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A Review of Advanced Materials and Micro-Nano Manufacturing Strategies for Flexible MEMS

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Abstract. As the demand for lightweight and flexible sensing in wearable devices and biocompatible devices surges, material properties and micro- and nano-processing have become the biggest obstacles to the industrialization of flexible MEMS. This paper compares the advantages and disadvantages of two PI film preparation routes, liquid-phase polymerization and vapor-phase deposition, in terms of temperature compatibility and batch potential, analyzes the trade-offs between thermal robustness, tensile flexibility, and environmental tolerance of PI, PDMS, and liquid-metal interconnect systems, and reviews the challenges of adapting three-dimensional assembly methods, such as low-temperature bonding, self-driven folding, and stacked lithography. Based on case comparisons, this paper proposes three major directions: optimizing the low-temperature speed curing process, constructing multi-physical field simulation models, and improving system-level reliability testing. This work provides a clear and feasible roadmap for realizing flexible MEMS from lab to marketable applications.

Keywords: Flexible MEMS, PI, Three-dimensional Microstructure

1. Introduction

In the emerging field of flexible electronics, integrated semiconductor devices and integrated smart sensors are rapidly evolving towards improved flexibility performance. Compared with traditional sensors with rigid characteristics, flexible sensors are low-cost, wear-resistant, lightweight, and simple in structure. In addition, flexible sensors maintain high sensitivity and scalability, and are used in many emerging fields, such as the biomedical field, smart transportation, wearable electronic devices, and smart homes [1].

The strategic design of flexible sensors, material selection, and fabrication methods is crucial to improve the sensitivity and reliability of flexible devices. The materials used in flexible sensors include substrate materials, active materials, and flexible electrodes. And because polymers are characterized by a simple preparation process, good chemical stability, and high mechanical compliance, they have become ideal materials for making flexible sensors. Commonly used polymers include polyimide (PI), polydimethylsiloxane (PDMS) and polyvinylidene fluoride (PVDF). Among them, polyimide can be manufactured in the form of films, fibers, foams, composites, and adhesives due to a combination of high thermal stability, mechanical strength,

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chemical resistance, dielectric properties, and biocompatibility. Since the 1990s, polyimide films have been used in the development of micromechanical sensor devices. The films are used in a variety of high-tech applications, including solar cells, flexible displays, flexible printed circuit boards, device packaging, and flexible sensors. In addition to commonly used polyimide films, PI is also used to prepare polyimide foams, polyimide fibers, and polyimide aerogels. Among them, porous PI aerogels and PI fibers can be used as triboelectric contact layers for triboelectric nanogenerators (TENGs) and can greatly improve the performance of TENGs [2].

This review discusses the materials generally used for the preparation of flexible MEMS, dissecting the properties of polyimide, elastomeric polymer (PDMS), and liquid metal interconnects in turn, as well as the multi-physics field coupling capabilities of nanofiller composites. The review analyzes in depth the limitations of the existing preparation processes and compares the differences in mechanical flexibility and electrical properties of different materials. This paper provides a clear path for the whole process of flexible MEMS from material screening to device integration, helping to realize the efficient transformation of micro-engineering ideas to macro-system applications.

2. Flexible MEMS preparation materials

2.1. Polyimide (PI)

Polyimide (PI) films are important in flexible microelectromechanical systems because of their excellent thermal and mechanical stability, but it remains a challenge to achieve uniform, defect-free coatings with precise thickness control through micromachining (Figure 1). To address these challenges, two main methods have been developed: liquid phase polymerization (LPP) and vapor deposition polymerization (VDP), each of which has its advantages in terms of film uniformity and conformality.

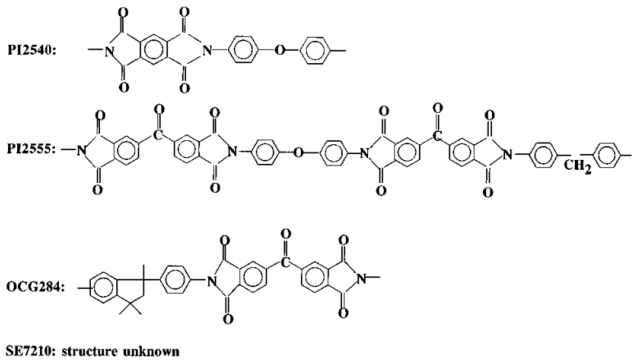


Figure 1. Chemical structure of polyimide

In the liquid phase polymerization method, the polyimide precursor is first dissolved in a solvent and then deposited onto the substrate by spin-coating, dip-coating, or spraying. Film thickness in spin-coating follows the classical convection and evaporation model: higher solution viscosity, lower spin-up rate, or longer spin-down time results in thicker films. For high aspect ratio (HAR) trench filling, which is critical in 3D integration, vacuum-assisted spin-coating enhances solvent penetration into deep via holes, resulting in conformal liners in silicon via holes with an aspect ratio of 15:1. Supercritical CO_2 helps reduce surface tension and enables void-free trench filling.

