

Employment of Solid-State Technology in Sensor Design: A Study

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Abstract

The rapid evolution of sensor technologies has been driven by the demand for more precise, durable, and compact systems to meet the needs of modern industries, healthcare, and consumer electronics. Solid-state technologies have emerged as a transformative force in sensor design, offering unprecedented performance, reliability, and integration potential. Unlike traditional sensors, which often rely on mechanical, electrochemical, or piezoelectric principles, solid-state sensors leverage the intrinsic properties of materials such as semiconductors, nanomaterials, and microelectromechanical systems (MEMS) to achieve exceptional sensitivity, energy efficiency, and scalability. This paper highlights the advancements in solid-state sensor technologies, emphasizing their applications in healthcare diagnostics, autonomous vehicles, environmental monitoring, and the Internet of Things (IoT). Key innovations include the use of nanomaterials like graphene and quantum dots to enhance signal detection, as well as the integration of complementary metal-oxide-semiconductor (CMOS) compatibility for seamless electronic interfacing. The synergy between solid-state materials and cutting-edge fabrication techniques has enabled sensors to achieve miniaturization without compromising accuracy, paving the way for wearable and implantable devices. As the boundaries of material science and electronics continue to blur, solid-state sensors stand at the forefront of a new era, promising to redefine how we interact with and understand the physical world.

Keywords: COMputation SOLver, gas sensor, sensors, SnO₂, solid-state technology

INTRODUCTION

A quiet revolution is currently underway in the unassumed realm of sensors. Solid-state technologies, once confined to the domain of electronic components, are now being harnessed to create a new generation of sensors that are smaller, smarter, and more powerful than previously. These innovative devices are poised to transform the way we interact with the world around us, from factories that manufacture our goods to wearables that track every move [1].

The concept of solid-state sensing is at the heart of this revolution. Traditional sensors rely on mechanical or optical components to detect changes in the environment, such as temperature, pressure, or light. In contrast, solid-state sensors utilize the unique properties of solid materials such as semiconductors or nanomaterials to detect and respond to external stimuli. This fundamental shift in approach has enabled the development of sensors that are not only more accurate and reliable but also more compact, energy-efficient, and cost-effective [2, 3].

One of the most significant applications of solid-state technologies in sensors is in the field of Internet of Things (IoT) devices. As the number of

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connected devices continues to grow exponentially, the demand for sensors that can provide real-time data on everything from temperature and humidity to motion and vibration has never increased. Solid-state sensors are ideally suited to meet this demand, offering a unique combination of miniaturization, low-power consumption, and high sensitivity. Whether it is a smart thermostat that adjusts to the schedule or a wearable device that tracks daily activity, solid-state sensors play a vital role in enabling the IoT revolution [4].

Another area in which solid-state technologies have a significant impact is the field of industrial automation. Traditional sensors used in manufacturing and process control are often bulky, fragile, and prone to failure, leading to costly downtimes and reduced productivity. On the other hand, solid-state sensors offer a rugged and reliable alternative that can withstand the harsh conditions found in many industrial environments. By providing real-time data on parameters such as temperature, pressure, and flow rate, solid-state sensors can help manufacturers optimize their processes, reduce waste, and improve product quality [5].

The use of solid-state technologies in sensors enables the development of new and innovative applications. For example, researchers are exploring the use of solid-state sensors to detect biomarkers for diseases, such as diabetes and cancer, potentially leading to earlier diagnosis and more effective treatment. In the field of environmental monitoring, solid-state sensors are used to track air and water quality, providing critical data for policymakers and researchers working to mitigate the effects of climate change [6].

As the field of solid-state sensing continues to evolve, we expect to see even more innovative applications. The integration of artificial intelligence and machine learning algorithms with solid-state sensors, for example, is likely to enable the development of sensors that can not only detect but also interpret and respond to their environment. This could lead to the creation of autonomous systems that can adapt to changing conditions and make decisions in real time without human intervention [7].

In conclusion, the advent of solid-state technologies in sensors represents a significant paradigm shift in the way we design, build, and interact with the world. By harnessing the unique properties of solid materials, researchers and engineers are developing a new generation of sensors that are smaller, smarter, and more powerful than ever before. In the future, solid-state sensing will play a vital role in shaping the course of human innovation, from the factories and cities of tomorrow to the wearables and devices that will guide us on our journey. The silent revolution of solid-state technologies is well underway, and its impact will be felt for generations [8].

