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Rational design of semiconductor metal oxide nanomaterials for gas sensing by template-assisted synthesis: a survey

Key words: Gas sensors; Chemi-resistors; Template-assisted methods; Nanostructure; Dimension

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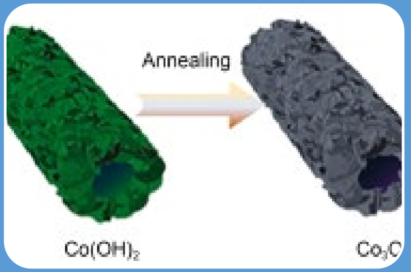
Gas sensors have received extensive attention because of the gas pollution caused by rapid construction of urbanization and industrialization

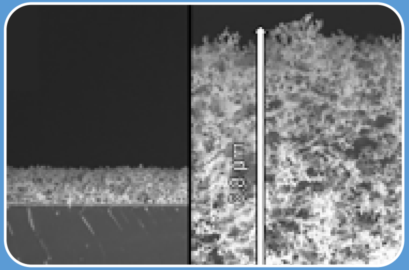
Sensing material	Gas	Temperature	Concentration/Response	T_{res} (s)	LOD (ppb)	Reference
rGO/$CuCoO_x$	NO_2	RT	1 ppm/64.76%	250	50	Ogbeide et al. (2022)
Pt@In_2O_3	Acetone	320 °C	1 ppm/6.23	11	10	Liu W et al. (2018)
ZIF-7/TiO_2	Formaldehyde	RT	5 ppm/1350	9	16	Jo et al. (2021)
GO/TiO_2	NO_2	RT	1.75 ppm/3.14	35	70	Giampiccolo et al. (2019)
Pd-$BiVO_4$	3-hydroxy-2-butanone	200 °C	10 ppm/103.7	12	200	Chen et al. (2020)
ZnO	NO_2	RT	1 ppm/29	22	0.2	Xia et al. (2020)
CeO_2-WO_3	Acetone	250 °C	0.5 ppm/1.31	34	500	Yuan KP et al. (2020)

Tendency and challenges

Gas sensors based on semiconductor metal oxide (SMO) have the advantages of high response, excellent repeatability, stability, and cost-effectiveness, and have become extremely important components in the gas sensor field.



Materials with regular structures and controllable morphology exhibit more consistent and repeatable performance.



However, during the process of material synthesis, because of the uncontrollability of the microcosm, nanomaterials often show irregularities, unevenness, and other shortcomings.

Motivation

Over recent decades, there has been a growing interest internationally in gas sensing to avoid environmental problems and human health damage.

Traditional methods need a specific device, are complicated to operate, and are unsuitable for timely monitoring of harmful gases.

1D nanomaterials based on template-assisted methods

- 1D nanomaterials contain mainly nanorods (Nasir et al., 2014; Zhang B et al., 2021), nanofibers (Kim DH et al., 2019, 2020), or nanotubes (Xue et al., 2016; Sharma et al., 2021).

- 1D nanostructured materials exhibit excellent electrical mobility, facilitating the transport of electrons, which is favorable for gas sensing performance.

