FLEXIBLE, TRANSPARENT, PRESSURE-SENSITIVE MICROFLUIDIC ARRAY FOR ARTIFICIAL TACTILE APPLICATIONS

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ABSTRACT

This paper reports the first effort to achieve large-area dynamic pressure mapping by a flexible and transparent microfluidic film, referred to as microflotronics, facilitating seamless integration with state-of-the-art microelectronics. The microflotronic devices offer a sensitivity of 0.45 kPa^{-1} and response time in millisecond range, which is at least an order of magnitude faster than that of its conventional solid-state counterparts. Several practical applications were successfully demonstrated, including surface topology mapping and dynamic blood pressure monitoring. The microflotronic devices offer an alternative approach to the solid-state pressure sensors, by offering an unprecedented sensitivity and ultrafast response time in a completely transparent, flexible and adaptive platform.

INTRODUCTION

Flexible pressure sensing has been a pertinent topic in both academic and industrial research over the past few years. For example, Javey's group utilized pressure sensitive rubber as the pressure sensing layer to modulate current in a thin-film transistor [1,2]. Bao's group utilized a hollow-sphere microstructure to perform resistive pressure sensing in conducting polymer film [3]. As a new innovative approach, we utilize a continuous microfluidic layer as the sensing element for large-area dynamic pressure mapping applications with an ultrahigh sensitivity of 0.45 kPa^{-1} in a compact, flexible, and transparent package as shown in Figure 1. Dissimilar to solid-state alternatives, the response time of the microflotronic device is in the millisecond range, which is at least an order of magnitude faster [1,3]. The overall device packaging can be as thin as 200µm with an optical transparency greater than 80%. The fabrication process of the device is fully compatible with the industrial-scale manufacturing of capacitive touchscreen devices and liquid-crystal displays.

Figure 1: Photographs of the microflotronic film 18 by 10 array with a 5×5mm² spatial resolution demonstrating ultra-flexibility and transparency.

METHODS

Operation Principle

Figure 2 illustrates the structural assembly of the microflotronic film which consists of flexible top and bottom polyethylene terephthalate (PET) membranes patterned with orthogonally aligned transparent indium-tin-oxide (ITO) microelectrode arrays, separated by mechanically supporting microstructures, between which is filled with a transparent microfluidic sensing layer. The impedance-based microflotronic sensing principle is demonstrated in Figure 3. The equivalent circuit of the microfluidic film was modeled to include the microfluidic film resistive element (R_L), the electrical double layer capacitance (C_{EDL}), and the parallel-plate capacitance (C_P). The force-sensing membranes experience deformation under external pressure, leading to displacement in the microfluidic volume which changes the capacitive and resistive values measured.

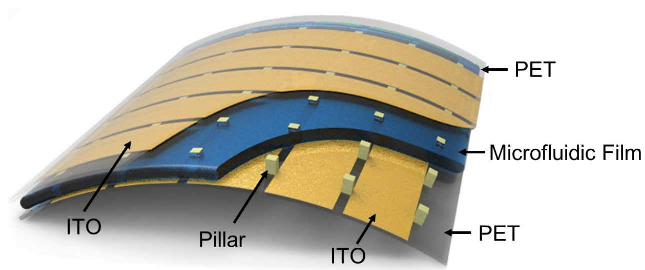

Figure 2: Schematic illustration of the microflotronic device structure, consisting of the top and bottom electrode layers with an orthogonally placed electrode array supported by a micropillar layer and filled with a microfluidic sensing layer.

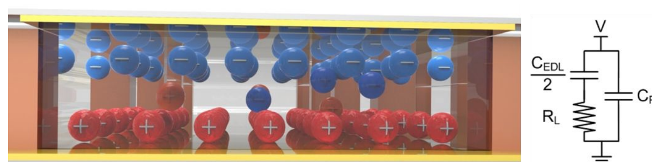

Figure 3: Cross-sectional sketch of the device sensing principle: ions in the microfluidic film accumulate at the liquid-electrode contacts which generate the EDL capacitances (C_{EDL}), liquid film is modeled as a resistor (R_L) and parallel plate capacitance (C_p) between the two electrodes.

Fabrication Process

First, the ITO electrodes were patterned using photolithography and wet etching. Then, UV patternable dielectric dry-film was laminated onto the substrate to form the micropillar array. Next, PDMS oligomer transfer and plasma-activated bonding was utilized to assemble the two electrode array films. Last, the working fluid was filled between the electrode films, and the inlet/outlet ports were sealed.

RESULTS

Characterization of Device Sensitivity

Figure 4a-c shows characterization results of the device sensitivity for different membrane thicknesses, spatial resolutions, and microfluidic layer heights. Specifically, the device sensitivity is evaluated as the relative resistance change ($\Delta R/R_0$) over the centralized pressure load (P).

Characterization of Response Time

Figure 4d-f summarizes the time-resolved experiment results to demonstrate the facilitated mechanical responses of DI

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water-filled and ethylene glycol (EG)-filled devices to 1Hz, 10Hz and 100Hz mechanical stimuli. Both microflotronic devices achieved a relaxation time in the millisecond range.

