

Lecture 13 “Nanomaterial-based sensors and analytical systems”

Goal of the lecture: To study the principles, structure, and operation of nanomaterial-based sensors and analytical systems, understand how nanomaterials enhance sensitivity and selectivity, and explore their applications in environmental monitoring, medicine, and modern analytical chemistry.

Brief lecture notes (text format): Recent advances in **nanotechnology** have revolutionized analytical chemistry by introducing **nanomaterial-based sensors**, which use nanoscale materials such as metal nanoparticles, carbon nanotubes, and graphene to detect chemical or biological substances with extremely high precision. A **sensor** is a device that converts a chemical, physical, or biological response into a measurable signal. When nanomaterials are incorporated, the resulting sensors exhibit improved **sensitivity**, **selectivity**, **response time**, and **stability** due to their unique electrical, optical, and catalytic properties. Nanomaterials' extremely large **surface area-to-volume ratio** allows more active sites for reactions, adsorption, or electron transfer, making them ideal for use in **analytical systems**.

1. Basic Components of a Sensor

A typical sensor system consists of three main parts:

1. **Receptor (Recognition element):** Interacts selectively with the analyte (e.g., enzyme, antibody, nanomaterial surface).
2. **Transducer:** Converts the chemical interaction into a measurable signal (electrical, optical, or thermal).
3. **Signal processor:** Amplifies, processes, and displays the signal.

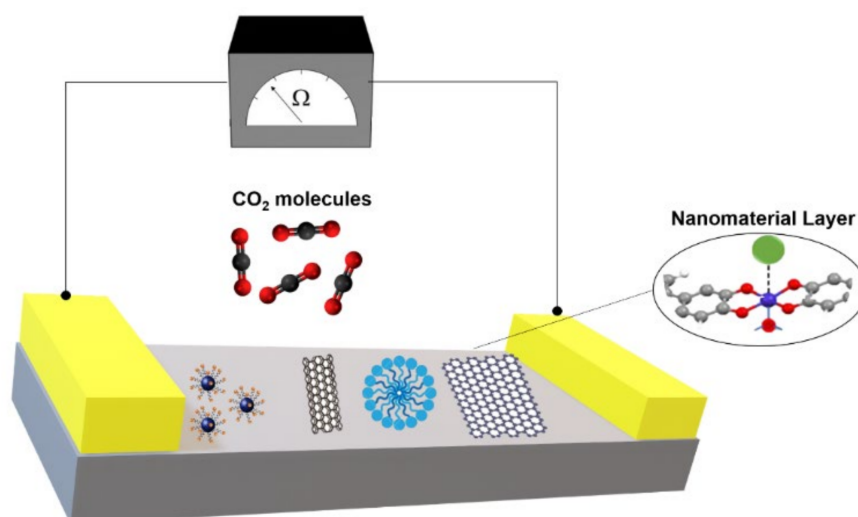


Figure 1 – General structure of a nanomaterial-based sensor (Nanomaterial-Based CO2 Sensors)

2. Types of Nanomaterials Used in Sensors

Type of Nanomaterial	Example	Key Property	Application
Metal nanoparticles	Au, Ag, Pt, Pd	Surface plasmon resonance, high conductivity	Optical and electrochemical sensors
Metal oxides	TiO ₂ , ZnO, SnO ₂	Semiconducting behavior, gas sensitivity	Gas and humidity sensors
Carbon-based nanomaterials	Graphene, carbon nanotubes (CNTs), fullerenes	High electrical conductivity, mechanical strength	Biosensors, electrochemical sensors
Quantum dots	CdS, CdSe, PbS	Size-dependent fluorescence	Optical biosensing, imaging
Polymer nanocomposites	Conductive polymers with nanoparticles	Flexibility and tunable surface	Wearable and portable sensors

These nanomaterials can be engineered to detect **gases, ions, biomolecules, heavy metals**, and even **pathogenic microorganisms** at very low concentrations.

