Supplementary information

1. Dynamic operation of the DMSE-TENG prototype

The kinetic $E_{kinetic}$ and elastic $E_{elastic}$ energy equations (1) (2) describe the energy applied to the arc-shaped dielectric-metal single electrode triboelectric nanogenerators (DMSE-TENG, prototype 1) (Fig. 2) system. Where $E_{kinetic}$ is the energy carried by the moveable arc-shaped dielectric layer that plays the role of contact material for triboelectricity. $E_{elastic}$ is the energy stored in the dielectric layer acting as a spring for separation after contact.

$$E_{kinetic} = \frac{1}{2}mv^2 = 0.34mJ \tag{1}$$

$$E_{elastic} = \frac{1}{2}kx^2N = 0.015\ mJ \tag{2}$$

The average velocity (v = 1.5 m/s) of the dielectric layer when the contact is made due the ball bearing impact was estimated with the equation $v = x/t$, where, x is the displacement of the ball bearing when it contacts the dielectric layer (x = 0.3 m) and t is the average time measured when it contacts the dielectric layer (t = 0.2 s). The spring constant (k = 0.59 N/m) was estimated based on the mass of the moveable dielectric layer (m_{PDMS} = 0.303125 g) according to Hooke's law $k = F/x$, where x is the displacement of the dielectric layer that is equal to the spacing between the two contacting surfaces (x = 5 mm). N is the number of springs considered for the arch shaped DMSE-TENG (N = 2).

Furthermore, to calculate the energy conversion efficiency (η) that is defined as the ratio between the electric energy ($E_{electric}$) delivered to the load resistor of 10 MΩ and the mechanical energy possessed by the DMSE-TENG produced in a single period of contact (t = 0.2 s). The electric energy released by the DMSE-TENG was calculated by:

$$E_{electric} = R\int_{t_1}^{t_2} I^2\, dt = 0.033\ mJ \tag{3}$$

Where I is the instantaneous current, and R is the load resistance. The I_{RMS} and instantaneous output current I during the impact tests (Fig. 3) was measured using an Agilent Technologies N6705B power analyser connecting the DMSE-TENG to an external load resistance of 10 MΩ. Consequently the η was calculated as [1]:

$$\eta = \frac{E_{electric}}{E_{mechanical}} x100\% = \frac{E_{electric}}{E_{kinetic} + E_{elastic}} x100\%$$

$$= \frac{0.033\ mJ}{0.015\ mJ + 0.34\ mJ} x100\% = 9.33\% \tag{4}$$

The above result shows the overall efficiency of the DMSE-TENG (prototype 1) that showed the highest output power performance (Triboelectric material combination of PDMS-silver conductive cloth tape).

2. Maximum surface charge density calculation

Fig. S1 (a) and (b) shows the theoretical maximum surface charge density σ_{max} (MSCD) using the ion injection method [2] that can be reach for the DMCS-TENG modeled prototypes using the dielectric materials (Polyimide and PDMS) with different thicknesses (d). The structure of the DMCS-TENG via theoretical analysis comparing the threshold voltage for the air breakdown (V_{a-b}) and the actual voltage drop (V_{gap}) across the air gap. Thus, when x starts to increase from 0 during the releasing half cycle of the DMCS-TENG, the V_{a-b} at any $x > 0$ needs to remain bigger than V_{gap} in order to avoid breakdown of air.

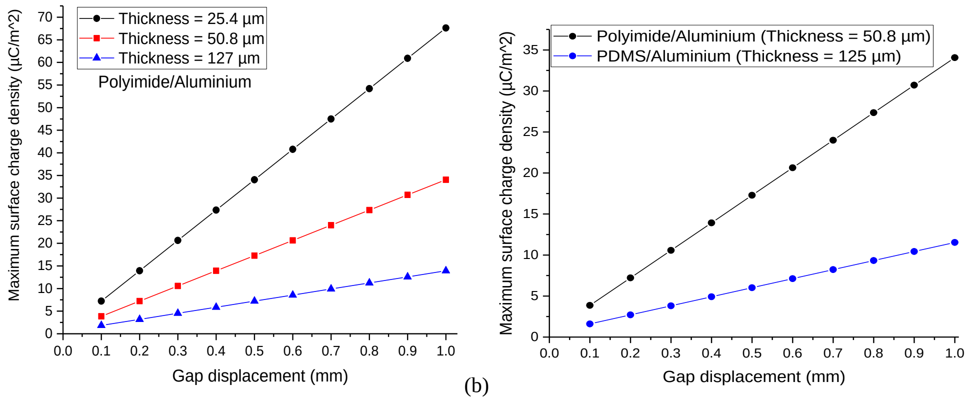
$$V_{a-b} - V_{gap} > 0 = \frac{A(Px)}{\ln(Px)+B} - \frac{d\sigma x}{\varepsilon_0(d + x\varepsilon_r)} > 0 \tag{1}$$

