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Electronic Supplementary Information

A flexible and highly sensitive capacitive pressure sensor based on conductive fiber with microporous dielectric for wearable electronics

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Analytical model for air/PDMS composite dielectric

The general relation governing the capacitance (*C*) of the capacitive sensor is related by,

$$C = \varepsilon_o \varepsilon_r \frac{A}{d} \qquad \text{(S1)}$$

Where, ε_o is the permittivity of the free space, ε_r is the relative permittivity of dielectic medium, *A* is the area of the electrode, and *d* is the separation between the electrodes. We supposed the initial distance between two electrodes is *d*, an initial vacuum fraction (porosity) of the porous PDMS is f_o, the relative dielectric constant of air is ε_a, and the relative permittivity of the polymer is ε_p.

Under an application of pressure, the vacuum fraction inside the microporous PDMS decreases linearly with compressive displacement (d_c). In the linear region, the vacuum fraction (f) is a linear function of d_c, which can be related as,

$$f = f(d_c) = f_o\left(1 - \frac{d_c}{d}\right) \qquad \text{(S2)}$$

Equation (S2) must hold true for the cases: (i) for no compression $(d_c = 0)$, which implies $f = f_o$ and (ii) for fully compression $(d_c = d)$, $f = 0$.

From a simple rule of mixture [1, 2], an effective relative permittivity (ε_r) is assumed to be,

$$\varepsilon_r = f\varepsilon_a + (1 - f)\varepsilon_p \qquad \text{(S3)}$$

Thus, relative change in capacitance is calculated as follows:

$$\frac{\Delta C}{C_o} = \frac{C - C_o}{C_o} = \frac{C}{C_o} - 1$$

$$\frac{\Delta C}{C_o} = \frac{d}{(d - d_c)} \frac{\lfloor f\varepsilon_a + (1 - f)\varepsilon_p \rfloor}{\left[f_o\varepsilon_a + (1 - f_o)\varepsilon_p \right]} - 1 \qquad \text{(S4)}$$

Where the terms $f_o\varepsilon_a + (1 - f_o)\varepsilon_p$ and $f\varepsilon_a + (1 - f)\varepsilon_p$ correspond to an initial relative permittivity and an effective relative permittivity at compression distance d_c , respectively.

Assuming same electrode area, we rearrange equation (S4) for $\varepsilon_a = 1$, results,

$$\frac{\Delta C}{C_o} = \frac{d}{(d - d_c)} \frac{\varepsilon_p - f(\varepsilon_p - 1)}{\varepsilon_p - f_o(\varepsilon_p - 1)} - 1 \qquad \text{(S5)}$$

From the equation (S5) it is clear that when an external pressure is applied, the denominator term $(d - d_c)$ and vacuum fraction, $f = f_o\left(1 - \frac{d_c}{d}\right)$ decreases with the compression distance (d_c) thereby leading to increase in $\Delta C / C_o$.

Dependency of the capacitance in an elastic modulus

The working mechanism in a capacitor is a change in strain (thickness) introduced by stress. First, the change in capacitance at the compression distance (d_c) introduced by strain is calculated as,

$$\Delta C = \varepsilon_o \varepsilon_r A\left(\frac{1}{d - d_c} - \frac{1}{d}\right) = \varepsilon_o \varepsilon_r \frac{A\varepsilon}{d - d_c} \qquad \text{(S6)}$$

where, $\frac{d_c}{d} = \varepsilon$ is compressive strain. So, equation (S6) can be written as,

$$\Delta C = \varepsilon_o \varepsilon_r \frac{A\varepsilon}{d - d_c} = \varepsilon_o \varepsilon_r \frac{A}{d\left(\frac{1}{\varepsilon} - 1\right)} \qquad \text{(S7)}$$

If we express compressive strain in terms of an elastic modulus (E) and stress (σ), equation (S7) will take the form,

$$\Delta C = \varepsilon_o \varepsilon_r \frac{A}{d\left(\frac{1}{\varepsilon} - 1\right)} = \varepsilon_o \varepsilon_r \frac{A}{d\left(\frac{E}{\sigma} - 1\right)} \qquad \text{(S8)}$$

Therefore, if relative permittivity is not known intrinsically, change in capacitance has the inverse dependency on elastic modulus (i.e. lowering the modulus by micro-structuring the dielectric material increases the change in capacitance).

