Structure and Dimension Effects on the Performance of Layered Triboelectric Nanogenerators in Contact-Separation Mode

Xing Yin[†,‡], *Di Liu*[†,‡], *Linglin Zhou*[†,‡], *Xinyuan Li*[†,‡], *Chunlei Zhang*[†,‡], *Ping Cheng*[†,‡], *Hengyu Guo*[†,‡,§], *Weixing Song*[†,⊥], *Jie Wang**[†,‡], *Zhong Lin Wang**[†,‡,§]

[†] Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 100083, China

[‡] College of Nanoscience and Technology, University of Chinese Academy of Sciences, Beijing 100049, P. R. China

[§] School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

[⊥]School Department of Chemistry, Capital Normal University, Beijing 100048, P. R. China

Corresponding Authors

*Email: wangjie@binn.cas.cn

*Email: zhong.wang@mse.gatech.edu

Author Contributions

Xing Yin, Di Liu contributed equally to this work.

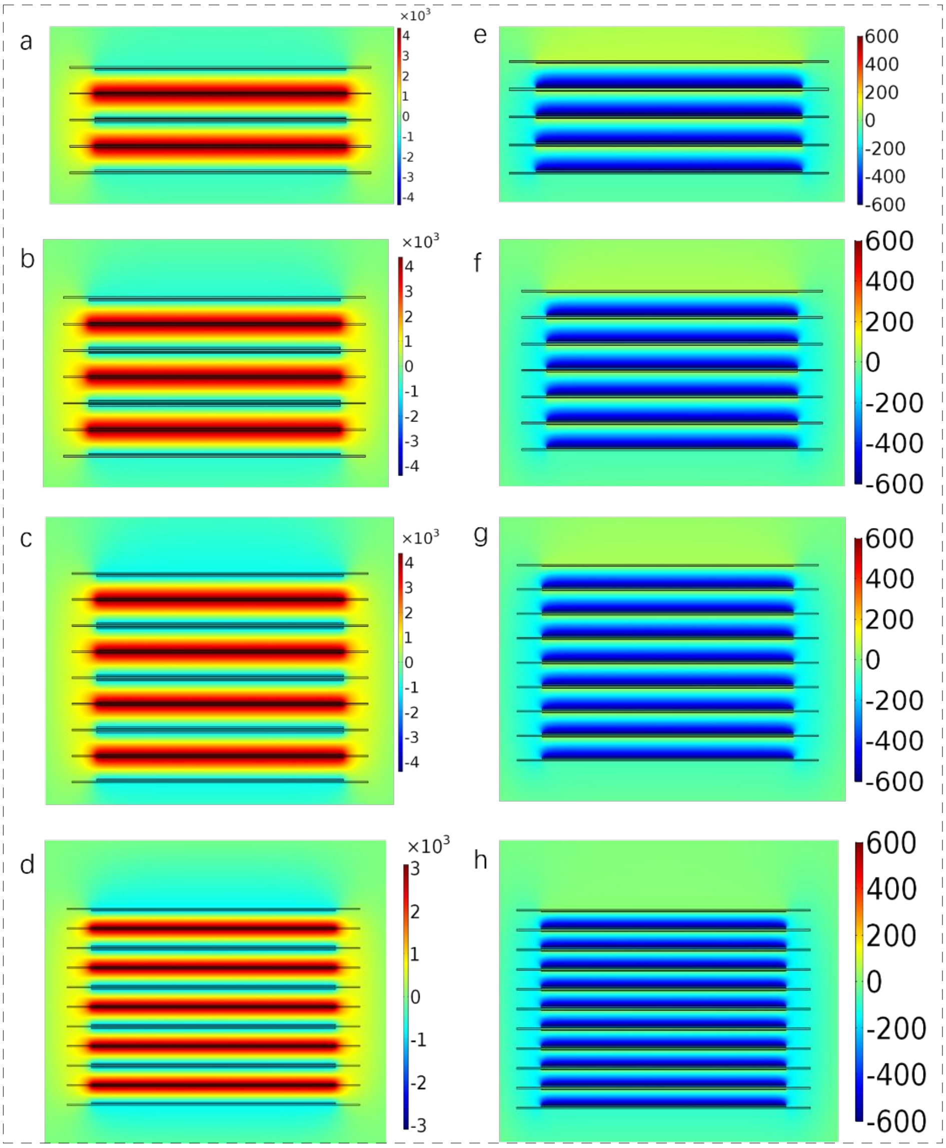

Figure S1. The COMSOL simulation of (a-d) SYM -TENG and (e-h) ALT -TENG with 4, 6, 8, 10 units. The gap distance of Cu and PTFE is 3mm, and the surface charge density is 50 μC m^{-2}. In open circuit condition, different direction of electrical field is built for the two structure.

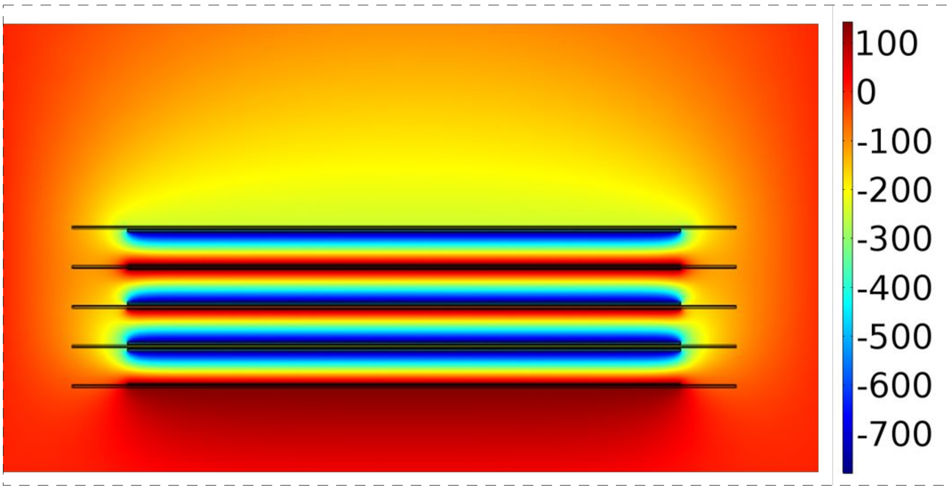

Figure S2. The COMSOL simulation for the combination of alternate and symmetrical structure TENG with 4 units.

