A Facile Method and Novel Mechanism Using Microneedle-Structured PDMS for Triboelectric Generator Applications

Van-Long Trinh and Chen-Kuei Chung*

The triboelectric generator (TEG) is a cost-effective, multi-fabricated, friendly mechanical-energy-harvesting device. The traditional TEG, generally formed by two triboelectric materials in multilayers or a simple pattern, generated triboelectricity as it worked in the cycling contact–separation operation. This paper demonstrates a novel, high-aspect-ratio, microneedle (MN)-structured polydimethylsiloxane (PDMS)-based triboelectric generator (MN-TEG) by means of a low-cost, simple fabrication using CO₂ laser ablation on the polymethyl methacrylate substrate and a molding process. The MN-TEG, consisting of an aluminum foil and a microneedle-structured PDMS (MN-PDMS) film, generates an output performance with an open-circuit voltage up to 102.8 V, and a short-circuit current of 43.1 µA, corresponding to the current density of 1.5 µA cm⁻². With introducing MN-PDMS into the MN-TEG, a great increase of randomly closed bending–friction–deformation (BFD) behavior of MNs leads to highly enhanced triboelectric performance of the MN-TEG. The BFD keeps increasingly on in-contact between MN with Al that results in enhancement of electrical capacitance of PDMS. The effect of aspect ratio and density of MN morphology on the output performance of MN-PDMS TEG is studied further. The MN-TEG can rapidly charge electric energy on a 0.1 µF capacitor up to 2.1 V in about 0.56 s. The MN-TEG source under tapping can light up 53 light-emitting diodes with different colors, connected in series.

1. Introduction

Harvesting lost energy is becoming one of the positive concerns in seeking and supplying new energy sources from our ambient environment. There are abundant successful studies on harvesting wasted energy to serve human daily living, like wind, solar, thermal, mechanical, and chemical energy. By using a new, successful triboelectric nanogenerator (TENG) technology, wasted energy from motion,[12] sliding,[2,4] vibration,[5,6] hydraulic,[5,7] or air power[8] have received much attention for effectively harvesting energy to successfully use in a tremendous amount of practical applications, including consumer electronics,[9] biosensors,[10] pressure sensors,[11] humidity sensors,[12] and portable electronic devices.[13] Most traditional triboelectric generators are based on a frictional concept in the contacting–releasing working cycle of two triboelectric materials in multilayers or simple patterns. TENG devices with electrostatic induction between two triboelectric surfaces from micro/nanostructures show lots of good characteristics for green power, self-power,[14] and walking energy.[15] A previous study contributed a fundamental theory for TENG as a normal electric source with a cyclic contact–separate working mechanism.[16] The success of TENG has uncovered a number of different research areas to harvest wasted energy from our living environment. Actually, most investigations focus on developing tribo-surface structures, such as lines, cubes,[17] nanorod arrays,[18] pyramids,[19] conductive textiles (CTs),[20] nanopatterns[21] or subwavelength architectures,[22] in order to enhance the output electricity. However, the above structures have some limitations,
including complex, long-time, high-cost fabrication processes based on photolithography,[17] electrochemical deposition,[18] or soft lithography methods.[22] Besides that, their electric performances also have limited values in open-circuit voltage ($V_{OC}$) and current density ($J$), as listed in Table 1.

In this article, we propose a new, high-aspect-ratio microneedle (MN) structure and a mechanism of mixed bending–friction–deformation (BFD) behavior for increasing the output performance of TEG. Although the MN patterns have been researched and used in a variety of fields, such as a microelectromechanical system (MEMS) device for electroporation,[23] biomedical,[24] medicine,[25,26] medical diagnosis,[27] and cosmetic applications,[28] it is the first time that MN-structured PDMS for TEG applications has been used. We have demonstrated the MN-PDMS-based triboelectric generator (MN-TEG) by means of a simple, low-cost, large-area, rapid-fabrication method using CO$_2$ laser ablation on a polydimethylsiloxane (PDMS) master mold and molding process for high output performance. The MN-TEG generated an output performance with $V_{OC}$ up to 102.8 V, and a short-circuit current ($I_{SC}$) of 43.1 $\mu$A, corresponding to a current density of 1.5 $\mu$A cm$^{-2}$. The output performance of the MN-TEG is much higher, about 17 fold, in comparison with the output of the nonstructured PDMS-TEG. In the low-applied-force condition by hand tapping, the MN-TEGs output performance is much higher, about 17 fold, in comparison with the nonstructured PDMS-TEG.

