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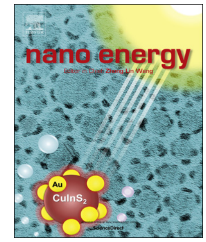

RAPID COMMUNICATION

Single-electrode triboelectric nanogenerator for scavenging friction energy from rolling tires

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Abstract
Triboelectric nanogenerator (TENG) is a novel energy harvesting device to convert mechanical energy into electricity based on the universally known triboelectric principle. In this work, we demonstrated an innovative design of single-electrode TENG (S-TENG) using PDMS to simulate the tire surfaces for scavenging the wasted friction energy from rolling tires. By fixing the PDMS S-TENG on a rubber wheel, the performance of scavenging friction energy was systematically investigated. The electric output of the S-TENG-on-wheel monotonically increased with the increase of the moving speed and weight load of the wheel. The maximum instantaneous power was obtained to be 1.79 mW at a load resistance of 10 MΩ, corresponding to the highest energy conversion efficiency of 10.4%. Multiple S-TENGs were implemented to the tires of a toy vehicle and instantaneously powered 6 commercial green light emitting diodes (LEDs) while the vehicle was moving on the ground. This successful demonstration provides a promising solution to scavenge the wasted friction energy from rolling tires, which may improve the fuel efficiency or the cruising ability of electric vehicles.
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Introduction

Due to the rapid-growing fossil fuel consumptions and global energy demands in the past decades, intensive research efforts have been devoted to the development of alternative renewable energy technologies. Harvesting mechanical energy from ambient environment is considered as an effective and promising approach to supplement the energy needs due to its great abundance and ubiquity [1–3]. In 2006, nanogenerator (NG) was developed using piezoelectric nanomaterials or nano-composites to harvest mechanical energy from various mechanical energy sources such as fluid or air flows, [4,5] ultrasonic waves, [6] deformations, rotations, [7,8] and human activities [9]. Most recently, Based on the coupling of triboelectric friction and electric induction, triboelectric nanogenerator (TENG) has been developed as a new principle for scavenging mechanical energy with orders-of-magnitude-enhanced electric output. Due to its simple design and broad material selection, TENG has quickly shown great promises as a power source for a wide range of applications, such as powering portable electronics, [2] self-powered sensors, [10] charging lithium ion batteries, [11] electrodeposition, [12] electrodegradation of dyes, [13] and electrolyzing water [14].

One of the most attractive merits of NG is its capability of scavenging the wasted mechanical energy in many different forms. Friction is a major energy loss in a rotation system, where rolling tires on the ground is the most common example. Statistics conducted by the US Department of Energy discovered that 5–7% of energy was consumed by the rolling resistance in vehicles (not including breaking loss) [15]. Harvesting this type of energy would be promising in improving the fuel efficient or the mileage per charge of electric vehicles. TENG has a desire configuration for harvesting energy from friction [16]. However, most reported TENGs employ a design that consists of a pair of thin film materials with different electron affinity and is coated with metal electrodes to output the induced charges [17]. This design imposes limitations in harvesting the friction energy from a tire when it‘s continuous rolling on the ground. Abrasion from the ground would quickly damage the functioning part. This challenge would be solved if the ground surface could act as one charge-generating material and the tire surface acts as the other one. Most materials on the ground surface like silica, cement, and even metals are electron donating materials [18]. When they are in contact with electron accepting materials such as polymer and rubber, opposite charges can be induced on both surfaces, and thus the triboelectric principle would apply. Polydimethylsiloxane (PDMS) is a flexible polymer with strong electron attracting ability, which has been successfully used in a variety of TENG development [19–21]. In this paper, we report a novel single-electrode TENG (S-TENG) design using rough PDMS thin films to simulate the tire surfaces for scavenging the wasted friction energy from rolling tires. By fixing the PDMS S-TENG on a rubber wheel, the friction energy scavenging capability was demonstrated and systematically investigated. Such a S-TENG device was implemented to the tires of a toy vehicle and instantaneously powered 6 commercial light emitting diodes (LEDs) while the vehicle was moving on the ground. This development offers a promising solution to recovering the friction energy from rolling tires, which may find a practical application potential in improving the vehicle's fuel efficiency, particularly for electrical cars.

Experimental section

Fabrication of PDMS S-TENG

A piece of sandpaper was taped at the bottom of a polystyrene plastic dish. Liquid PDMS elastomer and cross-linker were mixed with a ratio of 10:1 and then uniformly casted on the sandpaper. After 20 min degasing in vacuum and a thermal incubation at 90 °C for 1 h, a uniform PDMS thin film with a rough surface was formed. The film was then peeled off from the sandpaper. A piece of Cu foil with one side conductive adhesive was attached to the flat side of the PDMS thin film acting as the electrode to conduct the induced charges. Fig. S1 shows the SEM image of the sand paper mold surface. There are many micro peaks with sharp tips locate on the sand paper surface. These tips result in micro pores and rough surface of the PDMS thin film. The entire surface morphology corresponds to that of the prepared PDMS thin film.

S-TENG design and characterization

A LEO 1530 scanning electron microscope and Park XE-70 atomic force microscopy (AFM) were used to characterize the surface feature of the PDMS thin film. A S-TENG film with a size of $1 \times 1\ cm^2$ was attached onto the surface of a rubber wheel (7 cm in diameter) with the rough surface facing outward. The back electrode was connected to the metal rim on the wheel for induced charge collection. The total weight of the wheel is 0.5 kg. The wheel was driven by a computer-controlled linear actuator with controlled linear speeds. A polyoxymethylene plastic bar (61 cm in length) was added between the actuator and wheel to avoid the electric-field noise generated from the electromagnetic actuator. The electrical outputs of the TENG were measured using an Autolab PGSTAT302N station and an Agilent DSO1012A oscilloscope.

S-TENG on vehicle demonstration

6 PDMS S-TENGs ($1.5 \times 3.5\ cm^2$ each) were attached onto the tire surface of a toy car (each back wheel has 3 S-TENGs). A piece of Al foil was placed on the bottom of the toy car as the reference electrode. Commercial green LEDs connected in series were installed on the toy car as the vehicle’s headlights. Another electrode of the LED was connected to the reference electrode, which is equivalent to ground connection.

Results and discussion

The S-TENG design starts from the fabrication of a flexible PDMS thin film with rough friction surface. Liquid PDMS elastomer and cross-linker were mixed and uniformly casted

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