

Semiconductor Gas Sensor Materials for Selective Detection of Volatile Organic Compounds: From Materials Design to Sensing Mechanisms

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Volatile organic compounds (VOCs) are key indicators for environmental monitoring, workplace safety, process control, food quality assessment, and non-invasive diagnostics. Semiconductor metal oxide (SMOX) gas sensors are attractive for these applications because they are compact, inexpensive, highly sensitive, and compatible with microfabricated devices. However, selective detection of specific VOCs remains a central challenge, since many reducing gases induce similar resistance changes through overlapping surface oxidation reactions.

Our strategy is based on the rational design of gas-sensitive interfaces using SnO₂, WO₃, ZnO, In₂O₃-based mixed oxides, and related nanostructured materials. Colloidal and wet-chemical routes allow control of crystallite size, exposed surface, porosity, and the distribution of catalytic additives such as Pt, Pd, and other noble metals. These structural factors determine oxygen adsorption, VOC activation, lattice oxygen participation, and electron transfer at the sensor surface.

A major focus of this work is to move beyond empirical sensor screening toward mechanism-guided materials design. Operando diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS), Raman spectroscopy, UV-vis spectroscopy, gas analysis, ex-situ electron paramagnetic resonance (EPR), and simultaneous resistance measurements were combined to identify adsorbed intermediates, catalyst oxidation states, oxygen-vacancy-related sites, and lattice oxygen dynamics under actual sensing conditions. These analyses revealed that VOC sensing responses can arise from multiple pathways, including direct electron donation from adsorbed species, catalytic oxidation by chemisorbed oxygen, Mars-van Krevelen-type reactions involving lattice oxygen, and vacancy formation/healing promoted by noble-metal catalysts. Such mechanistic information clarifies why similar materials exhibit different selectivity patterns and why optimum operating temperatures depend strongly on both target gas and catalyst composition.

The present contribution will discuss how these insights can be translated into practical sensor design: choosing oxide matrices according to VOC reactivity, using Pt or Pd to control oxygen activation and reaction kinetics, engineering porous films for gas diffusion, and integrating sensor arrays with data-driven recognition methods. The combination of precise ceramic nanomaterial synthesis and operando analysis provides a powerful route to reliable, selective, and low-power VOC sensing. These studies demonstrate that semiconductor gas sensors should be viewed not only as simple resistance devices, but also as dynamic catalytic/electronic interfaces whose function can be designed from the atomic and molecular levels.

Keywords: semiconductor gas sensor; volatile organic compounds; metal oxide nanocrystals; operando spectroscopy; sensing mechanism

References

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