Supplementary Materials for

**Air/water interfacial assembled rubbery semiconducting nanofilm for fully rubbery integrated electronics**

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This PDF file includes:

- Characteristics of the FETs
- Calculation of the $\beta$ and $\alpha$ values of the transistor-based temperature sensor
- Finite element analysis (FEA)
- Circuit architecture designs of the rubbery inverters, NAND, and NOR
- Data acquisition of the active matrix rubbery tactile sensing skin
- Table S1
- Figs. S1 to S29
Characteristics of the FETs

The mobilities ($\mu_{FE}$) were calculated in the saturation regime by fitting the plot of the linear regime in the curve of $I_{DS}^{1/2}$ versus $V_{GS}$ based on the following equation:

$$I_{DS} = \frac{W C_i \mu_{FE}}{2L} (V_{GS} - V_{TH})^2$$  \hspace{1cm} (S1)

$$\sqrt{I_{DS}} = \sqrt{\frac{W C_i \mu_{FE}}{2L}} (V_{GS} - V_{TH}) = \sqrt{\frac{W C_i \mu_{FE}}{2L}} V_{GS} - \frac{W C_i \mu_{FE}}{2L} V_{TH}$$  \hspace{1cm} (S2)

$$\text{Slope} = \sqrt{\frac{W C_i \mu_{FE}}{2L}}$$  \hspace{1cm} (S3)

$$\mu_{FE} = \frac{2L}{W C_i} \text{(Slope)}^2$$  \hspace{1cm} (S4)

where $I_{DS}$ is the drain current, $\mu_{FE}$ is the field-effect mobility, $C_i$ is the gate dielectric capacitance, $W$ and $L$ are the channel width and length, respectively, $V_{GS}$ is the gate voltage, $V_{TH}$ is the threshold voltage. Note that mobility values were calculated based on the specific capacitance of the ion gel (9.8 uF/cm$^2$ at 1 Hz).
Calculation of the $\beta$ and $\alpha$ values of the transistor-based temperature sensor

The channel resistance change in the transistor based temperature sensor can be described by the Arrhenius relationship and the negative temperature coefficient (NTC) can be characterized with the $\beta$ parameter equation:

$$\rho = \rho_0 \exp\left[\frac{E_a}{k_B T}\right]$$

$$R = R_0 \exp\left(\beta / T\right)$$

where, $\rho_0$, $E_a$, $k_B$, and $T$, $R_0$, and $\beta$ are resistivity at infinite temperature, activation energy, Boltzmann constant, absolute temperature, resistance at infinite temperature, and thermistor constant, respectively. The $\beta$ represents the slope in the relationship between $\ln (R)$ and the reciprocal of the absolute temperature ($1/T$). The fitted plot in fig. S27B shows a slope of 6827.22 and an $R^2$ of 0.99.

The result of the resistance change depending on temperature was fitted by the obtained $\beta$ value (6827.22 K) with the $\beta$ parameter equation.

The temperature coefficient, $\alpha$, is described by differentiating the following equation.

$$\alpha = \frac{1}{R} \frac{dR}{dT} \times 100 = -\frac{\beta}{T^2} \times 100 \ (\%/\text{C})$$

The calculated $\alpha$ at the examined temperature range (24 to $45^\circ\text{C}$) is from -7.73 to -6.75%/\text{C}. 

Finite element analysis (FEA)

A three-dimensional (3D) finite element model was established to simulate the stretching behavior of the two-phase hybrid material on PDMS substrate in ABAQUS. The thicknesses of the hybrid material and PDMS substrate are 100 nm and 10 μm, respectively. The length and width of the whole model are 118 μm and 89 μm, with the pattern obtained from an experimental image. The details of the model are shown in the fig. S11A.

The Young’s moduli of the P3HT, SEBS, and PDMS are 0.27GPa, 6.9MPa and 2MPa, respectively. The Poisson’s ratios are 0.3, 0.45 and 0.45, respectively. To account for large deformation during stretching, the Mooney-Rivlin hyperelastic model was used. Shell elements (S4R) were used to discretize the thin hybrid material, and 8-node brick elements (C3D8R) were used to discretize the PDMS substrate.

