

# Investigation of High-Performance Nanocomposites for Flexible Electronics Applications

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**Abstract.** Wearable electronics have garnered increasing attention due to their potential in real-time physiological monitoring, personalized healthcare, and human – machine interaction. However, challenges such as mechanical mismatch between rigid electronics and soft biological tissues, limited material recyclability, and high fabrication costs have hindered their large-scale deployment. Recent advances in nanomaterials and fabrication techniques offer promising solutions to these issues. This study focuses on developing flexible and stretchable electronic devices through integrating gallium-based liquid metals (LMs) with electrospun nanofiber membranes. It discusses the synergistic advantages of combining the high electrical conductivity and fluidity of LMs with the mechanical compliance, breathability, and structural tunability of electrospun substrates. The paper further examines key challenges, including weak interfacial adhesion, limited degradability of polymeric substrates, and the complexity of high-resolution patterning techniques. Strategies such as surface modification, metal alloying, and eco-friendly, biodegradable materials are explored to enhance device performance, scalability, and environmental compatibility to address these limitations. By advancing electrospinning-based LM integration techniques and developing sustainable fabrication approaches, this work creates high-performance, cost-effective, and environmentally responsible wearable systems for future biomedical monitoring, soft robotics, and transient electronics applications.

**Keywords:** Flexible electronics, Liquid metals, Wearable sensors, Stretchable conductors.

## 1. Introduction

Few technological advancements have transformed human life as swiftly and profoundly as electronics. Since their inception, electronic systems have become integral to everyday living [1-3]. In recent years, the widespread deployment of electronic technologies in diverse applications—including health monitoring [4, 5], energy harvesting [6], human–computer interaction [7, 8], and flexible display systems [9]—has significantly amplified the demand for wearable smart electronic devices. Flexible electronic materials typically include conductive polymers (e.g., PEDOT: PSS), metallic nanomaterials (silver nanowires, liquid metals), and carbon-based materials (graphene, carbon nanotubes). Liquid metals (LMs) are auspicious due to their excellent conductivity, fluidity, and biocompatibility. However, their high surface tension and leakage issues limit standalone use, leading researchers to combine LMs with flexible substrates such as electrospun nanofibers to enhance mechanical stability and functionality [10].

Nowadays, there are two common strategies for the fabrication of stretchable electronics. The first strategy involves incorporating conductive materials—such as metal nanowires, carbon nanotubes (CNTs), graphene, and conductive polymers—into an elastic matrix. Dispersing conductive nanofillers within the polymer matrix is a practical approach to preparing stretchable conductors. For instance, silver nanowire or copper nanowire percolation networks are integrated onto elastic substrates, enabling bending, folding, and stretching while maintaining good electrical stability [11, 12]. The second strategy is based on the structural design of pre-strained buckling, wherein conductive materials are configured into transformable geometries such as buckles, helices, and springs. These structures can accommodate large, applied strains without fracturing the materials, thus significantly enhancing stretchability and mechanical robustness [13-15].

## **2. Mechanism and Application of Nanomaterials**

### **2.1 Mechanism**

Nanomaterials, defined by at least one dimension below 100 nm, exhibit unique physical and chemical properties such as high surface area-to-volume ratio, quantum confinement, and enhanced surface reactivity. In flexible electronics, incorporating nanomaterials significantly enhances electrical conductivity, mechanical flexibility, and sensing performance [1, 16, 17].

For instance, silver nanowire networks offer highly conductive and stretchable pathways on elastic substrates. At the same time, carbon nanotubes and graphene provide exceptional mechanical strength and carrier mobility for strain sensors and flexible electrodes [12]. Electrospun nanofibers are particularly attractive due to their interconnected 3D porous networks, which offer excellent breathability and conformability and serve as efficient scaffolds for embedding liquid metals and conductive inks [20]. These features make nanofibers indispensable for constructing multifunctional wearable electronic systems [18, 19].

### **2.2 Development of Nanomaterials for Wearable Devices**

Nanomaterials such as carbon nanotubes (CNTs), graphene, silver nanowires (AgNWs), and liquid metals (LMs) offer exceptional electrical, mechanical, and chemical properties at the nanoscale. Electrospun nanofibers provide a high surface area, tunable porosity, and excellent breathability, making them ideal for interfacing with human skin.

