



Low-Power Gas Sensors: Advances, Challenges, and Future Prospect

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Abstract:

‘Gas sensor is a device that primarily used to detect the presence of specific gases and concentration of gases across an area.’ Gas sensors play important roles in various sectors, which include industry, safety systems, medical and health care applications, environmental applications, and domestic applications for monitoring toxic and flammable gases. The power supply in gas sensors is essential for their operation, as it enables the detection and measurement of target gases. The specific need for a power supply depends on the type of gas sensor and its working principle. High-power gas sensors are suitable for applications requiring high sensitivity and continuous monitoring in fixed installations. Low-power gas sensors are ideal for portable, battery-operated, and energy-efficient applications. The choice between the two depends on the specific application. Low-power gas sensors are essential for various modern applications where energy efficiency, portability, and long-term operation are crucial. By implementing strategies like Material innovations, MEMS-based miniaturization, power management strategies, AI and Edge Computing for Smart Data Processing, energy harvesting and use of alternative sensing techniques, next-generation gas sensors can operate efficiently for various applications. This paper explores the fundamental principles of low-power gas sensing, recent developments in sensor architectures and materials, and highlights strategies to minimize energy consumption and future directions for low-power gas sensors.

Keywords: *Gas sensor, High-power gas sensors, Low-power gas sensors, MEMS, Artificial intelligence (AI), sensor architectures.*

Introduction:

Gas Sensors are specially designed to ensure a safety system, detecting hazardous gases, monitoring air quality, and enabling health diagnostics. Gas Sensors can detect gases like oxygen, carbon dioxide, many combustible, flammable and toxic gases. **‘Gas sensor is a device that primarily used to detect the presence of specific gases and concentration of gases across an area.’** Gas sensors play important roles in various sectors, which include industry, safety systems, medical and health care applications, environmental applications, and domestic applications for monitoring toxic and flammable gases. Conventional gas sensors, such as metal

oxide semiconductor (MOS) and electrochemical sensors often require significant power, limiting their suitability and applications for battery-operated or wireless applications. They require optimization to reduce energy consumption. With the increasing demand for energy-efficient and autonomous sensing systems, the development of low-power gas sensors has become a priority

The power supply in gas sensors is essential for their operation, as it enables the detection and measurement of target gases. The specific need for a power supply depends on the type of gas sensor and its working principle. Gas sensors require a stable and efficient power supply for reliable

operation. The power requirements vary based on the sensor type. A power supply is needed in Metal Oxide Sensors to heat the sensing element to the required temperature. Catalytic Bead Sensors rely on a heated catalyst to oxidize gases, requiring a constant power supply. In Optical Gas Sensors a power supply is required to operate the light source and photo detectors. A power supply is needed to amplify and process weak electrical signals for accurate measurement. Power supply is required for Data Transmission and Communication. Wireless gas sensors require power to transmit data to a central system or cloud. In modern gas sensors components like microcontrollers or embedded systems require a stable power supply to function. Some gas sensors require periodic calibration or self-diagnostic routines, which consume power. Many gas sensors include additional sensors (e.g., temperature, humidity) to compensate for environmental effects. These auxiliary sensors also require power. Even in low-power gas sensors, a minimal power supply is needed to support sleep modes, wake-up cycles, and intermittent operation. In some cases, gas

sensors are powered by energy harvesting systems (e.g., solar, thermal, or vibration energy). These systems still require a power management unit to store and regulate energy. Power supply design is crucial for optimizing energy efficiency and extending sensor lifespan. High-Power sensors (e.g., Metal Oxide Sensors - MOS) are typically powered by DC sources (batteries, adapters). Low-Power Sensors (e.g., Graphene, CNT, Conducting Polymers, MEMS-based Sensors) use energy-efficient circuits, duty cycling, and edge computing to conserve power. In conclusion, the power supply is a fundamental requirement for gas sensors, enabling their core functionality, signal processing, and communication. High-power gas sensors are suitable for applications requiring high sensitivity and continuous monitoring in fixed installations. Low-power gas sensors are ideal for portable, battery-operated, and energy-efficient applications. The choice between the two depends on the specific application. Following table gives the comparison and advantages of low power gas sensors over high power gas sensors.

S.N.	Aspect	High-Power Gas Sensors	Low-Power Gas Sensors
1	Power Consumption	High power consumption.	Low power consumption.
2	Operating Temperature	High temperatures.	Room temperature or low heating.
3	Heating Requirements	Requires continuous heating.	Minimal or no heating required.
4	Sensitivity	High sensitivity.	Moderate to high sensitivity.
5	Response Time	Fast response.	Slightly slower response.
6	Lifespan	Shorter lifespan.	Longer lifespan.
7	Portability	Bulky and less portable.	Compact and portable.
8	Cost	Higher operational costs.	Lower operational costs.
9	Maintenance	Frequent maintenance.	Low maintenance.
10	Energy Source	Requires constant power supply.	Can operate on batteries or energy harvesting
11	Environmental Impact	Higher carbon footprint	Environmentally friendly.
12	Integration	Difficult to integrate into small or portable systems	Easily integrated into IoT, wearables, and smart devices.
13	Duty Cycling	Limited or no duty cycling	Supports duty cycling and sleep modes for energy savings.

