

Integrated MOS Sensor Arrays: Multi-Gas Detection on A Single Chip for Environmental Monitoring

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Abstract

Recent advancements in Integrated Metal Oxide Semiconductor (MOS) sensor arrays have made them valuable technologies for advanced environmental monitoring, as they can detect multiple gases simultaneously on a single chip. Specifically, MOS sensor arrays have the potential to detect carbon monoxide (CO), nitrogen dioxide (NO₂), methane (CH₄), ammonia (NH₃), and volatile organic compounds (VOCs). Applications such as urban air quality monitoring, industrial site safety, and various smart city infrastructures can utilize multi-gas sensors. This paper examines the design, fabrication, and field deployment of multi-gas MOS sensor arrays from the perspectives of device architecture, transduction material selection, microfabrication strategies, and signal processing. The major challenges, including issues of cross-sensitivity, selectivity, drift, and size reduction, have been covered. Additionally, ways to mitigate these challenges through methods such as operational temperature modulation, temperature-assisted nanostructured materials, and machine-learning-based calibration have been discussed. This work provides a comprehensive overview of important technologies, methods, and concepts, highlighting the real capabilities of integrated MOS sensor arrays. These arrays could be utilized to create reliable, scalable, and cost-effective multi-gas sensing systems for next-generation environmental monitoring.

Keywords: Metal Oxide Semiconductor (MOS) Sensors; Multi-Gas Detection; Environmental Monitoring; Sensor Array Integration; Signal Processing and Calibration.

1. Introduction

Environmental monitoring is becoming a more critical concern with the increasing global emphasis on air pollution, climate change, and urbanization. According to the World Health Organization, nearly 91% of the world's population lives in areas that do not meet standards for safe levels of air pollution, which contributes to millions of premature deaths each year [1]. National and international legislation on acceptable limit levels of key pollutants, such as nitrogen oxides (NO₂), carbon monoxide (CO), methane (CH₄), ammonia (NH₃), and volatile organic compounds (VOCs), is growing rapidly and will undoubtedly continue to have enormous ramifications [2].

Traditional gas sensors, while effective in certain applications, are generally large and expensive and are designed to detect a single gas at a time. The limitations of traditional gas sensors prevent their potential use in integrated or real-time multi-gas monitoring applications, such as smart cities, wearable air quality monitors, disaster response systems, and industrial automation [2].

Closely related are integrated Metal Oxide Semiconductor (MOS) sensor arrays. The MOS sensor array consists of several MOS sensing elements, which are configured to detect a specific gas within the same substrate. The MOS sensor arrays essentially take advantage of the chemo-resistive properties of the doped or bare metal oxides SnO₂, ZnO, or WO₃, transforming the interaction between the gas and the respective sensing element into an electric signal [2] [3]. MEMS and CMOS fabrication techniques also fabricate these MOS sensor arrays, resulting in compact, low-cost, power-efficient, and IoT-friendly devices. The mass production and distributed sensing are facilitated by this small and module-sized format, which is useful in the concept of using sensor networks in environmental intelligence [4].

As the integration advances, several other technically challenging issues are encountered: cross-sensitivity across sensors, time dependence of the baseline, and selectivity problems in a mixed-gas atmosphere. The other limiting factor is their performance under different temperatures, humidity, and airflow conditions. Therefore, they need to be calibrated and compensated at any given environmental operating conditions [5]. To redress these disadvantages, scientists are currently in the process of integrating systems engineering intrinsic to hardware platforms with signal processing and machine-learning algorithms. The hybrid approach contributed to achieving selectivity and precision in gas detection, using thermal modulation as one of the methods, followed by PCA-based pattern recognition, and concluding with deep-learning classifiers [6]. The paper is a survey of the literature in the area of integrated MOS sensor arrays, which literally transforms the paradigm of environmental monitoring.

2. Overview of Metal Oxide Semiconductor (MOS) Gas Sensors

Due to their inexpensive nature, simplicity, and ability to interface with silicon-based microelectronics, MOS gas sensors still play an important role in contemporary environmental monitoring and industrial safety applications. They operate on the chemo-resistive sensing

principle; when gas molecules interact, the electrical resistance of a metal oxide material changes, providing real-time gas concentration measurement. Such performance depends on the material, temperature, gas flow, and humidity in the environment. Several metal oxides, such as SnO₂, ZnO, and WO₃, exhibit selective sensitivity to reducing or oxidizing gases, which can be further refined using catalytic additives (Pt, Pd, Au) or nanostructures in the sensing layer. However, the MOS sensors experience cross-sensitivity, long-term drift, and dependence on environmental conditions. Table 1 provides an overview of primary metal oxide materials, their target gases, and their advantages and limitations.

