
Frictionless multiphasic interface for near-ideal aero-elastic pressure sensing

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1. Supplementary Tables

1.1. Supplementary Table 1 Performance comparison of pressure sensors working in liquid environment.

Method	Linearity (R^2)	Degree of Linearity ($1/(1-R^2)$)	Hysteresis (%)	Nonlinearity (%)	Sensitivity	Pressure frequency range (Hz)	Working range (kPa)
Liquid EDL (impedance) ¹	0.99	100	9.08*	5.80*	- 2071.76 Ω /kPa*	-	0 - 26.66
Liquid EDL (capacitive) ²	0.97040*	33.78*	-	6.68*	34.51 pF/kPa	-	0 - 26.66
Hydrogel EDL (capacitive) ³	0.95979*	24.87*	-	9.41*	217 nF/kPa	20 - 3,000	0 - 0.07
Conductive sponge (resistive) ⁴	0.67305*	3.06*	-	35.22*	0.39/kPa (0 - 125 Pa) 0.02/kPa (125 Pa - 5 kPa)	0 - 10	0 - 5
Diaphragm/air cavity (capacitive) ⁵	0.993	142.86	4.3 $\pm$ 2.2	2.8 $\pm$ 1.5	0.03 pF/kPa*	2,600 (resonance) 530 (bandwidth)	0 - 53.33
Diaphragm/air cavity (resistive) ⁶	0.99879*	826.45*	-	1.83*	2.56 Ω kPa ⁻¹ μ m ⁻¹	-	0 - 9.33
Diaphragm/air cavity (resistive) ⁷	0.99831*	591.72*	-	2.40*	71.03 Ω /kPa	-	0 - 53.33
Diaphragm/air cavity (optical wavelength) ⁸	0.99384*	162.34*	-	4.78*	14.29 pm/kPa	0 - 1	0 - 13.33
Diaphragm/air cavity (capacitive) ⁹	0.92576*	13.47*		14.90*	3.1 fF/MPa	-	0 - 50,000
Triboelectric (open-circuit voltage) ¹⁰	0.993	142.86	-	7.15*	82.71 mV/kPa	0 - 1,000	0 - 22.61
eAir (this work)	0.99944 $\pm$ 0.00015	1,785.71	1.34 $\pm$ 0.20	1.49 $\pm$ 0.17	79.1 $\pm$ 4.3 pF/kPa	0 - 1,000	0 - 15

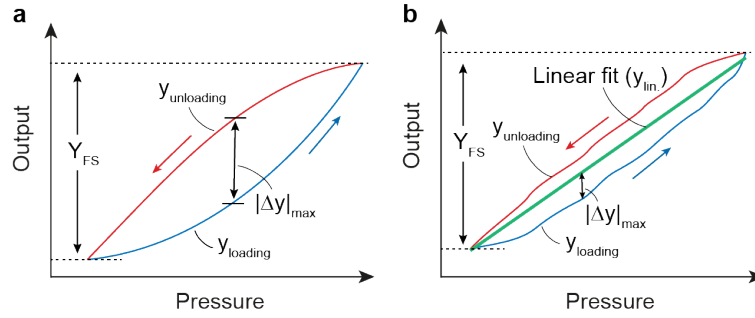
Note: An * indicates that the data is not directly provided in the cited article, and the values are extracted from the plots in the article by using a plot digitizer software. Performances of reported representative pressure sensors working in liquid environments are compared. The value of R^2 (coefficient of determination) has been commonly used for the evaluation of linearity. However, the R^2 value must be less than 1, and is easy to exceed 0.9, even though the sensing output curve does not "appear" to be linear with respect to pressure. The curves only "appear" to be linear when R^2 is greater than 0.99, but the values are so close to 1 that it is difficult to intuitively reflect the difference in linearity. Therefore, to highlight the difference in linearity between the different sensors, we also use the value of $1/(1-R^2)$ for comparison and name this value as the degree of linearity (DL). Linearities were calculated with consideration of both the loading and unloading curves if they were provided. In addition, sensitivities of devices with different mechanisms (thus may be measured in different physical units) were also listed in this table for performance comparison as the sensitivity is the universal metric for evaluating the performance of a sensor.

2. Supplementary Notes

2.1. Supplementary Note 1 Threshold Extraction Methods for Non-ideal Pressure Sensors

By analogy to the threshold-voltage extraction method in modelling MOSFETs, the forward/backward threshold pressures of the non-ideal pressure sensor are identified by using extrapolation in the linear region method¹¹. We define the loading and unloading pressure-output curve as $y = f_L(x)$ and $y = f_U(x)$, respectively (x represents for pressure, y represents for output). The forward threshold (P_{FT}) is defined as the corresponding pressure at the intersection of $y = f_L(0)$ and the linear extrapolation of $y = f_L(x)$ at its maximum absolute first derivative (slope) point (i.e., the point with highest sensitivity). Similarly, the backward threshold (P_{BT}) is defined as the absolute difference of the maximum loading pressure and the corresponding pressure at the intersection of $y = f_U(x_{max})$ and the linear extrapolation of $y = f_U(x)$ at its maximum absolute first derivative (slope) point. For ideal pressure sensors, the performance curves are linear, and the values of P_{FT} and P_{BT} are zero. The illustration is shown in **Fig. 1f**.

2.2. Supplementary Note 2 Definition of Hysteresis, Linearity, and Sensitivity



Supplementary Figure 1 | Definition of hysteresis and linearity. a, Definition of hysteresis. b, Definition of linearity.

Hysteresis (H) is defined as the maximum absolute difference between the loading curve ($y_{loading}$) and the unloading curve ($y_{unloading}$) at the same pressure as a percentage of the full range span (Y_{FS}) (Supplementary Figure 1a), i.e.,

$$H = \frac{|y_{loading} - y_{unloading}|_{max}}{Y_{FS}} \times 100\% \quad (Eq. S1)$$

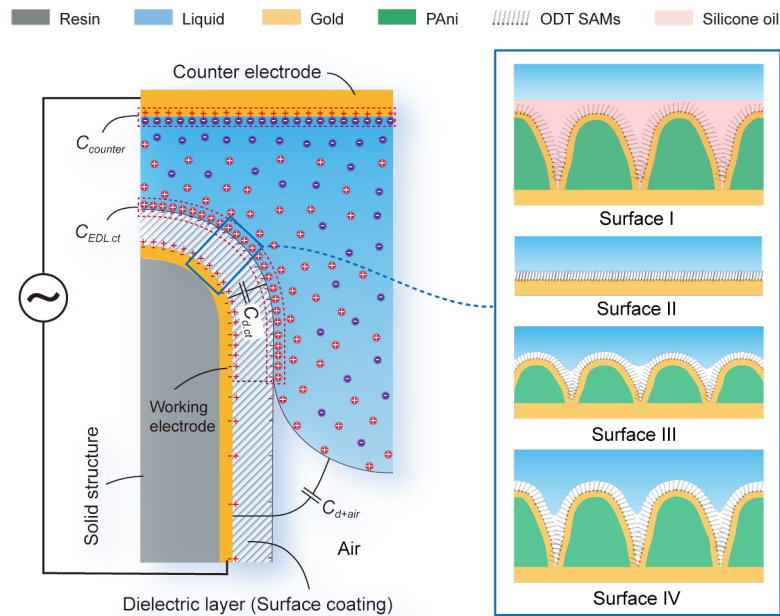
Linearity is quantified in two ways. One adopts the R-square (coefficient of determination) value of the linear fitting result using the Simple Linear Regression Model (computed by OriginPro software) with consideration of both loading and unloading. The other is to calculate the nonlinearity of the device performance curve. Here, the nonlinearity ($L_{non.}$) is expressed as a percentage of the full range span (Y_{FS}) occupied by the maximum value of the absolute value of the subtraction of the loading ($y_{loading}$) and unloading ($y_{unloading}$) curves at the same pressure from the linear fit line ($y_{lin.}$) (Supplementary Figure 1b), respectively, i.e.,

$$L_{non.} = \frac{(|y_{loading} - y_{lin.}|, |y_{unloading} - y_{lin.}|)_{max}}{Y_{FS}} \times 100\% \quad (Eq. S2)$$

Sensitivity is defined as the change in output value caused by a change in unit pressure.

An ideal pressure sensor with high accuracy should have a linear, zero-threshold, hysteresis-free, and sensitive response. Specifically, poor hysteresis and linearity cause sensing errors and signal distortion¹². And such sensors operate with limited consistency in sensitivity over their working ranges, thereby needing additional pressure-output calibration¹³.

2.3. Supplementary Note 3 Capacitance Analysis of Devices



Supplementary Figure 2 | Capacitance composition illustration of devices with different surface treatment details. The difference in the capacitance composition of devices with different surfaces is the capacitance due to the different coatings on the structural electrode surfaces, which is illustrated in the figure. The capacitance (C) of a device consists of the EDL capacitance at the liquid-counter electrode interface ($C_{counter}$) and the liquid-working electrode coating interface ($C_{EDL.ct}$), the dielectric capacitance ($C_{d.ct}$) between the working electrode and the surface coating-liquid interface, and the capacitance (C_{d+air}) between the working electrode and the liquid through air, and the interfacial capacitance of the non-active area (outside chambers) (C_0).

The capacitance (C) composition of devices and its equivalent circuit were illustrated in **Fig. 1c, e**, and **Supplementary Figure 2** shows the surface coating details between structural working electrode and liquid.

The device capacitance can be expressed as

$$C = \frac{1}{\frac{1}{C_0 + \frac{C_{d.ct}C_{EDL.ct}}{C_{d.ct} + C_{EDL.ct}}} + \frac{1}{C_{d+air}}} + \frac{1}{C_{counter}}} \quad (Eq. S3)$$

where C_0 is the interfacial capacitance of the non-active area, which is the area outside the chambers, i.e., the top area of the structural working electrode in contact with the liquid and the wires is encapsulated with insulations (SU-8 and polyimide). In contrast, the active area is defined as the inner surface area of the chambers, where the dynamic wetting happens.

Since the capacitance of each component follows physical principle of the parallel plate capacitor, their values can be calculated using $\epsilon A/d$, where ϵ is the permittivity of the dielectric material, A is the area of the plates, and d is the equivalent distance between the two plates. The capacitance between the noncontacted area of the structural electrode and the liquid-air interface through the surface coating layer and air, C_{d+air} , can be ignored as its equivalent d is

much larger than the other capacitors. $C_{d.ct}$ and $C_{EDL.ct}$ can be considered as an interfacial capacitance C_{ct} , i.e., the interfacial capacitance between the structural electrode and the liquid within the liquid-electrode contact area.

The Eq. S3 can be simplified to,

$$C \approx \frac{C_{ct} + C_0}{1 + (C_{ct} + C_0)/C_{counter}} \quad (Eq. S4)$$

For Surface I, the dielectric layer is a composition of ODT SAMs and silicone oil as PANi nanowires and the gold coated on the nanowires are conductive. The thickness of ODT SAMs is in few nanometers (thickness ≈ 2 nm, dielectric constant: ~ 2.1)^{14,15}, and the silicone oil is infused between the PANi nanowire induced nanostructures. Therefore, the dielectric layer is ultrathin. The unit capacitance of a Surface I treated electrode was measured as 1.87 ± 0.30 nF/mm².

