Electronic Supplementary information

A bio-inspired total current nanogenerator

Jun Dong,[a] Lili Zhu,[b] Pengju Guo,[a] Cunyun Xu,[a] Xusheng Zhao,[a] Shijing Yang,[a] Xiaofeng He,[a] Guangdong Zhou,[a] Gang Ma,[c] Hengyu Guo,*[d] Chenguo Hu,[d] Qunliang Song,*[a]

a. Institute for Clean Energy and Advanced Materials, School of Materials and Energy, Southwest University, Chongqing 400715, P. R. China.

b. College of Materials Science and Engineering, Yangtze Normal University, Chongqing 408100, P. R. China.

c. Key Laboratory of Medicinal Chemistry and Molecular Diagnosis of Ministry of Education, College of Chemistry and Environmental Science, Hebei University, Baoding 071002, China.

d. Department of Applied Physics, State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University, Chongqing 400044, P. R. China.

*Corresponding author. E-mail address: qlsong@swu.edu.cn; physghy@cqu.edu.cn.

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Other supplementary materials for the manuscript include the following:

Supplementary Figures

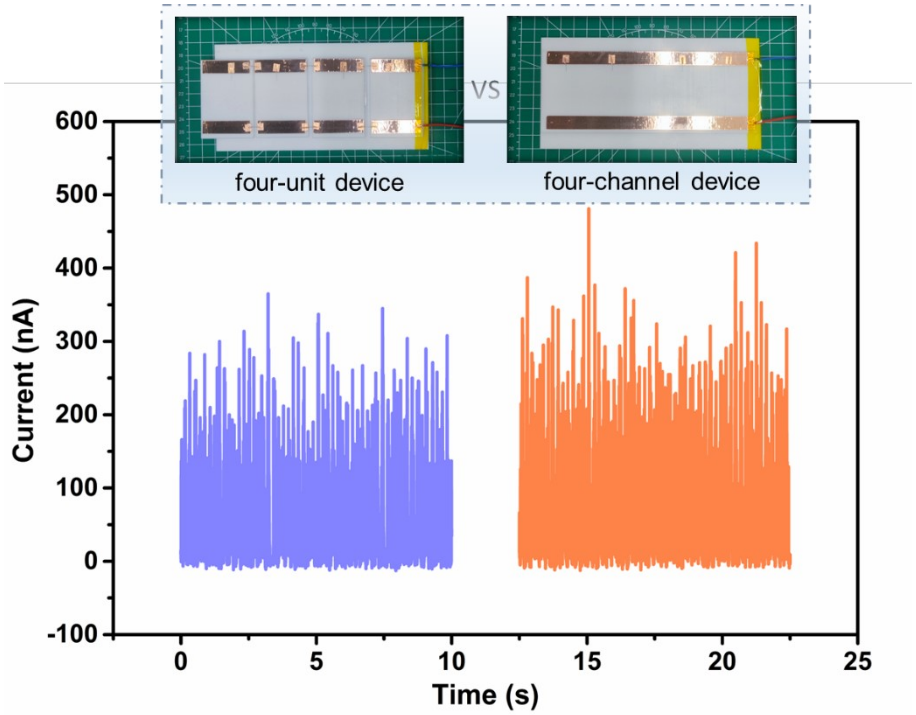

Fig. S1 Comparison of the four-unit device and the four-channel device. The output performances of them are very close.

