Electronic Supplementary Information

Microfluidic Tactile Sensors for Three-Dimensional Contact Force Measurements

*Baoqing Nie, Ruya Li, James Brandt and Tingrui Pan**

Interfacial Capacitance

For the equivalent circuit illustrated in Fig.2c, the electrical double layer (EDL) capacitance (C_{EDL}) is considered as a constant phase element (Z_{EDL}) instead of an ideal capacitor, which can be expressed as:

$$Z_{EDL} = \frac{Q}{\left(j\omega\right)^{p}} \qquad \text{(S1)}$$

where *Q* and P represent two constants given the phase delay at an EDL varying from 0° to 90° due to irregularity and inhomogeneity of the actual surface; ω is the angular frequency of the input signal; *j* is $\sqrt{-1}$.

Thus, the overall device impedance (*Z*) can be express as:

$$Z = \frac{\left(R + Z_{EDL} \times 2\right) \times \dfrac{1}{j\omega C_p}}{R + Z_{EDL} \times 2 + \dfrac{1}{j\omega C_p}} + R_{ex} \qquad \text{(S2)}$$

Where R is the liquid resistance and C_p is the co-planar capacitor presented between electrode strips. Here, the contact resistance R_{ex} should be included in the overall impedance during the experimental measurements.

Table S1 lists the parameters for the circuit elements by fitting the experimental impedance data, in which the interfacial capacitance can be back-calculated.

Table S1 the parameters for the circuit elements by fitting the experimental impedance data

Electrode Configurations	Z_{EDL}-Q /pF	Z_{EDL}-P	R /Ω	C_p /pF	R_{ex}/ Ω
Co-planar	30	0.89	300	40	1000
Parallel	19	0.87	300	5	1000

Back-Calculation of Three-Dimensional Loads

As shown in Fig. 4 in the Device Sensitivity, the force-capacitance sensitivity has been obtained both experimentally and theoretically. Thus the sensitivities in normal direction (z axis) and tangent directions (x-y axes), S_z, S_x and S_y, can be defined as:

$$S_z = \frac{(\Delta C_1 + \Delta C_2 + \Delta C_3 + \Delta C_4)}{F_z}$$
$$S_x = \frac{(\Delta C_3 - \Delta C_1)}{F_x} \qquad \text{(S3)}$$
$$S_y = \frac{(\Delta C_2 - \Delta C_4)}{F_y}$$

Where F_z, F_x and F_y are the contact force components in normal and tangent directions. ΔC_x (x =1,2,3 and 4) are the capacitance changes in the four detection channels, shown in Fig. 4a-b.

Thus a three-dimensional contact force can be back-calculated by the device sensitivity and the four capacitive outputs:

$$F = \frac{\Delta C_3 - \Delta C_1}{S_x}\vec{x} + \frac{\Delta C_2 - \Delta C_4}{S_y}\vec{y} + \frac{\Delta C_1 + \Delta C_2 + \Delta C_3 + \Delta C_4}{S_z}\vec{z} \qquad \text{(S4)}$$