For Surface II, the dielectric layer is the ODT SAMs. The unit capacitance of a Surface II treated surface was measured as 6.79 ± 0.64 nF/mm².

For Surface III and IV, as PANi nanowires are conductive, the dielectric layers are the ODT SAMs and the air trapped between the surface nanostructures induced by PANi nanowires (gold coated). The unit capacitance of Surface III and Surface IV treated electrodes were measured as 7.05 ± 0.16 nF/mm² and 7.98 ± 0.54 nF/mm², respectively.

The unit capacitance of bare gold electrode was measured as 97.3 ± 10.1 nF/mm². The unit capacitance was measured using two identically treated electrodes with the same area (1 cm²) immersed in $1 \times$ PBS solution, 1 cm apart, with 100 mVrms 100 kHz voltage applied. Note that the measured capacitance decreases with the distance between the electrodes in the solution, while the distance between the structural electrode and the counter electrode of the actual device is much smaller than 1 cm, so the unit capacitance obtained here is smaller than the unit capacitance inside the eAir device.

Moreover, all devices with different surfaces, the liquid-electrode contact areas on the structural working electrode are much smaller than the area of the counter electrode (3.2 mm²), which is confirmed by simulation results (**Extended Data Fig. 3**). Moreover, the capacitance of the non-active area can be divided into two parts: i) the exposed area of the top of the structural working electrode and part of the electrode area on the wall for wire leading out without encapsulation. This part is less than 0.6 mm², and it varies with the manual encapsulation of SU-8. The area has the same surface treatment as the device, thus the capacitance, C_0 is at the same order of magnitude of C_{ct} with consideration of both areas; ii) the area of the wires encapsulated with insulations (SU-8 and polyimide). As the insulations are very thick compared to the surface treatments, this part of capacitance can be ignored. Therefore, all devices with different surfaces follows the same relationship between capacitances: $C_{counter} \gg C_{ct} + C_0$.

Therefore, $(C_{ct} + C_0)/C_{counter}$ is much smaller than 1, Eq. S4 can be further considered as,

$$C \approx C_{ct} + C_0 \quad (Eq. S5)$$

C_{ct} can be calculated as $C_{ct} = \varepsilon_{ct}A_{ct}/d_{ct}$, ε_{ct} and d_{ct} are the equivalent permittivity and electrode distance between the structural electrode and the liquid-coating interface, A_{ct} is the contact area change induced by the liquid pressure between the liquid and the treated structural working electrode. Since for fixed surface treatment, the permittivity and distance are constants, we can define a constant $k = \varepsilon_{ct}/d_{ct}$. Therefore, we have the following equation for all devices with different surfaces,

$$C \approx C_0 + kA_{ct} \quad (Eq.S6)$$

Accordingly, we can consider that the capacitances of eAir devices are linearly proportional to their liquid-electrode contact areas within the designed structures.

2.4. Supplementary Note 4 Computational Fluid Dynamics (CFD) Simulation

A CFD simulation model is built in OpenFOAM to evaluate the capability of the single cell in hexagon-array devices. Two-phase flow with free surface is modelled by the volume-of-fluid (VOF) methodology. Under external pressure, the liquid is squeezed into the hexagonal holes and the air in the hole is compressed. This yields the increasing of internal air pressure which is balanced with external liquid pressure and capillary pressure (Laplace pressure). Considering the physics nature of this process, the compressible InterFoam solver is used for this study. It is an OpenFOAM solver for solving two compressible, immiscible fluids flow, with capturing interface using the VOF approach. Considering simulating the entire device is not computational acceptable, only unit hexagon cell is modelled, with subscribing symmetric boundary condition on the mid-surface of each wall. This model could well represent the behavior and response of free surface under external liquid pressure. By inputting the contact angle and assuming isothermal condition with ideal gas model, the CFD model can evaluate the changing of contact area at different external applied liquid pressure.

Simulations are conducted at water contact angles 88° , 94° , 111° , 114° , 132° , and 158° for corresponding designed surfaces with different advancing angles and receding angles, and the contact areas are evaluated at different applied external liquid pressure.

2.5. Supplementary Note 5 Wetting Process in a Hexagon Chamber with Different Receding Angles

The output performances of devices are directly influenced by the surface wetting process under varying pressure, which dominated by the surface wetting properties and resulting in the corresponding changes in liquid-electrode contact area. And the output capacitance of devices varies with contact area. The contact area changes with contact line movement, which is influenced by the surface pinning. And the surface pinning also determines the advancing and receding angles under changing liquid pressure. Therefore, it is crucial to investigate wetting processes of hexagon chambers with different advancing and receding angles. This can facilitate the understanding and prediction of the device performance.

All designed surfaces (Surface I-IV) are hydrophobic to avoid full wetting and allow efficient reversible contact line movement. This was suggested by testing the pillar-array device with pristine gold electrode, which exhibited an irreversible response to pressure (**Extended Data Fig. 1e, f**) due to the intrinsic hydrophilic surface of gold. Thus, hydrophobic surfaces are essential to establish a pressure-sensitive air layer. Two different situations of receding angles have been considered for the wetting process, i.e., receding angle larger than 90° and smaller than 90° (initial contact angle). **Fig. 3a-c** and **Extended Data Fig. 4** illustrate the two conditions and corresponding predicted response behavior, respectively.

2.5.1. Wetting process for receding angles larger than 90°

For the surface with a receding angle that larger than initial contact angle (close to 90°), we considered a cycle of loading and unloading pressure in a hexagon chamber as four regions:

Region A: The liquid-air interface sags inwards the hexagon chamber, the air entrapped in the chamber is compressed accordingly. The dynamic contact angle increases with the increasing liquid pressure, while the contact line is pinned to the edge of the chamber^{16,17} until contact angle reaches the advancing angle (**Fig. 3a, S1 to S2**). In *Region A*, negligible increasing contact area and capacitance occur which contributes to the forward threshold.

Region B: The contact line sweeps inward to the chamber due to the depinning effect, while the contact angle changes limitedly around advancing angle. The air is further compressed. The liquid-solid contact area increases sharply with liquid pressure in *Region B* (**Fig. 3a, S2 to S3**).

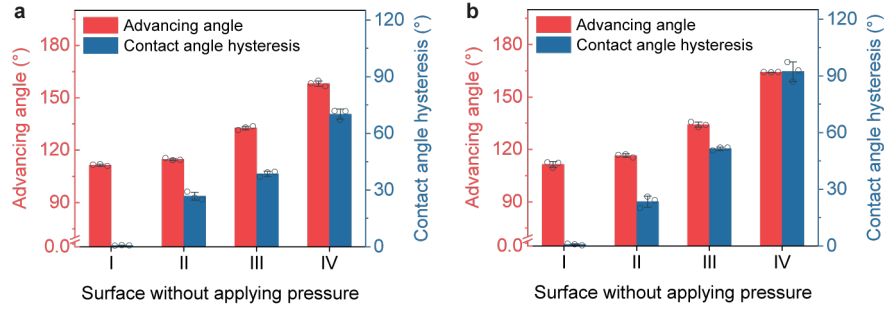
Region C: The dynamic contact angle decreases from the advancing angle until it reaches the receding angle ($> 90^\circ$) with decreasing liquid pressure, while the contact line is pinned and hardly moves, and the air is decompressed accordingly (**Fig. 3a, S3 to S4**). In *Region C*, negligible decreasing contact area and capacitance occur which contribute to the backward threshold.

Region D: The depinning contact line moves outwards with around receding angles ($> 90^\circ$) under the decreasing pressure, and the air is further decompressed. The contact line reaches the edge of the chamber, and the liquid-solid contact area decreases dramatically with decreasing pressure (**Fig. 3a, S4 to S5**). And then the dynamic contact angle decreases with decreasing pressure to the initial state (close to 90° , **Fig. 3a, S5 to S1**).

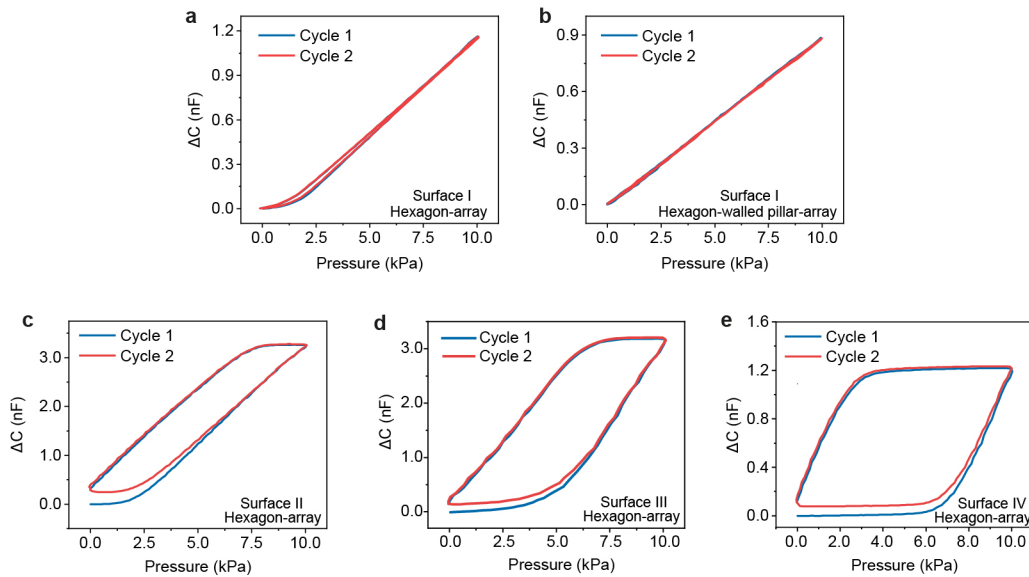
2.5.2. Wetting process for receding angles smaller than 90°

The wetting process is different when receding angle is smaller than 90°. During the first cycle, the liquid-air interface movement from *Region A* to *C* behaves the same as when receding angle is larger than 90°. The main difference occurs at *Region D*. Unlike the surface with a receding angle larger than 90° that the contact line can go back to the initial states (close to 90°) when the external pressure is zeroed, the contact line cannot return to the initial position, and additional contact area is shown when the receding angle is smaller than 90°. The explanation can be made that the extra volume caused by the convex curvature of liquid-air interface is compensated by the contact line with a position lower than the start point to keep the total air volume constant at zero pressure. Here we assume that the reversible compression process is an isothermal process with negligible air dissolution in liquid. As a result, the initial capacitance of the second cycle is larger than the first one due to the extra liquid-electrode contact area. Thus, the small receding angle ($< 90^\circ$) results in the non-repeat for the first two cycles. The complete wetting process for the first two cycles and the relationships between the change in liquid pressure against contact angle and contact area (or capacitance) are illustrated in **Extended Data Fig. 4**.