Table 1: Key Metal Oxide Semiconductor Materials and Their Gas Sensitivities

Metal Oxide	Target Gases	Advantages	Limitations
SnO ₂	CO, CH ₄ , H ₂	High sensitivity to reducing gases; stable response [1][2]	Sensitive to humidity; cross-sensitivity [2]
ZnO	Ethanol, Acetone, VOCs	Effective for VOC detection; tunable with doping [3] [4]	Limited oxidizing gas response [3][5]
WO ₃	NO ₂ , O ₃	High sensitivity to oxidizing gases; fast response [6] [7]	Requires precise temperature control [6][8]

In summary, MOS gas sensors provide a versatile and cost-effective solution for multi-gas detection, with their performance strongly influenced by the choice of metal oxide, sensor design, and operating conditions. Advances such as catalytic doping, nano-structuring, and precise thermal control have significantly improved sensitivity and selectivity, enabling deployment in diverse environmental and industrial applications. However, challenges like cross-sensitivity, baseline drift, and ecological dependencies remain critical considerations. Addressing these limitations through material engineering, advanced calibration, and signal processing strategies is essential for implementing reliable and accurate MOS sensor arrays in real-world monitoring systems.

3. Design of Integrated Sensor Arrays

Designing an integrated MOS sensor array requires careful consideration of material selection, chip architecture, thermal and electrical isolation, and signal conditioning. Unlike single-point gas sensors, arrays consist of multiple sensing elements with distinct response characteristics, enabling enhanced selectivity when combined with multivariate data analysis or machine learning algorithms. Proper design ensures reliable, real-time multi-gas detection in complex environmental conditions.

3.1. Chip-level architecture

An integrated MOS sensor array combines multiple sensing sites on a single chip to achieve simultaneous multi-gas detection. Each sensing site typically includes:

- Sensing Layer: Composed of metal oxide semiconductors such as SnO₂, ZnO, or TiO₂, either in pure form or doped with catalytic elements (Pt, Pd, Au, or rare-earth metals) to improve selectivity and response kinetics. Nano-structuring (nanowires, nanorods, or porous films) increases surface area, enhancing sensitivity and response speed.
- Localized Micro-Heater: Embedded beneath the sensing layer for precise thermal modulation, enhancing reaction rates and reducing baseline drift. MEMS-compatible materials like polysilicon or platinum allow high precision with low power consumption.
- Signal Conditioning Circuitry: Includes transimpedance amplifiers to convert resistance changes into voltage, ADCs for digital processing, and optional temperature and humidity sensors for environmental compensation. Some designs integrate multiplexers, noise filters, and reference electrodes for improved accuracy and drift mitigation.

This architecture enables high-density integration, energy efficiency, and reliable multi-gas detection in compact form factors [3][4].

3.2. Sensing material diversification

A variety of sensing materials is used to prepare a selective and reliable multi-gas detector. Despite the varying responses of various MOS materials, CO, CH₄, NO₂, and TiO₂ are highly responsive to SnO₂, ZnO, and TiO₂, respectively. A spoofing array can include several materials stacked so that each sensing element will react to a standard gas mixture with its own fingerprint. Such nano-structuring of the surfaces of sensing layers by introducing interference approaches can include nanowire, nanorod, or porous film methods. These methods are passive in nature regarding their action, coupled with nanostructured layers and spin. In addition to the positive influence of addition, interacting with doped-base MOS materials, especially catalytic metals like Pt, Pd, Au, or rare-earth metals, enhances adsorption kinetics, operating temperatures, and, above all, selectivities, which are required to sense trace levels of certain gases in the complex environmental conditions.

The spatial configuration of these different materials also has a more significant implication for the final output of the sensors. Sensing elements can be organized in a regular pattern or randomly to prevent cross-sensitivity and to display a more extensive repertoire of response patterns. Such variation allows the existence of an operational fingerprinting system where alternative response patterns can be subjected to machine learning algorithms, such as PCA, SVM, or neural networks. Thus, real-time measurement of numerous gases with built-in arrays of MOS sensors can provide scalable and flexible solutions for monitoring a broad spectrum of industrial, urban, and indoor environments.