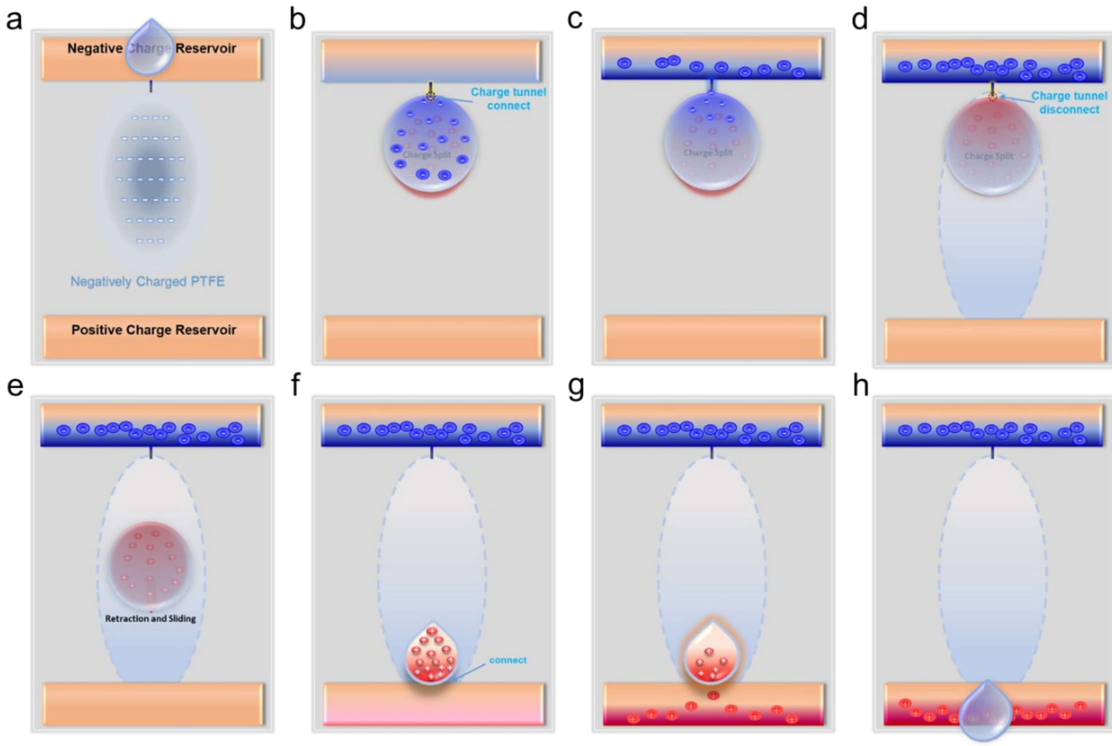

Fig. S2 Basic working process of an individual water charge shuttle. The working mechanism of WCS is described in detail in Note S1 and Movie S1.

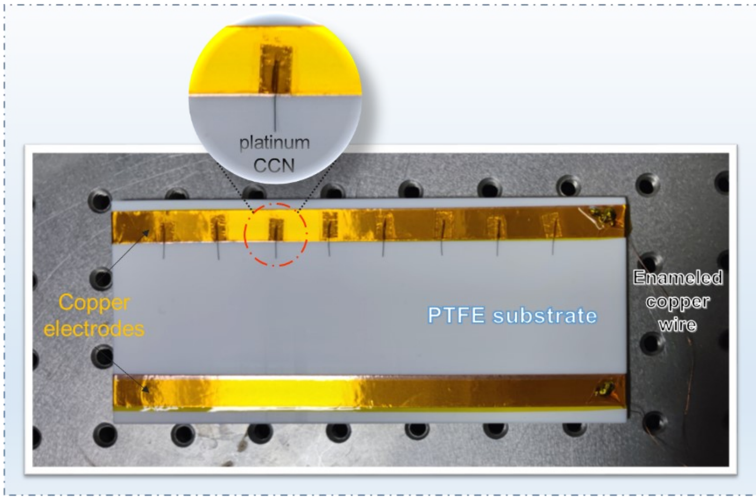

Fig. S3 Photograph of the assembled TC-TENG. The copper electrodes are fixed and protected by polyimide tape.

