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Perspective

Redefining solid–liquid interface probing via contact electrification-driven paradigm

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Solid–liquid interfaces underpin a wide range of physical, chemical, and biological processes [1], where microscopic charge, ion, and molecular dynamics dictate macroscopic system behavior. Probing these interfacial processes is therefore essential for understanding energy, matter, and information transport across phases [2]. A variety of techniques, including optical spectroscopies, scanning probe microscopies, and electrochemical methods, have been developed for this purpose [3]. However, these approaches typically rely on conductive or optically accessible substrates and external instrumentation, limiting their applicability to dielectric interfaces and non-equilibrium conditions. More critically, their steady-state nature prevents direct access to dynamic ion rearrangements and transient charge processes [4], highlighting the need for new strategies capable of operando probing of dynamic dielectric interfaces.

To address these limitations, triboelectric probes based on contact electrification establish a self-powered strategy for interrogating solid–liquid interfaces, enabling direct access to dielectric interfaces that are difficult to probe using conventional techniques. During solid–liquid contact and separation, interfacial electron transfer and ion adsorption induce charge redistribution, generating time-varying electric fields that are directly transduced into electrical signals encoding the instantaneous interfacial state. Unlike conventional approaches, this strategy operates without conductive substrates, external bias, or optical access, and remains effective under complex and non-equilibrium conditions, with intrinsic sensitivity to fast and transient ionic rearrangements, thereby providing a fundamentally different route to probing dielectric interfacial charge physics.

Early studies focused on quantifying net charge transfer during solid–liquid contact (Fig. 1a) [5]. With advances in device design, triboelectric probes have evolved to resolve spatial and temporal charge heterogeneity, enabling mapping of dynamic charge distributions and revealing features such as localized accumulation, asymmetry, and relaxation that are inaccessible to conventional techniques. Beyond charge quantification, contact electrification enables liquid identification through characteristic electrical signatures arising from differences in ionic composition and interfacial interactions (Fig. 1b) [6], and provides sensitive probing of surface properties and wetting behaviors by capturing charge-induced interfacial polarization and molecular interactions (Fig. 1c) [7]. These capabilities further extend to environmental monitoring [8], and they further extend to molecular sensing [9], where triboelectric responses track variations in temperature, hydrodynamics, and chemical composition (Fig. 1d and e). They also extend to biological systems, where interfacial charge modulation induced by biomolecular interactions enables label-free detection of proteins, pathogens, and binding events (Fig. 1f) [10]. Collectively, these studies demonstrate that contact electrification provides a versatile platform for transducing diverse interfacial processes into measurable electrical signals.

Collectively, these advances demonstrate that triboelectric probes via contact electrification provide a versatile platform for probing solid–liquid interfaces. Despite diverse sensing functionalities, the underlying physics can be unified by the dynamic evolution of electrical double layers (EDLs), which govern interfacial charge generation and ion redistribution [11]. Such dynamics are particularly difficult to access on dielectric interfaces due to their transient and non-equilibrium nature. In this context, contact electrification provides a unique operando window by directly transducing EDL dynamics into electrical signals.

Such capability enables dynamic EDL processes to be resolved into distinct stages of evolution, including formation, restructuring, and collapse, which become particularly evident in systems undergoing rapid interfacial transitions. A representative example of EDL formation arises during ice-water phase transitions (Fig. 2a) [12]. As solid ice begins to melt, nanometric liquid layers containing mobile H_2O, H^+, and OH^- species emerge at the interface. The triboelectric signal correspondingly increases with the availability of mobile charge carriers, decreases as the growing EDL screens interfacial charge transfer, and finally stabilizes once a fully developed diffuse layer is established, reflecting the nucleation and growth of the EDL. Under ambient liquid conditions, contact electrification further reveals EDL restructuring governed by electrolyte composition (Fig. 2b) [13]. For symmetric salts such as LiCl, the non-monotonic evolution of the electrical response reflects the transition from incomplete EDL assembly to compact double-layer formation and enhanced electrostatic screening. In contrast, asymmetric electrolytes, including Li[TFSI] and [EMIM]Cl, exhibit polar-