Importantly, the stability of surface property can also affect the wetting process and corresponding device performance. The transition from Cassie-Baxter to Wenzel state occurs when the applied external pressure exceeds the breakthrough pressure (critical pressure)¹⁸. This transition is influenced by the varying degrees of surface roughness and applied pressure. Therefore, for devices tested under changing pressure, they always show the non-repeat between the first and following cycles. During the pressure loading and unloading process, the surface wetting state may change due to the intrusion of water into the hierarchical micro/nanostructures¹⁹. Any increase in pressure drives water deeper between the primary micro-pillars, and also into the secondary PANi nanowires induced nanostructures on the micro-pillars surface. The surface wetting properties (Surface I - IV) were explored before and after applying liquid pressure. **Supplementary Figure 3** indicates the advancing angle and contact angle hysteresis of Surface I - IV (on flat glass substrates) before and after immersion under 10 kPa for 5 min. Surface I and II show a pressure-stable surface property even after water compression. For Surface I, slippery surfaces show extreme pressure stability up to 68 kPa²⁰. The infused silicone oil can minimize pressure-induced impalement into the porous structures and retain its function even under the increasing pressure. For Surface II, the close-packed ODT monomoleculars are arranged by lateral van der Waals interactions on gold. This can minimize the additional interaction between the ODT chains and outside liquid¹⁴ to exhibit a pressure-stable property. On the contrary, Surface III and IV show a significant increase in both advancing angle and contact angle hysteresis due to high roughness induced transition from Cassie-Baxter state to Wenzel state and contact line pinning. The different surface stability clearly reflects various corresponding device performances (**Supplementary Figure 4**).



Supplementary Figure 3 | Surface wetting property difference of designed surfaces before and after applying liquid pressure. **a**, Advancing angle and contact angle hysteresis of different types of surfaces (I-IV) without applying liquid pressure. **b**, Advancing angle and contact angle hysteresis of different types of surfaces (I-IV) after applying liquid pressure (10 kPa) for 5 min. For surfaces with large surface roughness (Surface III and Surface IV), both the advancing angle and the contact angle hysteresis increased after applying pressure, but there was no such trend for smooth surfaces (Surface I and Surface II). The surfaces show an increasing tendency of advancing and contact angle hysteresis in the order of Surface I-IV. All data are represented as mean values $\pm$ s.d. (3 samples) with the corresponding data points overlapped.



Supplementary Figure 4 | Sensing performance of devices with different surfaces over first two cycles. **a, b**, Consistent performance of the first and second cycles for hexagon-array device (Surface I, slippery surface) and hexagon-walled pillar-array device (Surface I, slippery surface). **c-e**, Inconsistent performance of the first and second cycles for hexagon-array device with different surfaces (Surface II, III and IV). The side length of single hexagon chamber unit is 40 μ m.

In summary, both the receding angle ($> 90^\circ$ or $< 90^\circ$) and surface stability affect the device repeatability and overall stability. Here, we discussed each type of surface and corresponding device performance in detail.

Surface I (receding angle: $110.8^\circ \pm 0.4^\circ > 90^\circ$) follows the wetting process and relationships illustrated in **Fig. 3a-c**. The silicone oil-infused nanostructured surface shows extreme pressure stability²⁰. The surface wetting state is stable before and after applying external pressure

(**Supplementary Figure 3**). The relative change of advancing angle is lower than 0.1%, and the contact angle hysteresis maintain below 1°. Therefore, the performance of both hexagon-array and hexagon-walled pillar-array devices show high repeatability (**Supplementary Figure 4a, b, and Fig. 4g**).

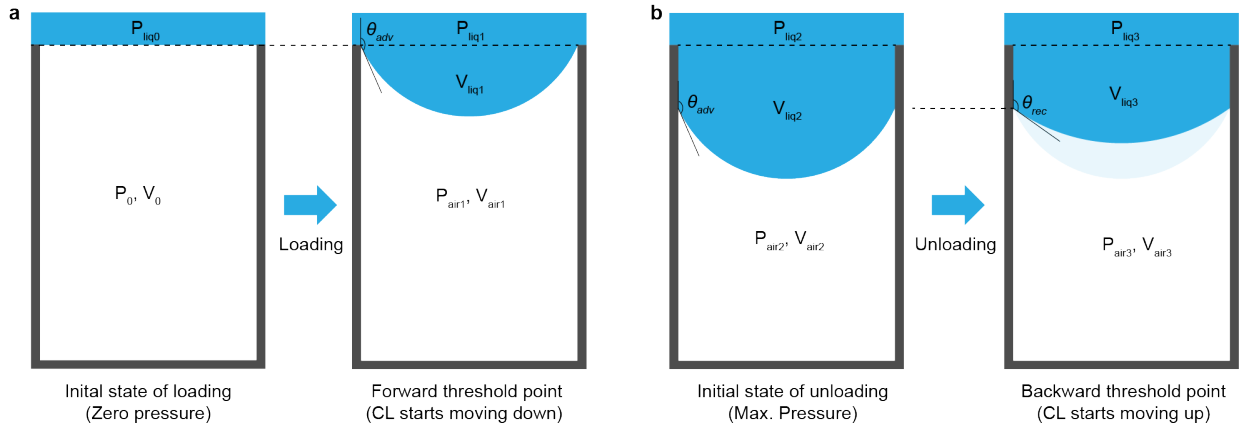
Surface II (receding angle: $88.5^\circ \pm 1.6^\circ < 90^\circ$) follows the wetting process and relationships illustrated **Extended Data Fig. 4**. It shows a pressure stable surface property that the advancing angle and contact angle hysteresis have minor changes ($< 2\%$ and $< 10\%$, respectively) due to the close-packed monomolecular. Thus, the devices treated with Surface II exhibit an inconsistent performance between cycle 1 and 2 (**Supplementary Figure 4c**) which confirms the assumption of the wetting process (**Extended Data Fig. 4a**).

Surface III (receding angle: $94.0^\circ \pm 0.4^\circ > 90^\circ$) follows the wetting process and relationships illustrated in **Fig. 3a-c**. However, the performance curves of the first and second cycles still show a difference (**Supplementary Figure 4d**). According to the contact angle measurement before and after applying external liquid pressure, the advancing angles are similar, but the receding angle was reduced to $70.9^\circ \pm 1.5^\circ$. The transition between the Cassie-Baxter and Wenzel states occurs on the nanostructured surface when increasing the liquid pressure¹⁹. The enhanced pinning effect leads to a variation in the receding angle, thus contributes to the non-repeatable response between the first and following cycles.

Surface IV (receding angle: $88.0^\circ \pm 1.6^\circ < 90^\circ$) follows the wetting process and relationships illustrated in **Extended Data Fig. 4**, and also exhibits a changing surface wetting properties before and after applying external liquid pressure. The difference between the first and following cycles (**Supplementary Figure 4e**) are caused by both small receding angle ($< 90^\circ$) and surface wetting instability.

For both above discussed wetting conditions of receding angles ($> 90^\circ$ or $< 90^\circ$), in a real hexagon chamber, the sink-depth field of the water-air interface is inhomogeneous under increasing liquid pressure due to its geometric shape¹⁸. As shown in the simulation results (**Extended Data Fig. 3**), different boundary conditions exhibit various sink depths. Thus, the movement of the contact line is not at the same level of depth, and the contact area does not change proportionally with changing liquid pressure around the turning states. As a result, the transition of device performance does not show a sudden change at the turning states, but a smooth gradual change. Moreover, for a hexagon-array device, the inconsistency due to 3D-printing quality and surface treatment uniformity of the multi hexagon chambers will also influence the overall device performance.

2.6. Supplementary Note 6 Thresholds of Devices



Supplementary Figure 5 | Illustration of forward threshold and backward threshold for the hexagon chamber structure. **a**, Wetting states from the initial state to the forward threshold point where the contact line starts moving down (the contact angle reaches the advancing angle, θ_{adv}). **b**, Wetting states from the max. loading pressure state to the backward threshold point where the contact line starts moving up (the contact angle decreases to the receding angle, θ_{rec}). V_{liq} with numbers are the volume of the liquid in the chamber at the corresponding states.

The equilibrium of the liquid pressure (P_{liq}), capillary pressure (P_{cap}), and the pressure of the entrapped air (P_{air}), determines the liquid-air interface and contact line movement in the hexagon chamber. P_{cap} is related to the chamber geometry and contact angle, while P_{air} is related to the ratio of the air volume in the chamber before and after being compressed.

The liquid pressure changes the profile of the liquid-air interface, thereby simultaneously changing contact angle and the entrapped air volume. The contact line starts to move only when the contact angle changes to the advancing angle or the receding angle. Thresholds occur in the pressure range where the contact line does not move. The resulted thresholds are determined by P_{cap} and P_{air} between the initial states and the points where the contact line starts moving. This process applies to both the loading and unloading processes.

When the liquid is pressed into the chamber, as a balance, we have

$$P_{liq} = P_{cap} + P_{air} \quad (Eq.S7)$$

Capillary pressure is inversely proportional to the radius of curvature of the liquid-air interface, where the radius is related to the contact angle and geometry of the chamber. In addition, the entrapped air underneath the liquid-air interface behaves like an elastic fluid²¹ with property of reversible deformation. Assuming an isothermal compression process for the entrapped air during compression and decompression, the air pressure is inversely proportional to the air volume, we have

$$P_0 V_0 = P_{air} V_{air} \quad (Eq.S8)$$

Where P_0 and V_0 are the initial pressure (atmospheric pressure) and volume of the air in the chamber, P_{air} and V_{air} are the pressure and volume of the air during the wetting process,

respectively. Thus, the forward threshold pressure (**Supplementary Figure 5a**), P_{FT} can be expressed as

$$P_{FT} = (P_{air1} + P_{cap1}) - P_0 = \frac{P_0 V_0}{V_{air1}} + P_{cap1} - P_0 \quad (Eq.S9)$$

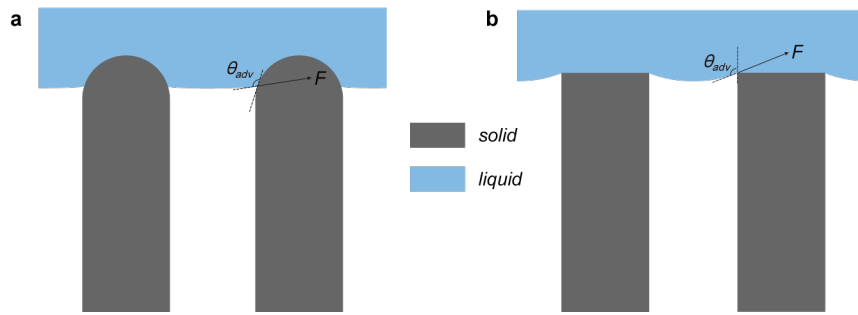
the backward threshold pressure (**Supplementary Figure 5b**), P_{BT} can be expressed as

$$P_{BT} = |(P_{air3} + P_{cap3}) - (P_{air2} + P_{cap2})| = \left| \frac{P_0 V_0}{V_{air3}} - \frac{P_0 V_0}{V_{air2}} + P_{cap3} - P_{cap2} \right| \quad (Eq.S10)$$

The numbers in the equations correspond to the values at the corresponding states in **Fig. 3a-c** and **Extended Data Fig. 4**.

Therefore, the thresholds are determined by the capillary pressure difference and the entrapped air pressure (or air volume) difference between the initial states and the points where the contact line starts moving, for both the loading and unloading processes. The relationships between the change in liquid pressure against contact angle, and contact area (or capacitance) are illustrated (**Fig. 3b, c** and **Extended Data Fig. 4b, c**).