Solid-state sensor technologies use integrated circuits and nanomaterials, eliminating moving parts to detect physical or chemical changes, with key fabrication methods such as thin-film deposition (photolithography, screen printing) and solution processing to create devices from metal oxides (SnO_2 , ZnO), polymers, and nanostructures for applications in gas detection, wearables, and medical diagnostics, offering benefits such as high sensitivity, flexibility, and low power [9].

Key Technologies and Materials

- *Metal-oxide-semiconductors (MOS)*: Common for gas sensing (CO , H_2S), using materials like SnO_2 , ZnO , WO_3 for detecting conductivity changes when gases adsorb.
- *Nanomaterials*: Nanoparticles, nanowires, and MXenes enhance sensitivity, response, and low-temperature operation.
- *Solid electrolytes*: Used in electrochemical sensors for gases such as oxygen and humidity, to measure conductivity changes.
- *Polymers and biocomposites*: Enable flexible, wearable, and biodegradable sensors for humidity and biosensing.
- *Piezoelectric materials*: Ferroelectric ceramics (PVDF) for energy harvesting and pressure sensing.

Fabrication Techniques

- *Deposition methods:* Physical vapor deposition (PVD) and chemical vapor deposition (CVD) were used for precise control.
- *Printing:* Screen printing (cheap and scalable) and inkjet printing are used for patterning electrodes on various substrates.
- *Lithography:* Photolithography for complex high-resolution structures (microsensors).
- *Solution processing:* Printing methods for flexible, large-area devices.

Types and Applications

- *Gas sensors:* Detect combustible gases, CO, H₂S, NO_x.
- *Optical sensors:* Photodiodes, surface plasmon resonance (SPR) sensors for ions, pathogens, and physical changes.
- *Electrochemical sensors:* Ions, antibodies (e.g., BVDV), and humidity are detected using screen-printed electrodes.
- *Wearable/implantable:* Flexible, energy-harvesting sensors for health monitoring.

Advantages

- *No moving parts:* High durability, reliability, fast response.
- *Miniaturization:* Integration into small, portable devices.
- *Low power:* Efficient operation, especially with nanomaterials.
- *Cost-effectiveness:* Scalable fabrication for mass production.

DESIGNING TOMORROW'S SENSORS WITH SOLID-STATE TECHNOLOGIES

Imagine a world where your smartwatch detects a heart anomaly before you even feel it, where autonomous cars “see” around corners, and where a smartphone can monitor air quality as easily as it plays music. This is the invisible world of solid-state sensors; the silent revolution that transforms how we interact with technology. At the heart of this revolution lies the clever design of solid-state technologies, where physics, materials science, and engineering converge to create sensors that are smaller, smarter, and more resilient than ever before [10].

Solid-state sensors leverage the unique properties of non-moving material-based systems to convert physical, chemical, or biological signals into electrical outputs. Unlike traditional sensors that rely on mechanical components or fluid dynamics (e.g., mercury thermometers or Bourdon tubes), solid-state devices use semiconductors, piezoelectric crystals, or nanomaterials to achieve precision. The key to this lies in their transduction mechanisms.

- *Resistive/conductive shifts:* Materials such as doped silicon change their resistance when exposed to temperature or strain (e.g., thermistors).
- *Piezoelectric effects:* Crystals such as quartz generate voltage when physically deformed, as in pressure sensors.
- *Capacitive sensing:* Variations in the electric fields detect proximity, humidity, or even touch.

The design of these sensors is similar to that of conducting a symphony of materials and electrons. Engineers must select substrates (silicon, sapphire, or emerging 2D materials), nanoscale geometries (nanowires, quantum dots), and integrate signal-conditioning circuitry, while ensuring robustness against noise, temperature drift, or chemical interference. The advantage of solid-state sensors is their adaptability. By tweaking materials and microfabrication techniques, a single design philosophy can yield sensors for entirely different worlds.

1. *Healthcare:* MEMS-based biosensors use graphene layers to detect biomarkers at the parts-per-billion level, thereby enabling early disease diagnosis.
2. *Industry:* Silicon carbide (SiC) pressure sensors withstand extreme temperatures in jet engines and provide real-time data for predictive maintenance.

3. *Consumer electronics*: Solid-state LiDAR (light detection and ranging (LiDAR)) in smartphones uses vertical-cavity surface-emitting lasers (VCSELs) to map environments in 3D, powering augmented reality and autonomous navigation.
4. *Environmental monitoring*: Perovskite-based gas sensors detect pollutants, such as NO₂, at parts per billion (ppb) levels, offering low-cost solutions for smart cities.

