Scalable fabrication of triboelectric nanogenerators for commercial applications

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Abstract. Harvesting mechanical energy from irregular sources is a potential way to charge batteries for devices and sensor nodes. Triboelectric effect has been extensively utilized in energy harvesting devices as a method to convert mechanical energy into electrical energy. As triboelectric nanogenerators have immense potential to be commercialized, it is important to develop scalable fabrication methods to manufacture these devices. This paper presents scalable fabrication steps to realize large scale triboelectric nanogenerators. Roll-to-roll UV embossing and lamination techniques are used to fabricate different components of large scale triboelectric nanogenerators. The device generated a peak-to-peak voltage and current of 486 V and 21.2 μA, respectively at a frequency of 5 Hz.

1. Introduction

As the non-renewable sources of energy are depleting at a fast pace, generating green and sustainable energy is a huge challenge. Harvesting mechanical energy from various sources in environment is a potential solution to generate electrical power at a micro and macro scale. Triboelectric mechanism has become a popular approach for mechanical energy harvesting owing to its high power output, easy fabrication and wide choice of materials [1, 2].

In any triboelectric nanogenerator (TENG) device, at minimum one out of two triboelectric layers comprises of a polymer film as they can hold charges for long duration due to their insulating properties. This is important as these embedded charges on polymer films are utilized to convert mechanical energy into electrical energy by changing the gap between two triboelectric layers. To improve the performance of triboelectric mechanism using polymer films, it is also important to pattern these polymer films to improve the effective contact area and triboelectric charge separation [3,
The current fabrication processes used to fabricate triboelectric nanogenerators are not scalable as they are limited by the chamber or substrate size. This poses a bottleneck towards the large scale fabrication and commercialization of these devices. In this paper, we propose a scalable fabrication process for large size TENG devices. The polymer films are fabricated by patterning using roll-to-roll ultraviolet (UV) embossing process. This process is used to fabricate very large size samples of patterned polyethylene terephthalate (PET) films. The device electrode was fabricated by laminating large size copper film on a liquid crystal polymer (LCP) film substrate. These components are then assembled together to realize large size device for mechanical energy harvesting using triboelectric mechanism.

2. Device design and fabrication

2.1. Design
The device uses triboelectric effect to generate charges by contact and separation between two triboelectric layers. The first triboelectric layer comprises of patterned PET film whereas the second triboelectric layer is fabricated by laminating large size copper sheet to a LCP substrate. The two materials are chosen as triboelectric pair as patterned PET film has a higher tendency of accepting electrons as compared to copper when the two triboelectric layers come in contact due to external mechanical force. Spacers at regular intervals between the two triboelectric layers to maintain the gap to avoid sagging of the large size films together hindering the contact separation process.

2.2. Fabrication
The large size patterned PET film used as first triboelectric layer was fabricated using roll-to-roll UV embossing [5]. The schematic of fabrication setup for roll-to-roll UV embossing is shown in Figure 1. The setup can be divided into four parts. First is the unwinding module which supplies the substrate PET film. The second part is the coating module which deposits UV curable resin on PET film using slot deposition process. Following the coating module is third part, which is UV embossing module for patterning microstructures on PET film. This module uses a patterned roller to transfer the required patterns and uses UV lamp placed beneath the embossing roller to cure the transferred patterns on the PET film. The fourth part is rewinding module that provides web tension for separating the embossed PET film from the embossing roller and then rewinds for collecting the embossed PET film. An optical image of a patterned PET film with line patterns (line pitch: 500 µm) using roll-to-roll UV embossing is shown in Figure 2. Large patterned films were cut into size of 40 cm x 40 cm size sheets. These patterned PET sheets were used to increase the contact area between the triboelectric layers during contact electrification.

For the second triboelectric layer, an 18 µm thick copper film was attached on top of 50 µm thick LCP substrate using lamination. To realize the complete device, 1 mm thick spacers were assembled on the patterned PET film in order to create a gap the two triboelectric layers as shown in Figure 2.
The copper film was then assembled on top of spacers. As the PET film has a large size, the film tends to sag down permanently onto the copper electrode which hinders the contact separation mechanism required for charge generation for mechanical energy harvesting. Therefore it is important to assemble spacers at regular spacing between copper and patterned PET triboelectric layer to help the large patterned polymer film rebound back to its original position after it is subjected to mechanical force. A schematic of the complete device is shown in Figure 2.

