MEMS

3D piezoelectric microsystems pop up

The compressive buckling of lithographically defined, two-dimensional patterns can create three-dimensional piezoelectric microsystems with a range of potential applications.

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Piezoelectric transduction has been used to build devices for energy harvesting, sensing and actuation, with applications in areas such as the automotive industry[1] and biomedicine[2,3]. Recently, there has been growing interest in piezoelectric devices for self-powered and wearable systems that can detect or harvest broadband, low-frequency mechanical stimuli including ambient vibrations or human motion[4–7]. Piezoelectric microsystems are typically fabricated using thin film processes, yielding devices with 2D configurations. Yet, such planar devices are typically tailored toward narrow-band, high-frequency applications or limited degrees of freedom in a 2D design space. Transforming conventional 2D structures into 3D could allow access to a greater diversity of operating modes. Writing in *Nature Electronics*, Yihui Zhang, Yonggang Huang, John Rogers and colleagues[8] demonstrate the fabrication of 3D piezoelectric microsystems via the compressive buckling of lithographically defined 2D patterns. The 3D piezoelectric microsystems offer new functionalities and improved device performance compared with their 2D counterparts[8].

The researchers — who are based at Northwestern University, Tianjin University, University of Missouri, Shanghai Jiaotong University and Tsinghua University — developed a fabrication scheme to create various 3D piezoelectric mesostructures with tailored geometries and mechanical attributes. The structures comprise a layer of piezoelectric polymer (polyvinylidene difluoride) sandwiched between two metallic electrodes. The fabrication scheme generally follows three main steps: 2D precursor designs are defined using planar microfabrication strategies; the structures with selected bonding sites are transfer printed onto a pre-strained elastomeric substrate; and the strain is released, such that the 2D geometry reversibly transforms via buckling to a 3D microsystem.

Although this general fabrication strategy yields a variety of unique device architectures, the researchers encountered difficulties when attempting to create certain 3D device geometries, such as those with a low-stiffness, serpentine design. In such cases, the ultralow stiffness structure fails to buckle off of the elastomeric substrate due to the adhesion energy between the geometry and the elastomer. In order to overcome this issue, Rogers and colleagues introduced a temporary support structure beneath the 2D precursor in the compressive buckling process. Following removal of the support structure, the 3D piezoelectric microstructure maintains its out-of-plane buckled configuration, which corresponds to a local energy minimum state (Fig. 1a).

Such 3D, low-stiffness structures have lower resonance frequencies and are capable of more complex modes of motion and

