Soft electronics

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Omnidirectional printing of stretchable electronics

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An elastic conductive ink — which is made of conductive fillers suspended in an emulsified elastomer matrix — can be used to print three-dimensional elastic conductors.

Stretchable electronic devices are of use in a range of applications including biosensors and stimulating electrodes. They can, in particular, be used to enhance the recording of physiological signals and improve the electrical stimulation of biological tissues by reducing the mechanical mismatch between the device and the human body. Ideally, stretchable electronics should offer tissue-like physical properties, as well as sufficient electrical capabilities, mechanical robustness and reliability. And with the rise of personalized devices and medicine, the ability to fabricate devices tailored to an individual would be a valuable addition.

3D printing using conductive inks is a promising strategy to create such devices. However, 3D printing of stretchable electronics has been limited to a layer-by-layer deposition, rather than truly

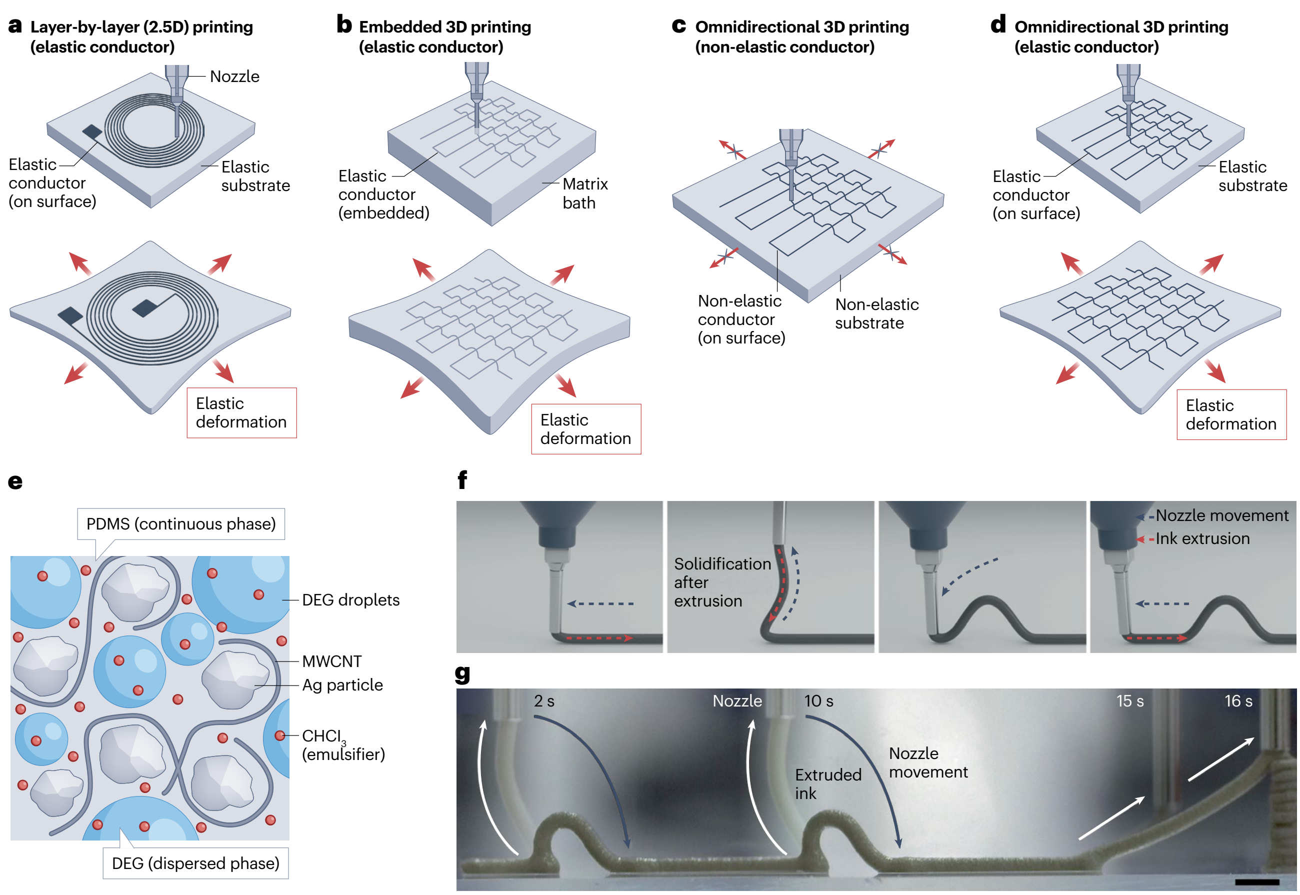

Fig. 1 | Omnidirectional 3D printing of elastic conductive ink. a, Schematic illustration of layer-by-layer (2.5D) printing of an elastic conductor on an elastic substrate. **b**, Schematic illustration of embedded 3D printing of an elastic conductor in a matrix bath. **c**, Schematic illustration of omnidirectional 3D printing of a non-elastic conductor on a non-elastic substrate. **d**, Schematic illustration of omnidirectional 3D printing of an elastic conductor on an elastic substrate. **e**, Schematic illustration of the emulsion-based elastic and conductive ink. **f**, Schematic illustrations of the omnidirectional direct-ink-writing process of the emulsion-based elastic conductive ink. **g**, Images of elastic wiring made from the emulsion-based elastic conductive ink with a series of self-supporting 3D geometries. Scale bar, 1 mm. PDMS, polydimethylsiloxane; DEG, diethylene glycol; MWCNT, multi-walled carbon nanotube; $CHCl_3$, chloroform. Panels **e**–**g** reproduced with permission from ref. 1, Springer Nature Ltd.

three-dimensional (3D) fabrication, due to the insufficient rheological properties of elastic conductive inks. Writing in *Nature Electronics*, Seungjun Chung and colleagues now report omnidirectional printing of stretchable electronics using an emulsion-based elastic conductive ink[1].

Three main strategies have been explored for the printing of stretchable electronic devices. The most widely adopted is layer-by-layer deposition of elastic conductive inks (Fig. 1a). This strategy has been used to fabricate stretchable electronics using various elastic conductive inks — including silver–elastomer composites[2,3], platinum–elastomer composites[4] and conducting polymers[5] — and on diverse substrates. However, it is essentially limited to the stacking of 2D structures ('2.5D') owing to its layer-by-layer nature. Alternatively, embedded printing of elastic conductive inks can be used to directly print 3D structures inside a matrix bath and fabricate stretchable electronic devices[6,7] (Fig. 1b). This strategy can create 3D