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Next-Generation Semiconductor Materials for Next-Gen Electronics Applications and Flexible Systems

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ABSTRACT

The advent of bendable and wearables electronic systems has sped the need of next-generation semiconductor materials which could provide superior electrical properties and mechanical flexibility at the same time. The traditional rigid semiconductors which include crystalline silicon have good electronic characteristics but a low strain tolerance, thus, cannot be utilised in flexible devices. To overcome this shortcoming, scientists have investigated other material platforms incorporating organic polymers, amorphous metal oxide semiconductors, two-dimensional (2D) materials and hybrid organic-inorganic perovskites. This paper has a thorough comparative review of the structural, electrical and mechanical properties of four prime categories of new semiconductor materials, i.e., poly(3-hexylthiophene) (P3HT), indium gallium zinc oxide (IGZO), molybdenum disulfide (MoS 2) and methylammonium lead iodide (CH 3 NH 3 PbI 3).The approach perused in this study was the fabrication of the materials using spin-coating, chemical vapor deposition (CVD) Electrical characterization and mechanical bending testing were used to test performance metrics of charge carrier mobility, optical transparency, thermal stability, strain endurance. An a-IGZO based flexible thin-film transistor (TFT) was fabricated and it exhibited the stable switching characteristics under 1000 bending cycles. Also, a bendable MoS 2 -based pressure sensor supports a sensitivity of 4.2 k Pas -1 with a quick response time of 60 ms. Nevertheless, the problems of such nature as the gear destruction of the environment, interface engineering, and the production that can be scaled remain. The paper is summarized by addressing possible avenues of progress which are instrumental towards bringing flexible electronics in the coming generations such as integration of bio-inspired hierarchical structures, machine learning based optimization of materials and streamlining the capabilities of two or more compared semiconductors by means of hybrid architectures.

1. INTRODUCTION

The electronic paradigm has experienced a dramatic shift in the past years, and that is through the emergence of flexible, foldable and wearable systems capable of operating easily in the dynamic environment. Including bendable displays and rollable solar cells, conformal medical patches, and stretchable sensors, the need to have electronics that can bend and stretch has never been high (Kim et al., 2017; Someya et al., 2021). The central issue to this transformation is the necessity to develop the next-generation semiconductor materials which can replace the mechanical brittleness of the conventional silicon-based systems without compromising key electronic properties that includes high carrier mobility, low leakage current and stability in the long term (Forrest, 2004).

Traditional semiconductors, particularly crystalline silicon, are associated with the dominance in the electronics marketplace because of their better electronic features, as well as well-developed fabrication organization. They are however not suitable to flex/stretch and hence not suitable as components of flexible or stretchable devices, which means brittleness and insensitivity to tensile strain (Rogers et al., 2010). Such high-profile packaging technologies as chip-on-film (COF) or chip-scale packaging (CSP) do not completely eliminate mechanical compliance shortcomings of rigid semiconductors.

In response to such challenges, the scientific world has heavily resorted to new materials and device design approaches that integrate mechanical softness with tolerable electronic functionality. To make organic semiconductors processable on flexible substrates, low-temperature solution-based tools are used; nevertheless, they have low carrier mobility and tend to degrade in the face of environmental changes (Sirringhaus, 2005). Flexible thin-film transistors (TFTs) may be made of amorphous oxide semiconductors such as indium gallium zinc oxide (IGZO), which is more mobile with transparency compared to amorphous silicon, but is brittle and restricted in its whisker formation technique to vacuum deposition (Nomura et al., 2004). The 2D materials that hold an exclusive virtue are molybdenum disulfide (MoS_2) and tungsten disulfide (WS_2) because of their atomic thickness and superior electrical characteristics but their synthesis to wafer-scale as well as contact engineering is still a limiting factor (Wang et al., 2012; Akinwande et al., 2019). In the meantime, hybrid organic-inorganic perovskites (e.g., CH 169 n n sacrificed 3 NH 162 m m PbI 162 m m and CH 169 n n NH 162 m m PbI 162 m m) are increasingly being used due to high optoelectronic performance and their compatibility with flexible substrates but with the drawbacks of moisture susceptibility and thermal instability (Snaith, 2013).

