

Highly Sensitive Flexible Pressure Sensors with Micro-structured Rubber Dielectric Layers

The development of an electronic skin is critical to the realization of artificial intelligence that comes into direct contact with humans, and to biomedical applications such as prosthetic skin. A technology for the production of electronic skin needs to be inexpensive and able to produce the skin with high throughput. In order to successfully mimic the properties of natural skin, large arrays of pixel pressure sensors on a flexible and stretchable substrate are required. While promising routes towards stretchable matrix-type substrates[1] and electrodes[2] were developed in the past, there is still a need for a low-cost, large-area compatible technology for the production of pressure-sensitive pixels that are sensitive in both the medium pressure regime (10-100 kPa) to low-pressure regime (<10 kPa, gentle touch around 1kPa).

We have developed flexible pressure sensors that employ the thin film capacitor and the organic field effect transistor device structures. The key component that enables the sensing of pressure in these devices is a thin dielectric layer of the biocompatible elastomer polydimethylsiloxane (PDMS) into which tiny structures (micro-structures) have been molded. The fabrication process is schematically shown in Figure 1. A dilute solution of the PDMS mixture of base and cross-linker is cast onto a Si wafer mold containing arrays of the inverse of the features to be replicated. A sheet of the flexible plastic PET (poly(ethyleneterephthalate)) is then laminated onto the mold. The PDMS film is cross-linked by the application of pressure and moderate heat. When the PET substrate is then lifted from the mold, it contains arrays of PDMS microstructures. Different micro-structures can be molded by this process; in this work we prepared lines with a triangular profile and pyramids. These micro-structures are replicated with high fidelity over the full size of a silicon wafer.

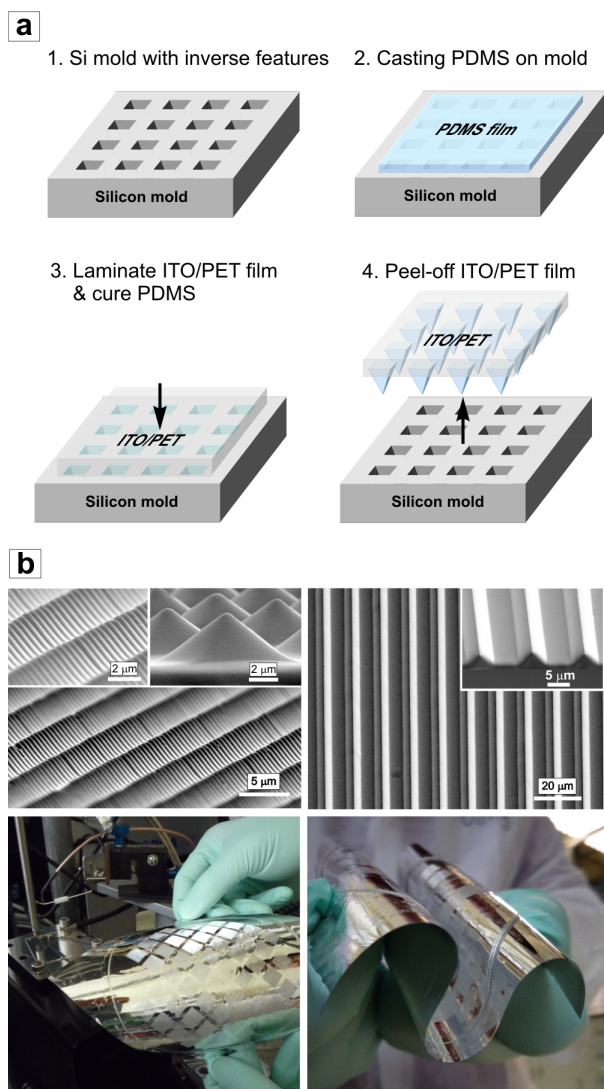


Figure 1. Schematic process for the fabrication of micro-structured PDMS films. A dilute solution of the PDMS mixture is drop cast onto a Si wafer mold; An ITO-coated PET substrate is laminated to the mold, and the PDMS film is cured under pressure. After curing, the flexible substrate is peeled off the mould. b, Scanning electron micrographs of micro-structured PDMS films with pyramid or line features. The pressure-sensitive structured PDMS films can be molded at full-wafer scale with high uniformity and fidelity on a variety of flexible, plastic substrates.