While the LPP process is simple and cost-effective, its reliance on solvents and heat curing can limit substrate compatibility. These limitations are overcome by VDP, which co-evaporates

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monomers trimellitic anhydride (PMDA) and oxydiphenylamine (ODA) onto a substrate in a vacuum to produce an oligomeric film that is then post-cured thermally to end up chemically identical to the LPP polyimide (see Figure 2). The VDP film exhibits excellent conformability in terms of rolled structure, smooth surface, and reduced porosity.

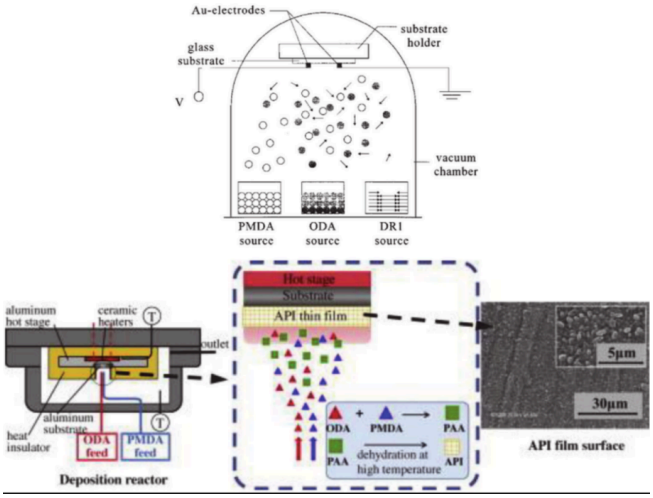


Figure 2. Polyimide film deposited from the vapor phase by VDP

In addition to fabrication processing, the inherent thermal stability and mechanical strength of PI are important factors in its use in MEMS. VDP-deposited PMDA-ODA spherical shells are not only comparable to commercially available PIs in terms of chemical resistance but also exhibit higher tensile strength and lower gas permeability. Composite strategies (e.g., grafting CNTs or carbon fibers coated with PIs) can further increase the tensile strength, thus broadening the application scope of strain sensors and load-bearing MEMS structures.

Although each of these techniques has its strengths in macroscopic film formation, the complex micro- and nanofunctions of flexible MEMS often require direct etching or construction of high-resolution patterns on PI films. To this end, researchers have developed photosensitive polyimides (PSPIs) - i.e., the introduction of photoactive chemical groups into PAA prepolymers or fully sialylated PI chain segments, which cause cross-linking or chain-breaking reactions under UV irradiation, thus realizing integrated photolithographic patterning. Negative-tone PSPIs can achieve features as low as 5-10 μm. These photopatterning strategies significantly reduce processing steps compared to conventional photolithography plus etching processes and maintain the thermal and mechanical properties of the PIs by minimizing additive levels [2].

In order to extend the planar micropatterning technique to three-dimensional structures, researchers have not only developed traditional bonding methods but also introduced self-assembly strategies. First, the bonding technique between polyimides greatly simplifies the stacking process of multilayer microfluidic networks and encapsulated MEMS sensors by utilizing pre-polymerized or softened layers. On this basis, heterogeneous interlayers (e.g., waxes, epoxies, or hydrophobic polymer nano-dispersions) were used to rapidly prototype vertical channel interconnections between multilayer PI plates to build more complex 3D geometries.

In addition to bonding techniques, stress-driven self-assembly provides new ideas for 3D PI microstructures. By designing metal/PI or dielectric/PI bilayers with different coefficients of thermal expansion, controlled bending can be induced during annealing or deposition temperature drop to construct microscale "hairy" cantilever beams, which can be used in scenarios such as air flow sensing. Further, laser origami and photocontrolled self-assembly methods combine locally sintered

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nano-inks or non-uniform photosensitive PI curing to precisely regulate the folding angle and achieve diverse shapes of microboxes and hinges [2].