2.7. Supplementary Note 7 Influence of Pillar Tip Shape on Thresholds

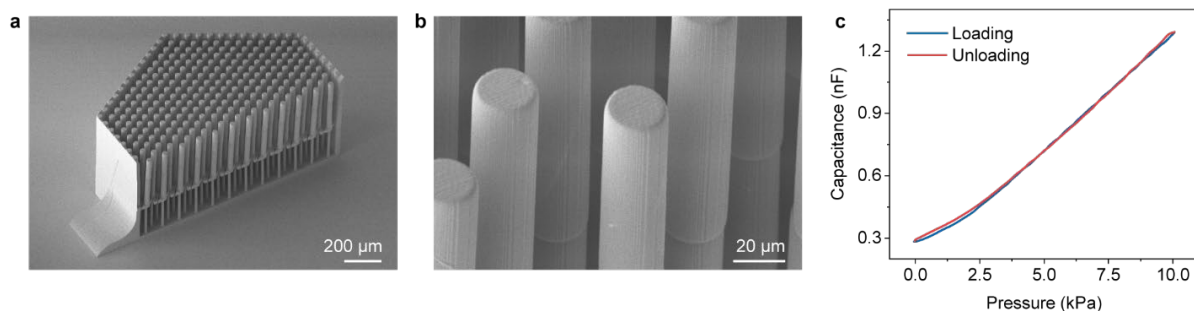


Supplementary Figure 6 | Illustration of the liquid surface tensional forces at the contact lines at the dome-shaped pillar tips (a) and flat pillar tips (b) when the contact angle first reaches the advancing angle during loading pressure.

A domed tip pillar array was adopted in the optimal structure of hexagon-walled pillar-array device. The purpose of dome tips is to mitigate the surface tensional force when pillars penetrate the water surface under low loading pressure conditions. This mitigation is manifested by reducing the length of initial contact line and altering the direction of surface tensional forces.

The resistance to spreading of liquids at edges with smooth transitions (e.g. round edges of dome tips) is much smaller than at sharp edges^{17,22}. Once the devices are submerged in water, the contact line on the dome tip is more prone to move under low pressure. As shown in **Supplementary Figure 6a**, when the water surface comes into contact with the curved dome tip under external low pressure, the contact angle, ideally equivalent to 180 degrees, thus the contact line cannot be maintained in equilibrium. The contact line will move downward in search of a position where the contact angle is at least reduced to the advancing contact angle. Due to the specific shape of the curved dome, the reference plane for evaluating the contact angle is the tangent plane at the location of the contact point that moves as the contact line moves along the dome surface. In addition, since the advancing angle of Surface I is about 111 degrees, the contact line reaches a force balance only when it moves to a position close to the pillar cylindrical surface when no additional liquid pressure was applied. In actual wetting scenarios, water spreads from one side of the device to the other, and the liquid front exerts additional pressure on the pillars during the spreading process, causing the pillars to penetrate deeper. Note that the length of the contact line also increases as it moves downward, which is determined by the hemispherical shape of the dome. Thus, during the wetting process of the contact line on the dome, both the initial inclination angle of the reference plane and the length of the contact line are conducive to reducing the surface tension resistance when the dome tip “pierces” the water at small pressures.

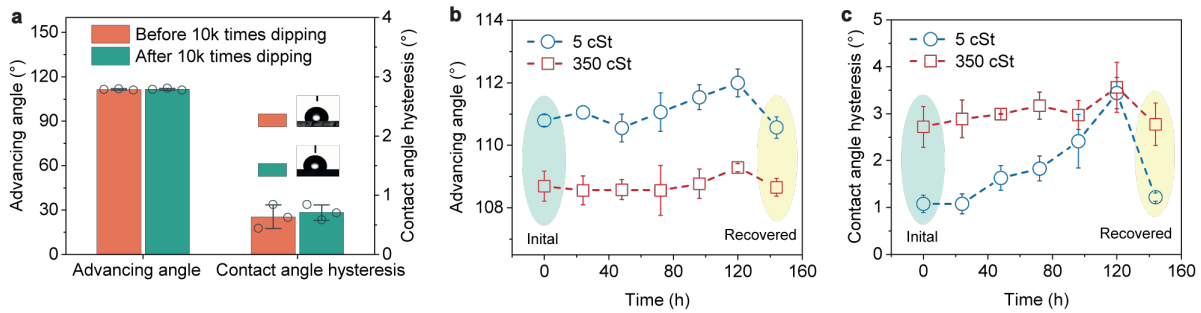
For flat tips situation (**Supplementary Figure 6b**), since the top flat surface shows 90-degree angle with the pillar cylindrical surface at the top edge, the initial contact angle, taken with the pillar cylindrical surface as a reference, is 90 degrees. The contact line length is initially the perimeter of the pillar, and the contact line is pinned at the top edge until the external pressure pushes the water to achieve an advancing angle, at which point the contact line starts to move.



Supplementary Figure 7 | Structure and performance of the hexagon-walled pillar-array device with flat pillar tips. **a**, SEM image of a half printed flat-tip hexagon-walled pillar-array structure. **b**, SEM image of flat-tip pillars. **c**, Pressure sensing performance of flat-tip hexagon-walled pillar-array device.

As an intuitive comparison (**Supplementary Figure 6**), when the external pressure is gradually increased, the direction of the liquid surface tensional force at the contact line on the flat tip pillar has a larger angle with the horizontal plane when the contact line first reaches the advancing contact angle. This results in a greater vertical force component of the surface tensional force, thus leading to greater resistance to water wetting downward, leading to greater forward threshold. To demonstrate the effectiveness of dome tips, we prepared hexagon-walled pillar-array devices with flat pillar tips as a comparison (**Supplementary Figure 7a, b**). The devices with dome tips do not exhibit a forward threshold, while the devices with flat tips show a threshold of 1.32 ± 0.37 kPa (**Supplementary Figure 7c**).

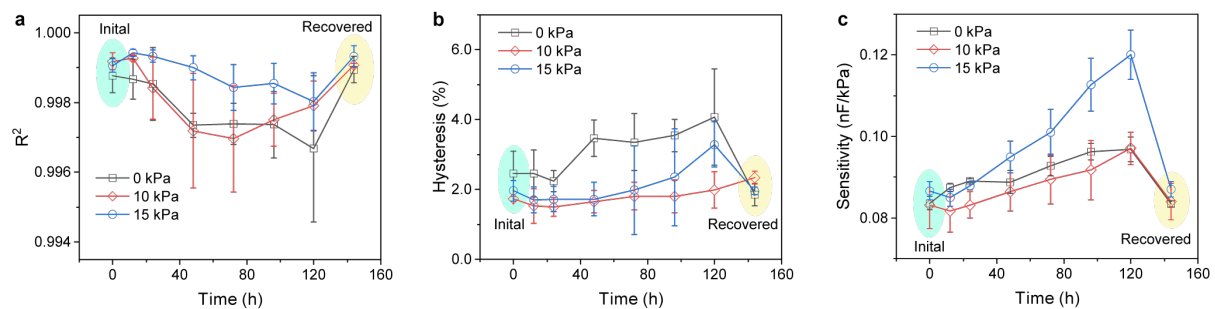
2.8. Supplementary Note 8 Stability Characterization of eAir



Supplementary Figure 8 | Stability of Surface I (slippery surface). **a**, Advancing angle and contact angle hysteresis comparison of slippery surface (Surface I with 5 cSt silicone oil) before and after 10,000 times dipping in $1\times$ PBS solution. Surface I is stable and shows negligible changes of advancing angle and contact angle hysteresis before and after 10,000 times dipping. Data are represented as mean values $\pm$ s.d. (3 samples) with the corresponding data points overlapped. **b**, **c**, Advancing angle and contact angle hysteresis variations over time. Data are represented as mean values $\pm$ s.d. (3 samples).

To assess the stability of the super-slippery surface (Surface I), we conducted tests of its stability under cyclic liquid shearing and long-term immersion in $1\times$ PBS solution. The advancing angle and contact angle hysteresis show negligible changes after 10,000 dipping cycles in a phosphate-buffered saline ($1\times$ PBS) solution, indicating its good stability (Supplementary Figure 8a).

Further, we fully immersed glass slides coated with Surface I (coated with 5 cSt silicone oil) in a $1\times$ PBS solution for 5 days to monitor the changes in surface wetting properties. The results show that the advancing angle and contact angle hysteresis both increase with the immersing time. However, it is important to note that the increase was not excessive but within a reasonable range as shown in Supplementary Figure 8b, c. The advancing angle increases by only $1.20 \pm 0.11^\circ$, and the contact angle hysteresis remains within 4° . This slight degradation in the slippery performance could be attributed to the loss of oil, which occurs due to the slow diffusion of oil into the PBS solution during prolonged immersion (for 5 days)²³.

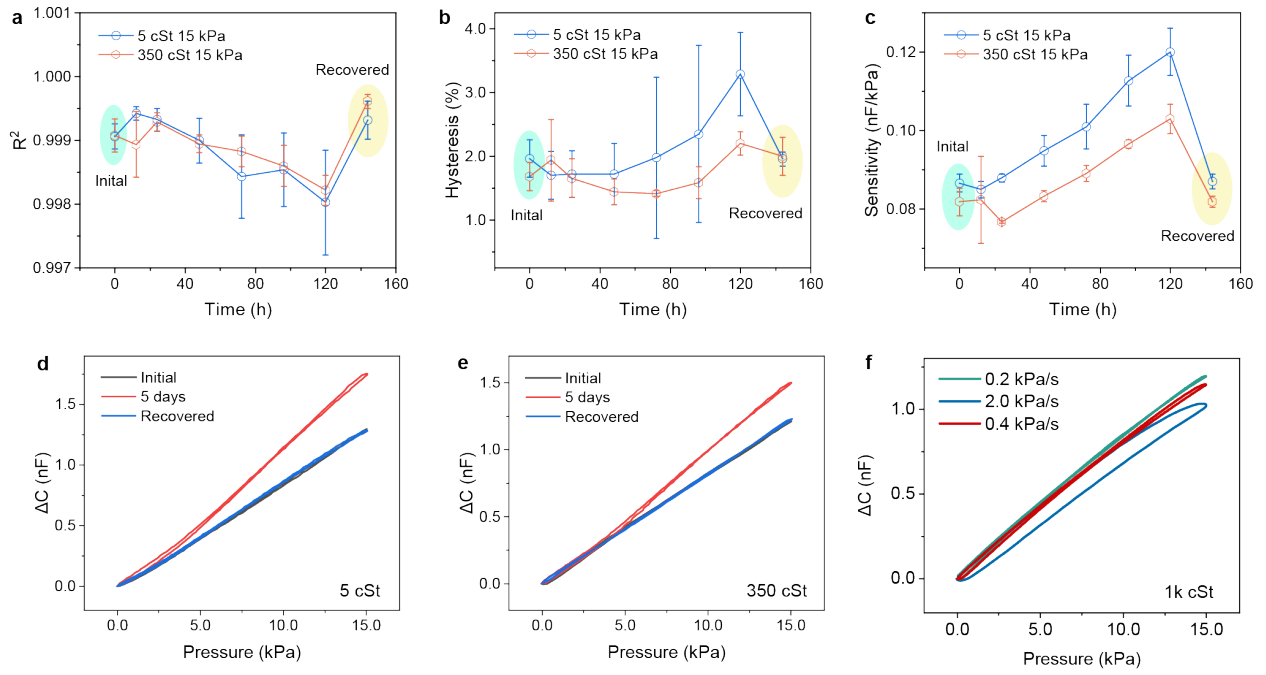


Supplementary Figure 9 | Performance variations over time of eAir immersed under $1\times$ PBS solution with maintained pressures at 0 kPa, 10 kPa, and 15 kPa (3 devices at each pressure) and the performance restored by reapplying the lubricant. **a**, Linearity (R^2 was adopted for evaluation) variation over time. **b**, Hysteresis variation over time. **c**, Sensitivity variation over time. Data are represented as mean values $\pm$ s.d. (3 samples).