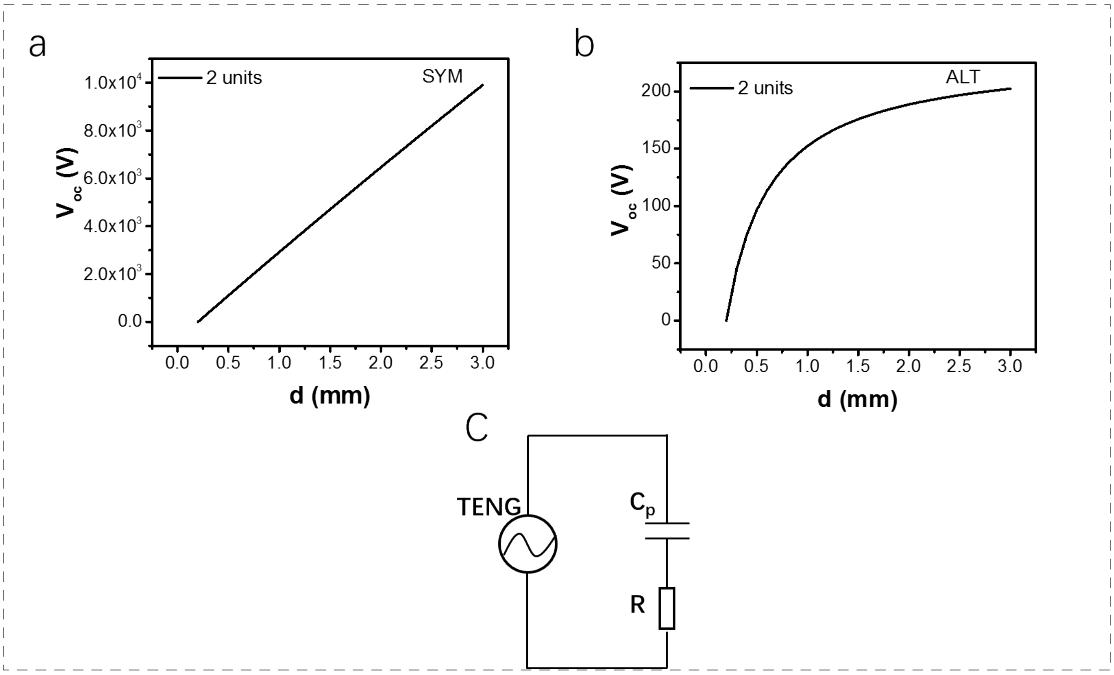

Figure S3. Open circuit voltage-separation distance relationship of ALT-TENG (a) and SYM-TENG (b). (c) The corresponding circuit when charging a capacitor by a TENG. In the initial state, the charge is set to be 0, and the result is a half motion cycle. The two structures could deliver different voltage characteristics due to parasitic capacitance.

In Figure S3c, a parasitic capacitance and a resistance is in series.

$$V_T = \frac{dq}{dt}R + \frac{q}{C} \tag{1}$$

With the initial condition of t=0, q=0. So we can get a differential equation as below

$$\int_0^q \frac{dq}{CV_T - q} = \frac{1}{RC}\int_0^t dt \tag{2}$$

$$\mathrm{V} = C_0(1 - e^{-\frac{t}{RC}}) \tag{3}$$

Consequently, equation (3) describes a charging curve of a capacitor that obtained in Figure S3b.