Overall, the integration of planar micromachining, bonding and self-assembly technologies provides multi-scale design capabilities for PI materials in flexible MEMS from submicron to millimeter level, constructing a microsystem design platform that retains the thermodynamic and mechanical advantages of PI while taking into account the structural diversity, which opens up more possibilities for applications such as soft robotics, bio-implantation and wearable sensing.

2.2. Elastomeric polymers (PDMS) and liquid metals

PDMS (polydimethylsiloxane) is one of the most commonly used flexible substrate materials due to its excellent flexibility, good biocompatibility, and high light transmission. In terms of microstructure processing, complex channels and concave-convex structures can be prepared by techniques such as micro casting, laser etching, or plasma etchin. More importantly, the PDMS surface itself is hydrophobic, which makes it difficult for functional or metal layers to be uniformly deposited. For this reason, plasma (O_2, Ar) or UV/ozone activation of the surface is often used, and hydrophilic groups such as -OH, -COOH are introduced to enhance interfacial adhesion with subsequent films or adhesives [3].

In the construction of interconnect layers, Ga-based liquid metals (e.g., EGaIn, Galinstan) are excellent materials for flexible interconnects due to their dual properties of "liquid deformability" and "metal high conductivity" [4]. More advanced solid-liquid dual-phase alloys (BGaIn) are heat-treated to form a microcrystalline "skeleton" in the mobile phase, which maintains the conductive path under stretching of more than 1000 %.

In specific integrations, liquid metals are often introduced into PDMS microchannels or prefabricated trenches by printing, injection, or electrochemical deposition. A nanoscale indium gallium oxide skin film is typically formed at the interface, which inhibits droplet merging, stabilizes the bit shape, and maintains good electrical contact. By optimizing channel geometry and wall wettability, linewidths in the 20 μm class and repeatable stretch probabilities in excess of 100 % can be achieved with minimal resistance drift after thousands of cyclic strains.

The flexible MEMS platform combining the above two can not only realize multi-physical field sensing, but also build high-density cross arrays through a liquid metal interconnection network, thus providing reliable soft interconnection solutions for flexible neuromimetic circuits, wearable energy harvesting, and management systems. In the future, the means of chemical modification of the interface between PDMS and liquid metal can be further explored to reduce the interconnect contact resistance, and microstructured design can be used to enhance the mechanical integration and performance stability of the overall device.

2.3. Polymer composites

The introduction of nanofillers to enhance polyimide or elastomer substrates to realize multi-physics field coupling functions, such as mechanical-electrical and temperature-control-electrical, has become a key strategy to improve device sensitivity and functional integration in flexible MEMS. For example, graphene/PI composites can be processed via electrical breakdown to form tunable conductive pathways [5]. When the stress is applied to the microstructure, the generation and closure of microcracks in the charring pathway are directly mapped to the resistance change, thus realizing the efficient conversion from mechanical force to electrical signal (see Table 1 for details).

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To overcome the problem of uneven current distribution of conventional EBDs in thick films, researchers have further developed the microscale EBD (μEBD) process - i.e., applying a constant current through precisely positioned metal microelectrodes on several micrometer-thick PI/graphene films, which enables highly localized charred regions and reproducible fabrication of highly consistent micro piezoresistive cells. The resulting composite shows good thermal stability and >20% elongation, suitable for flexible sensing [5].

Other nanofillers, such as carbon nanotubes and metal nanoparticles, can be co-polymerized with PI or PDMS to enhance thermal, electrical, and multi-field responsiveness. These composites enable pressure, temperature, and fluidic signals to be converted into electrical output in integrated MEMS.

Compared to pure PI, PI/graphene composites offer enhanced thermal stability and electrical consistency over wide temperature ranges. Meanwhile, PDMS-based systems show ultra-high stretchability and low modulus, supporting different application needs. Layered integration of nanofiller composites and liquid metals supports flexible devices operating across mechanical and thermal extremes.