3.3. Layout considerations

The layout requirements aim to ensure superior sensing capabilities while minimizing interference:

- Thermal Isolation: Micro-heaters can be separated or otherwise thermally isolated with respect to each other, such that there is no crosstalk between adjacent sensing elements, and each location operates independently.
- Electrical Isolation: Shielding or cable routing schemes may be used to provide electrical isolation against noise.
- Compact Integration: Layouts have to be high-density to provide as many sensing locations as possible without compromising their manufacturability and performance.
- Environmental Compensation: Compensation adjustments may be made in real time to sensor output in conjunction with a few basic environmental sensors, like temperature or humidity.

The same cross-sectional architecture also exhibits the basic design principles underlying an integrated MOS sensor array, showing the micro-heaters, sensing elements, and signal-conditioning circuits crowded into an extremely optimal design. Figure 1 presents a more

detailed view of the integrated cross-sectional architecture of the MOS sensor array, which includes built-in micro-heaters and sensing elements.

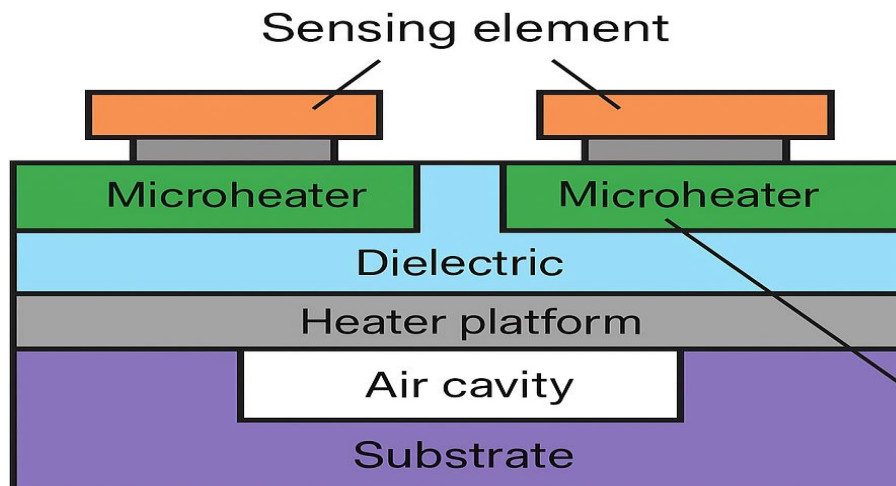


Fig. 1: Cross-Sectional Architecture of An Integrated MOS.

4. Fabrication Techniques

The production of integrated MOS sensor arrays, therefore, attracts materials science, MEMS engineering, and semiconductor device production to constitute a single multidisciplinary discipline. The performance of the sensors is highly accurate and reproducible; therefore, caution must be exercised regarding deposition procedures, material morphology, thermal processing, and secondary electronics. Even more sophisticated fabrication techniques are required to provide a sensor that has a very high sensitivity, a rapid response, and long-term stability, and can combine multiple independent sensor elements on a single chip [9][10].

4.1. Substrate and deposition

Most MOSFET sensors are made on silicon wafers for mechanical stability, thermal conductivity, and CMOS backend process compatibility; the sensing layer is basically deposited by thin film technology from metal oxide semiconductors such as SnO_2 , ZnO , WO_3 , etc. [9].

- Sol-Gel Processing: A precursor solution is spin-coated onto the substrate, followed by thermal annealing to produce a porous oxide film with controlled morphology and dopant distribution [11].
- RF Sputtering: Atoms are ejected from the target material by plasma for uniform deposition and strong adhesion of the film to the substrate [12].
- Chemical Vapor Deposition: Uses gaseous precursors to make conformal films over complex surfaces so that production can be scaled and doped films synthesized at high temperature [12].

The nano-structuring of the metal oxide layer into nanorods, nanotubes, or hierarchical porous networks further enhances the adsorption of gases, maximizes sensitivity, and lowers operating temperatures [13].

4.2. MEMS integration

Membrane-based microheaters locally heat the sensing layer without significantly increasing the temperature of the entire chip. Microheaters are formed by patterning and etching a layer of polysilicon or platinum using lithography techniques. Suspended membrane arrangements are usually employed to thermally isolate the sensing region from the substrate to minimize power consumption [14].

MEMS integrations allow extremely fast thermal cycling, which is critical for dynamic modulation techniques to enhance multi-gas discrimination. Furthermore, MEMS-based architectures allow for compact packaging and incorporation of ancillary sensors, such as temperature and humidity sensors, for added performance [10] [14].

