Design Guidelines of Stretchable Pressure Sensors-Based Triboelectrification

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In this paper, a comprehensive study for a stretchable self-powered pressure sensor is presented to investigate the structural parameters effect on the sensor sensitivity, and the pressure sensor is designed based on a vertical contact-separation mode triboelectric nanogenerator (TENG). By addressing the solid mechanics, electrical, and surface science effects, we discussed the fundamental physics of the TENG pressure sensor. Modeling and simulation by finite element method (FEA) are conducted to clarify the effects of the structural dimensions on the performance of the pressure sensor. In addition, the relationship between the deformation of an interfacial micro-nano structure and the applied pressure on a triboelectric energy harvester (TEH) is analyzed for different microstructures patterns and dimensions. Finally, a comparison is conducted between TENG pressure sensor based on the contact-separation mode (CS) and single electrode mode (SE). The results show that both structure sizes of the pressure sensor and TENG operating modes have a significant influence on the pressure sensitivity of the sensor.

1. Introduction

Pressure sensors is a fascinating topic for researchers because of its important role in the human–machine interaction. Much important research effort is focusing on how to improve the sensitivity, spatial resolution, response time, long-time stability, and cyclic reliability of the pressure sensor devices. To improve the pressure performance, the state-of-art micro/nanoscale fabrication is used which is accomplished through building a matrix of nanodevices on flexible/transparent substrates for high-resolution shape-adaptive pressure imaging. However, to work properly, all these sensors require external power resources.

To solve this issue, triboelectric nanogenerators (TENG) is proposed as a promising method to drive the sensors and as a sensor. TENG is an innovative energy harvesting and active sensing technique based on contact electrification and electrostatic induction, which is used for transportable devices, stretchable sensors, and wearable electronics. For example, single-electrode mode TENG is designed as a self-powered sensor. The basic theory of the TENG starting from the Maxwell equations, which gives a direct relation between Maxwell’s displacement current and the output of TENG, which means that TENGs are the applications of Maxwell’s displacement current in energy and sensors fields. Remarkable progress is achieved in the nanogenerator-based active sensor for possible applications, that is a self-powered, highly sensitive, and fast responsive pressure sensor based on the triboelectric effect. Stretchability of the TENG pressure sensor can lead to higher load capacity as well as improvement in the electric output.

A highly stretchable self-powered pressure sensor is developed based on contact-separation mode TENG (CS) which is created by our group using hyperelastic materials of urethane, silicone rubbers (Ecoflex-0030), and conductive Carbon Nanotubes (CNTs) electrodes. In this paper, we introduce the first comprehensive analysis on the performance of the developed stretchable pressure sensor under different mechanical loading conditions. Furthermore, we analyzed the relationship between the deformation of the interfacial micro-nano structure and the applied pressure on a triboelectric energy harvester (TEH). The analyses are performed using modeling, simulation, and validated using the electrical measurements to clarify the influence of the structural deformation with different microstructures, including a pyramid, hemisphere, and trapezoidal structures. Finally, a pressure sensor TENG is designed based on single electrode TENG mode (SE), then a comparison is performed between TENG pressure sensor based on contact-separation mode and single electrode mode.

2. Results and Discussions

Figure 1a shows a schematically configuration of the vertical contact-separation TENG pressure sensor. The pressure sensor...
consists of two layers, where the top layer is made of Silicone and the bottom layer made of Urethane. The electrodes are formed by CNT ink, which is prepared by a scalable and environmentally friendly method. A detailed explanation of the fabrication process of the pressure sensor is provided in the experimental Method section. The micro-patterns are fabricated on the contact surface of the Silicone layer, which can improve the performance of the pressure sensor by increasing the amount of generated triboelectric charges. The Method section introduces the details of the surface modification process. In addition, as shown in Figure 1a, the arrays of microstructures across the Silicone area are uniform and consistent.