Table 1. Comparison of values of PI film, PI/graphene composite film, PDMS, and PDMS+EGaIn in terms of Tg, tensile modulus, maximum strain, and cycling life

Material system	Tg (°C)	modulus (GPa)	maximum strain (%)	Cycle life (times)
PI Membrane	> 300	2–4	~ 20	< 1 000
PI+Graphene Composite	> 300	3–5	~ 30	> 5 000
PDMS	< –100	0.001–0.01	> 1000	> 10 000
PDMS+EGaIn	< –100	0.001–0.01	> 1000	> 10 000

3. Sensors and other applications

3.1. Thermal flow/micro flow sensors

In 2022, Koichi and Daiki et al. developed a flexible multidirectional MEMS flow sensor using a polyimide substrate for high-speed subsonic flow. The sensor measures the wall shear stress by thermal equilibrium of convective heat transfer and the flow direction by the temperature distribution around the micro-heater. The PI material plays a central role, firstly in the synergistic advantages of its physical and thermal properties. A 25-μm-thick Kapton® 100H-type PI film was used as the substrate for the study. Its high flexibility enables it to closely fit complex curved surfaces, such as turbine blades, and solves the limitation of conventional rigid substrates to flow perturbations. Through numerical simulations, it was found that the low thermal conductivity of PI significantly inhibits the longitudinal conduction of heater heat to the substrate, thus strengthening the dominant role of convective heat exchange and leading to a significant increase in the detection sensitivity of wall shear stress. It is further verified that the PI substrate does not show deformation or performance degradation when subjected to a temperature rise of 50K and shear stress of 35Pa in a high-speed flow of 30-170 m/s, which confirms its mechanical and thermal stability under extreme operating conditions. As a result, the sensor can be used in curved walls to evaluate complex separated flows often found in various fluid mechanics [5].

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3.2. Flexible pressure and humidity sensors

Flexible MEMS pressure sensors have also demonstrated excellent detection accuracy in medical health and sports monitoring. Taking PI and carbon nanotube (CNT) composite aerogel as an example, its porous structure is constructed by the freeze-drying process, and its piezoresistive characteristics show a high linear response in the range of 0.01-400 kPa. As shown in Figure 3, the structure uses freeze-drying and vacuum annealing steps to construct a multi-scale conductive network. The sensor is seamlessly integrated into shoe insoles or medical mattresses to capture real-time human movement data or local pressure changes in bedridden patients, providing a reliable basis for the diagnosis of gait abnormalities and early warning of pressure injuries. Another typical design is a capacitive sensor, which has been successfully applied to radial artery pulse waveform detection, with an error of less than 2 mmHg [6].

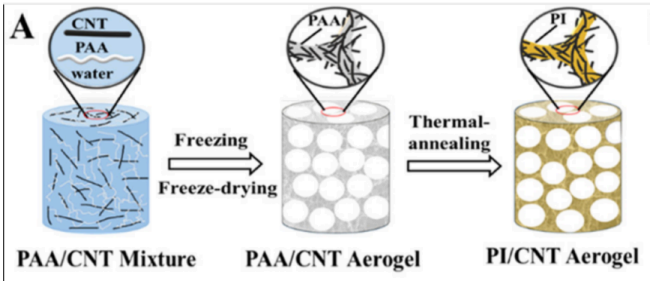


Figure 3. Porous network structure of CNT/PI composite aerogel with schematic preparation process [7]

In terms of environmental adaptability, design strategies for flexible MEMS materials offer potential technology paths for humidity sensing. For example, the hydrophobic bacterial cellulose/MXene composite film is modified by fluorination to maintain stable signal output in high-humidity environments, which is suitable for long-term wear scenarios. Breathable mask sensors adopt porous PDMS encapsulated electrode structures to safeguard gas permeability while realizing respiratory strength monitoring.The synergistic effect of its layered porous properties and hygroscopic materials creates the possibility of developing humidity-pressure dual-mode sensors [6].

3.3. TENG sensors

In 2025, Peng Wu's team systematically investigated the application of polyimide (PI) nanofiber membranes in friction electric nanogenerators (TENG). The team used electrospinning technology to prepare PI nanofiber membranes that combine flexibility, high-temperature stability, and high specific surface area. The experimental data show that with 18 wt% concentration of polyamidoacetic acid (PAA) solution as the precursor, after electrospinning and imidization, the resulting PI nanofiber membrane has an open-circuit voltage (VOC) of up to 5.98 V at room temperature. Notably, the material was able to output stable electrical signals under multimodal mechanical stimuli such as friction, stretching, and tapping. In addition, PI films have been widely used to construct high-temperature workable TENGs. As shown in Figure 4, the electrospun PI nanofiber film maintains good voltage output at 250 °C, indicating its stable self-powered capability in harsh environments.

