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Full paper

Facile and robust triboelectric nanogenerators assembled using off-the-shelf materials

Sai Sunil Kumar Mallineni[a], Herbert Behlow[a], Yongchang Dong[a], Sriparna Bhattacharya[a], Apparao M. Rao[a,*], Ramakrishna Podila[a,b,*]

[a] Clemson Nanomaterials Institute, Department of Physics and Astronomy, Clemson University, Clemson, SC 29634, USA
[b] Laboratory of Nano-biophysics and COMSET, Clemson University, Clemson, SC 29634, USA

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ABSTRACT

Triboelectric nanogenerators (TENGs) are emerging as a new panacea for sustainable energy generation through the conversion of random mechanical motion into useful electrical energy. The present TENGs are fabricated via bottom-up approaches using novel nanomaterials (e.g., graphene and carbon nanotubes) and patterned polymers (e.g., polydimethylsiloxane or PDMS), which limit the deployment of TENGs at scales ranging from microelectronics to grid integration. Here we demonstrate a top-down approach for fabricating low-cost and ultra-simple TENGs (U-TENGs) using off-the-shelf materials for immediate proliferation into the present energy landscape. Specifically, U-TENGs constructed using indium-tin oxide (ITO) transparent conducting nanofilms on polyethylene terephthalate (PET) and polyimide/Kapton adhesive tapes is demonstrated. U-TENGs are robust (> 20,000 cycles) and inexpensive (~$0.06 cm^{-2}) with < 5 min fabrication time, can achieve a peak voltage of ~500 V and power densities as high as ~490 μW cm^{-2} without the need for any nanopatterning, and operate over a wide range of temperatures up to 60 °C. Several practical applications of U-TENGs such as LED lighting, powering electronic calculator, textile integration, and passive vehicle/pedestrian monitoring are demonstrated.

1. Introduction

Triboelectric nanogenerators (TENGs), which convert random and irregular mechanical energy into usable electrical energy, could provide promising solutions to meet global energy needs in the near future [1]. Large-scale TENGs (area ~few km^2) have been proposed for harvesting electricity from slow, random, and high-force oscillatory ocean waves at the megawatt (MW) scale through the "blue energy" paradigm [2]. In addition to macroscopic energy generation and possible grid integration at the MW scale, small-scale TENGs (area: few mm^2-cm^2) are useful for powering LEDs [3–5], pressure sensors [6–9], wearable technologies [10–13], security detection systems [7], and transportation monitoring [14,15].

In vertical contact mode TENGs, an applied force (i.e., mechanical energy) is used to bring two electrodes (chosen based on their rank in the triboelectric series [16,17] with a caveat that at least one electrode is elastic) separated from each other by insulating spacers into frictional contact. The electron clouds shared between the electrodes during the initial frictional contact redistribute unevenly, according to the differences in electronegativity and the electrode contact area, upon releasing the applied force. This generates an electrical potential difference (V) between the oppositely charged electrodes (± Q) separated from each other, much like a parallel plate capacitor (energy: $QV/2$), which could be harvested in the form of electrical energy using an external circuit. Thus, the total electrical energy of a TENG is primarily dictated by: a) the difference in electropositivity/negativity between the electrodes that limits V and b) the contact area between the electrodes that determines Q. While choosing electrode materials ranked far apart from each other in the triboelectric series (materials list based on their charge affinity measured in C J^{-1}) could maximize the net potential difference, increasing the contact area through micro/nanopattering or different modes of operation (e.g., cyclic pressing of vertically separated electrodes, in-plane sliding of electrode [18]) can enhance Q. In vertical contact mode TENGs, the use of electrodes with micro and nanostructures has been shown to enhance the performance by ~150–200% with *apparent* areal power densities in the range of ~75 nW cm^{-2}–950 μW cm^{-2} (based on the total device area without considering the excess surface area arising from micro/nanopatterns; Table S1) [3,4,19–22]. According to the classical theory, the real area of contact between two surfaces is proportional to the load, roughness of the

* Corresponding authors at: Clemson Nanomaterials Institute, Department of Physics and Astronomy, Clemson University, Clemson, SC 29634, USA.
E-mail addresses: arao@g.clemson.edu (A.M. Rao), rpodila@g.clemson.edu (R. Podila).

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harder surface, and the elastic deformation of the softer surface [23,24]. In other words, the reported enhancements in micro/nano-patterned polymer-based TENGs are only apparent because the true surface area (arising from micro/nanopatterning) is not considered in the power density calculation. The existing complex device designs and laborious & expensive micro/nano fabrication processes are inherently prohibitive for scalable production of inexpensive TENGs and thus seriously limit their practical applications and market proliferation to niche areas. At this juncture, an immediately apparent question is: can the output energy and power of TENGs be increased using commercially available inexpensive scalable materials without the need for any micro/nanopatterning?

2. Experimental section

2.1. Fabrication and characterization of U-TENG

Commercially available ITO coated PET (Sigma-Aldrich, surface resistivity 60 Ω sq^{-1}) was used as the top and bottom electrodes. Two pieces of ITO/PET film were cut into 3.5 cm×2.75 cm rectangles. Kapton adhesive tape was attached to the ITO side of one of the two ITO/PET sheets. This acts as the bottom electrode while the top electrode was ITO/PET with ITO facing a Kapton film of the bottom electrode. Four pyrex insulating spacers (~4 mm×4 mm), cut from a microscope slide, were used to separate the electrodes with an air gap of ~1 mm (Fig. 1). All the electrical measurements (e.g., Fig. 2) were obtained using Yokogawa DL 9710L digital oscilloscope using the circuit schematic shown in Fig. S3. Temperature-dependent measurements were carried out using a thermocouple attached to the mounting base of home built pushing tester and Corning PC-420D hot plate. A 14 cm×14 cm U-TENG was assembled for powering up ~200 LEDs by simple foot tapping experiment and also for use in textile integration. Another 20 cm×28 cm large area U-TENG was assembled for use in passive vehicle/pedestrian monitoring applications.