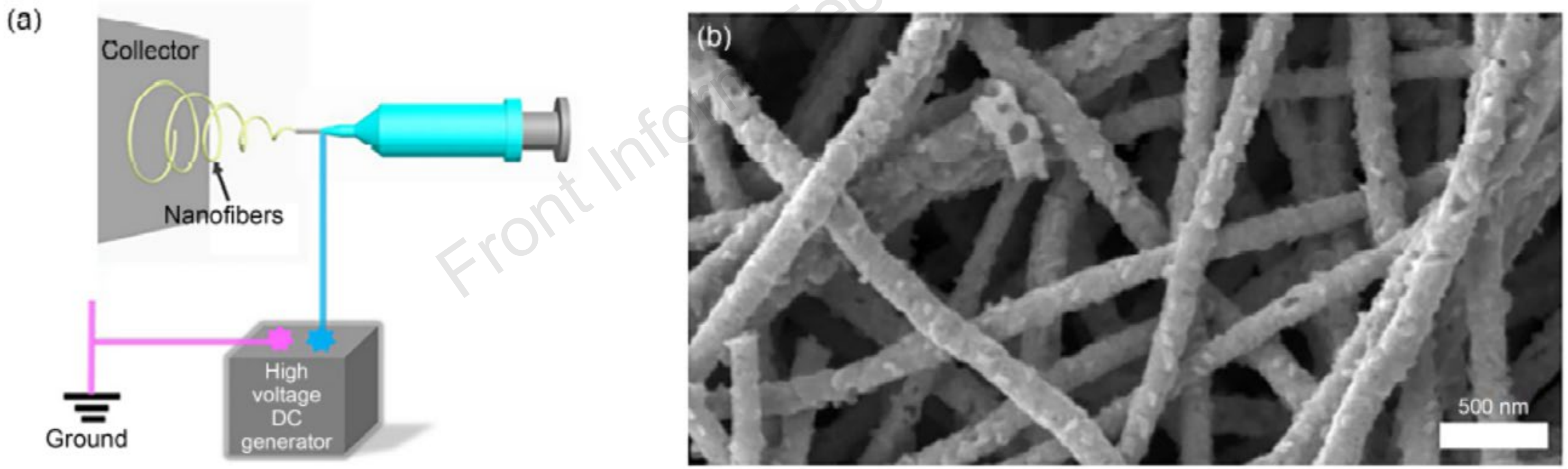


Fig. 1 Schematic of the basic setup for electrospinning (a) and a scanning electron microscope (SEM) image of Pr-doped $BiFeO_3$ (b)

2D nanomaterials based on template-assisted methods

- The synthesis of gas sensors based on 2D nanomaterials using a template-assisted method is relatively rare nowadays, but their performance is excellent (Ma et al., 2020; Wen et al., 2023).

- 2D nanomaterials are appropriate for the production of gas sensors due to their large specific surface area, excellent carrier mobility, and large number of adsorption sites.

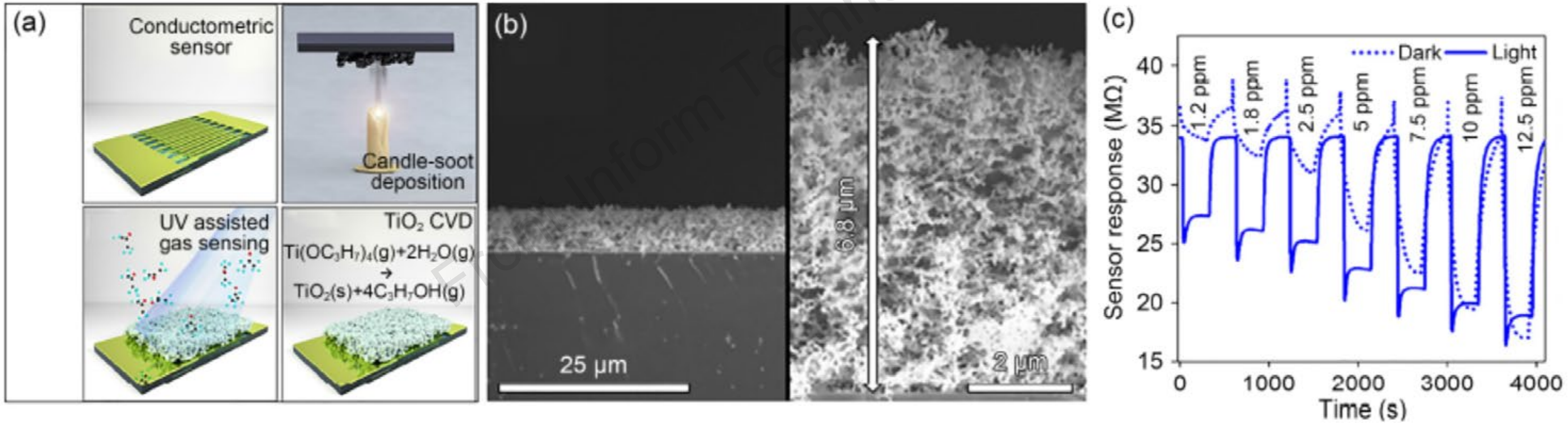


Fig. 5 Schematic of the fabrication process of a soot template TiO_2 gas sensor (a), different magnification scanning electron microscope (SEM) images showing the uniformity and thickness of the surface of a SnO_2 sensor device (b), and dynamic response curve of the SnO_2 gas sensor to different acetone concentrations (c)

3D nanomaterials based on template-assisted methods

◆ 3D nanomaterials generally have a large specific surface area, a stable structure, and good gas diffusion, making them ideal for use as gas sensitive materials.

