Comprehensive Analysis of Deformation of Interfacial Micro-Nano Structure by Applied Force in Triboelectric Energy Harvester

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Abstract

The correlation between the deformation of an interfacial micro-nano structure and the applied pressure in a triboelectric energy harvester (TEH) is analyzed for the first time. The modeling, simulation, visualization experiment, and electrical measurements are conducted in order to clarify the effects of the structural deformation, which governs the triboelectric charge density. The results imply that a small-sized structure is advantageous in output power, while a large-sized structure is advantageous in the pressure sensing range.

Introduction

Triboelectricity has long been considered an unwanted phenomenon and is the cause of breakdown in electronics, fires, and human discomfort. However, strong triboelectricity can be an effective energy source when utilized in an energy harvester. A triboelectric energy harvester (TEH), i.e. a triboelectric nanogenerator, intentionally generates strong triboelectricity through contacting two different materials, and it uses the strong triboelectric charges to drive an iterative current via electrostatic induction (Fig. 1) [1, 2].

Micro-nano structures are often formed on triboelectric surfaces in order to increase the effective contact area at the contact interface. The enlarged contact area generates larger triboelectric charges, which results in increased induced currents. Various interfacial structures, e.g. well-ordered microstructures, nanoparticle array structures, and nature-replicated structures, have been introduced for performance improvements in TEHs [3-5].

For conventional TEHs without interface micro-nano structures, applied pressure is not considered to be an important variable because triboelectric charging occurs whether the contact pressure is strong or not. However, when micro-nano structures are formed on the triboelectric surface, the applied pressure could critically affect the performance of TEHs due to the deformation behaviors of the interfacial micro-nano structures (Fig. 2). In this study, the correlation between the deformation of the interfacial micro-nano structures and the applied pressure is comprehensively analyzed using modeling, simulation, visualization experiments, and electrical measurements.

Experimental Setup

A rigid double-plate connected and supported by two springs was used as an experimental template in order to ensure iterative contact and separation operations (Fig. 3). An Ag-deposited silicon wafer was fixed to the top plate. The Ag layer had dual functions of being a triboelectric surface and a top electrode. A polymer layer (polydimethylsiloxane; PDMS), which was attached to the Au-deposited silicon wafer, was fixed at the bottom plate. The Au layer beneath the PDMS layer behaved as a bottom electrode and the polymer layer behaved as a counter triboelectric surface. According to the triboelectric tendency, PDMS is an excellent electron-accepting material while Ag is a good electron-donor material [5]. Therefore, PDMS can easily obtain electrons from Ag when they are brought into contact. The thickness of the PDMS layer was 400 μm.

A PDMS pyramid array was formed using the replica-molding process (Fig. 4) [6]. The master template of the replica-molding process was fabricated on a silicon wafer. A dot array was patterned on the wafer using photolithography, and the wafer was subsequently dipped into a KOH solution for the anisotropic etching of the silicon. Through splitting the sizes of the dot array, pyramid array structures with various sizes were fabricated (Fig. 5).

During the measurement, the shaker machine repeatedly applied pressure (P) to the top plate of the TEH (Fig. 6). The vibration frequency was 1 Hz and all electrical data were measured 3 min after the vibration began. The humidity, which is an important variable in TEH [5], was maintained at 55~65 % for equitable comparisons. The output open-circuit voltage and short-circuit current were measured using an electrometer (Keithley 6514).

Results and Discussion

Square-shaped open-circuit voltage and peak-shaped short-circuit currents were produced from the TEHs (Figs. 7 and 8). At the contact state, the distance between the top electrode and polymer surface was extremely close; therefore, positive charges accumulated at the top electrode in order to compensate the fixed negative triboelectric charges at the polymer surface. In contrast, in the separation state, the bottom electrode was closer to the polymer surface; thus, positive charges accumulated at the bottom electrode in order to compensate the fixed negative triboelectric charges at the polymer surface. The amount of positive charges flowing governs the output power of TEH (Fig. 7). Because the contact process caused by the instantaneous pressure occurs much faster than the separation process caused by the restoring force of the springs, the positive current peak at the contact process exhibited a higher intensity but a shorter flow time (Fig. 8). The total amounts of flowing charges during the contact and separation processes were the same. The strong instantaneous power of the TEHs was sufficient to directly light 25 serially connected LEDs without a storage component (Fig. 9).