structures beyond layer-by-layer deposition, but the requirement of a matrix bath with optimized rheological properties adds complexity to the printing process and the choice of substrate materials. Finally, omnidirectional printing has previously been used to fabricate 3D electronic devices without the need for a matrix bath (Fig. 1c) but it has been limited to non-elastic conductive inks — such as those based on silver particles[8] and liquid metals[9] — resulting in devices with limited stretchability. The realization of omnidirectional printing of stretchable electronics (Fig. 1d) has thus remained challenging.

To achieve omnidirectional printing of stretchable electronics, the researchers — who are based at the Korea Institute of Science and Technology, Chungbuk National University and Kyung Hee University — developed an elastic conductive ink with optimal rheological properties. The ink consists of an emulsified elastomer composite with immiscible, non-volatile solvents and conductive fillers (silver particles and multi-walled carbon nanotubes) that has a phase-separated microstructure (Fig. 1e). The ink has a pseudoplastic and lubricating behaviour that permits omnidirectional printing, while offering enough stability to self-support the printed 3D structures (Fig. 1f). Electrodes can be directly printed to create freestanding, out-of-plane 3D geometries with high stretchability (more than 150% strain) and high resolution (minimum feature size of less than 100 µm) (Fig. 1g).

The electrical conductivity of the printed material can be increased to 6,600 S cm^{-1} as a result of vaporization of the dispersion phase in the ink, as well as enhanced percolation of the silver particles by the multi-walled carbon nanotubes. The printed elastic conductor exhibits good electromechanical stability under cyclic deformations, showing stable electrical properties over 3,000 cycles of 50% strain. To illustrate the capabilities of the 3D printable elastic conductor, the team fabricated a stretchable on-skin electronic device with printed elastic interconnects. The device can measure and display body temperature via mini-light-emitting-diode arrays.

The omnidirectional printing method developed by Chung and colleagues could be a powerful tool for the fabrication of user-tailored, on-skin electronic devices. The approach could also be of use in other applications such as soft robotics. There is, however, potential for further development and improvement. For example, the electrical conductivity of the elastic conductor is several orders of magnitude lower than its metallic counterparts, and the demonstrated omnidirectionally printed 3D structures are limited to relatively simple arched or overhanging filaments. An elastomeric encapsulation is manually introduced after the omnidirectional printing of the conductors for mechanical and electrical robustness of the stretchable devices. Future research should focus on improving the properties of the elastic conductor and exploring the full potential of omnidirectional direct-ink-writing technology, which could include the creation of more diverse 3D geometries and the development of multi-material printing.

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Competing interests

The authors declare no competing interests.