Transmittance Measurement

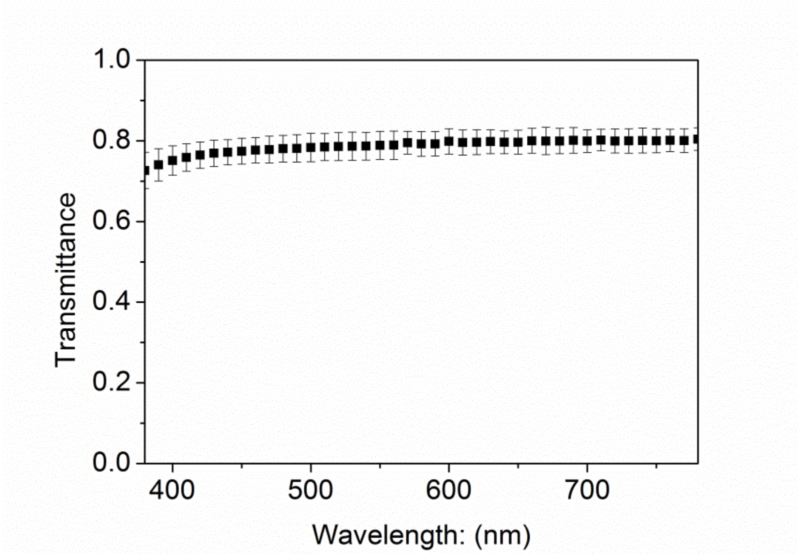

Figure S1 The transmittance of the three-dimensional microfluidic tactile sensor to visible light wavelengths. The measurement is conducted on 14 random points on the device. The error bars are shown on the graph.

Fabrication Process

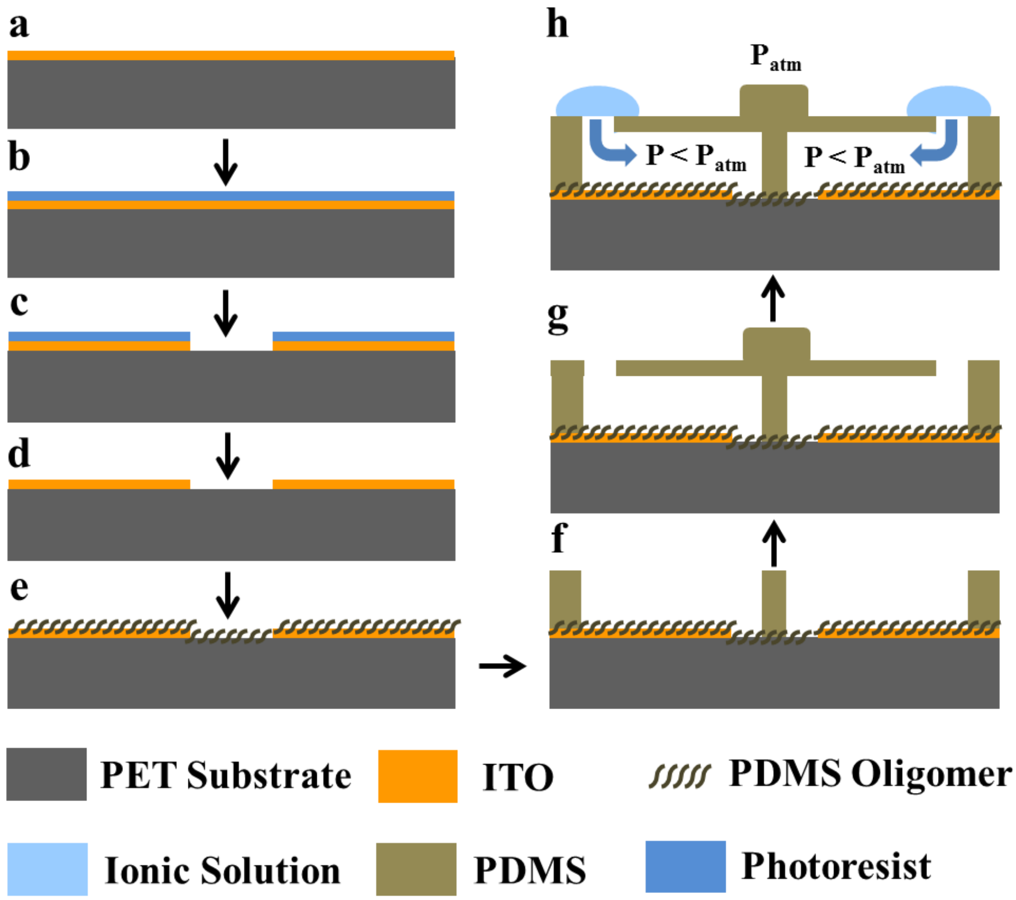

Figure S2 A schematic illustration of device fabrication process