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A Shape-Adaptive Thin-Film-Based Approach for 50% High-Efficiency Energy Generation Through Micro-Grating Sliding Electrification

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Effectively harvesting ambient mechanical energy is the key for realizing self-powered and autonomous electronics, which addresses limitations of batteries and thus has tremendous applications in sensor networks, wireless devices, and wearable/implantable electronics, etc. Here, a thin-film-based micro-grating triboelectric nanogenerator (MG-TENG) is developed for high-efficiency power generation through conversion of mechanical energy. The shape-adaptive MG-TENG relies on sliding electrification between complementary micro-sized arrays of linear grating, which offers a unique and straightforward solution in harnessing energy from relative sliding motion between surfaces. Operating at a sliding velocity of 10 m/s, a MG-TENG of 60 cm^2 in overall area, 0.2 cm^3 in volume and 0.6 g in weight can deliver an average output power of 3 W (power density of 50 mW cm^{-2} and 15 W cm^{-3}) at an overall conversion efficiency of ~50%, making it a sufficient power supply to regular electronics, such as light bulbs. The scalable and cost-effective MG-TENG is practically applicable in not only harvesting various mechanical motions but also possibly power generation at a large scale.

1. Introduction

Driven by rapid proliferation of electronic systems and by limitations of traditional power supplies, energy harvesting has become an increasingly attractive and important field in the past decade.[1,2] It enables self-powered, autonomous electronic devices and potentially large-scale power generation, covering a wide variety of applications in wireless sensors, biomedical implants, security and surveillance, infrastructure monitoring, and portable/wearable electronics.[2–4] Mechanical energy, due to its universal availability, is of major interest. Well-established transduction mechanisms for mechanical energy harvesting mainly rely on electrostatic, electromagnetic, and piezoelectric effects,[5–13] which have been extensively developed for decades. We recently demonstrated a class of triboelectric nanogenerators (TENG) that utilized triboelectrification for harvesting mechanical energy.[14–17] In order for practical applications of the TENG as a power source, the output power still needs to be substantially enhanced.

In this work, we report an ultra-high-power micro-grating triboelectric nanogenerator (MG-TENG) based on thin-film materials for harnessing triboelectrification between two sliding surfaces. Enabled by two sets of complementary micro-sized electrode gratings on thin-film polymers and by surface modification from nanoparticles, the MG-TENG offers an unprecedentedly high level of output power, which completely solves the major concern for triboelectrification in electricity generation. Operating at an in-plane sliding velocity of 10 m s^{-1}, a MG-TENG having a contact area of 20 cm^2 could generate sinusoidal-like AC current at an amplitude of 9.8 mA and at a frequency of 5 KHz. Under the matched load, an average effective power of 3 W was achieved, corresponding to power volume density of 15 W cm^{-3}. Having an efficiency of nearly 50%, it successfully powered multiple types of light bulbs, demonstrating the capability of the MG-TENG as a power supply for regular electronics. Due to the shape-adaptive design based on thin-film materials, the MG-TENG could be even applied onto curved surfaces, providing a unique and straightforward solution in harnessing relative sliding motions, in which other existing technologies cannot be implemented. As an approach that is cost-effective, simple-implementing, and scalable, the MG-TENG is suited to harvest a variety of mechanical energy not only for self-powered electronics but also for possible electricity generation at a large scale.

2. Micro-Grating Triboelectric Nanogenerator (MG-TENG)

2.1. Structural Design

A MG-TENG is composed of polytetrafluoroethylene (PTFE) thin films with a pair of metal gratings on opposite sides. As schemed in **Figure 1**a, the grating is a collection of metal strips

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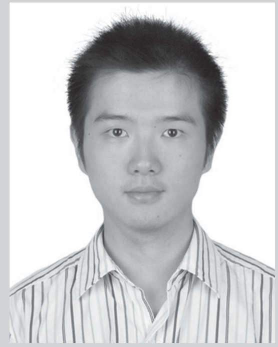
separated by equal-sized intervals. All of the strips are electrically connected by a bus at one end. The paired gratings are identical but complementary with relative displacement of half pitch (zoom-in view in Figure 1a). Figure 1b exhibits a photograph of the PTFE thin film with double-sided metal gratings. On the top surface, a layer of PTFE nanoparticles is applied as surface modification (Figure 1c). Two of the thin films with different length are prepared, which have a total area of 60 cm^2, a total volume of 0.2 cm^3, and a total weight of 0.6 g. They are then respectively applied onto the surfaces of two objects that have relative sliding, i.e., a slider and a guide (Figure S1). The motion direction is perpendicular to the metal strips. A breakdown of the generator in Figure S2 defines all components. Since the two metal gratings in the middle keep in contact, they form a common electrode called base electrode. The detailed fabrication process is presented in Experimental Section.