where P is the gas pressure for air at standard atmospheric pressure of 101 kPa, A and B are the constants determined by ε_r is the relative permittivity of the dielectric layer, and ε_0 is the vacuum permittivity. From equation (6), σ_{max} can be determined as follows [2]:

$$\sigma_{maxPDMS} = \left[\frac{AP\varepsilon_0(d+x\varepsilon_r)}{d(\ln(Px+B)}\right]min = \tag{2}$$

$$\left(\left(\frac{\left(\left((2.87\times10^5)\times(1)\times(8.8541878176\times10^{-12})\right)\times(0.000125+0.001\times(2.75))\right)}{((0.000125)\times(\mathrm{Log}[(1\times(0.001)+12.6)]))}\right)\times 0.5\right)\times 1000000 = \pm 11.53\ \mu\mathrm{C/m2}$$

From equation (2), we consider a scenario where the maximum gap (x) separation of the dielectric layer with the metal layer is 1 mm and the time duration is 30 seconds. It was calculated the maximum value that can be reached for the maximum surface charge density of the aforementioned dielectric layers with gap separation between 0.1 mm to 1 mm. As shown in Fig. S1 (a) and (b), the theoretically estimated σ_{max} tends to increase linearly with the maximum gap distance. The two tribo-charge surfaces were assigned to the model with the calculated value $\sigma_{PDMS} = \sigma_{max,PDMS} = \pm 11.53\ \mu C/m^2$ and $\sigma_{max,Polyimide} = \pm 34.06\ \mu C/m^2$. The reduction of d_{d1} from the range of tens of microns, will increase the σ_{max} value and the power output of the DMCS-TENG can be enhanced.



(a) (b)

Fig. S1. Theoretical relationship between maximum surface charge density (σ_{max}) using the ion injection method and the thickness (d_{d1}) at different gap distance (x) (a) between the polyimide dielectric layer with different thicknesses, and (b) polyimide vs PDMS layers of different thicknesses at different gap distance.

3. Modelling of dynamic operation of the DMCS-TENG prototype

The analysis of the frequency response of the Dielectric-metal contact separation mode triboelectric nanogenerators (DMCS-TENG, prototype 2) self-resetting system. This was measured by using a Pasco Scientific SF-550 mechanical shaker connected to a TF550 function generator (Fig. 9 (a) and (b)), guiding the vibration frequency swept from 25 to 300 Hz with an increasing step of 5 Hz for 55 seconds. Driving amplitude 20 Vpp (focused on the frequencies of interest 30, 80, 150, 200, 219 and 252 Hz) and based on the average measurements of acceleration, velocity and displacement of the top dielectric layer of the energy harvester measured with a PDV-100 Portable Digital Vibrometer.

The analytical model to calculate the maximum open-circuit voltage at the resonant frequency of the DMCS-TENG prototype through the motion of the oscillatory system can be described at device level as a damped system subjected to a harmonically varying force provided by the mechanical shaker table. The relative displacement of top plate is a function of the vibration frequency, which is given by [3, 4]:

$$X_p = \frac{F_0 \sin(2\pi f t - \emptyset)}{k\sqrt{(1-\left(\frac{f_0}{f}\right)^2)^2 + (\frac{2f_0\zeta}{f})^2}} \tag{1}$$

