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REVIEW

Issues Related with Commercialization and Mass Production of Flexible Devices

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Abstract

Flexible device is widely used in wearable device, biosensors, soft robotics, and foldable/rollable display, and still a lot of potential application are ahead. In this review, fabrication techniques and materials for flexible devices will be referred to. In the end, issues related with the commercialization of the flexible device will be discussed.

Keywords Flexible device · Wearable device · Biosensor · Foldable display · Manufacturing

Introduction

Flexible Device and its Prospect

Flexible devices are called electronic devices with high stretch ratio, which can be used in various applications. Most representative examples of commercial flexible devices are rollable-foldable displays, which were first introduced by SAMSUNG Display and LG Display [1, 2]. Other applications of the flexible devices are health and biomedical devices which can be used as wearable sensors for monitoring physiological parameters like heart rate, body temperature, and blood pressure, or monitoring health metrics such as glucose levels, hydration, and UV exposure (BioStamp Research Connect, MC10) [3–6]. Other application of the flexible device is soft robots which can adapt to their environment and are equipped with flexible electronic sensors and actuators [7–11].

Advancement and commercialization of flexible devices will give chances to bring new products in our life. Haptic [12–16] device with AR / VR display [17–19] is one of the possible usages of flexible device, which will be suitable interface for meta services [20–23]. Both exterior and interior part of the vehicle will be totally changed when flexible display become patchable into multi-curved surface. The interior cockpit of the vehicle will be changed into a full display panned which eliminates blind spots, as shown in Fig. 1.

Methods for Mass Production in Flexible Device

Most of the methods for fabricating flexible devices can be categorized into three: (1) Printing techniques [24–29], (2) Lithography and deposition methods [30–35], and (3) Hybrid and Roll-to-Roll process [36–43]. In the case of printing techniques, these methods are generally cost-effective and scalable, making them suitable for mass production. However, compared to lithography, printing techniques have relatively low yield rate, lower resolution, and material viscosity constraints, which can limit their applicability in certain scenarios.

Lithography and deposition techniques offer high resolution and the ability to create precise, high-quality features, often essential for specialized applications. However, they can be time-consuming, require expensive equipment, and may have limitations in terms of scalability and material compatibility.

In the case of hybrid and roll-to-roll processes, these methods are designed for high-throughput, continuous production and allow for the integration of different types of materials and components. However, they may require complex processes, have alignment challenges, and can be constrained by material compatibility and resolution limits.

Detailed methods with advantages and limitations are listed in Table 1.

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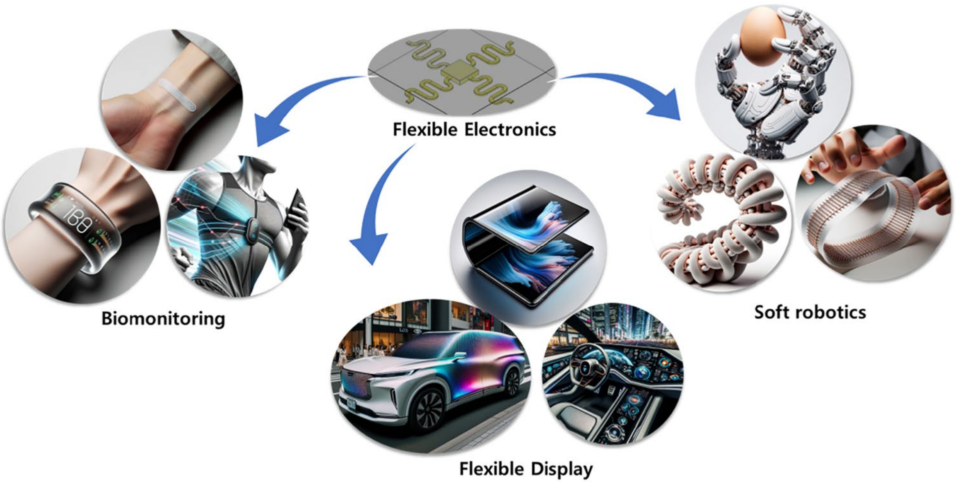

Fig. 1 Scheme for applications of flexible devices

Table 1 Manufacturing Methods used in fabricating flexible electronics

Manufacturing Method	Advantages	Limitations
Inkjet Printing	High resolution, material versatility, low waste	Slower throughput, nozzle clogging, limited to certain viscosities
Screen Printing	Cost-effective, scalable, suitable for thicker layers	Lower resolution, limited material compatibility
Gravure Printing	High-throughput, suitable for roll-to-roll, cost-effective	Lower resolution, limited to certain ink viscosities
Soft Lithography	High resolution, suitable for elastomeric materials	Time-consuming mold preparation, limited scalability
Nanoimprint Lithography	Nanoscale features, high resolution	High initial setup cost, limited material compatibility
Photolithography	High resolution, well-established	Complex process, less suitable for flexible substrates
Chemical Vapor Deposition (CVD)	High-quality thin films, uniform coverage	High temperature requirements, expensive equipment
Physical Vapor Deposition (PVD)	Uniform thin layers, material versatility	High vacuum requirements, limited scalability
Electrochemical Deposition	Cost-effective, suitable for various materials	Requires electrolyte solutions, limited to conductive materials
Transfer Printing	Allows integration of high-performance materials	Complex process, alignment challenges
Laser Patterning	High precision, suitable for various materials	High energy consumption, potential material damage
3D Printing	Design flexibility, multi-material capabilities	Slower throughput, limited resolution
Roll-to-Roll Printing	High-throughput, continuous production, scalable	Requires flexible substrates, limited resolution