Figure 1. a) Structural design of the stretchable TENG pressure sensor (contact and separation mode CS), SEM image of the micro-patterned Silicone, the inset shows the real figure of the pressure sensor b) a scenario describing the contact pressure dependence of the TENG. Device pressure sensitivity with flat, pyramid, hemi-sphere, and trapezoid microstructures at 0.14 mm gap, 14 mm in width, and 27 mm in length, c–e) electrical potential contour at different pressures up to 3 kPa for the pyramid, hemisphere, and trapezoidal microstructures pattern with schematic to show their parameters. f) The summarized relationship and linear fitting between $\Delta C/C_0$ versus applied pressure up to 4 kPa, vertical deformation corresponding to applied pressure up to 4 kPa, g) The curves for the contact length versus the applied pressure.
To extract the open circuit voltage profiles from Figure 1, a finite-element simulation is conducted in COMSOL to get a conceptual understanding of the pressure-deformation relationship. When the pressure applied is weak, the top metal plate only affects the tip section of the pyramid. In the case of “partial contact,” the TENG pressure sensor can only generate a small amount of triboelectric charge. When the pressure increases, the whole polymer surface comes into contact, and the generated triboelectric charges become saturated in this “full contact” condition. Figure 1c–e show the open-circuit voltage contours when different amounts of pressures is applied to the pyramid, hemisphere, and trapezoid microstructures. Then Figure 1f, when the charge results misconstrues. The two pressure zones are illustrated in Figure 1f, when the charge results (ΔC/Co) changes, the corresponding pressure sensitivity gives different results, while the semi-sphere, pyramid, and trapezoid microstructures give similar values, the flat structure results in a lower value. Moreover, Figure 1g shows the maximum contact length happens in the flat structure case, which is followed by the trapezoid structures, and the pyramid microstructure gives the smallest contact length when the applied pressure is up to 4 KPa. According to above results, the microstructures resistance to contact pressure leads to enhance pressure sensor sensitivity.

Figure 2a and b show the performance of the pyramid microstructures. The two pressure zones are shown in Figure 2a. In the low-pressure region (<0.5 KPa), the pressure sensitivity of gaps 0.14 and 0.5 mm is nearly the same, which is around 4(ΔV/V0)/KPa. Meanwhile, in the case of 1 mm gap structure, the pressure sensitivity in the low-pressure region (<1 KPa) is 0.8(ΔV/V0)/KPa. In the region beyond 0.5 KPa, the pressure sensitivity is 0.0625(ΔV/V0)/KPa for gaps 0.14 and 0.5 mm, and then both reach the stability. On the other hand, the pressure sensitivity of the 1 mm gap in the high-pressure region is 0.0625(ΔV/V0)/KPa. Therefore, based on normalized open circuit voltage results, an increase in the gap value leads to higher sensitivity in the low-pressure zone. Figure 2b shows the normalization of the transferred charges under different applied pressures. In the low-pressure region (<0.5 KPa), the pressure sensitivity of gaps 0.14 and 0.5 mm is nearly the same, which is at 1.5(ΔC/Co)/KPa. Meanwhile, the 1 mm gap has a pressure sensitivity of 0.2(ΔC/Co)/KPa in the low-pressure region (<1 KPa). In the region beyond 0.5 KPa, the pressure sensitivity for gaps 0.14 mm is nearly stable at 0.042(ΔC/Co)/KPa, and it is 0.13(ΔC/Co)/KPa in the case of 0.5 mm gap, which indicates higher sensitivity and pressure dictating limit. On the other hand, the 1 mm gap has a pressure sensitivity of 0.0667(ΔV/V0)/KPa in the high-pressure zone (>1 KPa). Therefore, an increase in the gap value leads to higher detect pressure limit and higher sensitivity for both normalized open circuit voltage and transferred charge.

As shown in Figure 2c and d, different pyramid microstructures with different lengths and spacing are modeled to study the influence of the microstructure parameters like length and spacing. In Figure 2c, the open circuit voltage distribution with an applied pressure of 3 KPa at different pyramid microstructure lengths is shown. Meanwhile, Figure 2d shows open circuit voltage distribution at applied pressure 3 KPa with different pyramid microstructures spacing. In addition, Figure 2e, we see the resultant different spatial arrangement of the silicone pyramid microstructures. The microstructures have a base of 20 μm and periodic spacing of 30, 40, 60, and 80 μm. We see that pattern with pyramids having the lowest spacing 30 μm is the least sensitive to mechanical pressure, and the most sensitive patterns are the pyramids with higher spacing (80 μm). Moreover, both experimental and simulation results obtain the same behavior. Also, both results show that the high sensitivity occurs at large spacing due to a low spacing density which results in high deformation.

Besides, Figure 2f shows the interspersed design of two patterns with different microstructures of base length 5 and 20 μm. As shown in Figure 2f, both experimental and simulation results show that large-size structure array has maximum sensitivity and pressure sensing range due to high deformation. While small-size structure pattern has more power output from the large-size structure pattern. Moreover, the sensitivity in experiment is always significantly lower than the simulation results, because the sensor is affected by the parasitic capacitance, which causes the voltage to drop below the simulated value. Which is common for friction generators.