For conceptual understanding of the pressure-deformation relationship, a finite-element simulation (COMSOL) as conducted in order to extract the displacement profiles (Fig. 10). Under a weak pressure, only the tip of the pyramid was affected by the top metal plate. In this 'partial contact' condition, only a small amount of triboelectric charge was generated. As the pressure increased, the entire polymer surface came into contact. The generated triboelectric charges became saturated in this 'full contact' condition. The expected pressure-deformation relationship was also experimentally visualized using a specifically designed experiment (Fig. 11). In this experiment, a transparent glass slide is used as the top plate instead of a metal-deposited silicon wafer. The top-view profiles of the deformed PDMS pyramid array placed under the glass slide can be observed using an optical microscope. From the result, the observed deformation profile was similar to the simulation.

For a deeper understanding of the pressure-deformation relationship, analytical modeling was conducted (Fig. 12). As the applied pressure increased, the increased deformation of the elastic pyramid produced a stronger restoring force in order to become force equilibrium. Therefore, the initial deformation in the early stage was sensitive to small pressure changes, but further deformation toward full contact required much stronger pressures. According to the modeling result, the open circuit voltage was proportional to $(\sigma T/\varepsilon)(TP/EL)^{2/3}$, where σ is the triboelectric charge density of the flat polymer surface, T is the thickness of the polymer layer, ε is the dielectric constant of the polymer, P is the vertical pressure, E is Young's modulus of the polymer, and L is the unit length of the pyramid structure.

From the electrical measurements, the open circuit voltage was sensitive to pressure changes in a small pressure range (i.e. partial contact conditions), but the increment ratio decreased in high pressure ranges (i.e. full contact conditions) (Fig. 13). The measured data for the small pressure range were well fitted to the partial contact model; however, the difference between the measured data and the model increased as the pressure increased (Fig. 14). The difference between the measured data and the partial contact model was severe for small-sized pyramid arrays, which could be understood because the partial contact range of the small-sized pyramid was smaller than that of the large-sized pyramid. That is, a TEH with a small-sized interface structure requires a small pressure to develop into the full contact condition, while the TEH with a large-sized structure requires a strong pressure to develop into the full contact condition. Based on these analyses, TEHs with small-sized nanostructures are advantageous for the output power, in particular for applications to harvest small forces. In contrast, large-sized microstructures are advantageous in the pressure sensing range when TEHs are used for pressure sensor applications (Fig. 15).

In order to ensure the endurance of the experimented TEH, the iterative contact and separation operations were conducted continuously over two days with a vibration frequency of 2 Hz (Fig. 16). The output-induced current was not significantly degraded during and after the stress.

Conclusion

The results of this study confirmed that the triboelectricity of micro-nano structures in TEHs was strongly influenced by the applied pressure. The analyzed results could provide guidelines for designing multi-purpose triboelectric devices that could be used as energy harvesters and pressure sensors. Engineers should carefully design the interfacial micro-nano structures considering the target application of the TEH.

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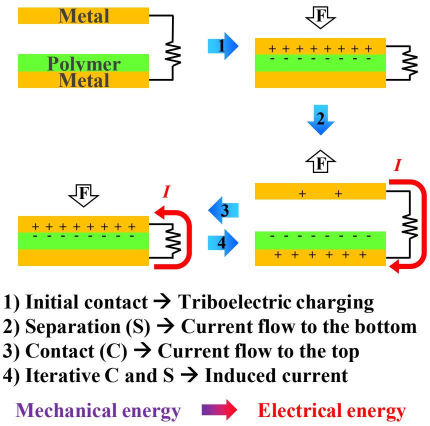


Fig. 1. Operating principle of the TEH. Fixed triboelectric charges at the polymer surface attract counter charges at the top and bottom electrodes at the separation and contact states, respectively.

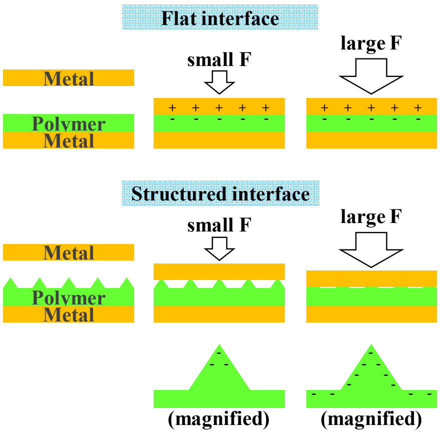


Fig. 2. Conceptual force dependency of TEH when the interface has a flat structure, and raised micro-nano structures. A greater degree of force dependency is anticipated when micro-nano structure exists at the interface.

