Supplementary Materials

Linear-grating triboelectric generator based on sliding electrification

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1. Analytical model for calculating the open-circuit voltage of the TEG

For simplicity of the mathematical derivation, the analytical model is built based on the following assumptions:

(1) The two sliding surfaces of the TEG are infinitely large because the lateral dimension is much larger than the vertical thickness.

(2) The generated triboelectric charges, which are non-mobile and non-annihilative, are uniformly distributed on the two surfaces. This is an excellent approximation if the two materials are insulative. In a case that one side is metal, this approximation is made for easy derivation.

(3) Both the aluminum and the PTFE thin film can be simplified as planar surfaces which retain their shapes instead of having deformation when sliding laterally.

Once the two surfaces contact with each other, triboelectric charges are created due to contact electrification. Based on assumption (2) and assumption (3), the lateral displacement l brings about uncompensated positive and negative triboelectric charges in the displaced areas on the upper surface and the lower surface, respectively (Fig. S1).

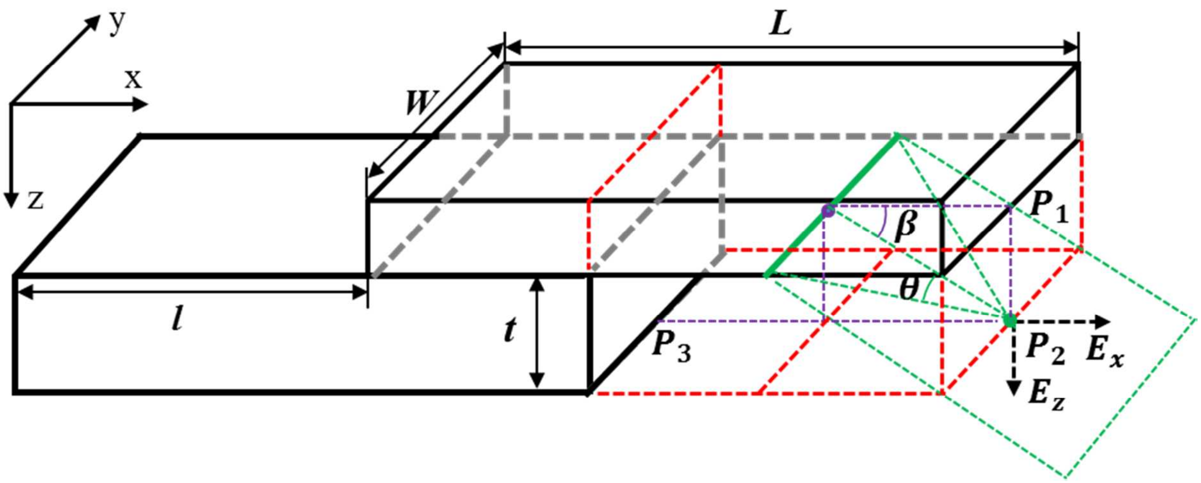

Figure S1. A schematic to illustrate the calculation of open-circuit voltage V_{oc} and the definition of the parameters.

If we define the electric potential of the copper electrode (U_{Cu}) to be zero, the open circuit voltage of the TEG is equal to the electric potential of the electrode electrode (U_{Al}), that is,

$$V_{oc} = U_{Al} - U_{Cu} = U_{Al} = U_{P_1} - U_{P_3} \tag{S1}$$

Also, the electric potential difference can be expressed as

$$U_{P_1} - U_{P_3} = \int_{P_1}^{P_3} E \cdot d\ell_{1\to3} = \int_{P_1}^{P_2} E_{1\to2} \cdot dt + \int_{P_2}^{P_3} E_{2\to3} \cdot dl \tag{S2}$$

Meanwhile, given assumption (1) and (2), we can consider the upper surface as charged plate of infinity in size, so that the electric lines of force are perpendicular to the surface of the plate as well as the patch from P_2 to P_3. As a result

$$\int_{P_2}^{P_3} E_{2\to3} \cdot dl = 0 \tag{S3}$$

and

$$U_{Al} = \int_{P_1}^{P_2} E_{1\to2} \cdot dt \tag{S4}$$

In order to calculate the electric field strength $E_{1\to2}$ in the path from P_1 to P_2, let us consider an infinite, charged line in the displaced area on the upper surface, as indicated by the solid green line in Fig. S1. And the corresponding electric field strength E_{sl} at P_2 can be quantitatively expressed as

