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Research Progress of 3D Printed Flexible Electronic Devices

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Abstract

With its high design freedom, wide material compatibility, and versatile processes, 3D printing technology has emerged as a revolutionary approach to the fabrication of flexible electronic devices, and has been shown to have tremendous applications in smart wearables, healthcare monitoring systems and soft robots. But traditional planar production processes are incapable of producing flexible electronics with complex structures and multifunctional integration, which is driving the development of novel manufacturing processes. This review paper comprehensively reviews the research progress of 3D printing in flexible electronics from a process point of view. First, it explains the working principles and technical features of common processes such as direct ink writing, photopolymerization, inkjet printing and laser-based printing. Secondly, it offers specific discussion on the current research progress of different processes in typical applications including flexible sensors, energy devices and soft actuators. Thirdly, it discusses the latest trends such as multi-process integration and structure-sensing system integration. The research shows that various manufacturing processes exhibit specific characteristics in terms of resolution, material composition and speed, while multi-process integration is a way to address the challenges of single-process technologies. Finally, this paper provides a summary of current challenges and future directions such as multi-process integration, 4D printing, artificial intelligence (AI) innovation and roll-to-roll (R2R) mass production, to guide technical roadmaps and process choices for researchers in the field of flexible electronics.

Keywords

3D printing, flexible electronics, direct ink writing, photopolymerization, inkjet printing

1. Introduction

Flexible electronics is a new electronic technology that combines organic/inorganic material electronic devices with flexible/durable plastics or thin metal substrates. Its special flexible, bendable, highly adaptable and stable, lightweight and portable nature provides a wide range of applications in areas including information technology, energy, healthcare and military. In addition, as electronic devices have improved, flexible electronics have attracted widespread attention. But these have yet to be mature and commercialised, leading to relatively high costs in materials, processes and equipment. When it comes to performance, flexible electronics are different from rigid electronics and still have issues with circuitry, data storage, and data communication. 3D printing (additive manufacturing) is a computer-aided process, which translates digital designs into real objects. It offers a new method of manufacturing flexible electronic devices. This fabrication technique has special advantages because of the flexible and bendable nature of flexible electronics. Numerous 3D printing techniques have been applied to flexible electronic devices. In the field of ink direct writing applied to sensors and soft robots, Davoodi et al. adopted DIW technology to develop the surface-doped porous silica sensors [1]. Photopolymerization for piezoelectric devices, on the other hand, Kumar et al. published a review of applications of photopolymerization technologies such as 3D lithography and digital optical processing for piezoelectric sensors and energy harvesters [2]. As for inkjet printing for high-resolution electrodes, Hartnett et al. proposed the SCALE process that combines UV micro-imprint lithography with inkjet printing, leading to great advancements in this field [3].

But there are also limitations on combining the two. The resolution of direct ink writing technology is constrained by the nozzles, light polymerization technology requires high sensitivity of materials to light, and inkjet printing technology is limited by the rheology of ink.

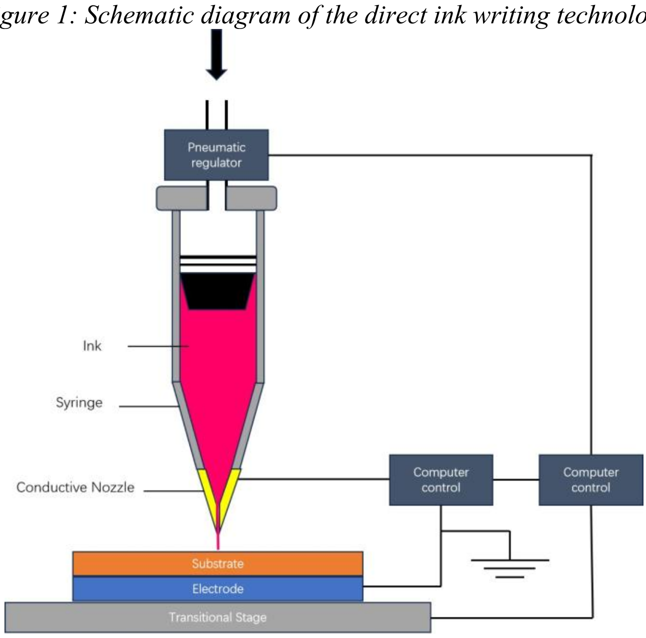
For this reason, this paper comprehensively reviews the key application and research progress of direct ink writing, digital optical processing, and inkjet printing technologies in flexible electronic devices. For the three typical additive manufacturing technologies mentioned above, this article will respectively describe the basic working principles, process characteristics and application scenarios in flexible electronics manufacturing. On this basis, this article provides a comparative analysis of the research progress in different application scenarios, and further highlight the advantages, disadvantages and research prospect of each technology in manufacturing flexible electronic devices.