2.2. Operating Principle

The MG-TENG operates in a unique principle that relies on the coupling between triboelectric effect and electrostatic induction.[14–17] Triboelectric effect, as the reason for most daily static electricity, is a common but underexplored phenomenon with very limited useful applications.[18–20] A basic operating unit is sketched in **Figure 2**a. It has a PTFE film with a metal electrode deposited on back side (back electrode). On front side, the PTFE film makes relative motion with another metal electrode (contact electrode). Since metal is more triboelectrically positive than PTFE, electrons are injected from metal into PTFE upon contact, producing negative triboelectric charges on PTFE surface and positive ones on metal surface.[21–24] At the aligned position in Figure 2a, triboelectric charges of opposite signs are completely balanced out. As the contact electrode slides apart, net electric field arises as a result of uncompensated triboelectric charges in the misaligned regions (Figure S3), driving free electrons from the back electrode to the contact electrode until the electric field is fully screened by induced charges on electrodes (Figure 2b, Figure S4). If the contact electrode is brought back towards the alignment position, triboelectric charges are rebalanced, leading to a back flow of the induced free electrons (Figure 2c).

The electricity generation process of an entire MG-TENG is based on the basic principle above. As schemed in **Figure 3**, components labeled in yellow and green belong to the slider and the guide, respectively. The entire MG-TENG is equivalent to two sets of units described in Figure 2 in parallel connection. The first set consists of the top electrode, the top film, and part of the base electrode on the guide. The second set is composed of the bottom electrode, the bottom film, and part of the base electrode on the slider. As the slider moves away from the aligned position in Figure 3a, free electrons are driven from both the top electrode and the bottom electrode to the base electrode by uncompensated triboelectric charges on the PTFE films. The two streams of electrons converge at the base electrode and add up because they are synchronized. The flow of electrons lasts until the base electrode is completely misaligned with respect to the bottom electrode and the top electrode (Figure 3a).



Dr. Guang Zhu is a postdoctoral fellow in Prof. Zhong Lin Wang's research group at Georgia Institute of Technology. He received his Ph.D. degree in Materials Science and Engineering at Georgia Tech in 2013 and his Bachelor degree in Materials Science and Engineering at Beijing University of Chemical Technology in 2008. His current research mainly focuses on designing, fabrication, and implementation of innovative miniaturized high-efficiency generators that harvest and convert ambient mechanical energy into electricity. They have widespread applications in self-powered electronics for wireless sensor networks and portable consumer electronics and in potentially large-scale power generation by harnessing mechanical energy from nature.

Dr. Zhong Lin Wang is a Hightower Chair and Regents's Professor at Georgia Tech. He is also the Chief scientist and Director for the Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences. His discovery and breakthroughs in developing nanogenerators establish the principle and technological road map for harvesting mechanical energy from environment and biological systems for powering personal electronics. His research on self-powered nanosystems has inspired the worldwide effort in academia and industry for studying energy for micro-nano-systems, which is now a distinct disciplinary in energy research and future sensor networks. He coined and pioneered the field of piezotronics and piezo-phototronics by introducing piezoelectric potential gated charge transport process in fabricating new electronic and optoelectronic devices. This historical breakthrough by redesigning CMOS transistors has important applications in smart MEMS/NEMS, nanorobotics, human-electronics interface and sensors.

Further motion in the same direction starts to bring the base electrode back towards alignment (Figure 3b) because the grating is a collection of identical repetitions. As a result, accumulated free electrons on the base electrode redistribute, generating two separate streams of electrons towards the top electrode and the bottom electrode until the aligned position is again achieved. Consequently, a cycle of electricity generation can be achieved by motion distance of a grating pitch. Therefore, it is the micro-grating design that enables alternating

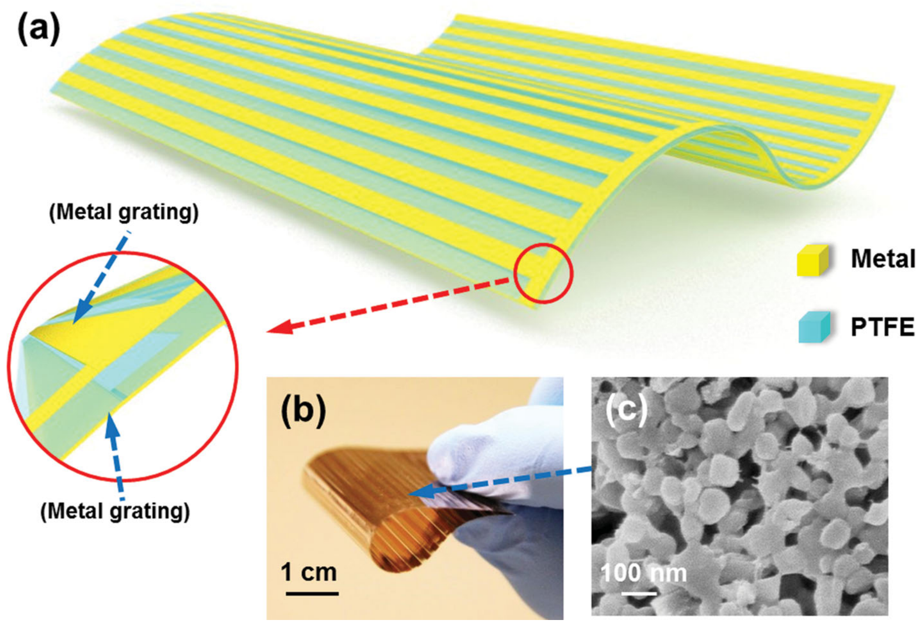


Figure 1. Device design of the MG-TENG. (a) Schematic illustrations of the thin film that composes of the MG-TENG. The zoom-in illustration (bottom left) reveals that the film consists of a PTFE layer and a pair of metal gratings that have complementary patterns. (b) Photograph of a flexible PTFE film with a pair of complementary metal gratings on both sides. The paired gratings are complementary, making central part of the film opaque. (c) SEM image of PTFE nanoparticles applied onto the surfaces on which friction takes place. They play a key role in enhancing energy conversion efficiency and mechanical robustness of the MG-TENG.