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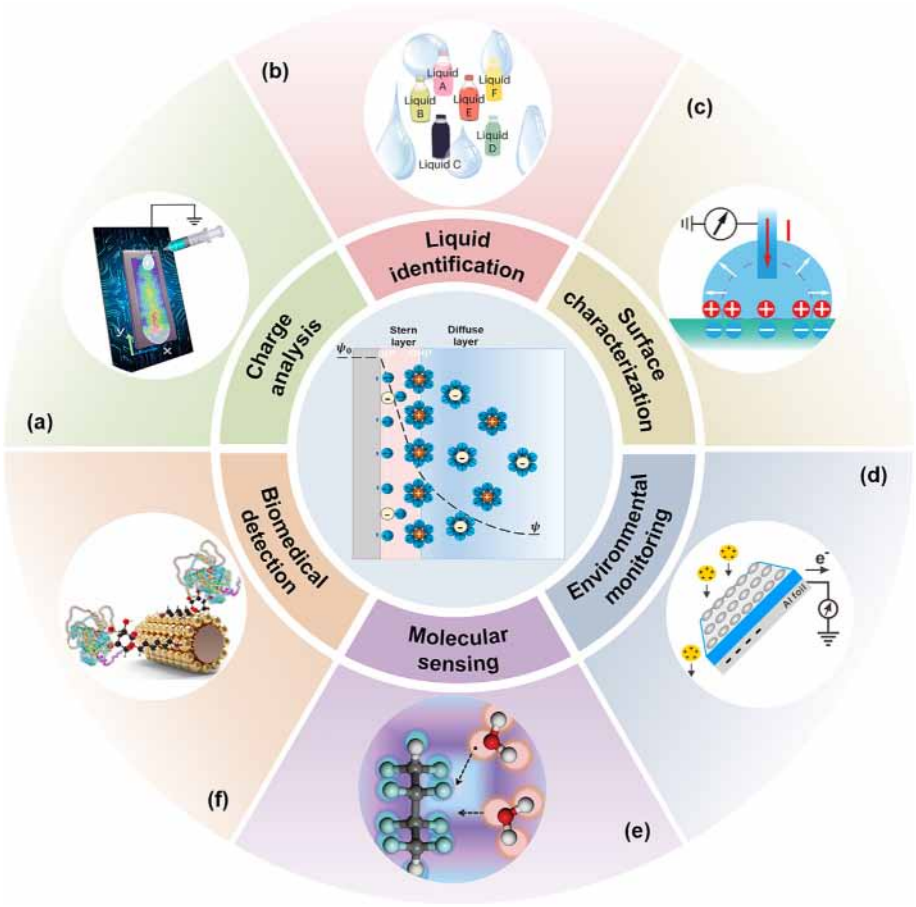


Fig. 1. Typical applications of triboelectric probes at solid–liquid interfaces. (a) Interfacial charge analysis. Reprinted with permission from Ref. [5], Copyright © 2023, American Chemical Society. (b) Liquid identification. Reprinted with permission from Ref. [6], Copyright © 2023, The Author(s). (c) Surface characterization. Reprinted with permission from Ref. [7], Copyright © 2024, Wiley-VCH GmbH. (d) Environmental monitoring. Reprinted with permission from Ref. [8], Copyright © 2019, The Authors. (e) Molecular sensing. Reprinted with permission from Ref. [9], Copyright © 2020, WILEY-VCH Verlag GmbH & Co. KGaA. (f) Biomedical detection. Reprinted with permission from Ref. [10], Copyright © 2021, Elsevier Ltd.

ity reversal at high concentrations, a direct signature of EDL charge inversion arising from ion-size disparity, hydration asymmetry, and preferential adsorption within interfacial layers (Fig. 2c) [14]. These observations highlight the sensitivity of triboelectric signals to ion-specific EDL reorganization. Temperature introduces a third regime corresponding to EDL destabilization and collapse (Fig. 2d) [15]. As droplets interact with heated dielectric surfaces, the triboelectric signal exhibits an increase-peak-decrease behavior. While moderate heating enhances molecular mobility and interfacial charge transfer within the EDL, approaching the Leidenfrost temperature leads to vapor-layer formation that suppresses interfacial coupling. The resulting signal collapse reflects the breakdown of the EDL structure, providing a direct electrical signature of EDL collapse. Together, these observations establish triboelectric signals as dynamic fingerprints of EDL evolution across formation, restructuring, and collapse regimes.