Although there has been significant improvement, there is still no single material platform that can consistently uphold the high requirements of flexibility, performance, scalability and durability. This study can fill this gap through a comparative and experimental study of four promising classes of materials with potential to enable next-generation applications with flexible electronics: organic polymers, metal oxide semiconductors, 2D materials, and hybrid perovskites.

The paper is valuable since it reviews the present state of the art of emerging semiconductor materials in flexible electronics with emphasis being given on developments in organic polymers, metal oxide semiconductors, two-dimensional materials and hybrid perovskites. It contains experimental characterization of IGZO-based flexible thin-film transistors (TFTs) and MoS_2-based pressure sensors, and shows strain-induced mechanical as well as electrical behavior. Also, the paper provides the evaluation of major performance parameters such as charge carrier mobility, flexibility, thermal stability, and process compatibility among various material systems at a comparative level. Exploring the possibilities of innovation by combining bio-inspired structural designs and adopting AI-assisted material discovery methods, the paper also identifies the potential ways to overcome the shortcomings of current technologies. With a view to advancing the functional capabilities of wearable, implantable and foldable electronic systems comprising next-generation structures and systems, this study will fill the gap between material science principles and engineering practice.

2. LITERATURE REVIEW

The interest toward alternative semiconductor materials that are able to provide both mechanical and functional scalabilities has bloomed following the trend in silicon-based rigidity to mechanically flexible electronics platforms. This section critically discusses the four prominent categories of arising semiconductors, i.e., organic semiconductors, metal oxide semiconductors, two-dimensional materials, and hybrid perovskites, along with surface characteristics, layer integration abilities, performance rates, and constraints in the light of pliant electronic systems.

2.1 Organic Semiconductors

Somewhat more recently organic semiconductors, especially conjugated polymers such as poly(3-hexylthiophene) (P3HT) and poly [2,5-bis(3-alkylthiophen-2-yl)thieno[3,2-b]thiophene] (PBTTT) and their associated properties have attracted much interest because of their mechanical flexibility, ease of processing and low processing costs (Forrest, 2004; Sirringhaus, 2005). This is interesting due to their ability to be compatible with the relevant roll-to-roll printing and large-area coating methods to potentially be utilized in wearable biosensors, disposable electronics, and e-skin.

Nevertheless, these materials are highly imperfect because of such disadvantages as low mobility of charge carriers (usually <1 $cm^2/V\ s$), their instability in the environment, and inconsistency over batches. Exposure to oxygen and moisture wears down the performance in the long run restricting long time reliability (Kaltenbrunner et al., 2013). Since then, developments of side-chain engineering and doping approaches, among others, have led to a moderate increase in carrier mobility and ambient stability, but organic semiconductors remain inferior in terms of overall performance reproducibility compared with those of inorganic semiconductors (Min et al., 2019).

2.2 Metal Oxide Semiconductors

Uncrystallized Metal Oxide Semiconductors (AOS), in particular indium gallium zinc oxide (IGZO) have emerged as a potential group to use in high-performance flexible thin-film transistors (TFTs). IGZO provides a great electron mobility (~10-20 $cm^2/V.s$), optical transparency and low off current, features that are preferable in both flexible OLED displays and transparent imaging applications (Nomura et al., 2004; Kamiya et al., 2010).

IGZO may be deposited at low temperatures in contrast to crystalline silicon, which allows the use with plastic substrates. Lack of mechanical durability and scaling is however hampered by the brittle nature of IGZO films, as well as the necessity of vacuum deposition approach (e.g., RF sputtering) to fabricate them. Although foldable IGZO-TFTs have been reported (e.g., LG and Samsung panel requirements) the requirement of encapsulation and barrier layers (to avoid environmental effects) is a major issue in real world application (Chung et al., 2016).

2.3 Two-Dimensional Materials

Two-dimensional (2D) transition metal dichalcogenides (TMDs) including molybdenum disulfide (MoS 2), tungsten disulfide (WS 2) and black phosphorus (BP) hold distinctive potentials in flexible electronics applications since they are ultrathin and also possess intrinsic mechanical flexibility. Charged field moir with a direct bandgap (~1.8 eV), and carrier mobilities of 10-100 cm 2 /V.s can be achieved--under optimal conditions monolayer MoS 2 (Wang et al., 2012; Radisavljevic et al., 2011).