The effect of the micro-structuring is best illustrated by a comparison of sensitivity and responsiveness of capacitive pressure sensors that make use of two different dielectric layers: micro-structured and unstructured PDMS films (Figure 2). One effect of the micro-structuring is a substantial increase in the device's response to the application of pressure. In Figure 2a, the relative capacitance change is plotted vs applied pressure. The pyramid-structured film (about 5 μm tall pyramids in square lattice with pitch of 6 μm) exhibits a maximum sensitivity of 0.55 kPa^{-1} (relative signal change per pressure), about 30 times higher sensitivity than the unstructured PDMS film of equal thickness (red curve) and still 5 times higher than the one-dimensionally structured film (green curve). This sensitivity is the highest reported for plastic thin film pressure sensors.

Another key benefit of the micro-structuring is highlighted by the pressure response curves shown in Figure 2b. The read curve shows the slow relaxation (creep) of the unstructured film back to its idle state after removal of a test weight. The reason behind this behavior is that in the solid PDMS film, material cannot be elastically displaced. Instead, the application of weight leads to an entanglement of the polymer chains that is only very slowly resolving upon removal of the load. This lengthy response time of unstructured PDMS films severely limits their usefulness as pressure sensors. In contrast, the greatly increased surface area in the micro-structured film reacts with elastic deformation to the application of weight. Therefore, the micro-structured films behave much more like a spring and they exhibit relaxation times in the millisecond range, which is much faster (10-100 times) than values reported in literature.

Figure 2c illustrates that these sensors are able to detect even ultra-small pressure loads. Placing a bluebottle fly on the pressure sensor corresponds to only 3 Pa pressure, but even this tiny pressure is being reliably detected and produces a measurable capacitance signal. We are not aware of any flexible pressure sensor with such high sensitivity to the application of static pressure loads.

Since the organic field effect transistor (OFET) is a key element in current and future organic electronics circuitry, we also integrated the micro-