4.3. Packaging

The casing of MOS sensor arrays forms the basis of shielding the device, offering a homogenous environment for sensing flue gas and providing a potential means to integrate the sensor into a working environment. Therefore, an effective package should allow not only sound diffusion of gases to the sensing layer but also ensure that the sensor is not subjected to moisture, dust, and particulate contamination [15].

The sensor enclosure materials include ceramics, polymers, metal frames, or a combination of these, chosen based on their suitability in terms of thermal conductivity, chemical inertness, and mechanical strength [15]. The more ornate packaging plans will also focus on thermal management, ensuring that the heat produced by microheaters is not wasted or dissipated into the package unnecessarily, and on signal integrity by minimizing EMI due to poor grounding and shielding. The inlet of the generator gas and diffusion path are so constructed that there is no dead zone, and all sensing elements are exposed equally [16] [17]. Other auxiliary sensors can also be incorporated into the package to enable on-chip temperature and humidity compensation, enhancing the overall reliability of the multi-gas measurements [18].

Table 2: Packaging Considerations for Integrated MOS Sensor Arrays

Aspect	Material / Technique	Function / Role
Gas access	Perforated ceramic or polymer caps	Ensures efficient gas diffusion to the sensing layer
Moisture/dust protection	Hydrophobic coatings, filters	Protects the sensor from environmental contaminants
Thermal management	Low thermal conductivity substrates, MEMS membranes	Limits heat loss, maintains microheater efficiency
Electrical isolation & EMI shielding	Metal or polymer enclosures with shielding	Maintains signal integrity and reduces noise
Integration of ancillary sensors	Embedded temperature/humidity sensors	Enables real-time compensation and improves measurement reliability
Mechanical stability	Ceramic or metal frame	Prevents mechanical stress and ensures longevity

5. Calibration and Signal Processing

The effectiveness of an MOS sensor array depends significantly on the quality of its calibration and data processing strategy. Due to the non-linear and overlapping response characteristics of MOS sensors, traditional univariate calibration methods are insufficient. Instead, multi-dimensional pattern recognition and machine learning techniques are required to extract gas-specific information accurately from complex sensor responses [5].

5.1. Baseline correction

Signal drift concerning MOS sensors is caused by factors such as extended usage, humidity, and temperature variations. To correct for expiring signals, baseline correction techniques like zero-gas reference and adaptive filtering are occasionally used to maintain signal quality. Automated environmental compensation with embedded systems can be established with a feedback loop.

5.2. Cross-sensitivity mitigation

One challenge of multisensor sensing is cross-sensitivity, meaning a sensor designed to detect one gas may respond to another. Cross-sensitivity decreases the specificity and can cause false positives. To deal with this, statistical tools such as -

- Principal Component Analysis (PCA),
- Independent Component Analysis (ICA), or
- Linear Discriminant Analysis (LDA)

are used to transform the multidimensional sensor data into orthogonal axes, making the gas signatures more easily discernible [5]. Such techniques are typically deployed within firmware or in cloud analytics platforms.

6. Thermal Modulation Techniques

MOS sensor arrays apply thermal modulation methods to increase their selectivity to gases and to eliminate overlapping response profiles. The sensing element temperature is dynamically adjusted to switch between the surface reaction kinetics of different gases. In addition, unlike the reaction rates and activation energies, each gas-MOS material pair has different reaction rates; therefore, the sensor array can generate different temporal patterns for each gas species through temperature modulation [6].

6.1. Modulation strategies

There are important thermal modulation waveforms:

- Sinusoidal modulation: The gradual changes in temperature between gases with similar kinetics are useful to differentiate.
- Triangular/step changes: These sudden changes lead to special response changes of certain gases.
- Pulse heating: one approach to resetting the sensor state is by desorbing surface-bound species using short pulse energy at elevated temperatures.

MEMS-based microheaters built directly under each sensing element could be designed to generate such waveforms. An appropriate waveform would be chosen and optimized based on an anticipated gas mixture and power limit.

