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An Overview of MOSFET-Based Sensor Design

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Abstract

In the past two decades, the MOSFET has transformed from a simple switch in digital logic to an analog powerhouse that can be co-fabricated with the sensing material on a single chip. Metal-oxide-semiconductor field-effect transistors (MOSFETs) have silently become the beating heart of modern sensor platforms, translating the faint whispers of physical, chemical, and biological phenomena into robust electrical signatures. This abstract surveys the latest advances that have turned the humble MOSFET from a passive switch into an active transducer, highlighting three converging trends: (1) nanoscale channel engineering that pushes the transistor's electrostatic control to the quantum limit, (2) hybrid integration of functional layers (e.g., graphene, piezoelectric oxides, and biorecognition membranes) directly onto the gate stack, and (3) ultra-low-power biasing schemes that exploit subthreshold operation and threshold-voltage modulation for energy-harvesting sensor nodes. By weaving together device physics, materials science, and circuit-level innovations, the review demonstrates how MOSFET-based sensors now achieve sub-ppm detection limits, millisecond response times, and seamless compatibility with standard CMOS fabrication lines. The abstract concludes by proposing a unified design framework that couples gate-functionalization chemistry with adaptive bias control, opening a pathway toward truly "smart" sensors that self-calibrate, self-power, and self-communicate within the emerging Internet of Things (IoT) ecosystem efficiently and intelligently.

Keywords: MOSFET, sensor design, BioFET, pressure sensor, system-on-chip (SoC), FinFET

INTRODUCTION

In the world of sensor design, MOSFETs are no longer just switches or amplifiers; they are the architects of signals, power, and intelligence. Below, we explore how MOSFET technology has become the backbone of today's sensor ecosystems, why its physics matters more than ever, and where the next wave of breakthroughs is likely to emerge.

MOSFET technology in sensor design leverages high input impedance and sensitive threshold-voltage regulation to create high-sensitivity, low-power, and compact sensing solutions. Key applications include MOSFET-based MEMS pressure sensors (utilizing piezoresistive effects), on-chip thermal sensors, and hybrid organic–Si photosensors.

They are favored for their low-power operation and ease of integration into CMOS circuitry, providing efficient, scalable, and cost-effective solutions for various sensing applications. Table 1 explains why MOSFETs were employed in sensor design. These qualities give the MOSFET a "Swiss-army-knife" reputation in sensor front ends, where every picowatt and every millivolt counts.

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Table 1. Why MOSFETs matter.

Feature	Why it is a game-changer for sensors
High input impedance	Allows the sensor element (often a high-impedance transducer) to be read without loading it down.
Low gate leakage	Enables ultra-low-power standby operation—critical for battery-powered wearables and IoT nodes.
Scalable geometry	From 180 nm down to sub-10 nm, MOSFETs shrink in step with demand for denser, smarter sensor arrays.
CMOS compatibility	MOSFETs can be fabricated alongside digital logic, yielding system-on-chip (SoC) sensor solutions.
Analog flexibility	Operate in many regimes: saturation (as a current source), triode (as a resistor), or sub-threshold (as an exponential transducer).

KEY MOSFET SENSOR TECHNOLOGIES

- *MEMS pressure sensors:* MOSFETs are placed at the edges of diaphragms to measure stress through changes in carrier mobility and threshold voltage, often using SiC for harsh environments.
- *On-chip temperature sensors:* Utilization of the temperature dependence of the drain current in a MOSFET to measure local temperatures on ICs.
- *Photosensors:* Hybrid organic-Si MOSFET structures are used to create sensitive photodiodes (e.g., green-sensitive DMQA or blue-sensitive Coumarin 6), where the MOSFET amplifies the signal.
- *Chemical/biosensors (BioFETs):* Although not explicitly detailed in the search, similar FET-based structures are used to detect specific molecules by changing the surface potential of the gate.

MOSFETs as the Bridge Between Physics and Bits

The Front-End Amplifier

Consider a piezoelectric pressure sensor with a cylindrical shape. Mechanical stress creates a minute charge, often in the femtocoulomb range. To convert this charge into a usable voltage, an electrical interface is required.

- Collect the charge without shunting it away.
- Amplifies the resulting voltage to a level compatible with downstream ADCs.
- Conditions the signal (filtering, biasing, temperature compensation).

A discrete MOSFET or an integrated MOSFET-based transimpedance amplifier (TIA) satisfies all three requirements. Because the MOSFET gate is insulated from the channel by a thin oxide, it can be directly tied to the sensor output node, presenting an input resistance that is effectively infinite. The resulting voltage appears across a feedback resistor, which can be implemented as an n-type MOSFET operated in the linear region, a so-called “MOS-resistor.” By carefully shaping the dimensions (W/L ratio) and biasing them in the subthreshold region, designers can achieve a mega-ohm to giga-ohm resistance with an area that would be impossible using an actual resistor.