Material and Structure Design in Flexible Device

Numerous materials and designs have been developed for stretchable electronics, and their scale are varied from mm to nano scale. The use of composite materials such as conductive polymers integrated into elastomers can provide both mechanical durability and electrical conductivity [44–49]. In situ polymerization methods are used to blend the materials at the molecular level, enhancing stretchability. Nanowires, nanotubes, and nanoparticles have been embedded into elastomeric substrates to provide conductivity while maintaining stretchability [50–55]. Materials like liquid metal alloys are adopted in making stretchable circuits. The intrinsic properties of these materials allow them to maintain conductivity even under strain. Incorporating self-healing polymers as a substrate can provide long-term durability [56–64]. Any ruptures or cracks in the material can be automatically healed, maintaining electrical conductivity, as shown in Table 2.

Instead of changing materials, implementing mechanical designs such as origami or kirigami can help in fabricating stretchable electronic devices. These designs can accommodate mechanical deformations while maintaining

Table 2 Summary of materials used in fabricating flexible electronics.

Material type	Description	Advantages	Disadvantages
Composite materials; Conductive polymers	Conducting Polymer-Based Bio-composites, [65]	Lightweight, flexible, and cost-effective.	Limited thermal stability, and gas permeability.
Nano material embedded System	Metallic nano-particles and nano-wires are used in stretchable circuits.	Provide conductivity while maintaining stretchability	Difficult to control its alignment and purity.
Liquid metal	Freeze casting of Liquid metal, [66]	Maintain conductivity even under strain.	Oxidation, biocompatibility.
Self-healing polymers as a substrate	Self-healing of a cut on an AGNWs, [67]	Long-term durability.	Material complexity, healing limitations, and processing

Table 3 Structure design used in the design of flexible electronics

Structure design	Description	Advantages	Disadvantages
Flat or Straight structure	screen printed straight-configuration a strain sensor, [78]	Provide both mechanical durability and electrical conductivity	Limited functionality Lack in rubustness
Origami or kirigami	screen printed Wavy-like configuration for a strain sensor, [78]	Provide conductivity and stretchability. Enables complex three-dimensional shapes	Design complexity High manufacturing technique

the functionality of the device. Incorporating microfluidic channels filled with liquid metal into elastomeric substrates can offer excellent electrical conductivity while maintaining stretchability, as shown in Table 3 [65–74].

Barrier for Commercialization of Flexible Devices.

Even if some stretchable electronics has been successively commercialized, still there are issues which hinders the advance of stretchable electronics. One of the main obstacles in the design and mass production of flexible electronics is getting vast volumes of material characteristics and device performance to be consistent and homogeneous. Also, manufacturing processes must be scalable in order to be able to adjust and optimize the efficiency of mass production. Balancing material costs with performance poses challenges in sourcing reliable and cost-effective materials in large quantities [79, 80]. The cost for stretchable conductive material is high due to the nano-materials such as Ag nanowire, CNT, Au nanoparticle, and the stacking of the device in unit area are limited due to the structure of the device itself [75–78]. The complex fabrication methods often require specialized equipment and controlled environments, adding to the cost.

Using mechanical patterns such as origami or kirigami in flexible electronics has its drawbacks. Firstly, complex folding patterns could eventually increase the concentration of mechanical stress, which could compromise the structural integrity of the device [85, 86]. Secondly, the intricacy of these designs could make mass production less efficient because they call for precise folding and assembly, which could be difficult to accomplish on a large scale [87, 88]. Furthermore, frequent folding and unfolding could cause wear and tear, which would reduce its long-term dependability. Achieving a balance between robustness and intricate designs that can be produced in large quantities is crucial in these kinds of applications [89]. Repeated stretching and relaxation cycles can lead to material fatigue, causing cracks or delamination in conductive pathways or substrates [79–86]. Uneven distribution of mechanical strain can lead to "hot spots" where failure is more likely to occur.

Poor adhesion between different material layers can result in delamination or peeling, especially under mechanical stress. Such mechanical degradation eventually causes conductivity degradation, and Joule heating problem of the device [87–93]. Several strategies can be used to improve Adhesion between distinct material layers in stretchable electronics and lower the possibility of delamination or peeling under mechanical stress [105–107]. Material surfaces can be altered by surface treatments like chemical or plasma treatments to enhance bonding [108]. Adhesion can be improved by using interfacial materials that are compatible or adhesion-promoting intermediary layers [109, 110]. Other successful tactics include designing flexible substrates with intrinsic adhesion-promoting qualities and optimizing material selection. Furthermore, investigating cutting-edge adhesive technologies—like bio-inspired adhesives or functionalized polymers—can strengthen the interlayer bonding in flexible electronic devices [111–114].

Conclusion

Stretchable electronics has been developed for more than a decade and commercialized products are now at hand. However, their cost for production is high, and development of reliable, high resolution, and energy effective devices are still becoming issues for advance of the flexible devices.

Future research in the manufacturing of flexible electronics should primarily concentrate on the development of novel materials that are more flexible, robust, and functional; self-healing technologies, biocompatible materials, and effective energy harvesting are important areas to be maximized. It will be of great importance to also address the issues of scalability and cost-effectiveness in future research works. Mass manufacturing of flexible electronics also need to give ethical standards, environmental sustainability, and human welfare top priority.

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Data availability The data used or analyzed during the preparation of this review paper are derived from published literature and publicly available databases. All references to the original sources are provided within the manuscript. No new data were generated specifically for this review.

Declarations

Conflict of interest None.

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