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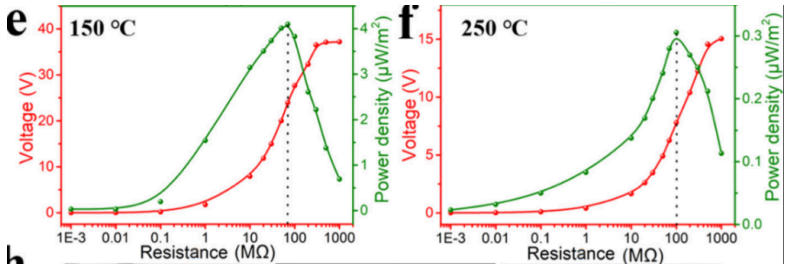


Figure 4. Output voltage and power density of PI-based electrospun film TENG versus external load resistance at 150 ℃ (e) and 250 ℃ (f) [8]

For the sensing function of TENG, the research team realized the precise decoupling of friction, electric, and piezoelectric signals by the Fast Fourier Transform (FFT) technique, confirming that the VOCs of PI nanofibers mainly originated from the friction electric effect. In the high-temperature performance test, the PI-based TENG demonstrated a unique advantage: its VOC was elevated to 11.76 V when the temperature was raised to 160°C, which is an 84.4% improvement over the room-temperature performance. Although the output retention drops to 56.8% after 10,000 cycles at 300°C, the thermal resistance far exceeds that of conventional materials such as PVDF (80°C) [9].

3.4. Reconfigurable antennas with flexible RF MEMS switches

As early as 2001, a reconfigurable conformal antenna based on microelectromechanical systems (MEMS) and flexible thin films was proposed for space-based radar. The reconfigurable antenna based on MEMS switches can be switched between two broadband, S-band and X-band, at a driving voltage of less than 10 V. Although this achievement does not use a fully flexible MEMS structure, it sets a precedent for the research and application of flexible RF MEMS.

In addition, switches, as the basic unit of flexible RF MEMS, have received the most attention. Wang et al. developed on an LCP flexible substrate both a cantilevered membrane-beam RF MEMS switch supported by two free beams and an air-bridged CPW switch capable of integration with a 3D RF front-end in an LCP reconfigurable architecture. It was also shown that the LCP-based switch can be used as a low-cost or high-performance alternative to silicon-based RF MEMS switches. When the switch was in the active state, the isolation at 20 GHz was about 20 dB, while the corresponding return loss was about 0.1 dB. When the switch was in the up position, the insertion loss at 20 GHz was about 0.08 dB, while the corresponding return loss was 18 dB. These findings have triggered the study of flexible RF MEMS. Patil et al. fabricated thin-film MEMS microbeams on 250 μm-thick flexible polyethylene terephthalate (PET) films. The flexural state of the substrate showed that 16.6% of the devices could withstand a tensile strain of 1.25%, while 50% of the devices could withstand a higher compressive strain of -2.5%. Thin-film silicon beams prepared on polyethylene terephthalate (PET) substrates resonated at frequencies up to 2 MHz when measured in vacuum, with quality factor values of about 500 [8].

4. Commentary

Although significant progress has been made in the preparation and application of flexible MEMS, there are still many challenges in process adaptation, material performance trade-offs, and system integration. The following is an in-depth review of the limitations of micromachining

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methodologies, the performance comparison of different material systems, and the controversies at the forefront of 3D assembly compatibility research.

4.1. Methodological limitations: triangular trade-off between process temperature, resolution, and cost

In the preparation of polyimide (PI) films, liquid-phase polymerization (LPP) is widely favored due to its low-cost equipment and simple operation. However, its reliance on solvent removal and complete film curing often results in annealing temperatures exceeding 300 °C, while also limiting compatibility with flexible substrates such as PET and PI films, as well as active electronic components [2]. In order to reduce the temperature, researchers have explored solvent substitution and supercritical CO_2-assisted percolation, which can lower the curing threshold and improve the thickness uniformity at 200°C, but also brings additional costs for precursor formulation and equipment modification.

Meanwhile, the gas phase polymerization method (VDP/CVD) can achieve nearly non-porous, ultra-flat PI coatings at 100-160°C. The self-limiting growth mechanism of ALD-PI not only improves the adhesion between different substrates but also allows precise control of the film's growth from a few nanometers to a few micrometers. However, the investment in a vacuum chamber and high-purity monomer makes the cost of equipment purchase and consumables far exceed that of LPP, and the low flux and inconvenient batch switching make it difficult to support the mass production of flexible electronics. For visual comparison, a schematic table of advantages and disadvantages of common preparation methods is given below (see Table 2).