6.2. Feature extraction from thermal profiles

As the temperature of the micro-heater cycles, the resistance of each MOS sensing element varies dynamically in a gas-dependent manner. This temperature-modulated response enhances selectivity by exploiting the different reaction kinetics of various gases with the metal oxide surface. From the time-resolved resistance profile, several key features can be extracted for further analysis:

- Peak Response at Each Temperature: The maximum change in resistance during each temperature plateau, which reflects the sensitivity of the sensor to specific gases at particular temperatures.
- Time to Reach Equilibrium: The duration required for the sensor to stabilize after a step change in temperature or gas exposure, providing information about adsorption/desorption dynamics.
- Area Under the Response Curve (AUC): Integrates the resistance change over time, capturing the overall interaction strength between gas molecules and the sensing surface.
- Derivatives and Hysteresis Characteristics: First and higher-order derivatives highlight the rate of response. In contrast, hysteresis patterns (differences between heating and cooling cycles) provide additional discriminatory information for complex gas mixtures.

These extracted features are then used as input for dimensionality reduction techniques, such as Principal Component Analysis (PCA), to reduce feature space while preserving variance, or fed directly into classification algorithms (e.g., Support Vector Machines, Random Forests, or Neural Networks) for real-time gas identification and quantification. By combining temperature modulation with advanced feature extraction, MOS sensor arrays achieve robust multi-gas detection with enhanced selectivity, even in the presence of interfering compounds.

6.3. Benefits and trade-offs

Thermal modulation essentially provides the selectivity of MOS sensors without physically modifying the sensing material. A single multi-sensor can perform the functions of multiple virtual sensors. These sensors can operate under different conditions by simply changing the temperature of the micro-heater, increasing array diversity and reducing the need for material doping or multi-layered sensing requirements. The improvement is accompanied by better discrimination between gases with overlapping sensor response profiles and an enhanced ability to detect multiple gases. Recent design research is refining microheater design, introducing feedback-based thermal control, and leveraging state-of-the-art machine learning models such as RNNs to obtain dynamic temporal structures in the modulated signal, which enhances classification performance [6]. Figure 2 shows the Sensor response curves to several thermal modulation profiles of CH₄ and NO₂. The figure demonstrates that temperature cycling presents specific resistance patterns per gas that can be applied to elevate selectivity and virtually multiplex the sensor.

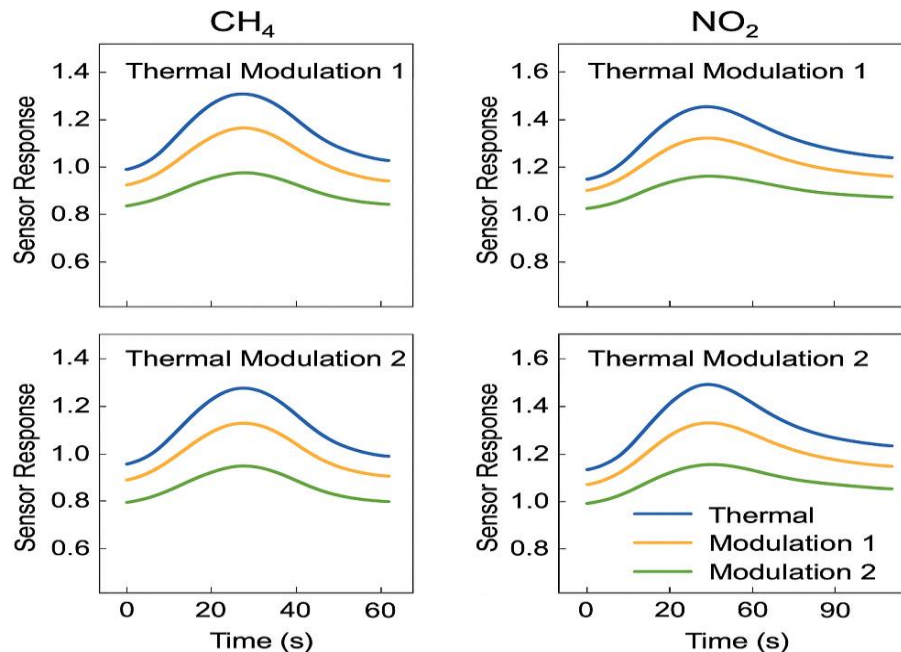


Fig. 2: Sensor Response Curves at Different Thermal Modulation Profiles for CH₄ and NO₂

7. Power management and low-power operation

Power consumption is a critical consideration for the deployment of MOS sensor arrays in battery-operated or energy-harvested platforms. Since these sensors often require high operating temperatures (200–400°C) for effective gas detection, achieving energy-efficient operation is essential for ensuring long-term performance, portability, and feasibility in IoT and wearable applications.