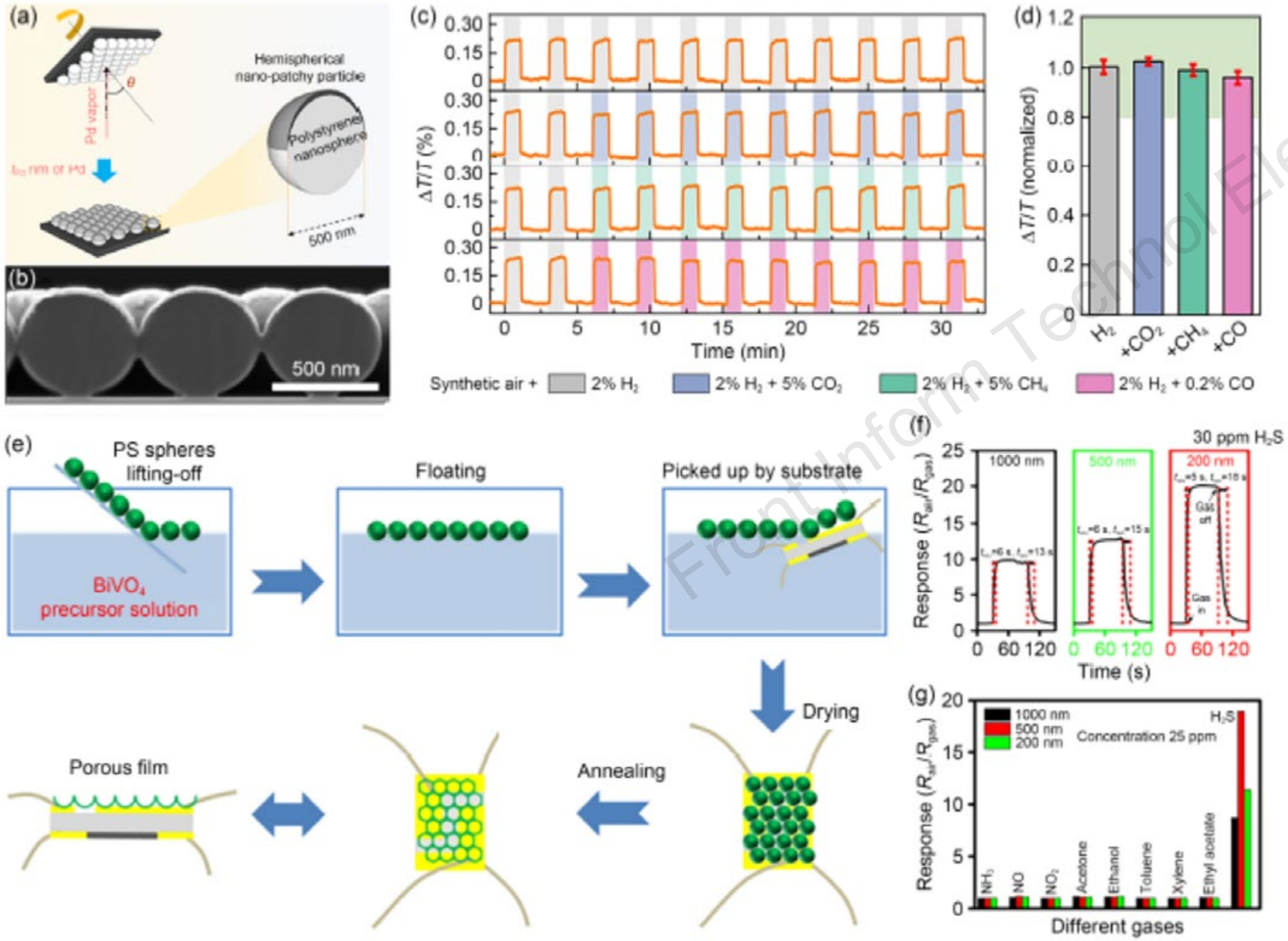
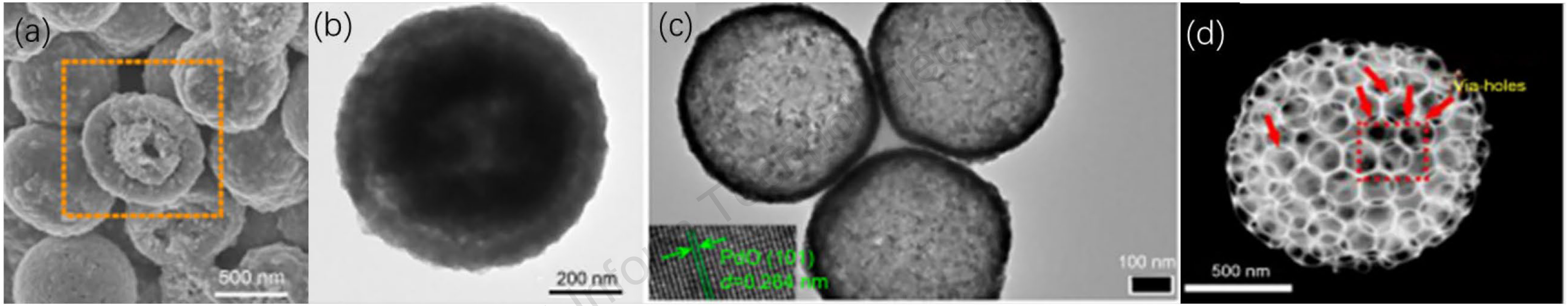


