

Rational Design of Soft Integrated Sensor Systems

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Abstract

This review examines the cutting-edge advancements in soft integrated sensor systems, underscoring their pivotal role in the evolution of next-generation electronics for applications spanning health monitoring, environmental sensing, human-machine interfaces, and the Internet of Things. The discussion centers on the development of stretchable sensors that exhibit heightened flexibility and sensitivity, the critical role of sensor arrays in facilitating multi-point measurements, and the ongoing challenges in their manufacturing. The integration of sensors with circuits is highlighted as essential for achieving multifunctional capabilities, with a focus on the progress of multimodal sensors that can detect an array of chemical and physical signals. The abstract concludes by emphasizing the imperative to further refine high-performance integrated sensor systems, addressing key challenges in stability sensing and wireless communication to realize their full potential in the realm of smart electronics.

Keywords

Soft Integrated Sensor Systems; Structure-Based Stretchable Sensors; Integrated Circuit Strategies.

1. Introduction

In the last ten years, considerable progress has been achieved in the enhancement of intelligent sensor systems for monitoring human health and detecting external stimuli.¹ A substantial body of research has been dedicated to the development of high-performance, skin-like stretchable sensors characterized by flexibility, sensitivity, and reliability. Despite this, the evolution of flexible integrated sensor systems remains an ongoing endeavor. To meet the demand for real-time, multi-point signal detection, there has been a surge in the development of sensor arrays, which are indispensable for tracking a variety of vital signs that single or dual-functional sensors cannot capture alone. Consequently, the interest in wearable, integrated multimodal sensor systems has grown, given their capacity to handle the intricate requirements of health monitoring, environmental sensing, HMI, and IoTs.²

Challenges notwithstanding, the successful integration of various bimodal and multimodal sensors into sensor systems has been noted. Notably, soft, integrated 3D sensor systems provide a broad spectrum of monitoring capabilities, such as temperature, strain, humidity, pressure, glucose levels, pulse oximetry, and the detection of multiple stimuli concurrently.³ Moreover, the development of integrated 3D sensor systems with adjustable sensing ranges and extensive coverage is crucial for versatile applications. Common fabrication techniques for 3D sensing structures include epitaxial growth, biomimicry, template-based methods, and carved templates, offering diverse ways to produce highly sensitive, flexible, and stretchable 3D sensor arrays suitable for medical diagnostics, environmental monitoring, IoTs, AI, and HMI.⁴

The synergy between sensors and circuits is pivotal for multifunctionality, particularly in harmonizing the detection of various stimuli from both the human body and the environment. This synchronization is vital for precise therapeutic interventions and swift environmental sensing, marking the integration

of stretchable sensors with circuits as a notable leap forward in healthcare and environmental monitoring.⁵

2. Integrated Soft Sensor Systems

2.1 Sensor Arrays

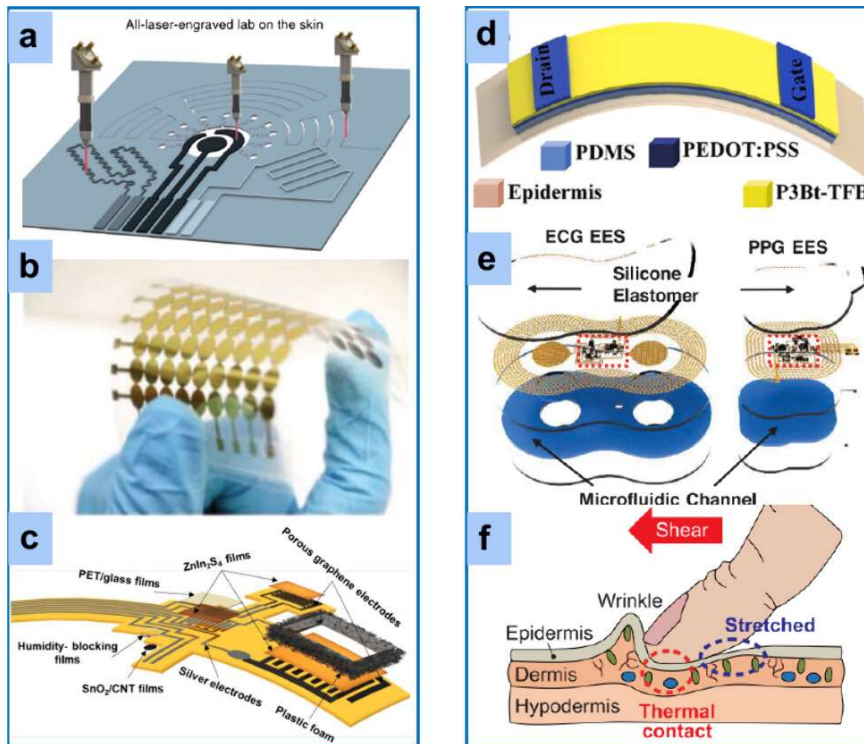


Figure 1. Sensor arrays.