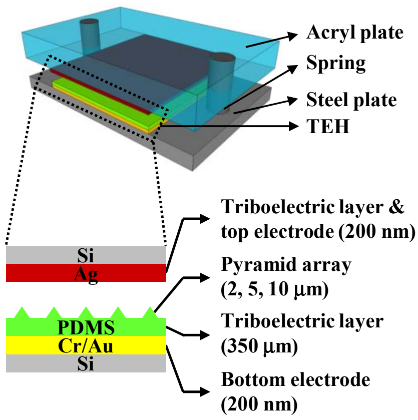


Fig. 3. Schematic of experimental device. The platform device is composed of two rigid plates supported by two springs at the edges. Ag and PDMS layers are used as triboelectric layers. PDMS layer contains pyramid array structures.

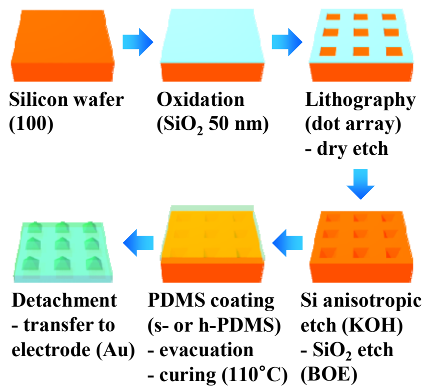


Fig. 4. Fabrication procedure of the PDMS layer with pyramid array structure using replica-molding process. A silicon mold template (an inverse pyramid array) is fabricated by natural anisotropic etch using KOH solution.

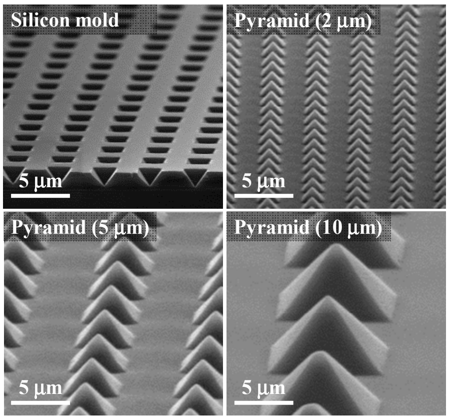
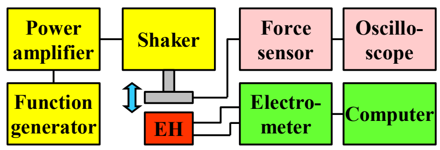


Fig. 5. SEM images of the silicon mold template and fabricated pyramid array structures with various sizes. Pyramid structures are selected due to their positive side-angle which is suitable for analyzing force dependency.



Electrometer	Keithley 6514
Shaker	LW-140-110
Sampling frequency	5 kHz
Cycling frequency	1 Hz
Warm-up time	3 min
Relative humidity	55~65 %

Fig. 6. Measurement set-up and experimental conditions. The shaker can apply tunable pressures to the triboelectric energy harvester, and output voltage and current are measured by electrometer.

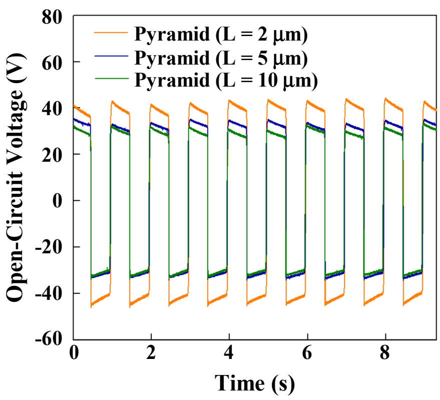


Fig. 7. Open-circuit voltage of TEH with pyramid array structures with various sizes. Voltage-decaying behavior at stationary state is caused by discharging of electrons through the parasitic resistance.

