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Multiphasic interfaces enabled aero-elastic capacitive pressure sensors

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Leveraging the air-trapping features of the lotus leaf, recent advancements in pressure sensors have introduced a unique aero-elastic capacitive pressure sensor using a gas-liquid-liquid-solid multiphasic interface. This innovation significantly enhances pressure sensitivity and reliability in challenging liquid environments due to its minimal hysteresis, excellent linearity, and negligible threshold effects. It promises to enable sensitive and reliable intra-body monitoring and improve surgical precision where biomechanical pressure sensing is necessary.

The advancement of pressure sensor technology has been a cornerstone in scientific and technological progress, playing a crucial role in environmental monitoring and healthcare.[1–3] This evolution has been driven by the goal of emulating the exceptional sensitivity and adaptability found in biological systems, achieved through advances in materials engineering and structural design.[4] Although traditional sensors have provided valuable insights, they often encounter difficulties in fluid environments where complex forces compromise their sensitivity and reliability. The development of sensors has aimed at enhancing linearity, minimizing hysteresis, and improving durability under various conditions.[5] Initial models, grounded in solid-state mechanics, offered robustness but lacked the necessary sensitivity for complex applications. Subsequent developments introduced new materials and designs to detect subtle pressure changes, yet faced challenges in liquid environments due to viscosity, density, and flow dynamics impacting sensor performance.[6]

Addressing these challenges, recent breakthroughs have adopted bioinspired approaches, leveraging the sophisticated evolutionary adaptations of natural systems. The eAir sensor, inspired by the microtextured surface of the lotus leaf, known for its exceptional non-wetting and air-trapping properties, marks a significant leap in liquid environment pressure sensing.[7] This sensor introduces a paradigm shift with its multiphasic interface that combines solid, liquid, and gas phases, creating an aero-elastic surface in synthetic systems. By mimicking the lotus leaf's efficiency in trapping air, it achieves unparalleled responsiveness to pressure changes. This sensor, characterized by ultra-low hysteresis and enhanced sensitivity, overcomes the limitations of previous technologies. Its precision in detecting minor pressure variations in fluidic environments, coupled with its high linearity and reduced threshold effects, expands its potential in critical biomedical applications, such as intra-body pressure monitoring and improving tactile feedback in surgical tools.

At the core of the sensor is its gas-liquid-liquid-solid multiphasic interface, inspired by the lotus leaf's air-trapping ability (Figure 1A). This interface features arrays of hexagon-shaped pillars that mimic the microscale structures of lotus leaves, facilitating water repellency and maintaining an air layer known as a plastron. This layer not only insulates the sensor but also dynamically adjusts the sensor's capacitance with changing pressures. The sensor distinguishes itself by operating without a threshold, exhibiting minimal hysteresis, and maintaining a remarkably linear response (Figure 1B). These characteristics are crucial for accurately handling complex pressure situations in fluid dynamics and medical applications. The design emulates the lotus leaf's efficient motion, allowing for swift and precise