7.1. Microheater optimization

Integrated microheaters are the primary contributors to power consumption. Several design strategies can improve power efficiency.

- Suspended MEMS membranes thermally isolate the heater from the bulk substrate, minimizing heat loss.
- Low thermal mass materials, such as polycrystalline silicon or platinum, allow rapid heating and cooling with reduced energy expenditure.
- Pulsed or duty-cycled operation, where the heater is activated only during sampling intervals, further reduces average power consumption without compromising sensor performance.

7.2. Circuit-level design enhancements

Power-efficient circuit design complements microheater optimization. Techniques include:

- Ultra-low-power CMOS amplifiers utilize sleep modes to reduce energy consumption during idle periods.
- Time-multiplexed sensing reduces simultaneous power draw by activating only one sensor at a time.
- Embedded power management units (PMUs) dynamically scale voltage and frequency to balance energy consumption with performance requirements.

7.3. Energy harvesting and autonomous operation

Ambient energy harvesting techniques can be harnessed to enable long-term, battery-free deployment of an MOS sensor array. Solar PV cells convert sunlight into electrical energy and can be a reliable source of power for outdoor monitoring stations. RF scavengers harvest energy from ambient electromagnetic fields present in Wi-Fi, cellular, and broadcasting signals. In contrast, piezoelectric generators convert the mechanical vibrations of machinery, human motion, or environmental sources into power. Together with duty-cycled microheater usage and low-power circuit designs, energy harvesting enables a whole sensor node to operate independently with an average power below 50 μ W, thus making long-term deployment at remote locations, wearable devices, or IoT networks feasible without frequent battery replacement or maintenance, which seriously enhances the portability and sustainability of such sensors [4][6].

7.4. Smart wake-up strategies

Such smart waking strategies enable the system to be in low-power modes most of the time, awakening the sensor array only when needed. The system could be activated upon the occurrence of a threshold, whether it's a sudden increase in gas concentrations, uncharacteristic environmental trends, or harmful compounds. It could also self-wake at periodic intervals for routine checks. Other possible wake-up triggers would be, for example, movement, temperature change assessment, or wireless provocation by a user. Together with low-power microheater control and energy harvesting, such an adaptive waking scheme would make operation of the whole MOS sensor array very energy-friendly and autonomous, yet always ready to immediately pick up on risky environmental instances.

8. Application Domains

The versatility of the integrated MOS sensor arrays has resulted in their application in various fields where a small, real-time, multi-gas sensor facility is required. Their flexibility, low cost, and simple integration into digital systems mean they are deployed as a myriad of monitoring networks across various scales, in wearable devices, and embedded in intelligent infrastructure. These sensor arrays expand the limits of information access in environmental science, industrial health and safety, health care, and agricultural enhancement, and are interdisciplinary in use in health, safety, and operational efficiency. Table 3 provides an overview of the areas of use, the types of gases to be monitored, and the applications.

Table 3: Application Domains of Integrated MOS Sensor Arrays

Domain	Key Applications	Target Gases	Deployment Examples
Urban Air Quality Monitoring	Smart city air surveillance, pollution source mapping	NO ₂ , O ₃ , CO, VOCs	Embedded in streetlights, bus stops, mobile monitoring vehicles [19][20]
Industrial Safety & Process Monitoring	Gas leak detection, process control	H ₂ S, CH ₄ , NH ₃	Oil refineries, chemical plants, manufacturing units [21]
Indoor Air Quality in Smart Buildings	HVAC-based real-time monitoring, pollutant control	Formaldehyde, benzene, VOCs	Integrated into building management systems, offices, and residential spaces [22]
Agriculture & Livestock Environments	Crop storage optimization, livestock health monitoring	Ethylene, NH ₃ , CO ₂	Greenhouses, barns, remote LPWAN-connected sensor nodes [23]
Healthcare & Personal Safety	Wearable exposure monitoring, breath analysis	VOCs, allergens	Smart bands, masks, hospital, and elderly care environments [24]
Disaster Response & Military	Air safety assessment post-disaster, chemical agent detection	CO, toxic gases, chemical warfare agents	Portable sensor kits, enclosed military habitats [25]

As shown in Table 3, integrated MOS sensor arrays offer multi-gas detection capabilities across diverse sectors, supporting real-time monitoring, safety assurance, environmental management, and healthcare applications.