The variations in contact angles in a prolonged period might contribute to the performance drift of eAir. To evaluate the stability of eAir over time when immersed underwater, we conducted tests of devices immersed in $1\times$ PBS solution with constant pressures of 0 kPa, 10 kPa, and 15 kPa, separately. The devices were monitored for a period of 5 days to observe any changes in performance, especially in terms of linearity, hysteresis, and sensitivity. The device was still functioning properly on the 5th day, but the device performance degraded over time, as shown in **Supplementary Figure 9**. Specifically, we observed a decrease in linearity and an increase in hysteresis and sensitivity. The degradation in device performance observed during the stability is within expectations, because the properties of the super-slippy surface can deteriorate over time, and the air inside the device also slowly dissolves into water over time. As previously mentioned, the loss of oil from the slippy surface degrades its frictionless properties, causing a delay in the movement of the multiphasic contact line. In addition, the loss of oil also reduces the thickness of the dielectric layer, leading to an increase in capacitance.

Despite the observed degradation, the performance variations were small and acceptable until the 48-hour mark, with a sensitivity change of less than 10%, negligible linearity change (with R^2 changing within 0.1%), and hysteresis remaining within 2.5%. Beyond 48 hours, the performance variations continued to increase, but the device still functioned properly without any performance breakdown. This indicates that there was still sufficient air within the device that was not dissolved completely. Theoretically, if there is a high volume ratio between water and air, the water-air interface may easily break down, resulting in a transition from Cassie state to Wenzel state²⁴. However, in our case, the dissolution process has been restricted as there is an ample amount of air in the external surroundings, and the droplet-air interface area in the environment is greater than the liquid-air interface area within the device. This leads to a rapid saturation of the droplet with dissolved air, preventing complete dissolution of the air inside the device.

Moreover, reapplying oil to the structured surface in the device can allow the sensing performance to be restored to the initial state, with a sensitivity change of less than 1%, negligible linearity change (with R^2 changing within 0.1%), and hysteresis remaining within 2% (**Supplementary Figure 9**). Therefore, the degraded performance of the device can be fully recovered. Even with encapsulated devices, reoiling is easy because the encapsulation film can be removed easily. Also, this process is simple and does not require any specialized equipment, making it feasible for users to perform on their own. In terms of real-world applications for the proposed demonstrations in this research, at low pressure testing range, our sensor's stability can sustain continuous measurement up to 5 days. By reoiling the device, a longer service life can be achieved. For grasper usage conditions and intracranial measurements, the current service life meets the necessary requirements, making our sensor a viable and suitable option.

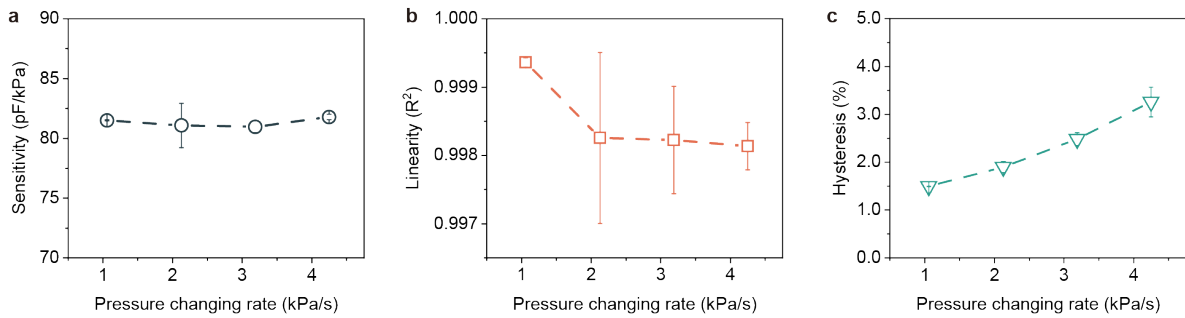


Supplementary Figure 10 | Performance variations of devices coated with different oil viscosities (5 cSt, 350 cSt and 1k cSt) over time. **a-c**, Performance variations of devices coated with 350 cSt and 5 cSt silicone oil over time. The devices were immersed in $1\times$ PBS solution and subjected to constant pressures of 15 kPa. The sensing performance was restored by reapplying corresponding silicone oil. Data are represented as mean values $\pm$ s.d. (3 samples). **d, e**, Performance of devices at the initial state, after 5 days, and after reapplying oil for 5 cSt and 350 cSt coated devices. **f**, sensing performance of a device coated with 1k cSt silicone oil subjected to different pressure change rates.

To further enhance the stability of the device, we propose increasing the viscosity of the silicone oil. While lower viscosity oil is desirable for achieving lower friction and contact line mobility, higher viscosity results in a lower oil loss rate and higher stability, making it suitable for creating a more stable slippery surface on the device. To evaluate the feasibility of the proposed strategy, we conducted tests of devices coated with different viscosities of silicone oil under a maximum claimed pressure of 15 kPa. Specifically, we monitored the sensing performance of devices coated with 350 cSt and 5 cSt silicone oil over time. The devices were immersed in $1\times$ PBS solution and subjected to constant pressures of 15 kPa. As shown in **Supplementary Figure 8b, c**, the 350 cSt silicone oil resulted in smaller surface property variation, especially for contact angle hysteresis. Additionally, as shown in **Supplementary Figure 10a-e**, the improved surface stability led to smaller variations in linearity, hysteresis, and sensitivity when compared to the 5 cSt silicone oil, indicating a more stable performance due to the lower oil loss rate of higher viscosity silicone oil. Therefore, increasing the oil viscosity is an effective way to enhance the device stability.

We further tested the device with silicone oil of 1k cSt and found that it can exhibit linear and low hysteresis performance at low pressure changing rates of 0.2 kPa/s (**Supplementary Figure 10f**). However, the sensing performance was found to be greatly affected by different pressure changing rates. Differently, for devices coated with low viscosity silicone oil (5 cSt), as shown in **Supplementary Figure 11**, the sensitivity remained unaffected by varying rates, and the linearity and hysteresis showed a small deterioration with increasing pressure changing

rates. Overall, the devices showed good performance consistency under different pressure changing rates.



Supplementary Figure 11 | Effect of pressure changing rate on sensing performance of eAir coated with silicone oil (5 cSt). a-c, Sensitivity, linearity, and hysteresis vary with pressure changing rate in the range of 0 - 10 kPa. The effect of pressure changing rate on sensitivity is negligible, while larger rates slightly reduce linearity and hysteresis performance. Data are represented as mean values $\pm$ s.d. (3 samples).

Terminal velocity is the constant speed an object can achieve when the drag force acting on it equals the gravitational force pulling it down. A more viscous lubricant can result in a higher drag force and a lower terminal velocity, while a less viscous lubricant can lead to a lower drag force and a higher terminal velocity²⁵. Slippery surfaces with higher viscosity may compromise droplet mobility and the speed of the moving droplet due to increased dragging and adhesive forces. As a result, when a larger driving force is applied, there may be a delay in contact line movement, leading to a larger advancing angle and contact angle hysteresis due to viscous dissipation and deformation of the liquid-air interface. Ultimately, this can have an impact on device performance.

Thus, to optimize device performance, it is crucial to use an oil with a high viscosity that provides a stable slippery surface property, while also allowing for a high terminal velocity. Based on the stability results, silicone oil with a viscosity of 350 cSt appears to be a good candidate for achieving stable device performance while maintaining relative stability. Also, further testing and evaluation using lubricants of different types and viscosities could help further optimize the device stability and performance.

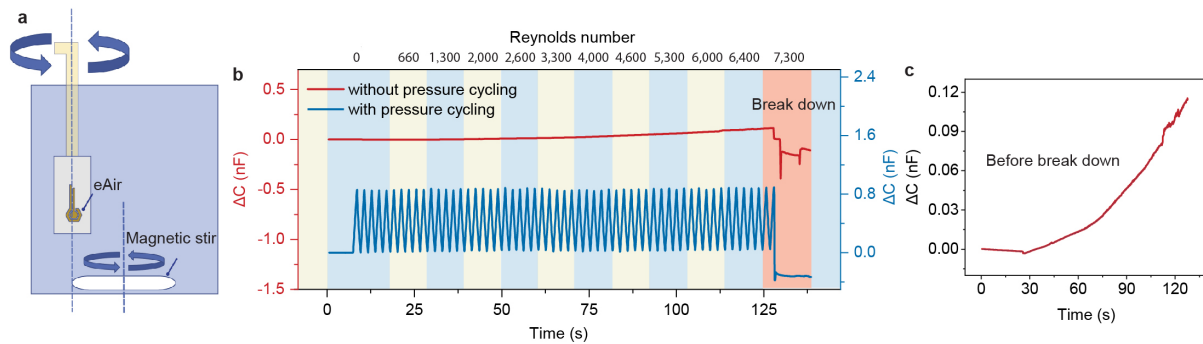
In addition to using higher viscosity lubricants, we are also exploring other avenues for future research, including improving the micro/nano-structures and modifying the surface lubricant locking mechanisms. We are also investigating the development of semi-liquid and solid super-slippery surfaces, as well as creating super-slippery surfaces with lubricant self-replenishing functions²⁶. Moreover, to improve device stability regarding air dissolution, we are examining the following aspects: i. replacing the PBS solution with a solution that has lower gas solubility; ii. using gases with lower solubility in PBS solution as the compressed gas in eAir, such as inert gases and hydrogen; iii. employing an air-supersaturated solution as a sensing medium; and iv. developing a method to regenerate gas within the device^{27,28}.

2.9. Supplementary Note 9 eAir Performance Stability under Turbulent Flow by a Magnetic Stirrer

The stability of the entrapped air, surface property and structure design of eAir chambers is critical for the reliable and durable device performance. We built a test environment with strong turbulence to evaluate the stability of eAir performance in liquid flow. The turbulent flow was generated by a magnetic stir. The Reynolds number (Re) can be determined by a dimensionless measure of the viscous effects in the rotating flows²⁹, which is introduced as

$$R_e = \frac{\Omega a^2}{\nu} \quad (Eq.S11)$$

Here Ω is the rotation frequency which is in the range of 0 - 16 s⁻¹, a is half of the length of magnetic stir (2 cm), and ν is the kinematic viscosity of the fluid (10⁻² cm² s⁻¹). We obtained Re up to 6,400. The transition from laminar to turbulent flow takes place when Reynolds number is 2,300 which is the critical Reynolds number³⁰. The device was tested under a fully turbulent environment, and surprisingly showed a stable performance. To further test the stability, additional setup was built that the device was placed under rotations (12 rpm) to face turbulent flow in various directions, as illustrated in **Supplementary Figure 12a**. The results obtained from this setup are shown in **Supplementary Figure 12b**. The results are consistent with the data presented **Fig. 4h** which reinforce the stability of the device's performance under the turbulent flow. In addition, the devices were further tested inside a turbulent flow without cyclic pressure to gain a clearer understanding of their performance changes as shown in **Supplementary Figure 12b, c**. At Reynolds number above 6,400, the high turbulent flow generates air pockets and voids which appear as bubbles in water due to the intense mixing of fluid. The bubble latched onto the device and caused a sudden capacitance drop and breakdown.



