報告番号	甲　第　14922　号

主　論　文　の　要　旨

論文題目　**Study of High-performance Ambient Energy Harvesters based on Instantaneous Charge Release**
(瞬時的電荷放電を用いた高性能環境発電素子に関する研究)

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論　文　内　容　の　要　旨

In recent years, there has been a mounting interest in harvesting ambient mechanical energy. This trend is driven not only by advances in energy harvesting technologies but also by the urgent need for alternative energy sources, especially with the advent of the Internet of Things (IoT) era. By transforming mechanical energy sources—like vibrations, human movements, water waves, or raindrops, etc.—into usable electrical energy, we present a promising avenue to address specific energy shortage challenges. While on a smaller scale these energies can fuel sensors, on a broader scale, they offer the potential to power households. In remote settings, powering sensors introduces notable difficulties. Traditional cabling is often unfeasible, and relying on batteries introduces ongoing maintenance, resulting in elevated operational costs. However, if we could effectively harvest the mechanical energy from the environment, such as vibration or rainfall to power them, these systems can operate over extended periods without incurring significant maintenance costs. What's more, for some portable and wearable devices, the size constraints often lead to limited battery life. Relying on stored power means devices might not last as long as desired. This is particularly concerning for implantable devices like pacemakers. Periodically replacing batteries in such devices undoubtedly increases discomfort and risk for patients. However, if we could harness the mechanical energy naturally produced by the human body, it could offer a sustainable solution to power these devices continuously, so that the power supply challenges would be effectively addressed. In a nutshell, considering the expected widespread deployment of sensors crucial for real-time health monitoring, infrastructure surveillance, environmental oversight, IoT, even and military tech, conventional battery-dependent solutions might soon prove inadequate. Nevertheless, the vast reserves of mechanical energy in our surroundings provide hope. Devices that efficiently convert mechanical energy into electrical energy could serve as the sustainable backbone for these next-gen energy harvesting technologies.

Given that the mechanical energy in environments is typically low-amplitude, inconsistent, and low-frequency, the anticipated energy harvesters must exhibit swift and efficient energy conversion capabilities. Thus, the existing mechanical energy harvesters do not meet this criterion perfectly. Addressing this challenge, our research delved into previous prevalent mechanical energy harvesting technologies and have put forth an energy harvesting strategy rooted in instantaneous charge transfer. Through this strategy, we've conceptualized energy harvesters leveraging both liquid-solid and solid-solid charge dynamics.

This dissertation is structured as follows:

In Chapter 1 and 2, there is a research background introduction and related literatures review. We give an overview and retrospective of the current mainstream techniques for harvesting mechanical energies. This encompasses piezoelectric, ferroelectric, triboelectric, and magnetostrictive mechanisms, with an intricate analysis of their technological feats and power generation attributes. We also spotlight the burgeoning field of triboelectric nanogenerators, charting their evolutionary course. Additionally, we debut a high-efficiency droplet-based electricity generator, illuminating its design and underlying power generation mechanism, especially emphasizing the novel concept of instantaneous charge transfer.

Then for Chapter 3, 4, 5 and 6, there is a research implementation which have been divided to be four parts. Grounded in the aforementioned research backdrop, we've developed two types of energy harvesters based on liquid-solid and solid-solid interfaces. Firstly, focusing on instantaneous charge transfer strategies between liquid-solid interfaces, efforts surrounding the design of measurement platforms, standardized specimen evaluations, material advancements, and structural optimization were initiated, all converging to refine the droplet-based electricity generator. Primarily approached from the following aspects:

In Chapter 3, we introduced an amorphous fluoropolymer of CYTOPT-M (Cyclic Transparent Optical Polymer) with the merits of high surface charge density and easy to be fabricated, as an intermediate layer to enhance the performance of DEGs. We found that by adjusting the thickness, surface charge density, and specific surface area of CYTOP on DEG, output could be improved. This laid a solid foundation for subsequent work.

In Chapter 4, for performance improvements on DEGs, to increase the current and transferred charge, we proposed a suspended needle surface electrode instead of a conventional surface electrode to minimize the impact of parasitic capacitance. With this structure, we achieved an output voltage exceeding 1200 V on a 50 μm FEP base for the first time. To further enhance the current, we introduced $BaTiO_3$ nanoparticles into the CYTOP film, which, while reducing the thickness of the electret, increased the surface charge density. We demonstrated that a CYTOP/ $BaTiO_3$ composite film with 1wt% $BaTiO_3$ achieved an output voltage of 900 V and a transferred charge of 151 nC, marking a new breakthrough in output.

In Chapter 5, to promote the practical application of DEGs, we introduced a protective film over the surface electrode. We demonstrated that DEGs with a protective film could resist acid and alkali corrosion and showed for the first time that water droplets could generate output without directly contacting the surface electrode. Furthermore, by adjusting the thickness of the protective film and combining the output theoretical formula, we proved the relationship between film thickness and output, demonstrating high output under a thin protective film. To address the issue of energy harvesting from multiple droplets in DEGs, we prepared integrated DEG based on two surface electrodes and multiple surface electrodes, effectively harvesting energy from multiple random droplets by adjusting the gap between the surface electrodes. Finally, we demonstrated the feasibility of energy harvesting under scattered droplets in multi-electrode DEGs.

In Chapter 6, drawing inspiration from the core strategy of instantaneous charge transfer, we introduced a new vibration energy harvester between solid-solid interfaces, with detailed designs, analyses, and a deeper delve into its power generation mechanism.

Finally for Chapter 7, there is a research conclusions and prospects, we contemplate the future trajectory of research and application realms based on this topic. Aligned with the current status of our research and recent developments in related fields, we further discuss the potential and future avenues grounded in this strategy, aiming at championing the vision of a battery-less, intelligent society.