Figure 2g–m illustrate the effect of substrate condition, where both rigid substrate and the stretchable substrate are studied, and two pressure zones can be observed in the figures. In the low-pressure region (<0.5 KPa), the pressure sensitivity of the rigid and stretchable substrate is nearly the same, which is around 4(ΔV/V0)/KPa. In the region beyond 0.5 KPa, the pressure sensitivity for rigid substrate is 0.026(ΔV/V0)/KPa, and it almost reaches the stability. On the other hand, in the high-pressure region, the stretchable case has a pressure sensitivity of 0.052(ΔV/V0)/KPa. So based on normalized open circuit voltage results, the stretchable substrate has higher sensitivity in the high-pressure region. Figure 2f shows the normalization of the transferred charge with different applied pressures. In the low-pressure region (<0.5 KPa), the pressure sensitivity of the rigid substrate is 1.6(ΔC/Co)/KPa. Meanwhile, the stretchable case low-pressure region <0.5 KPa has sensitivity of 1.5(ΔC/Co)/KPa. In the region beyond 0.5 KPa, the pressure sensitivity of the rigid case is nearly stable around 0.218(ΔC/Co)/KPa, and it is 0.42(ΔC/Co)/KPa in case of stretchable substrate, which means higher pressure sensitivity and pressure dictating limit. Moreover, the contact area of the stretchable substrate is lower than the rigid substrate.

As shown in Figure 3a, an important consideration is that through an applied pressure cycle, layers of elastomer above and below the cavity can potentially come into contact and adhere to one another. Figure 3a shows the parameters of the pressure sensor in the deformation state, the inset shows schematic for the three physics used in our study; triboelectrically, solid mechanics, and surface science. Here, by analyzing the model based on these physics, we can improve the performance of the pressure sensor. We also investigate the surface adhesion working region to define the proper dimensions that can prevent the pressure sensor from collapse. We first examine the flop of gaps (width w and gap g) to establish the governing mechanics. The deformation energy in a substrate of the elastomer below the gap is insignificant compared to that of the layer (thickness t).
above the gap. The total potential energy (per unit width in the out-of-plane direction) resulted from the layer deformation is \( U_{\text{total}} = U_{\text{deformation}}/C_0^2 b \gamma \) \( \langle 31 \rangle \):

\[
U_{\text{deformation}} = 12 D g^2 \left( w - b \right)^3
\]

where \( U_{\text{deformation}} \) represents the deformation energy of the top layer, and \( \gamma \) represents the work of adhesion between the top and bottom surfaces of the gap. The deformed region has an adhesion energy of \( -2 \gamma b \) and zero deformation energy. The undeformed regions are modeled as beams, with one end clamped and the other end subjected to zero rotation and deflection \( -g \). The normalized total potential energies, \( w U_{\text{total}}/D g^2 \), is calculated by:

\[
w U_{\text{total}}/D g^2 = \frac{12}{1 - \left( \frac{b}{w} \right)^3} - 2 \gamma \frac{b}{w}
\]

\[
w U_{\text{deformation}}/D g^2 = \frac{12}{1 - \left( \frac{V_{\text{total}}}{\rho C_0 (w - b/3)} \right)^3} - 2 \gamma \frac{b}{w}
\]

Figure 2. Device pressure sensitivity with flat and Pyramid at different gap, a and b) the summarized relationship and linear fitting between \( \Delta V/V_0 \) and \( \Delta C/C_0 \) versus applied pressure up to 4 kPa for the flat structure, c and d) electrical potential contour at different pressures up to 3 kPa for pyramid microstructures pattern with two different pyramid lengths. e) Sensitivity values plotted with spacing distance (pyramid) of the pyramid microstructures for pressure values less than 3 kPa, of microstructure silicone: pyramids with 20 \( \mu \)m height and spacing of 80, 60, 40, and 30 \( \mu \)m. f) Sensitivity values plotted with pyramid microstructures length for pressure values less than 3 kPa. Device pressure sensitivity with pyramid at gap 0.14 mm with different pyramid length and spacing between the microstructures Device pressure sensitivity with flat structures at 0.14 mm gap, 14 mm in width, and 27 mm in length, for rigid and stretchable substrate. g–m) The summarized relationship and linear fitting between \( \Delta V/V_0, \Delta C/C_0 \), and contact length versus applied pressure up to 4 kPa.
work of adhesion. Figure 3b shows the normalized total potential energy $\left( w^t U_{total}/\left(Dg^t\right) \right)$ versus normalized deformed length $b/w$ with several normalized values for the work of adhesion. The adhesion energy of Ecoflex is $\gamma_{Ecoflex} = 20\text{mJ \cdot m}^{-2}$.