2. Extrusion-Based 3d Printing Process and Its Role in Flexible Electronic Devices

2.1 Direct Ink Writing Technology

Direct ink writing is an extrusion forming 3D printing process. It uses air pressure to extrude functional ink with shear-thinning properties through micron-scale nozzles to deposit material in a layer-by-layer fashion in a controlled manner to build 3D structures. Fig 1 Schematic diagram of the direct ink writing technology. This process can be conducted at room temperature and can be used for high-precision fabrication of a wide range of materials, for flexible electronics.

Figure 1: Schematic diagram of the direct ink writing technology



2.2 Applications in Flexible Sensors

The direct ink writing technology has unique advantages, such as being able to use a variety of materials and having an excellent drawing ability. This is why it is mainly used in the preparation of flexible sensors, such as piezoelectric and capacitive sensors.

In the piezoelectric sensor industry, in 2026 Tariq et al. prepared a solution-based functional ink made of polyvinylidene fluoride-trifluoroethylene (PVDF-TrFE) copolymer [4]. The preparation of flexible wearable piezoelectric devices using DIW printing proves that DIW is suitable for preparing piezoelectric functional materials. Shi et al. in 2025 uncovered the effect of the surface corrugation texture on the output of the piezoelectric nanogenerator in DIW printing [5]. They discovered that adjustment of printing paths and overlap ratios allowed for regulation of surface microstructures and improvement of piezoelectric output. The research successfully used the fabricated piezoelectric sensor for badminton motion monitoring, with a motion recognition accuracy of 97.89%, which proved that DIW piezoelectric devices can be applied in sports monitoring.

In the area of capacitive and piezoresistive sensors, Davoodi et al. developed DIW printed surface-doped porous silica gel sensors in 2020 [1]. By adjusting the ink's composition and porous structure, they fabricated wearable sensors with excellent mechanical durability and high sensitivity to monitor human physiological signals in real-time. This work shows the versatility of DIW for designing three-dimensional sensors. In summary, DIW technology can improve the performance of flexible sensors, and shows excellent application performance in wearable applications (such as motion and physiological signals monitoring). This highlights the potential of direct ink writing as a tool to fabricate flexible electronics.

2.3 Flexible Energy Devices

Direct ink writing technology shows great potential in the application of flexible energy devices, particularly in the fabrication of flexible battery electrodes and piezoelectric nanogenerators.

For flexible batteries and supercapacitors, Lin et al. comprehensively reviewed the advances of DIW in flexible electrodes in 2025 [6]. The technology shows that through the control of rheological flow of inks and printing route, DIW technology offers the possibility to build thick electrodes with high loading of active materials and form ordered channels for electron/ion transport. DIW-printed electrodes show better areal capacity and rate capability than that of electrodes prepared using traditional methods. Additionally, multi-material printing allows for simultaneous printing of electrodes with non-active components, enabling integrated fabrication of flexible energy storage devices.

In energy harvesting, Shi et al. in 2015 applied the DIW method to produce flexible piezoelectric nanogenerators, focusing on the mechanism of the influence of surface corrugation textures on the output of the devices during the printing process [5]. Researchers have shown that fine-tuning of the microstructure of the surface of the piezoelectric active layer can be achieved by adjusting printing trajectories and the overlap ratio of successive layers, which can improve the nanogenerator's electrical output. Moreover, the device was effectively applied in badminton motion analysis, demonstrating the promising prospects of DIW piezoelectric nanogenerators in self-powered wearable sensors.

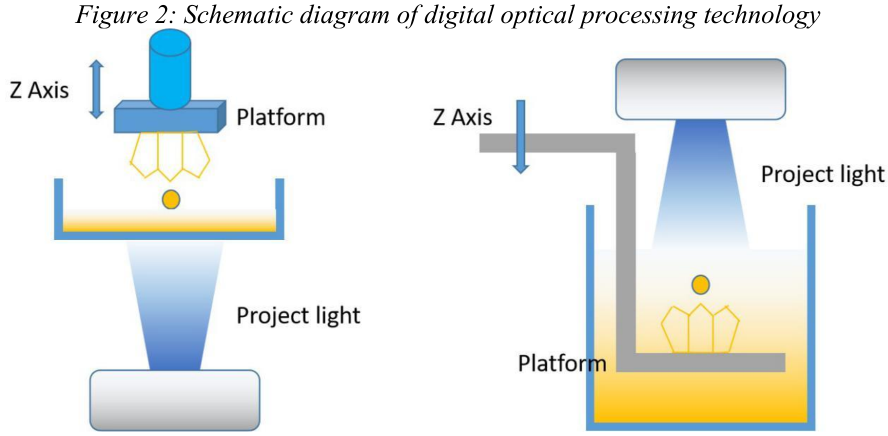
Overall, DIW printing facilitates the rapid advancement of flexible energy devices towards high performance and integration by taking advantage of its benefits for structural control in thick electrodes and flexibility in shaping piezoelectric materials [5, 6].

