Electronic Supplementary Material (ESI) for Lab on a Chip.

ELECTRONIC SUPPLEMENTARY INFORMATION

On-Skin Liquid Metal Inertial Sensor

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Experimental Section

Fabrication of Antenna and Electrodes. Silicon substrate is cleaned in an ultrasonic bath of acetone for 2 min. Latter step is repeated with isopropanol and then the substrate is blow-dried with nitrogen. A sacrificial layer of polyvinyl alcohol (water solution, 4.7 %wt, M_w=9000-10000, Sigma Aldrich) is spin-coated on the silicon substrate at 4000 rpm for 60s. The substrate is baked on a hot plate for 120 s at 100°C to evaporate the water. Dielectric layer (Elastosil P7670, Wacker) is spin-coated on the PVA layer at 4000 rpm for 20s. Dielectric layer is cross-linked on a hotplate for 3 min at 80°C. EGaIn (Ga 75%wt, In 25%, mp=16°C, 5N Plus, Lübeck) is sprayed through a steel stencil using an air brush (Master G22) at 2 bar pressure. Insulating silicone layer (Dragon Skin 10, Shore A=10, Smooth-On Inc.) is dissolved in hexane (1:1 vol.) and spray-deposited through a polyimide stencil using an air brush (Master E91). The layer is cross-linked on a hotplate at 80°C. A commercial nano coating (NeverWet) is applied to the polyimide stencil to prevent adhesion of the deposited eGaIn. Second layer of eGaIn is spray-deposited and as a final step, both electrodes and antenna are passivated by spray coating the Dragon Skin 10 silicone. The silicone layer is cross-linked on a hotplate at 80°C.

Fabrication of the Tilt Sensor. A 200 µm thick polyimide frame is attached to the sample. The sample is placed on the surface of the water and edges of the substrate are wetted with a swab. Within one hour, PVA sacrificial layer is dissolved and the sample is left floating on water. The membrane and the frame are blow-dried with nitrogen and flipped over for further processing. Glycerol droplet (diameter ≈ 8 mm) is dispensed using a syringe. EGaIn droplet is created on a tip of a syringe (in ambient atmosphere) and then submerged into the glycerol. For creating a membrane on the glycerol, Dragon Skin silicone is sprayed 3 times over the glycerol with intermediate baking on a hot plate at 80°C for 1 min.

Test samples for Characterization of the Tilt Sensor. Two gold electrodes (10 nm Cr, 100 nm Au) are e-beam evaporated on a glass substrate. A mixture of PDMS (Sylgard 184, 10:1wt. mix with the curing agent) and hexane (2:1wt) is used a dielectric and spin-coated over the electrodes at 3000 rpm for 60s. The silicone is cross linked on a hotplate at 80°C for 30min. The tilt sensor is fabricated as previously described over the electrodes.

Characterization of the Tilt Sensor. Test samples are attached to a motorized rotation stage, which is controlled using Matlab program. Output characteristic is obtained by tilting the stage in steps of 2° every second. For hysteresis measurements, output characteristic is obtained every 5 s. All static measurements are performed using an impedance analyser at 100 kHz (HP 4192A LF). Frequency and step response are measured using a prototyping embedded system CY8CKIT-059 (Cypress Semiconductor Corp). Sensor is connected between a ground and a designated pin. Embedded system is configured for readout of a capacitive button sensor. The tilting stage is controlled using Matlab. Gestures of the sensor are recorded by attaching the test samples on the wrist of a test subject and using the embedded system for the readout. Connecting wires in all measurements are separated from each other and immobilized to reduce parasitic capacitance and motion artefacts.

Wireless readout. A water soluble cellulose tape is attached to the sensor and the supporting frame is detached using a knife. The sensor is placed on a lower arm and a stream of water is used to dissolve and wash away the cellulose tape. A single turn coil is placed above the spiral coil of the sensor. A vector network analyser is connected to the single-turn coil and used to measure the power that gets reflected from the single-turn coil. Due to inductive coupling between the two coils, a drop of the reflected power is measured at the resonance frequency of the sensor.

