Developing 3-D electronics with pre-distorted pattern generation and thermoforming

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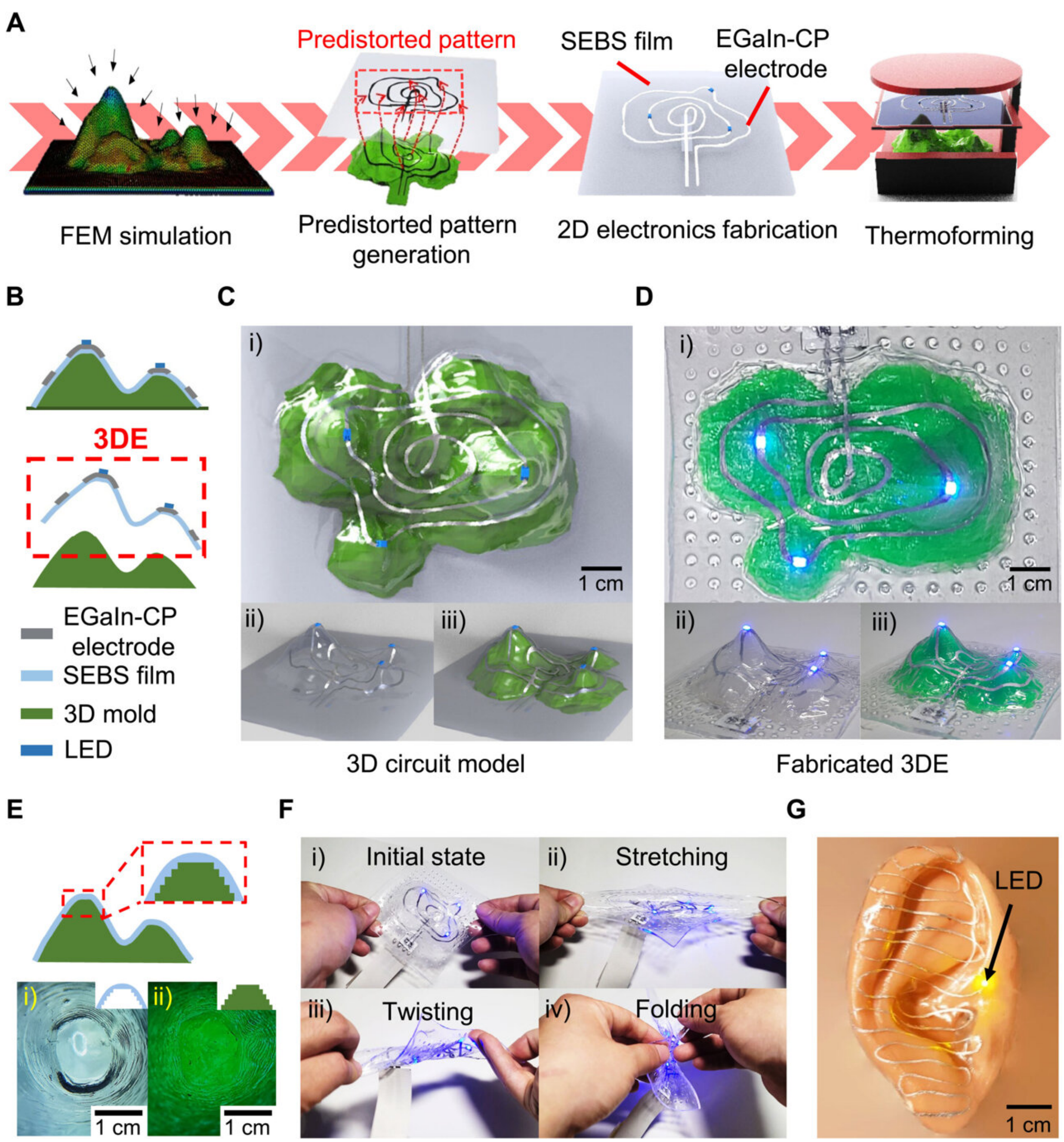


Overview of the fabrication method of 3DE based on predistorted pattern generation and thermoforming process (referred to as PGT3DE) featuring high customizability, conformability, and stretchability. (A) Basic mechanism of the PGT3DE. 3DE can be fabricated using thermoforming simulation and the predistorted pattern generation method. (B) Schematic cross-sectional illustration of fabricated 3DE based on PGT3DE. (C and D) Designed 3D circuit model (C) and fabricated 3DE (D) [(i) top view and (ii and iii) bird's eye view without the 3D mold (ii) and with the 3D mold (iii)]. (E) 3D conformal property of the thermoformed SEBS film with a microscope image of thermoformed SEBS film (i) and 3D mold (ii). (F) Electrical stability under various deformations; the 3DE is robust under stretching (ii), twisting (iii), and folding (iv) deformations without electrical disconnection. (G) Ear-shaped 3DE. The LEDs in the 3DE are well lit because of the successful electrical interconnection. Photo credit: Jungrak Choi, Korea Advanced Institute of Science and Technology (KAIST). Credit: *Science Advances*, 10.1126/sciadv.abj0694