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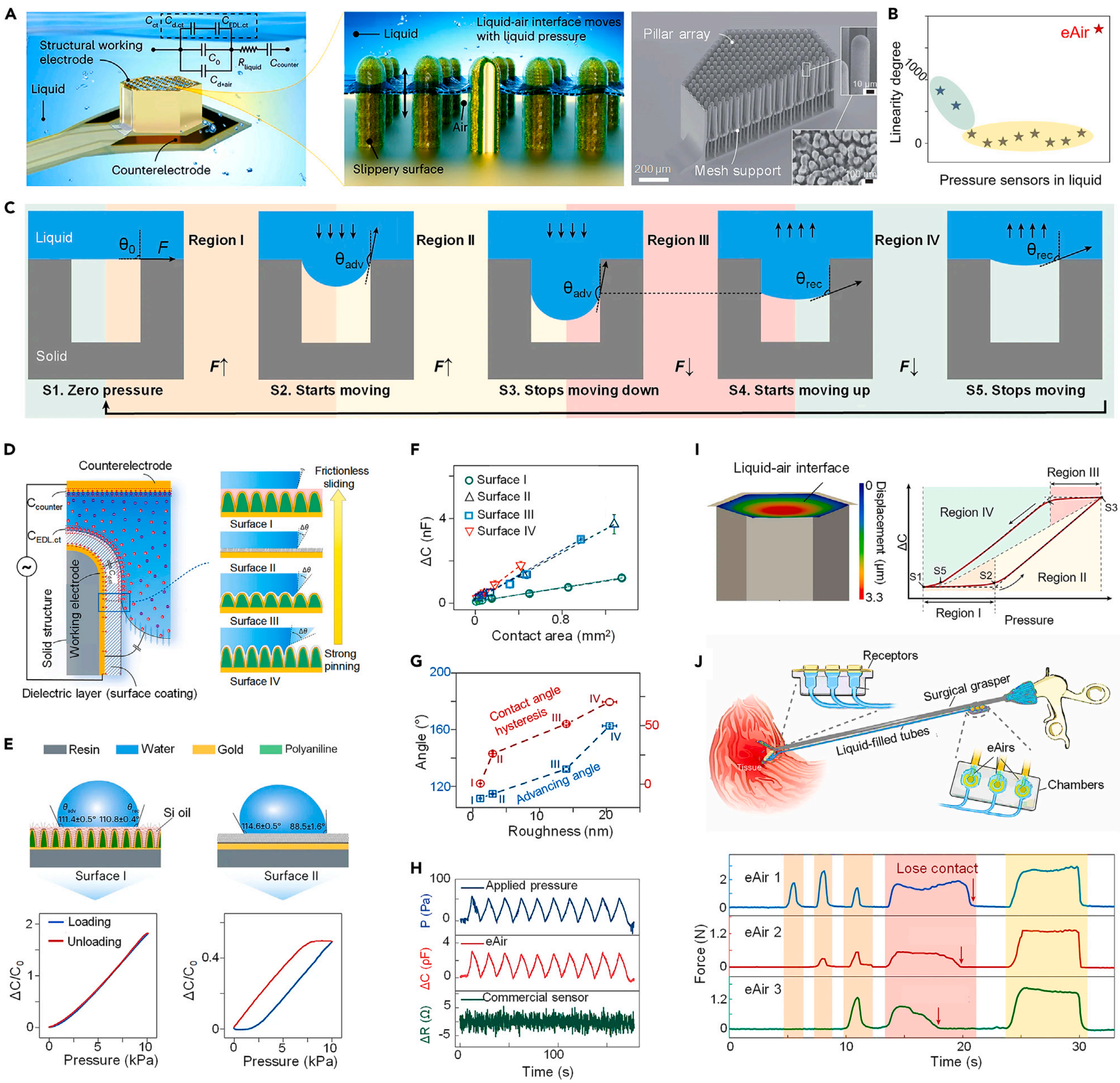

Figure 1. The aero-elastic capacitive pressure sensor working in aquatic environments

(A) Structure of the eAir device. It features nanostructured, lubricant-infused hexagonal pillars acting as electrodes, which alter capacitance in response to liquid pressure. An inset provides a circuit diagram highlighting various capacitance components.

(B) Linearity degree comparison between eAir and other sensors within liquid environments, focusing on the accuracy of pressure changes in predicting signal responses. Green, reported sensors with high linearity. Yellow, common liquid sensors with low linearity. The eAir sensor (marked with a red star) exhibits nearly ideal predictive capabilities.

(C) Liquid dynamics in hexagonal spaces. The stages (S1–S5) show liquid movement or stasis, propelled by capillary forces.

(D) Capacitor structure of the eAir device. From surface IV (strong pinning) to I (frictionless sliding), friction reduction enhances the sensor's response.

(E) Wetting characteristics of advancing (θ_{adv}) and receding (θ_{rec}) contact angles and device performance.

(F) Capacitance variations relative to contact area across hexagonal arrays with surfaces I–IV, showcasing a pronounced linearity in the response.

(G) Correlation of roughness to contact angle hysteresis and advancing angle for surfaces I–IV.

(H) Comparative performance of the eAir sensor against a commercial sensor, revealing the eAir sensor's superior signal-to-noise ratio.

(I) Pressure simulation in a hexagonal chamber. Liquid pressure causes interface bending without expanding the contact area when the contact lines remain fixed at the edges.

(J) A surgical grasper outfitted with eAir sensors for detecting tissue pressure. Force data from the eAir sensor captures different gripping actions on artificial tissue over time.

pressure adjustments, significantly improving upon the delayed responses and hysteresis typical of traditional sensors. This operational excellence results from the sensor's replication of the lotus leaf's near-friction-free movement, ensuring an immediate and accurate response to pressure changes.

The sensor translates mechanical pressures into electrical signals through wetting and dewetting processes within its hexagonal chambers (Figure 1C), ensuring accurate and reliable measurements by modifying the liquid-air interface's contact area with electrodes. This capacitance change, directly tied to the applied pressure, enables precise pressure sensitivity adjustments through controlled surface roughness and chemistry, facilitating a smooth transition between responsiveness states. Furthermore, enhancing the sensor's performance with specific surface roughness transitions it from strong liquid pinning to effortless sliding (Figure 1D), underscoring the critical role of nanoscale surface control in accuracy. The comparison of silicone oil and octadecyltrichlorosilane (ODT) coatings on the sensor's accuracy highlights the impact of surface-wetting properties on pressure detection, especially regarding response linearity and hysteresis (Figure 1E).