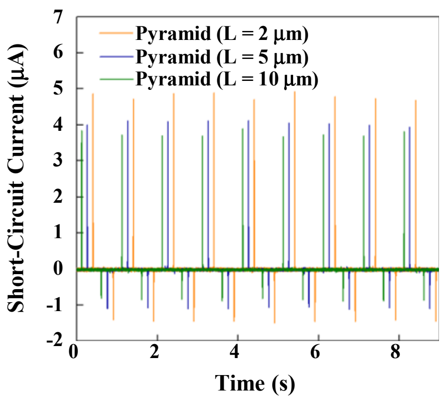


Fig. 8. Short-circuit current of TEH with pyramid array structures with various sizes. The instantaneous current is higher at the moment of contact because the contact process happens faster than the release process.

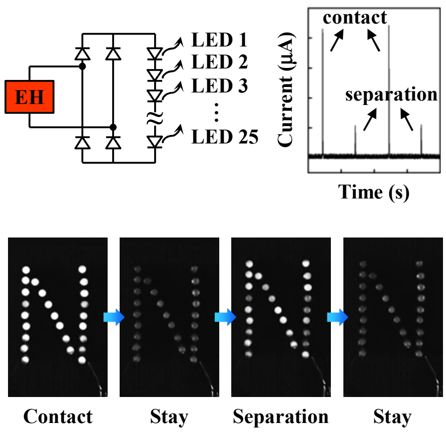
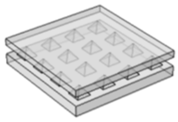
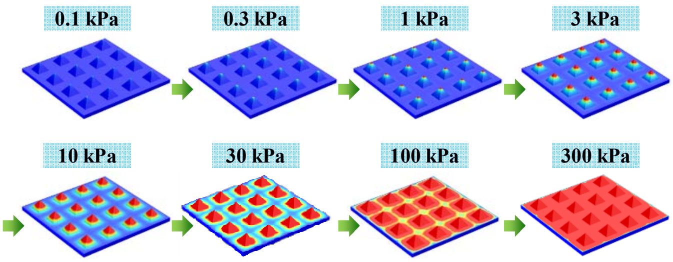


Fig. 9. Real-time operation of 25 LEDs directly connected to the TEH without any storage component. All LEDs are connected in series. Rectifying bridge circuit is inserted between the TEH and LEDs.



Property	PDMS	Metal
Density	965 kg/m^3	19300 kg/m^3
Young's modulus	2.1 MPa	70 GPa
Poisson's ratio	0.49	0.44



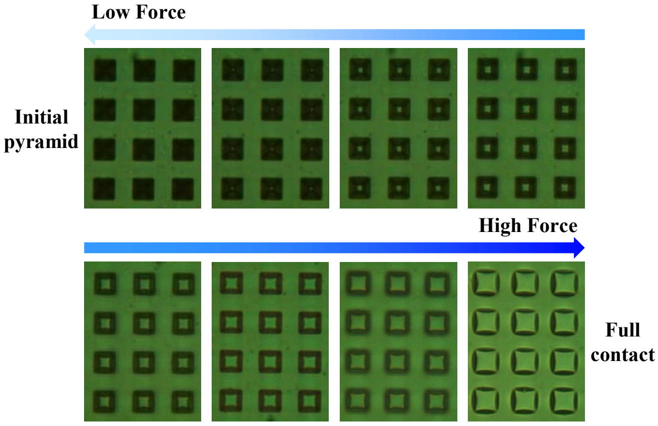
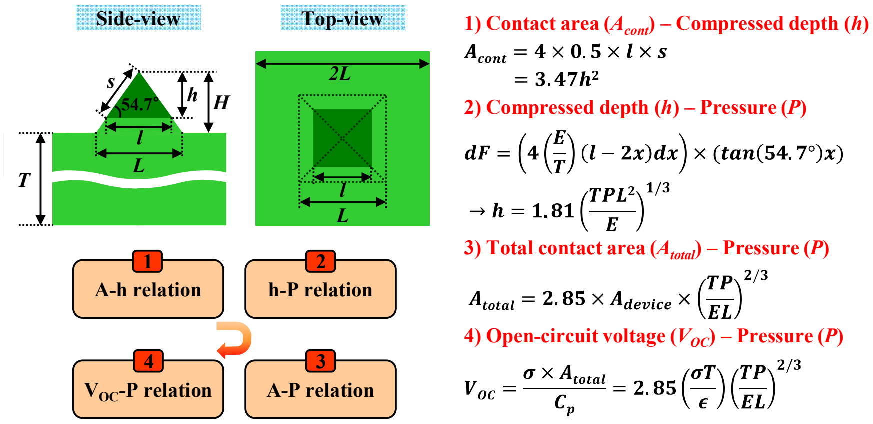


Fig. 10. Simulated displacement profile (COMSOL) with various pressures. The pressures are vertically applied to the top rigid metal plate, which delivers the force to the underlying pyramid array made of soft polymer (PDMS). The top plate is hidden in the color profiles for clearer visualization. Wider area are affected when stronger pressures are applied.

