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Editorial

Toward Intelligent Gas Sensors

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Gas sensors are evolving from passive detectors into intelligent systems that integrate functional materials, device engineering and data-driven learning to interpret complex chemical environments [1]. This evolution reflects a broader transition in electronics, in which sensing, computation and decision-making are increasingly co-designed at the device and system levels. Although advances in nanomaterials and microfabrication have substantially improved sensitivity, power consumption and form factor, most gas sensors continue to operate as reactive components, delivering electrical outputs without contextual interpretation. As applications shift toward distributed, wearable and autonomous platforms, this limitation has become increasingly restrictive.

In the context of electronics, intelligence in gas sensing does not originate from materials, devices or algorithms alone, but from their tight integration [2]. Intelligent gas sensors emerge when functional materials are engineered to produce information-rich signals, device architectures are optimised for low-power operation and scalability, and data-driven methods are embedded within sensing systems. This convergence aligns gas sensing with broader developments in edge computing, Internet-of-Things (IoT) technologies and cyber–physical systems.

Materials innovation remains foundational. Nanostructured metal oxides, carbon-based materials and two-dimensional semiconductors enable control over surface states, carrier transport and interfacial charge transfer [3]. Hybrid and heterostructured materials, in particular, offer routes to tune adsorption energetics and electronic coupling simultaneously, enabling selective responses at reduced operating temperatures. Defect engineering and interface modulation further allow dynamic control over sensing characteristics. From an electronics perspective, these materials are increasingly designed not only for sensitivity but to generate distinct, reproducible signal patterns suitable for downstream data processing.

Device architecture translates material functionality into system-level performance. Flexible and wearable gas sensors enable continuous monitoring in human-centric and mobile environments, placing new constraints on mechanical robustness, power consumption and signal stability [4]. Self-heated and self-powered designs reduce reliance on external power sources, which is critical for dense sensor networks and remote deployment. Sensor arrays, analogous to electronic noses, exploit device-to-device variability to encode chemical information across multiple channels. Such architectures shift the role of the sensor from a single transducer to a front-end interface for chemical information processing.

Data-driven signal interpretation is the defining element of intelligent gas sensors. Machine learning and artificial intelligence (AI) methods enable real-time discrimination of gas species, compensation for environmental fluctuations and mitigation of sensor drift [5],[6]. From a Nature Electronics perspective, this shift is significant: sensing performance increasingly depends on how effectively hardware and algorithms are co-optimised. Rather than relying on static thresholds, intelligent sensors perform pattern recognition and probabilistic inference, allowing robust operation under non-ideal and variable conditions. This redefines selectivity as a system property rather than a purely material one.

However, embedding intelligence introduces new technical challenges. Models trained under controlled conditions often fail to generalise across devices, batches or environments, reflecting strong dependencies on fabrication variability and operating conditions [7]. Limited access to standardised datasets and benchmarking protocols further complicates reproducibility and cross-platform comparison. These challenges highlight the need for hardware-aware learning algorithms, on-chip calibration strategies and standardised evaluation frameworks that are compatible with scalable electronic manufacturing.

At the system level, intelligent gas sensors are increasingly integrated within distributed electronic architectures. Edge computing enables low-latency signal processing directly at or near the sensor, reducing data transmission overhead and energy consumption. Cloud-based infrastructures support large-scale model training, sensor-to-sensor learning and long-term performance optimisation. The emerging use of digital twins, virtual representations synchronised with physical sensors, provides a promising route for predictive maintenance and adaptive control. Together, these approaches position gas sensors as active nodes within electronic systems rather than peripheral components.

Applications highlight the importance of this systems-level perspective. In environmental monitoring, networks of intelligent sensors enable high-resolution mapping of pollutants across space and time. In healthcare, breath analysis platforms combine low-power sensors with data-driven interpretation for non-invasive diagnostics. Smart buildings and industrial automation benefit from adaptive sensing systems that respond dynamically to changing conditions. In each case, intelligence enables tighter integration between sensing hardware and electronic control systems.

Despite progress, several barriers remain to large-scale adoption. Long-term stability and device-to-device reproducibility remain major concerns for deployment in safety-critical applications. Integrating sensing, computation and power management within compact form factors requires careful trade-offs between performance and complexity. Sustainability considerations, including material selection and energy efficiency across the device lifecycle, are also becoming increasingly relevant as sensor networks scale.

Looking forward, intelligent gas sensors are likely to evolve alongside advances in neuromorphic and in-memory computing. Brain-inspired architectures may enable ultra-low-power learning directly within sensor interfaces, reducing reliance on external processors. Multimodal electronic platforms that integrate gas sensing with thermal, optical or mechanical inputs will further enhance robustness and contextual awareness. Ultimately, gas sensors may transition from passive sensing elements to autonomous electronic subsystems, capable of adaptive operation and local decision-making.

The alignment of gas sensing with modern electronics marks a decisive shift, from isolated detection toward integrated, intelligent systems. Realising this vision will require continued progress in materials engineering, device integration and hardware–algorithm co-design. For gas sensors to fully participate in future electronic ecosystems, intelligence must be treated not as an add-on, but as a core design principle.

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