Table 2. Schematic representation of advantages and disadvantages of common preparation methods

methodologies	fire retardant temperature	Thickness Range	resolution	equipment cost	Batch processing difficulty
LPP	≥300°C	50 nm–10 μm	~1 μm	Low	Medium
Supercritical CO_2-assisted LPP	200°C	100 nm–5 μm	~0.5 μm	Medium	Medium-High
VDP	100–160°C	5 nm–1 μm	Self-limiting atomic level	High	High
ALD-PI	160°C	1 nm–500 nm	Tens of nm	Very high	Very high

Similarly, while lithography and laser direct writing technologies can easily achieve submicron and even nanometer-level pattern accuracy, their reliance on masks, deep ultraviolet light sources, and multiple development/etching steps drives costs and process complexity to their peak. Open-source “low-cost desktop lithography” solutions, while utilizing 405 nm laser diodes and SU-8 as alternatives to native DUV, still exhibit significant gaps in overall resolution and yield compared to professional equipment. Therefore, flexible MEMS processes urgently require a suitable solution that can achieve rapid curing at low temperatures while maintaining high-resolution formation and accommodating mass production—for example, photoresist PI combined with synchronous exposure and thermal cross-linking, or microwave-assisted curing technology, are emerging as research hotspots.

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4.2. Performance comparison: material system trade-offs in flexibility, electrical properties, and reliability

Polyimide (PI) films exhibit excellent thermal stability and structural support capabilities in flexible MEMS due to their glass transition temperature (Tg) exceeding 300°C and tensile modulus of 2–4 GPa [2].

To balance structural strength and electrical conductivity stability, researchers have attempted to incorporate graphene or carbon nanotubes (CNTs) as nanofillers into the PI matrix, forming PI/graphene composite films. Additionally, they demonstrate outstanding bending fatigue life, capable of withstanding over 5,000 cycles while maintaining functional integrity (see Table 3) [10]. In contrast, elastic polymer materials such as PDMS have an extremely low glass transition temperature (Tg) (<–100°C) and a very small tensile modulus (0.001–0.01 GPa), with a maximum strain capacity exceeding 1000%. When combined with liquid metal interconnects (such as EGaIn), the PDMS+EGaIn structure maintains less than 10% resistance drift even after undergoing large deformations (>1000%) and shows no signs of failure after over 10,000 bending cycles, demonstrating exceptional reliability.

In summary, PI-based materials emphasize thermal stability and structural strength, making them suitable for high-temperature environments and applications requiring rigid structures. Composite strategies such as graphene doping or liquid metal injection provide performance trade-offs and functional extensions for the aforementioned two material categories, laying the material foundation for the multi-scenario application of flexible MEMS. Table 3 systematically summarizes the comparison of key metrics such as Tg, modulus, strain limit, resistance stability, and cycle life for the four typical material systems mentioned above, to guide subsequent device material selection and system design.

Table 3. Comparison of different material systems in terms of key properties

Norm	PI Membrane	PI/graphene composite film	PDMS	PDMS+EGaIn
Tg (°C)	>300	>300	<–100	<–100
Tensile Modulus (GPa)	2–4	3–5	0.001–0.01	0.001–0.01
Maximum Strain (%)	~20	~30	>1000	>1000
Resistance Stability (20–300 °C)	Change >20 %	Change <5 %	N/A	N/A
Bending cycle life	<1000 times	>5000 times	>10000 times	>10000 times

4.3. Controversy and exploration: a study of three-dimensional assembly compatibility and system-level integration

To overcome the limitations of planar structures, PI–PI low-temperature bonding and interlayer adhesion techniques have been employed to construct multi-layer microfluidic and sensor stacks. However, under bonding conditions of 200–300°C, the interface experiences thermal stress relaxation and fatigue delamination in humid environments, hindering the long-term stability of implantable devices. Another approach is based on self-assembly driven by thermal expansion mismatch: transferring planar-patterned PI precursors onto pre-stressed elastic substrates, followed by strain release to generate controlled folding or “pop-out” structures. However, this method demands extremely precise control over layer thickness, pre-stress levels, and heating/cooling rates, with even minor fluctuations leading to significant deviations in folding angles and positions. As a result, a scalable closed-loop process has yet to be established.