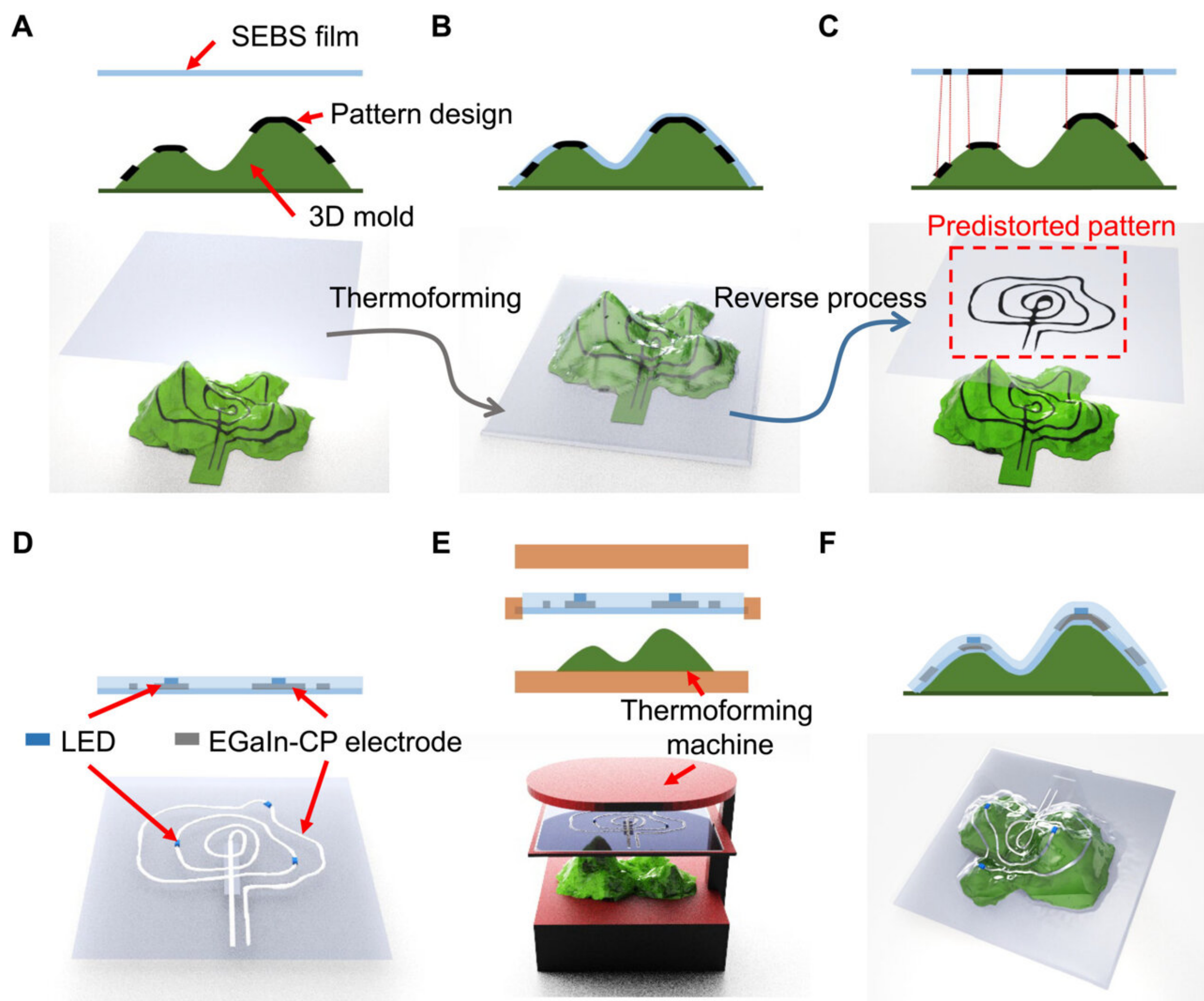
Three-dimensional electronics (3-DE) is attracting much interest due to the increasing demands for seamless integration on curved surfaces. Nevertheless, it is challenging to develop 3-DE with high customizable conformity and stretchability. In a new report now published in *Science Advances*, Jungrak Choi and a research team in mechanical engineering, materials science and science and technology in South Korea presented a method to form three-dimensional electronics based on predistorted pattern generation and thermoforming. Using thermoplastic elastomer and liquid-metal-based conductive electrodes, they accomplished high thermoformability and stretchability during device fabrication and function. The new technology can facilitate a wide range of functionalities in wearable technologies.

