FLEXIBLE ELECTRONICS

Within touch of artificial skin

Flexible arrays of transducers can now be fabricated with pressure sensitivity and response times approaching those of natural human skin.

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As humans, we interact with our immediate environment through our senses — sight, sound, smell, taste and touch. Emulation of the senses by electronic means has long been a grand challenge of artificial intelligence and is pivotal in the development of accessible and natural interfaces between man and machine. Sight and sound are the simplest technologically, and the past decades have seen significant developments in image acquisition and processing technologies, in addition to voice synthesis and recognition. From an electronic standpoint, smell and taste are one and the same, but despite significant advances in electronic nose[1] and chemical sensor[2] technologies, the sensitivity and discrimination levels of these engineered systems fall short of the performance of their human counterparts.

Touch also remains stubbornly difficult to mimic. The difficulty is not simply to identify transduction mechanisms that can detect mechanical resistance or static mass loads; touch emulation necessitates the development of high spatial-resolution, pressure-sensitive artificial skins capable of discriminating between local stimuli on a textured surface. For example, by applying a pressure of 10 kPa over a 1 cm^2 contact area, the human touch can typically detect local roughness variations with a spatial resolution of 50 μm. Coupled with the fact that the softest touch corresponds to a mass-loading sensitivity of better than 0.1 g per mm^2 (or about 1 kPa), this highlights the very real challenge of developing touch technology that can compete with the performance in humans.

As now reported in *Nature Materials*, separate research groups have addressed this problem in two distinct ways[3,4]. Both employ an active matrix array of transducers using flexible materials. Flexibility is desirable because it enables the fabrication of transducer arrays that can conform to curved surfaces, which is essential if these engineered materials are to serve as artificial skins for prosthetic devices or in applications where a high degree of spatial resolution is required. Where the groups differ is in their approach to the transduction mechanism and the types of substrate used. Ali Javey and co-workers[3] used Ge/Si-nanowire-array field-effect transistors (FETs) laminated on a flexible polyimide substrate with a pressure-sensitive rubber layer that acts as a tunable resistor in series with the nanowire FET (Fig. 1). On the other hand, Zhenan Bao and collaborators[4] microstructured polydimethylsiloxane (PDMS) films to produce pressure-sensitive capacitor arrays that are integrated into the gate dielectrics of an organic FET array (Fig. 2). Both report pressure sensors with response times of less than 100 ms and a dynamic range of 0.5–20 kPa or better, and each represents a significant advance in the state of the art. By tailoring the microstructured PDMS film, it is possible to achieve static load sensitivities as low as 3 Pa, and ultrafast millisecond response times[4]. In the approach of Bao and colleagues[4], array integration involves laminating the PDMS film onto a non-flexible silicon substrate, so the overall conformability is lost. However, these authors also reported a proof-of-concept flexible capacitive matrix-type pressure sensor (Fig. 2b). In contrast, the nanowire-on-polyimide approach ensures flexibility, and Javey and collaborators have