charge transport for numerous times in a small time frame, realizing the breakthrough in output current. The output charge from the MG-TENG is quantified by the following equation.

$$Q = (L / l)\sigma_{\text{induced}} A \quad (1)$$

where Q is the output charge defined as the overall amount of induced charges that can transport between electrodes regardless of the current direction, L is the sliding distance of the slider, l is the grating width that equals half pitch, σ_{induced} is the maximum density of induced charges on electrodes, and A is the contact area.

2.3. Characterization of the MG-TENG

2.3.1. Electric Output Measurement

To quantitatively characterize the output power of the MG-TENG, a linear motion was connected to the slider to provide mechanical force, while the guide keeps stationary. Driven by the linear motor that controls the sliding velocity, the slider makes reciprocating linear motion at a direction perpendicular to the metal strips (Figure S1). At a sliding velocity of 2 m s^{-1}, short-circuit current (I_{sc}) has continuous AC output at an average amplitude of 2 mA and constant frequency of 1 KHz (**Figure** 4a). For open-circuit voltage (V_{oc}), it oscillates between 0 and the maximum value of 500 V at the same frequency as I_{sc} (Figure 4b). With a bridge rectifier, the output charge without external load reaches 13.2 μC in 10 ms (Figure 4c), corresponding to an effective current ($I_{\text{effective}} = \Delta Q/\Delta t$) of 1.32 mA in short-circuit condition.[25] As indicated in the operating principle, two sets of units in the MG-TENG operate independently without interference. They produce synchronized currents that can add up. The inset in Figure 4c clearly exhibits separate output charge of the two sets. Each contributes approximately half of the overall output charge respectively.

It is noticed that the time span of a current cycle is determined by the ratio between the grating width and the sliding

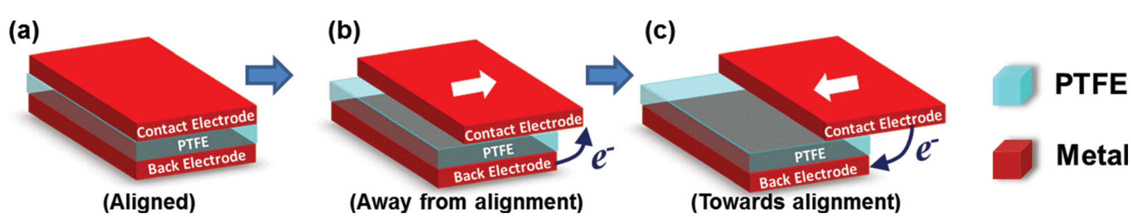


Figure 2. Basic electricity-generating unit in a MG-TENG that has a conductor-insulator-conductor system with two electrodes connected. (a) The contact metal is in alignment with the PTFE. (b) Relative in-plane motion introduces increasing misalignment between the contact electrode and the PTFE. In this process, uncompensated surface triboelectric charges increases, driving free electrons from the back electrode to the contact electrode. (c) Misalignment decreases as the contact electrode and the PTFE are moving back together, leading to a back flow of electrons from the contact electrode to the back electrode.

velocity (Figure 4a). Once an external load is applied, it brings about resistance and thus reduces the amount of electrons that can transport between electrodes within such a fixed time frame. This effect is revealed by the reduced $I_{\text{effective}}$ with increasing load resistance, as shown in Figure 4d. At the matched load of 1 MΩ, effective power ($P_{\text{effective}} = I_{\text{effective}}^2 R$, where R is the load resistance)[26] reaches the optimum value of 0.76 W at a sliding velocity of 2 m s^{-1}.

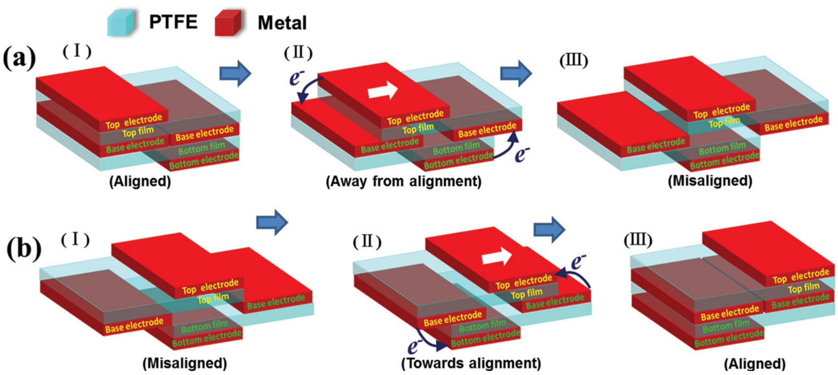


Figure 3. Overall process of electricity generation of the MG-TENG when both the top electrode and the bottom electrode are connected to the base electrode. (a) First half cycle of electricity generation process. Components marked in yellow and green labels belong to the slider and the guide, respectively. The sliding from the aligned state (I) to the misaligned state (II) corresponds to a flow of electrons towards the base electrode from the top and bottom electrodes. (b) Second half cycle of electricity generation process. Transition from the misaligned state (I) to the aligned state (II) is accompanied by the divergence of electron flow from the base electrode to the other two electrodes. Since the gratings are collections of repeated periodic patterns, continuous motion of the slider on the guide generates alternating current output.