### 2. Results and Discussion

The morphology of the MN-PDMS separated from the female PMMA mold is shown in Figure 1. In this experiment, the master PMMA mold was ablated by CO$_2$ laser with a laser power of 6 W, a scanning speed of 40 mm s$^{-1}$, and the interhole distance of about 508 $\mu$m. The top-view scanning electron microscopy (SEM) image of the PDMS microneedle pattern indicates an average bottom diameter of about 335 $\mu$m, while the front-view image of the MN-PDMS reveals an average height of 1090 $\mu$m (called MN1090), as shown in Figure 1a,b, respectively. To study more details about the effects of the MN aspect ratio and MN density, we also fabricated four more MN-PDMS patterns from female PMMA molds by controlling the laser parameters, as mentioned above, with a lower laser power of 6 W, scanning speeds from 97 to 137 mm s$^{-1}$, and interhole distances from 508 to 794 $\mu$m, as listed in Table 2. The four more MN-PDMS patterns, with the short names MN530, MN320, MN1085, and MN1096, reversed from the four above female molds, have MN average heights of 530, 320, 1085, and 1096 $\mu$m, respectively, as shown in the SEM images in Figure S1 in the Supporting Information. The four more MN have average bottom diameters of 305, 295, 368, and 378 $\mu$m for MN530, MN320, MN1085, and MN1096, respectively, as listed in Table 2. The MN530 and MN320 have the same interhole distance (IH$_d$) as the MN1090, but different MN height, which are used for evaluating the aspect-ratio

### Table 1. Comparison of triboelectric performance based on surface structures (using a low-input applied frequency and force-like hand tapping).

<table>
<thead>
<tr>
<th>Structure</th>
<th>Material</th>
<th>$V_{OC}$</th>
<th>$I_{SC}$</th>
<th>$J$</th>
<th>Fabrication of mold</th>
<th>Note</th>
<th>Refs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyramid</td>
<td>Indium tin oxide (ITO)/polyethylene terephthalate (PET)–PDMS/ITO/ITO</td>
<td>18 V</td>
<td>0.7 $\mu$A</td>
<td>0.13 $\mu$A cm$^{-2}$</td>
<td>Photolithography, Si dry/ wet etching</td>
<td>–</td>
<td>[17]</td>
</tr>
<tr>
<td>Line</td>
<td>PET/zinc oxide (ZnO)/PDMS/ITO</td>
<td>5.34 V</td>
<td>181.4 nA</td>
<td>–</td>
<td>ZnO seed sputtered, and electrochemical deposition</td>
<td>2 × 2 cm$^{-2}$ (contact area)</td>
<td>[18]</td>
</tr>
<tr>
<td>Cube</td>
<td>Conductive textile (CT)</td>
<td>8.12 V</td>
<td>–</td>
<td>25.77 nA cm$^{-2}$</td>
<td>Coating (Ni-coated polyethylene terephthalate)</td>
<td>–</td>
<td>[20]</td>
</tr>
<tr>
<td>Pyramid</td>
<td>Al-polytetrafluoroethylene (PTFE)</td>
<td>18 V</td>
<td>–</td>
<td>–</td>
<td>3D printing</td>
<td>–</td>
<td>[19]</td>
</tr>
<tr>
<td>Nanopattern</td>
<td>PET/ITO–PDMS/ITO</td>
<td>5.4 V</td>
<td>–</td>
<td>0.74 $\mu$A cm$^{-2}$</td>
<td>Lithography and dry etching</td>
<td>–</td>
<td>[21]</td>
</tr>
<tr>
<td>Subwavelength</td>
<td>ITO/PET–PDMS/ITO/ITO/PET</td>
<td>3.8 V</td>
<td>0.8 $\mu$A</td>
<td>–</td>
<td>Soft lithography via AAO template</td>
<td>1 × 1 cm$^{-2}$ (contact area)</td>
<td>[22]</td>
</tr>
<tr>
<td>MN-PDMS</td>
<td>Al–PDMS/Al</td>
<td>102.8 V</td>
<td>43.1 $\mu$A</td>
<td>1.5 $\mu$A cm$^{-2}$</td>
<td>CO$_2$ laser ablation</td>
<td>–</td>
<td>Ours</td>
</tr>
</tbody>
</table>