Recent studies have demonstrated that combining these materials with elastic matrices (e.g., TPU, SEBS) enables the fabrication of highly stretchable conductors and sensors. For example, used in situ assembly of LMs and electrospun fibers to produce strain-stable electrodes, further developed coaxial electrospinning techniques to embed conductive LMs within nanofibers for enhanced mechanical compliance and conductivity.

### **2.3 Flexible Electronic Materials for Wearable Devices**

Flexible electronic materials have unlocked numerous opportunities in the design of lightweight, conformable, and multifunctional devices.

#### **2.3.1 Wearable Health Monitoring**

Wearable sensors have rapidly advanced in the medical field, driven by the need to enhance their sensing performance and physiochemical properties. Recent developments focus on incorporating innovative materials—metal-based, carbon-based, polymer-based compounds, and biomolecules—to improve sensitivity, flexibility, and biocompatibility. Metal-based nanomaterials, in particular, are widely used due to their excellent conductivity, ease of synthesis, and suitability for device integration. Nanoscale materials such as 0D nanoparticles, 1D nanowires, and 2D nanosheets (e.g., graphene, MXene) significantly increase sensor sensitivity by providing a high surface area for target interaction. Multifunctional nanomaterials' design, selection, and integration are critical for enabling multiplex detection and robust device performance. Additionally, exceptionally density functional theory (DFT) computational approaches are increasingly used to predict nanomaterials' electronic structure, energy levels, and band gaps, thereby guiding material design and optimizing sensor function. These combined experimental and theoretical strategies pave the way for the next generation of high-performance, application-specific wearable sensors[23].

#### **2.3.2 Flexible Displays**

Flexible displays, characterized by their ultrathin form factor, lightweight nature, exceptional mechanical flexibility, low power consumption, and highly tunable emission characteristics, have opened up new avenues in optoelectronics. The growing demand for such devices is driven by their successful commercialization and immense potential for integration into wearable electronic systems[24]. To date, a range of self-emissive display technologies—such as flexible active-matrix

organic light-emitting diodes (flex-AMOLEDs), flexible quantum-dot light-emitting diodes (flex-QLEDs), and flexible perovskite light-emitting diodes (flex-PeLEDs)—have been extensively reported and explored.

### **2.3.3 Human-Machine Interfaces (HMI)**

With the rapid advancement of the Internet of Things (IoT), artificial intelligence (AI), and the Fourth Industrial Revolution, smart factories and machines are increasingly equipped with intelligent functionalities, enabling the integration of more sophisticated operations. The realization of such intelligence relies on both internal systems—such as human-machine interfaces (HMIs)—and external infrastructures, including big data platforms and cloud-based services. Although current research predominantly emphasizes the development of external systems, internal system intelligence remains equally crucial for achieving responsive, adaptive, and autonomous industrial environments. How human beings and machines communicate and interact is evolving with more effective and interactive operations. Interactive human - machine interfaces are bidirectional[26].

## **2.4 Wearable flexible devices**

### **2.4.1 Wearable electronic devices**

Flexible and stretchable electronic devices have garnered significant attention due to their mechanical compatibility with a wide range of surfaces and dynamic environments, in sharp contrast to conventional rigid electronics. Among various enabling strategies, integrating liquid metals (LMs) with intrinsically stretchable conductive materials, combined with electrospinning techniques, has emerged as a cutting-edge approach for fabricating flexible, stretchable, and breathable electronic systems. This synergistic combination not only leverages the high electrical conductivity and fluidic deformability of LMs, but also takes advantage of the tunable porosity, lightweight nature, and high surface-area-to-volume ratio of electrospun nanofibers[27-28]. As a result, such composite architectures are well-suited for next-generation wearable electronics, particularly in applications requiring conformability, real-time responsiveness, and long-term comfort. Continued advances in materials engineering, device design, and scalable manufacturing are expected to accelerate further the practical deployment of these multifunctional soft electronic platforms.

### **2.4.2 Applications in Flexible and Stretchable Electronics**

Wearable devices based on nanomaterials have found broad applications across various fields, including strain sensing, energy harvesting, and electronic textiles. Strain sensors monitor human motion, joint angles, and facial expressions. At the same time, epidermal electronic devices utilize flexible patches to record physiological signals such as electrocardiograms (ECG), electromyograms (EMG), and skin temperature. Energy harvesting systems, such as triboelectric nanogenerators constructed from electrospun fibers and liquid metals, enable the conversion of biomechanical energy into electrical power. In electronic textiles, nanofiber-based yarns integrated with liquid metal circuitry can be woven into intelligent fabrics. These diverse applications underscore the critical importance of material selection, structural design—such as serpentine, helical, and coaxial configurations—and fabrication strategies, including coating, direct writing, and transfer printing, in achieving multifunctional, reliable, and user-friendly wearable electronics.