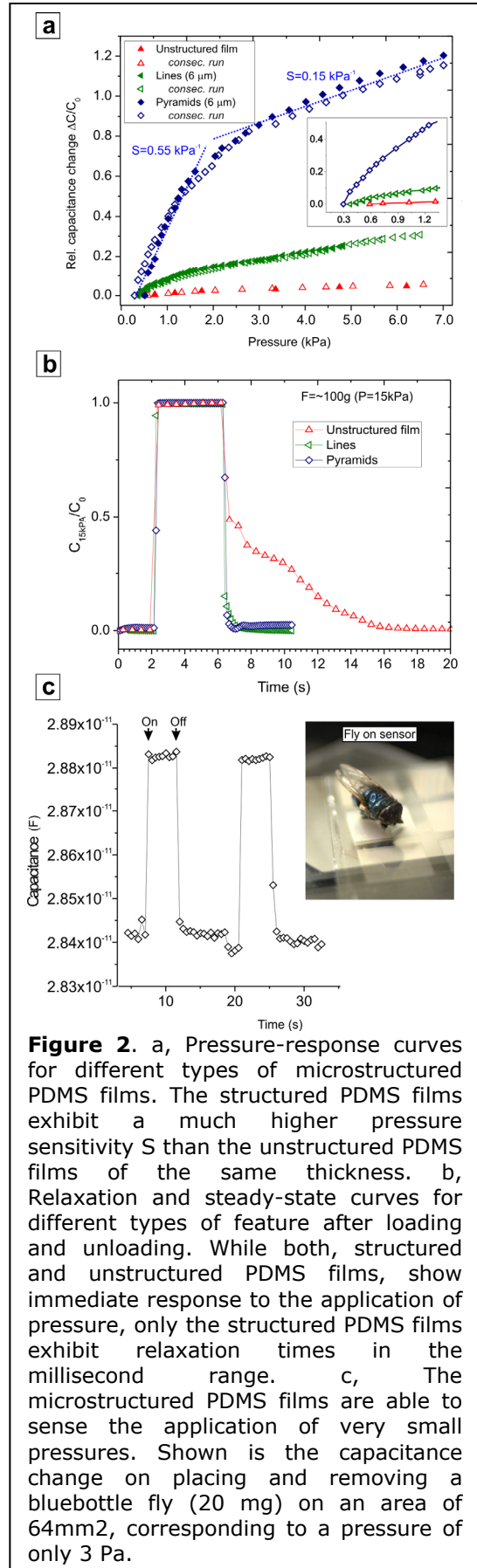
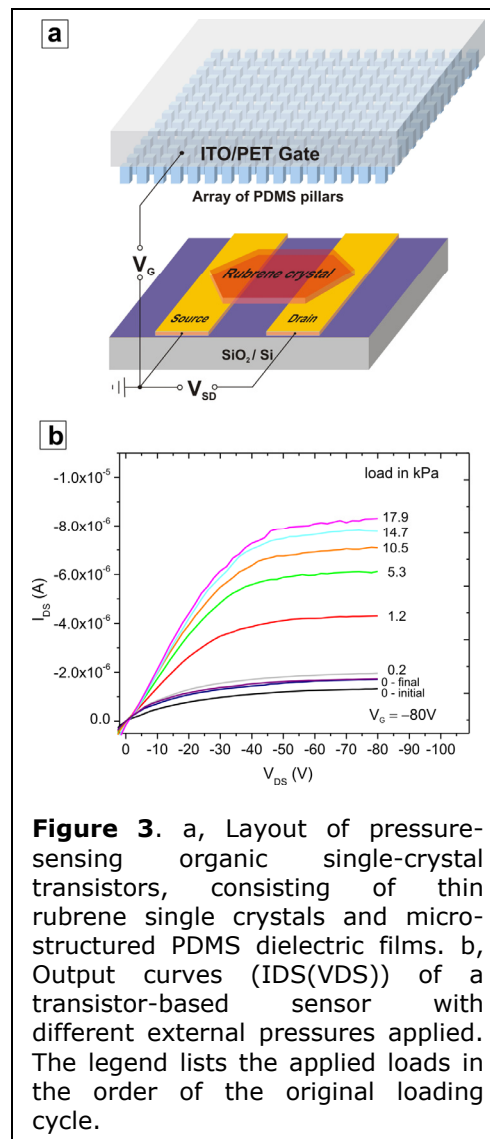


Figure 2. a, Pressure-response curves for different types of microstructured PDMS films. The structured PDMS films exhibit a much higher pressure sensitivity S than the unstructured PDMS films of the same thickness. b, Relaxation and steady-state curves for different types of feature after loading and unloading. While both, structured and unstructured PDMS films, show immediate response to the application of pressure, only the structured PDMS films exhibit relaxation times in the millisecond range. c, The microstructured PDMS films are able to sense the application of very small pressures. Shown is the capacitance change on placing and removing a bluebottle fly (20 mg) on an area of 64mm^2 , corresponding to a pressure of only 3 Pa.

structured PDMS films as dielectric layer into the OFET structure to produce the first intentionally “compressible” OFET. The layout of the device is schematically shown in Fig. 3a. For the measurements with the flexible pressure-sensitive top-gate chip, the bottom gate was set to ground. Figure 3b shows a series of output curves (the transistors source-drain current) as a function of external pressure. The transistor current increases in discrete steps in response to successively greater loads. This increase is caused by the compression of the dielectric layer which results in a reduction of the layer thickness, thereby simultaneously increasing capacitance and the gate electric field at the dielectric semiconductor interface. In time-resolved measurements, the OFET devices exhibit similarly rapid millisecond-regime response and relaxation times to the capacitive sensors.

Both passive capacitor devices and active OFET sensor devices employing these micro-structured elastomeric dielectric films have been demonstrated, exhibiting unprecedented pressure sensitivities. The fast response times in these sensors allows for a rapid collection of pressure information on both flat and curvilinear surfaces, which will potentially enable the development of highly intuitive human/computer user interfaces. The very high sensitivity, large workable pressure range and simple fabrication of these pressure sensors, based on a flexible, bio-compatible micro-structured rubber dielectric material, make them promising candidates for electronic-skin applications.



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