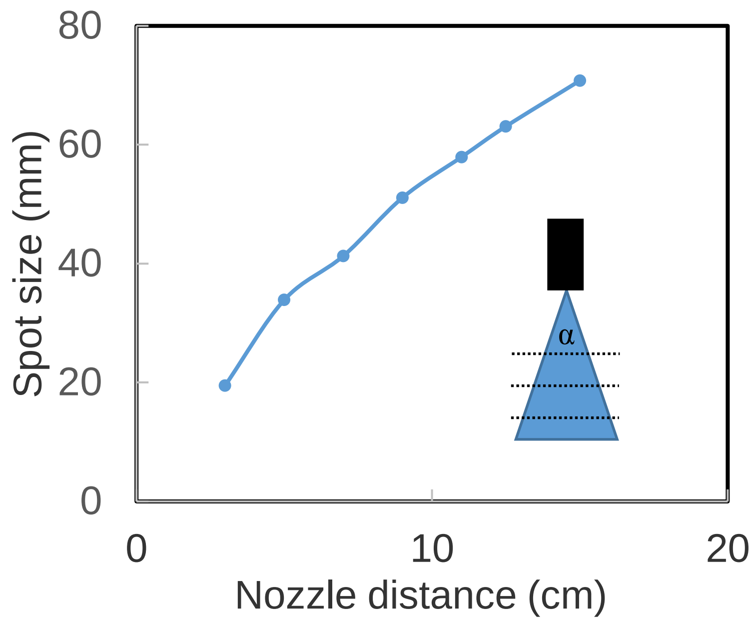


Figure S1: Size of the area covered by the spray-coater at different distances from the glass substrate.

Angle of the spray-coater's cone is:

$$\alpha = 2 * tan^{-1}\left(\frac{spot\ size/2}{nozzle\ distance}\right), \tag{1}$$

$$\alpha \approx 35°$$

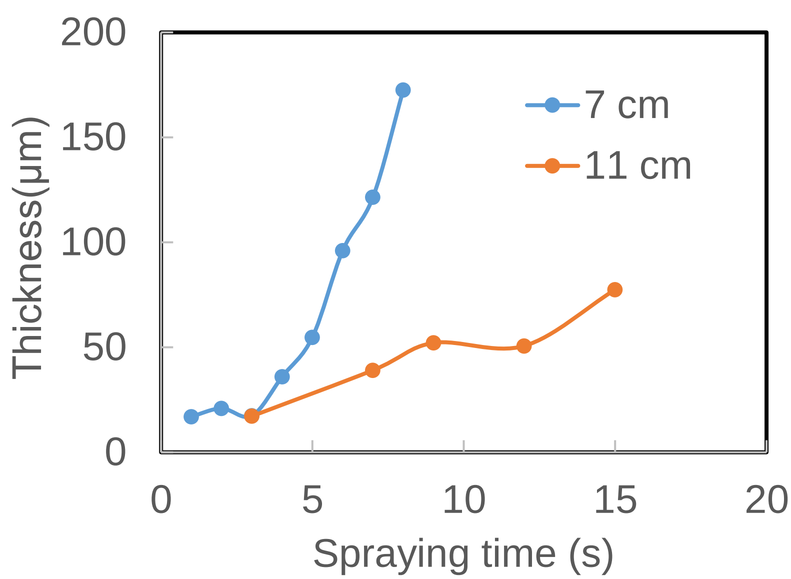
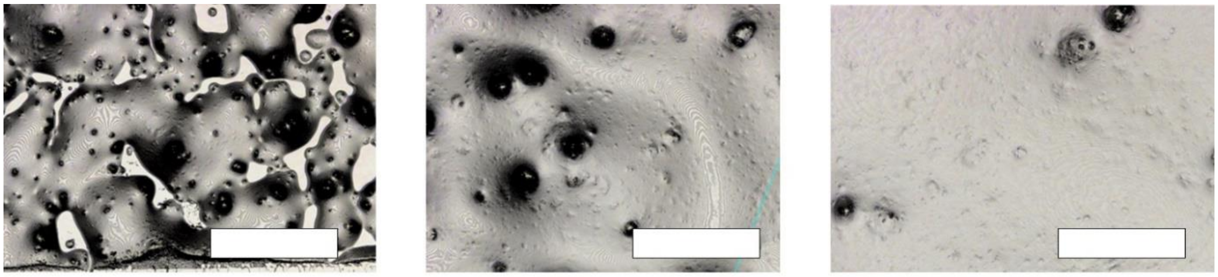
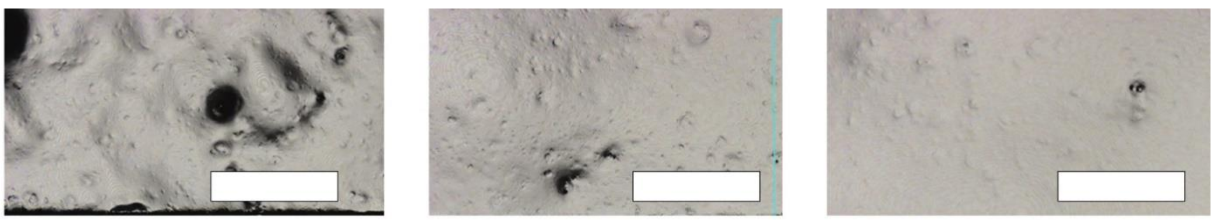