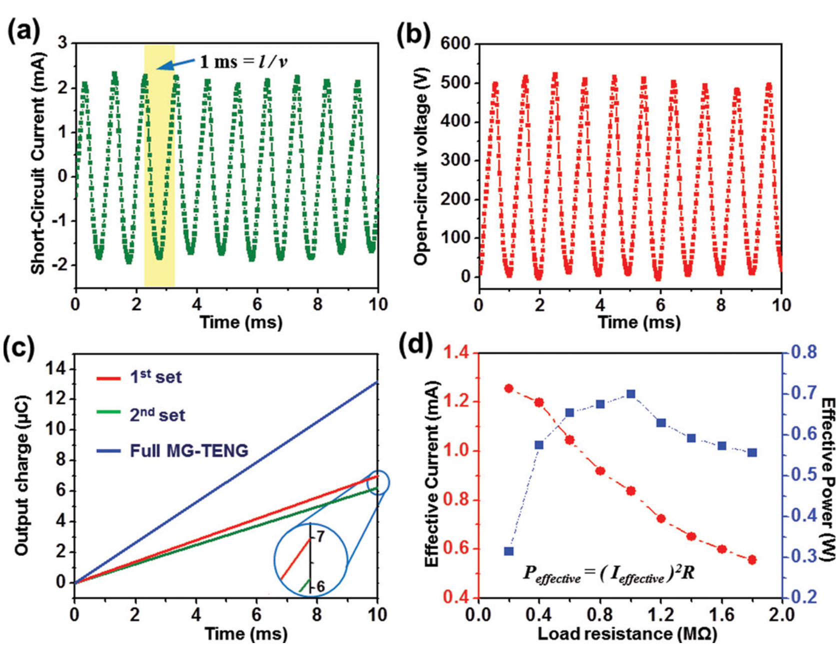


Figure 4. Results of electric measurements for a MG-TENG having a total area of 60 cm^2 and an effective contact area of 20 cm^2. (a) Short-circuit current (I_{sc}) at a sliding velocity of 2 m s^{-1}. (b) Open-circuit voltage (V_{oc}) at a sliding velocity of 2 m s^{-1}. (c) Output charge at a sliding velocity of 2 m s^{-1}. The overall output charge (blue curve) is composed of the output charge from two separate sets that generate electricity independently (red curve and green curve). (d) Load matching test at a sliding velocity of 2 m s^{-1}. Maximum effective power is obtained at the matched load of 1 MΩ.

2.3.2. Factors Determining the Electric Output

Sliding velocity is a major determining factor in electric output of the MG-TENG. A nearly linear relationship between the amplitude of I_{sc} and the sliding velocity can be obtained while the amplitude of V_{oc}, independent of the sliding velocity, remains at a stable value (**Figure 5**a). The sliding velocity also influences the optimum $I_{\text{effective}}$ (effective current at the matched load) as well as the corresponding matched load. Based on a series of load matching tests, Figure 5b exhibits a linear-like relationship between the optimum $I_{\text{effective}}$ and the sliding velocity. However, the corresponding matched load is approximately reversely proportional to the sliding velocity (Figure 5b). Therefore, the resultant optimum $P_{\text{effective}}$ is roughly linearly related to the sliding velocity (Figure 5c). The minor deviation from linear behavior in Figure 5a is likely attributed to finite inner resistance of the MG-TENG from the micro-sized metal gratings. As shown in Figure 5c, the optimum $P_{\text{effective}}$ of 3 W is achieved at a sliding velocity of 10 m s^{-1}, corresponding to a power density of 50 mW cm^{-2} (based on the overall area) and 15 W cm^{-3}.

Since triboelectric effect is a surface charging effect, the output charge of the MG-TENG is expected to linearly scale with the contact area between the two materials that have relative motion. With this regard, the scalability of the output charge in two dimensions was proved by changing the contact area (Figure S5). Furthermore, layers of MG-TENGs were stacked in the vertical direction to achieve multi-fold enhancement on the total contact area. PTFE thin films having patterned electrodes were applied on both sides of substrates (Figure S6). As revealed in Figure S7, the overall output charge of the stacked MG-TENGs equals the sum of the output charge from each layer, which indicates that the interference of electrostatic induction among different layers is negligible and does not affect the scalability in three dimensions.