Developing 3-DE

Three-dimensional electronics have high customizability, 3D conformability and stretchability to form state-of-the-art stretchable electronics in response to the increasing demands to form curvilinear surfaces for wearable sensors. The process to directly develop 3-DE with high customizability, 3D conformability and stretchability on any complicated surface are in high demand. Among the many development methods, thermoforming is a manufacturing technique that uses thermoplastic deformation of a plastic film onto a 3D shaped mold with the advantages of low fabrication cost, large area scalability and quick prototyping. In this work, Choi et al. developed a method for 3-DE based on pre-distorted pattern generation and thermoforming abbreviated as PGT3DE with a thermoplastic elastomer and liquid metal-based conductive electrode. During the 3-DE fabrication process, the team applied a highly stretchable thermoplastic elastomer-based substrate such as styrene-ethylene-butylene-styrene (SEBS) and a stretchable conductive electrode such as eutectic gallium-indium-based liquid metal mixed with copper microparticles.

Experimental overview

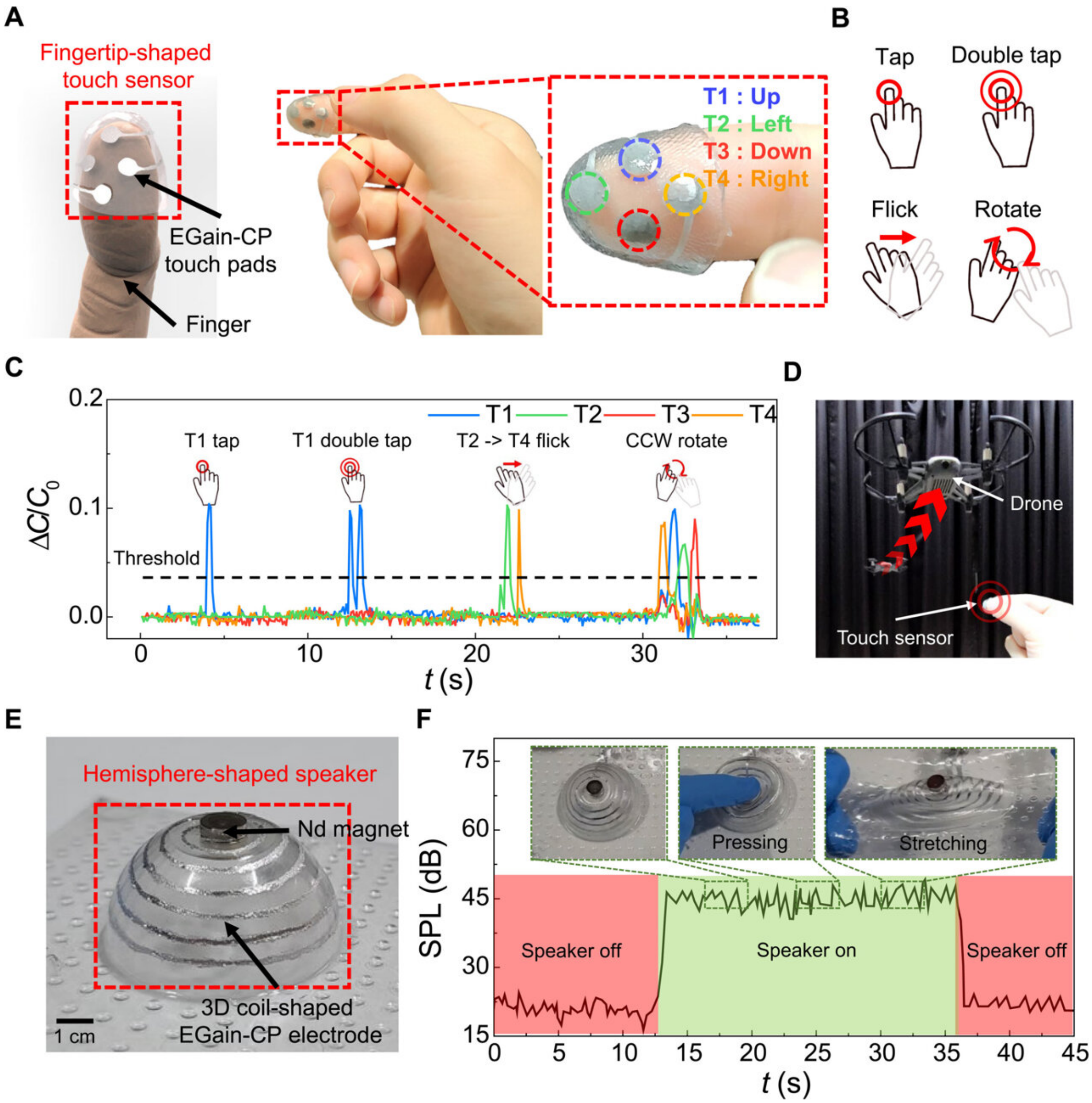
As proof of concept, the scientists designed a 3D circuit model and lit three LEDs on the 3D surface and noted its stretchability for flexible deformations, without electrical disconnection during the process. They also developed complicated shapes including an ear-shaped 3-DE. The team followed two key steps to form 3-DE based on the pre-distorted pattern generation and thermoforming (PGT3DE) method. In the first experimental step, Choi et al. generated a pre-distorted 2D pattern using finite element method (FEM) simulations and achieved 3D modeling of the designed 3-DE. In the next step, they used electrodes and electronic devices and placed them on the 2D planar film using the pre-distorted 2D pattern. Additionally, the team designed a circuit pattern of the 3-DE on the 3D mold surface using a modeling tool and established a map between the deformed 3D mesh and the surface of the 3D mold to transfer the circuit pattern. They completed the 3-DE fabrication by detaching it from the mold. The thermoforming process included complex thermoplastic deformations when the thermoplastic film adapted to the 3D mold. The team conducted sequential steps during the simulation.