Sensor arrays, with their ability to provide 2D mapping, are a significant advancement over single sensors that offer only single-point data. As the demand for multi-spot signal measurement grows, the necessity for flexible sensor arrays capable of *in vivo* mapping becomes more apparent. Their mechanical flexibility, planar mapping, and multi-location monitoring capabilities render them ideal for smart sensor applications, including real-time medical monitoring, on-site perspiration analysis, wearable pH sensing, thermal flow detection, temperature monitoring, and pressure distribution sensing.^{6, 7}

Despite their potential, the development and fabrication of sensor arrays, particularly for complex sensing tasks, present significant challenges. Simplifying the hardware and reducing costs remain pressing issues for practical applications. For health monitoring, temperature mapping is critical. Flexible and highly accurate thermal sensing arrays overcome the issue of untethered heat transfer, which can lead to inaccurate thermal sensing.⁸ These arrays use a low thermal conductive medium to enhance accuracy by up to 50 times in large-scale applications. Additionally, macroscale devices based on airflow distribution have shown success on high thermal conductive stages and curved surfaces, making them suitable for IoT applications.⁹

Pressure sensing is crucial for environmental monitoring. A flexible ferroelectric sensor with high pressure sensitivity (47.7 kPa^{-1} , detectable down to 1.3 Pa), a broad linear response range (0.0013 to 353 kPa), and stability over 5000 cycles at pressures up to 272 kPa, exemplifies this. Figure 1b shows a 3D touch sensor system capable of sensing and recording 3D information, fabricated using maskless laser processing for electrodes and spray coating of silver nanowires (AgNWs).¹⁰ This sensor array can monitor pressure wirelessly and has withstood over 30000 pressure cycles, offering a new dimension in flexibility. Furthermore, scalable piezoelectric ZnO thin-film transistors with high spatiotemporal resolution have been investigated, offering a spatial resolution of $100 \mu\text{m}$ and sub-10

ms temporal resolution, capable of measuring both normal and shear forces with sensitivity at 0.207%/mN, and maintaining performance after 10000 bending cycles.

However, the stretchability of these skin-inspired sensor arrays is often limited by the stretchability and functionality of electronic circuits and active materials, necessitating further improvement. Figure 1d presents an all-flexible tactile sensor with capacitive sensing, combining a double-side micro-pyramids dielectric layer with a liquid metal electrode. This sensor boasts high sensitivity up to 2.78 kPa⁻¹, an ultralow detection limit of approximately 3 Pa, a fast response time of 80 ms, and excellent durability over 10000 cycles. A stretchable ultralow pressure sensor array, fabricated by photo-reticulated strain localization films, is shown in Figure 1e, capable of detecting 1 g weight even in a bending state. Figure 1f displays an array of bipolar stretchable sEMG electrodes with a self-attention-based graph neural network, achieving approximately 97% gesture recognition accuracy, utilizing a nature- and kirigami-inspired design for a stretchable multichannel sEMG array with 30% strain.¹¹