Another major factor that influences the electric output of the MG-TENG is the dimension of the grating design, especially grating width and thickness of the dielectric film. Further scale-down of the grating width results in higher frequency of the output current. However, as the grating width approaches the thickness of the PTFE film, the amount of electrons that can transport in a single current cycle considerably reduces because of weakened in-plane polarization, as revealed by calculated results in **Table 1** via FEM simulation when

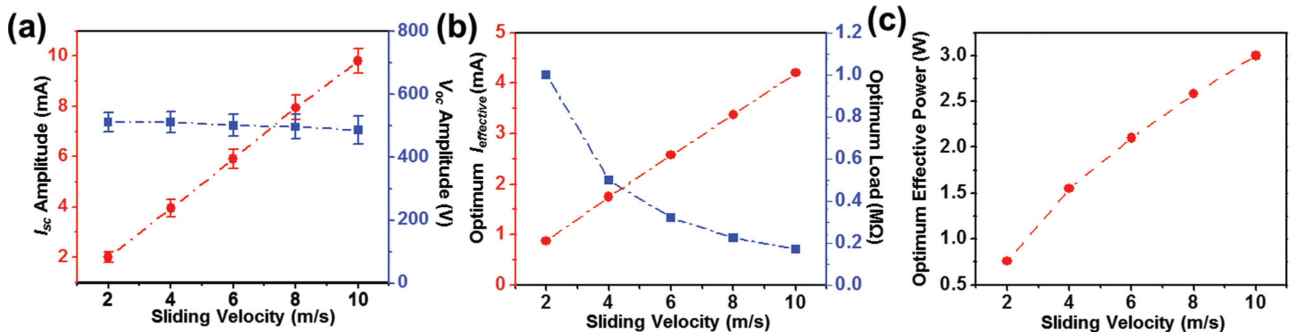


Figure 5. The effect of sliding velocity on the electric output of the MG-TENG. (a) Amplitude of I_{sc} and V_{oc} with varying sliding velocity. (b) The optimum effective current and corresponding load with varying sliding velocity. (c) The optimum effective power of the MG-TENG with varying sliding velocity.

the PTFE thickness is fixed at 25 µm. Based on the measured optimum $P_{effective}$ at grating width of 1 mm and numerical calculation results in Table 1, the optimum $P_{effective}$ at different values of grating width can be derived (**Figure 6**a). It is to be pointed out that the grating width is expected to linearly affect the matched load because it is in reverse proportion with the time span of a current cycle. As a consequence, if the grating width shrinks down to 50 µm, the optimum $P_{effective}$ is expected to reach the maximum value of 22.5 W at a sliding velocity of 10 m s^{-1}. Furthermore, scale-down of the PTFE thickness can also tremendously enhance the output charge (**Table 2**). When the PTFE thickness shrinks down to 5 µm, $I_{effective}$ in short-circuit condition is expected to reach the maximum value of 1.2 A (Figure 6b). However, the thickness is also determined by the fabrication process with a number of practical issues considered, such as manipulability and mechanical robustness of the thin film. For the currently adopted fabrication process that is easily scalable in size and does not demand sophisticated tools for patterning, the commercial cast PTFE film that is 25 µm in thickness is the smallest possible choice.

Table 1. Effect of grating width on charge transport of the MG-TENG.

Grating width (µm)	Triboelectric charge density ($\sigma_{triboelectric}$: µC m^{-2})	Maximum induced charge density ($\sigma_{induced}$: µC m^{-2})	$\sigma_{induced}/\sigma_{triboelectric}$ (%)
1000	330	317.526	96.22
750	330	314.028	95.16
500	330	307.296	93.12
250	330	289.938	87.86
100	330	247.929	75.13
75	330	226.611	68.67
50	330	194.535	58.95
25	330	135.102	40.94
10	330	73.788	22.36
7.5	330	61.545	18.65
5	330	41.745	12.65
1	330	17.523	5.31

2.3.3. Conversion Efficiency of the MG-TENG

The efficiency of the MG-TENG is defined as the ratio between input power from mechanical motion and electric power that is delivered to the load. To quantify the mechanical energy input, the slider was connected to the linear motion through an additional force sensor, which could measure the lateral force applied to the slider in the direction of sliding. Such a force is equivalent to the shear force between the two surfaces during sliding. By doing so, we were able to experimentally obtain the total input mechanical energy to the MG-TENG (Figure S8). With the electric energy that was experimentally measured, the efficiency reached nearly 50% when a matched load was connected. Such a high efficiency is attributed to not only large output power but also low-level losses resulting from nanoparticle-enabled surface modification. The nanoparticles shown in Figure 1c do not affect electric output, but significantly reduces the effective dynamic friction coefficient (**Table 3**) due to the following possible reasons. First, the sphere-shaped nanoparticles may partically convert sliding friction to rolling friction. Second, they play a role of interface layer by introducing a nanosized gap between PTFE and metal. Such spacing is expected to considerably lower the electrostatic attraction between triboelectric charges.[22] The substantially lowered friction then benefits durability of the MG-TENG, enabling long-term durability against wear (Figure S9).