The Mooney-Rivlin hyperelastic model coefficient are as follows:

\[
C_{10} = \frac{E}{5(1+\nu)} \quad \text{(S5)}
\]

\[
C_{01} = \frac{E}{20(1+\nu)} \quad \text{(S6)}
\]

\[
D_1 = \frac{2}{K_0} = \frac{6(1-2\nu)}{E} \quad \text{(S7)}
\]

\(\frac{E_{\text{P3HT}}}{270\text{MPa}}, \quad \nu=0.3, \quad C_{10} = 41.5384615, \quad C_{01} = 10.3846154, \quad D_1 = 0.008888889\)

\(E_{\text{SEBS}} = 6.9\text{MPa}, \quad \nu=0.45, \quad C_{10} = 0.95172414, \quad C_{01} = 0.23793103, \quad D_1 = 0.08695652\)

\(E_{\text{PDMS}} = 2\text{MPa}, \quad \nu=0.45, \quad C_{10} = 0.275862, \quad C_{01} = 0.068965517, \quad D_1 = 0.3\)
The rubbery inverter is designed to be a zero-$V_{GS}$ load unipolar inverter based on two p-type rubbery transistors. Specifically, the driver and load transistors have the same channel length and a channel width ratio of 1:4. Both the driver and the load transistors are integrated serially. Both the rubbery NAND and NOR gates were constructed based on two drivers (T_{D,A} and T_{D,B}) and one load (T_{L}) rubbery transistor. The channel length of all the drivers and load transistors were the same; the ratios of the channel width of the driver to the load of the rubbery transistors were 1:4 for the NAND and 1:3 for the NOR logic gates.
Data acquisition of the active matrix rubbery tactile sensing skin

The electrical properties of the single sensing node was characterized with Keithely 4200-SCS. The output voltage mapping from the $5 \times 5$ active matrix based fully rubbery smart skin was obtained from the data acquisition system with the custom LabView program. The voltage for the 5-word lines and $V_{DD}$ were applied by the NI PXI-6723 (National Instrument) through a SCB-68 shielded I-O connector block. The 5-bit lines were interfaced to NI PXI-6363 (National Instrument) through a SCB-68 shielded I-O connector block for readout of the output voltages.
Table S1. Comparison of our fully stretchable transistors with reported fully rubbery stretchable transistors.