Together, these studies establish contact electrification as a bias-free, operando approach for probing dynamic EDL behavior across chemical, structural, and thermal regimes. Crucially, the extracted information lies not in absolute signal magnitudes but in the evolution and characteristic patterns of the electrical responses, which encode key interfacial processes such as ion adsorption, hydration restructuring, electrostatic screening, charge inversion, and thermal collapse. By analyzing these signal dynamics, nanoscale interfacial charge evolution can be translated into physically interpretable macroscopic electrical signals. In this perspective, probing is inherently associated with resolving dynamic interfacial states rather than isolating individual parameters. Contact electrification thus establishes a new experimental paradigm for interrogating non-equilibrium interfacial electrostatics, particularly on dielectric surfaces. This capability enables systematic investigation of EDL formation, restructuring, and instability under diverse conditions, thereby advancing both the understanding and controllability of solid–liquid interfacial charge dynamics.

Despite the emerging capabilities of contact electrification for probing dielectric solid–liquid interfaces, several fundamental challenges still limit its quantitative interpretation and broader applicability (Fig. 2e). These challenges can be broadly categorized into three key aspects. Firstly, the quantitative interpretation of triboelectric signals remains limited. Although triboelectric probes sensitively reflect interfacial dynamics, most studies rely on relative signal variations rather than absolute metrics. The lack of direct calibration between electrical outputs and interfacial parameters, such as surface charge density, ion concentration, and EDL structure, hinders quantitative analysis, calling for well-defined calibration strategies and controlled experimental frameworks to establish quantitative structure-signal relationships. Secondly, decoupling coupled interfacial processes remains challenging. Triboelectric signals originate from the combined contributions of electron transfer, ion adsorption, hydration-shell restructuring, and EDL evolution, making it difficult to isolate individual mechanisms, particularly under non-equilibrium conditions. Addressing this issue requires multi-modal characterization approaches and integrated theoretical-experimental models to dis-