![Schematic of the complete device](image)

**Figure 2.** Assembly of the large scale triboelectric nanogenerators

2.3. *Working mechanism*

The schematic for operating mechanism of LS-TENG is shown in Figure 3. Both the triboelectric layers are initially uncharged before coming into contact with each other. As an external mechanical force is applied on the device due to different activities like walking, palm tapping etc., both the triboelectric layers come in contact with each other. This results into transfer of electrons from the copper film to patterned PET film due to copper’s higher tendency to donate electrons relative to PET. The charges on the patterned PET film are preserved due to its insulating properties. And the charges on conductive copper film can flow through the load resistor connected to the ground as electric potential changes at the copper electrode. As the applied force is released, the patterned PET film with the negative charges separates from the copper film. This results into an increase in the potential at the copper electrode. This leads to flow of electrons from the reference ground electrode towards the copper electrode. As the patterned PET film reaches the maximum point of separation between the two triboelectric layers, electrostatic equilibrium is reached and there is no flow of electrons in the load resistor connected between electrode and ground. Thereafter, the patterned PET film again approaches towards the copper film due to periodic mechanical force. This leads to the flow of electrons in the load resistor in opposite direction. The flow of electrons in the load resistor during the approaching and separating motion of triboelectric layers can be used to power an electrical load.

![Operating principle of the TENG](image)

**Figure 3.** Operating principle of the TENG
3. Results and discussion
The fabricated device was tested under different conditions to observe the device characteristics. The device was also demonstrated for practical applications for different situations. The voltage characteristics were measured using a 100 MΩ probe with DSOX3034A oscilloscope. The current characteristics were measured using a low noise SR570 current pre-amplifier. The testing results are discussed in the following sections.

3.1. Device characteristics at different operating frequencies
The large size device was tested using hand tapping to measure the generated voltage and current. The voltage and current output were tested at different tapping frequencies from 1 Hz to 5 Hz. Both voltage and current output were observed to increase as the frequency of applied force was increased as shown in Figure 4. The peak-to-peak voltage increased from 232 V to 486 V as the frequency increased from 1 Hz to 5 Hz. The peak-to-peak current increased from 7.2 µA to 21.2 µA as the frequency increased from 1 Hz to 5 Hz. The increase in voltage output with increased frequency is due to increased value of applied force as the tapping frequency increased. The higher applied force led to increased contact area between the triboelectric layers resulting in higher voltage output. The increase in the current output can be explained by the combined effect of the increased force and the reduction of the cycle time for the charges to flow in the external circuit as the tapping frequency increased.

![Figure 4](image)

3.2. Applications
The device was tested for different practical scenarios to demonstrate its applicability. The device was tested using a normal sized football bouncing on the large sized device. The device generated a peak-to-peak voltage of 78 V due to the ball bouncing on the large sized device as shown in Figure 5a. The device was also assembled on the back of a chair to harvest energy from reclining human motion as shown in Figure 5b. As the reclining angle increased from 5° to 20°, the peak-to-peak voltage increased.

![Figure 5](image)
increased continuously as shown in Figure 5b. The increase in reclining angle resulted into higher impact force which in turn led to higher output voltage. The assembled device at the back of chair was also tested to harvest mechanical energy from irregular motion of the human subject while working on a desktop computer. A commercial 3-axis accelerometer ADXL325 was used to measure the activity level of the human subject as shown in Figure 6. The TENG device generated peak-to-peak voltage and current of up to 85 V and 0.75 µA, respectively during high activity as compared to 35 V and 0.3 µA during low activity.

![Graphs showing voltage, current, and acceleration over time](image)

**Figure 6.** (a) Voltage and (b) current generated by irregular human motion

4. Conclusion
We have developed and demonstrated a process flow for large scale fabrication of TENGs with high throughput. Roll-to-roll UV embossing has been utilized to fabricate large size patterned polymer films. Using scalable fabrication processes, TENGs can be manufactured for commercial applications at a large scale. The device was tested different scenarios to demonstrate the practical application of the large scale device. The device generated a device generated a peak-to-peak voltage and current of 486 V and 21.2 µA, respectively.

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