| Semiconductor material | Initial field-effect mobility | Field-effect mobility under strain | Durability | Fully rubbery transistor? | Ref. |
|------------------------|------------------------------|-----------------------------------|------------|--------------------------|------|
| P3HT/SEBS              | 8.5 cm$^2$ V$^{-1}$ s$^{-1}$ | 8.1 cm$^2$ V$^{-1}$ s$^{-1}$ at 50% strain | 7.0 cm$^2$ V$^{-1}$ s$^{-1}$ at 50% strain | Yes | This work |
| DPPTTT/SEBS            | 0.59 cm$^2$ V$^{-1}$ s$^{-1}$ | 0.55 cm$^2$ V$^{-1}$ s$^{-1}$ at 100% strain | 0.5 cm$^2$ V$^{-1}$ s$^{-1}$ at 100% strain | Yes | 25 |
| P3HT/SEBS              | 0.006 cm$^2$ V$^{-1}$ s$^{-1}$ | 0.003 cm$^2$ V$^{-1}$ s$^{-1}$ at 50% strain | 0.002 cm$^2$ V$^{-1}$ s$^{-1}$ at 50% strain | No | 23 |
| P3HT                   | 0.034 cm$^2$ V$^{-1}$ s$^{-1}$ | 0.001 cm$^2$ V$^{-1}$ s$^{-1}$ at 160% strain | 0.01 cm$^2$ V$^{-1}$ s$^{-1}$ at 160% strain | No | 14 |
| P3HT/PDMS              | 0.02 cm$^2$ V$^{-1}$ s$^{-1}$ | 0.005 cm$^2$ V$^{-1}$ s$^{-1}$ at 100% strain | 0.01 cm$^2$ V$^{-1}$ s$^{-1}$ at 100% strain | Yes | 18 |
| P3HT /PDMS             | 0.015 cm$^2$ V$^{-1}$ s$^{-1}$ | 0.000017 cm$^2$ V$^{-1}$ s$^{-1}$ at 100% strain | no mention | Yes | 17 |
| P3HT /PDMS             | 1.4 cm$^2$ V$^{-1}$ s$^{-1}$ | 0.8 cm$^2$ V$^{-1}$ s$^{-1}$ at 50% strain | no mention | Yes | 24 |
Fig. S1. The photograph of the assembled pristine P3HT nanofilm. (A) As transferred on a wire loop. (B) 6 months after transferred. Photo Credit: Ying-Shi Guan, University of Houston.
Fig. S2. Transferred pristine P3HT nanofilm on different substrates. (A) glass (B) curvy surface of a plastic container. Photo Credit: Ying-Shi Guan, University of Houston.
Fig. S3. AFM measured thickness of the pristine P3HT nanofilm.
Fig. S4. The schematic illustration of the packing structure in the assembled pristine P3HT nanofilm.
Fig. S5. The gate current of the assembled pristine P3HT nanofilm based transistor.
Fig. S6. The output curve of the assembled pristine P3HT nanofilm based transistor.
Fig. S7. Transfer curve of the spin-coated P3HT film based transistor.
Fig. S8. The performance of the pristine P3HT nanofilm based transistor under mechanical strain. (A) The optical image of the pristine P3HT nanofilm under different mechanical strain (0%, 3%, 5%, and 8%). (B) The mobility of the pristine P3HT nanofilm based transistor under mechanical strains (3%, 5%, and 8%).
Fig. S9. The mobility value distribution of the transistors based on the composite nanofilm with different percentage of P3HT.
Fig. S10. The XRD pattern of the composite nanofilm with 65 wt% P3HT.
Fig. S11. The FEM simulation results. (A) A three-dimensional (3D) finite element model. (B) The simulated strain distribution of the composite nanofilm at 50% strain.
Fig. S12. Reliability test of rubbery transistor at 30% strain. The transfer curves of the transistors under different stretch-release cycles at 30% strain along and perpendicular to the channel length direction, respectively.
Fig. S13. The fabrication of the transistor array. (A) Schematic illustration of the transistor array fabrication. (B) The mobility value distribution of the transistor array based on the composite nanofilm.
Fig. S14. The $I_{on}/I_{off}$ map of the rubbery transistor array based on the composite nanofilm.
Fig. S15. The hysteresis loop of the transfer curve for the rubbery transistor based on 65 wt% P3HT at a scan rate of 10 mV/s.
Fig. S16. Transfer curve of the 65 wt% P3HT composite nanofilm based transistor after 0, 7 and 15 days of storage in air.
Fig. S17. The hysteresis loop of the VTC for the rubbery inverter at a scan rate of 10 mV/s.
Fig. S18. Static output characteristics of the rubbery NAND gate. Static output voltage of NAND gate under mechanical strains of 0% (A) and 50% (B) along and (C) perpendicular to the channel length direction. (D) The truth tables for rubbery NAND gate.
Fig. S19. Static output characteristics of the rubbery NOR gate. Static output voltage of NOR gate under mechanical strains of 0% (A) and 50% (B) along and (C) perpendicular to the channel length direction. (D) The truth tables for rubbery NOR gate.
Fig. S20. Schematic fabrication processes of the rubbery smart sensory skin with $5 \times 5$ transistor array based on an active matrix readout.
Fig. S21. Circuit diagram of the devices (5 × 5).
Fig. S22. Resistance change of the pressure-sensitive rubber sheet depending on applied pressure.
Fig. S23. Circuit diagram for measurement (Fig.5E)
Fig. S24. Circuit diagram for measurement (Fig. 5F)
Fig. S25. Pattern designed for the transistor-based temperature sensor and electrical stimulator on fingers.
Fig. S26. Pattern designed for the EMG electrode array.
Fig. S27. Temperature sensor measurement. (A) Temperature sensor calibration curve of transistor-based temperature sensor. (B) Plot of ln (R) versus 1000/T of the temperature sensor.
Fig. S28. Single pixel circuit of the electrical stimulator.
Fig. S29. The schematic structure and the detailed geometries of the rubbery transistor.