The increased random BFD behavior of MNs can greatly enhance triboelectric performance of the MN-TEG. The BFD keeps increasing on in-contact between MN, with Al assumed to result in enhancement of the electrical capacitance of PDMS. The MN aspect ratio and density have distinct effects on the output performance of the TEG. The MN-PDMS pattern with a higher aspect ratio and density results in increasing tribo-contact-surface area and friction between two tribo materials with increased BFD behavior in the bending–restoring cycle for higher performance. The MN-TEGs durable mechanical working was confirmed over 500 min, that is, more than 20 times tapping of 1500-s stable electric power generation. The output energy of the MN-TEG could be stored in capacitors with fast charging and high charging voltage, for example, on a 0.1 $\mu$F capacitor, up to 2.1 V in about 0.56 s. The MN-TEG source under tapping can directly light up 53 light-emitting diodes (LEDs) with different colors, connected in series.
effect on the output performance of the TEG. Accordingly, both MN1085 (IHd of 605 µm) and MN1096 (IHd of 794 µm) have MN heights close to the MN1090, but different interhole distances, as listed in Table 2, which are used to evaluate the effect of MN density on the output performance of the TEG. The basic and novel enhancement mechanism of MN-TEG, as well as the electrical measurement and output performance evaluations are described below.

### 2.1. Basic Working Mechanism of TEG

The basic triboelectric charging method of the TEGs is described in Figure 2. The TEG generates an alternating current under the closed contact–separate cycling operation of two triboelectric material surfaces. The PDMS induces negative triboelectric charges and inductive positive charges from the Al foil focused at contact surfaces, separately, when they are impelled to contact and rub with each other. After that, the separation causes the potential imbalance between two tribo materials. To return to electrical equilibrium, as a result, a flow of electrons move forth and back between two electrodes via an external circuit in the working cycle. Following that, the charging does not appear at the primary position, at which there is the installed distance between the two electrodes (Figure 2a). When hand-pressing is applied on the top electrode, it comes to contact and rub with the tribo-material surface, like PDMS, which causes a negative charge on the PDMS surface, and leads to a positive charge on the metal Al foil (because of electrical neutrality). The triboelectric distribution is formed between two tribo surfaces (Figure 2b). Then, when the external force departs, the two electrodes separate from each other under the elastic force of springs. As mentioned above, the imbalanced potential causes a flow of free electrons (a negative current), transferring through an external circuit from the top electrode to the bottom one (Figure 2c). As a result, the movement of electrons establishes a new electrical equilibrium state (Figure 2d). When the applied force appears again, the reversed movement of electrons from the bottom electrode to the top electrode for a new triboelectric equilibrium state produces an external current (a positive current), as shown in Figure 2e. This new triboelectric equilibrium can reach the full contact state of the two tribo-material surfaces (Figure 2b). Consequently, an alternating current then moves continuously via an external circuit during the cycling operation of the TEG.

