Flexible electronics

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Microcracked conductors for wearable sensors

Jihong Min, Yu Song & Wei Gao

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A stretchable and conductive micrometre-thick elastic conductor, which has a controlled morphology of microcracks, can be used in on-skin and implantable sensor applications.

Next-generation wearable and implantable electronic devices should be able to conform with the soft and dynamic surfaces of human tissue[1–3]. Current state-of-the-art flexible electronics can curve and bend to laminate on three-dimensional surfaces, but struggle to maintain a tight contact with surfaces that frequently undergo large deformations. To both conform and deform, devices composed of biocompatible elastic conductors are required. These conductors should, in particular, be stretchable, breathable and durable, all while maintaining stable conductivity[4–6]. Writing in *Nature Electronics*, Kenjiro Fukuda, Xiaodong Chen, Takao Someya and colleagues now report a micrometre-thick elastic conductor that offers powerful electrical and mechanical capabilities[7]. The conductor is created by controlling the morphology of microcracks in a gold film that is thermally evaporated on a 1.3-µm-thick polydimethylsiloxane (PDMS) substrate. The resulting PDMS–gold conductor can be stretched and deformed on curvilinear dynamic surfaces while maintaining stable conductivity (Fig. 1a).

Three main strategies have been explored in the design of elastic conductors: structural engineering of metallic thin films on elastomer substrates; patterning of intrinsically stretchable conductors such as liquid metals; and composite blending of conductive fillers and stretchable polymers[8]. Among them, structure-based approaches that incorporate metal films are prevalent due to the high conductivity of the resulting conductors. Patterning of metal films into serpentine and mesh structures is common, but autonomously formed gold microcrack structures on PDMS have also been shown before to offer excellent conductivity and cyclic strain durability[9]. Despite the good conductivity and strain resilience of these microcrack structures, one limitation is that their growth requires thermal expansion of the PDMS substrate during vacuum deposition. A key innovation in the approach of Someya and colleagues – who are based at various institutes in Japan, Singapore and China – is the introduction of a temporary 100-µm-thick PDMS substrate on which the 1.3-µm-thick PDMS layer sits during the thermal evaporation of the gold. The technique leads to the uniform growth of tri-branched-shape microcracks in the gold layer (Fig. 1b).

Thickness is an important element to consider when designing biocompatible elastic conductors for on-skin and implantable sensor applications. First, thinner elastic conductors are more breathable. On-skin wearable devices with low gas permeability can prevent the evaporation of sweat and volatile organic compounds from the skin, potentially causing irritation and discomfort. The highly breathable microcrack conductor offers a water loss speed of 11.9 mg h^{-1} mm^{-2},