Power-Management Switches

Many modern sensors are energy-harvesting sensors that draw power from light, vibration, or thermal gradients. The harvested energy is erratic, often a few microwatts; therefore, a MOSFET power gate is used to:

- Rectify the AC source (as part of a synchronous buck-boost converter).
- Isolate the sensor during low-power sleep modes.
- Hard switching is performed without introducing inductive spikes that would corrupt the sensor’s analog front end.

Advanced designs use dynamic threshold MOSFETs (DTMOS) that adapt their threshold voltage based on the supply, achieving sub-nanowatt idle currents, which are essential for long-lived wearables.

On-Chip Signal Conditioning

In a CMOS image sensor, each pixel contains a photodiode and a source follower MOSFET that buffers the charge-to-voltage conversion. Here, the MOSFET is the pixel's heart.

- Its subthreshold transconductance directly determines the conversion gain (µV/e) and, thus, the noise floor of the sensor.
- A floating-diffusion architecture uses MOSFETs to reset the photodiode, control the integration time, and read out the analog voltage row by row.
- Global shutter implementations rely on MOSFET switches that temporarily store the charge on a capacitor before simultaneous readout, eliminating motion blur.

All of this occurs inside a silicon die the size of a postage stamp, at a speed of billions of frames per second for high-speed cameras. Table 2 shows the sensor types designed using MOSFET technology.

These examples illustrate a common theme: the MOSFET is not just a passive component; it actively shapes the sensor's physics, whether by heating, biasing, or amplifying.

LITERATURE SURVEY

Metal-oxide-semiconductor field-effect transistors (MOSFETs) have long been the workhorses of modern electronics; however, their role has broadened far beyond digital switching. By exploiting the sensitivity of the MOS channel to external stimuli, such as charge, chemical species, temperature, strain, or photons, researchers have turned MOSFETs into versatile transducers that can be seamlessly integrated with CMOS readout circuitry. This survey collates the most influential contributions from the past two decades, highlighting how device geometry, gate engineering, and novel materials have been harnessed to address the demanding specifications of modern sensors (ultra-low power, high-density integration, and multimodal detection). Table 3 summarizes the fundamental attributes of MOSFETs used in sensor applications.

Table 2. MOSFET-centric sensor architectures.

Sensor type	MOSFET role	Notable implementation
Gas-Phase Chemiresistors (e.g., NO_2 or VOC detection)	Acts as a temperature heater (via a MOSFET in linear mode) & read-out amplifier for resistance change	SnO_2 nanowire sensor with MOSFET-controlled microheater.
MEMS accelerometers	Provides electrostatic actuation and capacitive read-out via MOSFET switches.	Capacitive comb-drive accelerometer integrated in a 65 nm CMOS-MEMS process.
Electrochemical biosensors	Forms a low-bias transimpedance front-end, preserving the delicate redox currents.	Glucose sensor on a flexible substrate using MOSFET-based TIA.
Optical photodiodes (SiPMs, APDs)	Operates as avalanche quenching MOSFETs and bias regulation.	LiDAR receiver arrays with MOSFET-controlled gain stages.
Magnetoresistive (GMR/TMR) sensors	Supplies bias currents and differential readout with MOSFET current mirrors.	Automotive wheel-speed sensors embedded in a CMOS-compatible process.

Table 3. Foundations: Why MOSFETs for sensors?

Attribute	Relevance to sensing	Key references
Gate-controlled carrier density	Small changes in surface charge cause measurable shifts in threshold voltage (V_TH).	[1] Sze & Ng, *Physics of Semiconductor Devices* (2020).
Scalable CMOS compatibility	Sensors can be fabricated monolithically with signal-conditioning ASICs.	[2] Lee et al., *IEEE J. Solid-State Circuits*, 2021.
Low-noise operation	Sub-threshold operation yields high transconductance-to-current ratios, ideal for weak signals.	[3] Hu & Kim, *Sensors & Actuators A*, 2022.
Flexibility of functionalization	Gate oxide or channel can be coated with polymers, nanomaterials, or biomolecules.	[4] Nguyen et al., *Adv. Funct. Mater.*, 2023.

These intrinsic properties have motivated the development of three major sensor families: chemical/biochemical FETs (ChemFETs/BioFETs), physical-parameter FETs (e.g., pressure, temperature, strain), and photonics-enhanced FETs (e.g., phototransistors, plasmonic-gated MOSFETs).

Chemical and Biological Sensing

Classic ChemFETs

Early studies used ion-sensitive field-effect transistors (ISFETs) to monitor pH and ion concentrations. The transition to MOS-based ChemFETs leveraged thin SiO_2 or high-k gate dielectrics, functionalized with ion-selective membranes.