2.2 Multimodal Sensors

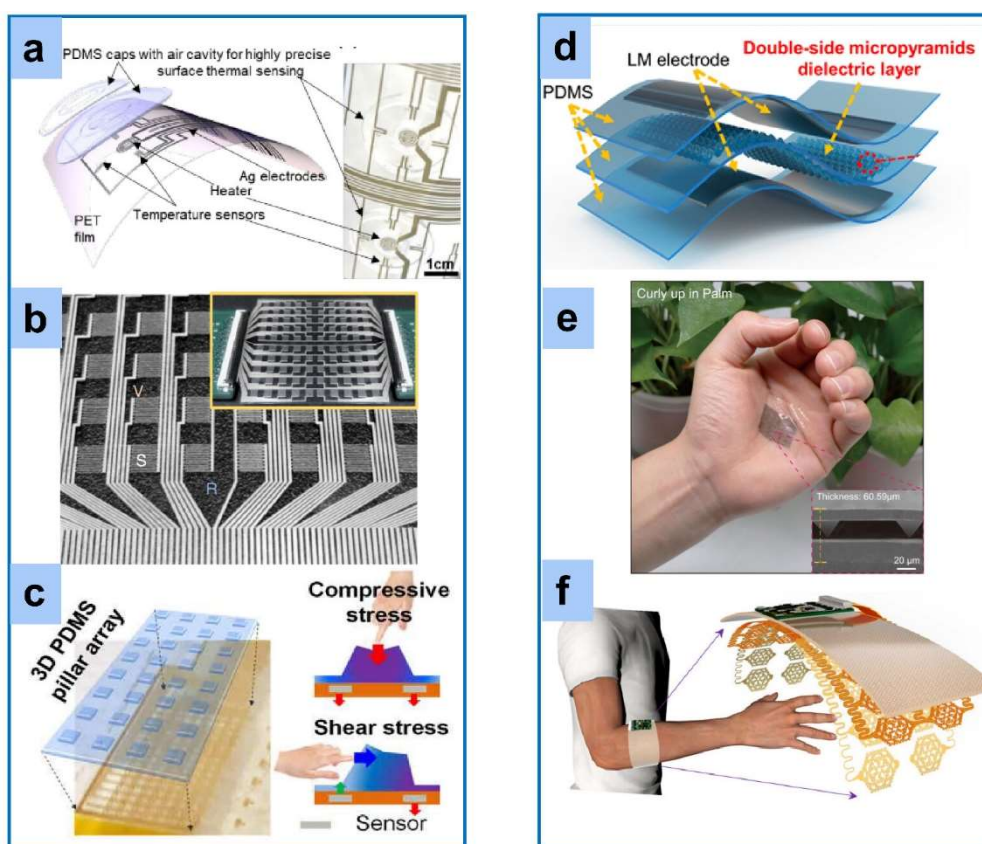


Figure 2. Multimodal sensors.

Multimodal sensors that emulate the skin and their integration with circuits are in high demand for practical uses. These sensors offer a more holistic detection capability, sensing both molecular analytes and physiological health indicators. They are anticipated to feature straightforward detection processes and seamless, miniaturized integration. Despite the challenges in merging chemical detection with physical monitoring in flexible, wearable systems, advancements have been made. For instance, a CO₂ laser-engraved multimodal sensor system (Figure 2a) has been developed to wirelessly track chemical signals and critical physical health indicators like temperature and respiration rates. Additionally, a flexible piezoresistive sensor capable of sensing pressure, sound, and acceleration is showcased in Figure 2b. This MXene-based sensor boasts a detection threshold of 9 Pa, a sensitivity of 99.5 kPa⁻¹, and maintains performance over 10,000 cycles¹². While multifunctional sensors are vital for human health monitoring, extending this capability to plants presents a significant challenge due to their biological intricacy. An integrated multimodal sensor

made from stacked ZnIn₂S₄ nanosheets (Figure 2c) has been introduced to monitor plant growth by sensing light illumination and maintaining steady humidity, allowing for the precise management of plant health over extended periods. These skin-inspired sensors show great promise for human-robot interfaces and sensor circuit integration.

For the widespread adoption of intelligent multimodal sensor systems, devices need to not only possess diverse sensing capabilities but also exhibit high stretchability to replicate human skin. Figure 2d illustrates an innovative, smart electronic skin that is printed using cost-effective and straightforward techniques, offering multimodal monitoring and energy conversion functions. This system can detect various environmental stimuli, including light, temperature, and strain, and exhibits excellent antibacterial properties, 30% stretchability, and a linear temperature sensitivity of 2.6% °C⁻¹. Such devices are poised for broad applications in HMI, soft robotics, and healthcare therapy. In neonatal care, continuous monitoring of vital signs is crucial, yet traditional platforms with rigid interfaces and complex wiring can be harmful to fragile skin. To overcome this, Chung et al. have developed ultrathin, wireless electronic systems for neonatal monitoring (Figure 2e), capable of recording vital signs and skin temperature without the need for batteries, offering soft mechanics and minimal skin irritation.¹³

Despite these advancements, decoupling multiple signals on a single device without interference remains a challenge. Figure 2f presents a deformable artificial multimodal ionic receptor that maintains consistent temperature measurements through 5000 stretching cycles at 30% strain, with no thermal hysteresis in repeated detections. This receptor can differentiate between thermal and mechanical signals by analyzing ion relaxation dynamics, highlighting the importance of material selection and sensor structure design in achieving multimodal sensors with effective sensing mechanisms.

