M.4: Development of flexible triboelectric nanogenerator for vibration energy harvesting

The rapid expansion of sensors, wearable electronics, and Internet-of-Things (IoT) technologies has intensified the demand for sustainable and maintenance-free power sources. In many real-world applications such as remote sensing and wearable systems, frequent battery replacement is impractical. Harvesting ambient mechanical energy available abundantly in the form of vibrations, human motion, airflow, and surface contact offers a promising alternative. Triboelectric nanogenerators (TENGs) have emerged as efficient devices capable of converting low-frequency mechanical energy into electrical energy, enabling self-powered electronic systems.

TENGs operation is based on the combined effects of triboelectrification and electrostatic induction. When two dissimilar materials come into contact, charge transfer occurs depending on their relative triboelectric polarity. Upon separation, an electric potential difference is generated, driving electrons through an external circuit. Repeated contact-separation cycles produce alternating electrical output. In the present work, a contact–separation mode flexible TENG was developed for vibration energy harvesting applications and tested under a periodic mechanical force of 30 N at a frequency of 4 Hz, representative of low-frequency ambient vibrations.

Zinc oxide (ZnO) thin film was employed as the tribopositive layer and polydimethylsiloxane (PDMS) as the tribonegative layer. ZnO is a multifunctional semiconductor with good flexibility, chemical stability, and tunable electronic properties, while PDMS offers high electronegativity, flexibility, and biocompatibility. Both layers were deposited on ITO-coated PET substrates, resulting in a fully flexible device architecture suitable for wearable and vibration-based applications. To overcome the limited output of conventional ZnO-PDMS TENGs, three systematic material-engineering strategies were adopted. First, ZnO was doped with 2 at.% aluminium (Al) to increase free electron concentration and reduce its work function. This enhanced the tribopositivity of ZnO, leading to improved charge transfer during contact electrification. Second, a thin SiO_2 interlayer was introduced between Al-doped ZnO and the ITO electrode to suppress electron diffusion from ZnO into ITO. Kelvin probe force microscopy measurements confirmed that an optimized SiO_2 thickness of ~100 nm effectively blocked electron loss and further reduced the effective work function of ZnO, resulting in enhanced output performance. Third, MoS_2 nanoflowers were incorporated into the PDMS matrix to improve its charge storage capability. An optimized MoS_2 concentration of 6 wt.% formed a nanocapacitor network within PDMS, increasing its dielectric constant without inducing electrical leakage. The schematic of flexible TENG and the corresponding band diagram showing triboelectrification are shown in Fig. M.4.1 a and b respectively.

By combining Al-doped ZnO, an optimized SiO_2 interlayer, and MoS_2 enhanced PDMS, the flexible TENG exhibited a significant improvement in electrical output. The optimized device generated an open-circuit voltage of ~369 V and a short-circuit current of ~28 µA (Fig. M.4.1 c), compared to ~112 V and ~7.8 µA for the pristine ZnO-PDMS TENG. The maximum instantaneous power density reached ~1.8 mW/cm^2 at an optimized load resistance (Fig. M.4.1 d). The device demonstrated excellent mechanical robustness and operational stability, maintaining stable output over 10,000 contact-separation cycles and showing negligible degradation over six months. The harvested energy was successfully used to charge commercial capacitors (1–10 µF) and directly power array of 400 LEDs (Fig. M.4.1 e), showing its capability for low-power electronic applications.

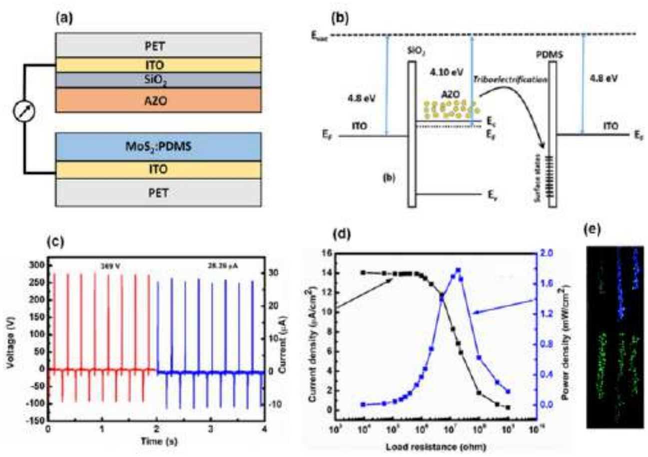

Fig. M.4.1: (a) Schematic of ZnO TENG, (b) band diagram showing triboelectrification, (c) open-circuit voltage & short circuit current, (d) current and power density with the load resistance and (e) flashing of 400 LEDs using the rectified output of TENG

This work highlights a systematic approach to enhance flexible TENG performance through electronic and interfacial engineering. The developed ZnO-based flexible TENG shows strong potential for self-powered sensors, wearable electronics, smart flooring, and low-power IoT systems, contributing toward sustainable and battery-free energy solutions.

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