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Electret materials for tele-perception

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Tele-perception is an emerging non-contact sensing paradigm that enables long-range perception and establishes a new interface for intelligent human-machine interaction. Unlike conventional tactile sensing, tele-perception relies on material-generated spatial electrostatic fields, placing unprecedented demands on electret materials capable of generating, retaining and dynamically regulating electric fields. However, current electret research lacks a unified materials framework tailored to tele-perception. Here, we establish a materials perspective that classifies tele-perception electrets into electron-trapping and iontronic electret systems. Electron-trapping electrets generate persistent electrostatic fields through electron trapping and dielectric polarization, whereas iontronic electrets enable adaptive field modulation through ionic migration and space-charge redistribution. We further propose a paradigm shift from passive charge-trapping materials to active spatial electric-field engineering, establishing a unified materials design strategy for next-generation tele-perception toward embodied intelligence, autonomous robotics, and intelligent sensing in complex and dynamic environments.

INTRODUCTION

With the rapid advances in intelligent robotics, embodied intelligence and self-powered sensing technologies, non-contact information acquisition is becoming a key capability for next-generation intelligent systems. Beyond extending the sensing range, tele-perception establishes a fundamentally new human-machine interaction interface by enabling information exchange prior to physical contact.[1,2] Unlike conventional tactile sensing, which relies on direct mechanical interaction, tele-perception employs material-generated spatial electrostatic fields as information carriers to mediate long-range interactions between objects and sensors. Realizing this sensing paradigm requires electret materials capable of generating, retaining and dynamically regulating stable spatial electric fields over extended distances while maintaining robust performance under complex and continuously changing environments. Developing such materials therefore represents a fundamental challenge that extends beyond conventional charge storage, demanding new electret design strategies for long-range electric-field generation, stabilization and modulation.

Recent advances in electret materials have shifted from optimizing individual material compositions to engineering the coupled regulation of charge trapping, dielectric polarization, interfacial structure and ionic transport. Through the rational control of charge generation, trapping, transport and dissipation, together with the spatial distribution of electric fields, electret materials have achieved substantial improvements in field stability, charge-retention capability and environmental robustness. Despite these advances, electret-material research remains fragmented across distinct research disciplines, including triboelectricity, ferroelectric materials, dielectric electrets and iontronics, where material mechanisms are typically investigated in isolation and optimized for specific device architectures. Consequently, a unified materials framework that links electret mechanisms with the functional requirements of tele-perception is still lacking. Moreover, the fundamental relationships between different electret mechanisms and their corresponding materials design principles remain insufficiently understood, limiting the rational development of next-generation tele-perception materials.

From the perspective of electret mechanisms, materials for tele-perception can be broadly categorized into two complementary classes: electron-trapping electrets and iontronic electrets. Electron-trapping electrets generate persistent spatial electrostatic fields by stabilizing electronic charges through trap engineering, dielectric polarization, interfacial defects and molecular design. In contrast, iontronic electrets regulate spatial electric fields through ionic migration, space-charge redistribution and electrical double layer (EDL) formation, or through high-energy ion implantation to establish stable ionic charge states. Although these two classes rely on fundamentally different mechanisms, they share the common objective of generating stable and controllable spatial electrostatic fields that serve as information carriers for tele-perception.

In this Perspective, we establish a unified materials framework for tele-perception electrets based on electron-trapping and iontronic mechanisms (Figure 1). Although electronic trapping, dielectric polarization, and ionic space-charge effects are well-established in classical electret physics, these fundamental mechanisms remain decoupled from practical sensing implementations. This work bridges the gap between canonical dielectric principles and tele-perception material design criteria. We discuss electron-trapping electrets for persistent electrostatic-field generation via trap engineering, and review iontronic electrets that realize dynamic field modulation through ionic redistribution. Such a classification paradigm provides a novel route to evolve conventional passive charge-trapping dielectrics toward advanced active spatial electric-field engineering.

STRATEGIES FOR ELECTRON-TRAPPING ELECTRETS

Electron-trapping electrets constitute one of the most mature electret material platforms, relying on engineered electronic trap landscapes within dielectric matrices to immobilize injected charges and maintain persistent electrostatic fields. The trap depth distribution and dielectric relaxation behavior jointly dictate the magnitude and long-term persistence of space charges stored within polymer-based dielectrets. By controlling trap density, depth and spatial distribution, these materials enable stable field generation required for tele-perception. Current strategies for improving electret performance primarily focus on physical regulation of trap structures and polarization states, including ferroelectric polarization engineering, high-permittivity filler incorporation, interfacial defect design and advanced processing technologies.

