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Editorial

Mechanism-Guided Materials and Structural Design for High-Performance Nanogenerators

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The advancement of sensor systems that facilitate our daily lives relies on small, disposable batteries, which contribute to environmental pollution. Self-powered sensor technology, a battery-free approach, offers a powerful option for addressing this problem. With the emergence of nanogenerators in the mid-2000s, the development of effective devices for harvesting ambient energy has been a primary focus of research. Notably, investigation of mechanisms, structural optimization, material engineering, and electrode modulation are the main techniques that enhance nanogenerator performance, resulting in high-output devices with practical applications.

Efficient, cost-effective devices can be developed from an understanding of the mechanism governing triboelectrification in polymers when they become tribo-positive. Fatti et al. unveiled that the substantial positive charge of polyoxymethylene is caused by homolytic C-H bond cleavage when the polymer comes into contact with a metal surface; then, the carbon oxidation state changes and causes an electron transfer to the counter-surface [1]. Their findings suggest that triboelectrification of the polymer is related not only to heterolytic material transfer but also to material chemistry. Nevertheless, studies on tribo-positive TENG materials operating under harsh conditions are still limited. Pan et al. developed a highly tribo-positive polyamide by incorporating amide groups with electron-donating properties into the polymer backbone, enabling energy harvesting at increased temperatures and illustrating a general design strategy for tribo-positive TENG materials that are suitable for harsh environments [2].

Beyond materials design, electrode architecture and friction-layer engineering also play important roles in determining TENG performance. Kisomi and colleagues engineered several electrode patterns, pyramid, spherical, and cube, to optimize the TENG device's performance across four different modes [3]. They found that the cube-pattern electrode had a higher voltage (384 V) than the flat electrode (233 V) in sliding mode; likewise, the spherical-pattern electrode displayed 1.7 times the output voltage of the flat electrode in contact–separation mode. Their study suggests that electrode pattern optimization should be mode-specific in order to efficiently improve TENG performance. A challenge in the optimization of TENG friction layers is balancing the properties of materials. Candido and co-workers examined the use of cellulose acetate doped with zinc oxide (ZnO) and titanium dioxide (TiO_2) [4]. They found that the roughness of ZnO-doped cellulose acetate membranes is governed by the degree of dopant aggregation, and that devices based on these membranes perform better than those using undoped cellulose acetate.

Charge-density maximization is a foremost consideration to achieve high energy conversion when designing TENG materials and structures. Cui and colleagues present mechanisms and approaches that exploit multi-charge-storage layers to boost charge density and highlight additional benefits attainable through specific material and structural

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innovations [5]. This new charge-storage technique offers a potential route to substantially increase charge density. In addition, improving the energy conversion of wind-driven TENGs (WD-TENGs) is crucial. Fang et al. optimized a wind-turbine structure by developing a rotational double-electrode-layer wind-driven TENG that leverages gravity and centrifugal-force-regulated contact to reach mechanical-to-electrical conversion efficiencies above 10% [6].

Enhancing the light-harvesting efficiency of nanogenerators can be achieved using coupled-effect materials. Xue et al. fabricated MXene/ZnO heterojunction nanogenerators that utilize the pyro-phototronic effect to harvest broadband light at temperatures up to 200 °C [7]. Slight stretching enhances performance through piezoelectric charge-induced shifts in the Schottky barrier height, highlighting the promise of combined pyro- and piezo-phototronic effects for improved energy harvesting. Although zinc oxide nanowires (ZnO NWs) are widely used in the piezoelectric field, research on the influence of growth-process conditions, particularly pulsed-liquid injection metal–organic chemical vapor deposition (PLI-MOCVD), is limited. Bui et al. investigated how the flow rates of oxygen gas and a diethylzinc solution affect the formation and piezoelectric properties of ZnO NWs [8]. This discovery reveals that PLI-MOCVD can control both the size and piezoelectric properties of ZnO NWs, providing a powerful route to PENG performance optimization at both the single nanowire and array scales.

The limited stretchability and flexibility of current ferroelectret nanogenerators (FENGs) considerably hinder their practical implementation in wearable electronics. Song et al. developed ultrathin, stretchable, and twistable FENGs based on Ecoflex/graphene with controllable porosity that can recognize facial muscle movements, thereby supporting facial condition monitoring and improving quality of life, marking a significant advancement in face-wearable technologies [9]. Likewise, a coaxial fiber triboelectric sensor made of conductive materials, a poly(vinylidene fluoride–hexafluoropropylene) (PVDF-HFP)/carbon nanotubes (CNTs)/carbon black composite, and a PVDF-HFP/MoS_2 matrix as the conductive electrode and the triboelectric layer, respectively, demonstrates high sensitivity and stability in sensing finger movement [10].

Nanogenerators, particularly triboelectric nanogenerators, have been extensively studied because of their simple structures and broadly available materials; improvements in their performance to achieve higher output have been ongoing using the following strategies: elucidating mechanisms, optimizing devices, tailoring materials, and modifying electrodes. Research on tribo-positive materials is gaining attention owing to the limited number of studies in this area. Moreover, fabricating devices for energy harvesting under harsh conditions, such as strong acids, strong alkaline solutions, and high temperatures, should be considered to expand the nanogenerator's utilization. As efficient nanogenerators continue to improve, it is foreseeable that they will transition from proof-of-concept devices to widespread practical devices, establishing them as a key technology for future sustainable energy harvesting.

Conflicts of Interest: The author declares no conflicts of interest.

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