9. Case Studies and Deployments

Integrated MOS sensor arrays in real-time applications provide a snapshot of the actual performance, robustness, and applicability of sensor systems across various environmental domains. The case studies provide examples of the potential for practical application in urban settings, personal use, and emergency response issues, and list specific benefits and an array of performance parameters, including selectivity, response time, detection limits, stability, and the absence or presence of compensation for environmental parameters.

9.1. Smart city implementations

Transport Canada commissioned a network of low-cost air quality monitoring nodes with integrated MOS sensor arrays for use in New Delhi, aiming to obtain paired street-level detail with satellite imaging and traditional monitoring sites. The monitoring nodes used Wi-Fi and low-power wide-area networks (LPWAN) for connectivity, while cloud-based machine learning algorithms were used for sensor calibration and predictions [17].

9.2. Wearable sensors

MOS sensor arrays have been integrated into wearable health devices, smart bands, and patches that can continually monitor exposure to gases such as NO₂, VOC, and ozone in urban settings [18]. In one pilot project on a university campus, participants wore wristbands with ZnO and SnO₂ sensors to help define the location of the primary pollutants. The data was paired with students' smartphones, which provided real-time alerts when exposure increased as well as logging previous exposures, providing usable and participative air quality monitoring [19].

9.3. Emergency response kits

The use of portable MOS sensor-based kits by emergency response teams for in-situ diagnosis has gained attention at earthquake-prone or industrial-accident sites in recent times. A European defense consortium created a foldable system based on a microcontroller and SnO₂ and WO₃ sensors to detect multiple gases, CO, CH₄, and NH₃, and it was deployed in 10 seconds. They were also challenged by simulated chemical spills to test their quick detection limits, as well as their capacity to behave reliably in the field [20].

All these case studies demonstrate the range of applications that integrated MOS sensor arrays can offer, from infrastructure-scale sensing to wearable personal exposure determination and rapid-enabled emergency response. The performance characterization of deployments is often based on selectivity indices, response and recovery times, limit of detection, long-term stability, temperature compensation styles, and humidity compensation styles to assure sound real-world performance [22], [23].

10. Performance Metrics and Evaluation

An evaluation of the integrated MOS sensor array's performance in the real world uses critical parameters to define accuracy, response, stability, and robustness to the environment. Such metrics must be used to benchmark the reliability of the sensor for applications from urban air quality monitoring to wearable and emergency-response systems.

10.1. Selectivity index

Selectivity is a measure of the capacity of the sensor to identify a target gas among other competing species. It is generally measured relative to the sensor response to the target gas at the same environmental conditions as the possible interferents. An extensive selectivity index implies a higher discrimination and a low chance of false positives, which is especially relevant to complex multi-gas settings [2].

10.2. Response and recovery time

Response time is defined as the time it takes the sensor to reach 90 percent of its final signal response after the sensor is exposed to a target gas, and recovery time is the time it takes for the sensor to stabilize at its baseline after the gas has been removed. Both emergency gas detection and mobile environmental surveillance are real-time monitoring requirement applications that need rapid response and recovery.

10.3. Limit of detection (LOD)

The limit of detection LOD is the minimum level of a target gas that can be distinguished with confidence over the baseline noise. Sub-ppm LODs are frequently necessary where hazardous respiratory gases, like formaldehyde and NO₂, are concerned. Some of the factors within the LOD include the sensing layer thickness, the microheater temperature control, and signal amplification circuitry design [1][5].

10.4. Long-term stability

Long-term stability evaluates the drift in baseline resistance and sensitivity over extended operation, particularly under continuous exposure to environmental variations. The performance of the sensing layer is enhanced through careful material selection, encapsulation techniques, periodic recalibration, and controlled ageing [6].

10.5. Temperature and humidity compensation efficiency

MOS sensors are inherently sensitive to environmental conditions, particularly temperature and humidity. Compensation efficiency is measured by comparing sensor outputs with and without correction algorithms across a range of environmental conditions. Integration of humidity and temperature sensors, combined with data-driven approaches such as machine learning models, significantly improves compensation accuracy and ensures reliable gas detection in real-world scenarios [7].

11. Challenges and Limitations

Despite their demonstrated versatility, integrated MOS sensor arrays face several technical and operational challenges that must be addressed to ensure long-term reliability and accuracy in real-world deployments. Key limitations arise from material degradation, environmental interferences, calibration complexity, power constraints, and inherent variability among sensors. Understanding these challenges is critical for designing robust sensor systems and implementing adequate compensation and adaptation strategies. Table 4 summarizes the main difficulties, their underlying causes, and potential mitigation approaches.

