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Periodic bicontinuous structure enhanced steady non-equilibrium chemical sensing for efficient gas discrimination

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MAIN TEXT

Artificial olfaction holds immense promise for the digitization of gas information and realizing high-precision, real-time detection of gaseous analytes in diverse practical scenarios, from environmental monitoring to clinical disease diagnosis[1,2]. In the past decade, metal oxide semiconductor (MOS) based gas sensors have become the most mainstream platform for artificial olfaction due to their high sensitivity, low cost, and good stability[3,4]. However, conventional MOS sensors typically produce low-dimensional, equilibrium-based signals with weak feature differences, making it difficult to achieve accurate gas discrimination in complex environments. As a result, researchers have long relied on large-scale sensor arrays to improve selectivity, which inevitably increases system complexity, power consumption, and integration difficulty[5,6].

Recently, inspired by the function of periodic bicontinuous structure in organisms, Chen and colleagues offered a paradigm-shifting solution for breaking the above dilemma and advancing the development of single-sensor artificial olfactory intelligence[7]. During mammalian rhythmic breathing, the periodic bicontinuous structure covering alveolar epithelial cells and mitochondria enables ultrafast gas diffusion and efficient gas-solid interfacial reactions by virtue of its interconnected open channels, large specific surface area, and low mass-transfer resistance [Figure 1A]. Drawing on this natural inspiration, the authors rationally designed a steady nonequilibrium gas sensing system based on artificial periodic porous structures and the pulse heating (PH) technique to enrich gas sensing features for high-accuracy gas discrimination [Figure 1B]. The periodic mesoporous tin oxide (P-mSnO_2) with a well-defined single primitive cubic bicontinuous architecture was synthesized by using self-assembled block copolymer cubosomes as a soft template. Benefiting from its highly ordered pore structure, large pore size, and abundant surface-active sites,

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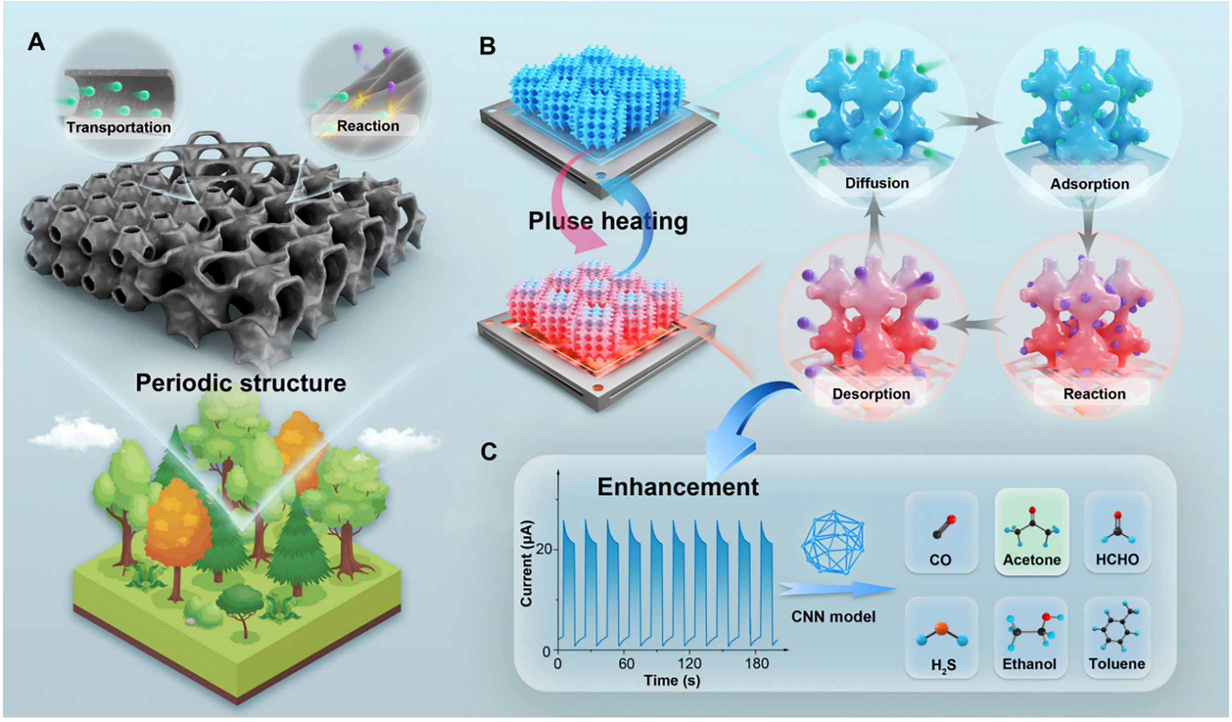