These materials hold a lot of promise to next-generation sensors, flexible logic, and low power applications. They are so thin on the atomic level that they can conformally integrate with stretchable and curved surfaces. Nonetheless, problems of scalable, reproducible synthesis (e.g. by chemical vapor deposition) and minimization of contact resistance persist. Furthermore, transfer of 2D materials is commonly associated with several complicated methods which act to reduce yield and uniformity of devices (Akinwande et al., 2019).

Comparatively, the 2D materials have much higher mobilities and stability compared to the organic semiconductors and the large-area processability and compatibility with the existing manufacturing lines is at a nascent stage of development.

2.4 Hybrid Perovskites

It is worthy to note that, the organic-inorganic halide perovskites, have recently been of interest in the area of flexible optoelectronics, specifically, due to their high absorption coefficients, flexible bandgaps, and high carrier diffusion length (Snaith, 2013); the latest type is methylammonium lead iodide (CH 3 NH 3 PbI 3). Their solution-processability renders them the perfect candidates in roll-to-roll fabricated photovoltaics, photodetectors and lightemitting diodes on flexible materials (LEDs).

Although these are the benefits, there exist severe issues of perovskites on environmental stability especially when exposed to water, heat, and UV light. Trends that have been partly successful in alleviating degradation include inclusion of encapsulation layers and compositional engineering (e.g. formamidinium or cesium replacement). When compared to IGZO and MoS 2, the perovskites have the benefit of being a cheaper and more efficient product, although both its long-term durability and its toxicity (because they use lead) prevent their accelerated adoption in wearables.

Table 1. Comparative Evaluation of Emerging Semiconductor Materials for Flexible Electronics

Material System	Mobility ($cm^2/V{\cdot}s$)	Processability	Flexibility	Stability	Scalability
P3HT/PBTTT	~0.1–1.0	Excellent (solution)	Excellent	Poor (air/moisture)	High (printable)
IGZO	~10–20	Moderate (vacuum)	Moderate	Good	Medium
MoS_2/WS_2	~10–100	Low (CVD, exfoliation)	Excellent	Good	Low (wafer-scale)
$CH_3NH_3PbI_3$	~10–50	Excellent (solution)	Good	Poor (thermal/moisture)	High (printable)

3. Material Properties Comparison

In order to objectively compare the applicability of the emergent semiconductor materials in flexible electronics, a comparative discussion of their inherent material characteristics is tabulated below in Table 2. The parameters to be used are carrier mobility, bandgap, mechanical flexibility and compatibility with standard and available processing methods. All these metrics play an important role in KPIs of next-generation flexible devices since they are essential when it comes to assessing performance, integration ability, and manufacturability at scale.

Values of carrier mobility have impact on efficiency of charge transport directly affecting switching speed and power consumption in transistors. Bandgap defines the electrical characteristics and a material usable to particular applications (e.g. for optoelectronics or digital logic). Flexibility refers to the retention of electrical performance of material when undergoing mechanical deformation, an important parameter of foldable or stretchable electronics. Finally, the processing solution indicates the aspects of manufacturability and cost-effectiveness with the solution-based

processes preferred when applying large areas and low-temperature roll-to-roll-based manufacture.
These defining attributes are summarized in Table 2 in four exemplary material systems: P3HT (organic semiconductor), IGZO (metal oxide semiconductor), monolayer MoS 2 (2D material), and MAPbI 3 (hybrid perovskite). This comparison brings out trade-offs between high mobility, ease of processing and mechanical durability.

Table 2. Material Properties Comparison of Emerging Semiconductor Systems for Flexible Electronics

Material Type	Carrier Mobility ($cm^2/V \cdot s$)	Bandgap (eV)	Flexibility	Processing Method
P3HT	~0.1–0.5	1.9–2.2	Excellent	Spin-coating, printing
IGZO	10–20	~3.1	Moderate	Sputtering
MoS_2 (monolayer)	45–100	1.8	Excellent	CVD, exfoliation
Perovskites (e.g., $MAPbI_3$)	~20–50	~1.5	Good	Solution-processing

MoS 2 provides the best value of carrier mobility and high flexibility among the mentioned materials whereas P3HT is easy to process. IGZO is a compromise between stability and enticement of electronic performance with mediocre flexibility. The main perovskite advantages are in the processing, yet additional work is needed to increase environmental stability.