Fig. 6 Schematic of the process for fabricating PdCo NP/PMMA nanomaterials (a), a cross-sectional scanning electron microscope (SEM) image of NPs (b), response of PdCo NPs to 2% H_2, 2% H_2+5% CH_4, 2% H_2+5% CO_2, and 2% H_2+0.2% CO (c), the standard deviation from 2% H_2 (d), schematic of the procedure for preparation of an ordered porous $BiVO_4$ gas sensor (e), characteristic curves toward 30 ppm H_2S (f), and response of gas sensors based on different thickness to 25 ppm of different gases (g)

Carbonaceous, SiO_2 spheres , high molecular weight polymer and metal organic framework (MOF) templates



A scanning electron microscope (SEM) image of semiconducting metal oxide 3D nanomaterials prepared by glucose (a), a field emission scanning electron microscope (FESEM) image of $NiCo_2O_4$ double-shelled hollow spheres (DHSs) (b), a transmission electron microscope (TEM) image of PdO hollow shells (HSs) (c), and an SEM image of IO-$(Ga_{0.2}In_{0.8})_2O_3$ (d)

Other templates

◆ Other templates could be used to fabricate 3D nanomaterials with a complicated structure, resulting in a large specific surface area.

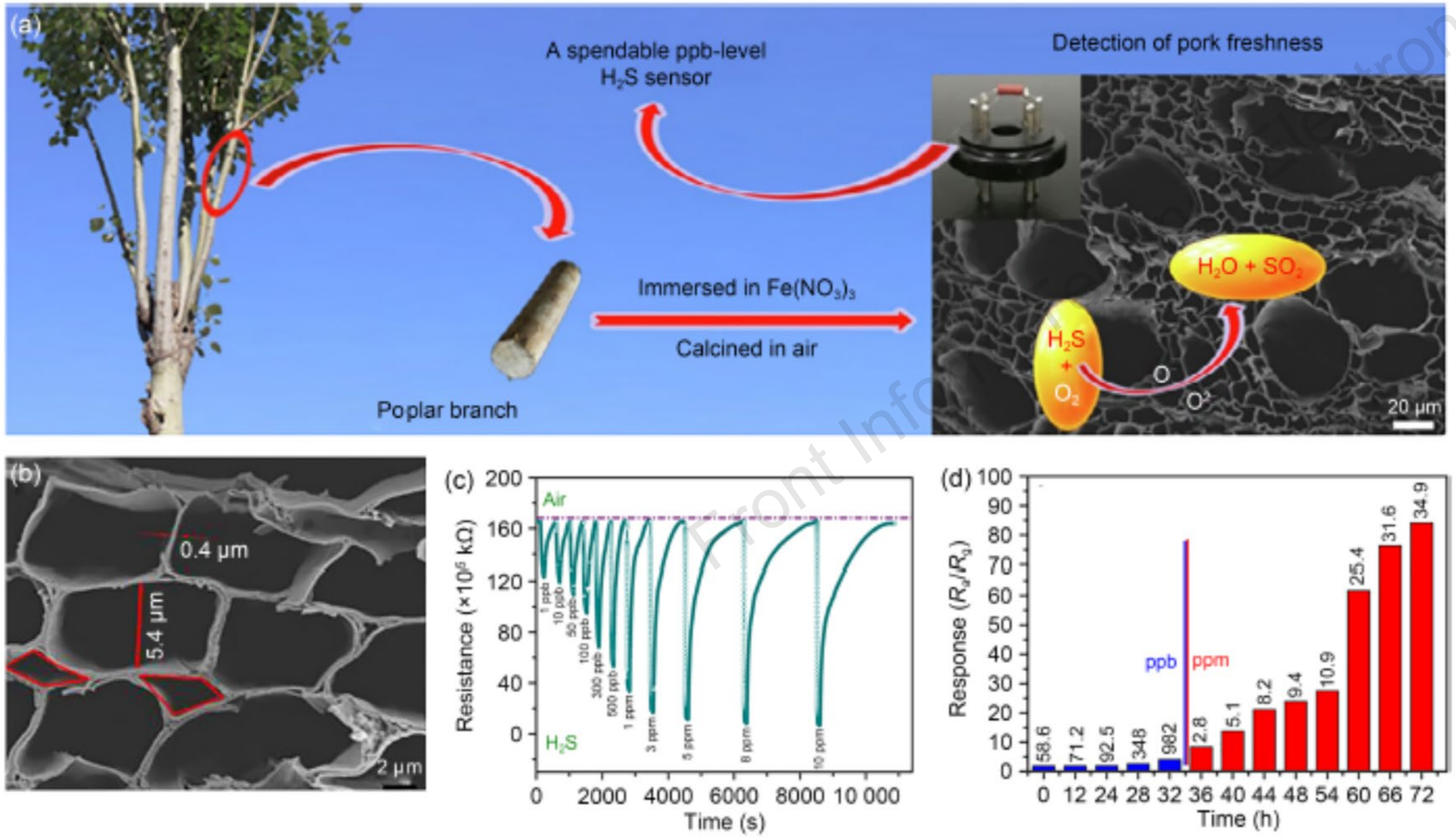


Fig. 13 Schematic of the synthesis process and sensing device of porous α-Fe_2O_3 tubules (a), a scanning electron microscope (SEM) image of Fe-600 (b), response/recovery curve to different concentrations of H_2S (c), and real-time detection of the H_2S concentration of pork at different time intervals (d)

Conclusions and outlook

In this review, the research progress of gas sensors based on template-assisted synthesis methods in recent years is summarized, including 1D, 2D, and 3D nanomaterials, as well as the morphology and properties of these materials synthesized by different templates, such as biomass, carbonaceous, and polymeric materials. For 1D nanomaterials, semiconductor nanomaterials prepared using the template-assisted method have a uniform morphology and complex surface structure, excellent gas diffusion, and a large number of active sites, efficiently accelerating the reaction rate, increasing the gas detection ability of the gas sensor, and ensuring long-term stability and repeatability.

The field of gas sensors has made substantial use of the template-assisted synthesis technique. Looking ahead, the components of the template will develop toward high performance and low cost. For instance, the potential of biomass material, which is in line with the development path, cannot be overlooked as an inexpensive and environmentally beneficial resource. It could resolve many issues with the template-assisted method at this time due to its uniform structure and straightforward treatment process.

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