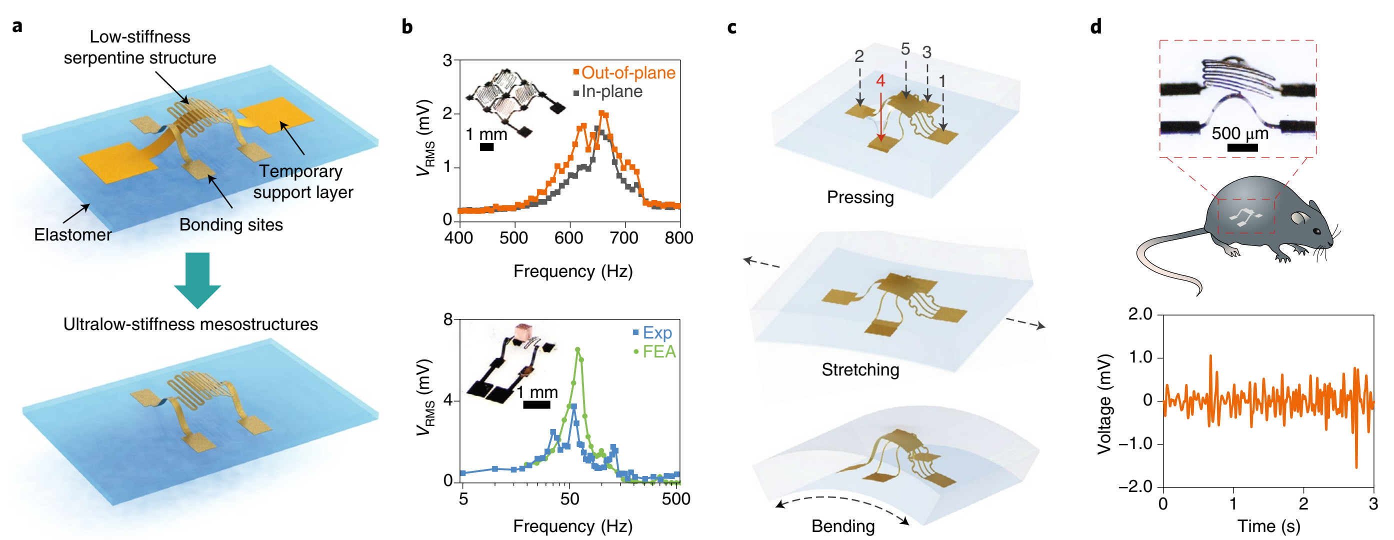

Fig. 1 | 3D piezoelectric microsystems and their potential applications. a, Fabrication of an ultralow-stiffness piezoelectric microsystem with a serpentine design using a temporary support layer. **b**, Application of an ultralow-stiffness, 3D piezoelectric microsystem for multidirectional (top) and broadband (bottom) vibrational energy harvesting. Exp, experimental data; FEA, finite element analysis. **c**, Application of a 3D piezoelectric microsystem with an asymmetric design for detecting the magnitude and the position/direction of applied mechanical stimuli such as pressing, stretching and bending. **d**, Application of the 3D piezoelectric microsystem as a bio-integrated device when implanted in the hind leg of a mouse, and the output signal generated from mouse trotting. Credit: adapted from ref. [8], Springer Nature Ltd nonlinear deformations, when compared with their 2D counterparts. Consequently, they offer new opportunities for vibrational energy harvesting, particularly in small-scale and bio-integrated applications. The 3D configuration enables the device to generate analogous electrical outputs in response to both in-plane and out-of-plane vibrations (Fig. 1b). Furthermore, both experimental and finite element analysis (FEA) results confirmed that the ultralow-stiffness serpentine design — coupled with the nonlinear deformations of the 3D microstructures — allowed the devices to harvest vibrational energy at a broad range of frequencies (5–500 Hz). This includes mechanical excitations at low frequencies, comparable to those of ambient vibrations, machine-induced vibrations and human motion (Fig. 1b).

In addition to vibrational energy harvesting, the 3D piezoelectric microsystems can be configured to respond to various mechanical stimuli, including applied normal forces, stretching and bending (Fig. 1c). For this purpose, a device with an asymmetric 3D structure was encapsulated in a soft silicone elastomer for physical protection. The 3D configuration of the device, along with its asymmetrical design, allows for the detection of the magnitude of the applied stimuli, as well as their position or direction. Specifically, due to the asymmetrical structure of the device, pressing on five different locations results in local deformations and output signals with distinctive shapes that can act as fingerprints for identifying the position of the original force. Likewise, the same strategy can be used to sense applied strains in stretching/bending, as well as the direction of the exerted stimuli.

The 3D piezoelectric microsystems can also be employed as biomedical implants for applications in sensing and energy harvesting. For this purpose, a 3D piezoelectric device was implanted in the hind leg of a mouse. It was observed that the deformation of the 3D device as the mouse moved yielded detectable and consistent output signals (Fig. 1d). In contrast, utilizing a 2D device resulted in unstable signals and lower amplitudes in specific cases of movement due to the smaller magnitudes of the device deformations.

The approach of Rogers and colleagues could be used to develop novel 3D electromechanical transduction microsystems for a critical set of applications, ranging from human–machine interfaces to biomedical implants. To this end, long-term studies of device functionality and stability in response to different mechanical stimuli and environmental conditions will need to be performed, in order to validate these initial experiments. In addition, other design schematics should be explored to improve the signal-to-noise ratio of the devices for sensing applications. The scalability of these devices could also be exploited to enable large-scale applications and multiple minima states on the same chip for broader harvesting. Finally, it will be interesting to investigate the feasibility of this approach for fabricating piezoelectric actuators with complex, 3D geometries and controlled deformations, as well as device architectures with multiple functionalities — such as combined actuation and sensing/energy harvesting — within a single system[9,10]. ❐

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