3. MG-TENG as a Power Source for Commercial Electronics

To demonstrate the capability of the MG-TENG as a power source, it was directly connected to regular light bulbs without using a storage or power regulation unit. Driven by the electric motor, the slider moves at an average velocity of around 1 m s^{-1}. Different types of bulbs include 9 white spot lights (0.6 W each, **Figure 7**a, Supporting Movie 1), a white globe light (120 V each, Figure 7b, Supporting Movie 2), and 10 multi-color decoration candelabra lights (0.35 W each, Figure 7c, Supporting Movie 3). The obtained illumination output was sufficient for lighting up objects (Figure 7d, Supporting Movie 4) as well as printed texts (Figure 7e, Supporting Movie 5) in the darkness. The demonstrations lasted for several minutes without observable decay in

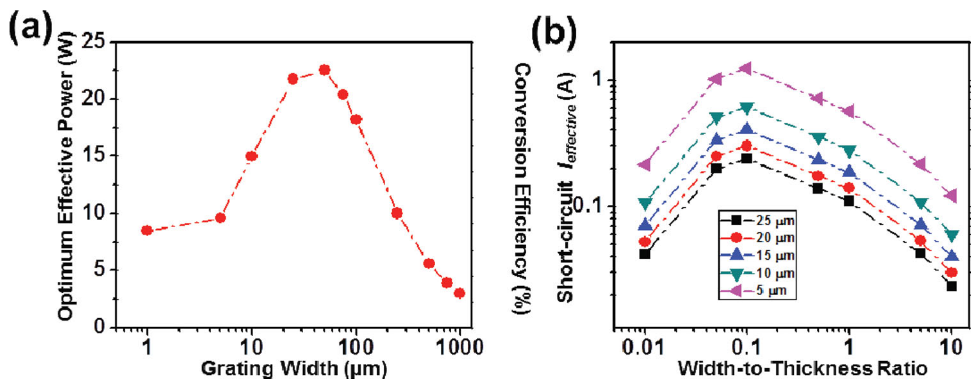


Figure 6. The effect of grating feature size on the electric output of the MG-TENG. (a) The optimum effective power with scale-down of the grating width at a sliding velocity of 10 m s^{-1}. The PTFE thickness remains at 25 μm. The x-axis is log-scale. (b) Effective current in short-circuit condition as a function of the ratio between the grating width and the PTFE thickness. At a fixed ratio, thinner PTFE corresponds to higher short-circuit $I_{effecitve}$. Both axes are log-scale.

Table 2. Effect of PTFE thickness on charge transport of the MG-TENG.

PTFE thickness (μm)	Width-to-thickness ratio[a)]	Triboelectric charge density($\sigma_{triboelectric}$: μC m^{-2})	Maximum induced charge density($\sigma_{induced}$: μC m^{-2})	$\sigma_{induced}/\sigma_{triboelectric}$ (%)
100	0.1	330	34.617	10.49
50	0.2	330	49.269	14.93
10	1	330	132.264	40.08
5	2	330	189.288	57.36
1	10	330	284.163	86.11
0.5	20	330	303.402	91.94
0.1	100	330	323.037	97.89

[a)]The grating width is fixed at 10 μm.

the light output, corresponding to a total of 100 thousand cycles of output current within the same period.

4. Applicability of the MG-TENG

4.1. Concept of Use

The unique operating principle and device configuration of the MG-TENG make it applicable to a wide range of circumstances as long as relative sliding between two surfaces is involved. First of all, it is suited to harness a variety of mechanical motions that are directly applied onto the MG-TENG because reciprocating motion can be readily obtained through conversion of other forms of mechanical motions. For example, rotation can be easily transformed into reciprocating motion through crankshafts. In this case, any rotation is a potential target source. For instance, the swing of limbs during people walking represents a rich reserve of mechanical energy that can be potential target source for the MG-TENG, which can easily provide velocity of several meters per second. Moreover, the thin-film-based design is shape-adaptive. The PTFE thin films with linear gratings can be adhered onto curved surfaces instead of planar ones (Figure S10), e.g. surfaces of cylindrical tubes that have matched inner diameter and outer diameter. For example, if the grating electrodes are parallel to the cylinder's length, electricity generation relies on relative rolling between the two cylinders; or if the grating electrodes are perpendicular to the cylinder's length, the MG-TENG can be excited by relative piston motion between the two cylinders. Given such unique adaptability, multiple forms of mechanical motions can be addressed.

Table 3. Effect of PTFE nanoparticle-based modification on dynamic frictional coefficients.

	With PTFE nanoparticles	Without PTFE nanoparticles
$\mu_{m\text{-}m}$[a)]	0.25	0.38
$\mu_{p\text{-}p}$[b)]	0.21	0.32
$\mu_{p\text{-}m} = \mu_{m\text{-}p}$[c)]	1.37	3.87

[a)]$\mu_{m\text{-}m}$ is the dynamic frictional coefficient between metals; [b)]$\mu_{p\text{-}p}$ is the dynamic frictional coefficient between PTFEs; [c)]$\mu_{p\text{-}m}$ and $\mu_{m\text{-}p}$ are the dynamic frictional coefficients between PTFE and metal.