Ferroelectric polymers, such as PVDF and PVDF-TrFE, exhibit substantially increased β-phase content and highly ordered molecular dipole alignment after polarization treatment. The internal electric fields arising from spontaneous and remanent polarization can effectively strengthen charge confinement and retention. Building on this principle, the incorporation of high-permittivity ferroelectric fillers, including $BaTiO_3$ and $Pb(Zr,Ti)O_3$, can generate abundant deep traps through interfacial polarization and dielectric mismatch, thereby enhancing local electric-field intensity and increasing the steady-state surface charge density.[3] Advanced manufacturing approaches, including rheological forging, rapid quenching-assisted polarization and precise crystalline-phase regulation, can further optimize polymer-chain orientation and create controllable crystalline-amorphous interfacial defects, enabling the deliberate construction and optimization of deep trapping states.[4] Through the coordinated regulation of polarization, microscopic defects and interfacial structures, physical strategies can promote stable electron trapping and long-term charge storage.

Beyond macroscopic physical regulation, chemical modification provides molecular-level control over polymer electron affinity, trap-energy landscapes and interfacial charge dynamics, offering enhanced structural tunability and processing reproducibility. The incorporation of polar functional groups, including fluorinated, carbonyl and amino moieties, can modulate molecular electron-density distributions and tailor the electron-donating

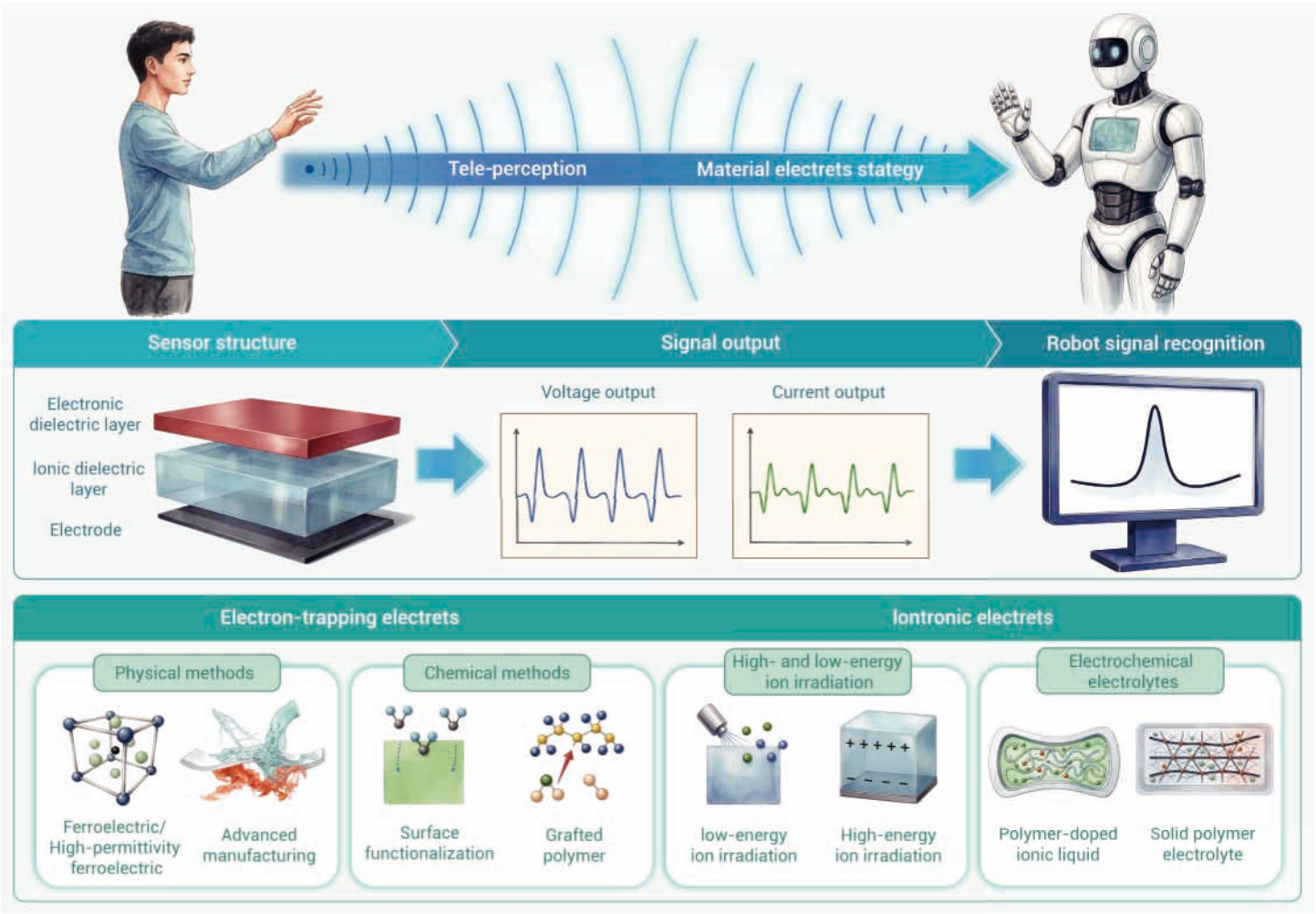


Figure 1. Electret materials for tele-perception systems.

