

High Performance Gas Sensors and Biomimetic Olfactory Systems Based on Ordered Nanotube Array Structures

Chen Wang^{1,*}, Peng Sun¹, Geyu Lu¹

¹ State Key Laboratory of Integrated Optoelectronics, College of Electronic Science and Engineering,
College of Integrated Circuits, Jilin University, 2699 Qianjin Street, Changchun, China

**email:* eechenw@jlu.edu.cn

Ordered nanotube arrays fabricated on nanoporous alumina membranes provide a versatile and scalable platform for advanced gas sensing and artificial olfaction. Benefiting from ultrahigh surface-to-volume ratios and well-defined vertical channels, these architectures enable precise material engineering and diverse device configurations. We present a series of devices exploiting this platform to address key challenges in sensitivity, selectivity, integration, and real-world applicability. First, a microheater-integrated nanotube array (MINA) sensor achieves parts-per-trillion detection of hydrogen, acetone, toluene, and formaldehyde (measured limits of detection as low as 40 ppt and theoretical ~ 7 ppt) under continuous heating. Remarkably, under pulse heating, the same single sensor discriminates multiple gases via transient conductance feature extraction, overcoming the selectivity bottleneck without sensor arrays. To achieve highly selective detection of a specific pollutant, a ZnO nanosheet catalytic filter with top-bottom electrode configuration on the nanotube array isolates the sensing layer from filter-induced electrical crosstalk. The sensor delivers a response of 815% to 1 ppm NO₂ and a theoretical detection limit of 1.86 ppb at 250 °C, while suppressing interferences and humidity.

Expanding to biomimetic systems, we monolithically integrated up to 10,000 individually addressable sensors on a single chip, mimicking the receptor diversity of biological olfactory systems. A suspended-mask sputtering method creates a 2D material composition gradient (ZnO, NiO, In₂O₃, WO₃) across the array, generating diverse response patterns. Coupled with convolutional neural networks, the chip classifies eight gases with 99.04% accuracy. It also deconvolutes binary gas mixtures with an average relative error below 8% over 3 months and distinguishes 24 distinct odors. Multi-sensor fusion by mounting an olfactory chip onto a quadruped robot dog was also demonstrated. Combining vision and olfaction, the robot identifies objects inside blind boxes—showcasing the potential in security, search-and-rescue, and smart robotics. For practical applications, a 9-array chip tailored for cold-chain food monitoring detects ammonia, ethanol, trimethylamine, and hydrogen sulfide—key spoilage markers—at ppb levels. It successfully identifies seven food types, tracks freshness over seven days, and accurately evaluates mixed food combinations, demonstrating reliable real-time performance in refrigerated environments. Meanwhile, a miniaturized olfactory chip integrated into an AI-wearable biometric ring analyses skin-emitted volatile organic compounds, classifying six dietary intakes and three physical activity statuses with over 98% accuracy, validated by gas chromatography-mass spectrometry. Collectively, our work establishes ordered nanotube arrays as a foundational technology for high-performance gas sensors and biomimetic olfactory systems, with broad implications for environmental monitoring, healthcare, food safety, and intelligent automation.

Keywords: Nanotube array; Oxide gas sensor; Selective detection; Olfactory chip; Pattern recognition

References

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