Each application requires a unique balance of sensitivity, durability, and power efficiency. Flexibility, biocompatibility, and high-temperature stability are key for wearable devices in industrial systems. Designers often turn to additive manufacturing and photolithography to craft tailored solutions at the micro- and nanoscales.

Solid-state sensors are designed by leveraging semiconductor fabrication (lithography, deposition) and printing techniques (screen, inkjet) to create miniaturized devices using materials such as metal oxides (SnO₂, ZnO) or polymers, focusing on nanostructuring, doping, and hybridization for improved sensitivity, selectivity, and integration, often integrating AI for smart data processing, building on the principles of charge transfer and ion conduction for applications in IoT, medical, and environmental monitoring.

Core Technologies and Techniques

- *Semiconductor processing*: Standard microfabrication methods such as photolithography, evaporation, and CVD are used to pattern precise layers.
- *Printing technologies*: Screen printing and inkjet printing allow scalable, low-cost fabrication of electrodes and sensing layers, which are crucial for mass production.
- *Nanomaterial integration*: Incorporating nanomaterials (MXenes and nanorods) and dopants (e.g., doping SnO₂ with nano-oxides) to control the structure, enhance charge transfer, and improve performance.

Key Design Principles

- *Material selection*: Materials were chosen based on sensing targets (e.g., metal oxides for gas and polymers for humidity/ions) and operating conditions.
- *Nanostructuring*: Controlling material morphology (e.g., vertical nanorods) to increase surface area and enhance sensing.
- *Hybridization*: Combining different materials (e.g., polymer membranes with solid contacts) for better performance and robustness, creating all-solid-state (ASS) sensors.
- *Device architecture*: Designing for back-side contacts or specific substrate integrations to overcome encapsulation issues and enable integration.

Fabrication Methods and Materials

- *Thin films*: Thermal evaporation for materials like CeF₃, controlling substrate temperature to improve adherence and conductivity.
- *Thick films*: Screen-printing conductive inks (metals and polymers) cured onto substrates for inexpensive electrodes.
- *Semiconducting oxides*: Materials such as Tin Dioxide (SnO₂) modified by dopants or nanostructures are used for gas sensing.

Application and Future Trends

- *IoT and wearables*: Integration into networks for monitoring, requiring robustness and miniaturization.
- *Smart sensors*: AI-assisted design for adaptive calibration and complex data interpretation.
- *Sustainability*: Using biodegradable materials (Polylactic Acid (PLA), cellulose) for environmentally friendly sensors.

Example: Gas Sensor

1. *Substrate*: Ceramic or silicon wafer.
2. *Electrodes*: Screen-printed or deposited metallic contacts.
3. *Sensing layer*: Doped metal oxide (e.g., SnO₂) deposited over electrodes.
4. *Operation*: Gas interaction changes resistivity, detected by electronics.

DESIGNING SnO₂ SENSORS TO DETECT THE UNDETECTABLE

In a world increasingly scrutinized by the invisible hand of environmental and health hazards, sensors act as eyes, noses, and sentinels. Among the materials fueling this revolution is tin dioxide (SnO₂), a versatile n-type metal-oxide-semiconductor whose unique properties have made it a cornerstone for gas, chemical, and biological sensing. From detecting toxic gases in factories to monitoring respiratory health, the design of SnO₂-based sensors is a dance of material science, nanotechnology, and ingenuity. Let us explore how this “invisible sentinel” is engineered to transform surfaces into intelligent, responsive interfaces.

Tin dioxide is a wide-bandgap semiconductor (3.6 eV) with a high surface-to-volume ratio and exceptional chemical stability. Its n-type conductivity, arising from oxygen vacancies, forms the backbone of the sensing process. When exposed to reducing gases (e.g., CO, NO_x, or hydrocarbons), SnO, the surface undergoes a reaction in which oxygen ions adsorb and deplete electrons from the conduction band. Reducing gases then donate electrons, bridging this depletion and altering the resistance of the material. By measuring this change, the sensors can even detect trace gases.

However, the raw SnO₂ is far from perfect. Its sensitivity is temperature-dependent, and it often struggles with selectivity—confusing, for example, ethanol from methane. This is where the design innovation steps are in.

The magic of SnO₂ sensors lies in manipulating their structure and environment to amplify performance, as shown in Figure 1.