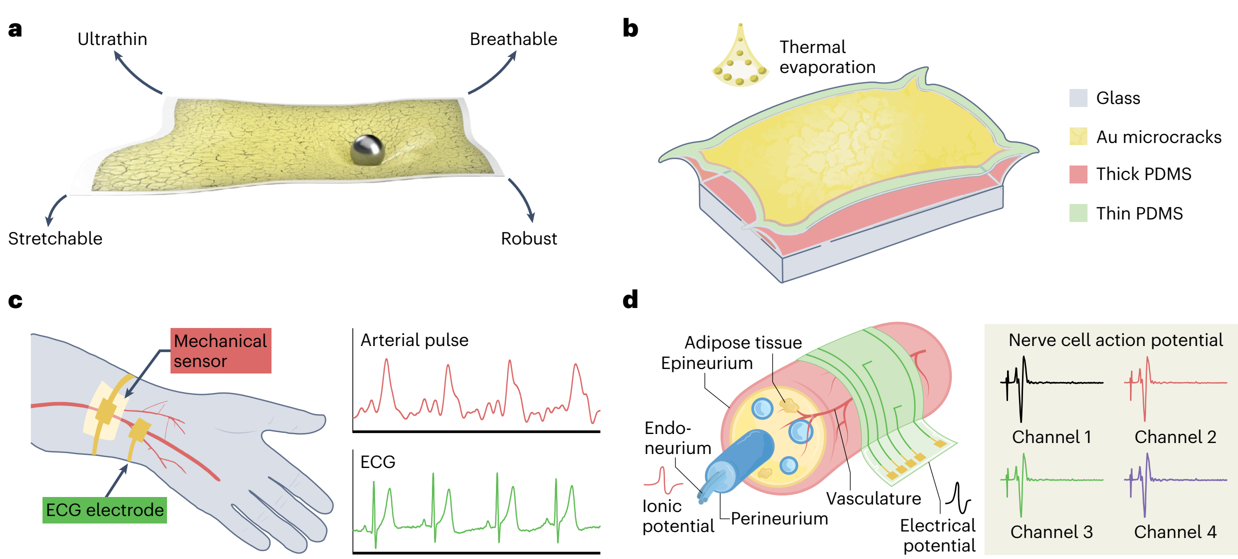

Fig. 1 | Microcracked PDMS–gold elastic conductors for on-skin and implantable sensors. a, Illustration of the elastic conductor, which is ultrathin, breathable, stretchable and robust. **b**, Schematic of structural setup during thermal evaporation of gold on the 1.3-µm-thick PDMS substrate. The approach includes a temporary 100-µm-thick PDMS substrate that supports the formation of the microcracks. **c**, Schematic illustration of the use of the conductor in an electrocardiogram (ECG) electrode and wearable mechanical sensor, which can be used for on-skin arterial pulse measurements. **d**, Schematic illustration of the use of the conductor in implantable neural electrodes, which can form gap-free interfaces with nerve tissue in order to acquire nerve cell action potentials. Figure adapted with permission from ref. [7], Springer Nature Ltd.

which is higher than the typical transepidermal water loss speed of human skin (4–10 mg h^{-1} mm^{-2}). Next, thinner elastic conductors exert less mechanical stress on human tissue during deformation. If a stretched-out elastic conductor exerts substantial tension on human tissue, discomfort and complications can arise. However, the ultrathin conductor only requires a small force of 38.9 mN to achieve 100% deformation. Finally, ultrathin devices are less stiff and can conform better to curved surfaces, improving sensor contact and performance.

While the thickness of the conductor plays an important role in determining biocompatibility, stretchability and durability are still the main criteria for elastic conductors. High stretchability is critical for forming conformal contact with tissue and allowing unrestricted movement on dynamic surfaces. It also prevents any strain-induced damage during the handling process. Despite being ultrathin, the conductor developed by Someya and colleagues could be stretched up to 300% and bear a weight of 20 g without losing its high conductivity. It could also maintain its resistance after stretch and release testing at a tensile strain of 100%, with only a 1.7% change after 5,000 cycles.

With the addition of a 22-nm-thick ionically conductive adhesive polymer layer, the conductor could form seamless contact with a person's skin and was able to withstand vigorous skin deformations and strong water rinsing. After 8 h of extensive wear, which included vigorous exercise, the electrode was still intact and could transmit high-quality electrocardiogram signals (Fig. 1c). The conductor was also engineered into a 3-µm-thick multilayer wearable sensor and used to measure arterial pulse waves. Furthermore, the conductor was used as implantable neural electrodes for neuromodulation and neural signal recording, and its ultrathin profile meant that it could be tightly wrapped around a rat nerve tissue without any air gaps (Fig. 1d). To test the neuromodulation capabilities, the electrodes were used to selectively activate muscle tissue by stimulating different fascicles of the sciatic nerve. To test the neural signal recording capabilities, the electrodes were used to record compound nerve action potentials in response to subdermal electrical stimulation of the rat paw.

Ultimately, elastic conductors are assembled into stretchable electronic devices. In the work of Someya and colleagues, the elastic conductors were used in stretchable biosensors wired to external measurement circuity, but elastic conductors have also been widely used as stretchable interconnects between rigid electronic components, forming rigid island stretchable circuits[10]. Elastic conductors are also needed in the development of stretchable antennas and stretchable semiconductor devices, which could eventually lead to fully stretchable electronic devices[2,4,6]. Different applications require different things from elastic conductors. For instance, on-skin sensing may benefit from a thinner elastic conductor to improve contact and comfort, but a thinner conductor may be prone to degradation if used in an implantable device. There are numerous considerations when designing elastic conductors, and various materials and structures should continue to be explored in order to create next-generation devices.

Jihong Min, Yu Song & Wei Gao ✉
Andrew and Peggy Cherng Department of Medical Engineering, California Institute of Technology, Pasadena, CA, USA.
✉e-mail: weigao@caltech.edu

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Competing interests

The authors declare no competing interests.