Figure S2: Thickness of DS10 layers that were spray-coated from distance of 7 cm and 11 cm on a glass substrate.



t = 1 s, h = 17 μm | t = 2 s, h = 20.9 μm | t = 4 s, h = 36 μm

Figure S3: Surface of the DS10 layers that were sprayed at 7 cm distance. Micrographs are acquired on the portion of the substrate directly under the spray nozzle. Micrographs and the thickness *h* of the layers are measured using a confocal laser scanning microscope. Dark spots in the image are pinholes or significantly thinner parts of the layer. Scale bar, 400 μm.



t = 3 s, h = 17.2 μm | t = 7 s, h = 39.1 μm | t = 9 s, h = 52.1 μm

Figure S4: Surface of the DS10 layers that were sprayed at 11 cm distance. Micrographs are acquired on the portion of the substrate directly under the spray nozzle. Micrographs and the thickness h of the layers are measured using a confocal laser scanning microscope. Dark spots in the image are pinholes or significantly thinner parts of the layer. Scale bar, 400 μm.

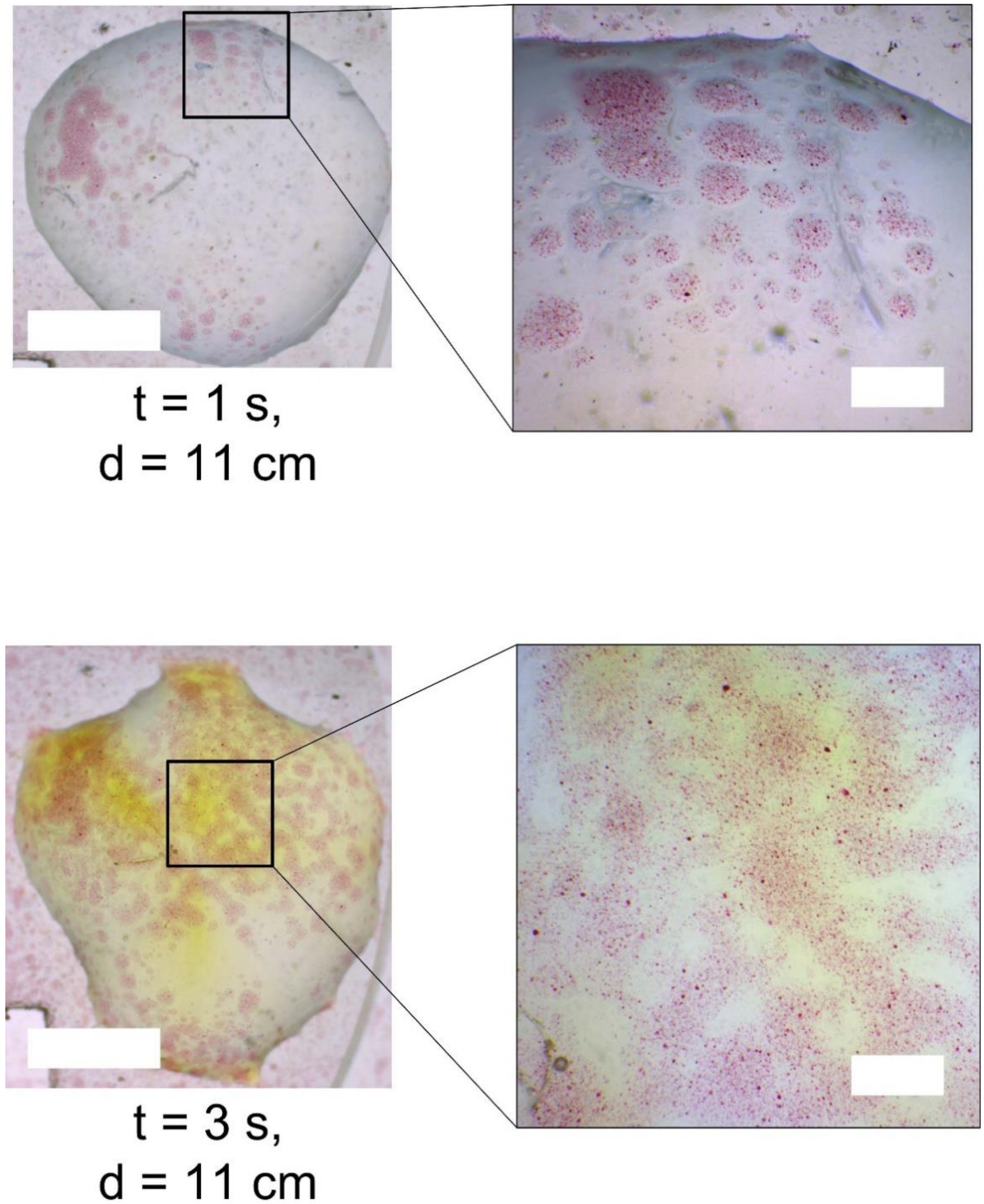


Figure S5: Forming a container on the surface of a glycerol droplet by spray-deposition of DS10 silicone in hexane (1:1 vol). A red pigment is added to the silicone for imaging purposes. Scale bar, 2.5mm; 500 µm zoomed micrographs.

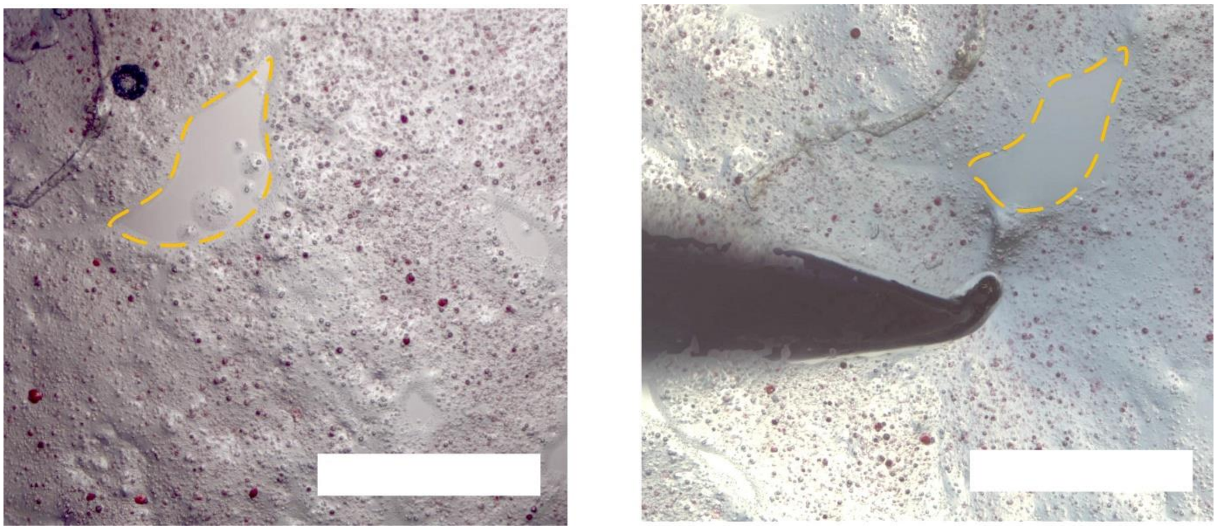


Figure S6: Detail of the container's surface after 6 s of spraying at 11 cm distance. The right image shows a needle deforming the container. A dashed line is used to highlight a spot that is not covered by the DS10 coating. Scale bar 400 μm.