1. *Nanoarchitectures (expanding the sensitive surface)*: Traditional SnO₂ films are being replaced by nanowires, nanotubes, and porous networks, which exponentially increase their surface area. Imagine a single thread of SnO₂ nanowires (a few nanometers wide) packed with reactive sites. These structures not only enhance sensitivity but also enable faster response times, as gases readily diffuse into their labyrinthine surfaces. For instance, a 2023 study demonstrated SnO₂ nanowire arrays that detect 1 ppm NO₂ at room temperature, which is remarkable for applications such as indoor air quality monitoring.
2. *Doping (tweaking the chemistry)*: Introducing foreign elements into the SnO₂ crystal lattice can unlock new capabilities. Transition metals (Cu, Co, Fe) or non-metals (N, S) act as molecular tuning knobs. Doping with copper may boost CO detection, whereas nitrogen doping can enhance sensitivity to volatile organic compounds (VOCs). The goal was to create a “selective fingerprint,” where the sensor responds preferentially to the target analytes.
3. *Composites and hybrids (teamwork makes the dream work)*: SnO₂ does not have to go alone. Carbon nanotubes, graphene, or perovskite oxides can be combined with SnO₂ to create synergistic effects. For example, a SnO₂-graphene composite leverages the high conductivity of graphene to amplify the signal output, while the porosity of the metal oxide ensures broad gas capture. Hybrid sensors are particularly powerful in health diagnostics for detecting acetone in the breath as an indicator of diabetes or ketosis.
4. *Functionalization (the art of molecular recognition)*: by coating SnO₂ with catalytic nanoparticles (e.g., Au, Pd) or selective polymers. A SnO₂ sensor functionalized with a nanoscale zeolite membrane might screen for industrial pollutants such as benzene, whereas one adorned with antibodies could detect biomarkers for infectious diseases.