3. Photopolymerization-Based 3d Printing Process and Its Use in Flexible Electronics

3.1 Digital Light Processing Technology

Digital optical processing technology is a light curing 3D printing technology. It uses digital micromirror devices to project ultraviolet light onto photosensitive resin, which then cures layer-by-layer to quickly form three-dimensional objects. Fig 2 is Schematic of digital optical processing technology. This technology has high precision and high speed, which can be used for integrated manufacturing of high-resolution microstructures for flexible electronics.

Figure 2: Schematic diagram of digital optical processing technology



3.2 Application in Soft Actuators and Sensors

DLP technology offers high-precision forming, making it an ideal technology for producing soft actuators and flexible sensors.

For soft actuators, DLP technology facilitates the manufacturing of micron-scale complex deformable structures (resolution up to 1 μm) for producing complex structures such as pneumatic networks and joints [7]. High-precision DLP with gray-scale control enables gradient distribution of crosslinking density within a single material system by controlling the grayscale distribution of light intensity. This allows printed pneumatic actuators to perform complex deformations including stretching, twisting, contraction and bending, thereby facilitating more complex design for soft robotics functional devices [7].

In flexible sensor applications, the high-resolution nature of DLP technology makes it possible to print microstructure arrays for increased sensitivity. DLP-printed dome-shaped ionic gel capacitive sensor reaches sensitivity up to 15.1 kPa^{-1}, which is much higher than the conventional planar structure. This improvement is due to DLP's capability to accurately build micro-dome arrays, which result in larger variations in contact area under pressure [7].

3.3 Revolution in Volume 3d Printing

Volumetric 3D printing technology has also had a significant impact on the development of flexible electronics. This technology enables the rapid solidification of 3D objects in resin molds via multiple exposures. This process wholly eliminates the interlayer boundaries, thereby overcoming challenges such as poor interlayer bonding and anisotropy in conventional photopolymerization processes.

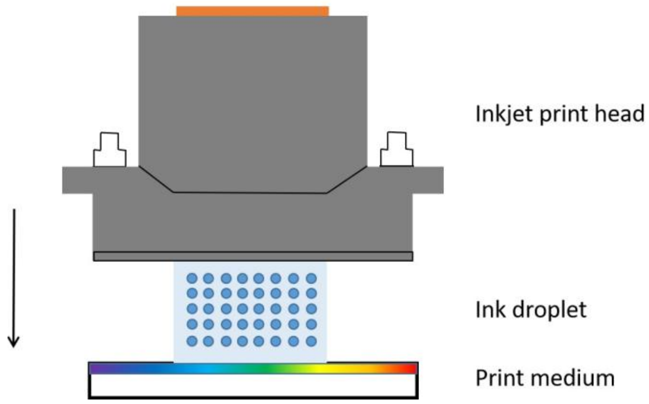
In 2024, Peng et al. pioneered the first application of volumetric 3D printing technology in the manufacturing of ion-conductive elastomers which has the advantage of effectively dealing with high-viscosity liquids and increasing the manufacturing productivity [8]. Through light dose control, gradient regulation of mechanical properties is achieved, and its special feature of “overprinting” allows for continuous printing around complex structures, offering a new method for composite manufacturing. The above-mentioned study also successfully fabricated a freestanding conductive spring structure, which exhibits the free-form capability of volumetric printing in cantilever structures. The prepared ionic conductive elastomer has good optical transparency, conductivity, thermal stability and adhesion. It has been used in strain sensors and triboelectric nanogenerators, showing great potential in human-machine interface, smart wearables and self-powered sensors [8].

4. Inkjet Printing and Laser-Assisted 3d Printing Processes and Their Applications in Flexible Electronic Devices

4.1 Inkjet Printing and Laser-Assisted Processes

Inkjet printing is a layer-by-layer deposition of functional ink via droplet ejection, and can be used for creating conductive patterns and sensors for flexible electronics. Fig 3 Schematic of inkjet printing. Laser-based techniques use laser pulses to achieve nozzle-free, precise material transfer, allowing high-viscosity materials to be processed. These methods show great potential in creating metal microstructures and electrodes. These are key technologies of flexible electronic 3D printing.

Figure 3: Schematic of inkjet printing



4.2 Inkjet Printing of Flexible Electrodes

Inkjet printing technology is low cost, high precision and highly flexible, and has been used to fabricate flexible electrodes.