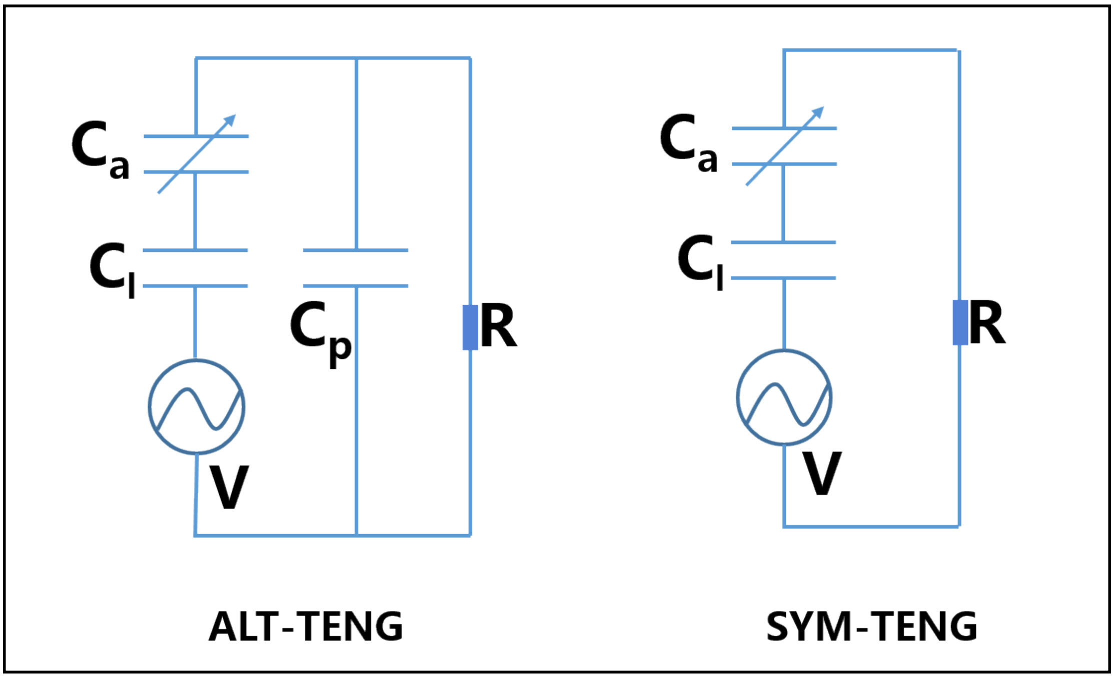

Figure S4. Simplified equivalent circuit of ALT-TENG (left) and SYM-TENG (right), C_I is inherent capacitance and C_a is air capacitance.

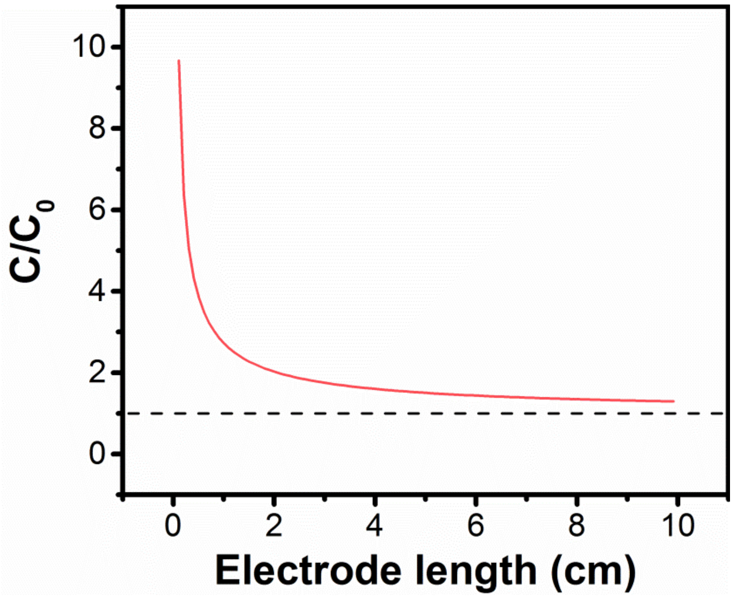

Figure S5. Influence of electrode length on C/C_0. C is actual capacitance, C_0 is ideal capacitance. Air gap is set to be 2 cm. The actual capacitance is close to the ideal condition (Parallel plate capacitor). This curve is calculated by the following fundamental theory of edge effect in TENG. Where l is the electrode length, d is gap distance between two electrodes.

$$C = \frac{\varepsilon_0 \omega l}{d}\left\{1+\frac{d}{\pi l}\left\{1+\ln[1+\frac{2\pi l}{d}+\ln(1+\frac{2\pi l}{d})]\right\}\right\} = \frac{\varepsilon_0 \omega l}{d}(1+\alpha(\frac{d}{l}))$$

$$\frac{C}{C_0} = 1+\alpha(\frac{d}{l}) = 1+\frac{d}{\pi l}\left\{1+\ln[1+\frac{2\pi l}{d}+\ln(1+\frac{2\pi l}{d})]\right\}$$

