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Supporting Information

A primary-secondary triboelectric nanogenerator with charge excitation shift in a wind-driven alternating operating mode

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Note1: Calculation process of V_2.

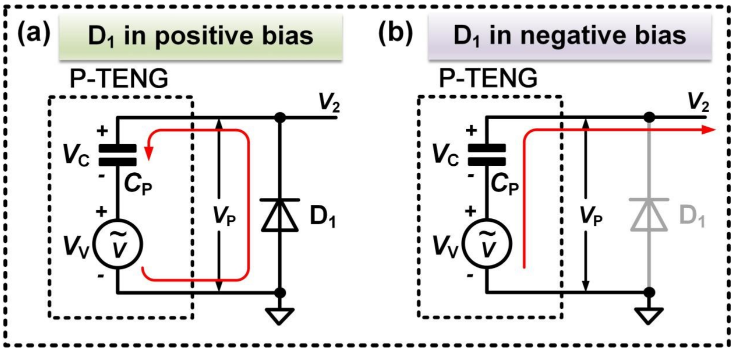

Fig. S1. Working process of doubler diode D_1. (a) Working process with D_1 in positive bias. (b) Working process with D_1 in negative bias.

P-TENG can be equivalent to the series of a capacitor C_P and an AC voltage source V_V in the circuit, as displayed in Fig. S1. Suppose V_P and V_C are the voltage of P-TENG and C_P, the positive maximum value and negative maximum value of V_V are V_{max1} and $-V_{max2}$ respectively, where $V_{max1}>0$ and $V_{max2}>0$. The voltage of V_2 is

$$V_2=V_P=V_C+V_V \tag{S1}$$

If $V_P \leq 0$, D_1 is in positive bias and is equivalent to short circuit, as exhibited in Fig. S1a. In this situation, C_P is charging and current flows from V_V to C_P (red line in Fig. S1a). According to Kirchhoff's voltage law (KVL), it has

$$V_C+V_V=0 \tag{S2}$$

So the voltage of V_2 is

$$V_2=V_C+V_V=0 \tag{S3}$$

When $V_V=-V_{max2}$, V_C reaches its maximum value,

$$V_{\mathrm{C\_max}}=V_{\mathrm{max2}} \tag{S4}$$

If $V_{\mathrm{P}}>0$, D_1 is in negative bias and is equivalent to open circuit, as exhibited in Fig. S1b. So

$$V_2=V_{\mathrm{max2}}+V_{\mathrm{V}} \tag{S5}$$

When $V_{\mathrm{V}}=V_{\mathrm{max1}}$, V_2 reaches its maximum value,

$$V_{2\_\mathrm{max}}=V_{\mathrm{max1}}+V_{\mathrm{max2}} \tag{S6}$$

Specially, if $V_{\mathrm{max1}}=V_{\mathrm{max2}}=V_{\mathrm{max}}$, the maximum value of V_2 is

$$V_{2\_\mathrm{max}}=2V_{\mathrm{max}} \tag{S7}$$

Note2: Calculation process of transferred charges.

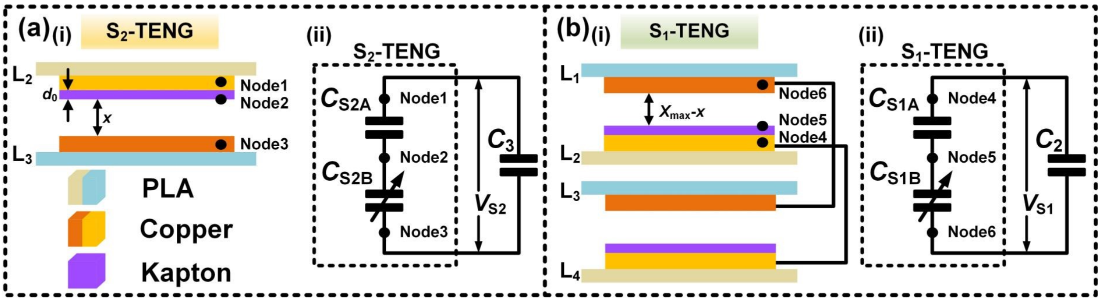

Fig. S2. Equivalent circuit diagram of S_1-TENG and S_2-TENG. (a) Equivalent circuit diagram of S_2-TENG. (b) Equivalent circuit diagram of S_1-TENG.