Supplementary Figure 12 | **a.** Setup of device test in turbulent flow with rotations on the device. **b.** Comparison of device performance with and without pressure cyclic testing under turbulent flow conditions until failure. **c.** Device drift plotted at a larger scale under increasing turbulent flow conditions without pressure cyclic testing.

We explain the stability of eAir under turbulent flow for following reasons.

First, in the absence of cyclic pressure, there is an increasing trend in capacitance because of the continuously rising impact pressure with stir speed (**Supplementary Figure 12c**). However, the most turbulent environment ($Re = 6,400$) only generates a pressure around 250 Pa which is significantly smaller than the cycling pressure (10 kPa). As a result, the capacitance variation

((8.31±1.30) %) between the initial state and maximum turbulent flow state ($Re = 6,400$) is not significant in **Fig. 4h** and **Supplementary Figure 12b**.

Second, when the devices were tested inside a turbulent flow without cyclic pressure, there is an increasing trend in capacitance but not random noise. This indicates that there was no significant Wenzel-state wetting between the pillars induced by the turbulent flow. The Cassie-Baxter state of underwater eAir provides a significant slippage effect due to the presence of air between the microstructures, thereby reducing the impact from the external liquid flow^{31,32}, and preventing random data and noise from occurring.

Nevertheless, the increasing hydrostatic pressure and complicated flow may still break down the entrapped air content over time³³. To design a structure with a long air trapping longevity, the stability of the Cassie-Baxter state is important. Patankar reported that there are two ways for a Cassie-Baxter state to transfer to a Wenzel state, which are based on the depinning or sagging transition, respectively³⁴.

To avoid broken down situations through either these two mechanisms, proper design of the length of the pillars and distances between the pillars are critical to ensure the water-air interface cannot contact the bottom of the air chamber^{35,36}. In our design, the pillars are designed to be long enough which ensures the “depinning and sag transition” impossible during the target pressure range. To determine the critical height of the pillars, the sag criterion for the transition from Cassie-Baxter to Wenzel state is calculated by

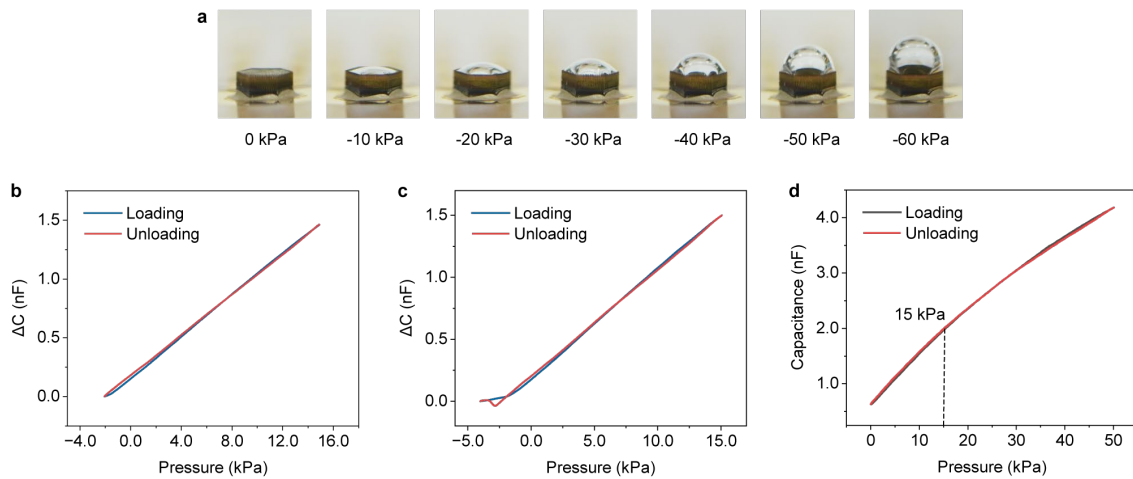
$$h_c > R \left(1 - \sqrt{1 - \frac{l^2}{4R^2}} \right) \quad (Eq.S12)$$

where h_c is the critical pillar height, l is the pillar pitch distance, R is the radius of the curvature based on the pressure which is equal to

$$R = \frac{2\sigma_{la}}{P_{lip} - P_{air}} \quad (Eq.S13)$$

σ_{la} is the surface tension of the interface between liquid and air, $P_{lip} - P_{air}$ is the pressure difference between water and air. For the eAir design, the length of the added pillars (from pillar tip to the mesh support, 300 μm) is significantly larger than the critical height, h_c . An increase in pillar height and a decrease in pitch distance will reduce the wetting critical height, and increase the longevity even under fluctuating pressure³⁷. Although long-term air dissolution remains a problem, eAir still show promising mechanical and electrical stability during the cyclic (**Fig. 4g**) and turbulence tests (**Fig. 4h**). Further investigations and optimizations on the device stability are still worth for future research.

2.10. Supplementary Note 10 eAir under Negative Pressure and High Pressure



Supplementary Figure 13 | eAir under negative pressures. **a**, Photos of air bubbles on the eAir device structure under a series of negative pressures. **b**, Sensing performance of eAir within the pressure range of -2 kPa to 15 kPa. **c**, Sensing performance of eAir within the pressure range of -4 kPa to 15 kPa. **d**, Sensing performance of eAir within the pressure range of 0 to 50 kPa.

The air entrapped in eAir remains on the device under negative pressure as low as -60 kPa and does not detach. As shown in **Supplementary Figure 13a**, we subjected the eAir device to various negative pressures and observed a noticeable bubble protrusion at the top of the eAir structure when the pressure was reduced to -10 kPa. As the pressure decreased further, the size of the bubbles increased; however, the bubble's edge remained pinned to the top edge of the structure's wall even when the pressure reached -60 kPa, the lowest pressure our testing setup can achieve. This negative pressure is significantly lower than the claimed operating range of 0 - 15 kPa for eAir.

Moreover, we found that eAir devices maintain the same sensitivity and linear response as in the ranges of 0 - 15 kPa even when pressure was as low as -2 kPa (**Supplementary Figure 13b**). This is because, at zero pressure, the dome tip pillars were already partially penetrated in water. Under slight negative pressure, the water-air interface moves outward, but it does not detach from the pillars until the pressure falls below -2 kPa. However, when the pressure reached to -4 kPa, the water located at the central position of the structure started to detach from the pillars, generating an air bubble that is “out” of the inner structure and causing the device to cease exhibiting a linear response to pressure (**Supplementary Figure 13c**).

eAir also responds to pressures exceeding the stated 15 kPa. As shown in **Supplementary Figure 13d**, eAir can respond to pressures as high as 50 kPa. It could potentially respond to even higher pressures, but due to the limitations of our testing setup's pressurizing capability, we only measured up to a maximum pressure of 50 kPa. eAir exhibited low hysteresis within 0 - 50 kPa and maintained a linear relationship between capacitance and pressure within the 0 - 15 kPa range, but as the pressure continues to increase, the sensitivity gradually decreases, exhibiting undesired performance of non-linearity. This is because as the pressure increases, the air becomes increasingly difficult to compress. The same change in pressure results in a

smaller change in volume of air and a reduced change in the water-electrode contact area with increasing pressure.

2.11. Supplementary Note 11 Factors Affecting the Responses of eAir

The influences of different factors were explored and discussed to show how they affect the performance of eAir including the device testing orientation, temperature, electrical frequency, pressure changing rate, oil coating amount, and oil viscosity. Capacitance response of eAir were tested at different facing orientations against gravity. eAir maintains high linearity, low hysteresis, and consistent sensitivity performance with different facing orientations since its internal spacings were much smaller than capillary length (2.71 mm at room temperature), thus it maintains consistent performance across tests with different orientations (**Extended Data Fig. 9b**). For the influence of temperature, eAir showed an increasing sensitivity with temperature, but still preserved high linearity and low hysteresis at different ambient temperature (**Supplementary Figure 17**). For the test of the test signal frequency dependency, 1 kHz and 10 kHz were also tested except for 100 kHz (**Supplementary Figure 18**). The pressure changing rate is also considered. The sensitivity was not affected by the different rates. However, the linearity and hysteresis exhibit a trend of deterioration with the increasing pressure changing rate (**Supplementary Figure 11**), since the surface drag force will increase with the flow velocity relative to the object³⁸. On the contrary, lower viscosity of the lubricants could contribute to a drag reduction at the surface³⁹ and reduce the hysteresis (0 - 10 kPa, **Supplementary Figure 19**), thus 5 cSt silicone oil was chosen as the optimal lubricant. Moreover, the oil amount also affects the sensing performance that the increasing coating volume optimize the linearity and hysteresis with a sacrificial of sensitivity (**Supplementary Figure 20**), we chose 5 μL of the diluted oil as the optimal amount for surface lubricating for eAir.

3. Supplementary Videos

3.1. Supplementary Video 1 Existence of Air Layers on Underwater Lotus Leaf Surface

This video shows the existence of air layers trapped on underwater lotus leaf surface. When a superhydrophobic lotus leaf is immersed in water, it appears a shiny silver surface. This is because a thin layer of air is trapped on its surface textures. From the optical microscope image, an obvious light reflection of the water-air interface can be observed. The other lotus leaf was treated with O₂ plasma. The surface became hydrophilic. When the leaf was immersed in water the surface textures were fully wetted. There was no silver reflection observed even through the optical microscope as there was no trapped air layer on the leaf surface.

3.2. Supplementary Video 2 Structure Optimization from Hexagon to Hexagon-Walled Pillar-Array Structures for Performance Improvements

This video illustrates the cross-section view of wetting states differences between single hexagon structure and hexagon-walled pillar-array structure. For the hexagon structure, the initial state liquid-air interface appears slightly sagged. The liquid-air interface continues to sag downwards when an external underwater pressure is applied. In the small pressure region (*Region A*), the dynamic contact angle increases with the increasing pressure. However, the contact lines are pinned at edges and do not move. No increase in liquid-electrode contact area and corresponding capacitance show at *Region A*. As a result, for the device with hexagon structure, there is a forward threshold pressure, P_{FT} , in terms of sensing performance. When the dynamic contact angle reaches the corresponding advancing angle, the contact lines start to move, and the device shows a linear sensing response to pressure. Ideally, the transition between the forward threshold and the linear response region is sharp, but the real device performance shows a gradual transition. This can be attributed as: i) the real surface can hardly provide a perfectly uniform wetting property, so the movements of contact lines can be inconsistent within the same hexagon chamber and across different chambers in the array; ii) the hexagonal geometry allows the contact lines to curve under pressure with different sink-depth field, so the contact angle at different positions may reach the advancing angle at different times, thus the transition from *Region A* to *Region B* is gradual. In summary, for devices with hexagon structures, forward thresholds (P_{FT}) are exhibited, caused by the pinning effect of contact lines movement.