$$E_{sl} = \int_{-\theta}^{+\theta} \frac{\sigma}{4\pi\varepsilon_0} \cdot \frac{\cos\theta}{\sqrt{t^2+l^2}} \cdot d\theta = \frac{\sigma}{2\pi\varepsilon_0} \cdot \frac{\sin\theta}{\sqrt{t^2+l^2}} \tag{S5}$$

where ε_0 is the permittivity of vacuum, *t* is the thickness of the PTFE film, *l* is the displacement, and σ is the line charge density

$$\sigma = \frac{q}{WL} \tag{S6}$$

where q is the total triboelectric charges, *W* and *L* are the width and length of the two sliding surfaces, respectively. Meanwhile, in our case, compared with the PTFE's thickness, the charged line is considered to be infinitely long, thus,

$$\theta = 90^{\circ} \tag{S7}$$

Upon combination and simplification, E_{sl} can be expressed as

$$E_{sl} = \frac{q}{2\pi\varepsilon_0 WL\sqrt{(t^2+l^2)}} \tag{S8}$$

However, only the component along Z axis of the electric filed strength E_{sl} is parallel to the electric field, making the effective electric filed strength expressed as

$$\mathrm{E}_{eff} = E_{sl} \cdot \sin\beta \tag{S9}$$

$$\sin\beta = \frac{t}{\sqrt{t^2+l^2}} \tag{S10}$$

Upon combination and simplification,

$$\mathrm{E}_{eff} = E_{sl} \cdot \sin\beta = \frac{q}{2\pi\varepsilon_0 WL} \cdot \frac{t}{(t^2+l^2)} \tag{S11}$$

Thus, the total electric filed strength $E_{1\to2}$ generated at P_2 along the z-axis by the triboelectric charges on the entire displaced area of the upper surface can be calculated as

$$E_{1\to2} = \int_0^l \frac{q}{2\pi\varepsilon_0 WL} \cdot \frac{t}{(t^2+l^2)}\, dl = \frac{q}{2\pi\varepsilon_0 WL} \cdot \tan^{-1}\left(\frac{l}{t}\right) \tag{S12}$$

Submit the Equation *(S12)* into the Equation *(S4)*

$$U_{Al} = \int_0^t E_{1\to2} \cdot dt = \int_0^t \frac{q}{2\pi\varepsilon_0 WL} \cdot \tan^{-1}\left(\frac{l}{t}\right)\, dt \tag{S13}$$

Finally, the open-circuit voltage V_{oc} between the two electrodes can be expressed as

$$V_{oc} = U_{Al} = \frac{q}{2\pi\varepsilon_0 WL} \cdot \left[\frac{l}{2}\ln(t^2 + l^2) + t\tan^{-1}\left(\frac{l}{t}\right)\right] \tag{S14}$$

2. Fabrication process of the grating TEG

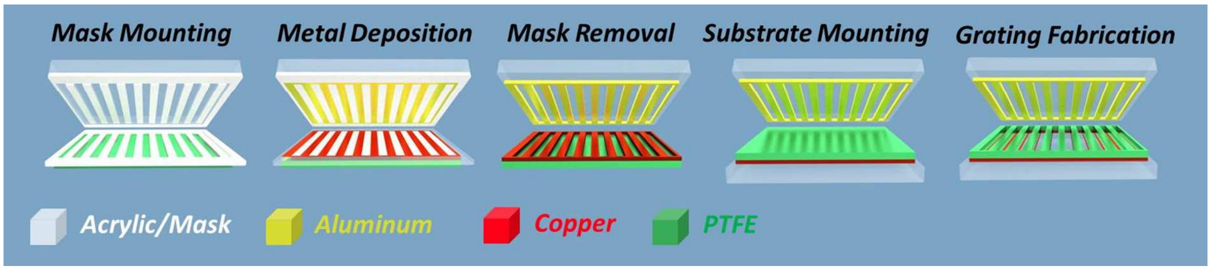

Figure S2. Fabrication process of a grating TEG.

3. Illustration and explanation of Equation 2

Although the grating design sacrifices half of the contact area and thus half of the triboelectric charges, induced free electrons can be pumped back and forth between metal electrodes by multiple times because of the grating design. How many times the electrons can be pumped is linearly related to the number of grating units. For the structure with 2 units, the two effects described above compensate with each other. In this work, for the process in which the grating units move from aligned position to displaced position, the current is defined as positive. If the non-grating structure can generate the amount of charge $Q_{(non)}$ for a single sliding process, the grating structure with 2 units can generate total charge of (2q'+|- q'|+ q')= $Q_{(non)}$ in the sliding process with the induced electrons pumped back and forth for 3 times. This process is illustrated in the Fig. S3, making the output charge equal to that from non-grating structure. As defined in the manuscript, q' is the induced charges generated from a single grating unit for a displacement of the unit length. Here, it needs to be pointed out that the parameter q' is not constant but dependent on the number of grating unit (q'= $Q_{(non)}$/2N). With grating unit number larger than 2, the grating structure outplays the non-grating one.