The equivalent circuit diagram of S_2-TENG is exhibited in Fig. S2a. It equivalents to the series of a fixed capacitor C_{S2A} and a variable capacitor C_{S2B},

$$C_{\mathrm{S2A}} = \frac{\varepsilon_0 \varepsilon_{\mathrm{r}} A}{d_0} \tag{S8}$$

$$C_{\mathrm{S2B}}(x) = \frac{\varepsilon_0 A}{x} \tag{S9}$$

where ε_0 and ε_{r} denote vacuum permittivity and relative permittivity of dielectric material, d_0 represents the thickness of dielectric material, A is the active area of S_2-TENG, x stands for the distance from L_2 to L_3, which satisfies $0 \leq x \leq X_{\max}$, and $X_{\max}$ is the maximum value of x. So the equivalents capacitor of S_2-TENG is

$$C_{\mathrm{S2}}(x) = \frac{1}{\dfrac{1}{C_{\mathrm{S2A}}} + \dfrac{1}{C_{\mathrm{S2B}}(x)}} = \frac{\varepsilon_0 \varepsilon_{\mathrm{r}} A}{\varepsilon_{\mathrm{r}} x + d_0} \tag{S10}$$

Let Q_2 be the total charges of S_2-TENG and buffer capacitor C_3,

$$Q_2 = Q_{\mathrm{S2}}(x) + Q_{\mathrm{C3}}(x) \tag{S11}$$

where Q_{S2} and Q_{C3} are the charges in S_2-TENG and C_3 respectively. It can be further expressed as

$$Q_2 = C_{\mathrm{S2}}(x) V_{\mathrm{S2}}(x) + C_3 V_{\mathrm{C3}}(x) \tag{S12}$$

where V_{S2} and V_{C3} represent the voltages of S_2-TENG and C_3. According to KVL, it has

$$V_{\mathrm{S2}}(x) = V_{\mathrm{C3}}(x) \tag{S13}$$

From equation (S10), (S12) and (S13), it has

$$V_{\mathrm{S2}}(x) = \frac{\varepsilon_{\mathrm{r}} x + d_0}{\varepsilon_{\mathrm{r}} C_3 x + d_0 C_3 + \varepsilon_0 \varepsilon_{\mathrm{r}} A} Q_2 \tag{S14}$$

So

$$Q_{\mathrm{S2}}(x)=C_{\mathrm{S2}}(x)V_{\mathrm{S2}}(x)=\frac{\varepsilon_0\varepsilon_{\mathrm{r}}A}{\varepsilon_{\mathrm{r}}C_3x+d_0C_3+\varepsilon_0\varepsilon_{\mathrm{r}}A}Q_2 \tag{S15}$$

It shows that charges in S$_2$-TENG varies with x, so the transferred charges of S$_2$-TENG are from contacted state to separated state,

$$\begin{aligned} Q_{\mathrm{TR2}}&=Q_{\mathrm{S2}}(0)-Q_{\mathrm{S2}}(X_{\max}) \\ &=\frac{\varepsilon_0{\varepsilon_{\mathrm{r}}}^2AC_3X_{\max}}{(d_0C_3+\varepsilon_0\varepsilon_{\mathrm{r}}A)(\varepsilon_{\mathrm{r}}C_3X_{\max}+d_0C_3+\varepsilon_0\varepsilon_{\mathrm{r}}A)}Q_2 \end{aligned} \tag{S16}$$

Let η_2 be the charge transfer efficiency of S$_2$-TENG,

$$\eta_2=\frac{Q_{\mathrm{TR2}}}{Q_2} \tag{S17}$$

η_2 reaches its maximum value when $X_{\max}\to\infty$,

$$\eta_{2\_\max}=\frac{\varepsilon_0\varepsilon_{\mathrm{r}}A}{d_0C_3+\varepsilon_0\varepsilon_{\mathrm{r}}A}=\frac{1}{\dfrac{C_3}{C_{\mathrm{S2A}}}+1}<1 \tag{S18}$$

It indicates η_2 can not reach 100%, and is related to C_3. If C_3=0 (short circuit), charge transfer efficiency is 100% which is the same as common TENG.

As to S$_1$-TENG, the active area is twice of S$_2$-TENG, and the distance is $X_{\max}$-x, as depicted in Fig. S2b. The corresponding equations are listed below,

$$V_{\mathrm{S1}}(x)=\frac{\varepsilon_{\mathrm{r}}x-(\varepsilon_{\mathrm{r}}X_{\max}+d_0)}{\varepsilon_{\mathrm{r}}C_2x-(\varepsilon_{\mathrm{r}}C_2X_{\max}+d_0C_2+2\varepsilon_0\varepsilon_{\mathrm{r}}A)}Q_1 \tag{S19}$$

$$Q_{\mathrm{S1}}(x)=\frac{-2\varepsilon_0\varepsilon_{\mathrm{r}}A}{\varepsilon_{\mathrm{r}}C_2x-(\varepsilon_{\mathrm{r}}C_2X_{\max}+d_0C_2+2\varepsilon_0\varepsilon_{\mathrm{r}}A)}Q_1 \tag{S20}$$

$$Q_{\mathrm{TR1}}=\frac{-2\varepsilon_0{\varepsilon_{\mathrm{r}}}^2AC_2X_{\max}}{(d_0C_2+2\varepsilon_0\varepsilon_{\mathrm{r}}A)(\varepsilon_{\mathrm{r}}C_2X_{\max}+d_0C_2+2\varepsilon_0\varepsilon_{\mathrm{r}}A)}Q_1 \tag{S21}$$

where Q_1 is the total charges of S$_1$-TENG and buffer capacitor C_2.

