REALIZATION OF TRIBOELECTRIC ENERGY HARVESTERS USING STEEL-POLYMER MICROFABRICATION METHODS

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ABSTRACT

Triboelectric nanogenerators (TENG) are developed for wireless and batteryless keyboard applications, using steel-polymer microfabrication methods including lithography, electrochemical etching, hot embossing and thermo-compression bonding. Microfabricated steel electrode and polymer film (polyethylene naphthalate (PEN)) are used for the first time to implement a TENG of conductor-to-dielectric contact-mode type. Crab leg shaped design is applied on 50 µm thick steel film to harvest energy. Triboelectric effect between polydimethylsiloxane (PDMS) and steel surfaces is characterized. Maximum instantenous power density of 6 µW/cm2 is achieved for 1 mm displacement of 1 Hz motion. Triboelectric surface charge density between steel and PDMS surface is found as 3.2 µC/m2.

INTRODUCTION

TENGs are promising energy harvesters that convert mechanical energy into electricity by triboelectrification and electrostatic induction. They offer simple and cost effective solutions to wireless and batteryless systems of portable electronics, self-powered sensors [1] and wearable or implantable biomedical devices [2]. They can generate very high open circuit voltages with typical values ranging from 120 to 1200 V. Since generated energy of TENGs depends on surface area not volume, they can be flexible and stacked [3-5]. There are many materials, mostly polymers, to choose from as active layers in device implementation. In addition, their efficiencies can be enhanced easily by micro and nano surface texturing, which increases their effective surface areas [6]. Significant improvements have been achieved rapidly in this field since 2012. Current density of 15.5 µA/cm2 and power per area of 313 W/m2 are reported [7, 8]. Energy conversion efficiency of 39% has been demonstrated [9]. Textile-based wearable ones have been developed [10, 11].

The motivation of this study is to produce TENGs for different practical wireless and batteryless applications, such as keyboards (Figure 1), using easy and cost efficient microfabrication methods, which allow batch fabrication. Even with the increased interest on TENGs, there are still uncharacterized materials for their triboelectric effects such as PDMS and steel. This study also makes this characterization.

CONCEPT AND PRINCIPLE

In order to achieve simple and inexpensive steel-polymer microfabrication methods to fabricate TENGs, steel electrode is attached between two PEN substrates using hot embossing and thermo-compression bonding. Stainless steel has reliable mechanical properties to fabricate movable electrode which can act as spring for a certain distance of movement without plastic deformation. Crab leg shaped design is used in order to achieve out of plane actuation, forming a parallel plate capacitor with the fixed electrode on the substrate surface. Due to its coefficient of thermal expansion (CTE) of 17 x 10^{-6} K^{-1} which is well matched to the CTE of stainless steel, 125-µm-thick PEN sheet is used as substrate to attach steel on without buckling [12]. These PEN substrates act as a spacer to limit movement distance of steel electrode to avoid plastic deformation.

For better efficiency, materials towards positive side of the triboelectric series must be selected for one active layer and material towards negative side for the other active layer. This way, higher surface charge densities between the active layers of the device can be achieved after triboelectrification. In this study, PDMS which is close to the most negatively charged materials, and steel which is located near the bottom of positively charged materials [7], close to neutral ones, is used as active layers of device.

There are two common device structure for harvesting energy via triboelectrification which are called contact mode and sliding mode [1]. Herein, we are focused on contact mode device structure in which energy can easily be harvested from direct mechanical motions such as pressing or tapping. This mode is also useful to harvest energy from many daily motions such as walking, and running.