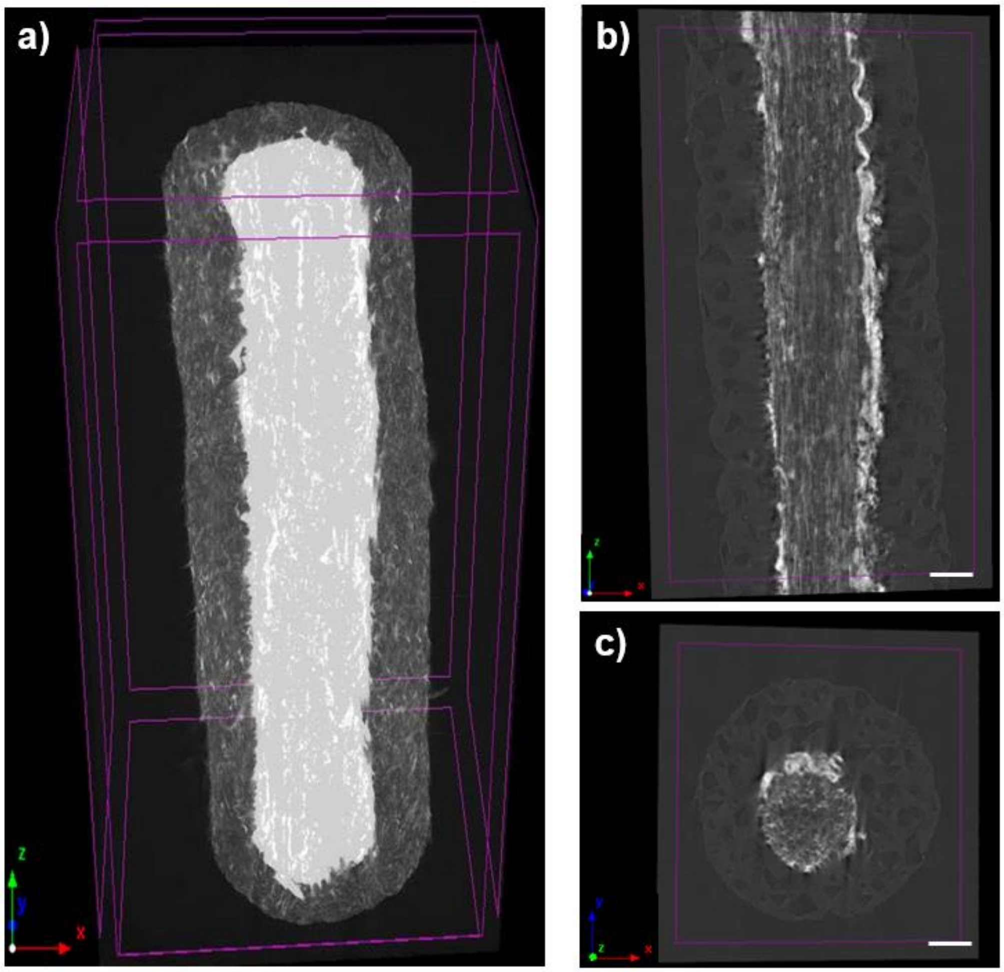

Fig. S1. X-ray microcomputed tomography (micro-CT) images a) showing 3-dimensional view of the microporous PDMS coated on the conductive fiber, b) vertical cross-section from the center and c) horizontal cross-section showing micropores. The scale of white bar represents 200 µm. Skyscan 1172 was used to take the micro-CT images.