Table 4: Key Challenges and Limitations of Integrated MOS Sensor Arrays

Challenge	Description	Potential Mitigation
Sensor Drift and Aging	Baseline resistance and sensitivity drift due to grain coarsening, surface contamination, or prolonged exposure to reactive gases	Regular calibration, aging-resilient coatings, and material optimization [12]
Cross-Sensitivity and Interference	Overlapping responses from similar gases or humidity, complicating gas discrimination	Thermal modulation, algorithmic compensation, hybrid sensor integration [15]
Calibration Complexity	Multi-gas calibration requires extensive datasets across varying conditions.	Transfer learning, federated learning, automated calibration protocols [16]
Power and Thermal Management	High power demand from MEMS heaters and thermal crosstalk between sensors	Low-power heater design, thermal isolation strategies, duty-cycling, energy harvesting [14]
Device-to-Device Variability	Differences in material deposition, packaging, or operating conditions leading to inconsistent responses	Sensor-specific calibration, adaptive machine learning models [11][17]
Limited Selectivity Without Post-Processing	Intrinsic material limitations reduce discrimination in complex gas mixtures.	Advanced signal processing, complementary sensing modalities (electrochemical, optical) [18]

Addressing these challenges requires an interdisciplinary approach that integrates advances in nanomaterials, MEMS fabrication, low-power electronics, signal processing, and machine learning to develop reliable, scalable, and robust MOS sensor platforms suitable for the next generation of environmental monitoring.

12. Future Directions

The next generation of integrated MOS sensor arrays is expected to evolve along multiple synergistic fronts to address existing limitations and meet emerging application requirements. Key areas of advancement include hybrid sensor fusion, embedded AI and edge computing, digital twin modeling, flexible and printable sensor technologies, federated and transfer learning for smart deployment, and integration into real-time environmental intelligence systems. Collectively, these innovations aim to enhance selectivity, sensitivity, scalability, and

autonomous operation, enabling MOS sensor arrays to play a central role in smart cities, healthcare, industrial safety, agriculture, and environmental monitoring. Table 5 provides a concise summary of these future directions, highlighting their features and potential impact.

Table 5: Future Directions for Integrated MOS Sensor Arrays

Future Direction	Key Features	Potential Impact
Hybrid Sensor Fusion	Integration of MOS with electrochemical, PID, or infrared sensors	Improved selectivity and classification of complex gas mixtures [13]
Embedded AI & Edge Computing	On-device inference using TinyML or Edge Impulse	Real-time decision-making with reduced latency and power consumption [16]
Digital Twins	Virtual modeling of sensor behavior under varying conditions	Accelerated design, remote calibration, predictive maintenance [14]
Printable & Flexible Sensor Arrays	Fabrication on PET/polyimide using inkjet or screen printing	Conformable, low-cost, large-area deployment in wearable, packaging, or building-integrated sensors [23]
Federated & Transfer Learning	Collaborative model training and adaptation across sensors	Enhanced privacy, reduced communication overhead, scalable deployment [24]
Real-Time Environmental Intelligence Systems	Integration with meteorological and geographic analytics	Actionable insights for disaster response, urban planning, public health, and climate research [25]

These future directions underscore the interdisciplinary evolution of MOS sensor arrays, combining advances in materials science, electronics, AI, and environmental monitoring to create more intelligent, autonomous, and widely deployable sensing platforms.

13. Conclusion

IMOS sensor arrays are becoming one of the new technologies of real-time multi-gas environment monitoring. Scalable, low-cost single-chip sensing enables applications for smart cities, industrial automation, agriculture, healthcare, and disaster response. The authors of this paper presented the architecture, material, fabrication, calibration, power management, and signal processing of the built-in MOS sensor arrays with some advantages, such as selectivity, miniaturization, and cost-efficiency, and some disadvantages, such as drift, cross-sensitivity, and complicated calibration. Thermal modulation, machine learning, and embedded AI have now reached a stage of sufficient maturity to offer this high degree of intelligence and responsiveness to real-world applications like wearable devices and urban monitoring networks. The current capabilities expansions may be viewed as the solution to the flexible electronics, digital twins, and federated learning of the future. With the further development of the science of fabrication and the increased integration of interdisciplinary activities, integrated MOS sensor arrays will soon become an essential instrument to support environmental resilience, human well-being, and data-based urban planning to enable intelligent, informed governance.

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