

Full paper

Study on friction-electrification coupling in sliding-mode triboelectric nanogenerator

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ABSTRACT

Triboelectric nanogenerator (TENG) is regarded as a revolutionary technology for harvesting clean and sustainable energy with low cost. Here, sliding-mode TENGs based on both graphene sheets embedded carbon (GSEC) and amorphous carbon (a-C) films were designed and their friction-electrification coupling properties were studied. The GSEC and a-C films were fabricated by electron irradiation assisted physical vapor deposition in an electron cyclotron resonance (ECR) plasma system. A novel testing platform that can simultaneously measure friction force, output voltage and output current was designed and assembled for studying the friction-electrification coupling of sliding-mode TENG. In the case of GSEC and a-C films slid against Polytetrafluoroethylene (PTFE) film, the open-circuit output voltage, the short-circuit output current density, the peak power density and the maximum instantaneous energy conversion efficiency were 13.5 V, 0.35 $\mu\text{A}/\text{cm}^2$, 0.63 mW/cm^2 and 8.61% for the GSEC film based TENG, and 8.5 V, 0.24 $\mu\text{A}/\text{cm}^2$, 0.5 mW/cm^2 and 7.71% for the a-C film based TENG, respectively. The results implied that the GSEC film exhibited a higher electric output performance compared with the a-C film. The origin of high electric output performance of the GSEC film based TENG was ascribed to the edge and channel effects of graphene sheets. These findings shed light on the application of carbon films in friction-induced nanoenergy field.

1. Introduction

With the rapid development of portable electronics, smart wearable devices and sensor networks, harvesting energy from ambient environment to reduce the use of batteries has attracted worldwide attentions. Researchers have devoted great efforts to find alternative forms of energy such as thermoelectricity [1,2], piezoelectricity [3,4], pyroelectricity [5], biofuels [6] and nanogenerator to power the wearable electronics [7]. Recently, triboelectric nanogenerator (TENG) receives widespread attentions due to its high energy conversion efficiency, high output voltage and low cost [8–12]. In the four fundamental working modes of TENG, sliding-mode TENG is an important one [13], which is triggered by relative sliding between triboelectric layers [14–16]. Especially, some researchers have found that frictional behavior at the contact interface has an influence on the energy conversion efficiency, output current, output voltage and power of TENG [17,18]. However, to the author's knowledge, little research has been devoted to investigate the frictional behavior at the sliding interface of TENG. Moreover, the relationship between frictional behavior and

electrification performance is vague. Clarifying the relationship between friction behavior and electrification performance could promote the practical application progress of sliding-mode TENG.

It is well known that sliding-mode TENG requires two triboelectric layers with opposite charges to establish a potential difference. In the aim of achieving the high output voltage, output current and output power, both polymer films and metallic films have been used as the triboelectric layers [19–22]. However, the corrosion of metal in water or humid environment is a common problem for supplying stable nanoenergy, and new materials for harvesting nanoenergy need to be developed. Carbon is environmental friendly and abundant on earth. Graphene is a rapidly rising star material [23], as a two-dimensional “aromatic” monolayer of carbon atoms with sp^2 atomic configuration, the graphene exhibits exceptionally physical properties [24–26]. Some studies have demonstrated that graphene can store electric charge for a period of time, which add its suitability for electronics and TENG [17,27–32]. Lately, our group has proposed a new method to fabricate graphene sheets embedded carbon (GSEC) film in electron cyclotron resonance (ECR) plasma with low energy electron irradiation [33]. In the process of depositing GSEC film, excess electrons may be stored in

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graphene sheets. This is similar to electron n-type doping in epitaxial graphene [34]. Theoretical calculation and experimental results have demonstrated that the edge-quantum wells of graphene sheets in GSEC film can capture excess electrons from plasma beam [35,36]. Due to under-coordination, the length of C-C bond at edge will contract significantly compared with that at center to lower the total energy. The potential well to the neighbor electrons will be deepened at the edge site with a consequence of localized densification of charge, energy and mass. In the growing process of GSEC film under low energy electron irradiation, excess electrons tend to be captured by the edge-quantum wells of graphene [35]. Based on the above studies it was anticipated that GSEC film has excellent electric property similar to graphene and may be suitable for TENG. Therefore, it was worthwhile to investigate the friction-electrification performances of GSEC film.

In this study, we introduced a novel testing platform to study the friction-electrification performances of GSEC and a-C films slid against PTFE film. The friction coefficients of GSEC and a-C films against PTFE film were measured. Besides, the electric output performance including output voltage and output current at sliding interface were simultaneously measured. Finally, the relationship between friction coefficient and electric output performances was discussed.