Fabrication process of the PGT3DE. (A) Design of 3DE circuit pattern on 3D mold. (B) Thermoforming simulation. (C) Predistorted pattern generation. (D) Patterning the EGaIn-CP electrode and mounting electronic devices on 2D planar SEBS film based on the predistorted pattern. (E) Thermoforming process. (F) Fabricated 3DE. Credit: *Science Advances*, 10.1126/sciadv.abj0694

Electrical characterization of the material and potential applications

Researchers had previously recommended an EGaIn-CP electrode as a promising material to power stretchable devices due to its high electrical conductivity, adhesive property, and stretchability. In this work, Choi et al. used a similar setup and facilitated pattern resolution of the EGaIn-CP electrode using two different printing methods including stencil printing and fiber laser printing.



Demonstration of 3DE for touch sensor and speaker applications. (A to D) Fingertip-shaped capacitive touch sensor. (A) Schematic illustration and photographs of the fingertip-shaped touch sensor. The sensor is composed of four touch pads (T1, T2, T3, and T4). (B) Gesture control functions. Four touch pads allow not only four simple taps but also several gesture controls such as double tap, flick, and rotation. (C) Capacitance changes over time when gesture control functions were applied. CCW, counterclockwise. (D) Quadcopter drone control using the touch sensor. The touch sensor was successful in controlling a quadcopter drone. (E and F) Hemisphere-shaped speaker. (E) Photograph of the hemisphere-shaped speaker. (F) Characteristic of the speaker. The speaker generated sound well with little sound distortion under mechanical deformations such as pressing and stretching. Photo credit: Jungrak Choi, KAIST. Credit: *Science Advances*, 10.1126/sciadv.abj0694

They noted how the length of the electrode increased during thermoplastic and elastic deformations, without electrical disconnection and with excellent signal recovery to ensure stable performance and a long lifetime. The team then operated the electrode up to a temperature of 65 degrees Celsius. To examine the potential applications of the proposed technology, Choi et al. demonstrated a 3D wearable touch sensor and a speaker with 3D geometries. During sensor applications, they used a fingertip-shaped capacitive touch sensor allowing users to wear the sensor comfortably and press the touch pad, while maintaining a stable electrical connection. The team used four touch pads to form the touch sensor, and included simple taps such as double tap, flick and rotation as maneuvers. Using the touch sensor, they then facilitated the control of a drone for landing, take-off, flip movements, and rotations. They also created a 3D shaped speaker and measured its successful function by measuring the sound pressure level. Using the PGT3DE (pre-distorted pattern generation and thermoforming) system, Choi et al. additionally showed the wireless, battery-free functionality of 3-DE systems.

Outlook

In this way, Jungrak Choi and colleagues developed a manufacturing method known as PTG3DE, which included pre-distorted pattern generation and thermoforming methods to form three-dimensional electronics (3-DE). The method provided customizable design freedom and 3D conformal contact across a variety of complicated surfaces. They designed the 3-DE precisely using FEM (finite element method) simulations and fabricated them using pre-distorted pattern generation. The constituents allowed high stretchability and seamless electronic integration. The team showed the versatility of the technology by building a touch sensor, speaker and wireless, battery-free systems with 3D geometries.

More information: Jungrak Choi et al, Customizable, conformal, and stretchable 3D electronics via predistorted pattern generation and thermoforming, *Science Advances* (2021). DOI: 10.1126/sciadv.abj0694

Dae-Hyeong Kim et al, Stretchable and Foldable Silicon Integrated Circuits, *Science* (2008). DOI: 10.1126/science.1154367