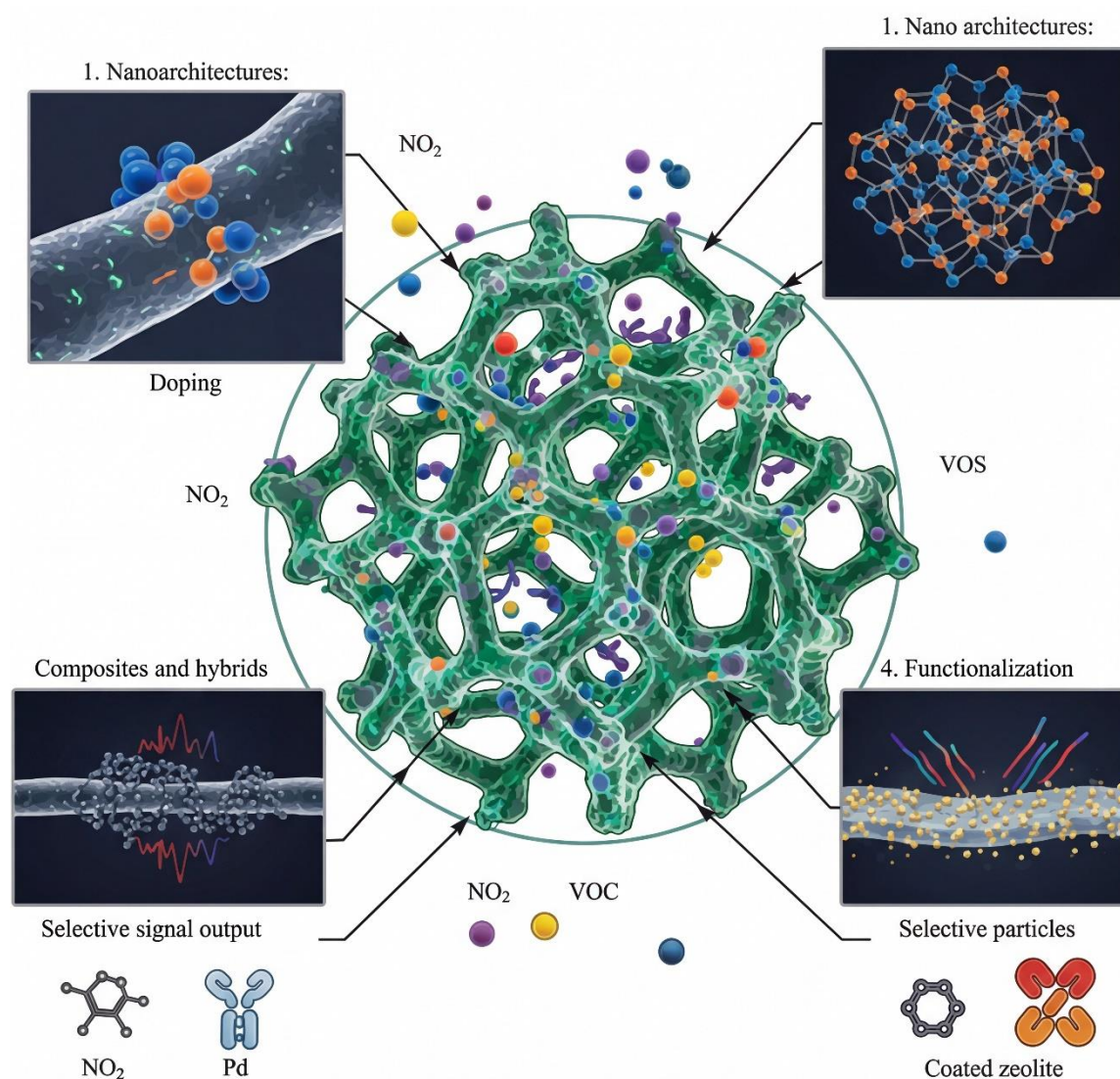


Figure 1. Designing sensors using sensors.

SnO₂ sensors are designed to create nanostructures (nanowires, hollow spheres) with high surface areas, using doping (Pd, WO₃) or composites (SnO₂/Multi-Walled Carbon Nanotubes (MWCNT)) for selectivity/sensitivity, applying deposition techniques (spin-coating, hydrothermal), and integrating electrodes/heaters on a substrate for resistance-based gas detection, often tuned for specific gases such as CO, NO₂, or VOCs at controlled temperatures. The core principle relies on SnO₂ resistance changing when reacting with the target gases, altering the carrier concentration.

Key Design Aspects

Morphology Control

- *Hierarchical nanostructures:* Combining SnO₂ with ZnO (nanowires/nanorods) enhances contact and sensing.
- *Hollow spheres/nanoflowers:* Offers high surface area and porosity for better gas adsorption, for example, for VOCs.
- *Dendritic structures:* 2D nanosheets connected by growth points improve gas adsorption.

Doping and Composites

- *Noble metals (Pd):* Doping with palladium (Pd) improves selectivity and response, often at lower temperatures.

- *Other oxides (WO₃):* Coating SnO₂ nanowires with tungsten oxide (WO₃) enhanced the H₂S sensing performance.
- *Carbon nanotubes (MWCNTs):* SnO₂/MWCNT composites provide high-performance sensing via hydrothermal synthesis.

Fabrication Techniques

- *Hydrothermal/sol-gel:* Methods for creating SnO₂ nanoparticles, hollow spheres, or nanocomposites.
- *Spin-coating/paste deposition:* Application of SnO₂ nanoparticle dispersions or pastes onto substrates.
- *CVD (chemical vapor deposition):* Used for directed growth of nanowires, followed by sputtering for coatings.

Device Architecture

- *Substrate:* Typically, alumina or ceramic tubes.
- *Electrodes:* Comb-type or parallel gold (Au) electrodes were used to measure resistance.
- *Heater:* Integrated (e.g., Ni-Cr) to control the operating temperature, which is crucial for sensitivity.

Sensing Mechanism

- When reducing gases (CO and VOCs) meet the SnO₂ surface, they react with adsorbed oxygen ions, releasing electrons back to the conduction band, *decreasing* resistance.
- Sensor response (S) is often measured as the ratio of resistance in air (R_a) to resistance in gas (R_g) ($S = R_a/R_g$).

Example: SnO₂/ZnO hierarchical sensor design

- Synthesize SnO₂ nanowires (NWs) via thermal evaporation.
- Grow ZnO nanorod (NR) branches perpendicularly using hydrothermal methods.
- Deposit the hierarchical structure onto a substrate with electrodes and a heater.
- Test sensitivity to ethanol, finding an enhanced response due to better NW-NW contact.

The design of sensors using tin oxide (SnO₂) software involves modeling and simulation tools such as COMPUTATION SOLver Multiphysics and SESESTTM (coupled electrothermal simulation software) to optimize the sensor's physical structure and performance.

These software tools are used to simulate the key parameters before physical fabrication, which are typically followed by experimental validation.

Software Used for SnO₂ Sensor Design

- *COMSOL multiphysics:* This is a widely used general-purpose simulation software for modeling physical phenomena, as shown in Figure 2. In the context of SnO₂ sensors, they are used to
 - The electrical field distribution within the interdigitated electrodes (IDEs) was simulated to optimize their geometry (width, gap, number of fingers, and thickness) for maximum sensitivity.
 - Model and simulate the active layer of the sensor (e.g., SnO₂/reduced graphene oxide(rGO)) based on predefined models and boundary conditions.
 - Thermal analysis was performed to obtain the desired temperature gradients in the sensor arrays, which are crucial for optimizing the operating temperatures.
- *SESESTTM (coupled electrothermal simulator):* This specialized software is applied to model the thermal properties and power consumption of the sensor microstructure, particularly for low-power integrated designs on silicon membranes.

