# Plasma-enabled energy harvesters based on low dimensional materials

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The rapid advancement of microelectronics and wireless technologies has led to the development of smart cities and wireless sensor networks. However, the increasing demand for wearables, smart electronics, and connected sensors raises concerns about energy management for billions of wireless and portable devices. Providing a small battery to every single device is unsustainable due to maintenance, energy losses, waste, or pollution, and resource constraints.

Energy harvesters and nanogenerators offer a promising solution by generating electric power from local environments and residual energies. The development of multisource and multifunctional energy scavengers and scalable fabrication processes is crucial for the realization of self-powered microsystems and on-site energy harvesting. In this communication, we demonstrate the advantage of plasma and vacuum-based techniques as a synthesis approach for fabricating nanostructured functional materials for their application as self-powered sensors or energy harvesters like piezoelectric, triboelectric, and pyroelectric nanogenerators for different applications.

We introduce paper-based self-powered sensors and piezoelectric nanogenerators as flexible, inexpensive, and environmentally friendly devices [1]. We used a microwave electron cyclotron resonance reactor to deposit polycrystalline ZnO nanocolumnar thin films on common paper supports at room temperature. Kinetic Monte Carlo simulation tools helped elucidate the shadowing mechanism behind the characteristic microstructure, texturization, and porosity of ZnO thin films that enhanced the piezoelectric behavior of the material [2]. We assembled piezoelectric devices by embedding ZnO films in polymethylmethacrylate (PMMA) and using Au thin layers as electrodes in different configurations, laterally and vertically connected. We present the response of the different devices and their performance under realistic scenarios, analyzing their durability and their capabilities for their usage as sensors or energy harvesters.

Triboelectric nanogenerators have also emerged as a promising solution for kinetic energy harvesting in various applications, from small wireless devices to large-scale systems. While most solutions rely on triboelectric polymeric layers with long-lasting charges, we focus on Polydimethylsiloxane (PDMS) as a model triboelectric layer and explore the effect of plasma treatments on TENG power performance. Besides, to address the challenge of energy harvesting from low-frequency movements up to acoustic vibrations, we propose a nanostructured 3D core@multishell [3] hybrid piezo-triboelectric nanogenerator architecture [4]. By optimizing crystalline texture, ZnO thickness, nanowires aspect ratio, and surface chemical modification as plasma-mediated treatments or perfluorinated grafting of PDMS surfaces (which promotes higher voltage outputs and reliable reproducibility under realistic operation conditions), we were able to demonstrate the successful activation of the system up to 800 Hz. We also explored the substitution of the elastomeric matrix for functional ferroelectric polymers such as PVDF and copolymers to synergistically enhance the piezoelectric characteristics of the devices as well as lead into multisource pyroelectric-piezoelectric nanogenerators.

As the ultimate step towards exploiting water as a clean and renewable energy source is to harness low-frequency flows in liquid motion, triboelectric nanogenerators have emerged as promising actors for this aim. However, the output power of drop energy harvesters is still limited due to suboptimal device architecture and material properties. Controlling the nanostructures as well as the surface behavior can lead to the exploitation of drop micro-energy harvesting systems. By embedding 1D nanowires or 3D core@shelll nanostructures within polymeric matrixes with chemically modified surfaces, we produced tunable contact angle surfaces for charge accumulation and liquid-solid electrification. By fabricating a full set of liquid-solid triboelectric nanogenerators with different wetting behaviors, compositions, and configurations, we analyzed their electrical outputs under various activation conditions and we disclosed a microscale triboelectric nanogenerator that can harvest high-density electrical power from drops through a single, submillisecond event. The proposed mechanism relies on an instantaneous electrical capacitance variation owing to the high-speed contact of drops with electrodes' active areas. We discuss the role of precharged effects in the time characteristic of conversion events and demonstrate a microscale structure that resembles pixels in a charge-coupled image sensor. This architecture can be adjusted for different liquids and scales, making it compatible with various triboelectric surfaces.

## References

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