or electron-accepting characteristics of polymer matrices, thereby optimizing triboelectric polarization and electret performance.[5] In parallel, backbone-grafting strategies enabled by techniques such as atom-transfer radical polymerization have emerged as a powerful approach for engineering polymer electrets.[6] By introducing high-permittivity side chains or polar functional segments into polymer backbones, these strategies allow simultaneous regulation of dielectric properties, crystalline structures and trap-energy distributions, resulting in enhanced electron-trapping capability and improved electric-field stability. Compared with conventional surface modification approaches, molecular grafting offers more homogeneous, robust and durable structural control, providing a scalable pathway toward the rational design and fabrication of high-performance electret materials.

Overall, electron-trapping electrets leverage the synergistic integration of physical regulation and molecular-level chemical engineering to achieve multidimensional control over electronic trap structures, spanning macroscopic morphology, interfacial architectures and molecular energy landscapes. These strategies effectively enhance charge confinement while suppressing charge dissipation and recombination, providing a robust materials foundation for the generation of high-density, long-lived and stable electrostatic fields required for tele-perception applications.

STRATEGIES FOR IONTRONIC ELECTRETS

Iontronic electrets represent an emerging class of functional electret systems that fundamentally extend the charge-trapping paradigm beyond conventional electron-trapping mechanisms. By exploiting advances in ion-beam processing and electrolyte-based materials engineering, these systems generate electrostatic fields through ionic space-charge engineering, introducing new degrees of freedom for field generation, stabilization and regulation. Unlike conventional electrets, where charge retention relies primarily on localized electronic traps, ion-based strategies enable the reconstruction of polymer surface chemistry and bulk charge distributions through controlled ion incorporation and retention. High- and low-energy ion irradiation and implantation can establish spatially distributed and structurally stable fixed-charge regions within polymer matrices, producing persistent built-in electric fields with reduced charge dissipation. For example, low-energy ion irradiation can modify polymer surface electronic structures and regulate electron-donating and electron-accepting characteristics, thereby enhancing surface charge accumulation and steady-state charge density.[7] Notably, low-energy ion irradiation is largely confined to polymer near-surface regions: it mainly induces bond scission, radical reactions and surface functional-group reconstruction to tailor surface electronic trap states, and the improved charge-storage capability originates from chemically remodeled surface properties rather than massive foreign ions embedded deep in polymer bulk. Alternatively, Cu^+ ion implantation at a fluence of 1×10^{16} at·cm^{-2} realizes permanent ion trapping and stable space-charge layers in polymers.[8] Selected for its high charge density, heavy mass and negligible passive diffusion within PTFE, Cu^+ generates persistent electrostatic fields without continuous external polarization and forms space charge layer, providing a distinct materials strategy for constructing durable and tunable electret fields. Such ion-derived buried space-charge layers fall within the real-charge electret regime; their long-term stability is dominated by ion confinement, local trapping sites and thermally activated relaxation inside polymer matrices. Distinct from surface-dominated low-energy ion irradiation, high-energy Cu^+ implantation drives heavy Cu^+ species penetrating into polymer subsurface bulk, where the implanted ions are kinetically immobilized to form buried ionic space-charge layers. The heavy mass of Cu^+ suppresses its passive thermal diffusion inside

dielectrics such as PTFE.

Beyond energetic-ion-based bulk modification, emerging electrolyte-derived strategies, including ionic liquids and solid polymer electrolytes (SPEs),[9,10] have further expanded the materials landscape and functional tunability of iontronic electrets. These electrolyte-based systems contain abundant dissociable ions that can undergo stimulus-responsive redistribution within polymer matrices. Upon mechanical deformation or electrostatic excitation, mobile ions migrate directionally and accumulate at interfaces, leading to the formation of compact and stable EDL. These dynamically reconstructed interfacial structures regulate charge distribution, enhance local electric-field intensity and improve field stability by suppressing charge dissipation pathways. Unlike conventional electrets with largely fixed charge distributions and limited post-fabrication tunability, SPE-based iontronic electrets provide an additional degree of freedom through the engineering of ion species, concentration, ionic mobility and migration kinetics. Such control enables dynamic modulation of surface potential, polarity and electret output, transforming electret design from passive structural optimization toward actively regulated ionic-field engineering.