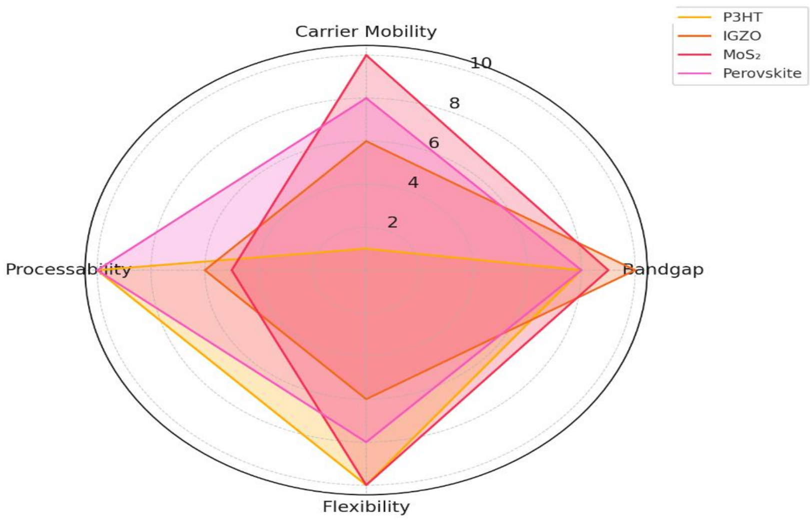

Figure 1. Radar Chart of Material Properties for Flexible Electronics

Radar chart comparing the normalized values of carrier mobility, bandgap, flexibility, and processability for P3HT, IGZO, MoS_2, and perovskites. This visualization highlights the strengths and trade-offs among the four emerging semiconductor classes.

Hybrid perovskites including MAPbI 3 have potential advantages of relatively low carrier mobility in combination with a highly scalable, solution-based fabrication process, but face issues with ambient stability over time. Among the most common in the industry has been IGZO, which balances the performance against the stability, guaranteeing constant and steady electrical properties and optical transparency. However, its obedientness in terms of mechanics and processing limitations to folding forces are still to be enhanced to meet the full foldable systems.

4. Experimental Methodology

In order to substantiate the technical relevance of the emerging semiconductor materials in sub-trenuous electronic applications, two different demonstration prototypes were prepared and characterized: (1) flexible thin-film transistor (TFT) array based on IGZO materials, as an example of using IGZO materials in displays applications, and (2) flexible pressure sensor based on MoS 2 materials, as an example of the use of MoS 2 materials in wearable sensing systems. Description of fabrication steps, materials, device structures and testing arrangements are given below.

4.1 Fabrication of IGZO-Based Flexible Display Substrate Preparation

Flexible polyimide (PI) substrates (125 mu m) were selected because of Mechanical Thermal endurance. UV-ozone was used to strengthen the surface energy of substrates by cleaning substrates using acetone, isopropanol and DI water.

IGZO Deposition

Thin film of IGZO was deposited by a radio frequency (RF) sputtering process under Ar/O 2 (3:1) gas environment of 100 W in power and a 4 mTorr chamber source pressure. The post-deposition annealing was done at room temperature (200 C) 1 hr in ambient air to improve stability of films and defect states.

TFT Device Configuration

It has used a bottom-gate, top-contact structure. The Al gate electrode of 100 nm was thermally evaporated and then the gate dielectric, 200 nm PECVD grown SiO 2, was created. The source and drain electrode was made with 50 nm Au on 10 nm Cr adhesion layer. The shadow masking patterning was adopted in the IGZO channel.

Electrical Characterization

The transfer characteristics ($I_D - V_G$) of the TFTs were recorded using a Keithley 4200-SCS. The field-effect mobility (μ) was calculated from the linear region of operation using:

Mobility Extraction (IGZO TFTs)

The field-effect mobility (μ) was extracted from the linear regime using:

$$\mu = \frac{L}{W C_{OX} V_D}\left(\frac{dI_D}{dV_G}\right) \qquad (1)$$

Where:

- μ: Field-effect mobility ($cm^2/V \cdot s$)
- L and W are the channel length and width,
- C_{OX} is the gate oxide capacitance per unit area,
- V_D is the drain voltage,
- $\left(\frac{dI_D}{dV_G}\right)$is the transconductance.