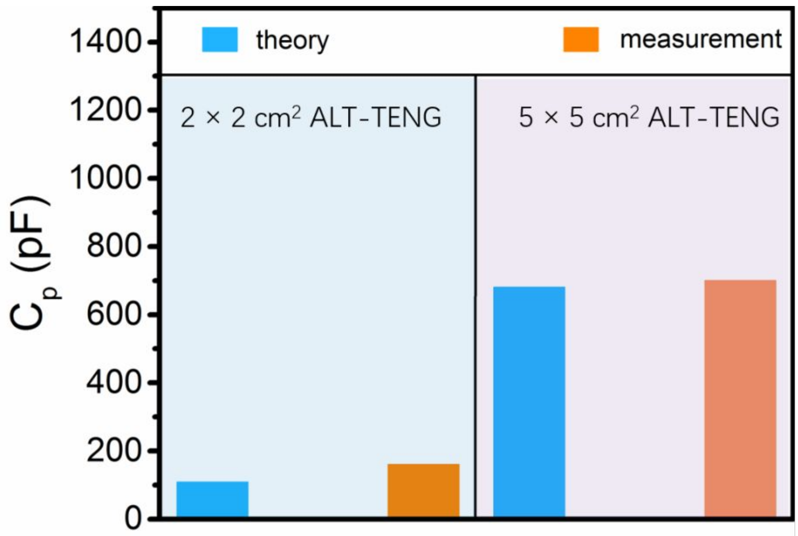

Figure S6. Parasitic capacitance of the one unit in layered TENG at compression state. Blue icon is ideal C_p, yellow icon is correction value when considering edge effect, and purple icon is measure value by digital multimeter. For 2 × 2 cm^2 ALT-TENG $C_{measurement}/C_{theory}$=55.56%, 5 × 5 cm^2 ALT-TENG $C_{measurement}/C_{theory}$=2.9%, which indicate that C_p can be enhanced by edge effect.

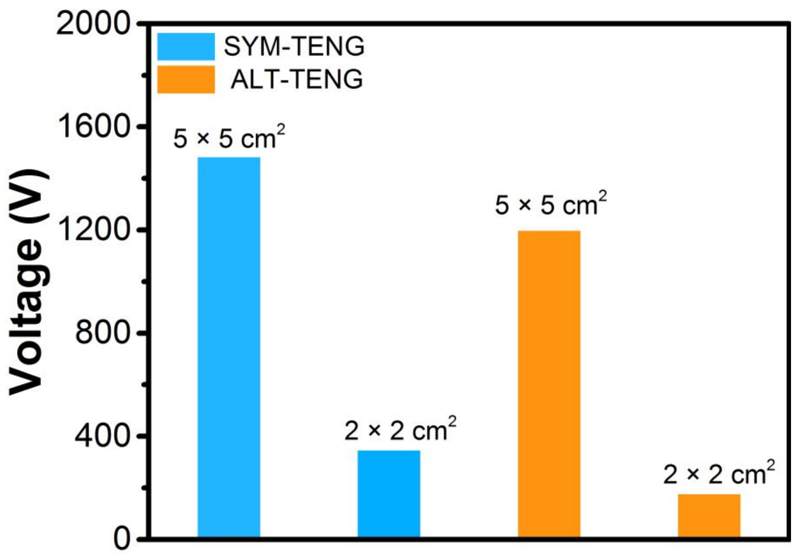

Figure S7. Open-circuit voltage of symmetrical and alternate TENG with 2 × 2 cm^2 and 5 × 5 cm^2 contacting area.