2.3 Sensors Integration with Circuits

The integration of integrated circuits with biological systems significantly amplifies the capabilities of scalable, skin-inspired sensor systems, facilitating applications in medical diagnostics, human-machine interfaces (HMIs), artificial intelligence (AI), and the Internet of Things (IoTs). These soft, skin-conforming integrated circuits typically consist of three key components: sensors, HMI input/output devices, and circuits for information processing. While there has been successful demonstration of stretchable input/output devices and flexible sensing materials within integrated circuit systems, the development of stretchable circuits continues to pose a significant challenge¹⁴. The convergence of sensors and circuits paves the way for the creation of high-density sensor systems, which may involve extensive areas with either a single layer or stacking multiple layers (Figure 3a–c). Figure 3a illustrates a fully integrated, wearable ultrasonic system-on-patch designed for monitoring deep tissues in motion. This innovative patch enables continuous surveillance of physiological signals from depths of approximately 164 mm, including central blood pressure, heart rate, and cardiac output, over a duration of up to 12 hours. Figure 3b presents a wearable olfactory feedback system, operable wirelessly and programmatically, tailored for olfactory virtual reality experiences. Additionally, Wan et al. have introduced a biocompatible and biodegradable light-curable conductive ink, alongside an all-in-one flexible system capable of conducting in situ injection and photonic curing of the ink, as well as monitoring biophysiological information (Figure 3c). These advancements underscore the potential of integrated circuits in enhancing the functionality and adaptability of skin-inspired sensor systems.

Integrated circuits in wearable sensors enable the relentless surveillance of human physiological signals, biopotentials, and critical medical data, thereby actively sensing and managing human health. Among the spectrum of wearable health monitoring devices, sophisticated integrated medical monitoring systems have garnered considerable commercial interest, particularly for their applications in skin sensation and environmental perception. Accurate signal discrimination is pivotal in integrated sensing circuits, as distinguishing vital signs from environmental noise is inherently challenging. High-sensitivity, multifunctional sensors often introduce substantial background noise

during human motion monitoring. A strategic approach to this issue involves enhancing the selectivity of health signals through the design of active material structures. For example, a wearable sweat analysis platform that integrates an electrode array with a wireless flexible printed circuit board has been reported. This array includes sensors for sweat induction (such as Na^+ , Cl^- , and glucose) and sensing electrodes. Additionally, differential amplifiers based on organic thin-film transistors are favored for their ability to amplify signals and eliminate noise in vital sign monitoring.¹⁵

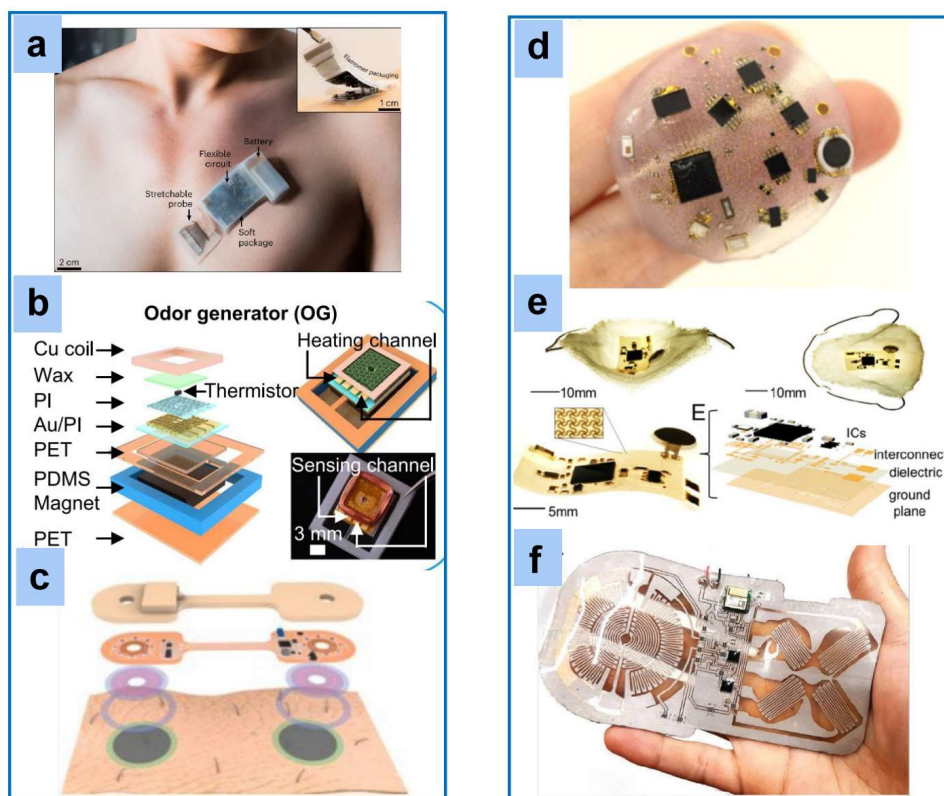


Figure 3. Sensor integration with circuits.