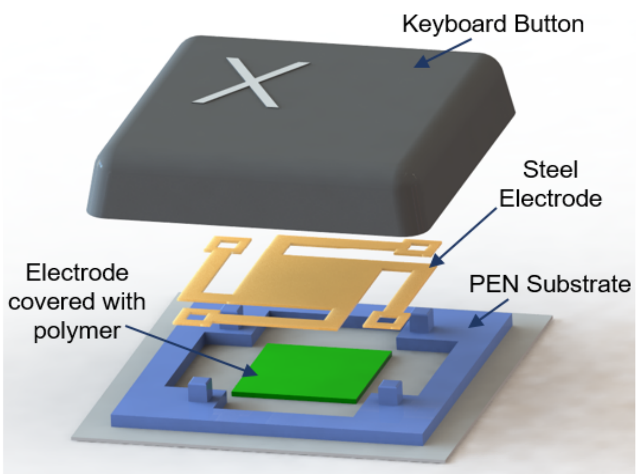

Figure 1: Demonstration of the triboelectric energy harvester in wireless and batteryless keyboard application.

FABRICATION

Fabrication of the device starts with the application of lithography on stainless steel film. Photoresist is spin coated and patterned with the crab-leg design on a 4 cm by 4 cm steel film, which is properly cut and shaped with scissors. This is followed by electrochemical etching of steel, which etches through 50-µm-thick film in NaCl-H_2O (1:4 by weight) solution by applying 3 A/cm^2 electrical current density [13] for two minutes. Steel film after electrochemical etching is shown in Figure 2.

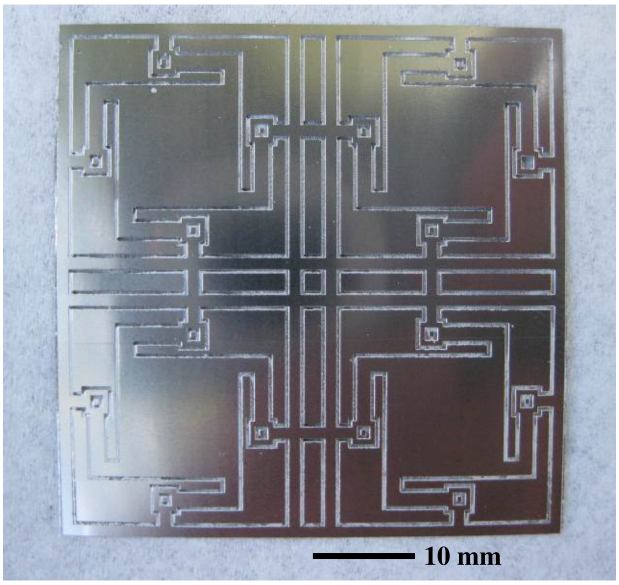

Figure 2: Steel film after electrochemical etching.

In order to help in dropping the etched-through pieces and removing the rough residues around the remaining pieces, wet etching of steel in HNO_3-HCl-H_2O (1:3:10) solution is used. Figure 3 shows the crab leg electrodes after this wet etching.

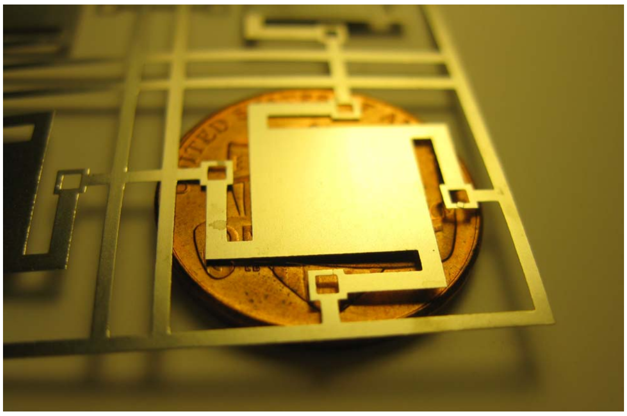

Figure 3: Microstructures (on a penny) formed on steel film after wet etching.