2.2. COMSOL finite element simulation

Finite-element simulations were performed using Multiphysics COMSOL with electrostatics module to theoretically model the U-TENG and estimate its maximum possible output voltage. Figs. 3a–d show the simulation of neutral, pressing, and release stages corresponding to a separation of 1, 0, 0.5, and 1 mm between the ITO and Kapton electrodes.

3. Results and discussion

We demonstrate that TENG output can be increased by choosing pairs of materials such that: i) one electrode is a compliant polymer ranked lower in the triboelectric series (i.e., easily charged negatively) with relatively low compression modulus but high compressive yield strength (to eliminate plastic deformations at higher loads), and ii) the other electrode is a thin conducting film with nanoscale roughness ranked higher in the triboelectric series. Based on these criteria, we used commercially available off-the-shelf products such as indium-tin oxide (ITO) transparent conducting films (thickness ~130 nm) on polyethylene terephthalate (PET) and polyimide/Kapton adhesive tapes (charge affinity: −70 nC J^{-1}, compressive modulus: 2.5 GPa, compressive yield strength: 150 MPa) to demonstrate an ultra-simple, robust and inexpensive TENG device (~$0.06 cm^{-2}) which can be fabricated under ~5 min, referred henceforth as U-TENG. Notably, U-TENGs exhibit (i) power densities of ~190 μW cm^{-2} (based on the total device area i.e. 3.5 cm×2.75 cm) and ~490 μW cm^{-2} (based on pushing tester contact area with diameter ~20 mm) without the need for any nanopatterning; and (ii) a maximum open-circuit output voltage (V_{OC}) of 480 V, short-circuit current (I_{SC}) of ~50 μA, and maximum peak power of 1.7 mW with no loss in performance for > 20,000 cycles. Moreover, U-TENGs were able to rapidly charge commercial capacitors (1–10 μF and voltage up to 60 V) in less than 10 min, and power electronic devices and components (e.g., handheld calculator, LEDs). Our finite-element based models clearly evidenced that the resulting outputs originated from charge-induction through triboelectric effects (discussed later in Fig. 3). Lastly, U-TENGs displayed a consistent output voltage of ~480 V even under extreme climate conditions, proving that they can function efficiently at any temperature between ambient to ~60 °C.

As shown in Figs. 1a–b, in the U-TENG device, the ITO (from the top-electrode) and Kapton (bottom electrode) are the contacting surfaces leading to triboelectrification. The use of commercially available ITO/PET and Kapton electrodes provides many advantages such as: i) reduced fabrication time without pre-processing leading to low device cost compared to traditional TENGs, which may require expensive and time consuming lithographic micro-patterning or metal-electrode deposition (see Table S1), ii) high electric power outputs due to differences in work functions (ϕ) of ITO (ϕ =4.8 eV) and Kapton (ϕ =4.3 eV), iii) long cycle life resulting from high thermal stability, high tensile strength (234 MPa), and high dielectric strength (240 V/μm) of Kapton and high electrical conductivity of ITO (~10^4 S cm^{-1}),

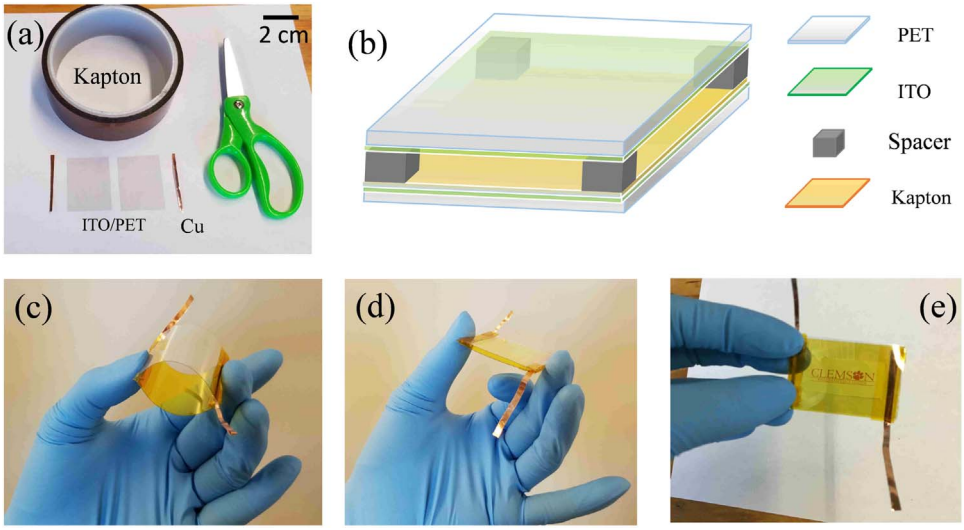

Fig. 1. (a) Materials for fabrication of U-TENG, viz., ITO/PET (3.5 cm×2.75 cm), Kapton polyimide adhesive tape, and Cu connecting wires. (b) Schematic of U-TENG, (c) U-TENG flexed to show top and bottom electrodes distinctively, (d) U-TENG in its natural state with a 1 mm air gap separating the top and bottom electrode. (e) Optical transmittance of U-TENG implies that it can be readily employed in applications that require light to pass through the U-TENG.