Need for Low-Power Gas Sensors:

Low-power gas sensors are essential for various modern applications where energy efficiency, portability, and long-term operation are crucial. The need for these sensors arises due to several key factors like IoT and Wireless Sensor Networks (WSNs) require energy-efficient sensors that can operate on battery power or energy harvesting which are used for environmental monitoring in smart cities, homes, and industries. Portable gas detectors, Wearable sensors and medical devices like breath analysis sensors operate efficiently with limited energy sources and minimal power consumption for extended battery life. In remote locations like oil rigs, factories, mines low power consumption allows sensors for long-term deployment without frequent battery replacement. Sensors powered by solar energy or energy harvesting techniques in smart Agriculture and Greenhouse Monitoring can operate autonomously. Low-power sensors enhance survivability in extreme and remote conditions and operate for long durations with limited power sources. Reducing power consumption lowers operational costs and minimizing heating requirements reduces overall energy demand in industrial applications. Lower energy consumption and Self-powered gas sensors contribute to reduced carbon footprint and sustainable energy usage. The need for low-power gas sensors is driven by their ability to operate efficiently in IoT, medical, industrial, environmental, and defense applications. By optimizing power consumption, these sensors enable long-term, sustainable, and cost-effective gas monitoring in various sectors.

Strategies for Reducing Power Consumption:

Reducing power consumption in gas sensors is critical for applications such as

IoT, portable devices, and environmental monitoring. Various techniques have been explored to develop energy-efficient gas sensors, including:

Material Innovations: Use of nanomaterials such as metal oxide nanostructures, graphene, MXenes, and transition metal dichalcogenides (TMDs) enable gas sensing at room temperature, improve sensitivity at lower operating temperatures reducing energy requirements. Response time and efficiency of gas sensor can be improved by Nanowire based sensing elements. Hybrid and composite materials can be used to enhance selectivity and reduce power requirements. Metal-Organic Frameworks (MOFs) have tunable porosity and high gas adsorption capabilities which improve selectivity and enable operation at lower power levels.

MEMS-Based Miniaturization: Microelectromechanical systems (MEMS) technology helps to create miniaturized sensors. Heating elements enables localized heating, reduces reduced operating temperatures and reducing overall power consumption. Thin-film sensors use low-power deposition techniques to reduce energy needs.

Power Management Techniques: Intermittent operation and duty cycling significantly reduce power consumption by activating sensors only when necessary. Instead of continuous sensing, operating the sensor in short bursts can reduce average power consumption. Use of low power microcontrollers and energy-efficient analog-to-digital converters reduces energy consumption. Based on changing environmental conditions temperature Modulation can be done to adjust the heating profile

Self-Powered and Energy Harvesting Sensors: Technologies such as thermoelectric, piezoelectric, and photovoltaic energy harvesting support self-

sustaining gas sensors. Triboelectric nanogenerators and biofuel cells offer alternative power sources for sensor operation. Combining gas sensing with solar cells gives better option.

AI and Edge Computing for Smart Data Processing: AI-based signal processing improves accuracy and compensates for lower power operation. Edge computing minimizes continuous data transmission. Edge computing reduces wireless transmission power by processing data locally rather than sending it to a cloud server. Artificial Intelligence (AI) plays a transformative role in sensor operation, data processing, and system management. Adaptive Sensing and Duty Cycling, Predictive Maintenance and Calibration, Context-Aware Sensing, Compressive Sensing, AI-Based Power Scaling, Edge AI Processing, Temperature Modulation, Smart Data Transmission, Protocol Optimization, Fault Detection and Energy Recovery, Multi-Sensor Fusion and Selective Activation, Machine Learning for Material Optimization, Anomaly Detection and Event-Driven Sensing etc are applications of AI in low power gas sensors.

Alternative Low-Power Sensing Mechanisms: Instead of conventional MOS or electrochemical sensors, alternative mechanisms such as Optical Sensors, FET-Based Sensors etc can be used. Plasmonic and infrared-based sensors, operate at room temperature with low-power light sources and FET-Based Sensors use semiconductor technology for ultra-low-power gas sensing. Bio-Inspired Sensors mimic biological olfactory receptors, improving efficiency.

Conclusion:

Low-power gas sensors are essential for applications ranging from environmental monitoring, industrial safety, healthcare, and smart technologies. Reducing power consumption in gas sensors requires a multi-faceted approach. By implementing

strategies like Material innovations, MEMS-based miniaturization, power management strategies, AI and Edge Computing for Smart Data Processing, energy harvesting and use of alternative sensing techniques, next-generation gas sensors can operate efficiently for various applications. These strategies have paved the way for more energy-efficient and high-performance sensors. This paper explores the fundamental principles of low-power gas sensing, recent developments in sensor architectures and materials, and highlights strategies to minimize energy consumption and future directions for low-power gas sensors.

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