In the next step of the fabrication, 125-µm-thick DuPont Teijin Q65FA heat stabilized PEN film as substrate is laser cut to shape anchor and suspension regions on the substrate. Then, steel crab-leg electrodes are embedded into PEN substrate by using hot embossing. This is achieved by pressing this steel electrode under 2500 pound load at 140 °C (Figure 3a-b). After integrating steel electrode to PEN substrate, both this substrate and another PEN film that is laser-cut as cover plate are put into ethanol-chloroform (1:1) solution for 5 minutes in order to activate their surfaces for bonding. For bonding PEN cover to substrate, thermo-compression bonding at 120 °C under 1500 pound load is applied as illustrated in Figure 3b-c. Square shaped holes on the steel electrode increase the bonding area at anchor regions and help to hold steel electrode firmly between two PEN films. Fixing steel electrode between two substrates also limits the maximum displacement to 125 µm, which is the thickness of the PEN substrate for this case.

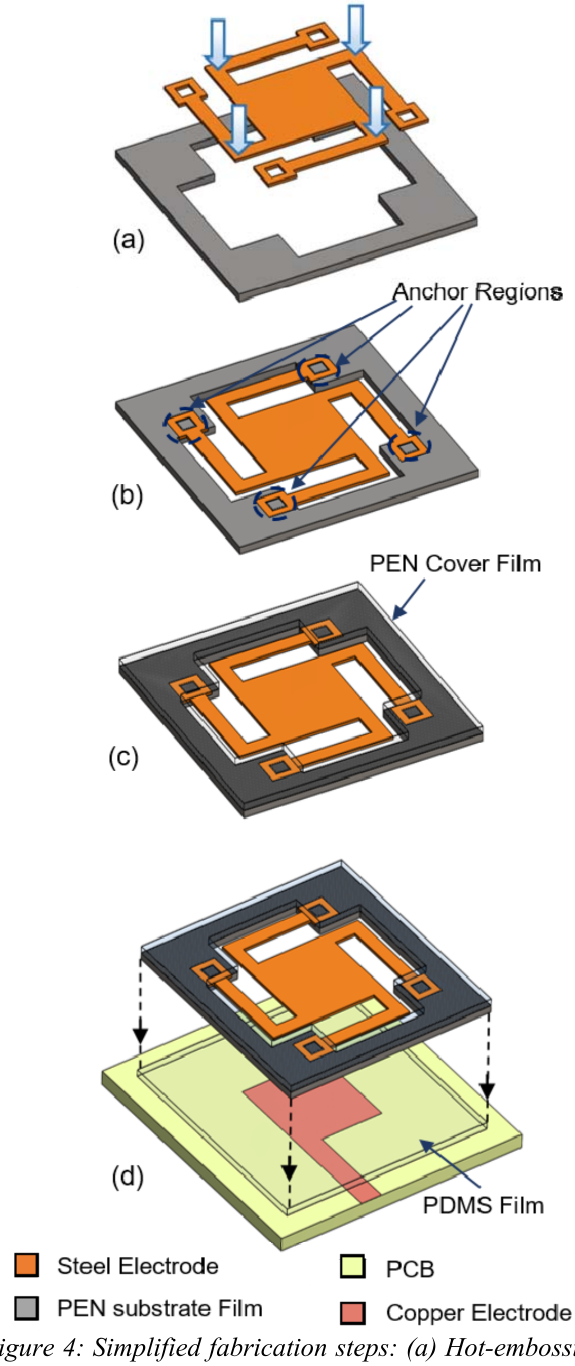

Figure 4: Simplified fabrication steps: (a) Hot-embossing of PEN and crab-leg shaped steel electrode at 140 °C under 2500 pound load (b & c) Thermo-compression bonding of substrate and cover PEN films at 120 °C under 1500 pound load for steel electrode integration, (d) Attachment of steel electrode, which is between two PEN films, to PDMS film, which covers copper electrode.

In the final step of fabrication, a copper electrode on printed circuit board (PCB) is coated with 150 µm thick PDMS dielectric layer and cured overnight. PDMS solution is prepared by mixing its elastomer and curing agent with a weight ratio of 10:1 (Sylgard 184 silicone elastomer kit). Finally, steel electrode incorporated between two PEN layers is placed on PDMS layer, which covers the copper electrode (Figure 3d).