Where f is the vibration frequency, F_0 is the external force amplitude, which is $F_0 = m_0 a$, a is the acceleration of the shaker system. ϕ is the phase angle and ζ is the damping coefficient of the DMCS-TENG system. In the vibration process, due the non-uniform contact between the dielectric-metal layer, generates the output-circuit voltage V_{oc} for an electric potential difference between the two electrodes as follows:

$$V_{oc} = \frac{\sigma x}{\varepsilon_0} \tag{2}$$

Where σ is the triboelectric charge density, ε_0 is the vacuum permittivity and x is the distance variation between the layers in contact. For a system in vibration, the layer separation is relative to the displacement of the top layer (dielectric layer). As a result, substituting equation (1) into equation (2), the open circuit is given by:

$$V_{oc} = \left(\frac{\sigma}{\varepsilon_0}\right)\left(\frac{(m_0 a)(\sin(2\pi f t - \emptyset))}{k\sqrt{\left(1-\left(\frac{f_0}{f}\right)^2\right)^2+\left(\frac{2f_0\zeta}{f}\right)^2}}\right) \tag{3}$$

Based on equation (3), the open-circuit voltage of the DMCS-TENG can be determined by parameters such as time t, vibration frequency f and phase angle $\emptyset$. However, the maximum open-circuit voltage V_{ocmax} is only a function of vibration frequency, which can be expressed by:

$$V_{ocmax} = \left(\frac{\sigma}{\varepsilon_0}\right)\left(\frac{m_0 a}{k\sqrt{\left(1-\left(\frac{f_0}{f}\right)^2\right)^2+\left(\frac{2f_0\zeta}{f}\right)^2}}\right) \tag{4}$$

Consequently, the V_{ocmax} at resonant frequency ($f = f_0$) can be expressed as:

$$V_{ocmax} = \left(\frac{\sigma}{\varepsilon_0}\right)\left(\frac{m_0 a}{2k\zeta}\right) \tag{5}$$

where m_0 is the mass of the top plate, k is the stiffness coefficient of each spring, and a is the acceleration of the mechanical shaker table and the damping coefficient ζ of the DMCS-TENG system that is 0.30 calculated by $\zeta = \frac{2m_0 ln2}{T_{\frac{1}{2}}}$ [6]. Where $T_{1/2} = t_1 - t_2 = 0.009s$, is the time of the open circuit-voltage generated by the DMCS-TENG in one cycle of external vibration (Fig. S2).

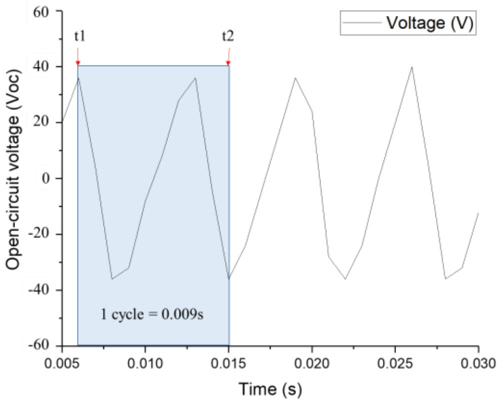


Fig. S2. Open-circuit voltage generated by the DMCS-TENG in one cycle of external vibration at 150 Hz.

Consequently, the total energy conversion efficiency (η) of the DMCS-TENG (prototype 2) self-resetting system with Polyimide-honeycomb patterned Al foil was defined as the ratio between the input mechanical energy caused by the mechanical shaker table and the generated electric energy that is delivered to the load (10 MΩ) by the DMCS-TENG (at the aforementioned oscillating frequencies through the practical experiments). The efficiency was determined by the equation (6) [1].

$$\eta = \frac{E_{electric}}{E_{mechanical}} x100\% = \frac{E_{electric}}{E_{kinetic} + E_{elastic}} x100\% \tag{6}$$