The partial derivative results of V_{S1} and V_{S2} to x are

$$\frac{\partial V_{\mathrm{S1}}}{\partial x}=\frac{-2\varepsilon_0{\varepsilon_{\mathrm{r}}}^2AQ_1}{[\varepsilon_{\mathrm{r}}C_2x-(\varepsilon_{\mathrm{r}}C_2X_{\max}+d_0C_2+2\varepsilon_0\varepsilon_{\mathrm{r}}A)]^2}<0 \tag{S22}$$

$$\frac{\partial V_{\mathrm{S2}}}{\partial x}=\frac{\varepsilon_0{\varepsilon_{\mathrm{r}}}^2AQ_2}{[\varepsilon_{\mathrm{r}}C_3x+(d_0C_3+\varepsilon_0\varepsilon_{\mathrm{r}}A)]^2}>0 \tag{S23}$$

It shows V_{S1} and V_{S2} have the opposite variation trends as x varies, so they are a pair of differential voltages. When one of them is increasing, the other one must be decreasing, and vice versa. It verifies again that S$_1$-TENG and S$_2$-TENG can take turns to accomplish the process of charge excitation and output.

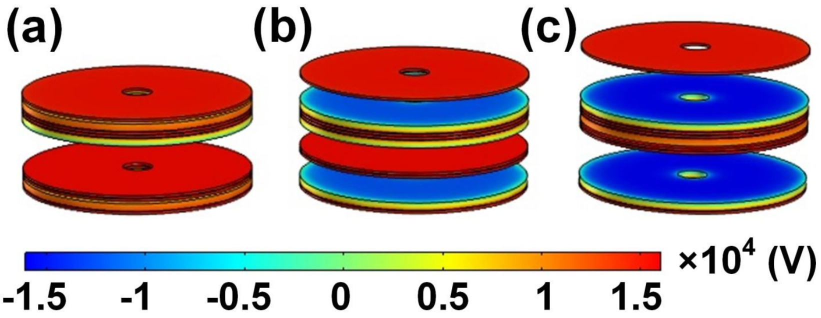

Fig. S3. The simulation of electrode potential.

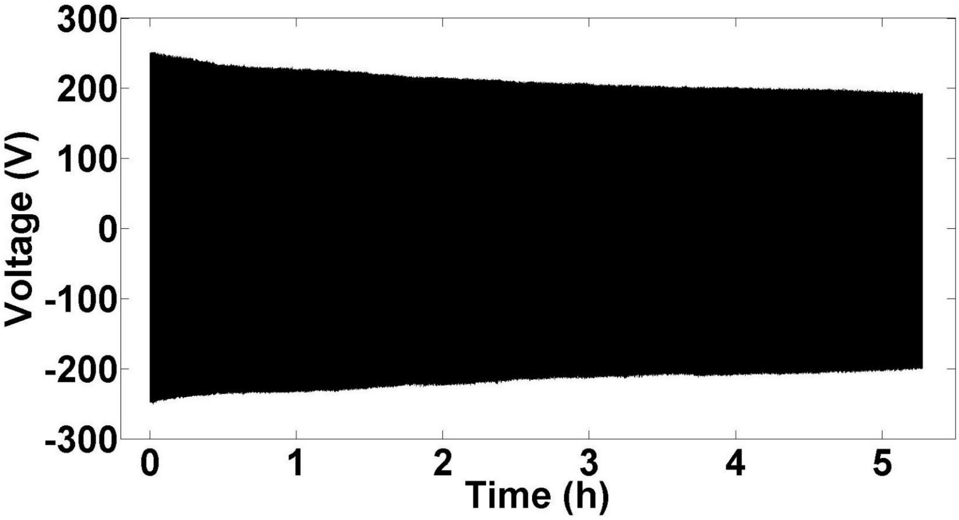

Fig. S4. The basic durability test of the device.

Table S1. Power density comparison with other charge excitation works.

name	CST-greenhouse	MF-CE-TENG	O-TENG	PS-TENG
shape	arch	rectangle	rectangle	ring
size(mm)	200×157	198×138	50×50	outer diameter: 92 inner diameter: 12
area(m^2)	3.14E-02	2.73E-02	2.50E-03	6.53E-03
power	107.09 μW	5.17 mW	697 μW	4 mW
density(mW/m^2)	3.06	189.2	278.8	612.4
Ref.	[S1]	[S2]	[S3]	This work

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