A major challenge in achieving high-resolution patterns in conducting patterns is the “coffee ring effect”. In 2025, Hartnett et al. proposed the SCALE process, which integrates ultraviolet micro-imprint lithography with inkjet printing: first, a micro-imprinting process is used to pattern channels with a width of 3.5 μm of the electrodes onto the flexible substrate, followed by inkjet printing of silver ink into the reservoir, enabling self-filling of the pattern through capillary action. This approach overcomes the need for multi-layer alignment and allows the fabrication of 3.5 μm high-resolution electrodes and a 100% device yield [3].

With inkjet printing, in the realm of flexible energy storage, Li et al. in 2016 showed that the printing process can precisely control the position of the active material, which is ideal for fabricating fork-finger micro-battery electrodes [9]. Multilayer printing results in high areal capacity. Inkjet printing also shows good roll-to-roll processability, which is suitable for mass production [3, 9]. It is anticipated that the main applications of this technology will be flexible displays and wearable energy storage devices.

4.3 Innovation in Laser-Assisted Printing

Laser-assisted 3D printing technology is a breakthrough in the traditional processing of thermosetting materials. Laser-assisted 3D printing technology offers a disruptive approach to forming thermosetting materials. The combination of in-situ laser induction and printing jets allows thermosetting inks to cross-link and cure in real time. It allows the direct printing of complex structures with horizontal overhangs and spatial curvatures without the need for support materials, with a resolution of 50 μm and an aspect ratio of up to 50 [10].

The key benefit of this fabrication process is its dynamic property control. The laser power density can be tuned to control the density of crosslinking, and as a result, gradient control of mechanical and electrical properties. A ten-fold tunability range is achieved for the mechanical properties, and a twenty-fold tunability range is achieved for the electrical properties.

In flexible packaging, it allows direct printing of complex three-dimensional packaging layers onto flexible substrates, without the need for assembly. The technology shows great promise for applications in flexible electronics packaging, soft robotics and biomedical applications.

5. Multi-Process Integration and Integrated Manufacturing

5.1 Example of Mixed Processes

Most 3D printing technologies have their restrictions: for example, photopolymerization technology can achieve high-precision complex structures, but are restricted to relatively few functional materials; direct ink writing technologies are compatible with a wide range of materials, but their performance is limited by resolution. Blended processes are a game-changing development.

The DIW+SLA hybrid process proposed by Chen et al. in 2025 is a typical example of structure-sensing integrated manufacturing [11]. This research used SLA printed flexible finger sleeve substrates, and printed graphene/carbon nanotube/silicone rubber dielectric composites with DIW in selected areas of the finger sleeve for in-situ integration of capacitive sensing units and mechanical structures. The developed smart finger sleeve can be used for real time gesture recognition without the tedious process of sensor unit alignment and assembly in conventional manufacturing processes. In 2023, Song et al. also combined 3D printing with machine learning to create surface microfluidic electronic skin [12]. This research used multi-material 3D printing to manufacture flexible sensing arrays with microfluidic channels, and integrated machine learning algorithms for multimodal signal processing, enabling accurate health monitoring. Research has demonstrated that hybrid processes not only overcome the obstacles of multi-material integration, but also enable functional diversification of intelligent electronic systems.

5.2 Process and Material Selection

Various 3D printing technologies have different strengths in printing accuracy and material compatibility, and should be chosen accordingly. In 2025, Kumar et al. performed a comparative study of five additive manufacturing technologies (SLA, SLS, FDM, DIW and inkjet printing) for flexible piezoelectric devices and suggested that SLA/DLP is preferred for precision printing and DIW for material versatility [2]. In 2026, Li et al. also noted that the production of flexible batteries must take into account both the rheological properties of the electrode materials and processing technologies [9]. These reports reveal a transition from “process-driven” to “function-driven” strategies in the field, in which applications drive the developments. The function-driven approach is taken to reverse select the best process-material combinations.

6. Conclusion

This work comprehensively reviews recent research in 3D printing technologies (extrusion molding, photopolymerization, inkjet printing, laser-assisted printing) for flexible electronic devices. Extrusion molding exhibits great versatility in terms of materials and shows great potential in flexible sensors and energy devices; photopolymerization offers high accuracy and is a key process for soft actuators and complex structures, while volumetric 3D printing allows for rapid prototyping without interfaces; inkjet printing and laser-assisted printing have their own strengths in high-resolution patterning and support-free structure manufacturing, respectively; multi-process composite printing also overcomes the limitations of single printing processes, achieving structural-sensing-drive integration. These developments have transformed flexible electronic devices from simple structures to multifunctional integration, and have played an important role in a variety of fields, including smart wearables and human-machine interfaces.

At present, 3D-printed flexible electronic devices still encounter issues such as a single process cannot provide all-round features, multi-material interface stability and efficiency. In the near future, innovations in multi-process, 4D printing, machine intelligence, and roll-to-roll production processes will enable their mass production.

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Conflicts of Interest

The authors declare no conflict of interest.

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