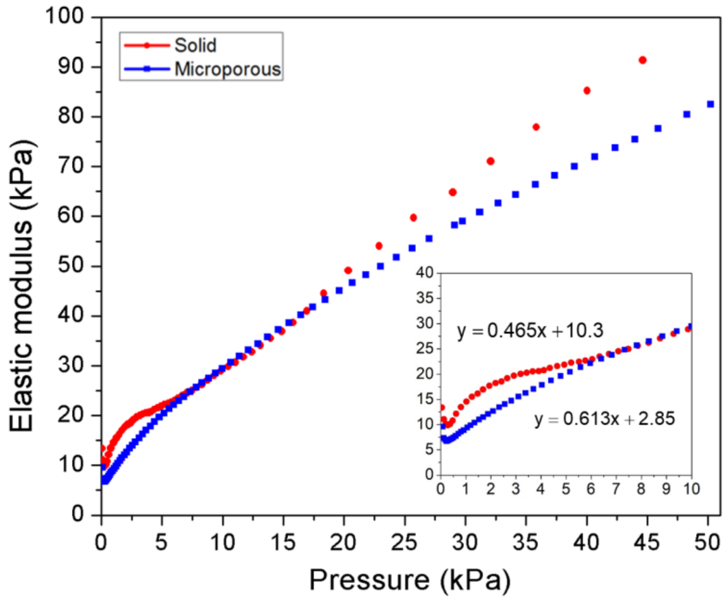

Fig. S2. Elastic modulus of the dielectric materials as a function of pressure. The microporous PDMS has lower elastic modulus (as seen from the inset) at low pressures and it increases slowly with pressure as compared to solid PDMS.

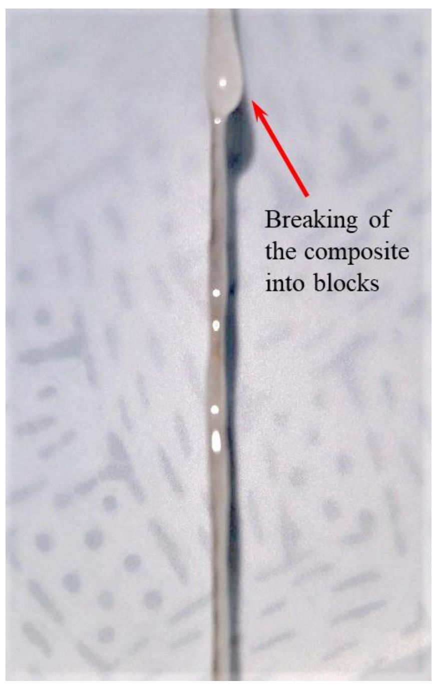

Fig. S3. Unstable morphology corresponding to drops sliding down the fiber. At high concentration of glucose particles (glucose/PDMS volume ratio of 1.3), due to a high zero shear viscosity, the composite hardly or couldn't flow along the fiber. The continuous liquid thread breaks into gel-like blocks.

Table S1: Various glucose to PDMS polymer ratios (v_g/v_p) with porosities, sensitivities and their error deviations (standard deviations).

Sample	Glucose:PDMS composite (g:g)	Glucose:PDMS (v:v)	v_g/v_p	ϕ(%)	Sensitivity (kPa^{-1}) for <10 kPa	Deviation on sensitivity (kPa^{-1})
1	0:2.2	0:2.28	0	0	0.156	0.0017
2	3.35:2.2	2.17:2.28	0.95	48.8	0.278	0.0025
3	4.45:2.2	2.96:2.28	1.3	56.5	0.297	0.0152
4	6:2.2	3.86:2.28	1.7	63	0.313	0.0167