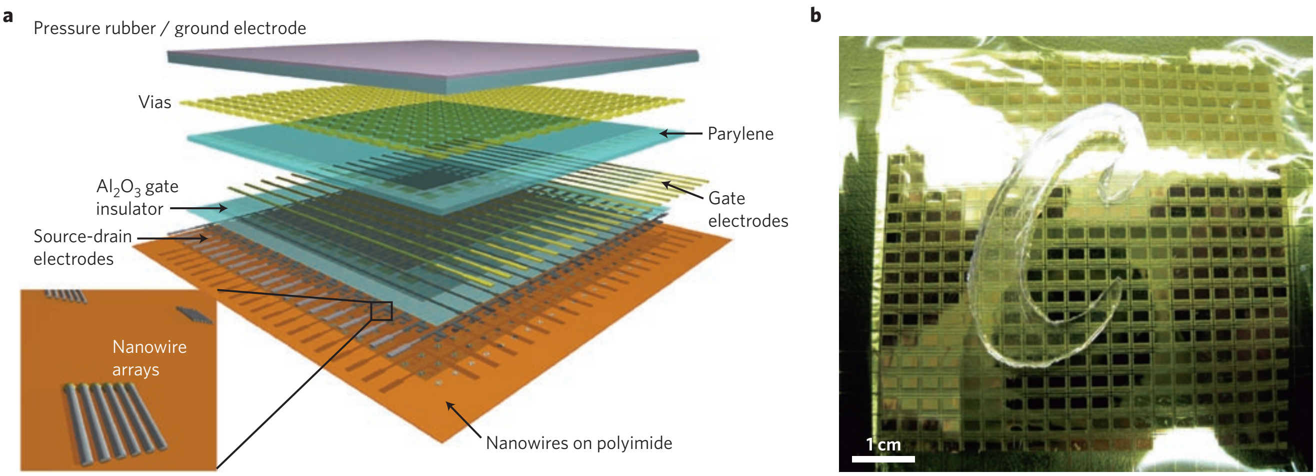

Figure 1 | Artificial skin based on arrays of Ge/Si nanowires. **a**, Illustration of the passive and active layers of the nanowire-based electronic skin. Ge/Si nanowires are transferred to a polyimide layer by contact printing after which source–drain electrodes are patterned and layered with an Al_2O_3 gate dielectric and an Al top gate. A pressure-resistive rubber is then connected to the active layers via holes to the source contact on each nanowire FET. A grounded Al layer is deposited on the rubber, which enables the latter to act as a tunable resistor in series with the nanowire FET. **b**, Photograph of a PDMS mould in the shape of the letter C, placed on top of the nanowire arrays. The area associated with the C is ~3 cm^2, and after application of a normal pressure of 15 kPa the spatial distribution of the load was successfully read by the nanowire FET array. Figure reproduced from ref. 3.

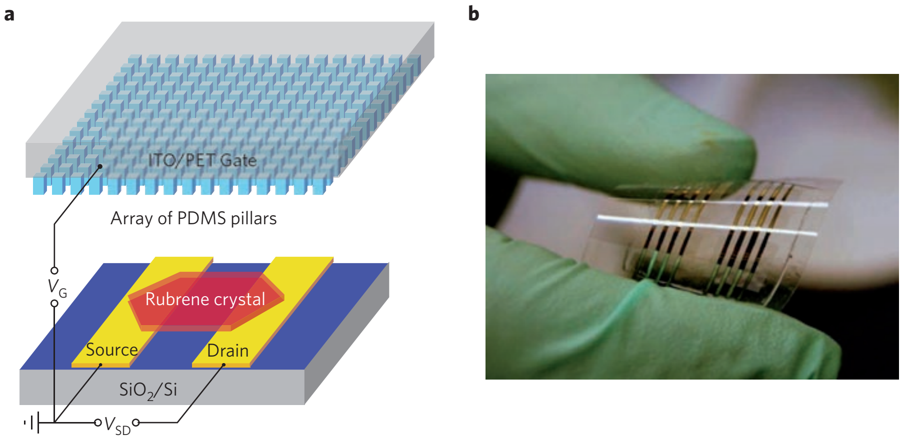

Figure 2 | Flexible array of transducers on microstructured PDMS films. **a**, Schematics of a pressure-sensing organic single-crystal transistor, consisting of a thin rubrene single crystal and a structured PDMS dielectric film, supported on a SiO_2/Si substrate. The structured PDMS film acts as a pressure-sensitive capacitor array that is integrated into the indium tin oxide/polyethylene terephthalate (ITO/PET) gate dielectrics of the organic FET array. **b**, Photograph of a PET film with microstructured PDMS on aluminium metal lines. A second layer of PET with the same metal-line patterns was subsequently placed orthogonally to the PET film with microstructured PDMS in between for a proof-of-concept flexible capacitive matrix-type pressure sensor. Figure reproduced from ref. 4.

demonstrated repeated bending to a 2.5 mm radius without appreciable degradation in performance[3].

Performance aside, perhaps the most remarkable aspect of these studies is how they elegantly demonstrate that it is possible to exploit well-established processing technologies to engineer low-cost innovative solutions to important technical problems. There remain, however, significant opportunities for further innovation. The millimetre-scale separation between pressure-sensitive pixels in the present active matrix arrays must be decreased to better mimic the tactile sensing properties of human skin, or calibrated to account for off-centre loading of the transducing elements. Moreover, the active channel materials used in each case have their own drawbacks: the potential for statistical fluctuation in the number of nanowires in the channel[3], particularly at increased integration densities; or, in the case of organic FETs[4], the high voltage operation necessary, coupled with the impracticality of using single-crystal rubrene as the channel material in large-area arrays. That said, the prototype artificial skins reported have successfully emulated the pressure sensitivity of human skin, and have done so in a manner that allows for macroscale integration of sensor arrays.

Having mastered touch together with the other four senses — albeit with varying degrees of success — there is no reason not to consider other sensory capabilities, or the possibility of combining a range of sensors into a single integrated artificial skin. One can readily imagine the incorporation of sensors that enable the detection of local temperature, the presence of light or electromagnetic fields, or even humidity levels. The addition of piezoelectric nanowire arrays may even help emulate the enhanced sensitivity provided by human hair follicles.

The potential uses of artificial skin extend beyond prosthetic applications. It is easy to conceive the development of precision tools with enhanced dexterity and tactile sensing capabilities, such as those required in minimally invasive surgical procedures. Other potential uses involve the integration of touch capabilities into flexible and scrollable display technologies. Whatever the eventual application, the key enablers will be low-cost, large-area sensor arrays on flexible substrates; and in this regard, the present studies represent important milestones in the development of ultrasensitive touch technologies. ❐

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