RESULTS AND DISCUSSION

To characterize triboelectrification between steel and PDMS surfaces, measurements and SPICE simulations are done. Equivalent circuit model of TENG used for SPICE simulations [14] is shown in Figure 5. Structural layers of the device are also drawn in this figure showing related device parameters.

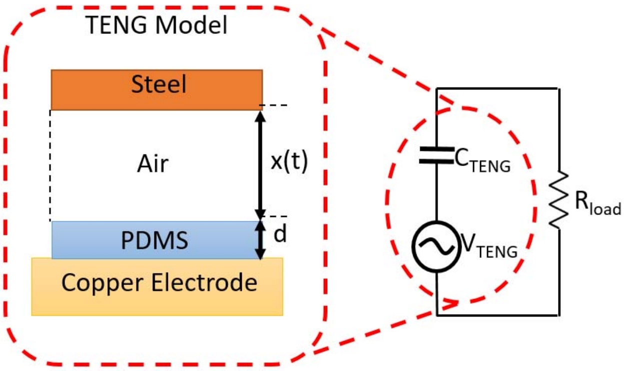

Figure 5: TENG model and equivalent circuit.

According to this model voltage generated by TENG (V_{TENG}) and its internal capacitance (C_{TENG}) can be described by the following equations:

$$V_{TENG} = \frac{\sigma x(t)}{\varepsilon_0} \quad (1)$$

$$C_{TENG} = \frac{\varepsilon_0 A}{\left(\frac{d}{\varepsilon_r}\right) + x(t)} \quad (2)$$

where σ is the surface charge density, A is the effective contact area between steel and PDMS surfaces, d is the thickness and ε_r the dielectric constant of the PDMS layer, ε_0 is the permittivity of air and x(t) is the time variant gap between steel electrode and PDMS.

In order to characterize triboelectric effect between steel and PDMS and find the value of the formed surface charge density, energy harvesters with 22 cm^2 effective area A, ~150 µm PDMS thickness d, and maximum displacement distance of 1 mm between PDMS and steel surfaces are used in measurements. Figure 6 shows the measured voltage on 345 MΩ load resistance with respect to time during 1 Hz periodical motion of pressing and releasing of steel electrode.

These experiments are repeated while changing load resistance. Instantaneous power is calculated from the average of the maximum peak voltage values for different loads. Figure 7 shows instantaneous power per area when load resistance changes from 10 to 650 MΩ. Maximum power density of 6 µW/cm^2 is achieved. Surface charge density is extracted as 3.2 x10^{-6} C/m^2 from the SPICE simulations that fit to these experimental results.

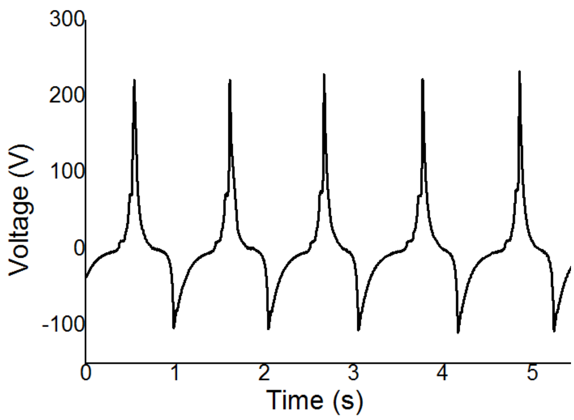

Figure 6: Voltage vs time measurement for characterization of triboelectrification between steel and PDMS (R_{load} = 345 MΩ).