Fig. 11. Optical microscope images visualizing the deformation of the PDMS pyramid array. The images are taken while vertical forces are applied to a transparent glass slide on the pyramid array. The bright parts in the pyramids are the compressed regions where forces are focused, and the dark parts are uncompressed regions, which maintain initial shape.



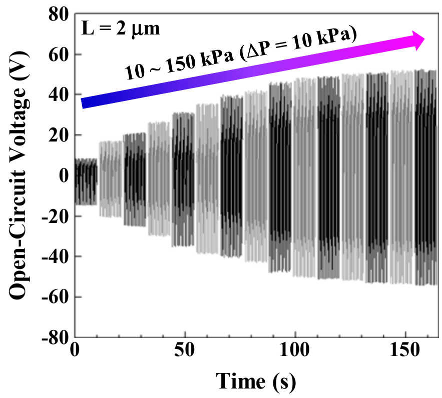
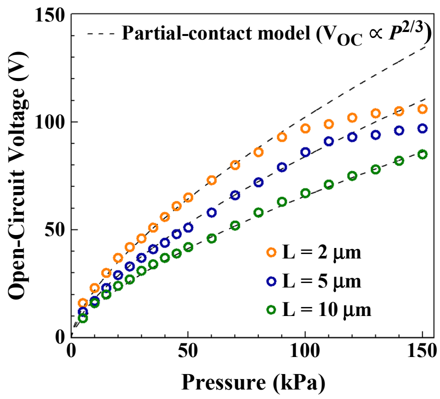
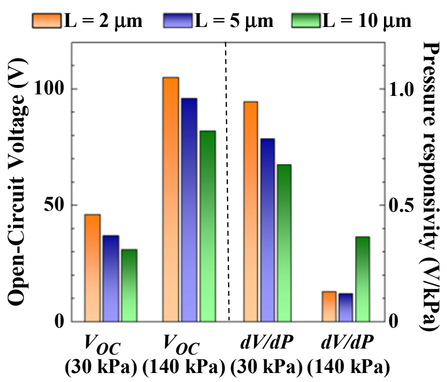


Fig. 12. The analytical model of the relationship between open-circuit voltage (V_{OC}) and applied pressure (P). The model is only valid for a pyramid array structures made of soft polymer. The dark green part of the pyramid indicates a contacted part, *i.e.* a compressed part, and the bright green part indicates the other part without deformation. This model is only applicable for the partial contact condition, i.e., the compressed depth (h) is smaller than pyramid height (H).

Fig. 13. Measured open-circuit voltage of TEH with a pyramid array structure. As stronger pressure is applied, larger area is contacted generating larger triboelectricity, so open-circuit voltage is increased.





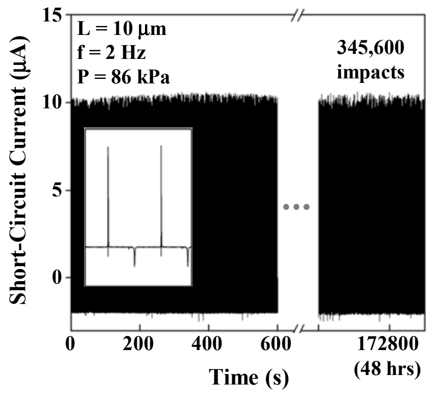


Fig. 14. Correlation of pressure and open-circuit voltage. Under strong pressure, the measured value from the small-sized pyramid is not fitted to the partial-contact model because small-sized pyramid easily get into full-contact mode.

Fig. 15. Open-circuit voltage (V_{OC}) and pressure sensitivity (dV/dP) under two different pressure conditions. The small-sized pyramid is advantageous on the output power, but disadvantageous on the pressure sensing range.

Fig. 16. Endurance characteristic of the experimented TEH. Output power is not significantly degraded for 2 days of stress. Applied pressure was 86 kPa, which is the strongest pressure used in this work.