The normalized total potential energy at $b/w = 0$ exceeds that of the ground state (i.e., the undeformed state), thereby suggesting that roof collapse does not occur spontaneously—it instead requires an external stimulus (e.g., an external pressure). The gap does not return to its undeformed state once we remove a perturbing external pressure when the minimal total potential energy is positive when the normalized work of adhesion is less than a critical value $\gamma_c = 55$ such that there is no stable layer deformation for $\gamma < \gamma_c$ (weak adhesion). For $\gamma > \gamma_c = 55$ (strong adhesion), the deformation state is stable because the minimal total potential energy is negative. Figure 3c plots the normalized pressure distributions in the lower layer surface for the flat structure pressed by the upper layer plate for different values of pressures. The contact area $A_c$ can be regarded as the location of the tensile peak stress, which is colored by the deepest shade of red in the current color scheme. It can be seen that the maximum compressive contact pressure at the center of the contact area forms a sharp peak. The deformation eventually becomes saturated as the applied pressure further increases, when whole the area of the flat structure is fully in contact with the top metal plate.

Figure 4 shows the influence of the TENG dimensions on the pressure sensitivity. Figure 4a shows the effect of dielectric width in terms of voltage and charge. Figure 4a, shows the normalization of the transferred charge with different applied pressures. In the low-pressure region ($<2\text{KPa}$), a pressure sensitivity of width $10\text{mm}$ is $0.375\Delta C/\text{KPa}$. While, in case of low pressure region of width $14\text{mm} < 2\text{KPa}$ has sensitivity of $0.45\Delta C/\text{KPa}$, and width $18\text{mm}$ has a sensitivity equal to $0.45\Delta C/\text{KPa}$. In the region beyond $0.5\text{KPa}$, the pressure sensitivity ($0.0107\Delta C/\text{KPa}$) for $10\text{mm}$, $0.0014\Delta C/\text{KPa}$ for $15\text{mm}$ nearly stable response, and it is $0.007\Delta C/\text{KPa}$ in case of width $18\text{mm}$. These results show that a lower layer width leads to higher pressure sensitivity and pressure dictating limit, but it also indicates that optimization is necessary to find the optimum width, which leads to highest pressure sensitivity.

Figure 4b shows the influence of the dielectric thickness on the open circuit voltage, and a fluctuating behavior can be observed. First $V_{OC}$ decreases with the increasing of dielectric thickness then it begins to increase after thickness equal to 0.2 mm. From the previous results, the thickness parameter has a large influence on the sensor’s sensitivity, therefore, an optimization should be performed to obtain the highest sensitivity. Figure 4c shows the pressure sensitivity at different micro/nano structure lengths. We observed that both contact length and maximum stress are smaller in case of nanostructure. Figure 4c, shows the normalization of the transferred charge with different applied pressures. In the low-pressure region ($<2\text{KPa}$), a pressure sensitivity of microstructure is $0.4\Delta C/\text{KPa}$. While, in case of low pressure region of nanostructure $<2\text{KPa}$ has sensitivity of $0.2\Delta C/\text{KPa}$. In the region beyond $2\text{KPa}$, the pressure sensitivity $(0.0214\Delta C/\text{KPa})$ for microstructure, $0.0104\Delta C/\text{KPa}$ for nanostructure nearly stable response. Which indicates the better sensitivity and higher pressure detecting limit with microstructure scale patterns. In addition, as shown in Figure 4d, the contact length in the case of microstructure is much higher than that of the nano structure.

Based on the understanding of the Maxwell’s displacement current, a relation between the second term of Maxwell’s relation $\partial P/\partial\text{(Maxwell’s displacement current)}$ and the TENG output, so that the differences between TENG modes can be investigated.[24] Figure 4e schematically represents the configuration of the vertical single electrode TENG pressure sensor. The pressure sensor is made of one main layer where this layer is made from Silicone. This layer contains separate carbon nanotube electrode associated with a copper tape to connect each key to an external circuit. Another electrode attached on the bottom of the silicone layer as a reference electrode. A comparison between single electrode mode (SE) and contact and separation mode (CS) is presented, which can be seen in Figure 4f–h. As shown in Figure 4f, we find the deformation happens in the case of CS mode is larger than the one of SE mode. Furthermore, as shown in Figure 4g, CS mode has a larger strain and stretching value at low pressures.