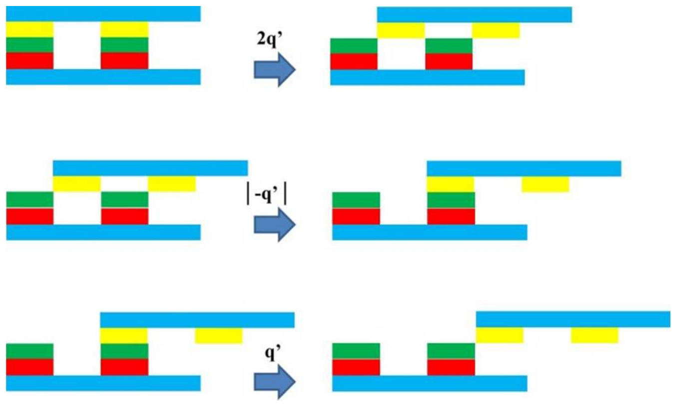

Figure S3. The schematics that show the breakdown of charge generation process for a grating generator with 2 units.

4. Analysis on the shape of the current peaks from a grating generator

For the grating structure, the current peaks do resemble a wave packet. But the pattern is not symmetric. The reason for such a resemblance is explained as follows. The magnitude of current peaks is determined by two factors, i.e. motion velocity and the amount charge for each peak.

First, the effect of motion velocity will be discussed. The relative reciprocating motion between the Al electrode and the PTFE film is realized by a linear motor. For the reciprocating motion, the two ending points are the position where the substrates are fully aligned and the position where they are fully displaced. For a single sliding process, the motor first accelerates until it reaches a maximum velocity and then decelerates until it came to a stop. Since higher motion velocity corresponds to larger current magnitude, for current peaks in a single sliding process, peaks in the middle are larger than those at the two ends, generating a pattern similar to a wave packet. Such a pattern is clearly illustrated in the following figure.

Second, the effect of charge amount is discussed as follows. For a grating structure, as the two substrates slide apart, the amount of induced charges by sliding over a distance of the grating length decreases because of reduced contact area. Since more charges correspond to larger current peaks, the peaks at the starting point (where the two substrates are aligned) are larger than those at the ending point (where the substrates are fully displaced). Therefore, the current peaks are not symmetric. As illustrated in the following figure, peak #1 is larger than #15; peak #2 is larger than #14; peak #3 is larger than #13.

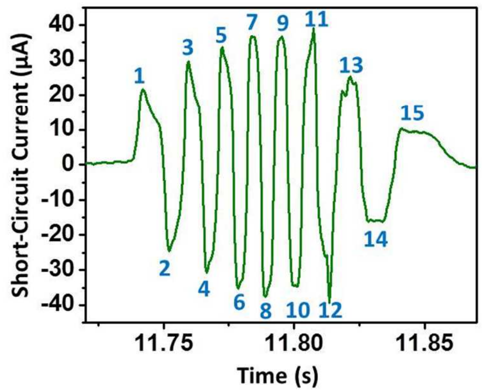

Figure S4. Short-circuit current from a grating generator with 8 grating unit.

5. Estimation of the effect from misorientation angle

In an ideal case, the TEG system can achieve the best output performance if the two sliding surfaces can completely coincide with each other at aligned position (Fig. S3a). However, in reality, it is impractical to make a perfect match.

We define a new term, angle of misorientation δ, which is the angle between the two central axes of the sliding surfaces, as indicated in Fig. S3.