To minimize P_{FT} and improve the linearity of the device performance except applying slippery surface, a pillar array is added inside the hexagon structure. In the small pressure region (*Region A*), similarly, the dynamic contact angle on the hexagon wall increases without contact lines movement. Nevertheless, the single pillar shows a much shorter contact line length which offers a much smaller capillary pressure and weaker pinning effect. During the liquid spreading process onto the devices, there is additional pressure applied on the pillars. Thus, in initial wetting state, the pillars already pierce into the sagged liquid-air interface in some depth causing an initial contact area between liquid and solid pillars. The contact area continues to increase at small pressures (much smaller than the forward threshold of a device without pillars). And the addition of pillar array also increases the sensitivity at initial pressures of loading and unloading, resulting in near zero-thresholds. Considering the printing and fabrication limitation, such as the effective pillar array density, structure strength, stability, and printing time, we chose a large dimension of hexagon structure (side length: 615 μm , height: 520 μm) as the outside wall and add pillar array with an optimized density (center-to-center spacing: 50 μm) inside. The overall performance of hexagon-walled pillar-array devices show a negligible threshold pressure and extremely high linearity. The optimization of the structure design achieves an optimal pressure sensing performance (**Extended Data Fig. 9a**), and more possible structural engineering for further improvements of underwater pressure sensors is also expected in future research.

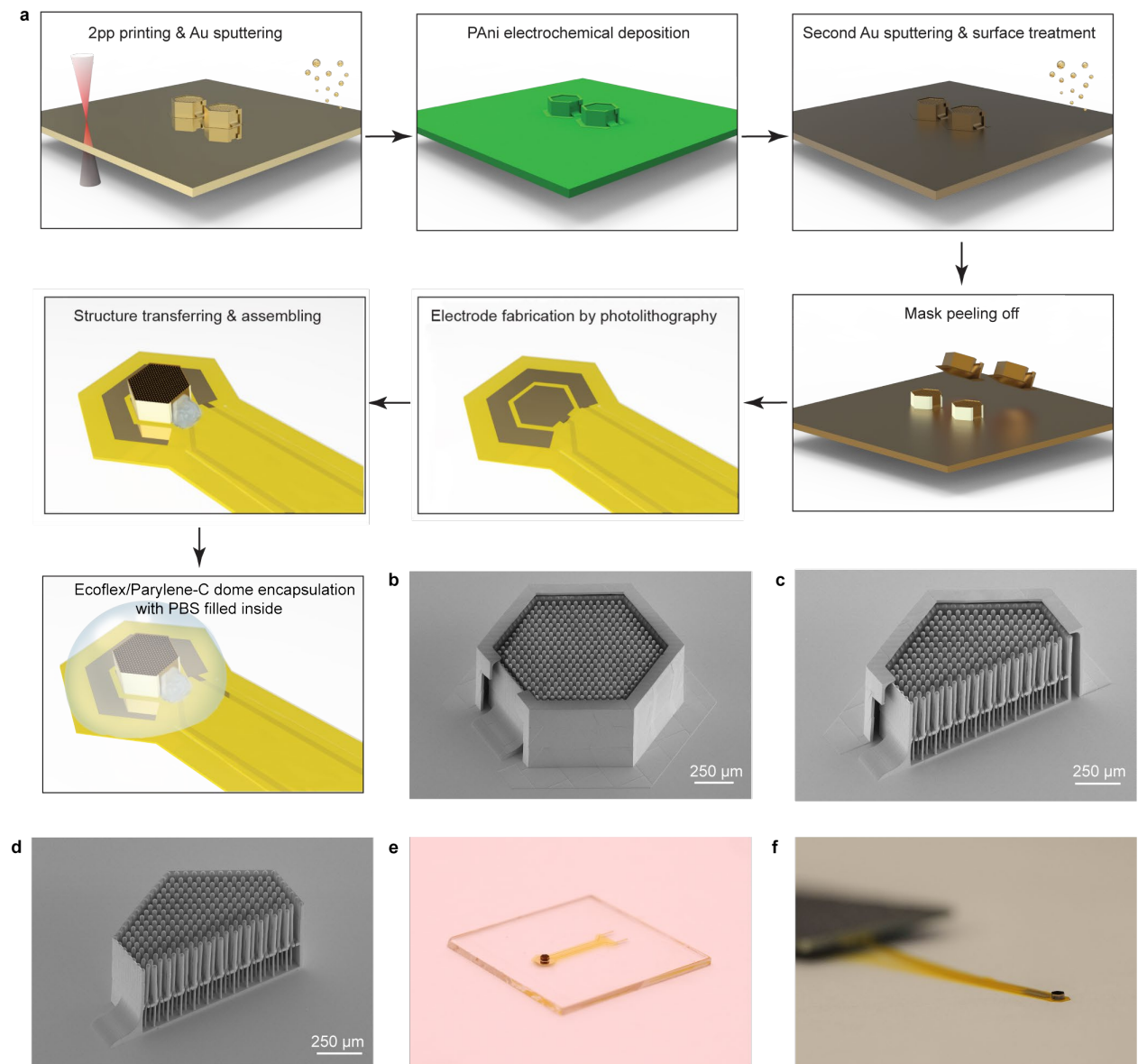
3.3. Supplementary Video 3 Performance Test of eAir under Turbulent Flow

This video shows a device tested in a turbulence flow. The turbulence flow was generated by a magnetic stirrer with a stir bar, and the external pressure was simultaneously changed between 0 to 10 kPa cyclically using a customized setup as described in **Methods**. The performance remains stable under the stir speed in the range of 0 - 1,000 rpm.

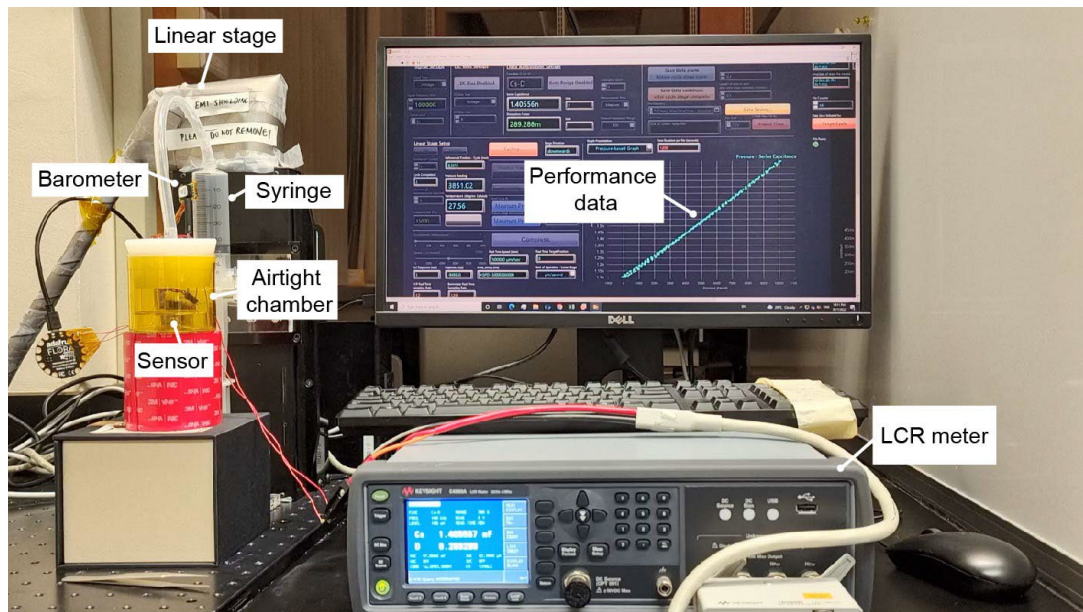
3.4. Supplementary Video 4 Laparoscopic Grasper with eAirs

This video displays a laparoscopic grasper equipped with an array of three eAir devices for tactile feedback during a simulated laparoscopic surgery. The sensorization details are described in **Methods**. In this video, we demonstrated three operations of grasping “tissue” in sequence. First, we grasped the artificial tissue with incremental grasping depths, resulting in different contact position, the three eAir devices could tell the exact contact position between the grasper jaws and the tissue, allowing us to adjust the grasping position accordingly. Second, we grasped the tissue with a light force, and then pulled the grasper to move the tissue. The response from eAirs revealed that the receptors lost contacts one after the other, indicating that tissue slippage occurred due to the insufficient grasping force. Finally, we grasped the tissue with greater force and shook the grasper. Small variations in eAir readings were observed without any contact loss, indicating that the tissue was firmly grasped by the jaws and the tissue slippage was avoided.

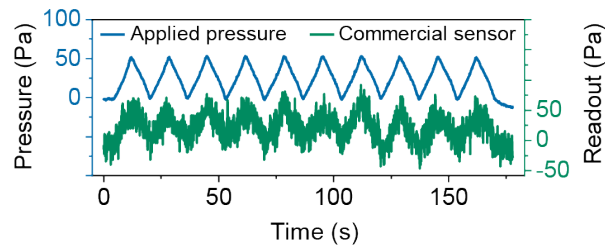
4. Supplementary Figures



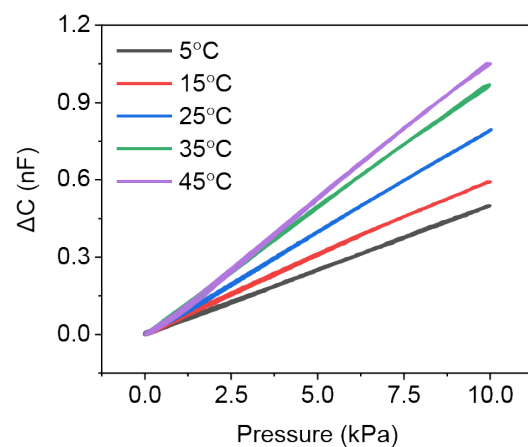
Supplementary Figure 14 | Fabrication flow and images of eAir. **a**, The fabrication flow of eAir devices. **b-d**, SEM images of device structure with shadow mask cover, half device structure with shadow mask cover, and half device structure without shadow mask cover, respectively. The mask cover was designed to reduce the exposed area on the outside of devices during sputtering and form the pattern of electrode for wiring. The mask cover was removed after surface treatment. **e**, Photo of a device mounted on glass substrate. **f**, Photo of a device mounted on flexible polyimide substrate.



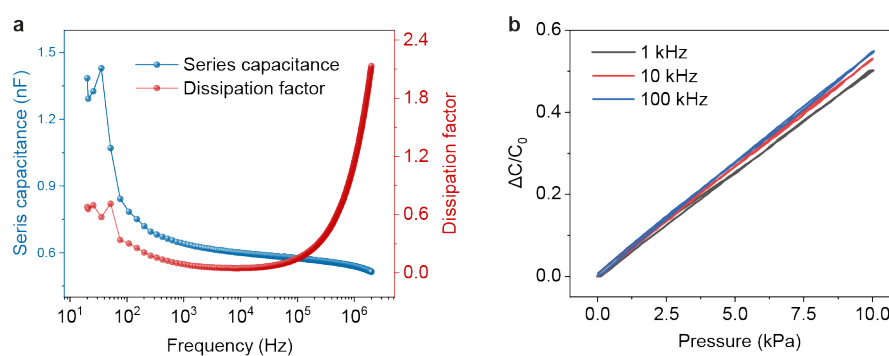
Supplementary Figure 15 | Test setup for pressure sensing performance characterization.