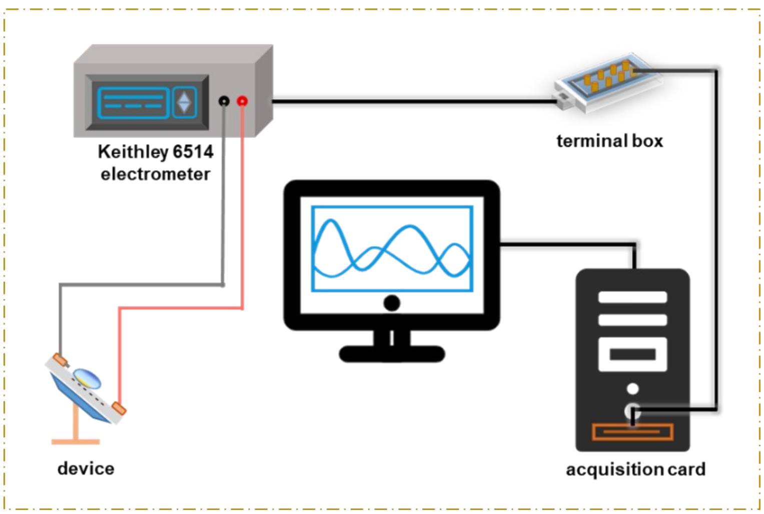

Fig. S4 Schematic diagram of the electrical test system in this work. The output performance of TC-TENG is collected by the Keithley 6514 electrometer, a terminal box, a data acquisition card (NI PCI-6259) and the LabVIEW software on the desktop.