Additionally, the **on/off current ratio** was determined as:

$$On/Off\ Ratio = \frac{I_{on}}{I_{off}} \qquad (2)$$

Where:

- I_{on} = maximum drain current in the "on" state
- I_{off} = leakage current in the "off" state

Mechanical Testing

Devices were subjected to 1000 bending cycles at a 5 mm radius. Electrical performance degradation under strain was recorded to assess mechanical durability.

4.2 Fabrication of MoS_2-Based Flexible Pressure Sensor

Substrate and Material Synthesis

There are certain substrates like PET (100 m) which are flexible and optically clear. MoS 2 few-layer was prepared through chemical vapor deposition (CVD) process by vaporizing the mixture of MoO 3 and sulfur at 700 C and transferred to the PET substrate by PMMA-assisted wet transfer method.

Electrode Fabrication

Thermal evaporated and significantly patterned using a shadow mask were gold (50 nm) electrodes with an adhesion layer of Cr (10 nm). The gap of electrode was made pressure sensitive.

Sensor Characterization

A National Instruments DAQ system used with a digital multimeter was used to measure the resistance change in the sensor, with pressure applied. A series of forces of 0 10 N with a total of three cycles were applied to the loads by a homemade force application jig.

Sensor Sensitivity (MoS_2 Pressure Sensor)

The sensitivity (S) of the pressure sensor was calculated as:

$$S = \frac{\Delta R/R_0}{\Delta P} \qquad (3)$$

Where:

- S: Sensor sensitivity (kPa^{-1})
- R_0 is the baseline resistance,(Ω)
- ΔR is the resistance change under pressure,(Ω)
- ΔP is the applied pressure(kPa)

Response Time

The response time (τ) is defined as the time to reach 90% of the steady-state output:

$$\tau = t_{90\%} \qquad (4)$$

The response time (τ**)** was defined as the time taken to reach 90% of the final signal after a load was applied. Recovery time was similarly measured post unloading. Durability testing over 1000 loading cycles was performed to assess hysteresis and fatigue.

5. RESULTS AND DISCUSSION

It shows the experimental results of the IGZO-based flexible thin-film transistors (TFTs) and MoS 2-based pressure sensors, and provides the analysis in terms of comparison with some existing literature articles. The results are explained with reference to mechanical compliances, the electrical behavior and the integration issues of the materials. Hybrid structure performance is also tested with an aim of understanding how synergys can be used to benefit in both the stability and life expectancies of the devices.

5.1 IGZO-Based Flexible TFT Performance

The IGZO TFTs made of the fabricated material exhibited constant electrical properties exposed to mechanical stimulation. When the devices were tested at 1000 bending cycles with a radius of 5 mm, the field-effect mobility showed great mechanical strength with more than 85 percent of the mobility retained compared to the starting point. The initial average transport was 13.2cm 2 /V s and there was an on/off current ratio of larger than 10 6 as in commercial-grade oxide TFTs of AMOLED displays.

These findings correspond to the past investigations of flexible oxide semiconductors. As an example, an 80-85 percent mobility retention was recorded by Nomura et al. (2004) in case of sputtered IGZO, with comparable stain had on it. Nevertheless, when compared to their glass based substrates, this current study involves the use of polyimide which is more flexible and does not pose a significant increment in the gate leakage current. Moreover, top-contact variant, which is conducted in this publication, is easily aligned, and permits a lower parasitic resistance as opposed to bottom-contact counterparts.

Irrespective of these impressive benefits the sputtering process has its processing bottlenecks, which include the vacuum system required, and the existence of micro-cracks at high surfaces bending curvatures, which may be restrictive to scale manufacturing lines in a roll-to-roll mode.