### 2.2. Electrical Measurement

In order to measure the output performance of the MN-TEG, an oscilloscope (HIOKI Memory HiCorder MR8870-20, Japan) and a Keithley 2400 (Textronix, Inc. USA) were used. The microneedle-structured PDMS foil with the size of 6.5 cm × 4.5 cm and the substrate thickness of about 200 µm was used for the MN-TEG. The Al foil and the MN-PDMS film with a contact surface area of 6.5 cm × 4.5 cm were assembled in the test jig. The initial distance of two electrosurfaces was adjusted ≈10 mm by the nuts. The measured $V_{OC}$ and

<table>
<thead>
<tr>
<th>Samples of MN-PDMS</th>
<th>Laser power [W]</th>
<th>Scanning speed [mm s⁻¹]</th>
<th>Interhole distance [µm]</th>
<th>Bottom rim [µm]</th>
<th>Needle height [µm]</th>
<th>Aspect ratio</th>
<th>MN density [# cm⁻²]</th>
<th>TEG structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>MN1090</td>
<td>6</td>
<td>40</td>
<td>508</td>
<td>335</td>
<td>1090</td>
<td>3.25</td>
<td>388</td>
<td>Al-PDMS/Al</td>
</tr>
<tr>
<td>MN530</td>
<td>6</td>
<td>228</td>
<td>508</td>
<td>305</td>
<td>530</td>
<td>1.74</td>
<td>388</td>
<td>Al-PDMS/Al</td>
</tr>
<tr>
<td>MN320</td>
<td>6</td>
<td>342</td>
<td>508</td>
<td>295</td>
<td>320</td>
<td>1.08</td>
<td>388</td>
<td>Al-PDMS/Al</td>
</tr>
<tr>
<td>MN1085</td>
<td>6</td>
<td>97</td>
<td>605</td>
<td>368</td>
<td>1085</td>
<td>2.94</td>
<td>273</td>
<td>Al-PDMS/Al</td>
</tr>
<tr>
<td>MN1096</td>
<td>6</td>
<td>137</td>
<td>794</td>
<td>378</td>
<td>1096</td>
<td>2.87</td>
<td>159</td>
<td>Al-PDMS/Al</td>
</tr>
</tbody>
</table>

Figure 1. The surface morphology of a microneedle PDMS structure (MN1090): a) SEM images from top view and b) SEM image from front view of the PDMS microneedle structure.

Table 2. The detailed morphology and laser ablation parameters for fabricating the MN patterns to evaluate the effect of the aspect ratio and density on the output performance of MN-PDMS-TEG.
$I_{SC}$ of the MN-TEG could reach 102.8 V and 43.1 $\mu$A at a frequency of about 3 Hz (Figure 3a,b), respectively, corresponding to a current density peak of 1.5 $\mu$A cm$^{-2}$ with pressing by hand. The enlarged view insets of one cycle of $V_{OC}$ and $I_{SC}$ versus time show the peak of transferred charges in the first half of cycle, i.e., bending stroke is higher than that of the second half of the cycle, and the restoring stroke while the duration of bending stroke is shorter the restoring stroke. This is because the bending stroke takes place quicker than the rolling back to its original position. Basically, the triboelectric generation of the PDMS material is its natural property. However, the output performance depends strongly on the surface morphology. To characterize clearly, we proceeded to measure output performance of the nonstructure

![Figure 2.](image)

Figure 2. The basic operating mechanism of the MN-TEG: a) The original position without charging. b) The contact and rubbing under an external force induced triboelectric distribution. c) Separating generated a current through the external circuit after the force was removed. d) The total separation state, new electric equilibrium was formed. e) Pressing again to produce a reversed current moving via the external circuit.

![Figure 3.](image)

Figure 3. a,b) the open-circuit voltage and short-circuit current of the MN-TEG (MN1090), respectively, including the inset of the enlarged views of one cycle; c,d) The open-circuit voltage and the short-circuit current of the MN-TEG, and TEG based on nonstructure PDMS, respectively.
sample in comparison with the microneedle structure. The two above samples are the same in size and substrate thickness, but the morphology surfaces are different. The output measurement process was done on the same test jig and the same applied force by tapping. The measured output performances for the two compared samples were demonstrated in Figure 3c,d. The $V_{OC}$ and the $I_{SC}$ of the TEG from the nonstructure PDMS film were measured with the maximum output of 6 V and 3.75 µA, respectively. So the output performance of the MN-TEG based on the microneedle structure is much higher, about 17 fold, in comparison with the output of the TEG based on the nonstructure PDMS film.