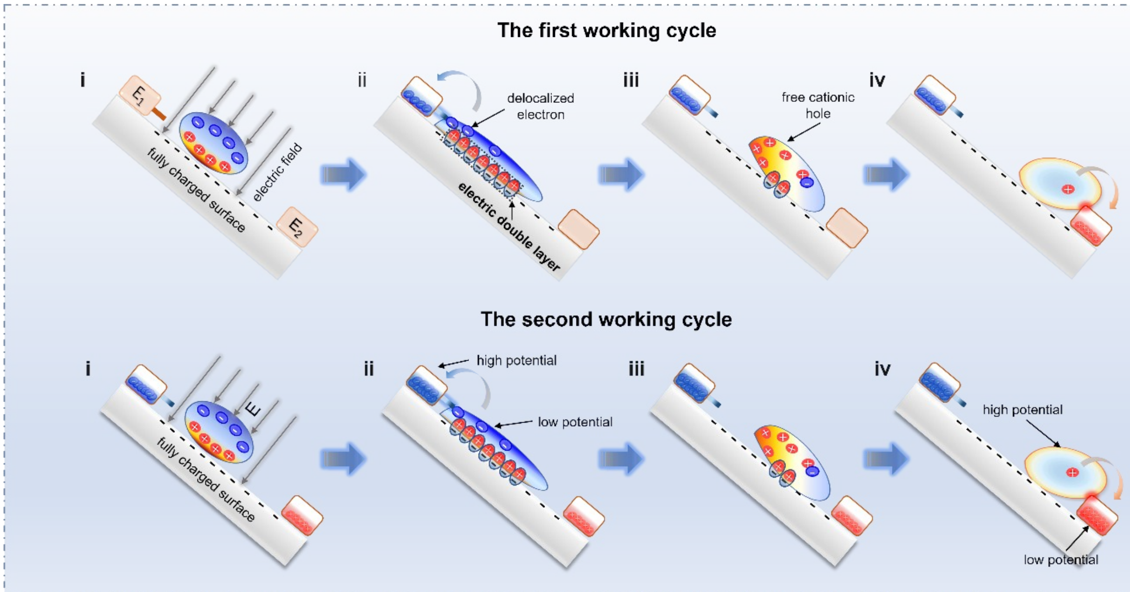

Fig. S5 Interfacial physical process of TC-TENG at fully charged surface of PTFE. The processes of the first cycle and the second cycle are slightly different due to the charge pumping effect. When the first droplet impinges the negatively charged PTFE surface and spreads to contact the CCN, the delocalized electrons in the water will be rapidly conducted from the WCS to the top electrode until the potential equilibrium on both sides is reached. Then the droplet shrinks and slides downward, the positive charges adsorbed on the PTFE surface are gradually peeled off and become free cationic hole. When the droplet touches the bottom electrode, the cationic hole will be rapidly conducted from droplet to the bottom electrode until the potentials on both sides reach equilibrium as well. When the second droplet impinges the PTFE surface and spreads, the negative charges in WCS will continue to be pumped into the top electrode since the potential of the top electrode is still higher than that of WCS (determined by the surface potential of PTFE). Similarly, the positive charges will continue to be pumped into the bottom electrode. As the charge pumping proceeds, the output voltage of the device is continuously elevated and accordingly the charges transferred from the WCS to the negative charge reservoir are gradually decreasing due to the reduced potential difference. When the potential of the WCS and the negative charge reservoir reaches the equilibrium state, the WCS cannot pump the charges to the reservoir any more, and the output voltage of the device finally saturates.