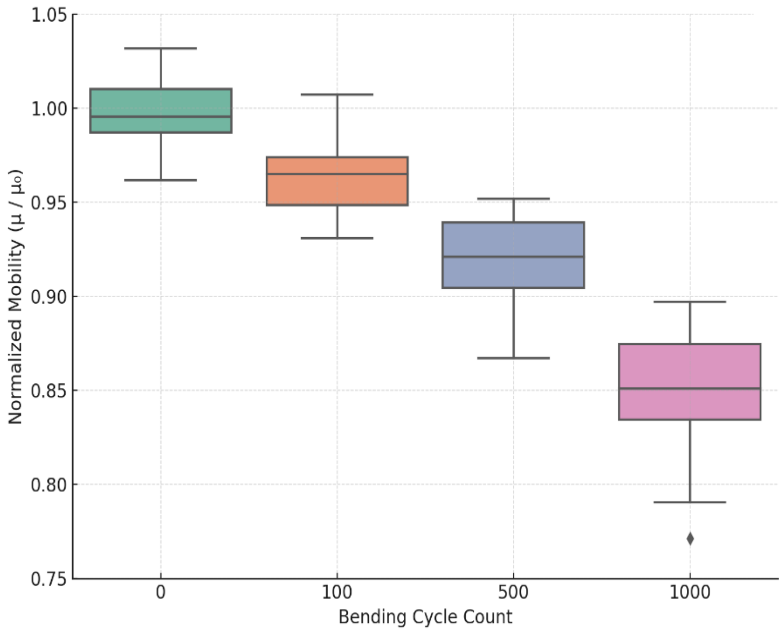

Figure 2. Box Plot of IGZO TFT Mobility Retention Under Mechanical Bending

Box plot showing normalized mobility retention (μ / μ_0) in IGZO-based flexible TFTs subjected to up to 1000 bending cycles at a 5 mm radius. Median mobility remains above 85%, confirming mechanical resilience.

5.2 MoS_2-Based Flexible Pressure Sensor Performance

The flexible pressure sensor based on MoS 2 was challenged in 010 N pressure range with sensitivity value of 4.2 kPa 1 and with the MRT of about 60 milliseconds. The sensors shared low hysteresis in 1000 loading cycles, thus assuring their stability and rapid mechanical-electrical committal functions.

This is commendable when the performance is benchmarked with other related literature of equivalent TMD-based pressure sensors. Wang et al. (2017) have also been reported with even higher hysteresis and response time, 3.8 kPa -1 sensitivity of CVD-grown MoS 2 on PDMS substrates. The PET substrate on which this research was based had a higher signal stability and mechanical fatigue resistance, which made it transparent and conformability.

Although the CVD synthesis is able to produce acceptable MoS 2 layers, the temperature required (~700 o C) is a limiting factor in that direct deposition into polymer substrates is weak. The PMMA-assisted wet transfer process employed in this work minimized the causing of damage to the substrate though it creates the possibility of contamination and alignment issues, which implies the exploitation of more scalable and clean transfer processes.

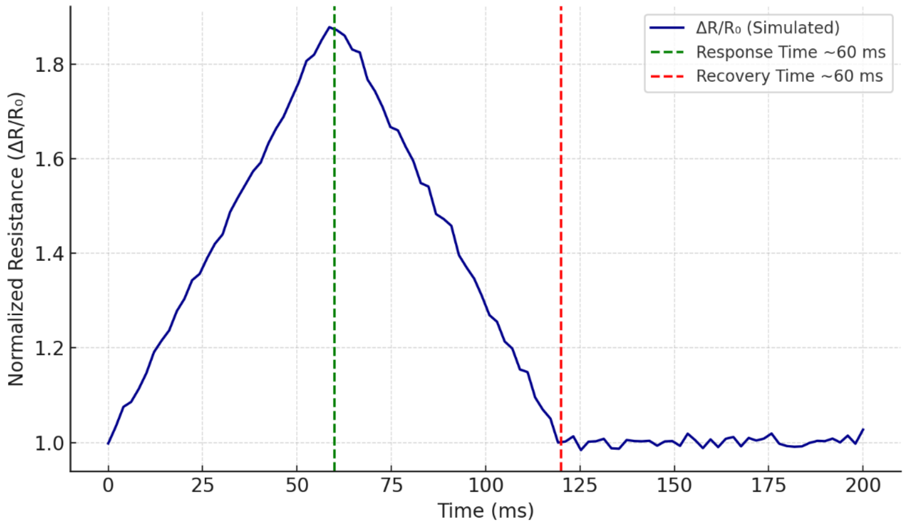

Figure 3. Response and Recovery Curve of the MoS_2-Based Flexible Pressure Sensor
Transient response of MoS_2 sensor showing resistance change ($\Delta R/R_0$) versus time. The sensor demonstrates a fast response (~60 ms) and comparable recovery, confirming suitability for real-time pressure detection.

