Liquid identification with a mechanical-electric dual-mode strategy

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Accurate liquid identification is crucial for a wide range of applications such as on-site environmental monitoring, point-of-care testing, and food safety.[1,2] Commonly applied analytical techniques including chromatography and spectroscopy offer high precision. However, they are always confined to laboratory settings due to their operational complexity and high cost. Emerging portable devices suffer from limited detection scope, susceptibility to environmental interference, and reliance on target-specific reagents. Hence, there remains an urgent need for the development of advanced sensing strategies with high sensitivity, broad detection capability, and operational simplicity. Triboelectric nanogenerators (TENGs) have shown great promise for liquid sensing by converting interfacial mechanical contact into electrical signals. Recent advances have witnessed progresses in areas such as triboelectric spectroscopy,[3] taste simulation,[4] and heavy metal analysis. However, the identity is encoded in both physical and chemical properties, which is quite difficult to be analyzed with a single-mode signal. Accurately discerning complex liquids based solely on electrical outputs is still a great challenge.

Recently, Wen's group developed a solid-liquid triboelectric sensor (SL-TS) that synergistically integrated droplet mechanics with interfacial contact electrification.[5] The breakthrough lies in the system-level integration and functional repurposing of well-established materials. This commentary delves into its core innovations: the material philosophy, the ingenious signal decoupling mechanism, and the way to resolve inherent ambiguities in conventional sensing.

WORKING PRINCIPLE

Interface engineering for dual-mode function

Inspired by the superhydrophobic microstructure of lotus leaves, Wen et al. first fabricated a ZnO-PDMS composite interface that exploited the "non-Hookean" deformation behavior of liquid droplets together with charge transfer during solid-liquid contact. While both ZnO and PDMS were widely used materials, the prepared PDMS-coated ZnO nano-forest was engineered not merely for superhydrophobicity or high electrical output. Actually, the materials synergistically fulfilled both roles for the critical dual-mode sensing interface. As illustrated in Figures 1A-B, the SL-TS compressed a droplet between a top fluorinated ethylene propylene (FEP)/ITO plate and a bottom ZnO-PDMS/Al plate. A controlled droplet (optimized at 50 μL) was compressed between the plates via a linear motor, triggering two parallel responses. The superhydrophobic surface (contact angle up to 151.9°) was crucial for the mechanical response, ensuring sensitive and reproducible droplet deformation. Concurrently, this material pair enabled an efficient electrical response via contact electrification, where the liquid's chemistry modulated charge transfer and the open-circuit voltage (V_{oc}).

Acquisition of signals

The first signal is the pure mechanical response. As the droplet deformed, a compressive force was generated. For initial device characterization, a high-precision electronic balance measured the droplet's reaction force, providing