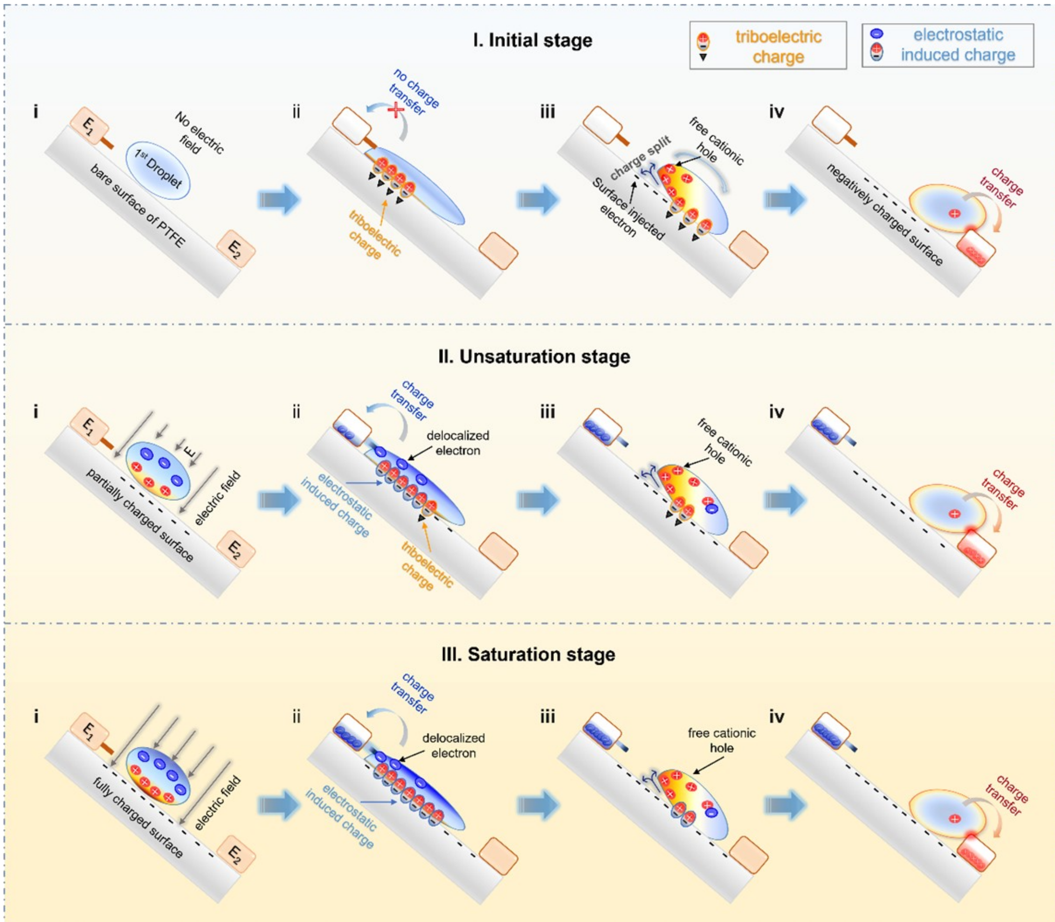

Fig. S6 Charge transfer process of TC-TENG in three working stages: initial, unsaturation, and saturation stages. (I) In initial stage, negative triboelectric charges from the first droplet are injected into the contact region on the bare surface of PTFE due to solid-liquid (S-L) contact electrification. And the positive triboelectric charges (cationic holes) left in the droplet are bounded at the S-L interface. Then the positive charges are peeled off from the S-L interface and transferred to the bottom electrode E_2. At this stage, electrons are all injected into PTFE and positive charges are transferred to E_2. (II) In unsaturation stage, when the droplet impinges the partially charged surface of PTFE, negative charges (delocalized electrons) generated by electrostatic induction are transferred from droplet to the top electrode E_1, of which the behavior is similar to that of the fully charged surface but with smaller magnitude. Electrons can also be injected from droplet into the unsaturation surface of PTFE, of which the behavior is similar to that of the bare surface. Then, free positive charges containing both electrostatic induced charges and triboelectric charges are peeled off and transferred to the E_2. At this stage, negative charges on E_1 come from electrostatic induced charges and positive charges on E_2 come from both electrostatic induced charges and triboelectric charges. (III) In saturation stage, as the PTFE is fully charged and no electrons are injected into the surface, negative charges transferred to the E_1 and positive charges transferred to the E_2 both come from electrostatic induced charges.