Secondly, the MG-TENG it is capable of addressing inertial force through rational design, especially low-frequency and large-amplitude vibrations that are difficult to be addressed by micro-vibration harvesters because of limited room for displacement, e.g., swing of human ankle which can provide an acceleration as high as 100 m s^{-2} during walking.[27]

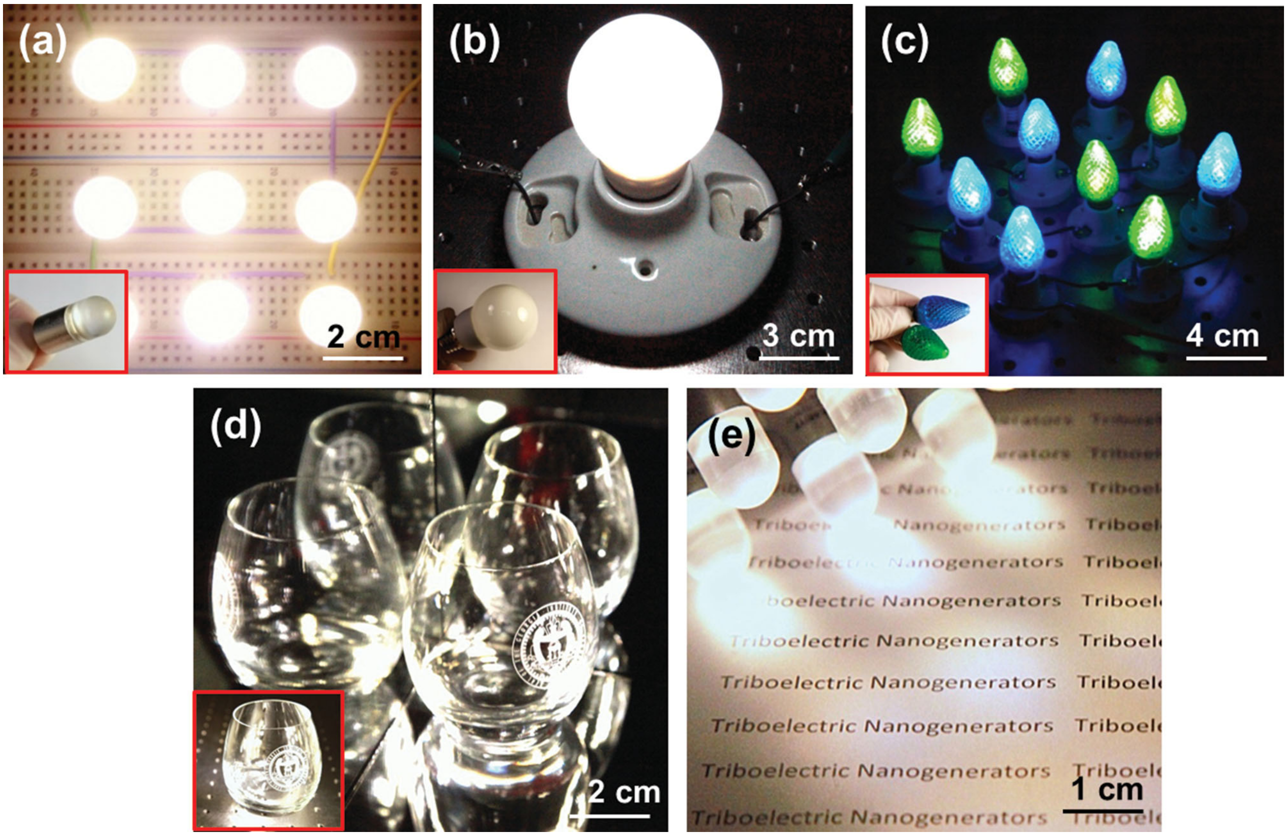


Figure 7. Demonstrations of the MG-TENG as a direct power source for regular light bulbs. (a) Photograph of 9 spot lights (each: 0.6 W and 12 V) in serial that are powered by the MG-TENG in complete darkness. Inset: a spot light in hand. (b) Photograph of a G16 globe light (120 V) that is powered by the MG-TENG in complete darkness. Inset: a globe light in hand. (c) Photograph of 10 C7 candelabra lights (each: 0.35 W, 12 V) in serial that are powered by the MG-TENG in complete darkness. Inset: a candelabra light in hand. (d) Photograph of a glass cup sitting on a mirror. Illumination is realized by the 9 spot lights in complete darkness with the MG-TENG as a power source. There is a Georgia Tech seal printed on the cup body. Inset: the glass cup sitting on a table with lights powered by the MG-TENG. (e) Photograph of printed text on paper illuminated by the 9 spot lights in complete darkness with the MG-TENG as a power source. The font size is 12 points.

Furthermore, the frictional damping in the MG-TENG results in broader bandwidth response, making it have more tolerance on the change of the vibration excitation frequency. Therefore, it is a proper solution for harvesting energy from irregular vibrations that have relatively large fluctuation or shift in frequency, such as human motions.

Additionally, given the scalability of the MG-TENG, it can be even potentially used for large-scale electricity generation by capturing mechanical energy in nature including wind and ocean wave, which can induce very high moving velocity of the MG-TENG due to large input of mechanical energy. Therefore, the MG-TENG can be used to address both a variety of "direct" forces and inertial forces, particular low-frequency large-amplitude, and irregular vibrations. Specific applications include self-powered wireless sensors, charging portable/wearable electronics, and large-scale energy generation as well.