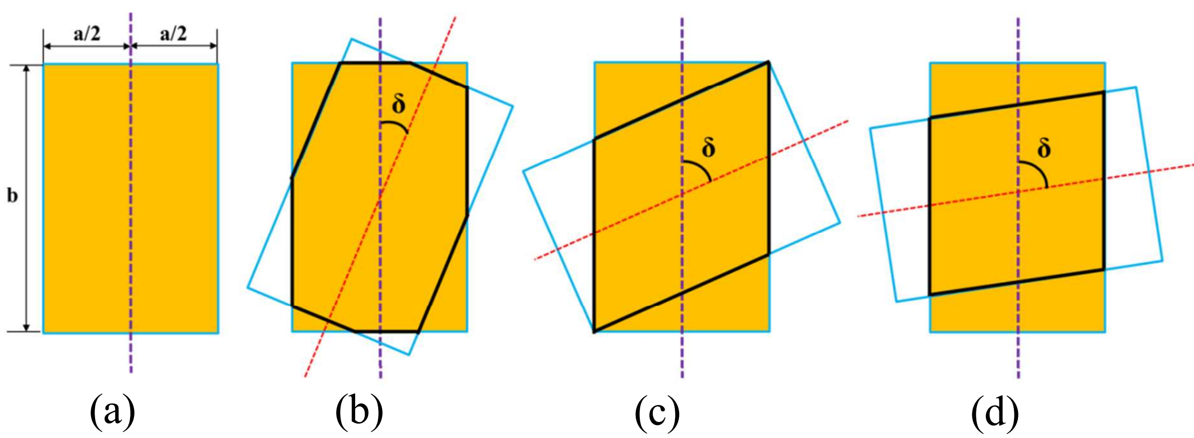

Figure S5. Sliding cases with different angles of misorientation δ. (a) $\delta = 0^{\circ}$, a perfect match. (b) $\delta < 2\tan^{-1}\left(\frac{a}{b}\right)$. (c) A critical mismatch point when $\delta = 2\tan^{-1}\left(\frac{a}{b}\right)$. (d) $\delta > 2\tan^{-1}\left(\frac{a}{b}\right)$.

The two surfaces are identical rectangles with width a, length b and $a < b$, thus the effective contact area of the two surfaces in the sliding process is a function of a, b and δ, mathematically can be expressed as

$$S_{eff} = \mathrm{ab} - [\left(\frac{\mathrm{a}}{2} - \frac{b}{2}\tan\frac{\delta}{2}\right)^2 + \left(\frac{b}{2} - \frac{\mathrm{a}}{2}\tan\frac{\delta}{2}\right)^2]\tan\delta. \quad \textit{(S15)}$$

when $\delta < 2\tan^{-1}\left(\frac{\mathrm{a}}{b}\right)$.

And $$S_{eff} = \frac{\mathrm{a}^2}{\sin\delta}, \quad \textit{(S16)}$$

when $\delta \geq 2\tan^{-1}\left(\frac{\mathrm{a}}{b}\right)$.

Base on the calculation in Equations *(S15)* and *(S16)*, it is safe to conclude that the effective contact area of the two surfaces decreases as the angles of misorientation δ increases from $0^{\circ}$to 90°, which shows negative effect on the output of the TEG.

6. Estimation of the energy conversion efficiency:

Accurately, calculating the energy conversion efficiency is not an easy task because it is hard to calculate the input mechanical energy in the frictional process. Here we can only give a rough estimation.

Mechanical Energy:

We first consider the mechanical energy input to each grating for a sliding distance of L. With considering the mismatch contact area during the sliding, the input energy to overcome the friction force between the top layer and the bottom layer is:

$$\Delta E = 1/2\ \mu \cdot \Delta m \cdot g \cdot L \quad (\textit{S17})$$

where μ is the dynamic friction coefficient between the two layers, Δm is the mass of each grating, g is the gravitation acceleration, and L is the length of the grating.

With considering the dynamic sliding between the top and the bottom layer for a grating of N units, the total input mechanical energy to overcome the friction is

$$E = N^2 \cdot \Delta E \quad (\textit{S18})$$

For N = 10, L = 3.1 mm, Δm = 1 g, L = 3.1 mm, the dynamic friction coefficient between PTFE and steel is in the range of 0.05 to 0.2, so the estimated input mechanical energy E is in a range of from 0.078 to 0.31mJ (http://en.wikipedia.org/wiki/Friction).

Generated electric energy:

For a grating TEG with 10 units, a sliding process over the entire length of the TEG generates 2.8 uC of charges. The sliding process takes 6.4 cm/(0.6 m/s) = 0.1 s. Therefore, the average output current is 2.8 uC/0.1 s = 28 μA. Our previous study shows that the maximum output energy occurs at a load of 1 MΩ. Besides, the ratio between the actual output current at the load of 1 MΩ and the short circuit current is roughly 0.55 (Zhu, G. *et al*., *Nano Lett.* **12,** 4960–4965 (2012)). Thus, the maximum output power is $I^2R = (28\ \mu A \times 0.55)^2 \times 1\ M\Omega = 0.24$ mW. The output total energy within 0.1 s is: 0.24 mW × 0.1 s = 0.024 mJ.

The conversion efficiency is 8 to 31%.