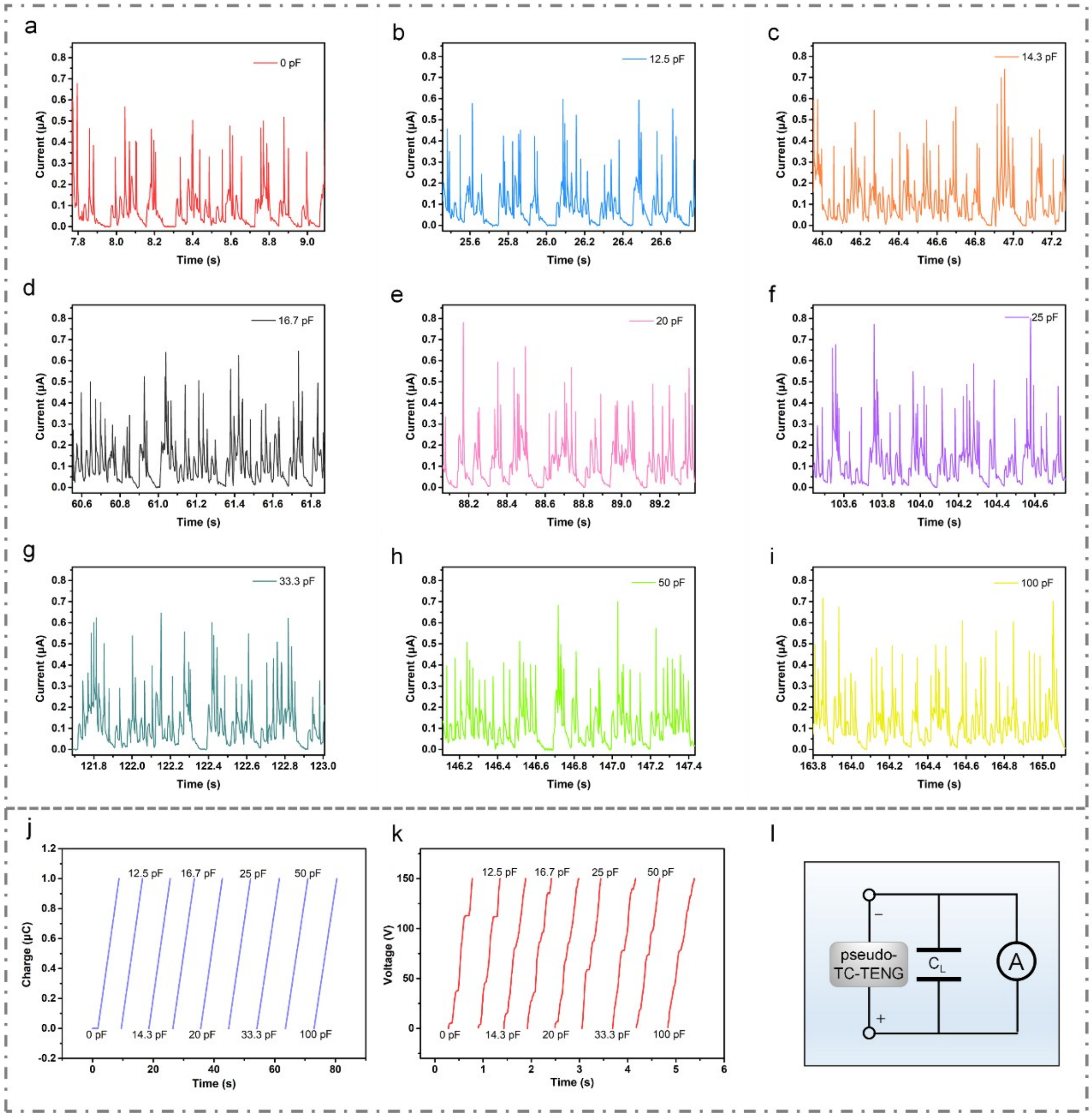

Fig. S7 Effect of capacitance variation on output performance of pseudo-TC-TENG. (a-i) Enlarged diagram of output current at different capacitance. (j) Transferred charge at different capacitance. (k) Output voltage at different capacitance. (l) Corresponding test circuit diagram. The results show that the external capacitance has no significant effect on the output performance of pseudo-TC-TENG, which demonstrates its good output stability and adjustability.

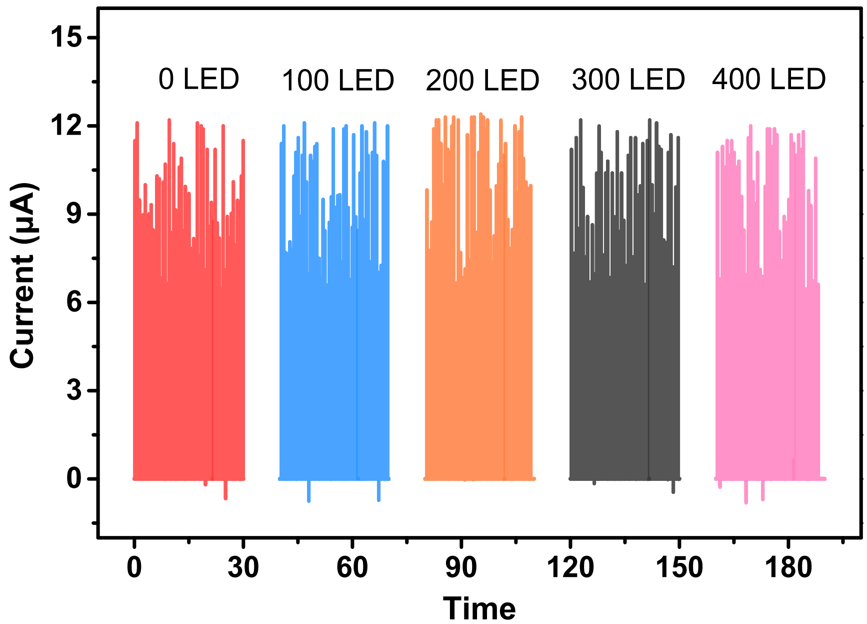

Fig. S8 Output currents of different LEDs under a GDT with the turn-on voltage of 800 V. The results show that the output current has good stability, indicating that the TC-TENG has a good self-modulation output performance.