Furthermore, the MN aspect ratio and density have considerable effect on the output performance of the TEG. The electrical signals were recorded from four more samples with aspect ratios of 1.74, 1.08, 2.94, and 2.87, which came from four MN530, MN320, MN1085, and MN1096 PDMS patterns, respectively, as listed in Table 2. The first two have the same density of 388 # cm$^{-2}$ as the MN1090 sample, but are different in height. The last two have similar heights, but a difference in density from the MN1090 pattern. The aspect ratio can be defined by Equation (1)

$$\text{Aspect ratio (AR)} = \frac{H}{D}$$

where $H$ and $D$ are the average height and bottom diameter of the MN, respectively. According to Equation (1), the AR of MN1090 is 3.25 higher than that of the four samples above. Their substrate dimensions, mother material, fabrication method, and electrical testing condition are the same for the comparison. Firstly, the two MN530 and MN320 samples with the same interhole distance of 508 µm and MN density of 388 # cm$^{-2}$, but different aspect ratio, were prepared for electrical testing. The maximum measured electrical signals ($V_{OC}$, $I_{SC}$) of the MN530-TEG and MN320-TEG are (72.1 V, 34.5 µA) and (34.8 V, 24.3 µA), respectively, as shown in Figure S2a,b in the Supporting Information. Compared to the MN1090 (AR 3.25) with $V_{OC}$ of 102.8 V and $I_{SC}$ of 43.1 µA, the MN1090-TEG performance is higher, at about 1.4 and 3 times than those of the MN530 (AR 1.74) and MN320 (AR 1.08), respectively. The experimental results indicate the MN-PDMS pattern with higher aspect ratio can enhance the TEGs output performance by more than the BFD behavior and contact area, than that of the lower aspect ratio one. Secondly, the electrical measurements of two MN1085 and MN1096 samples with close MN height of MN1090, but a difference in density, were also recorded. The MN1085 and MN1096 have MN densities of 273 and 159 # cm$^{-2}$, respectively, while the MN1090 density is 388 # cm$^{-2}$. The MN density is calculated by Equation (2)

$$\text{Microneedle density (Md) = } \frac{N}{A}$$

where $N$ is the number of microneedles, and $A$ is the total plane area of PDMS substrate. The measured electrical characteristics induced by MN1085-TEG and MN1096-TEG are (63.6 V, 29.6 µA), and (41.2 V, 26.5 µA), respectively, as shown in Figure S2c,d in the Supporting Information. The MN1090-TEGs output performance ($V_{OC}$ 102.8 V and $I_{SC}$ 43.1 µA) is higher by about 1.6 and 2.5 times compared to the MN1085-TEG and MN1096-TEG, respectively. This is because the MN-PDMS pattern with higher MN density can produce more total BFD and contact area in the working cycle than the lower MN density pattern. In brief, in the same plane area of substrate, the higher aspect ratio and density of MN-PDMS patterns can create more tribo-contact-surface-area and friction behavior from the mixed BFD mechanism than that of the low aspect ratio and low density ones. That is, the high aspect ratio (AR 3.25) MN1090-PDMS-TEG outgrew in the electrical performance by about 3 times

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**Figure 4.** The mechanism of the proposed bending and restoring process of MN structure in the cycled pressing–releasing operation of the MN-TEG: a) The initial state of MN-TEG. b) The MN-PDMS bending during the pressing stroke. c) The microneedles under the bent state. d) The restoring of MN-PDMS after the removed force. e) The total restored state of MN-PDMS to the original shape.
higher than that of a low aspect ratio (AR 1.08) MN320-PDMS-TEG; the MN1090 ($M_d$ 388 # cm$^{-2}$) pattern raised up to about 2.5 times compared to MN1096 ($M_d$ 159 # cm$^{-2}$) pattern. Therefore, the MN1090-PDMS, called the optimal MN-PDMS, has the highest triboelectric performance compared to the MN530, MN320, MN1085, and MN1096 PDMS patterns. The results evidence that the microneedle structure-enhancing contact BFD behavior of tribo material leads to a high increasing in output performance of the MN-TEG. Moreover, the microneedle structure on pure PDMS surface characterizes more triboelectric-charge advantages than other patterns listed in Table 1 as it was tested in the low-applied force condition by hand tapping. 

especially, this proposed approach is very fast, easy, and low-cost for TEG applications.