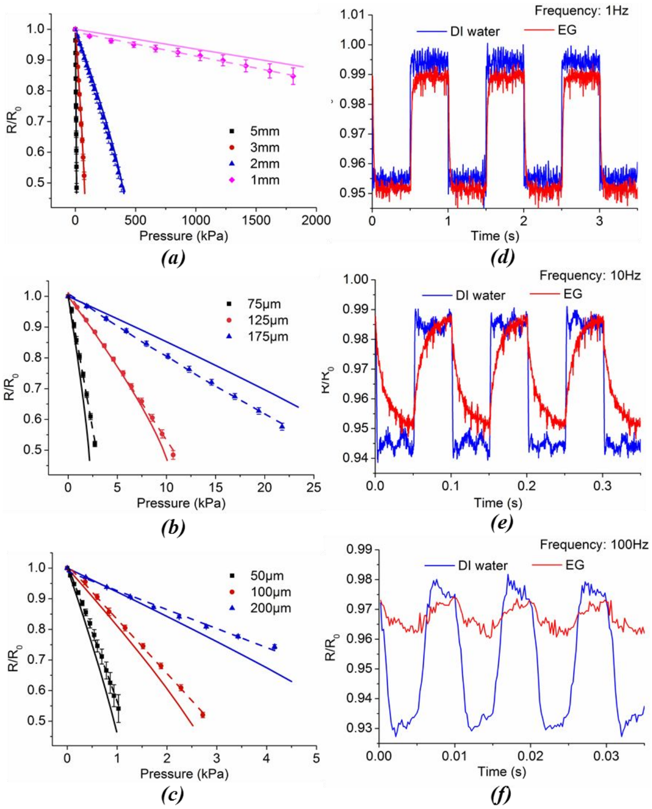

Figure 4: Experimental results (dots) with fitting curves (dash lines) against theoretical predictions (solid lines) of the microflotronic device sensitivity with different (a) spatial resolutions, (b) membrane thicknesses and (c) microfluidic layer heights. Mechanical response result under stimuli of (d) 1Hz, (e) 10Hz and (f) 100Hz.

Surface Topology Mapping

An 18 by 10 pixel array with a total surface area of 9×5 cm^2 was fabricated to demonstrate surface topology mapping capability. As shown in Figure 5, the pressure distribution of the letter-shaped polymeric stamp pressed onto the microflotronic film was clearly resolved.

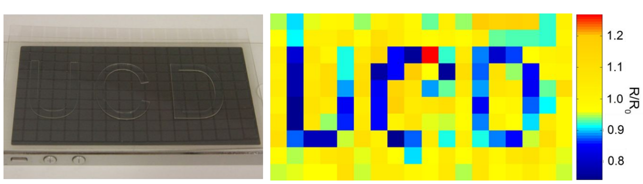

Figure 5: Result for polymeric stamp surface topology pressure mapping.

Radial Arterial Pressure Mapping

Unlike existing arterial tonometry systems [4], the proposed microflotronic film array offers not only real-time and continuous recording of the pulse pressure waveform, but also automatic pulse tracking that determines the optimal positions for pulse recording by analyzing the dynamic pressure distribution over the skin surface. Aligning the device on the wrist along the radial artery, the pressure variation under the 3 by 3 microflotronic array during one cardiovascular cycle was mapped as shown in Figure 6a. One recorded waveform gave an example of the signal acquired from the array. The optimal pulse tracking positions were determined based on the maximum pressure variations measured as shown in Figure 6b-d. By providing the dynamic pressure mapping result with ultrahigh sensitivity, the microflotronic device demonstrated its potential to automatically locate and resolve the arterial pulse waveforms with the delicate pressure events detected non-invasively.

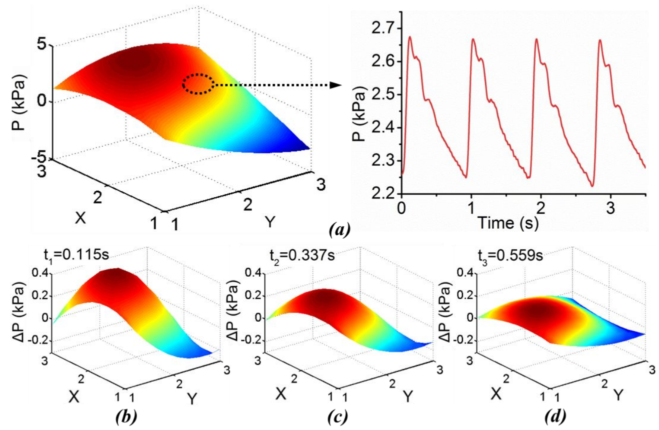

Figure 6: Non-invasive radial arterial pressure mapping. (a) Static pressure distribution on the 3 by 3 microflotronic array with three discrete radial artery waveforms recorded. During cardiovascular cycles, the consecutive pressure distribution maps on the skin surface were plotted at distinct physiological events: (b) systolic pressure peak t_1=0.115s, (c) dicrotic notch t_2=0.337s, and (d) diastolic runoff t_3=0.559s.

CONCLUSION

A flexible, transparent, pressure-sensitive film has been reported utilizing an embedded microfluidic sensing layer to achieve pressure and force mapping over various surface topologies. This novel microflotronic film offers a new flexible sensing interface that can be highly advantageous for emerging medical and electronic applications, such as health monitoring, medical prosthesis, 3D touchscreens, and human-machine interfaces, where device sensitivity, surface adaptability, and large-area mapping are all essential.

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