Figure 1. Schematic illustration of the P-mSnO_2 sensing system for high-performance single-sensor artificial olfaction. (A) Nature-inspired periodic architecture for efficient gas transport and interfacial reactions; (B) Pulse heating-modulated dynamic sensing process (diffusion, adsorption, reaction, desorption) on the periodic mesoporous SnO_2 unit; (C) CNN-assisted high-accuracy discrimination of multiple gases based on enhanced nonequilibrium response signals. This figure is reproduced from reference[7] under the terms of the CC BY-NC-ND 4.0 license. P-mSnO_2: periodic mesoporous tin oxide; CNN: convolutional neural network.

this bioinspired P-mSnO_2 significantly accelerates gas transport and strengthens interfacial catalytic reactions, especially during the pH sensing process. Compared with disordered mesoporous tin oxide (D-mSnO_2) and commercial SnO_2 particles, the P-mSnO_2-based sensor proactively generates stable, repeatable nonequilibrium response signals featuring prominent and consistent overshoot peaks, which serve as unique chemical fingerprints for each gas species.

With the assistance of a convolutional neural network (CNN) for processing PH gas sensing features, the P-mSnO_2-based sensor achieves an exceptional 99.8% discrimination accuracy toward six representative gases at low concentrations (1-5 ppm), including toluene, acetone, ethanol, hydrogen sulfide, formaldehyde, and carbon monoxide, outperforming conventional D-mSnO_2 and commercial SnO_2 particle sensors [Figure 1C]. More importantly, the authors quantitatively revealed the mechanism governing the distinct PH sensing curves for gas molecules, highlighting the synergistic contributions of gas adsorption capacity, diffusion coefficient, catalytic reaction barrier, and electron transfer number as crucial influencing factors. Therefore, the thermodynamics and kinetics are both important in determining the characteristic features of PH gas sensing signals.

This work elegantly demonstrates how bioinspired periodic bicontinuous structures can fundamentally enhance sensing performance by boosting mass transport and interfacial activity. It not only breaks the long-standing cross-sensitivity bottleneck of MOS gas sensors but also establishes a universal strategy for constructing single-sensor artificial olfactory systems with high precision, miniaturization, and low power consumption. While the current system shows promising performance, the impact of material stability on the long-term recognition accuracy of devices still requires comprehensive investigation and validation. Looking forward, the design principle established here can be readily extended to other metal oxides and even to applications such as pulse electrocatalysis, ion batteries, and photothermal sensing, where coupled thermodynamic and kinetic processes are critical.

In summary, this study represents a major advance in bioinspired sensing materials and nonequilibrium detection strategies, opening a new avenue toward high-performance artificial olfactory intelligence for real-world gas detection. By integrating periodic bicontinuous structures with steady nonequilibrium PH sensing technology, this work is expected to overcome the long-standing bottleneck between sensor simplicity and recognition accuracy, enabling a single sensor to achieve precise, stable, and high-accuracy discrimination of multiple gases without relying on large-scale sensor arrays. In particular, the established PH system leverages structurally enabled active mass transport and enhanced interfacial dynamics under periodic thermal modulation to establish a steady nonequilibrium sensing state, ensuring reliable performance even in complex scenarios. More importantly, the design philosophy that couples bioinspired ordered porous architectures with nonequilibrium dynamic modulation provides a versatile paradigm for next-generation high-performance intelligent sensing and catalytic materials.

DECLARATIONS

Authors' contributions

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Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

Not applicable.

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Haick, H. is an Associate Editor of the journal *Micro Nano Science*. Haick, H. was not involved in any steps of editorial processing, notably including reviewers' selection, manuscript handling, and decision making. Wu, W. declares that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

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