Coupled In-Situ Contact Mechanics and Electrical Performance in Triboelectric Nanogenerators

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Abstract

The increasing demand for sustainable power sources for small sensors and microelectronic devices has driven interest in alternatives to conventional batteries. Triboelectric nanogenerators (TENGs) have emerged as a promising energy-harvesting technology. This work presents a systematic approach to investigate the influence of loading conditions (normal load and frequency), material properties, and multi-scale surface roughness on triboelectric performance. Multiscale, controlled rough surfaces were fabricated on soft polymeric substrates. The results reveal a strong correlation between surface roughness, real contact area, and electrical output, providing new insights into the coupled contact mechanics and electromechanical response of TENG systems.

Possible Sessions

Tribology and Contact
Nano & Micro-mechanical testing
Condition Monitoring

Introduction

As the world moves toward a more digital and sustainable future, there is a rapidly growing demand for reliable, distributed energy sources to power various electronic devices. Although batteries are widely adopted due to their portability and ease of integration, they suffer from inherent limitations, including limited lifespan, the need for frequent recharging or replacement, and environmental concerns associated with disposal. Consequently, there is an increasing need for self-sustaining energy solutions capable of harvesting and generating electricity in situ and on demand.

In this context, triboelectric nanogenerators (TENGs) have emerged as a promising class of energy-harvesting devices and have attracted significant attention from the scientific community [1]. TENGs operate based on the coupling of contact electrification and electrostatic induction, enabling the sustainable conversion of ambient mechanical energy, such as vibrations, sliding or rubbing motion, and impacts, into usable electrical energy. Since their development in 2012, extensive research efforts have mainly focused on improving their output performance through material selection, electrical circuit design, and device optimisation [2]. Despite these advancements, the fundamental understanding of the underlying contact mechanics, tribological interactions and governing charge generation remains limited. TENG operation is broadly classified into two primary modes: contact–separation and sliding (Fig. 1), each governed by distinct interfacial mechanics and charge transfer characteristics.

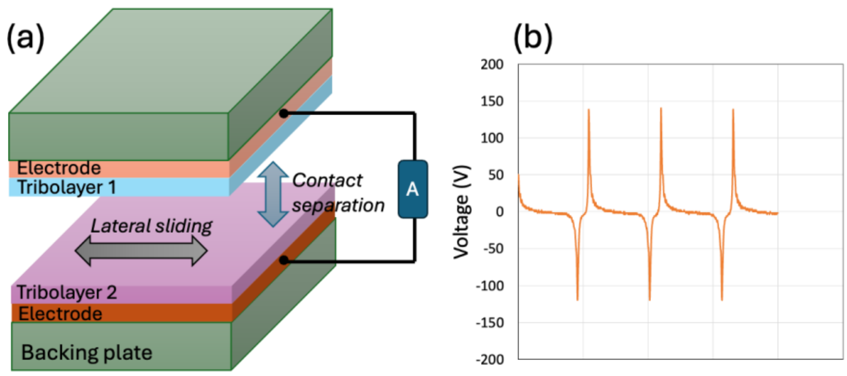

Figure 1: (a) Schematic of a triboelectric nanogenerator operating in contact–separation and lateral sliding modes. (b) Representative plot of voltage output from a flexible TENG.

The aim of this work is to develop a comprehensive understanding of the influence of loading conditions, tribo-material properties, and multi-scale surface roughness on the triboelectric performance of TENGs [3]. To achieve this, surfaces with precisely controlled roughness profiles were systematically designed through numerical modelling and subsequently fabricated on various elastomeric substrates using advanced additive manufacturing, injection moulding, and micro-replication techniques [4].

In-house TENG devices were developed by integrating flexible tribolayers with thin conductive electrodes, enabling enhanced conformability and efficient charge transfer. A dedicated experimental setup was further designed and implemented to enable simultaneous, real-time measurement of critical parameters, including applied contact force, triboelectric output signals (current, voltage, and charge), and the corresponding real contact area at the interface.

Results

The results of the 3D optical surface profiler investigation of negative moulds and replicated tribolayers confirm high replication quality and repeatability over a wide range of roughness (up to 100 μm). Controlled contact-separation experiments were conducted under a wide range of operating conditions, including varying normal loads, excitation frequencies, and dwell (hold) times, to replicate realistic working scenarios. The experimental findings reveal a clear and systematic correlation among surface morphology, real contact area evolution, and electrical output characteristics. The real contact area is found to be a governing factor influencing triboelectric performance. In addition, the developed TENG device demonstrates a high electrical output power density of 4.0 W/m². These results advance the fundamental understanding of TENG operation and guide the design of more efficient energy-harvesting systems.

References

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