Composite Kevlar Fabric-Based Triboelectric Nanogenerator with Anti-Impact and Sensing Performance

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Abstract. An enhanced Kevlar-based triboelectric nanogenerator (EK-TENG) was developed by integrating shear thickening materials and graphene on Kevlar fabric, exhibiting excellent safeguarding and stable sensing capability in harsh loading environments. The maximum peak power density of EK-TENG reached 25.8 mW/m^2 under oscillator loadings of 40 N and 10 Hz, enabling direct powering of commercial LEDs, capacitors, and supercapacitors. Moreover, the 30-layer EK-TENG effectively dissipated low-speed drop hammer impact force from 1820 N to 439 N. With its anti-ballistic property, EK-TENG demonstrated resistance against bullet shooting at a velocity of 126.6 m/s, surpassing the performance of neat Kevlar at 90.1 m/s. Additionally, EK-TENG exhibited exceptional safeguarding properties by absorbing and dissipating up to 87.4% of explosion wave energy under blast loading conditions. EK-TENG also functioned as a self-powered sensor capable of generating voltage signals in response to various impact loadings for monitoring external stimuli. Finally, a smart EK-TENG based wireless alarm system with high sensitivity was designed to monitor and warn impact dangers, which opened up a new avenue for the development of next-generation intelligent protection.

Possible Sessions

9. Impact, blast and high strain rate, 21. Soft matter, 24. Testing of composite materials

Introduction

The rapid evolution of smart wearable electronic devices has sparked significant interest in flexible triboelectric nanogenerators (TENGs) for diverse applications, including health monitoring and human-machine interaction. Traditional fabric-based TENGs have exhibited limited mechanical performance, rendering them vulnerable to damage from impact loads, leading to structural deterioration and diminished electrical efficiency [1,2]. Consequently, there exists an imperative to innovate and pioneer novel fabric-based TENGs with enhanced anti-impact capabilities. Kevlar, renowned for its high tensile modulus, low density, and outstanding flexibility, emerges as an ideal candidate for the development of innovative fabric-based TENGs [3]. A recent successful strategy involved enhancing the mechanical properties of Kevlar by incorporating shear-thickening materials onto the fabric [4]. These materials, characterized by rate-dependent mechanical properties, significantly augmented fiber friction and anti-impact performance. Consequently, the synergistic combination of shear-thickening materials with Kevlar fabric has the potential to develop an impact-resistant TENG, facilitating the realization of perception, transmission, and alarm functionalities in extreme environments.

Results and Discussion

Preparation and Triboelectric Performance of EK-TENG. The fabrication process of EK-TENG was depicted in Fig. 1a, involving the immersion of Kevlar fabric in SiO_2-based shear thickening fluid (STF) to create Kevlar/STF. A graphene-ethanol mixture was then applied to the Kevlar/STF surface, and a conductive wire was attached to the graphene layer. Depositing a shear stiffening gel (SSG) solution formed a thin film, and the final EK-TENG was obtained through oven drying. The triboelectric transducing mechanism relied on the coupling effect of triboelectrification and electrostatic induction (Fig. 1b). Fig. 1c showed the output voltages of the 5 × 5 cm^2 EK-TENG under varying applied forces at a loading frequency of 10 Hz, revealing an increasing trend corresponding to the applied forces. Functioning as a power source, EK-TENG effectively charged commercial capacitors (Fig. 1d). With promising triboelectric performance, EK-TENG held potential as a reliable power source for diverse electronic devices.

Impact resistance and sensing properties of EK-TENG. The impact resistance and sensing capabilities of EK-TENG were assessed through various tests. Initially, the yarn pull-out test characterized fiber friction (Fig. 2a), revealing that the EK-TENG's maximum pull-out force at 5 mm/s was about 14 times greater than that of neat Kevlar, indicating increased yarn friction with the incorporation of STF and SSG (Fig. 2b). Subsequently, low-velocity drop hammer impact tests were conducted (Fig. 2c), demonstrating consistently smaller maximum impact forces on the EK-TENG compared to other fabrics under various dropping heights, highlighting its superior safeguarding performance (Fig. 2d). The anti-impact properties of EK-TENG were further examined through high-speed ballistic impact tests, revealing a ballistic limit velocity of 126.6 m/s, surpassing that of neat Kevlar at 90.1 m/s (Fig. 2e, f). Increasing ballistic impact velocities led to enhanced peak voltages and reduced positive voltage duration (Fig. 2g), suggesting potential sensing applications under ballistic impact conditions. Additionally, anti-shockwave performance was investigated under air blast conditions (Fig. 2h). The EK-TENG demonstrated superior energy absorption, with an 87.4% attenuation in transmission wave peak pressure compared to a 304 stainless steel plate (Fig. 2i). Furthermore, EK-TENG exhibited voltage signals even under explosive shocks, showcasing its potential utility in ultra-hazard sensing (Fig. 2j). These results highlighted EK-TENG's exceptional impact resistance and sensing capabilities, paving the way for its application in wireless impact alarm systems.