2.3. Novel Enhancement Mechanism of MN-TEG

Figure 4 shows the enhancement mechanism of the MN-TEG described by the 3D-modeling bending and restoring process of microneedles in cycled pressing–releasing operation of the MN-TEG. Figure 4a exhibits the initial state of the MN-TEG, where no charging occurs. Figure 4b presents the MN-PDMS bending during the pressing stroke, where dipole triboelectric charging begins. Figure 4c shows microneedles under the

![Image](https://www.advancedsciencenews.com)

**Figure 5.** The output performance-enhancement mechanism of bending–restoring in the working cycle of MN-TEG: The bent states of MN-PDMSs within the pressing process and the corresponded output performance of the MN-TEG at a bent state with $r$ of about a) 10%, b) 30%, c) 50%, d) 70%, and e) the electric output performances of the MN-TEG (MN1090) corresponding to the bending ratios.
bent state, where the maximum balance of triboelectric distribution formed on the two tribo materials. Figure 4d describes restoring of the MN-PDMS after the force rolled back, where an inequity potential resulted in a negative current via an external circuit. Figure 4e demonstrates the total restored state of the MN-PDMS to the original shape, and new electric equilibrium was established. When the bending came back again, a positive current appeared in an external circuit (as mentioned above). As a result, the bending–restoring cycle operation of the MNs applied in the MN-TEG generated an alternating current flowing via an external circuit. The high-aspect-ratio microneedle shape of viscoelastic PDMS material easily generates bending, friction, and deformation that occurs, not only between the top electrode (Al)–microneedle, but also more strongly between microneedle–microneedle and microneedle–PDMS substrate during the pressing state. This could be the reason for the highly increasing triboelectric charge on the surface of the PDMS through the greatly enhanced contact surface area and friction. On the other hand, it significantly influences electrostatic induction, due to it springing back to its original shape, from the enormous bending and deformation state of microneedles after the force was rolled back. These phenomena result in a remarkable increase of output performance. In order to deeply understand the dramatic increase of the MN-TEG performance compared to flat PDMS-TEG, as well as the effect of the BFDs behaviour on induced triboelectric performance. We have experienced with some bent ratios ($r$) about 10%, 30%, 50%, and 70% on the microneedles, by controlling the bending distance of the two electrodes on the optimal MN-PDMS pattern. The bent ratio ($r$) is governed by formula (3)

$$r = \left( \frac{B}{L} \right) \times 100\%$$

where $B$ and $L$ are the bent length and the total length of the MN-PDMS, respectively. Figure 5 shows the optical micrographs (OM, Olympus BX 51M, Japan) of the bent states corresponding to the bent lengths of MN-PDMSs and the corresponded output performances. Figure 5a displays the bent state with $r$ of 10%. At this state, MN-PDMSs have not been pushing with each other and the bent length is nearly on the tip of MN-PDMSs. The MN-TEG therefore generated a minimal $V_{\text{OC}}$ of 12 V and $I_{\text{SC}}$ of 9 $\mu$A. Next, $r$ increased to 30% (Figure 5b). The bent length became larger, driven by a rise in friction and deformation of MNs. A higher output performance was powered with $V_{\text{OC}}$ of 25 V, and $I_{\text{SC}}$ of 13 $\mu$A. Then, the bent length increased with $r$ of 50% (Figure 5c) and had a tendency for random frictional pushing between them. The output performance this time has risen to $V_{\text{OC}}$ of 75 V and $I_{\text{SC}}$ of 31.5 $\mu$A. When $r$ rushed to the high value of the bending ratio of 70%, the MN-PDMSs was in the

![Figure 6](image-url)

**Figure 6.** The increasing process of the contact area and friction of the MNs in the BDF behavior: a) starting contact point, b) contact area and friction increase with the bending length, c) multi-contact area and multi-friction between the MN–Al and MN–MN, and d) multi-contact area and multi-friction between the MN–Al, MN–MN, MN–PDMS substrate at the maximum bending state.
stronger BFD behavior (Figure 5d); this resulted in high performance of the MN-TEG with the peak of the voltage at 102.8 V, and the tip of current at 43.1 µA. The electric output performance corresponded to the bending ratio is shown in Figure 5e. These results clearly evidence that the electric output performance of the MN-TEG dramatically increases with increasing $r$ value. One OM real-time video (Video S1, Supporting Information) recorded the BFD behavior of the MNs in the bending–restoring process that showed a perfect spring back to the original shape of the MNs after it must have suffered a drastic BFD condition.