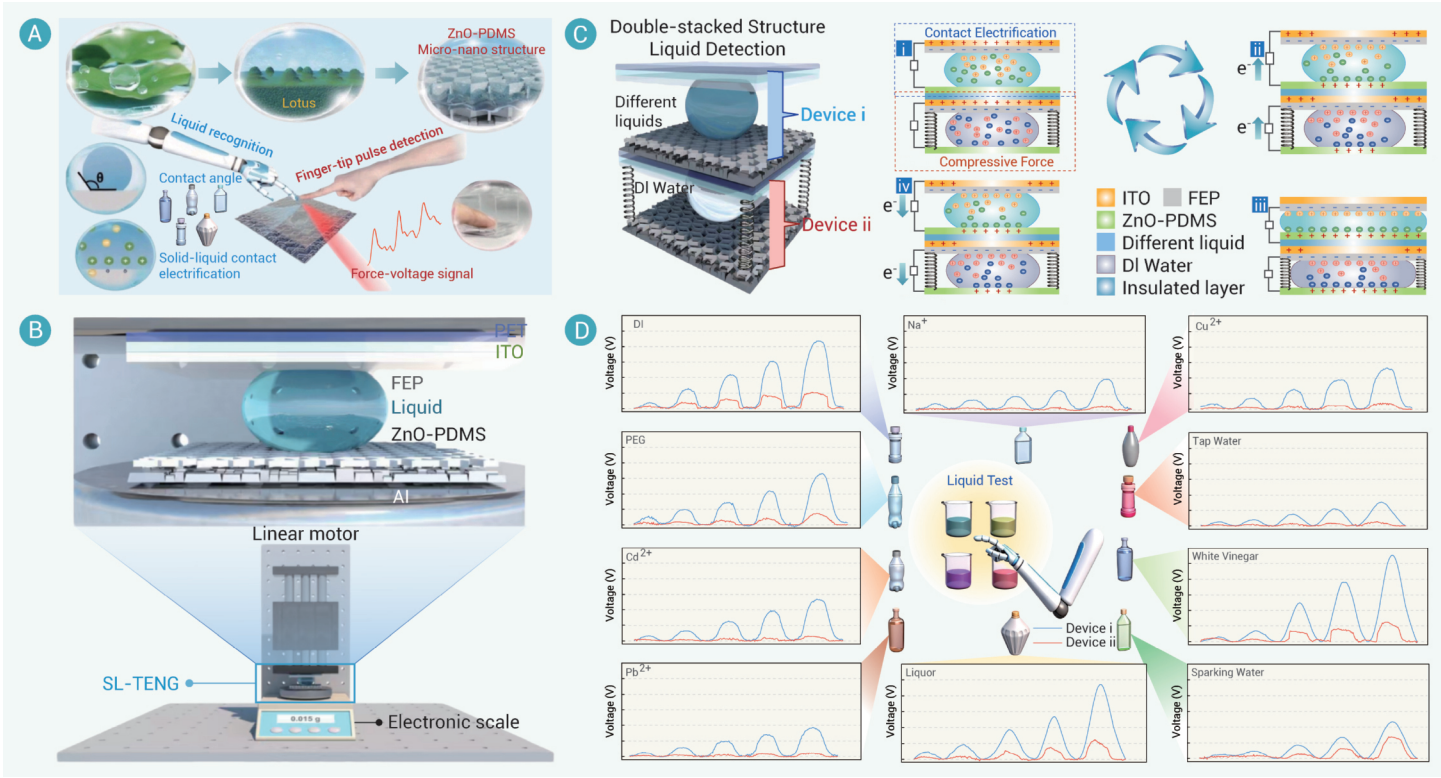

Figure 1. The liquid identification platform based on dual-mode triboelectric sensing strategy (A) Illustration of liquid recognition and fingertip pulse detection based on ZnO-PDMS SL-TS. (B) Illustration of the detailed structure of SL-TS. (C) The working illustration of the SL-TS under compression and release. (D) Two devices' voltage signals of different liquids for the compression displacement of 650, 1000, 1350, 1700, and 2050 μm. Reproduced with permission.[5] Copyright©2025, Springer Nature.

a direct, noise-free measurement to calibrate the exceptional sensitivity of 281 mV/Pa. In the final intelligent system, the external electronic balance was eliminated by a double-stacked structure. The bottom device fixed deionized water, acting as the force transducer. Its constant chemistry ensured any change in its electrical output was solely ascribed to the physical compression force, providing a real-time electrical readout of the mechanical stimulus. The second signal was the electric response. The solid-liquid interface contact electrification, the ion shielding in the liquid, and the difference in electronegativity of solid-liquid interface led to distinct electrical signals for different liquids, establishing a universal and highly accurate liquid identification approach.

SENSING PERFORMANCE

The sensor demonstrated exceptional performance across multiple metrics, establishing its robustness and versatility. It exhibited outstanding stability, maintaining consistent output over 5,000 compression cycles and for 10 days, with reliable operation across a range of temperatures and relative humidity levels. The high reliability provided a solid foundation for its sophisticated sensing capabilities. It generated distinct "fingerprints" for various liquids. Ionic solutions (Na^+, Pb^{2+}, Cu^{2+}, Cd^{2+}) showed unique concentration-dependent trends in sensitivity and saturation voltage. The resolution of 0.1% was achieved for alcohol. Complex daily liquids could be well distinguished. In addition, the underlying contact electrification mechanism (involving electron transfer, ion adsorption, and electric double-layer formation) were elucidated. Furthermore, different liquids generated different electrical signals even under the same compression conditions. The phenomenon was originated from distinct interfacial processes. For instance, the trend variations between Pb^{2+} and Na^+ solutions were attributed to differential modulation of charge transfer and surface tension dynamics by ionic properties (e.g., radius, valence state). The dual-mode strategy crucially overcame single-mode ambiguity. A high-ionic-strength liquid might produce a high electrical signal from strong charge transfer, while a low-surface-tension liquid might produce a similar signal from easy deformation. Thus, a single electrical measurement could not differentiate these scenarios. Wen's approach provided concurrent, independent readouts: the mechanical signal quantified deformation, while the liquid's electrical signal carried chemical information, eliminating possible ambiguity.

INTELLIGENT RECOGNITION VIA A DOUBLE-STACKED STRUCTURE AND DEEP LEARNING

To enable rapid liquid identification without external force sensors, Wen's group designed a novel double-stacked device (Figure 1C). Device i held the test liquid, outputting a hybrid voltage signal. Device ii provided the pure mechanical voltage signal. This configuration allowed simultaneous measurements of two voltage signals: one primarily influenced by contact electrification (from the test liquid) and the other by mechanical force transmission. When a compressive force was applied to the uppermost plane, the resulting pressure drove the upper surface of Device ii downward. Contact electrification generated negative charges on the FEP surface, inducing positive charges on the adjacent electrode. As the top plate descended, the FEP surface became progressively shielded by the droplet, forming an electric double layer that drove a forward current. During the release, reduced shielding led to a lower potential at the top electrode, generating a reverse current until equilibrium was restored. This cyclic process yielded a repeatable electrical signature.

The computational decoupling was conducted by a gated recurrent unit (GRU) network, which was fed with the synchronous hybrid voltage signal and pure mechanical voltage signal. It learned to isolate the mechanical contribution from hybrid voltage signal, extracting a purified "contact electrification fingerprint" of the liquid's chemistry. While single-channel classification gave accuracies of 82% and 59% (electric response and mechanical response), dual-channel feature fusion and decoupling achieved 99% accuracy for ten liquids (Figure 1D), creating a reliable "droplet fingerprint library".

CONCLUSION

Wen's work represents a significant leap in portable sensing technology through system-level innovation. By integrating interface engineering, dual-mode signal decoupling, and deep learning, the SL-TS achieves unparalleled accuracy and sensitivity in liquid identification. Unlike conventional electrochemical sensors that require specific functionalization, this platform offers a universal detection strategy. It also demonstrates how the strategic functional integration of well-established materials can solve persistent sensing challenges. Moreover, the dual-mode measurement overcomes the ambiguity inherent in single-signal TENGs when analyzing complex liquids. Future research may focus on expanding the library of identifiable liquids, miniaturizing the system into a handheld device, and exploring applications in real-world scenarios such as on-site water quality analysis, beverage authentication, and biomedical fluid testing. This technology paves a promising avenue for the next generation of intelligent and highly accurate sensory systems.

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AUTHOR CONTRIBUTIONS

All authors contributed to and approved the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.