Figure 4h shows the normalization of the transferred charge when different amount of pressures is applied. It can be observed that in the low-pressure region ($<2\text{KPa}$), the pressure...
sensitivity is 0.45 \( (ΔC/C_0)/\text{KPa} \) for the CS mode and 0.3 \( (ΔC/C_0)/\text{KPa} \) for the CS mode. In addition, in the region where pressure is beyond 2 KPa, the pressure sensitivity in the CS mode is limited around 0.004 \( (ΔC/C_0)/\text{KPa} \), and the pressure sensitivity is around 0.025 \( (ΔC/C_0)/\text{KPa} \) in the SE mode, which shows the SE mode has higher sensitivity and higher pressure dictating limit. Therefore, according to the results from normalized open circuit voltage analysis, the SE working mode can provide a higher sensitivity in the low-pressure zone. In addition, the value of pressure detecting limit in the SE mode is higher than the CS mode.

3. Conclusions

This paper presents a highly stretchable self-powered pressure sensor, which is developed based on the vertical contact-separation mode Triboelectric Nanogenerators (TENG). Modeling and simulation by finite element method (FEA) are showed to explain the effects of the structural sizes on the act of the pressure sensor. The simulation results show that among all the options, the hemisphere microstructure can provide the highest sensitivity and stretchability. The systematic theoretical studies on the pressure sensor gap indicate that the critical normalized...
work of adhesion of the proposed TENG pressure sensor is around 55 mJ m\(^{-2}\). Furthermore, the results also show that a larger gap can provide higher sensitivity and stretchability in the low-pressure region, while in the high-pressure region the gap changes has limited effect on the sensitivity. The study outcomes also show that the stretchable substrate leads to higher sensitivity and pressure detecting range. A comparison between two TENG working modes (CS and SE) shows that the SE model can provide more sensitivity than the CS mode. The results in this paper can be used as guidelines for future design of triboelectric pressure sensors.

4. Experimental Section

**Preparation of CNT Ink:** Carbon nanotubes (P2-SWNT, Carbon Solution Inc.) were scattered in deionized water with the extent of 1.65 mg mL\(^{-1}\). SDS (Sigma Aldrich Inc.) was furthermore included as a surfactant with the extent of 10 mg mL\(^{-1}\). The course of action of carbon nanotube was at that point sonicated utilizing Branson 2510 sonicator for 30 min. The course of action was at that point utilized to trade onto the Urethane or Silicone surfaces.

**Preparation of the Silicon Film with Micro-Pyramid Patterns:** The fabricate method started from photolithographic planning of 1 in. (100) Si wafers with thermally created SiO2 on beat. The wafer was etched by means of KOH reply for make the recessed components of a pyramid. In the wake of being cleaned with CH32CO, isopropyl alcohol, and ethanol in gathering, the Si molds were treated with trimethylchlorosilane (Sigma Aldrich) by gas arrange silanization to enable the basic peel-off of the silicone film from the Si shape in the going with walk. In the wake of setting up a silicon film at that point degassing handle beneath vacuum, the mix was turn secured on the Si frame at 500 rpm for 60 s. After the warm COMSOL simulation.

**Solid Mechanics Module:** Strain distribution on the stretchable device was calculated by means of finite element method (FEM) for the silicone (Ecoflex-30) layer, and urethane layer. For the silicone layer, the Uniaxial tensile test data, are imported to COMSOL Solid Mechanics module and the Yeoh 3rd order model was used to fit the experimental data. Tensile Strength for Ecoflex-30 is taken as 200 psi, 100% Elongation as 503 psi and Elongation at Break 900%. Based on the observation of the curve trend, it seems that the Mooney–Rivlin 5-parameter model is a proper fit for prediction of the material behavior. For the urethane layers, the uniaxial test data, are imported to COMSOL Solid Mechanics module and the Yeoh 3rd order model was used to fit the experimental data. Tensile strength for urethane is taken as 1360 psi, 100% elongation as 503 psi and elongation at break 876%. Based on this graph, a strain energy model can be curve fitted to describe this stress-strain curve. Accordingly, the curve can fairly match a Yeoh 3rd order model. After defining the hyperelastic module for both materials, we run the simulation and import the new deformed shape to the electrostatic module to get the electric output with difference pressures.

**Electrostatic Module:** Finite element simulations were developed to show the electric potential distribution in the TENG and the charge transfer between the electrode 1 and electrode 2 by modulating the relative distance between the silicon and urethane using COMSOL software. The model here is around 14 mm × 27 mm in size. The thickness was varying. The triboelectric charge density on both tribo-layer was assigned as 50 μC m\(^{-2}\), uniformly. The calculated results of the electric potential distribution with gap distances according to the imported shape from the solid mechanics module, so the electrostatic-solid mechanics coupling was implemented.

**Electrical Measurements:** The outputted current and voltage were gained and documented through a voltage preamplifier (Keithley 6514 System Electrometer) using adapted LabVIEW interface.

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**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

**Conflict of Interest**

The authors declare no competing financial interest.

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