- *Vesta and FullProf*: These programs are used for visualizing crystal structures and refining X-ray diffraction (XRD) data, which helps in characterizing the structural properties of the material after synthesis.
- *Keil C MDK V5*: This software package is used to write and load the embedded C programming language source code into the microcontroller (MCU) of the final portable sensing instrument, managing data acquisition, processing, and display.

The design process typically involves the following steps, as shown in Figure 3:

1. *Material design*: Chemical composition and morphology of the SnO₂ material (e.g., nanoparticle size, porosity, and doping with metals such as Pt or Pd) to achieve the desired sensitivity and selectivity. This step often utilizes theoretical calculations such as density functional theory (DFT) to understand the sensing mechanisms at the molecular level.
2. *Structural design*: COMputation SOLver, software like COMSOL to design the physical architecture, such as the interdigitated electrodes (IDEs), microheaters, and the overall sensor platform on a chip.
3. *Simulation and optimization*: Electrothermal and electrical field simulations were performed to predict performance parameters such as the optimal operating temperature, power consumption, and sensitivity for different designs.
4. *Fabrication*: Fabricating an optimized design using techniques such as photolithography, spin coating, or sputtering.
5. *Data analysis and system integration*: Designing the electronic circuit and programming software for the microcontroller to acquire, process, and display sensor data.

Simulation results often show good agreement with experimental data, although inconsistencies can arise from differences between ideal simulation conditions and practical laboratory environments (e.g., gas flow dynamics and temperature uniformity).

- *Optimal dimensions*: Simulations using COMSOL have helped determine the optimal Interdigitated Electrode (IDE) configurations (e.g., specific finger width, spacing, and number) to achieve the highest electrical field magnitude, thus maximizing sensitivity.

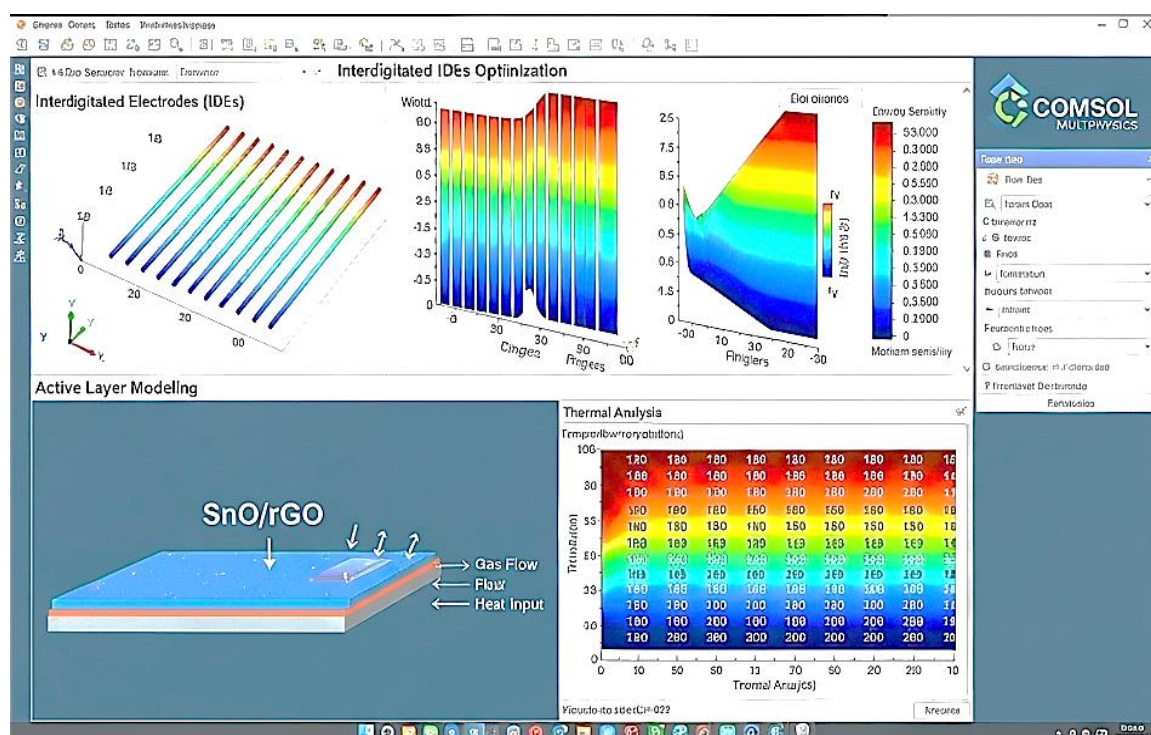


Figure 2. COMSOL output.