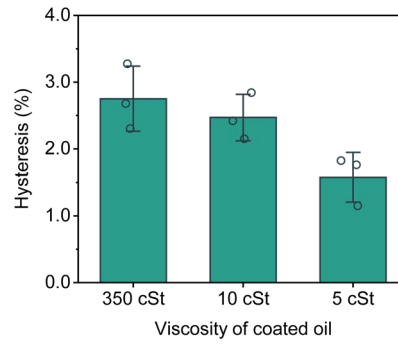
Supplementary Figure 16 | Comparison of cyclic test with a commercial sensor (IntraSense) in the range of 0 to 50 Pa. The readout of the commercial sensor was obtained with the official evaluation module with a Wheatstone bridge to amplify the output signal. Despite the use of the Wheatstone bridge circuit, significant noise can be seen.



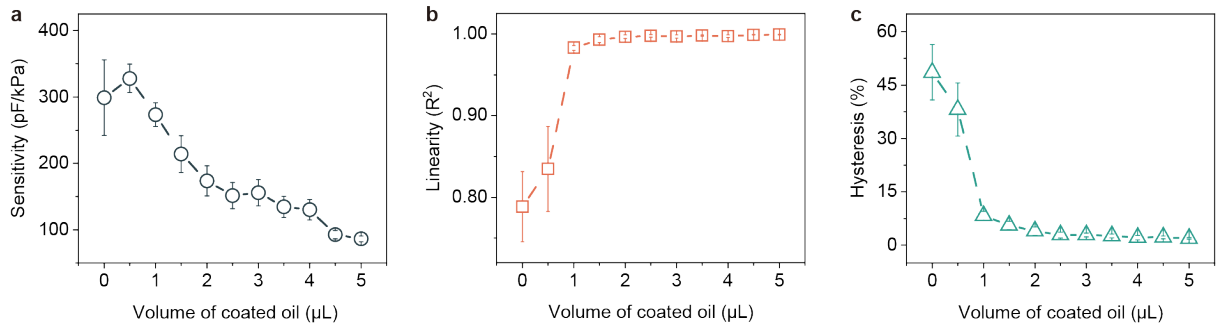
Supplementary Figure 17 | Capacitance response of eAir under different temperatures. eAir maintain linearity and low hysteresis performance over the 5 °C to 45 °C range. The devices were tested in 1× PBS with cyclic pressure applied.



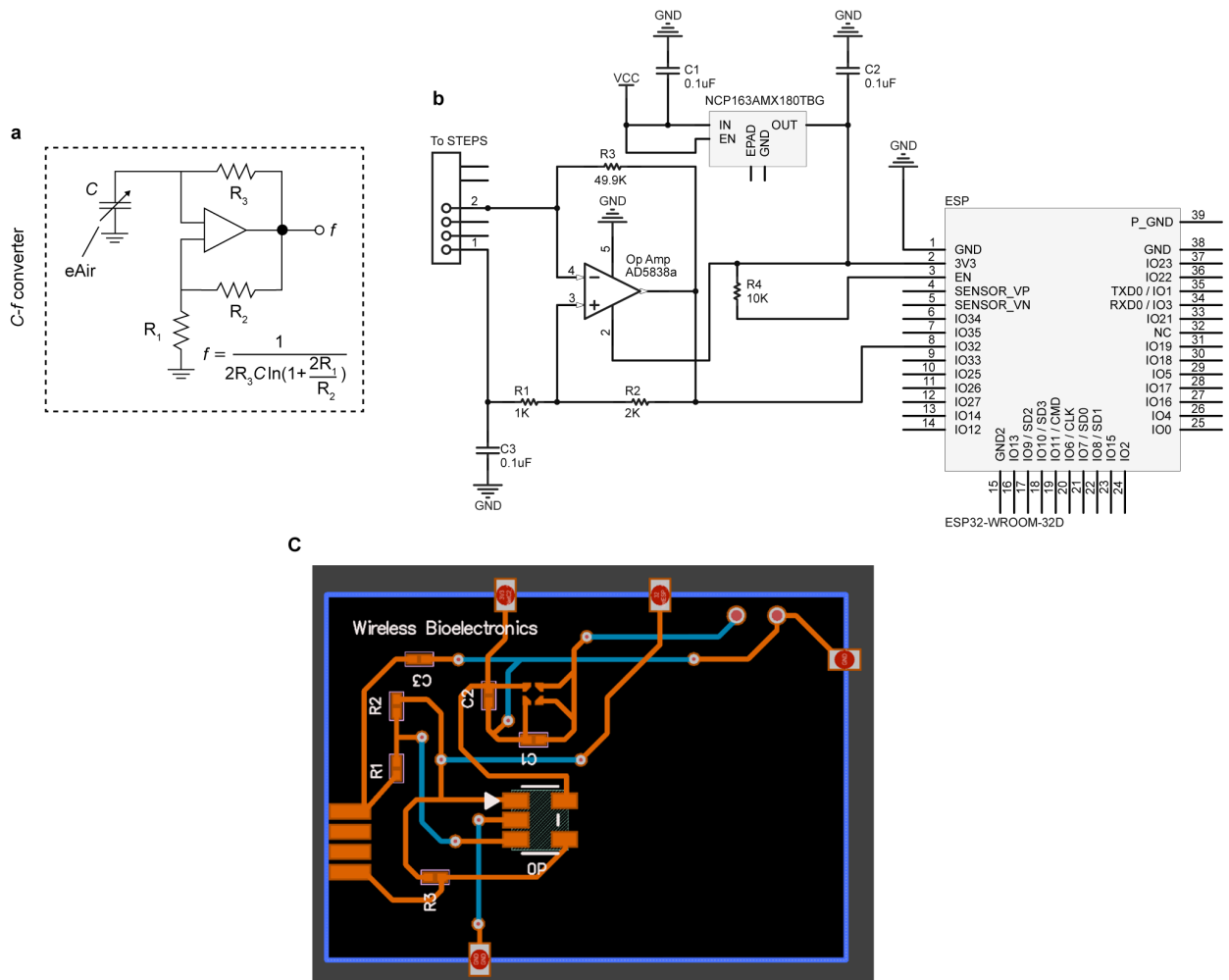
Supplementary Figure 18 | Effect of frequency on eAir performance. **a**, Test signal frequency sweep from 20 Hz to 2 MHz of an eAir without external pressure applied. **b**, Capacitance response of eAir tested at different frequencies with cyclic pressure applied.



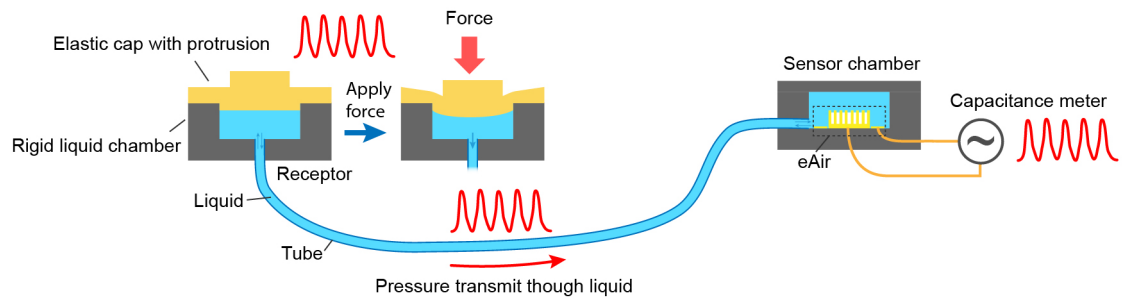
Supplementary Figure 19 | Effect of viscosity of coated oil on hysteresis performance of eAir. Devices were coated with the same volume of oils (5 μ L, 0.1% v/v silicone oil diluted in n-heptane) and tested at the same pressure. Data are represented as mean values $\pm$ s.d. (3 samples) with corresponding data points overlapped.



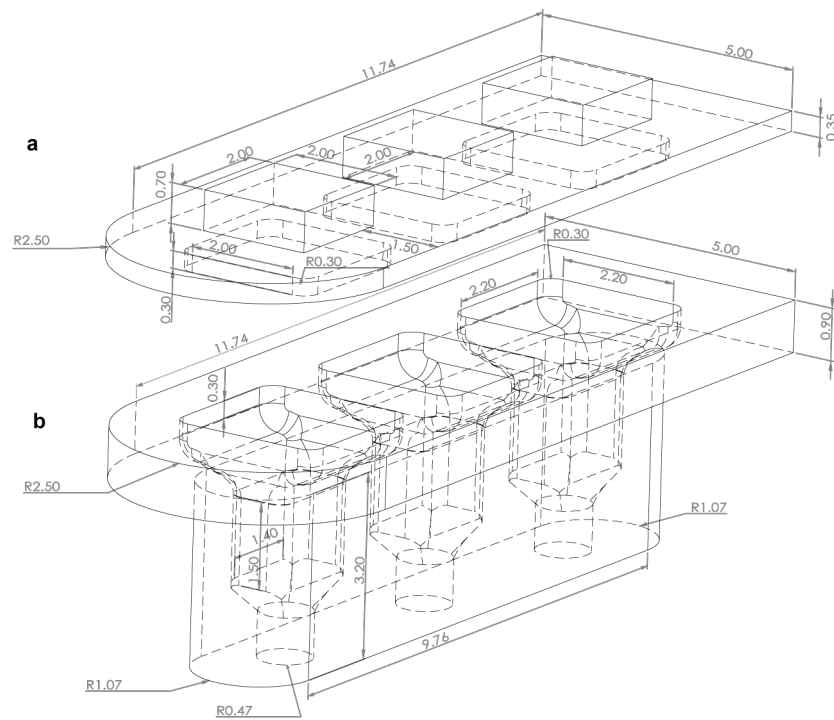
Supplementary Figure 20 | Effect of volume of coated diluted oil on sensing performance of eAir. a-c, Sensitivity, linearity, and hysteresis vary with the volume of coated diluted oil (0.1% v/v of 5 cSt silicone oil diluted in n-heptane). All three performance parameters tend to be optimal after 5 μL of the diluted oil was applied. Data are represented as mean values $\pm$ s.d. (5 samples).



Supplementary Figure 21 | Wireless module circuit design. a, Schematic of the wireless sensing circuit that encodes varying pressure signal into wirelessly detectable frequency signal. b, Schematic circuit design of the wireless module. c, PCB layout of the oscillation circuit.



Supplementary Figure 22 | Working mechanism of eAir for remote force sensing. The applied force presses the protrusion, deforming the elastic cap and squeezing the liquid in the rigid chamber. The liquid then flows into the sensor chamber through the tube, compressing the air within the eAir device and producing a capacitance response to the applied force. Since this process is reversible, eAir can detect the force being applied to the receptor from a location other than where the force is being applied.



Supplementary Figure 23 | Dimensions of receptors. a. Elastic cap with protrusions. **b.** Rigid liquid chamber. The unit used here is millimeters.

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