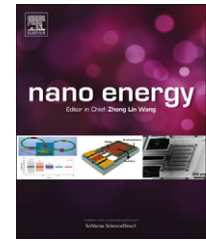


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RAPID COMMUNICATION

Finger typing driven triboelectric nanogenerator and its use for instantaneously lighting up LEDs

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Abstract

Harvest mechanical energy with variable frequency and amplitude in our environment for building self-powered systems is an effective and practically applicable technology to assure the independently and sustainable operation of mobile electronics and sensor networks without the use of a battery or at least with extended life time. In this study, we demonstrated a novel and simple arch-shaped flexible triboelectric nanogenerator (TENG) that can efficiently harvesting irregular mechanical energy. The mechanism of the TENG was intensively discussed and illustrated. The instantaneous output power of single TENG device can reach as high as ~4.125 mW by a finger typing, which is high enough to instantaneously drive 50 commercial blue LEDs connected in series, demonstrating the potential application of the TENG for self-powered systems and mobile electronics.

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Introduction

Recently, research on light-weight, flexible, and even wearable electronics have attracted much attention for its potential applications including but not limited to, wearable display,

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artificial electronic skin, and distributed sensors [1,2]. A key component for these applications is the power source that is as flexible as the electronic sheet itself. Harvesting energy from ambient energy source including solar, thermal energy and mechanical energy could assure the independent and sustainable operating of such systems without the use of a battery or at least extending the life time of a battery [3-5].

Irregular mechanical energy, including ambient noise, airflows and activity of the human body, is probably the most common energy sources in our living environment and almost available anywhere at any time, which could be an ideal source of energy for mobile electronics. Piezoelectric

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nanogenerators (PNGs) [6-16] and triboelectric nanogenerators (TENGs) [17-20] have been developed to harvest irregular mechanical energy with variable frequency and amplitude in our environment based on the piezoelectric effect and triboelectric effect, and they have been demonstrated to power small electronic devices, such as a small liquid crystalline display (LCD) screen [21] and electrochromic device [22]. Here we demonstrate a novel and simple design of the TENG for efficiently harvesting mechanical energy. A fingertip typing can generate an output voltage of up to ~ 125 V, and the output power is sufficient to lit up 50 LEDs connected in series. By conjunct with a transformer for enhancing the output current, the TENG can power a commercial infrared transmitter with an output current of ~ 6 mA at ~ 1 V. Our study unambiguously demonstrates the application of the TENGs for self-powered system.

Experimental

Fabrication of the TENG

The design of the TENG is presented in Figure 1a. The fabrication process started with a rectangular (3.5 cm \times 2.5 cm) polytetrafluoroethylene (PTFE) film (0.20 mm in

thickness, Figure 1b). Cu layer (200 nm) was deposited on the upper surface of PTFE by sputter coating, and used as the top electrode. Specially, the Cu-coated PTFE film will be bent toward the polymer side because of the large difference in thermal expansion coefficients, which results in an arch-shape structure. Then PTFE side of the hybrid film was placed onto another rectangular (3.5 cm \times 2.2 cm) polyethylene glycol terephthalate (PET) film (0.22 mm in thickness). The inner surface of PET film was coated with PVA nanowires prepared by electrospinning, and then deposited with a thin Ag layer (100 nm in thickness) by sputter coating as the bottom electrode (Figure 1c). Before assembling of the device, the inner surface of the PET film was rubbed with cellulose paper to charging the surface of PTFE film. According to the triboelectric series, [23] that is, a list of materials based on their tendency to gain or lost charges, electrons are injected from cellulose paper to PTFE, resulting in net negative charges (Q) on the PTFE surface. It is reported that PTFE can contain charge densities up to $\sim 5 \times 10^{-4}$ C/m² with theoretical lifetimes of hundreds of years [24,25]. During the assembling process, the inner surface of the PTFE film faced Ag layer of the PET film, then the edges of the two films along the length axis were fixed by Kapton tape, forming an arch-shaped device (inset of Figure 1a).