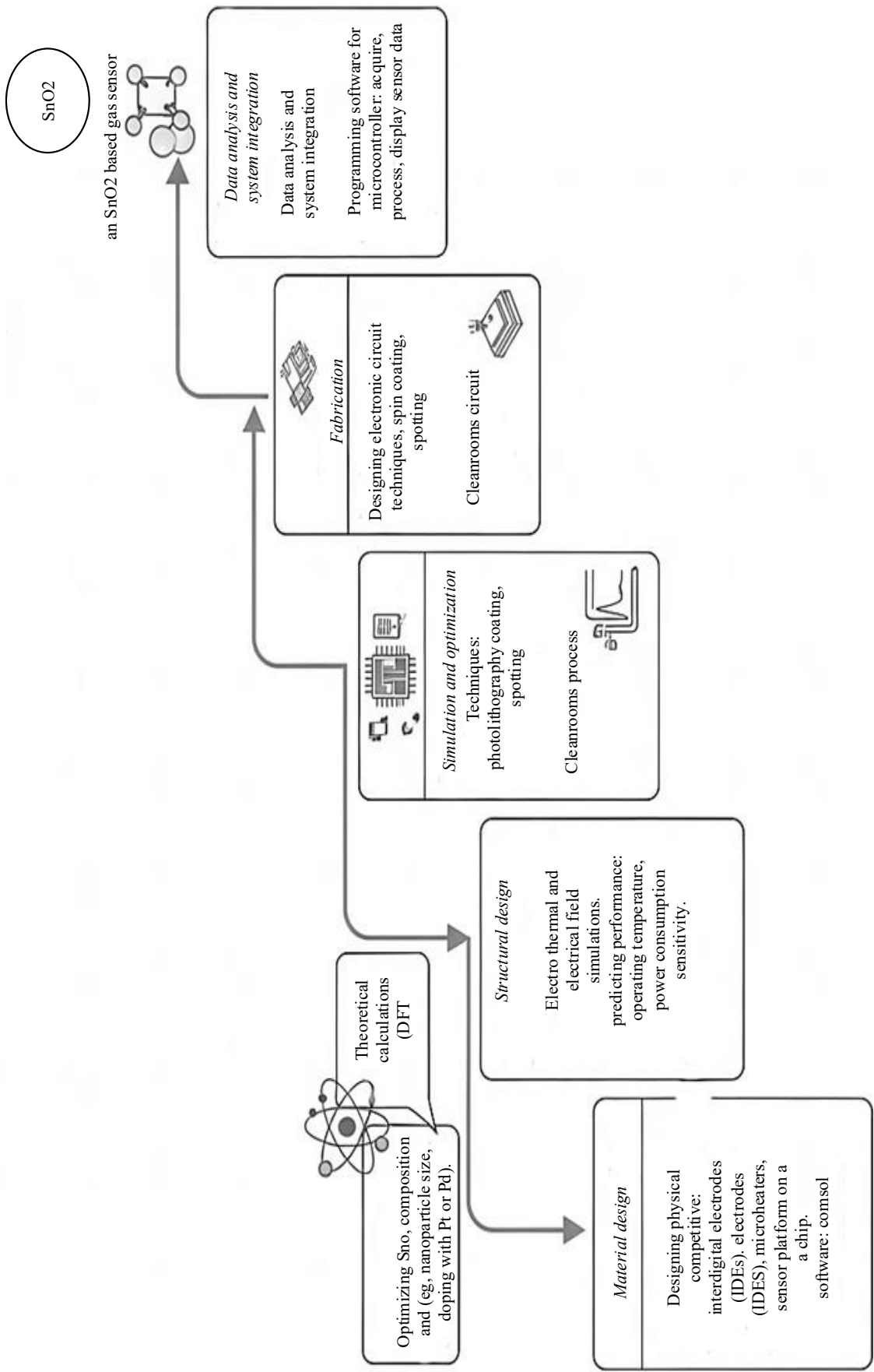


Figure 3. Design steps of gas sensor using SnO₂.