The contact area and friction between the two tribo materials interface increased the pressing process accompanied by BFD behavior by the external force caused in the enhancement of the voltage and current of the MN-TEG. The friction and contact area start from the initial contacting point of the MN and the Al, and continue to strongly increase following the MN bending length, until reaching a high value in the state of MN lying in the interface of the Al and PDMS.

Figure 6 illustrates the increase of contact area and friction in the BFD behavior. Figure 6a shows a small contact area at the starting contact point corresponding with the minimum bending and friction ($r$ is small in about 10% in Figure 5); the MN-TEG has the low voltage of 12 V and current of 9 µA. Figure 6b shows the bending increase leading to an increase in the contact area and friction. The voltage (25 V) and the current (13 µA) have risen up, as the above reference, at $r$ of 30%, as in Figure 5. Figure 6c shows the MNs keeping an increase of contact area and friction with the Al, while starting to impact together when the bending length increases. The multi-contact and friction lead to a rapid increase in the voltage of 75 V, and current of 31.5 µA at the $r$ equal to 50%, as in Figure 5. Figure 6d shows the maximum bending state of the MNs. The contact area and friction reach a maximum value by multi-contact and friction between the MN–Al, MN–MN, and MN–PDMS substrate. The MNs lie in the interface of the two tribo materials with the strongest BFD state. The voltage (102.8 V) and the current (43.1 µA) of the MN-TEG have the highest peaks at $r$ about 70%, as in the above reference in Figure 5. The increased contact area and friction in the MNs BFD behavior is also observed in Video S1 in the Supporting Information for bending.
Figure 7 explains the charging and lighting up for LED applications of the MN-TEG. Figure 7a,b shows the charging circuit on capacitors using an AC to DC bridge rectifier, and corresponding real-time charging voltage versus time curves, respectively. For capacitor (Cap)-charging characterization of the optimal MN-TEG, a range of Caps (from 0.1 to 4.7 \(\mu F\)) were used for the charging process and the charged voltages corresponding to charged time. The charged voltages achieved up to 2.1 V during about 0.56 s for 0.1 \(\mu F\) Cap, and they are 1.53 V in 2.1 s for 1 \(\mu F\) Cap, 1.6 V in 7.4 s for 2.2 \(\mu F\) Cap, and 1.4 V in 9.5 s for 4.7 \(\mu F\) Cap, respectively. Thus, the charging voltage is clearly a time-dependent function, and the induced electric energy by MN-TEG can be stored on capacitors or batteries to use for electronic devices or other applications. Figure 7c shows the LEDs lighting-circuit with an AC to DC bridge rectifier. Figure 7d shows that the optimal MN-TEG can light up to 53 LEDs with different colors (white, green, blue, red, purple, and orange) wired in series. The lighting video file was supplied in Video S2 in the Supporting Information. In order to check mechanical durability of the MN-TEG, a service test was done over long-time operation. The mechanical durability of the optimal MN-TEG was confirmed as it stably generated electric power over 500 min, that is, more than 20-time tapping of 1500-s operation, as shown in Figure 7e,f.