The primary challenge in integrated sensor circuits lies in the immature system-level integration, where the spatial distribution and stretchable properties of integrated systems require optimization. The stretchability of rigid circuit components on flexible substrates particularly limits the flexibility and comfort of these devices. While optimized circuit design strategies can achieve multifunctional circuits without cross-coupling, current approaches often involve 2D layouts of microcomponents and interconnects. The introduction of 3D architectures bypasses the engineering restrictions and performance limitations of traditional 2D designs, with stacking multiple active layers to monitor external stimuli proving an effective decoupling method. Figure 3d showcases a 3D soft circuit system facilitated by deterministic compressive buckling, optimizing mechanical stability and electrical robustness through 3D interconnect configurations in stretchable integrated sensor systems, with a notable radial stretch of up to 70%. Figure 3e presents a stretchable oral cavity sensor system for sodium intake measurement, crucial for hypertension management. This stretchable hybrid electronic system offers ultrathin, low-profile soft electronics and wireless monitoring, contrasting with existing intraoral devices and overcoming communication distance limitations and continuous operation challenges of passive wireless telemetry.

The complexity and cost of fabrication methods for integrated systems are significant barriers to commercialization. In resource-limited settings, the development of effective, low-cost, and accessible fabrication techniques for integrated circuits is essential. The urgent need for improved integration techniques of flexible electronic circuits in sensor systems is clear. Gallium-based liquid

metals, with their unique combination of fluidity, conductivity, stretchability, self-healing capabilities, and biocompatibility, are ideal for flexible electronics manufacturing. Enabled by a liquid metal composite, a block copolymer, and an electrochemical material recycling technique, a microchip-integrated soft-matter 3R electronics system with a remarkable 1700% strain is showcased in Figure 3f.

3. Conclusion

This review underscores the latest breakthroughs in stretchable integrated sensor systems, pivotal for the future of electronics. It delves into structure-based flexible sensors, material-based wearable devices, and integrated stretchable sensor systems, detailing how structural designs like serpentine, microcrack, wrinkle, and kirigami endow sensors with essential attributes such as stretchability, softness, stability, and sensitivity. These innovations are laying the groundwork for the creation of multifunctional, stretchable sensor circuits compatible with skin-like substrates.

Crafting a high-performance integrated sensor system with superior sensing capabilities is a complex, interdisciplinary endeavor that necessitates the synergistic combination of diverse parameters. Such systems are anticipated to revolutionize various fields, including artificial intelligence, human-robot interfaces, medical treatments, and the Internet of Things. Despite significant progress, the development of multimodal sensor systems remains nascent, particularly concerning the detection and integration of multiple stimuli. The current strategies for enhancing sensor systems' stretchability and sensing performance include: (i) planar structural design, which amalgamates various designs within a single plane to boost functionality; (ii) spatial structure design, transitioning from 2D planar layers to 3D multilayer configurations to amplify complexity and capability; and (iii) integrated circuit strategies, which refine integration techniques to expand the sensor systems' effective area and optimize circuit layout. Constructing 3D sensor structures like domes, spheres, pyramids, walls, rods, pillars, and sheets from a variety of 3D micro/nanomaterials enhances surface area and sensitivity for sensing applications. These strategies are instrumental in propelling the evolution of the next generation of multifunctional and highly efficient stretchable integrated sensor systems.

For structured-based sensors, universally desired properties include high flexibility, broad sensing range with competitive sensitivity, minimal hysteresis, linearity, durability, stability, and swift response and recovery times. Moreover, these sensors must align mechanically with human skin for secure adhesion and to emulate skin-like functionality, which is vital for optimal performance in health monitoring, HMI, and wearable technology applications.

Beyond the aforementioned challenges, additional issues such as stability sensing and wireless communication must be resolved for the practical deployment of intelligent integrated sensor circuit systems. Stability sensing is essential for ensuring reliable long-term performance in dynamic and harsh settings, while wireless communication is crucial for facilitating uninterrupted data transfer between sensors and external devices, enabling real-time monitoring and interaction. Addressing these challenges and requirements will position integrated sensor circuits as the forefront of next-generation electronics.

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