The eAir sensor leverages surface engineering to improve its interfacial wetting properties, boosting sensitivity and accuracy by linking increased contact area with changes in capacitance (Figure 1F). This approach exemplifies the sensor's precision optimization through controlled hysteresis, enabling quick responses and consistent repeatability. Figure 1G illustrates the relationship between nanoscale surface roughness and wetting characteristics, revealing that a decrease in roughness leads to a reduction in both the advancing angle and hysteresis. This underscores the critical role of surface topography in improving the sensor's precision and reliability. Comparative analyses with a commercial sensor reveal this sensor's superior performance in terms of linearity, sensitivity, and durability (Figure 1H), suggesting it could exceed existing fluid environment technologies. The sensor's dynamic pressure response demonstrates the deformation of the liquid-air interface within hexagonal chambers and its effect on capacitance (Figure 1I). The sensor's behavior can be described by the equation $C(P) = \frac{A\epsilon_{air}}{d_{air}(P)} + \frac{A\epsilon_{liquid}}{d_{liquid}(P)}$, where A denotes the electrode interface area for each layer, and P influences the thicknesses of the air and liquid layers, $\mathbf{d}_{air}(P)$ and $\mathbf{d}_{liquid}(P)$, respectively. This formula adjusts the effective dielectric constant, ϵ, between the electrodes. This indicates the sensor's adeptness in detecting pressure variations, highlighting its accuracy, sensitivity, and ability to revert to its initial state after deformation. Its integration into surgical instruments, such as graspers connected by liquid-filled tubes (Figure 1J), enables the sensor to transform mechanical forces into measurable pressure changes. This capability offers invaluable real-time tactile feedback, enhanced by an air entrapment mechanism that assures increased sensitivity and minimal hysteresis for dependable, repeatable outputs. Further enhancements in pillar spacing and the application of lubricant-infusion techniques can improve the nanostructured surface's slipperiness, which is crucial for the sensor's quick reset after decompression.

The eAir sensor's bioinspired design incorporates an elastic air layer and a gas-liquid-liquid-solid multiphasic interface, drawing inspiration from the lotus leaf's air entrapment and ultra-slippery surface. This design achieves unparalleled precision and sensitivity in pressure detection through a near-friction-free motion of the contact line. It avoids liquid pinning by utilizing a pillar array infused with lubricants to create an ultra-slippery interface. Nano- and microscale-structured electrodes within hexagonal chambers are optimized for capacitance modulation in response to pressure changes, ensuring repeatability, sensitivity, and a consistent response that outperforms traditional pressure sensors. However, the integration of multiple processes into a single cohesive unit presents several challenges: (1) Enhancing the sensor's performance in complex liquid environments, characterized by variable pressures and flow conditions, requires a comprehensive understanding of the dynamics of capillary forces and the stability of the entrapped air layer under fluctuating pressures.[8] This requires advanced simulation and experimental approaches to refine the sensor's responsiveness and reliability in these environments. (2) Mimicking the lotus leaf's water repellency in the sensor's design—by maintaining an air layer—poses a challenge in ensuring uniform control over its surface-wetting characteristics for consistent wetting and dewetting.[9] An in-depth investigation into nanostructures and coatings is essential to ensure a uniform response to pressure variations. (3) Addressing forward threshold effects and hysteresis, which significantly impact accuracy, requires a redesign of the microstructural architecture. This is crucial for enabling a more immediate and balanced response to pressure changes.[7] (4) Embedding the sensor in surgical tools, such as laparoscopic graspers, without compromising sensitivity or durability under operating conditions, is a complex challenge.[10] It underscores the importance of advancements in materials science, fluid dynamics, and biomedical engineering to overcome these hurdles.

The eAir sensor represents a paradigm shift in pressure sensing technology by seamlessly integrating nanotechnology and bioinspired design principles. Mimicking the lotus leaf's exceptional air-trapping capabilities, this innovative pressure sensor introduces a unique gas-liquid-liquid-solid multiphasic interface that overcomes the limitations of traditional sensors in liquid environments. Its near-friction-free motion of the contact line, facilitated by the hexagonal pillar array and lubricant-infused ultra-slippery interface, enables ultra-low hysteresis and remarkably high sensitivity. This breakthrough performance, characterized by minimal threshold effects and excellent linearity, holds immense potential for critical applications demanding precision. From enhancing intra-body monitoring to providing invaluable tactile feedback in surgical instruments, the eAir sensor paves the way for advancements in healthcare and beyond. While the integration of multiple processes into a cohesive unit presents challenges, such as optimizing responsiveness in complex liquid environments and ensuring uniform surface-wetting characteristics, further research into micro-/nano-structures and coatings will undoubtedly refine and expand the capabilities of this bioinspired technology.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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