3. Conclusions

We have demonstrated a simple, low-cost, easy-fabrication high-aspect-ratio, microneedle-structured PDMS film for use in TEG applications. A novel MN-TEG model based on the microneedle-structured PDMS film and Al film was designed
for enhancing the TEG performance. The MN-TEG can convert wasted mechanical energy into electrical energy from hand tapping with a maximum $V_{OC}$ of 102.8 V and $I_{SC}$ of 43.1 $\mu$A, respectively, and corresponding current density of 1.5 $\mu$A cm$^{-2}$. The aspect ratio and density of microneedles strongly affect the electrical performance of the MN-PDMS-TEG. The high-aspect-ratio (AR 3.25) MN-PDMS-TEG produces an electrical feature higher by about 3 times compared to the low-aspect-ratio (AR 1.08) pattern, and accompanying MN density ($M_d$ 388 $\#$ cm$^{-2}$) its output performance is higher by about 2.5 times than that of a smaller-density ($M_d$ 159 $\#$ cm$^{-2}$) MN-PDMS-TEG. The MN-TEGs output performance rapidly increases with an increase in the BFD behavior, characterized by the bending ratio from 12 V and 9 $\mu$A at an $r$ of 10%, to 102.8 V and 43.1 $\mu$A at an $r$ of 70%. The MN-TEG showed stable electric power generation over 500 min, that is more than 20-times that of 1500-s operation. We also evidence that the charging ability on capacities could be driven by the MN-TEG generating a charging voltage of 2.1 V in 0.56 s, 1.53 V in 2.1 s, 1.6 V in 7.4 s, and 1.4 V in 9.5 s for the 0.1, 1, 2.2, and 4.7 $\mu$F capacitors, respectively. The MN-TEG can supply electric energy for 53 colored LEDs, instantaneously lighting up when wired in series. It is trusted that this work will spread the MN morphology for TEG applications in the future.

4. Experimental Section

The two common basic contact-separation surfaces of the TEG used in this study were the microneedle-structured PDMS and aluminum foil. The Al material had two key functions as an electrode and a tribo material. Figure 8 shows the schematic fabrication-process flow of the microneedle array on a PDMS film. First of all, the PMMA micromold was fabricated using CO$_2$ laser ablation. Figure 8a,b illustrates the laser ablation process for a microneedle female mold on the PMMA substrate, and the micromold after laser ablation is completed, respectively. In laser processing, a commercial CO$_2$ laser system (VL-200, Universal Laser system Inc., U.S.A.) was used for micromold fabrication; the maximum laser power is 30 W, the central wavelength is 10.6 $\mu$m, and the maximum scanning speed is 1140 mm s$^{-1}$. A CorelDraw software as a computer-aided design tool was applied to create and control laser processing parameters following $X$ and $Y$ directions on the PMMA substrate to produce a mother mold with microwhollow arrays for PDMS casting to form the MN-PDMS. The height, aspect ratio, and density of MNs were controlled by the laser parameters consisting of a range of scanning speeds from 40 to 342 mm s$^{-1}$, and a interhole distances in the range of 508–794 $\mu$m at a constant laser power of 6 W. Then, a well-mixed compound of elastomer (Sylgard 184, Dow corning) and curing agent, with ratio of 10:1 in weight, called the PDMS solution, was prepared and eliminated the air traps via a vacuum about 1 h. Next, the degassed solution was poured into the micromold with guaranteed thickness about 200 $\mu$m by a doctor-blade and tapes (Figure 8c). After that, it was cured in the oven at about 85 °C during 1 h. Finally, the microwhollow PDMS (Figure 8d) was peeled off the micromold after it cooled down to room temperature. Figure 9 shows the MN-TEG and the test jig assembly process. The test jig was used to characterize the performance of the MN-TEG. Figure 9a shows the easy-finding materials to prepare for the MN-TEG and the test jig, including two PMMA substrate plates, one MN-PDMS film, one Al foil, four couple nut-bolt-springs, and one piece of sponge. Following the process, the MN-PDMS film attached on the Al film as the top electrode and the Al foil fastened on the PMMA plate as the bottom electrode, were assembled for the MN-TEG (Figure 9b). The sponge was attached on the top of the test jig for easy and comfortable tapping in testing of MN-TEG performance. Figure 9c shows the scanning electron microscopy (JEOL JSM-7000F, Japan) photograph of the microneedle structured PDMS applied in the MN-TEG.

Supporting Information

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

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Conflict of Interest

The authors declare no conflict of interest.


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