Analytical Model and Simulations

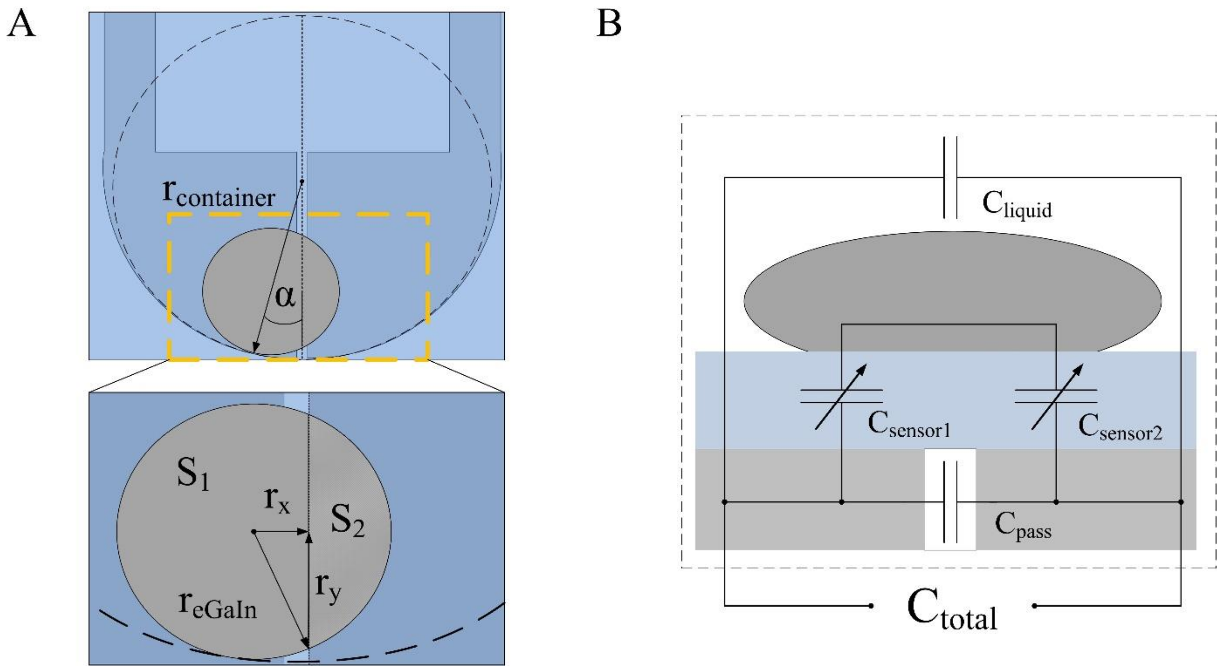


Figure S7: a) A scheme of the test sensor. Two electrodes are formed from a half circle with the same radius as the container ($r_{container}$). Detailed schematic shows the overlaps S_1 and S_2 between the droplet and the corresponding electrodes. b) A complete electrical schematic of the inertial sensor. Parasitic capacitance C_{pass} comes from the passivation/insulation between the electrodes and C_{liquid} from the fringing electric field in the surrounding liquid (glycerol, ε_r = 42.5 at 25°C). Both of the parasitic capacitances are included in the finite element simulation but not in the analytical model.

Analytical solution does not take into account the C_{pass} and C_{liquid}.

$$C_{total} = \frac{C_{\mathrm{sensor1}} C_{\mathrm{sensor2}}}{C_{\mathrm{sensor1}} + C_{\mathrm{sensor2}}} + C_{pass} + C_{liquid} \quad (2)$$

$$> \frac{\varepsilon_0 \varepsilon_r}{t} \frac{S_1 S_2}{S} = \frac{\varepsilon_0 \varepsilon_r}{t} \frac{(S - S_2) S_2}{S} = C'_{total}, \quad (3)$$

From geometry of the sensor in Figure S7 the following relations are valid.

$$S = r_{eGaIn}^2 \pi \quad (4)$$

$$r_x = (r_{container} - r_{eGaIn}) \sin(\alpha) \quad (5)$$

$$r_y = \sqrt{r_{eGaIn}^2 - r_x^2} \quad (6)$$

$$S_2 = S \frac{2\tan^{-1}(\frac{r_y}{r_x})}{2\pi} - r_x r_y \quad (7)$$

The analytical solution is obtained after inserting the expressions for S_2 and S into the Equation 3.