- *Key milestone:* Bergveld's ISFET (1970) and its MOS adaptation (1998) demonstrated sub-mV resolution for pH detection [5].
- *Modern advances:* High-k HfO_2 gates functionalized with self-assembled monolayers (SAMs) provide <1 μM detection limits for metal ions, with a drift of <0.1 mV/h [6].

BioFETs

BioFETs translate biomolecular binding events into electrical signals.

Two strategies dominate.

1. Direct immobilization of receptors on the gate oxide and
2. Integration of nanomaterial channels (e.g., graphene and MoS_2) that act as both transducers and channels.

Silicon-Nanowire (SiNW) BioFETs

50 nm SiNWs patterned by top-down lithography achieved femtomolar detection of DNA hybridization (limit of detection, LOD ≈ 10 fM) with real-time kinetics [7].

2D Material BioFETs

MoS_2 FETs functionalized with aptamers reported a LOD of ≈ 0.5 pM for thrombin, benefiting from atomically thin channels that bring the sensing surface into immediate proximity with the conduction path [8].

Emerging Functionalization Scheme

- *Molecularly imprinted polymers (MIPs):* MIP-gated MOSFETs enable the selective detection of small organic compounds (e.g., pesticides) with selectivity factors >1000 [9].
- *Hybrid enzyme–MOF (metal-organic framework) layers:* Enzyme encapsulation in ZIF-8 films on the gate yields a stable amperometric response for glucose monitoring without external mediators [10].

Physical-Parameter Sensing

Pressure and Strain

Piezoresistive MOSFETs (PMOS and NMOS) exploit changes in carrier mobility under mechanical stress. Recent studies have focused on gate-stress-engineered transistors, where a buried oxide (BOX) layer mediates strain transfer from a MEMS diaphragm to the channel.

Demonstrated performance: 0.5 Pa resolution in capacitive MEMS-integrated MOSFET pressure sensors fabricated in 28 nm bulk CMOS, with power consumption <1 μW [11].

Temperature

Thermal sensing is often realized by monitoring the VTH drift (ΔVTH/ΔT). The proportional-to-absolute-temperature (PTAT) MOSFET remains the backbone of on-chip temperature monitoring; however, recent dual-gate MOSFETs enable differential temperature readouts with sub-mK accuracy, which is suitable for thermal imaging arrays [12].

Magnetic Field

A magnetoresistive MOSFET (MR-MOSFET) incorporates a ferromagnetic source/drain region. Spin-orbit coupling modulates the channel conductance, achieving sensitivities comparable to Hall plates while maintaining CMOS compatibility [13].

Photonic and Optoelectronic Sensing

Silicon-Photonic MOSFETs

The integration of a waveguide-coupled photodetector directly into the MOSFET gate (gate-under-illumination) creates a phototransistor that combines a high gain with wavelength selectivity. Recent silicon-photonic platforms have demonstrated on-chip spectrometers with a resolution of <5 nm using an array of wavelength-selective MOSFETs [14].

Plasmonic-Enhanced MOSFETs

Metal nanostructures deposited on the gate generate localized surface plasmon resonances (LSPR) that amplify the electric field at the gate oxide–channel interface. The resulting LSPR-MOSFET exhibited sub-ppb detection of volatile organic compounds (e.g., benzene) by monitoring the V_{TH} shifts induced by the adsorbed molecules [15].

DISCUSSION

Metal-oxide-semiconductor field-effect transistor (MOSFET) technology is foundational to modern sensor design, enabling the creation of compact, low-power, highly sensitive, and intelligent sensors that can be integrated directly into silicon chips. MOSFET-based sensors function by monitoring changes in the electrical characteristics of a transistor (such as threshold voltage, drain current, or conductance) induced by external environmental or physical stimuli.

Key Advantages of MOSFET in Sensor Design

- *CMOS compatibility:* MOSFET sensors can be fabricated alongside traditional CMOS signal-processing circuits on the same chip, reducing manufacturing costs and improving system integration.
- *Low power and small area:* MOSFET-based sensors are generally smaller and consume less power than bipolar junction transistor (BJT) counterparts, making them ideal for Internet-of-Things (IoT) devices and wearable technology.
- *High sensitivity:* MOSFET sensors can achieve high sensitivity for various physical and chemical parameters through proper design (e.g., using subthreshold region operation or advanced structures).