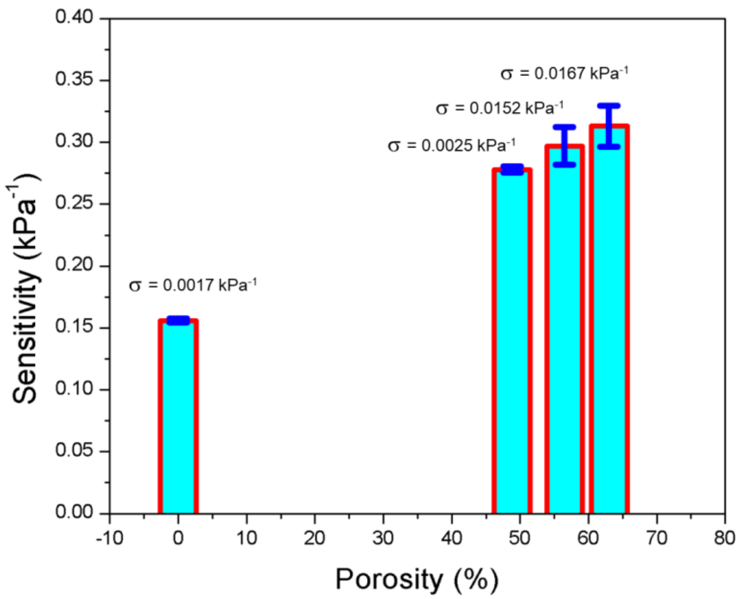

Fig. S4. Sensitivities and their error deviation from mean value for different values of glucose to PDMS composition. Higher value of glucose to PDMS ratio, v_g/v_p can give better sensitivity but resulted inconsistency in sensitivity values since the microporous PDMS suffered from unstable fiber morphology.

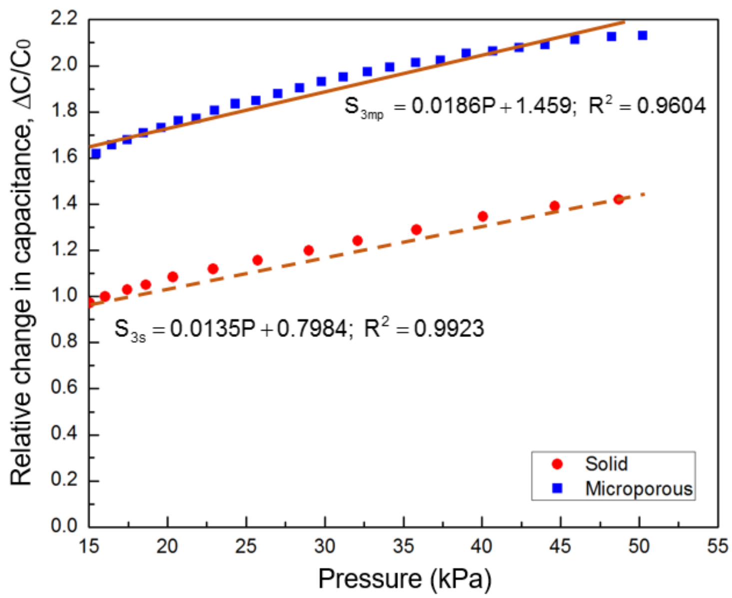

Fig. S5. Relative capacitance change $(\Delta C/C_o)$ *in response to external pressure for >15 kPa. In the higher pressures, the contact area induces lower effective stress because pores appeared to be completely closed. Although the sensitivity in this region is lower than that of the first region, but higher than solid PDMS-coated feature.*