3. Mechanisms of Sensing

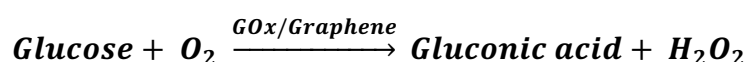
The working principle of nanomaterial-based sensors depends on changes in measurable properties after interaction with the target analyte:

- **Electrochemical sensors:** Detect changes in current, voltage, or resistance.
Example: Graphene-modified electrodes for detecting glucose or dopamine.
- **Optical sensors:** Measure changes in light absorption, fluorescence, or surface plasmon resonance (SPR).
Example: Gold nanoparticles show color changes upon aggregation, used in colorimetric detection of DNA or heavy metals.
- **Mass-sensitive sensors:** Detect changes in mass using piezoelectric materials or nanocantilevers.
- **Thermal sensors:** Measure heat produced or absorbed during a chemical reaction.

4. Electrochemical Sensors Based on Nanomaterials

Electrochemical sensors are among the most widely used analytical devices. They rely on electron transfer between the analyte and the electrode surface. Nanomaterials improve their performance by enhancing electrical conductivity and providing catalytic sites.

Example:



The generated hydrogen peroxide is electrochemically detected at the electrode, producing a current proportional to glucose concentration.

This principle is used in **glucose biosensors**, a vital tool in diabetes management.

5. Optical Nanomaterial-Based Sensors

Optical sensors use the interaction of light with nanomaterials to detect analytes. **Surface plasmon resonance (SPR)** in gold and silver nanoparticles causes strong absorption and color changes when molecules bind to their surfaces. Example: Gold nanoparticles exhibit a red-to-blue color shift upon aggregation, enabling **colorimetric detection** of biomolecules and toxic ions.

Quantum dots (QDs) are also used for **fluorescence-based sensing** due to their bright and tunable emission. Their emission wavelength depends on particle size, allowing multicolor detection.

Table 1 – Comparison of Conventional and Nanomaterial-Based Sensors

Feature	Conventional Sensor	Nanomaterial-Based Sensor
Sensitivity	Moderate	Very high
Detection limit	μM – mM range	nM – pM range
Response time	Seconds to minutes	Milliseconds to seconds
Device size	Bulky	Miniaturized / portable
Stability	Moderate	Excellent
Cost	Higher	Decreasing with development

The development of nanomaterial-based sensors is rapidly progressing toward the creation of **smart analytical systems** that combine nanotechnology with **artificial intelligence (AI)**, **machine learning (ML)**, and the **Internet of Things (IoT)**. These intelligent systems are capable of **real-time data acquisition, analysis, and wireless communication**, enabling **autonomous monitoring and decision-making** in a wide range of fields. In **healthcare**, wearable nanobiosensors integrated with AI algorithms can continuously monitor vital signs such as glucose, oxygen, or stress-related biomarkers, and instantly alert patients or doctors when abnormalities are detected. In **environmental monitoring**, IoT-connected nanosensors can track air or water pollution levels and transmit data to centralized systems for early warning and preventive action. In **industrial automation**, networks of nanosensors embedded in machinery can detect temperature changes, gas leaks, or chemical imbalances, allowing predictive maintenance and improving safety. Furthermore, the integration of nanomaterials with **flexible electronics** and **microfluidic devices** enables the development of **portable, low-cost lab-on-a-chip systems** capable of performing complex analyses outside traditional laboratories. The future of nanomaterial-based analytical systems thus lies in **intelligent, interconnected platforms** that combine nanoscale sensitivity with computational power, creating the foundation for **next-generation diagnostics, environmental protection, and smart manufacturing**.

Questions for self-control:

1. What are nanomaterial-based sensors, and how do they differ from conventional sensors?
2. Describe the main components of a sensor and their functions.
3. What is the role of nanomaterials in improving sensor performance?
4. Give examples of electrochemical and optical nanomaterial-based sensors.
5. What are the main applications of nanomaterial-based analytical systems?

Literature:

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