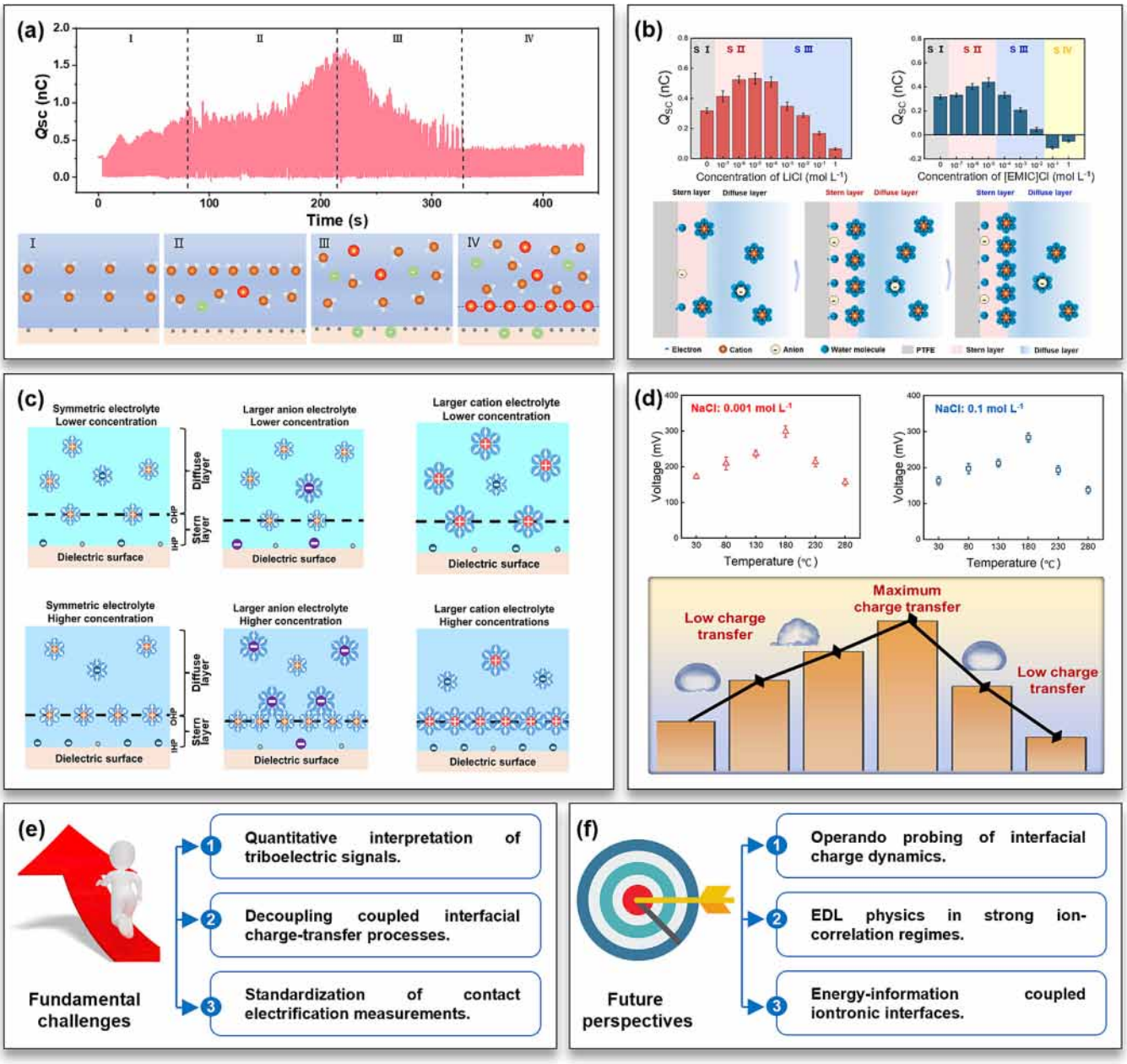


Fig. 2. Characterizing the dynamic behavior of EDLs at dielectric solid–liquid interfaces via triboelectric probe. (a) EDL formation during ice-water phase transition. Reprinted with permission from Ref. [12], Copyright © 2024, Elsevier Ltd. (b) Electrolyte-dependent EDL restructuring. Reprinted with permission from Ref. [13], Copyright © 2024, Wiley-VCH GmbH. (c) Charge inversion in EDL under asymmetric electrolytes. Reprinted with permission from Ref. [14], Copyright © 2025, The Author(s). (d) Thermal destabilization and collapse of EDL. Reprinted with permission from Ref. [15], Copyright © 2024, Elsevier Ltd. (e) Fundamental challenges in quantitative triboelectric probing of dielectric solid–liquid interfaces. (f) Future perspectives of triboelectric probing for dielectric solid–liquid interfaces.

entangle the interplay between different charge-transfer processes. Thirdly, standardization of measurements is still lacking. Strong sensitivity to contact conditions, wetting dynamics, and environmental factors leads to limited reproducibility and comparability across systems. The development of standardized measurement protocols and benchmarking methodologies is therefore essential to ensure consistency and scalability. Collectively, overcoming these challenges will enable the transition of contact electrification from an empirical sensing approach to a quantitative and predictive framework for probing interfacial electrostatics at dielectric solid–liquid interfaces.

Once these fundamental challenges are addressed, contact electrification-based triboelectric probes hold significant promise for future development (Fig. 2f). By directly converting interfacial charge organization into electrical signals, this approach enables access to interfacial electrostatics beyond the limits of conventional electrochemical methods. Several emerging directions can be envisioned. Firstly, triboelectric probing enables operando interrogation of interfacial charge dynamics, as its signals originate from transient charge redistribution during solid–liquid contact, allowing real-time tracking of EDL formation, disruption, and reconstruction in dynamic processes such as phase transitions, droplet impact, frictional contact, and catalytic reactions. Secondly, it further provides a unique platform for exploring EDL physics in strong ion-correlation regimes, including concentrated electrolytes, seawater, and ionic liquids, where classical models break down, and where phenomena such as charge inversion, ion crowding, and asymmetric ion organization can be directly

revealed through interfacial charge redistribution. Thirdly, the direct coupling between interfacial ionic reconfiguration and electrical output opens opportunities for developing energy-information coupled iontronic interfaces, in which dynamic EDL structures function not only in charge separation but also in signal generation and processing. Together, these directions indicate that triboelectric probes may evolve from diagnostic tools into versatile platforms for both probing and engineering dynamic electrostatic phenomena at dielectric solid–liquid interfaces.

In summary, triboelectric probes via contact electrification could establish a fundamentally new approach for interrogating solid–liquid interfaces by directly translating dynamic interfacial charge organization into electrical signals. By framing triboelectric responses as dynamic fingerprints of EDL evolution, this perspective provides a unified physical picture linking interfacial charge transfer, ion redistribution, and electrostatic coupling across diverse environments. Beyond offering operando access to non-equilibrium interfacial processes on dielectric surfaces, this approach redefines probing as the resolution of dynamic interfacial states rather than static parameter extraction. Ultimately, triboelectric probing may evolve from a diagnostic tool into a general platform for probing, controlling, and harnessing dynamic electrostatic phenomena at dielectric solid–liquid interfaces.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2026.04.064.

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