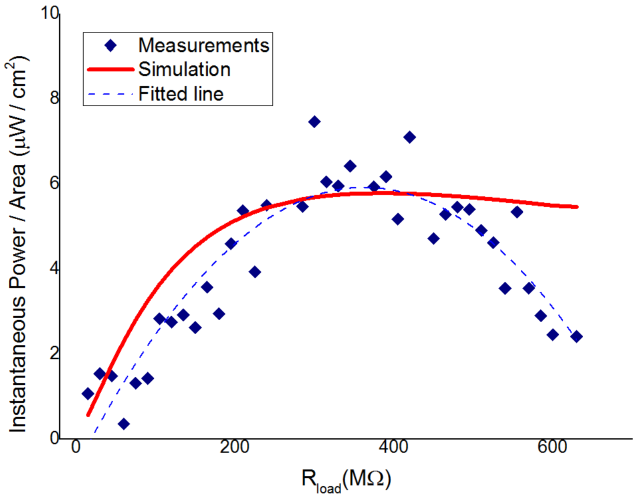

Figure 7: Load resistance (R_{load}) vs. instantaneous power per area graph of the device.

Finally, microfabricated steel-PDMS crab leg device is tested. To measure harvested voltage of the fabricated device, it is placed into a 3D printed stage to generate press and release cycles with a frequency of 1 Hz as shown in Figure 8.

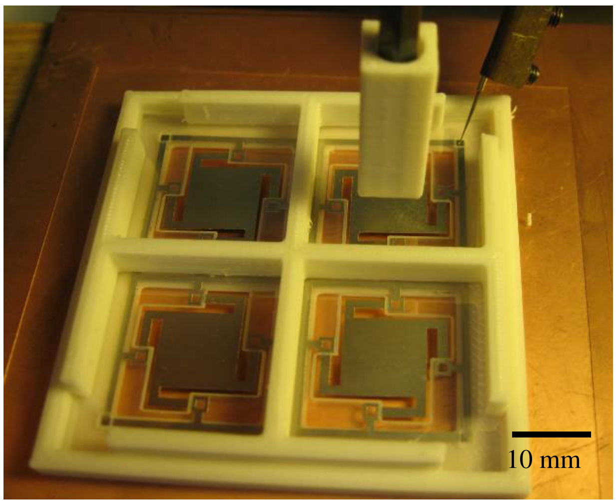

Figure 8: Device under test.

Resulting generated voltage versus time graph across load resistance of 2 GΩ connected to the harvester is shown in Figure 9. Peak-to-peak voltage of 40 V is achieved in these measurements.

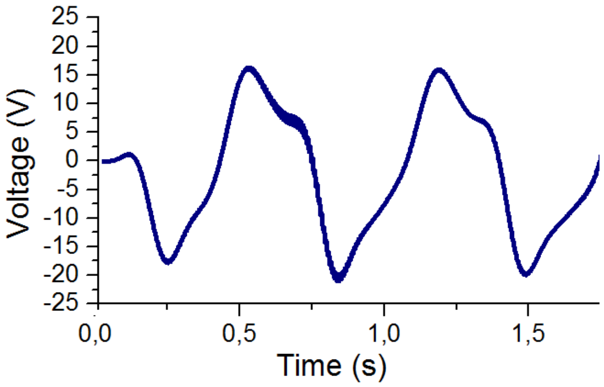

Figure 9: Voltage vs. time graph of the device while periodically pressing and releasing the steel electrode ($R_{load} = 2$ GΩ).

CONCLUSION

In this paper, a reliable and batch-fabricatable TENG platform which has maximum instantaneous power per area of 6 μW/cm^2 is introduced. The fabricated device uses crab leg shaped steel electrode and PDMS layer. The device can have higher efficiencies with its surfaces nano-structured, which effectively increases active area of the device and lowers its equivalent impedance. The latter is important when used with power managing integrated circuits, which can achieve impedance matching and maximum power transfer at practical impedance levels of couple MΩ. In addition, coating surface of the steel electrode with a polymer of more positive contact charging such as nylon 6,6 can dramatically improve the performance of the device. It is also possible to enhance its power density by stacking thin layers of steel and polymer.

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