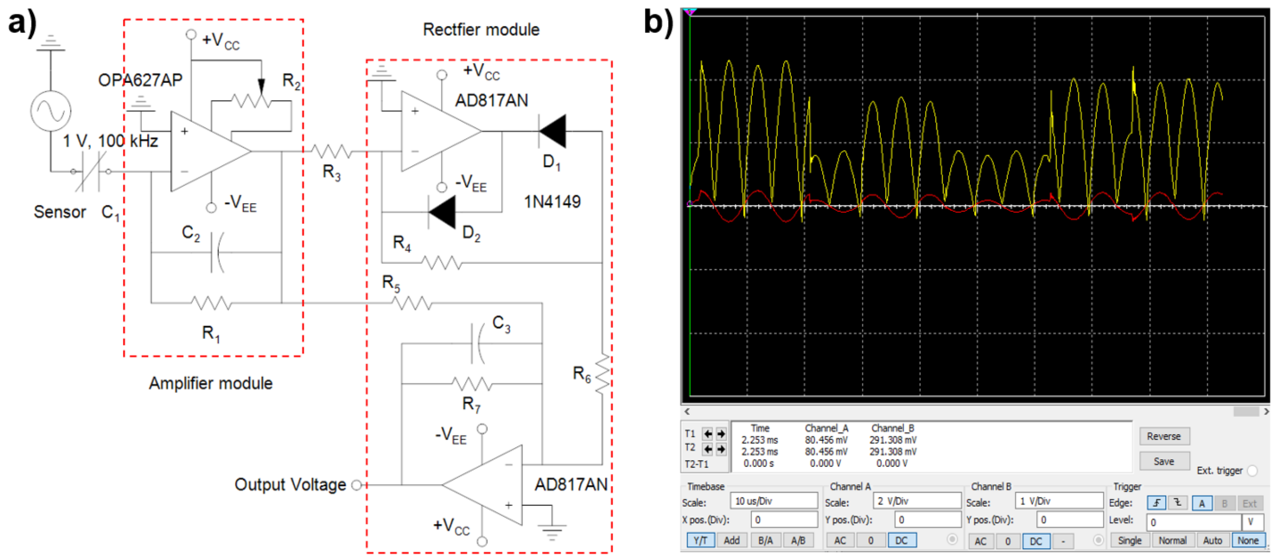

Fig. S6. a) Capacitance detection circuit for the measurement of the output voltages. The output of operational amplifier module is linearly varied with input and the ratio of reference capacitor (C_2) to sensor capacitor (C_1). The output signal from amplifier module is then rectified by full-wave rectifier module. The preferable choice of AD817 was due to its excellent ac-characteristics and low current flexibility. The gain of the amplifier was adjusted to $|-2|$ and, a potentiometer of 100 kΩ was also connected to the amplifier to attenuate low offset voltage drift and b) Simulated circuit response for the random variation of a tunable capacitor (C_1). Capacitance values were varied at the rate of 5% of its maximum capacitance. NI Multisim-National Instruments was used for the simulation of the circuit.

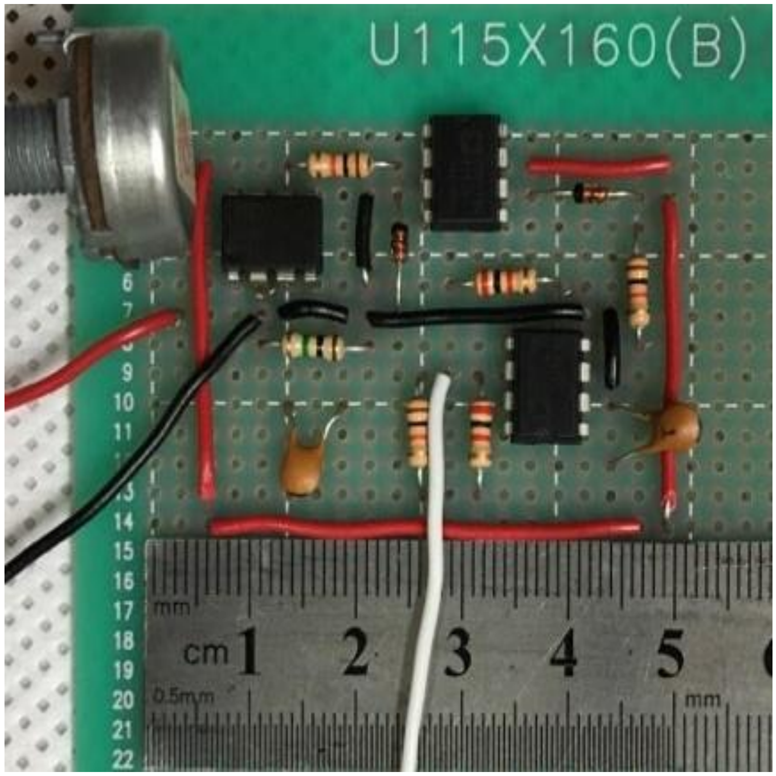

Fig. S7. PCB layout of the capacitance detection circuit for the measurement of output voltage.

Notes and references

1 P. Barber, S. Balasubramanian, et al., *Materials*, 2009, 2, 1697.

2 T. L. Weadon, T. H. Evans, et al., *IEEE Sens. J.*, 2014, 14, 4411.