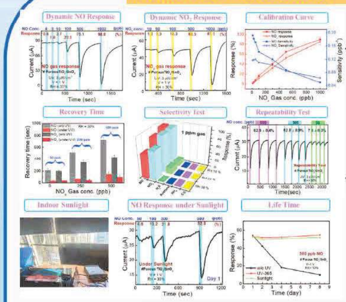
Experimental Process and Characterization



❖ A porous TiO_2/SnO_2 structure was prepared via a simple sol-gel process, with TiO_2 as a photocatalyst and SnO_2 as the NOx sensing material. The SEM images serve as evidence of the unique porous structure of the TiO_2/SnO_2.

❖ UV LED (365 nm) light was integrated to enhance gas sensing through photocatalytic activation.

Results and discussions

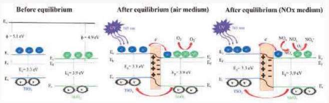


NOx sensing Results

❖ The sensor operates at low voltage (1 V) and able to detect low concentration gas such as 4 ppb NO and 10 ppb NO_2 at room temperature

❖ The sensor achieves improved recovery time and extended lifetime under ultra-low UV power (3 µW/cm²), which can be harvested from indoor sunlight.

NOx sensing Mechanism under UV



Reaction: $NO\,(ads) + O_2^-\,(ads) + e^- \rightarrow NO_2^-\,(ads) + O^-\,(ads)$, $2NO_2\,(gas) + O_2^-\,(ads) + e^- \rightarrow 2NO_3^-$

❖ TiO_2, with 3.3 eV band gap (365 nm), exhibits photocatalytic effect on the TiO_2/SnO_2 sensor. It helps the reactivity of adsorbed oxygen sites.

Conclusions

- ❖ A SnO_2-based relative humidity/respiratory sensor was developed using a low annealing temperature (<50°C), achieving high-resolution detection of RH changes as small as **0.1%**, a challenging feat according to the literature. The flexible sensor also effectively monitors human respiratory rates and modes, making it suitable for detecting respiratory diseases and environmental changes.
- ❖ The nanostructured Au/SnO_2-based H_2S sensor detects ultra-low concentrations **(2–500 ppb)** with a high response of 280% at 500 ppb H_2S under low operating power **(0.5 V).** This sensor is ideal for detecting oral gases related to diseases such as halitosis, periodontitis, and oral cancer.
- ❖ The UV-activated porous TiO_2/SnO_2 sensor utilizes a photocatalytic effect under low UV power (3 µW/cm²), significantly improving recovery time, recovery ratio, and **lifespan** while detecting ultra-low NOx levels (4 to 1000 ppb) at room temperature. This makes it suitable for diagnosing breath-related diseases like asthma.
- ❖ All sensors are designed for **low-power operation**, reducing carbon emissions and promoting sustainable development.

Publication

1. **M. Deb**, C.J. Lu* and H.W. Zan*, "Achieving Room-Temperature ppb-Level H_2S Detection in a Au/SnO_2 Sensor with Low Voltage Enhancement Effect", *ACS sensors*, 2024, 9(9):4305-4973.
2. **M. Deb,** M.Y. Chen, P.Y. Chang, P.H. Li, M.J. Chan, Y.C. Tian, P.H. Yeh, O. Soppera*, H.W. Zan*, "SnO_2-based ultra-flexible humidity/respiratory sensor for analysis of human breath", *Biosensors*, 2023, 13(1):81.
3. Y.C. Chiu, **M. Deb**, P.T. Liu*, H.W. Zan*, Y.R. Shih, Y. Kuo, D.B. Ruan, K.J. Gan, C.C. Hsu. "Sputtered ultrathin WO_3 for realizing room-temperature high-sensitive NO_2 gas sensors", *ACS Applied Electronic Materials*, 2023, 5(11):5831-40.
4. **M. Deb**, Y. Ghossoub, L. Noel, P.H. Li, H.Y Tsai, O. Soppera*, and H.W. Zan*, "High Efficient UV Activated TiO_2/SnO_2 Surface Nano-Matrix Gas Sensor: Enhancing Stability for ppb-Level NOx Detection at Room Temperature", *ACS Applied Materials & Interfaces*, (Under review).