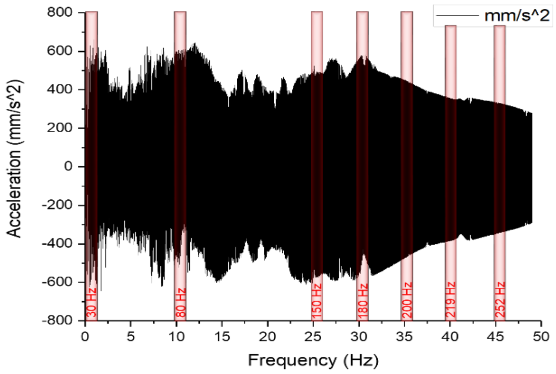
The E_{ele} generated by the DMCS-TENG under the load resistance of 10 MΩ shows an energy output between 0.40 of 13.02 μJ during a time of 60 s. The kinetic and elastic energy applied to the DMCS-TENG by the mechanical shaker ($E_{mechanical} = E_{kinetic} + E_{elastic}$) was calculated by equation (7) and (8). The average acceleration a, velocity v and average displacement x of the top dielectric layer when the contact is made between layers (dielectric-metal) at the aforementioned oscillating frequencies. Such values were between 319.62 to 559.29 mm/s^2, 163.95 to 343.59 mm/s and between 0.10 to 0.26 mm, measured with a PDV-100 Portable Digital Vibrometer as shown in Fig. S3 (a), (b) and (c). Considering as spring the bending of the top layer, and as constraints the attached kapton tape used to bound four sides of the conductor layer with the dielectric layer that generates the self-resetting system (Depicted in Fig. 9 (a) in the manuscript). The bending stiffness ($k = F/x$ = 4 to 6.14 N/m) was estimated based in the mass and average displacement x of the moveable top dielectric layer (Fig. S3 (c). N is the number of springs considered for the DMCS-TENG (N = 1), F is the force used by the mechanical shaker to move the DMCS-TENG prototypes ($F = ma$, $m_{Polyimide} = 2g$).

$$E_{kinetic} = \frac{1}{2} m v^2 = 26.87\ to\ 81.96\ \mu J \tag{7}$$

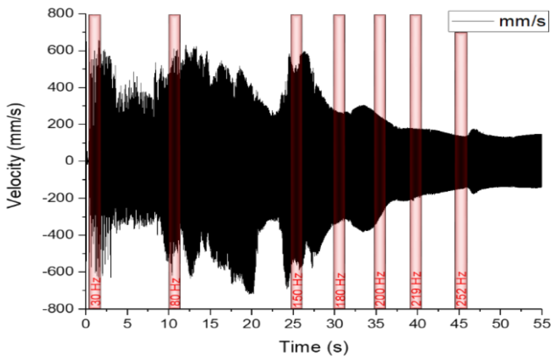
$$E_{elastic} = \frac{1}{2} k x^2 N = 0.03\ to\ 0.14\ \mu J \tag{8}$$

The energy applied ($E_{mechanical}$) to the DMCS-TENG by the mechanical shaker table was calculated to be between 26.91 to 82.11 μJ, which indicates an efficiency between 1.51 to 15.85 % among the oscillating frequencies of 30 to 252 Hz that accounts all the electricity generated by the residual vibrations of the device. The highest efficiency was calculated at 150 Hz and acceleration of 559.29 mm/s^2, followed by 30 Hz with an acceleration of 549.14 mm/s^2 as shown in Fig. 11 according to the experimental measurements.

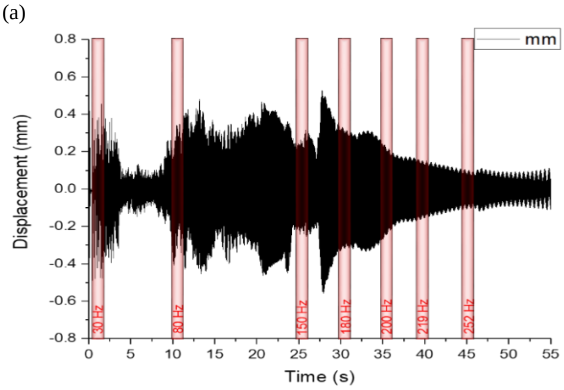
$$\eta = \frac{E_{electric}}{E_{mechanical}} x100\% = \frac{E_{electric}}{E_{kinetic} + E_{elastic}} x100\% = 1.51\ to\ 15.85\% \tag{6}$$



(a)



(b)



(c)

Fig. S3. (a) Acceleration, (b) velocity and (c) displacement of the top dielectric layer when in contacts the conductor layer of the DMCS-TENG prototype during the vibration frequency swept from 25 to 300 Hz with an increasing step of 5 Hz for 55 seconds (Measured with a PDV Portable Digital Vibrometer).

References

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