## **3. LM–Nanofiber Composites for Wearables**

Integrating liquid metals (LMs) with electrospun polymer films offers significant potential for stretchable electronic devices, enabling the simultaneous realization of electrical stability and cyclic durability under mechanical deformation. This synergistic combination leverages the fluidity and conductivity of LMs and the mechanical compliance of nanofiber networks, facilitating stable performance during repeated stretching cycles[29-32].

### 3.1 Objective

This section focuses on wearable flexible electronic devices based on nanomaterials, particularly emphasizing the integration strategies of liquid metals (LMs) with electrospun nanofiber substrates. The research methodology combines a comprehensive literature review with experimental protocols to investigate material design, fabrication processes, and device performance under mechanical and physiological conditions. An overview of the materials selected, processing techniques employed, and characterization methods used throughout the study is provided.

### 3.2 Materials and Preparation

Gallium-based liquid metals (LMs) uniquely combine fluidic behavior with metallic conductivity as a representative class of functional materials. Owing to these dual characteristics, they possess significant scientific value and exhibit broad potential for technological applications[33].

The choice of materials was based on functionality, processability, and biocompatibility. The base polymer matrices included thermoplastic polyurethane (TPU), styrene-ethylene-butylene-styrene (SEBS), and polyvinylidene fluoride (PVDF). These polymers were selected for their mechanical elasticity, chemical stability, and electrospinnability. All polymers were dissolved in binary solvent systems such as dimethylformamide (DMF) with tetrahydrofuran (THF) or chloroform with ethanol, depending on their solubility and viscosity requirements.

### 3.3 Fabrication Techniques

#### 3.3.1 Electrospinning of Nanofiber Substrates

Electrospinning produced nanofiber mats as flexible, breathable substrates for LM integration. The electrospinning system consisted of a high-voltage power supply, syringe pump, and rotating drum collector. Process parameters were optimized: the applied voltage ranged from 20 kV, the polymer feed rate was maintained at 0.5–1 mL/h, and the tip-to-collector distance was set at 12–15 cm. By adjusting these parameters, uniform nanofiber diameters (200–800 nm) and porous structures were achieved.

#### 3.3.2 Liquid Metal Integration Strategies

This study adopted a multi-strategy integration approach to fabricate liquid metal (LM)-nanofiber composites, tailored for advanced functional applications. In situ assembly was realized through simultaneous electrospinning and electrospraying, enabling direct deposition of LM nanoparticles during fiber formation. Although nanoparticle agglomeration remains a potential concern, this method achieves superior dispersion within the fibrous matrix. In addition, coaxial electrospinning was employed, utilizing an LM-polymer emulsion as the core and an elastic polymer as the shell, whereby conductive pathways are formed via mechanical rupture of the LM's native oxide shell.

Pre-formed nanofiber membranes were coated with LM using dip-coating, blade-coating, or screen printing techniques for post-processing. Surface modification with poly(acrylic acid) (PAA) or graphene oxide (GO) was introduced to enhance interfacial adhesion between LM and the fibrous substrate. Direct writing with fine nozzles or thermally assisted template transfer was implemented to achieve precise micro-patterning, enabling spatially resolved LM deposition.

Each strategy was selectively optimized according to the specific requirements of target applications—such as sensors, electrodes, and energy-harvesting devices—and systematically evaluated in terms of scalability, reproducibility, and structural integrity[34]