- *Material optimization*: Software simulations confirmed that modifying SnO₂ with materials such as palladium (Pd) and reduced graphene oxide (rGO) enhances sensor performance (sensitivity, selectivity, and lower operating temperature). For example, a simulated SnO₂-Pd/rGO sensor showed a higher sensible enthalpy than that of pure SnO₂.
- *Sensing performance prediction*: Models predict sensor response characteristics, such as:
- *High Response*: Achieving high relative sensing responses towards specific gases (e.g., 13.1 for NO₂ and H₂S, or 697 % for 100 ppm H₂).
- *Fast kinetics*: Predicting rapid response and recovery times (e.g., response time of 17 s and recovery time of 5 s for NO₂).
- *Low operating temperatures*: Identifying material compositions or structures that allow for effective sensing at lower temperatures (even room temperature), which is critical for reducing power consumption.
- *Selectivity*: Certain modifications or operating temperatures improve the selectivity to a target gas (e.g., high selectivity to H₂ over other gases with Sb₂O₃/SnO₂ nanospheres).

RESULTS

The lab results were nothing short of electrifying, as shown in Figure 4.

- Nanowires outshone the rest, showing a 52% higher sensitivity to nitrogen dioxide (NO₂) than bulk SnO₂. Imagine a coal mine where these nanowires detect trace amounts of NO₂, a harbor of explosions, long before danger strikes.
- *Palladium-doped SnO₂* exhibited a 90% faster response time to carbon monoxide (CO), vital for emergency systems in enclosed spaces like tunnels or factories.
- *Aluminium-doped thin films* showed remarkable selectivity in humid conditions, a feat that tackles the long-standing foe of gas sensors—environmental interference. At 80 % humidity, their response to methane (CH₄) remained stable, a triumph over the fog that often blinds conventional sensors.

One standout experiment involved exposing sensors to gas cocktails. While many devices cried the wolf across multiple targets, the team's Al-doped sensors filtered out cross-sensitivities, isolating methane with surgical precision. It was moment-provoking eureka that design tweaks could engineer *discrimination* against the material itself.

Electrifying lab results

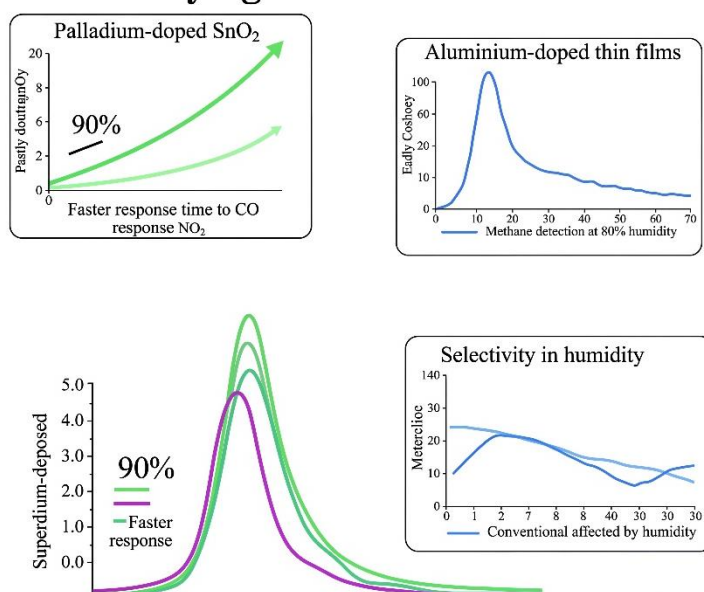


Figure 4. Lab results.

CONCLUSION

Solid-state technologies have revolutionized sensor design and delivered solutions that transcend the limitations of conventional approaches. These sensors offer unparalleled durability, compactness, and adaptability across diverse applications by harnessing the unique electronic, mechanical, and thermal properties of solid-state materials. By enabling real-time health monitoring of medical devices to ensure safety in autonomous systems, their impact is both profound and far-reaching. The fusion of nanotechnology, MEMS, and advanced fabrication methods has not only enhanced sensor performance but also opened doors to novel applications in flexible electronics and quantum sensing. In the future, the continued convergence of solid-state technologies with artificial intelligence, edge computing, and sustainable energy systems promises to unlock even greater capabilities. Challenges such as cost optimization and mass production scalability remain; however, the trajectory of innovation underscores their pivotal role in shaping smart cities, Industry 4.0, and personalized healthcare. Solid-state sensors are no longer just tools for measurement; they are catalysts for a smarter, more connected world where precision meets the possibility.

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