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At the system level, integrating flexible sensors, energy harvesting (TENG/thermoelectric), and edge AI devices onto the same substrate presents multiple conflicts in terms of temperature, humidity, electromagnetic compatibility, and thermal management. Currently, there is a lack of standardized simulation and accelerated aging test processes for such multi-physics coupling, and system reliability assessments still need to move beyond the laboratory demonstration phase.

5. Future expectations

In future flexible MEMS, three-dimensional microstructures and hierarchical design will be essential to transcend planar limits and enable true multifunctional integration. Compression-flexion self-assembly transforms two-dimensional lithographic patterns on pre-strained elastic substrates into wires, film-wire composites or folded boxes, all while remaining compatible with mature micro-nano fabrication techniques. By tuning substrate strain and precursor geometry, one can precisely dictate the final form, enriching device morphologies for soft-robot end-effector actuation, microneedle array implantation, and deformable optics. Layering polyimide tubes and using three-dimensional lithography enables complex sensing, transmission and control units to be mounted onto curved surfaces with precise alignment and planar encapsulation, creating vertical interconnects between inner and outer layers. Such curved-surface microsystems open up new possibilities for in vivo biochemical monitoring and flexible microfluidics, laying the foundation for seamlessly integrating microstructures and expanded functionality in next-generation implantable devices.

Looking ahead, integrating these 3D strategies with advanced printing, degradable or self-healing polymers, and multiphysics simulation—alongside low-temperature, fast-curing lithographic materials and flexible interconnect layers—could yield truly multi-layered system-on-chip flexible MEMS. Standardized process evaluation and accelerated aging protocols will be crucial to ensure long-term stability and reliability in complex environments, unlocking unprecedented design freedom and performance in wearable health monitors, autonomous soft-robot sensors, and implantable medical systems.

As flexible MEMS evolve toward self-powered intelligent nodes, triboelectric nanogenerators (TENGs) and micro-photovoltaics will integrate with edge AI to enable real-time local sensing and decision-making. Recent research shows that the tidal-like electrical signals generated by TENG can directly drive microwatt-level neuromorphic accelerators and enable sensing, preprocessing and feature extraction at the edge without a continuous external power supply [11]. Combined with lightweight convolutional or event-driven neural networks, TENG outputs can classify respiratory rate, micro-expressions and environmental vibrations in real time and filter out critical events locally, reducing communication energy by over 80% and achieving millisecond-level response times. A reinforcement-learning framework can further optimize TENG materials and geometry according to vibration frequency and amplitude, automatically adjusting energy harvesting strategies to maintain stable output and extend device life.

Flexible micro-photovoltaic films deliver steady indoor power with 70–80% efficiency under low light and less than 10% degradation after 1,000 hours of testing, making them ideal backup sources. Intelligent power management units switch supply modes within milliseconds, allocate photovoltaic energy to AI inference modules, and store surplus in micro-capacitors or flexible solid-state batteries, while dynamically scaling AI model complexity to match available power. Overcoming challenges in hybrid power management design, low-temperature process compatibility, and multiphysics-coupled aging tests will be vital to realize fully autonomous, low-latency, energy-efficient flexible MEMS for smart wearables, distributed environmental monitoring, and implantable medical devices.

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6. Conclusion

This paper successively examines the core technological elements of flexible MEMS from a multi-dimensional perspective: firstly, the liquid-phase and gas-phase preparation paths of polyimide films illustrate the profound influence of process parameters on thermo-mechanical properties; secondly, it analyzes the key significance of the interconnection design between PDMS and liquid metal for the reliability of flexible interconnections; and through the example of nano-packing composites, it demonstrates the mechanism of realizing the function of multiphysical field coupling. Based on this, this paper proposes an optimization strategy combining low-temperature fast curing and high-precision molding, and suggests the introduction of multi-physical field simulation and accelerated aging tests to guarantee system stability. Looking ahead, with the development of hierarchical 3D integration and intelligent adaptive platform, as well as the cross-fertilization of "self-driven + edge AI" and "micro-photovoltaic energy management" technologies, flexible MEMS is expected to move from experimental validation to large-scale application, and to provide the best solution for the development of soft and flexible devices. It is expected that flexible MEMS will move from experimental validation to large-scale application, opening up new opportunities for cutting-edge fields such as soft body robotics, wearable health monitoring, and implantable medicine.

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