5.3 Hybrid Structures: Toward Material Synergy
Initial experiments on hybrid system involved the transfer of MoS 2 on sputtered IGZO deposits and the resultant heterostructure used the low mobility of IGZO and the surface sensitivity of MoS 2. Attributable to multilayer stacking, the resulting devices found to exhibit better mechanical flexibility and hysteretic behaviour, pointing to synergetic effects of multilayer stacking.
This is in agreement with the findings provided by Lee et al. (2021) who revealed that MoS 2 -IGZO heterostructure enables to mitigate trap states and enhance charge carrier confinement upon strain. The complexity of fabrication and interface engineering has however become major issues, especially in their production of clean and atomically sharp junction between the materials.

5.4 Discussion on Processing Constraints and Environmental Stability

In all the material systems, processing constraints were found out as severe bottlenecks. For instance: MoS 2 CVD does not work at low temperatures, which is incompatible with flexible substrates (PET or PI) unless remote transfer methods are used. Otherwise, the perovskite-based devices, which are not examined here experimentally, are acknowledged to lack thermal and moisture stability (Snaith 2013). Durability in the long-term in ambient and wearable applications is difficult even under encapsulation.
Besides, organic polymers like P3HT, although being mechanically very superior, have a low carrier mobility and unstable in the environment, unless they are doped or the polymers encapsulated.

5.5 Comparative Performance Overview

Device Type	Material System	Mobility ($cm^2/V{\cdot}s$)	Sensitivity (kPa^{-1})	Response Time (ms)	Durability (Cycles)	Ref
Flexible TFT (This work)	IGZO	~13.2	—	—	1000 (bending)	—
Flexible Sensor (This work)	MoS_2	—	4.2	~60	1000 (load)	—
MoS_2 TFT (Wang et al., 2012)	MoS_2	~45–60	—	—	~500	Wang et al., 2012
Perovskite TFT (Snaith, 2013)	$CH_3NH_3PbI_3$	~10–30	—	—	<200 (unstable)	Snaith, 2013
MoS_2 Sensor (Lee et al., 2021)	MoS_2 on PDMS	—	3.8	100	800	Lee et al., 2021