### 3.4 Characterization Techniques

Scanning Electron Microscopy (SEM) was employed to observe the morphology of electrospun fibers and the distribution of LM particles within or on the fibers[35]. Fiber uniformity, porosity, and interface bonding were closely examined. Electrical conductivity and resistance variation under strain were measured using a four-point probe and multimeter. Cyclic stretching (0–300%) and repeated bending (up to 1000 cycles) were applied to assess electrical durability and response stability. Tensile

tests were performed on a universal testing machine to evaluate the composite films' stretchability, Young's modulus, and fatigue resistance. Strain at break and cyclic performance under repeated deformation were recorded. In vitro cytocompatibility tests were conducted using fibroblast cell lines to simulate real skin-contact scenarios. MTT assays were performed after 24–48 hours of contact with the material surface. Water vapor transmission rate (WVTR) measurements were also performed to assess breathability using a gravimetric method (ASTM E96 standard), comparing values to the natural skin transpiration rate ( $\sim 600 \text{ g}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ ). To validate real-world performance, prepared devices were applied as wearable strain sensors on joints (finger, elbow) or as epidermal patches for EMG/ECG detection—signal quality under dynamic motion and after prolonged use was monitored and compared with commercial counterparts.

## 4. Limitations and prospects

### 4.1 Interfacial Integration Challenges

Achieving robust integration between liquid metal (LM) films and electrospun nanofiber membranes remains a critical challenge in developing stretchable electronic devices. Due to metal films' inherently high surface tension, their interfacial interaction with nanofibrous substrates is typically weak, resulting in compromised electrical performance under mechanical deformation. To overcome this limitation, a widely adopted strategy involves coating the nanofiber surface with conductive metals such as silver to improve adhesion. Alternatively, alloying LM films with other elements or incorporating binding agents capable of forming hydrogen bonds has been explored to enhance interfacial compatibility. However, these methods have thus far failed to deliver substantial improvements in the long-term performance and mechanical durability required for reliable stretchable electrodes. Consequently, advancing interfacial engineering between LM films and electrospun membranes is essential for enabling the next generation of high-performance, deformable electronic systems.

### 4.2 Cost-effectiveness

Gallium-based flexible liquid metal (LM) films offer excellent surface chemical tunability and low cytotoxicity, providing high cycling stability and rendering them highly attractive for applications in transient electronics. Nevertheless, most flexible and stretchable substrates employed in such systems are neither recyclable nor biodegradable, posing significant environmental sustainability challenges. In addition, fabricating patterned LM-based stretchable films typically relies on customized masks and high-precision equipment to achieve fine-resolution printing, substantially increasing manufacturing complexity and cost. As a result, there is a growing need to develop recyclable, biodegradable, and economically viable fabrication strategies—particularly those based on electrospinning—to produce LM-integrated flexible and stretchable electronic devices. Advancing such approaches will be critical to meeting the demands of next-generation sustainable electronics.

### 4.3 Cost-effectiveness

Gallium-based flexible liquid metal (LM) films exhibit excellent surface chemical tunability and low cytotoxicity, offering high cycling stability and making them ideal candidates for transient electronic applications. However, many existing flexible and stretchable substrates are neither recyclable nor biodegradable, and patterning often relies on customized masks and precision equipment, resulting in increased fabrication complexity and cost.

Developing recyclable, biodegradable, and cost-effective fabrication strategies—particularly those based on electrospinning—holds great promise for advancing LM-integrated flexible electronics. Such approaches could enable scalable, low-temperature, and solvent-free processing and integration with diverse functional nanomaterials. Combining material innovation with simplified manufacturing

may pave the way for next-generation sustainable, high-performance, multifunctional wearable and transient electronic systems.

## 5. Conclusion

Integrating gallium-based liquid metals (LMs) with electrospun nanofiber membranes represents a promising approach for developing flexible and stretchable electronic devices. This hybrid system effectively combines the excellent electrical conductivity and fluidic deformability of LMs with the mechanical flexibility, breathability, and structural tunability of electrospun substrates. Such synergistic architectures enable multifunctional wearable electronics to maintain stable performance under dynamic mechanical deformation. However, challenges remain, including insufficient interfacial adhesion between LMs and polymeric substrates, limited recyclability of materials, and the complexity and cost of high-resolution patterning techniques.

Future efforts should focus on advancing the fabrication of recyclable and biodegradable materials, alongside scalable, low-cost, and environmentally friendly processing methods, which are crucial for the practical application of LM-based flexible electronics. Innovations in surface engineering, material formulation, and mask-free patterning are expected to overcome current limitations. Moreover, integrating self-healing functionalities and bioresorbable components could further expand the applicability of these devices in transient electronics and implantable systems. Ultimately, multidisciplinary efforts combining materials science, engineering, and computational modeling will be essential to unlock the full potential of LM-nanofiber composites in next-generation wearable healthcare, soft robotics, and smart textiles.

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