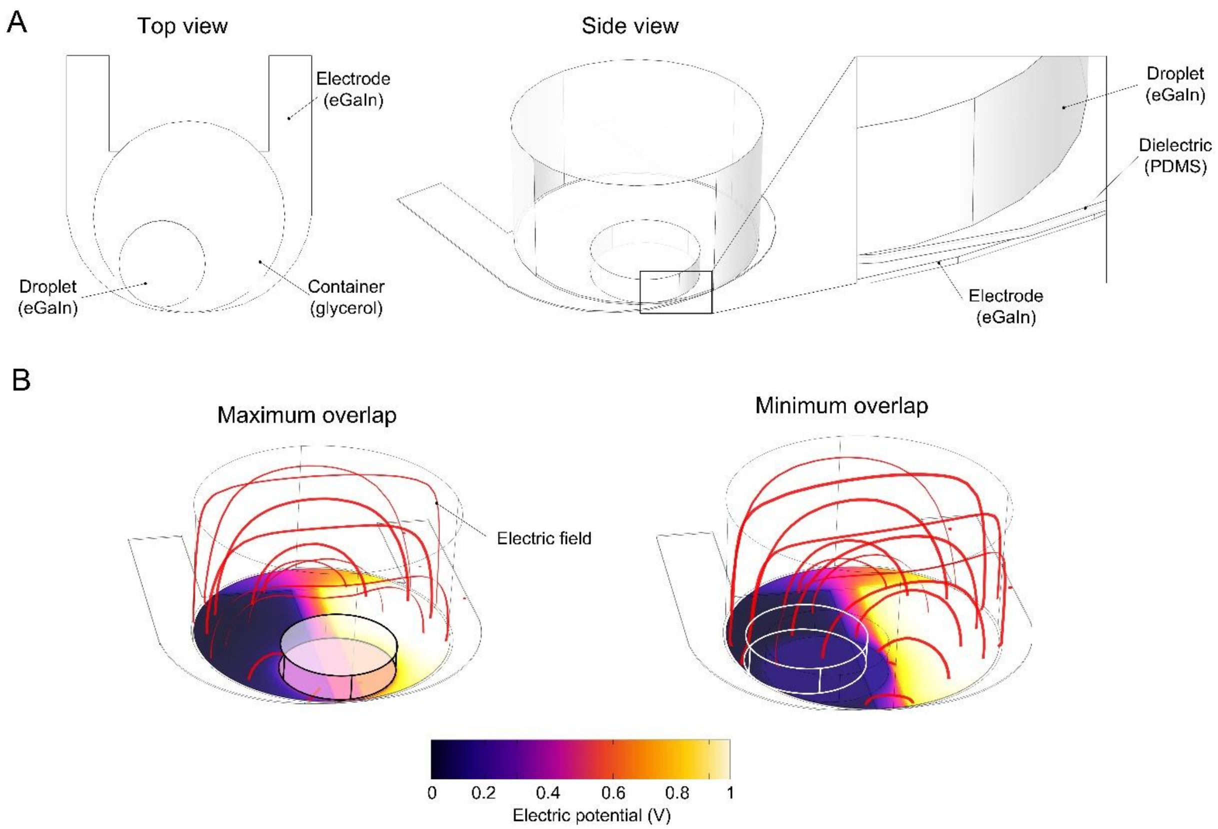


Figure S8: a) Domains of the model in Comsol used for electrostatic simulation. b) Output of the simulation: red lines denote the direction of the fringing electric field and the heat map indicates the distribution of the electric potential in the middle of the membrane (dielectric).

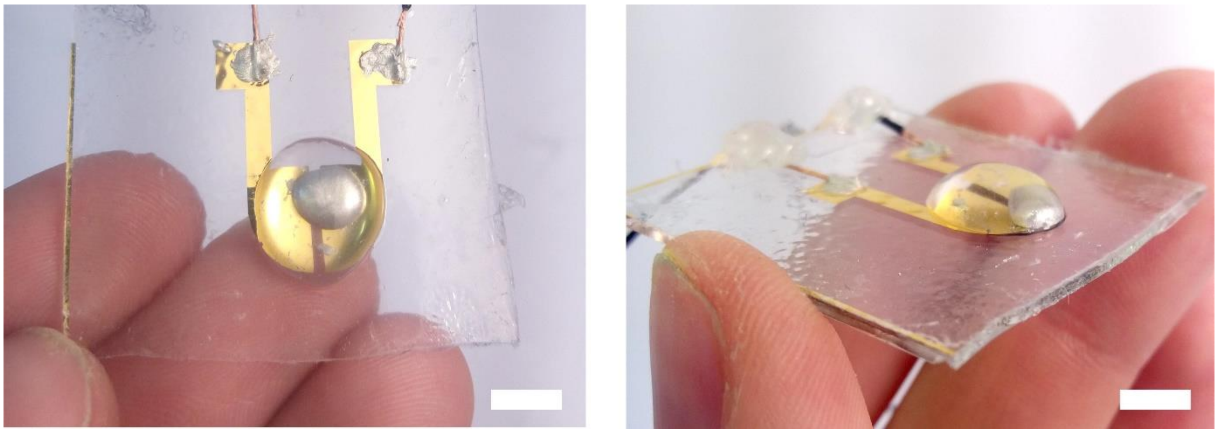


Figure S9: Top and side view of the test sensor for verifying simulation results. Sensors are fabricated on a glass substrate using shadow evaporation of gold electrodes and spin-coating of PDMS as a dielectric (20 μm). Connecting copper wires are attached using silver-filled epoxy adhesive. Scale bar, 6 mm.