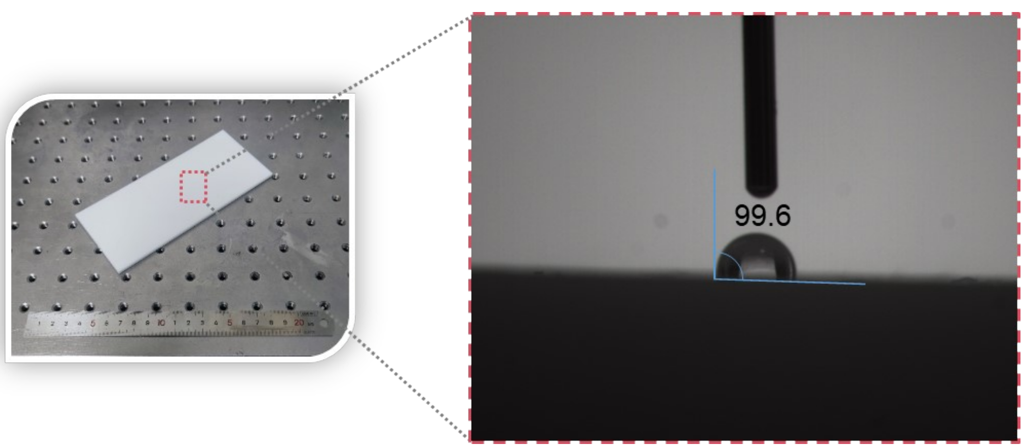

Fig. S9 Contact angle of water on PTFE substrate. The result demonstrates the good hydrophobicity of PTFE friction layer.

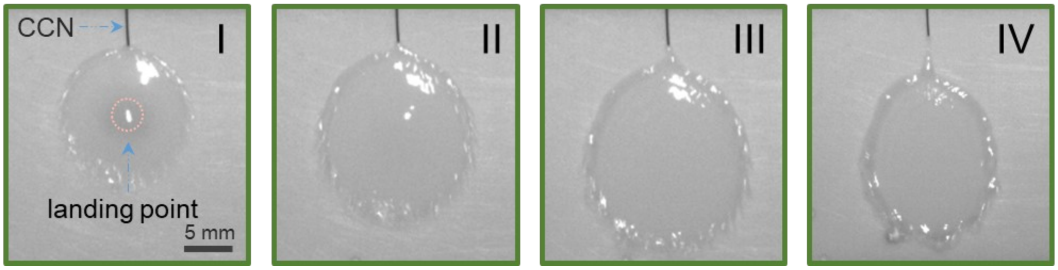

Fig. S10 Top view snapshots for various stages of droplet impact on PTFE. The preferred impinging location of the water droplet is several millimeters directly below the CCN.

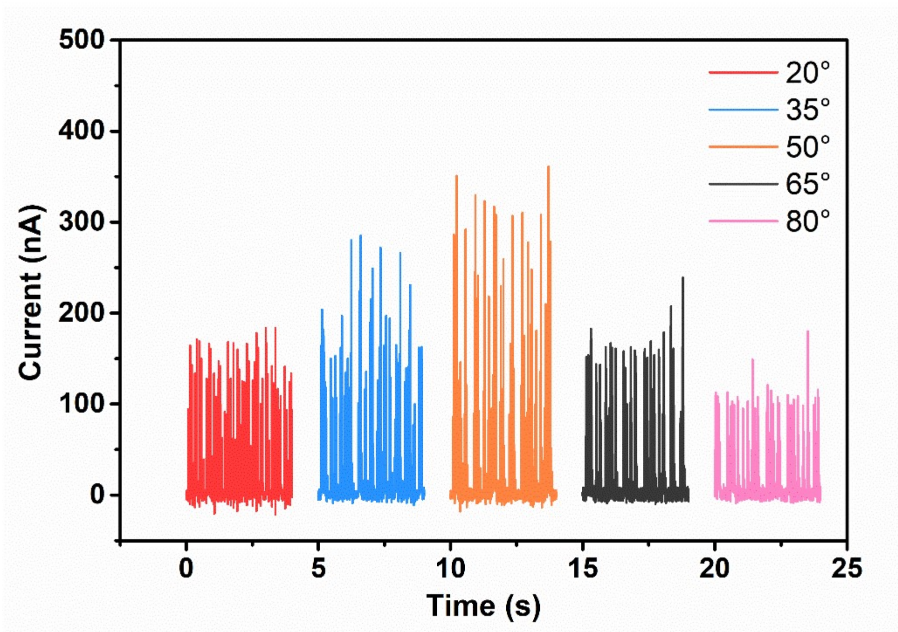

Fig. S11 Output performance of the pseudo-TC-TENG under different tilting angles. The preferred tilting angle of this device is around 50°.