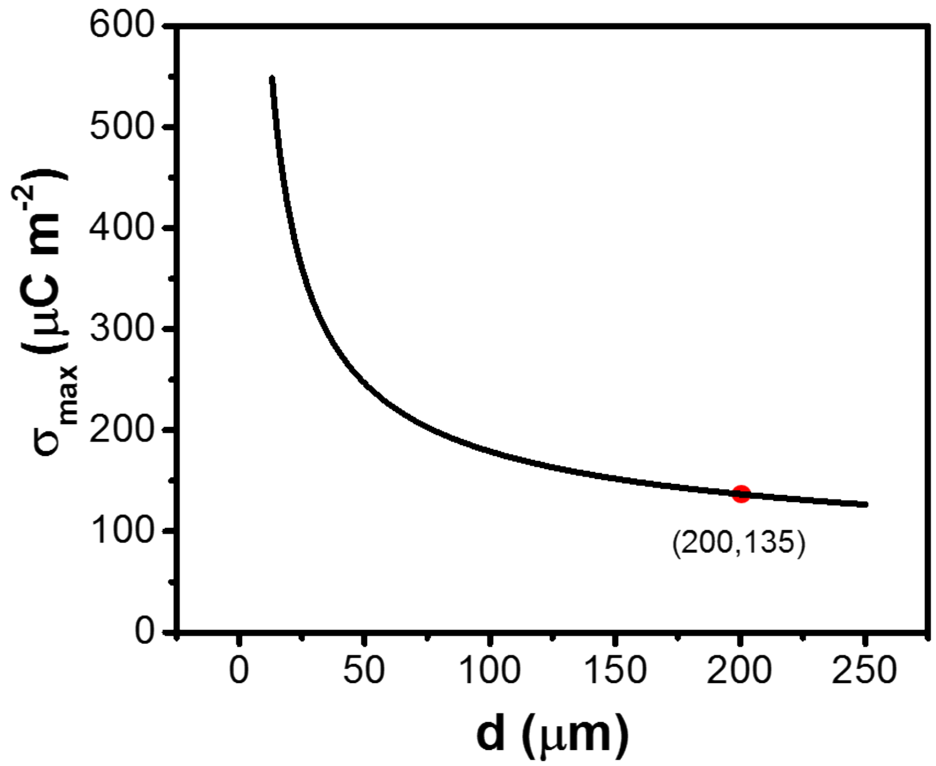

Figure S8. Theoretical calculation on the relationship between maximum surface charge density (σ) and the thickness (d) of PTFE films. In this work, the thickness of PTFE film is 200 μm, and its maximum surface charge density is 135 μC m^{-2}.

The achievable surface charge density will be limited by the breakdown electric field of the air in the proximity region. For the breakdown voltage of a gas between two plates at a small gap distance, it follows the Paschen curve (equation 1). The actual voltage drop across the air gap in the contact-mode TENG is described in equation (2)

$$V_{b-a} = \frac{A(Px)}{ln(Px) + B} \quad (1)$$

$$V_{gap} = \frac{d\sigma_0 x}{\varepsilon_0(d + x\varepsilon_r)} \quad (2)$$

V_{gap} curve is required to stay below the voltage of air breakdown. So we can get maximum surface charge density of a TENG with the dielectric thickness d (equation 3).

$$\sigma_{max} = \left(\frac{AP\varepsilon_0(d + x\varepsilon_r)}{d(\ln(Px) + B)}\right)_{min} \quad (3)$$

This theory is also confirmed by ion-injection method for contact-separation mode by Ref. 21 in manuscript.

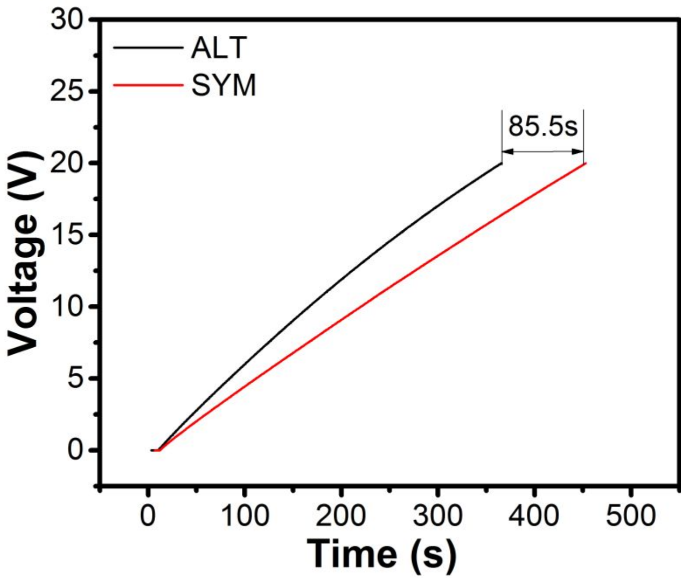

Figure S9. The charging curves of a commercial capacitor (47 μF) powered by two types of layered TENG, showing fast charging characteristic in alternate structure.