4.2. Comparison to Other Techniques

Compared with other technologies, the MG-TENG provides a unique solution in taking advantage of relative motions between surfaces, in which existing technologies cannot be implemented. The thin-film based structure makes it shape-adaptive and thus applicable to even curved surfaces. In comparison to traditional electromagnetic generators in terms of electric output power, it provides a substantially higher output voltage but smaller output current. Therefore, it delivers an output power that is comparable to that of an electromagnetic generator when both of them operate at their corresponding matched load. More importantly, the distinction in fundamental mechanism differentiates our device from the traditional generator and results in a number of advantages. Firstly, the MG-TENG has high output power as well as light weight and small size because it is fabricated from thin-film materials. In contrast, the usual generator has a bulky structure in order to maintain decent output power.[27] As a result, the MG-TENG is superior in power density in terms of both power-to-volume ratio and power-to-weight ratio. This advantage is especially important for developing self-powered portable/wearable electronics, where size and weight management are important. Secondly, since the MG-TENG relies on surface charging effect, it only requires very small amount of materials, which are conventional materials that are readily available. With scalable and straightforward fabrication process, the MG-TENG is significantly cost-effective, an unparalleled advantage for potential practical applications. Finally, our generator has its unique applications. It provides a straightforward and even only solution to harvesting energy from sliding motion between two surfaces, which cannot be achieved by the usual generator. It needs to be further noted that the MG-TENG can be made from materials other than the PTFE here as long as they own similar triboelectric property. The broad choices of materials enable special applications, e.g. those in healthcare where biocompatibility is required.

5. Conclusions

In summary, we develope a new type of electricity-generation method that takes advantage of triboelectrification, a universal phenomenon upon contact between two materials. Based on polymer thin films that have complementary linear electrode arrays, the MG-TENG effectively produces electricity that is sufficient for powering regular electronics as two contacting surfaces relatively slide. The shape-adaptive design of the MG-TENG suggests its wide applications in dealing with a variety of mechanical motions. Given its high electric output power and other significant advantages in weight, volume, cost, scalability and adaptability, the MG-TENG is a practically promising approach in harvesting mechanical motions for self-powered electronics as well as possibly producing electricity at a large scale.

6. Experimental Section

Preparation of a Slider: 1. Make a mask that has hollow grating patterns. The mask material is thin acrylic sheet (1.5 mm thickness). The grating unit has length of 4 cm and width of 1 mm with interval of 1 mm in between. So the pitch size is 2 mm. The overall size of the grating pattern is 5 cm by 4 cm. Carved through the acrylic sheet to make the grating pattern become hollow; 2. Prepare a PTFE film with dimensions of 5 cm by 4 cm by 25 μm; 3. Place the PTFE film below the acrylic mask; 4. Treat the exposed PTFE surface with Argon plasma at power of 100 W for 30 seconds; 5. Deposit 20 nm of Ti by sputtering on the exposed surface of PTFE through the windows of the acrylic mask; 6. Subsequently deposit 500 nm of copper by sputtering; 7. Flip over the PTFE film and align the acrylic mask by shifting half pitch perpendicular to the grating units, making grating patterns on opposite sides complementary; 8. Deposit 20 nm of Ti and then 500 nm of copper on the other side of the PTFE film; 9. Electrically connect lead wires to the two metal grating networks on both sides of the PTFE film; 10. Spread the PTFE flat out on the surface of an acrylic sheet; 11. Evenly spray water-based PTFE nanoparticle suspension on to the PTEF film, and dry by air blow.

Preparation of a Guide: The process flow for fabricating a guide is similar to a slider. The difference is that the guide has larger length (15 cm) than the slider. Correspondingly, the acrylic mask and the PTFE thin film have larger length in the fabrication process. All other dimensions and processing remain the same.

Operation Setup of the MG-TENG: 1. Fix the guide onto a flat stationary stage; 2. Put the slider onto the guide. PTFE thins films of the two parts are in contact; 3. Make alignment so that the linear grating on the slider is parallel to that on the guide; 4. Attached the slider to a linear motor, which can introduce relative motion between the slider and the guide; 5. The lead wires from the two metal gratings in contact are connected, forming one output terminal. It is also called base electrode; 6. The lead wires from the other two metal gratings on the back of PTFE films are connected, forming another output terminal; 7. The two output terminals are connected to measurement system or electronics for electric measurement and applications, respectively.

Numerical Calculation via COMSOL: 1. Open-circuit condition: 2D modeling is used. Electrostatic module is selected to do the calculation. The dimension of the geometry is the same as a real device. A circle is drawn to circumscribe the whole generator. The circle has infinite size compared to the dimension of the device. It is set to be grounded, indicating zero electric potential at infinity. Surface charge density is applied onto the contact surfaces on PTFE and metal; 2. Short-circuit condition: The difference with the previous model is that the two metal electrodes are also grounded, indicating that they are electrically shorted. After computation, Line integration is used to find out the charge density on electrodes. Therefore, the amount of charge that transport between electrodes in shot-circuit condition can be derived.

Supporting Information

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

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[25] Submitted by the measured output charge, Equation 1 yields the maximum induced charge density to be 330 μC mthat is consistent with previous reports.
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