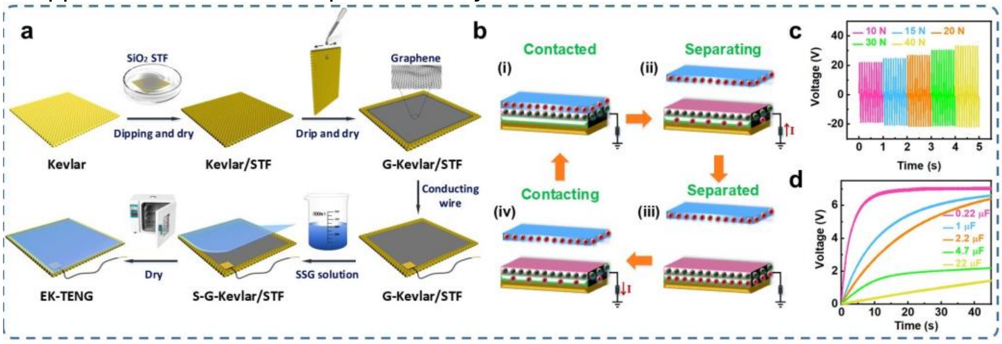

Fig. 1 Preparation and triboelectric performance of EK-TENG. (a) Fabrication schematic; (b) Working mechanism; (c) Force-dependent output voltages at 10 Hz; (d) Voltage charging curves of capacitors with various capacitances.

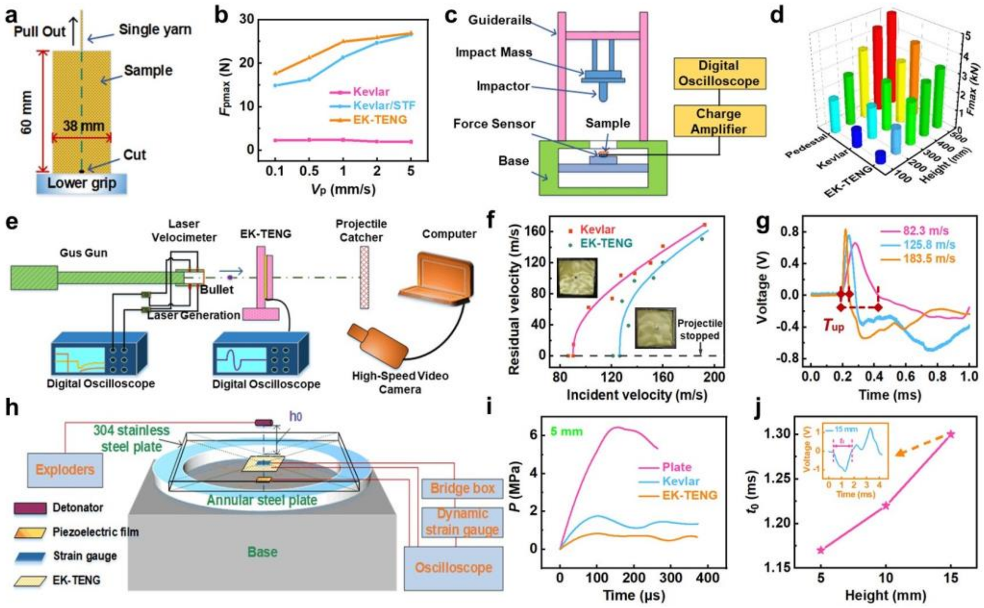

Fig. 2 Impact resistance and sensing properties of EK-TENG. (a) Yarn pull-out test schematic; (b) Maximum extraction forces; (c) Drop hammer experimental equipment schematic; (d) Maximum impact forces; (e) High-velocity ballistic impact system schematic; (f) Residual velocities of neat Kevlar and EK-TENG under various impacts; (g) Voltage signals of EK-TENG generated by bullet impacts; (h) Explosion test system schematic; (i) Pressure-time history of transmitted waves at a 5 mm explosion height; (j) Sensing signals generated by EK-TENG under explosion.

Conclusion

In summary, a flexible and wearable enhanced Kevlar-based triboelectric nanogenerator, incorporating STF, graphene, and SSG onto Kevlar fabric, was developed. It exhibited favorable anti-impact properties and stable self-powered sensing in high-speed loading environments, showcasing significant potential for applications in remote emergency rescue and automated security systems.

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