Supplementary Tables

Table S1 Reference electric characteristic of GDT diodes.

Model	DC spark-over voltage (V) 100 V/s	Minimum insulation resistance (GΩ) DC Test voltage	Maximum capacitance (pF) 1 MHz	Dimension parameter (mm)
GDT-350	350	DC 100V >1	1.5	8×6
GDT-470	470	DC 250V >1		
GDT-600	600	DC 250V >1		
GDT-800	800	DC 250V >1		
GDT-1000	1000	DC 250V >1		

Table S2 Reference parameter of LEDs.

Attribute	**Value**
Bulb diameter	5 mm
Forward voltage	3.0-3.2 V
Forward current	20 mA
Impulse current	100 mA
Light-emitting angle	20°

Supplementary Notes

Note S1 The working process of the WCS.

At time t_1, the falling droplet will gradually spread on the negatively charged PTFE surface and complete the splitting of electron-hole pairs in water under the action of the interfacial electric field. The state of the WCS at this moment corresponds to Fig. S2b. At time t_2, the droplet continues to spread, and when it reaches the vicinity of the maximum area, it will contact the charge collecting needle of TE. At this moment, the delocalized electrons in the water will be rapidly conducted from the WCS to the TE until the potential equilibrium on both sides is reached. The state of the WCS at this moment corresponds to Fig. S2c. At time t_3, when the droplet shrinks and slides downward, the positive charges (which are used to form the electric double layer) adsorbed on the PTFE surface are gradually peeled off from the hydrophobic surface and become free positive charges. The state of the WCS at this moment corresponds to Fig. S2e. When the droplet continues to slide down and touches the BE at time t_4, the positive charges will be rapidly conducted from droplet to the BE (the electrons on electrode flow back to water) until the potentials on both sides reach equilibrium as well. The state of the WCS at this moment corresponds to Fig. S2g.

Note S2 The features of the TC-TENG.

This unique TC-TENG has the following detailed features:

First, an innovative compact on-surface electrodes is developed, which is quite different from the back electrode structure commonly used in conventional TENGs. It is thus easy to construct, and compatible with common electrode preparation processes such as sputtering, thermal evaporation or even simple painting and sticking, and it can be applied to films, plates or even any hydrophobic surface (such as paint coatings, plastics, leaves, etc.).

Secondly, a thick commercial PTFE plate is used as a negative friction layer instead of thin PTFE film. Herein, PTFE is not only an electret material with good charge storage capacity and stability, but also has very excellent contact electrification characteristics with water. Therefore, the PTFE surface does not need to be charged in advance, and the required charged surface can be obtained spontaneously through contact electrification in the first few working cycles. Meanwhile, when the surface charges of PTFE escape during the working process, they can be timely supplemented through contact electrification. In addition, the use of PTFE plate eliminates potential problems caused by the thickness, insulation and uniformity of the film. As a result, both the repeatability and stability of the device are improved.

Thirdly, the CCN structure is introduced. The needles made of inert Pt can not only make contact/separate from water effectively for circuit switching function, but also collect charges more effectively through the tip effect. Besides, without the CCN, the slight adhesion between the droplet and the electrode will affect the detachment of droplet and delay the separation moment, thus greatly inhibiting the separation process of positive and negative charges. And it is thus difficult to build the WCS architecture.

Fourthly, the gas discharge tube is used to mimic the neural controller of an electric ray and a capacitor can boost the output when necessary. The simple fabrication process, and the universal on-surface electrode structure can be easily extended to any hydrophobic material in large areas, showing its good adaptability, versatility, and cost-effectiveness.