Types of MOSFET Sensor Technologies

1. *ISFET (ion-sensitive FET):* Replacing the metal gate with a sensitive membrane allows for the measurement of ion concentrations in solutions and is widely used in pH, chemical, and biological sensors.
2. *FGFET (floating-gate FET):* Incorporates a sensing gate to convert chemical signals and a control gate for biasing, often used in biosensing.
3. *EGFET (extended-gate FET):* Maintains the conventional MOSFET structure but extends the gate to connect to a sensing membrane, offering better thermal/chemical stability and disposable sensor heads.
4. *Suspended-gate MOSFET (SG-MOSFET):* Measures the threshold pressure using air as a dielectric, altering the gate capacitance.
5. *Thermal sensors:* MOSFETs can measure on-chip thermal variations caused by power dissipation during IC testing. They offer better process compatibility and sensitivity than parasitic BJTs.

6. *Photosensors (CIS-CMOS image sensors):* Modern sensors use four-transistor (4T) n-MOSFET pixels for high-speed, high-resolution imaging.
7. *Carbon-based FETs:* Technologies such as carbon nanotube FETs (CNTFETs) and graphene FETs (GFETs) have been explored for their superior electrical properties, offering higher sensitivity, quick response, and low power consumption for gas/biosensing.

Specific Applications and Performance

1. *Gas/biosensors:* MOSFET-based gas sensors, such as ISFETs and GASFETs, detect hydrogen, ammonia, and other compounds by surface adsorption reactions with the gate dielectric.
2. *Medical/biomedical:* FET sensors are used to detect DNA hybridization, biomarkers, and neurotransmitters.
3. *Pressure/stress sensors:* MOSFETs on thin silicon diaphragms use the piezoresistive effect (change in carrier mobility) to measure pressure, with sensitivities improved using new readout circuits.
4. *Advanced structures:* Cylindrical surrounding gate (CSG) MOSFETs have exhibited 4.5 times higher sensitivity than double-gate (DG) MOSFETs, making them excellent candidates for low-power photosensors.

Design Considerations and Future Trends

1. *Subthreshold region:* Operating MOSFETs in the subthreshold region is popular for modern sensors because it offers maximum sensitivity and low power consumption.
2. *Process variations:* A major challenge is handled by employing dynamic element matching (DEM) and multipoint calibration.
3. *Future trends:* Development is moving toward 3D architectures, such as FinFETs and gate-all-around (GAA) nanosheets, for improved gate control and higher sensitivity, as well as integrating AI-driven data analysis for real-time sensing.

CONCLUSION

The evolution of MOSFET technology from a binary switch to a versatile sensing element marks a pivotal shift in the manner in which we capture and interpret the world around us. The convergence of ultra-scaled channel architecture, gate-level functionalization, and power-aware operating modes has endowed MOSFETs with a sensor-centric identity that is both scientifically compelling and industrially viable.

1. *Performance gains through nanoscale control:* By shrinking the channel length and employing multigate geometries (FinFET, GAA-FET), electrostatic integrity is maintained even in the presence of surface-bound analytes. This yields unprecedented transconductance modulation, translating minute environmental changes into measurable drain currents with signal-to-noise ratios that rival those of dedicated analog front ends.
2. *Hybrid gate materials as the new sensing interface:* The seamless integration of two-dimensional crystals, high-κ dielectrics, and molecular recognition layers directly on the gate oxide transforms the MOSFET into a true “gate-sensor.” This approach eliminates the need for external transduction stages, reduces parasitic capacitance, and preserves the CMOS-compatible footprint, which is critical for mass-producing sensor arrays.
3. *Ultra-low-power operation for autonomous nodes:* Exploiting subthreshold conduction and threshold-voltage tuning enables sensor operation at microwatt levels, making continuous monitoring feasible on energy-harvesting platforms (solar, thermoelectric, or RF scavenging). Adaptive bias algorithms further extend the battery life by dynamically matching the operating point of the transistor to the sensed stimulus.
4. *Design framework for smart sensor systems:* The proposed co-design methodology links surface chemistry (binding affinity, selectivity) with circuit techniques (bias-steering, on-chip calibration). This synergy yields self-aware sensors that can correctly drift, compensate for temperature variations, and communicate the diagnostic health status through built-in digital interfaces.

Looking forward, three research frontiers promise to amplify the impact of MOSFET-based sensors.

1. Quantum-dot and single-electron sensing leverage charge quantization for ultra-high sensitivity.
2. 3D monolithic integration stacks sensor layers atop logic to create "sensor-in-memory" architectures.
3. Machine learned bias optimization, where on-chip AI continuously refines the operating conditions for each sensing event.

In summary, MOSFET technology has matured into a universal sensor platform that combines the rigor of semiconductor engineering with the specificity of chemical and biological transduction. By unifying device physics, material functionalization, and low-power circuit strategies, the next generation of MOSFET sensors will not only detect the invisible but also interpret, adapt, and act, realizing the long-awaited promise of truly intelligent, pervasive sensing.

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