2. Experimental section

2.1. Deposition of carbon films

An electron irradiation assisted physical vapor deposition in ECR plasma processing system was used for fabricating GSEC and a-C films. In the ECR system, 2.45 GHz microwave with a power of 500 W was introduced to the plasma chamber through a rectangular waveguide and a quartz window. Two sets of magnetic coils were arranged around the chamber to achieve a microwave ECR condition (magnetic flux density, 875 G). Mirror confinement electron cyclotron resonance (MCECR) plasma was generated when DC power was supplied to both of the magnetic coils. A cylindrical carbon target was located in the middle of the two magnetic coils as solid carbon source for films deposition. The detailed information about the system had been reported in our previous works [36–38]. The GSEC and a-C films with thickness of 100 nm were deposited on p-type Si (100) wafers (resistivity: $< 0.0015 \Omega \text{ cm}$, thickness: $525 \mu\text{m}$) with the size of $2.5 \text{ cm} \times 2.5 \text{ cm}$. The Si wafers were cleaned with ethyl alcohol and deionized water bath successively by ultrasonic wave. Thereafter, the Si wafers were dried naturally and mounted on the sample holder. The background pressure of the vacuum chamber was pumped down to $7 \times 10^{-5} \text{ Pa}$, and the working gas of argon was introduced to keep the chamber pressure to be $4 \times 10^{-2} \text{ Pa}$. The GSEC film was fabricated under an electron irradiation energy of 50 eV and an irradiation density of 65 mA/cm^2 . The a-C film was produced under an electron irradiation energy of 5 eV and an irradiation density of 15 mA/cm^2 .

2.2. Nanostructures characterization

The nanostructures of GSEC and a-C films were observed by using a transmission electron microscope (TEM, JEM-3200, JEOL) with electron acceleration voltage of 300 kV. The bonding structures of the GSEC and a-C films were characterized by using laser confocal Raman spectroscopy (LabRAM HR Evolution, Horiba) with a 532 nm laser. The surface morphologies of GSEC and a-C films were measured by using an atomic force microscope (Dimension Edge, Bruker) with a scanning range of $5 \mu\text{m} \times 5 \mu\text{m}$. The measurements were repeated three times and an average value was obtained.

2.3. Fabrication of TENG

Generally, a TENG mainly consists of an up-part and a down-part. In this work, PTFE film was selected as the up-triboelectric layer, Si wafer,

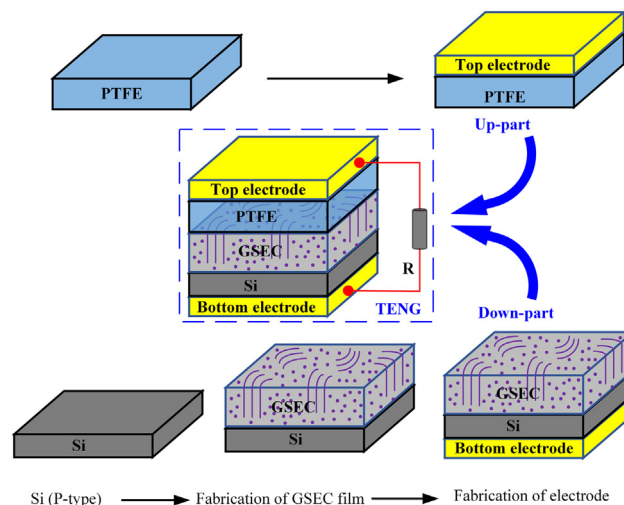


Fig. 1. Schematic illustration of the fabrication processes of GSEC film based TENG. A piece of PTFE film was cleaned and a top copper electrode was attached on the upper surface. GSEC film was deposited on the polished surface of Si and a bottom copper electrode was attached on the unpolished surface of Si. When the two parts were integrated with a load circuit, a GSEC film based TENG was fabricated.

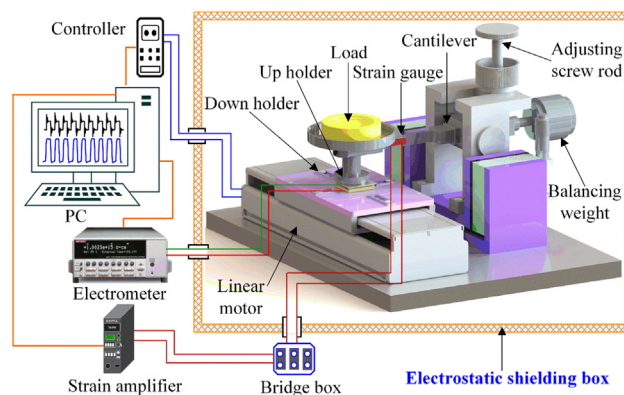


Fig. 2. Schematic diagram of the novel testing platform for evaluating friction-electrification coupling of sliding-mode TENG. Two parts of TENG were mounted on the up and down holder. The adjusting screw rod and balancing weight were used to control the contact level status of the two parts. The linear motor drove the down-part reciprocating moving, thus the two parts periodical overlap and separation. The strain gauges were pasted on the cantilever for detecting the friction force. An electrometer was used to measure the output voltage, and a low noise current preamplifier was used to measure the output current. An electrostatic shielding box was designed to improve the anti-interference property and all apparatus were well grounded.

GSEC and a-C films were selected as the down triboelectric layer. Fig. 1 shows the fabrication processes of GSEC film based TENG. Up-part: a PTFE film with dimensions of $2.5 \text{ cm} \times 2.5 \text{ cm} \times 0.01 \text{ cm}$ was cleaned in the ethyl alcohol and deionized water bath successively by ultrasonic wave. Then, a conductive copper tape was attached on one side of the PTFE film as the top electrode. Down-part: firstly, the surface of GSEC film was blown clean. Then, a layer of conductive copper tape was attached on the unpolished surface of Si wafer as the bottom electrode. When the two parts were integrated with a load circuit, a GSEC film based TENG was fabricated. The fabrication processes of a-C film and Si based TENG were identical to that of GSEC film based TENG.

2.4. The novel testing platform

A novel testing platform which can simultaneously measure the

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