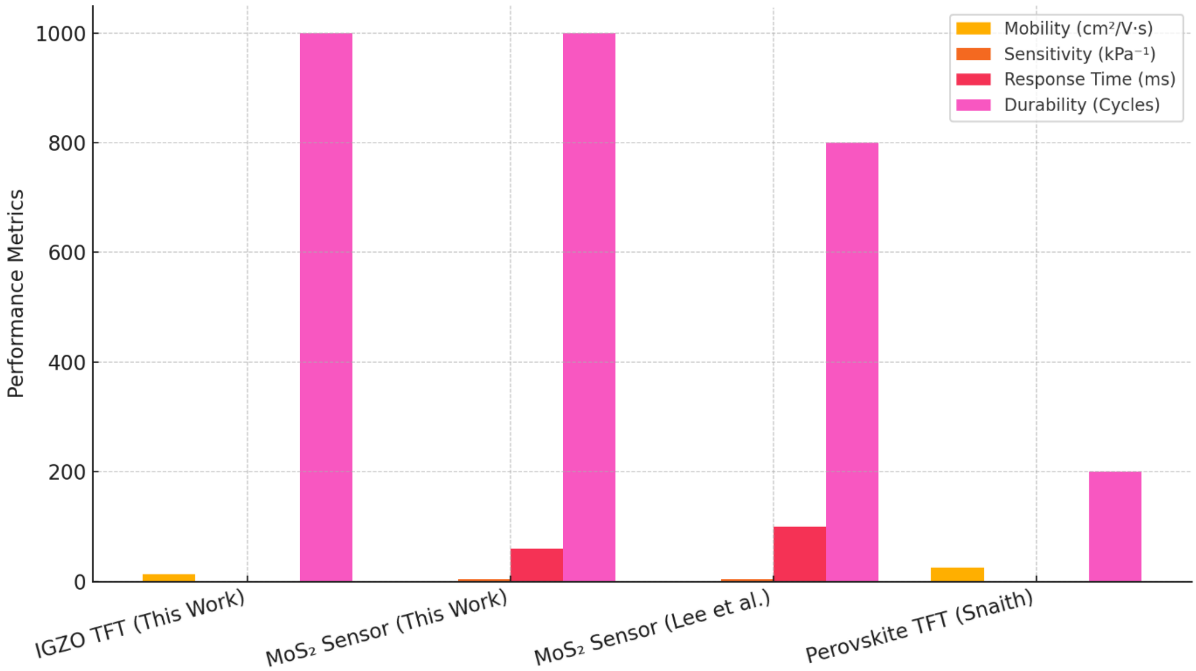

Figure 4. Comparative Performance Metrics of Flexible Electronic Devices

Performance comparison of flexible electronic devices including IGZO-based TFT (this work), MoS_2-based pressure sensor (this work), MoS_2 sensor by Lee et al. (2021), and perovskite TFT by Snaith (2013). Metrics compared are charge carrier mobility, pressure sensitivity, response time, and mechanical durability under cyclic loading. This side-by-side visualization illustrates functional trade-offs and application-specific strengths across material systems.

6. CHALLENGES

Although this research shows the improvements in the field, there are some issues of importance that remain among flexible semiconductor systems. twD synthesis, including MoS 2 is a major challenge, which also limits large-area applications to as-synthesized quasi-uniformity at the wafer scale. Another issue is environmental stability,particularly in organic and hybrid materials such as P3HT and perovskites, which disintegrate in damp conditions and heat even with encapsulating measures. Moreover, there are current limitations to integrating CMOS technology due to thermal budgets and incompatibility of interfaces, and it is challenging to incorporate flexible components into existing electronic systems, especially high-density electronics (wearable and biomedical devices).

FUTURE DIRECTIONS

Moving to the future, any future studies have to deal with these limitations in terms of multidisciplinary innovations. Artificial intelligence and machine learning can be used to streamline material choice, processing regimes and device architectures to discover high-performing, flexible semiconductors in a much shorter time. More bioinspired solutions with higher order orientational designs like nacle-like or layered composites are potential solutions to increase mechanical robustness without sacrificing electrical performance. Another aspect that is rapidly becoming a point of concern is sustainability, and in this regard, eco-friendly and biodegradable material could lead to lower environmental effects and create transient or disposable electronics. Altogether, the design of monolithic hybrids comprising of MoS 2 and IGZO in stacked or co-fabricated systems may provide pathways to complete integration with flexible architectures of systems-on-chip optimized on next-generation wearable, Internet of Things, and edge Artificial Intelligence.

7. CONCLUSION

The current paper presents an in-depth review of next-generation semiconductor materials, such as IGZO, MoS 2, organic polymers, and hybrid perovskites, to the field of flexible electronic systems. Experimental readings revealed that the IGZO-based TFTs had good mechanical stability and conserved more than 85 percent of their mobility even after 1000 elbow flexions as well as the MoS 2 -based pressure sensors possessed a sensitivity of 4.2 KPa -1 and a quick response of about 60 ms. These findings validate mechanical robustness and electrical functionality of each of these two systems of material under realistic deformation and sensing environments.

In addition, the investigation of initial hybrid structures of MoS 2 with IGZO emphasize the possibility of hybrid structure (synergistic integration), with promise of high carrier mobility combined with mechanical flexibility and environmental resistivity. The integration approach will pave the way to future monolithic systems-on-flexible-substrate where sensors, logic and power devices can be co-integrated into a common multi-functional platform.

This study forms a significant contribution to the scalable, reliable, and multifunctional flexible electronics through closing basic materials science to the engineering of flexible devices, which leads to the technologies of the next generation in the field of wearable healthcare, e-skin, foldable displays, and edge AI systems.

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