Overall, the defining advantage of iontronic electrets lies in their ability to integrate persistent field generation with dynamic field regulation. In contrast to static electronic electrets, where charges are immobilized after polarization, ions in iontronic systems can function simultaneously as stored charge carriers and mobile regulatory species. This dual role enables adaptive control over the magnitude, polarity and spatial distribution of electrostatic fields, providing iontronic electrets with unique capabilities for field trapping, signal modulation and environmental adaptation.

CONCLUSION AND OUTLOOK

Tele-perception redefines electret materials from passive charge-storage dielectrics to active spatial electric-field engineering platforms. To advance electron-trapping electrets, future strategies focus on full charge-cycle regulation, including graded energy landscape design, multilayer dielectric stacking, heterointerface modification, and charge-blocking layer integration, enabling precise control over charge injection, migration, trapping, and long-term field stabilization. For iontronic electrets, core optimization strategies involve nanoconfined ionic pathway construction, hydrophobic network engineering, moisture-barrier encapsulation, and water-tolerant ion pair screening to suppress humidity-induced ion drift and performance degradation. Key evaluation metrics, namely field intensity, spatial-field distribution, effective sensing distance, field retention, dynamic response speed, environmental stability, and field tunability, set standardized benchmarks for tele-perception electret design. These criteria demarcate the performance boundaries of the two electret families. Iontronic electrets deliver superior tunability and fast response via ionic-pathway engineering and moisture-resilient modification, whereas electron-trapping electrets feature high field intensity, uniform spatial distribution and long-term charge retention. These divergent merits support targeted material screening and optimization for diverse non-contact sensing scenarios.

These two electret categories support distinct non-contact tele-perception application scenarios. Benefiting from ultra-stable and long-duration electrostatic fields, electron-trapping electrets are applicable to static tasks, including stationary gesture identification, long-range proximity monitoring, and steady non-contact hovering perception. By contrast, iontronic electrets with reversible field modulation capability are well-suited for dynamic interactive tasks, including real-time trajectory tracking, continuous motion perception, and time-resolved robotic non-contact sensing. The synergy of electronic and ionic mechanisms enables programmable spatial field manipulation, providing a feasible material strategy for emerging wearable intelligence and high-precision embodied tele-perception systems.

REFERENCES

1. Du Y., Shen P., Liu H., et al. (2024). Multi-receptor skin with highly sensitive tele-perception somatosensory. *Sci. Adv.* **10**:eadp8681. DOI:10.1126/sciadv.adp8681
2. Du Y., Shen P., Liu H., et al. (2025). Meta- structured electret heterointerface for resilient and adaptive tele-perception in embodied intelligence. *Matter* **8**:102363. DOI:10.1016/j.matt.2025.102363
3. Wang J., Wu C., Dai Y., et al. (2017). Achieving ultrahigh triboelectric charge density for efficient energy harvesting. *Nat. Commun.* **8**:88. DOI:10.1038/s41467-017-00131-4
4. Liu Z., Huang Y.-z., Shi Y., et al. (2023). Creating ultrahigh and long-persistent triboelectric charge density on weak polar polymer via quenching polarization. *Adv. Funct. Mater.* **33**:2302164. DOI:10.1002/adfm.202302164
5. Li S., Nie J., Shi Y., et al. (2020). Contributions of different functional groups to contact electrification of polymers. *Adv. Mater.* **32**:2001307. DOI:10.1002/adma.202001307
6. Lee J. W., Cho H. J., Chun J., et al. (2017). Robust nanogenerators based on graft copolymers via control of dielectrics for remarkable output power enhancement. *Sci. Adv.* **3**:e1602902. DOI:10.1126/sciadv.1602902
7. Li S., Fan Y., Chen H., et al. (2020). Manipulating the triboelectric surface charge density of polymers by low-energy helium ion irradiation/implantation. *Energy Environ. Sci.* **13**:896-907. DOI:10.1039/c9ee03307f
8. Šutka A., Fiedler H., Linarts A., et al. (2026). Space charge drives electromechanical conversion in ion-implanted polymers via an apparent piezoelectric effect. *Phys. Rev. Lett.* **136**:056203. DOI:10.1103/th79-cjz6
9. Han J. H. and Moon H. C. (2025). Monolithically integrated ionic triboelectric nanogenerators for deformable energy harvesting and self powered sensing. *npj Flexible Electronics.* **9**:114. DOI:10.1038/s41528-025-00491-8
10. Ryu H., Lee J.-H., Kim T.-Y., et al. (2017). High- performance triboelectric nanogenerators based on solid polymer electrolytes with asymmetric pairing of ions. *Adv. Energy Mater.* **7**:1700289. DOI:10.1002/aenm.201700289

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AUTHOR CONTRIBUTIONS

All authors contributed to and approved the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.