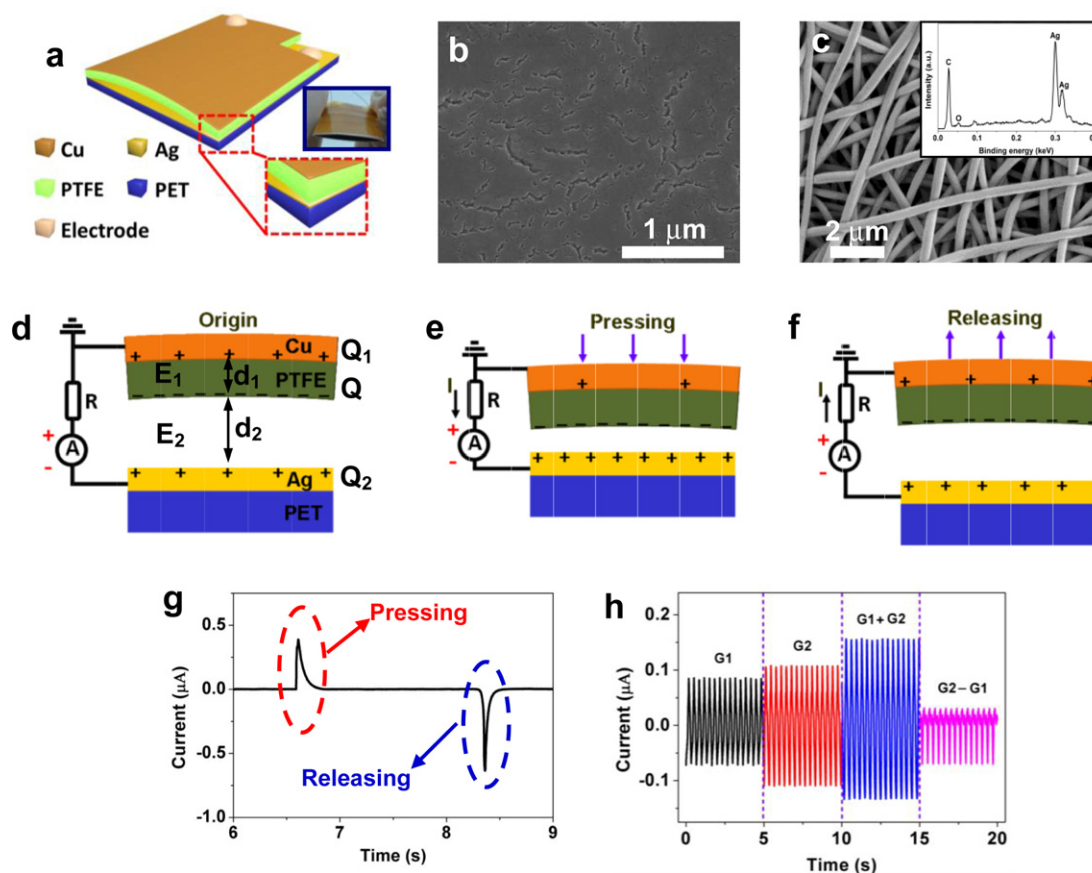


Figure 1 (a) Schematic diagram and digital photography of an arch-structured flexible triboelectric nanogenerator. SEM images of (b) PTFE film and (c) Ag coated PVA nanowires on PET film. Inset shows the EDS spectrum of the Ag coated PVA nanowires. Equivalent circuit of the TENG with an external load of R when the device is at (d) origin, (e) pressing and (f) releasing states and (g) the corresponding current-time curve, respectively. (h) Linear superposition tests of two TENGs ($G1$ and $G2$) connected in parallel with the same polarity ($G1+G2$) and opposite polarity ($G1-G2$).

Results and discussions

Power generation mechanism of TENG

In a simplified model, the equivalent circuit of the TENG with an external load of R is illustrated in Figure 1d, f and g, in which the device can be regarded as a flat-panel capacitor. As the inner surface of the PTFE was charged

with negative charges of Q while the Cu electrode was grounded, the Cu electrode and Ag electrode would produce positive charges of Q_1 and Q_2 , respectively, due to the electrostatic induction and conservation of charges, where $-Q=Q_1+Q_2$ at any moment. Assuming that the charges distributed is uniformly on the surface of PTFE, Cu and Ag, thus

$$-\sigma = \sigma_1 + \sigma_2 \quad (1)$$

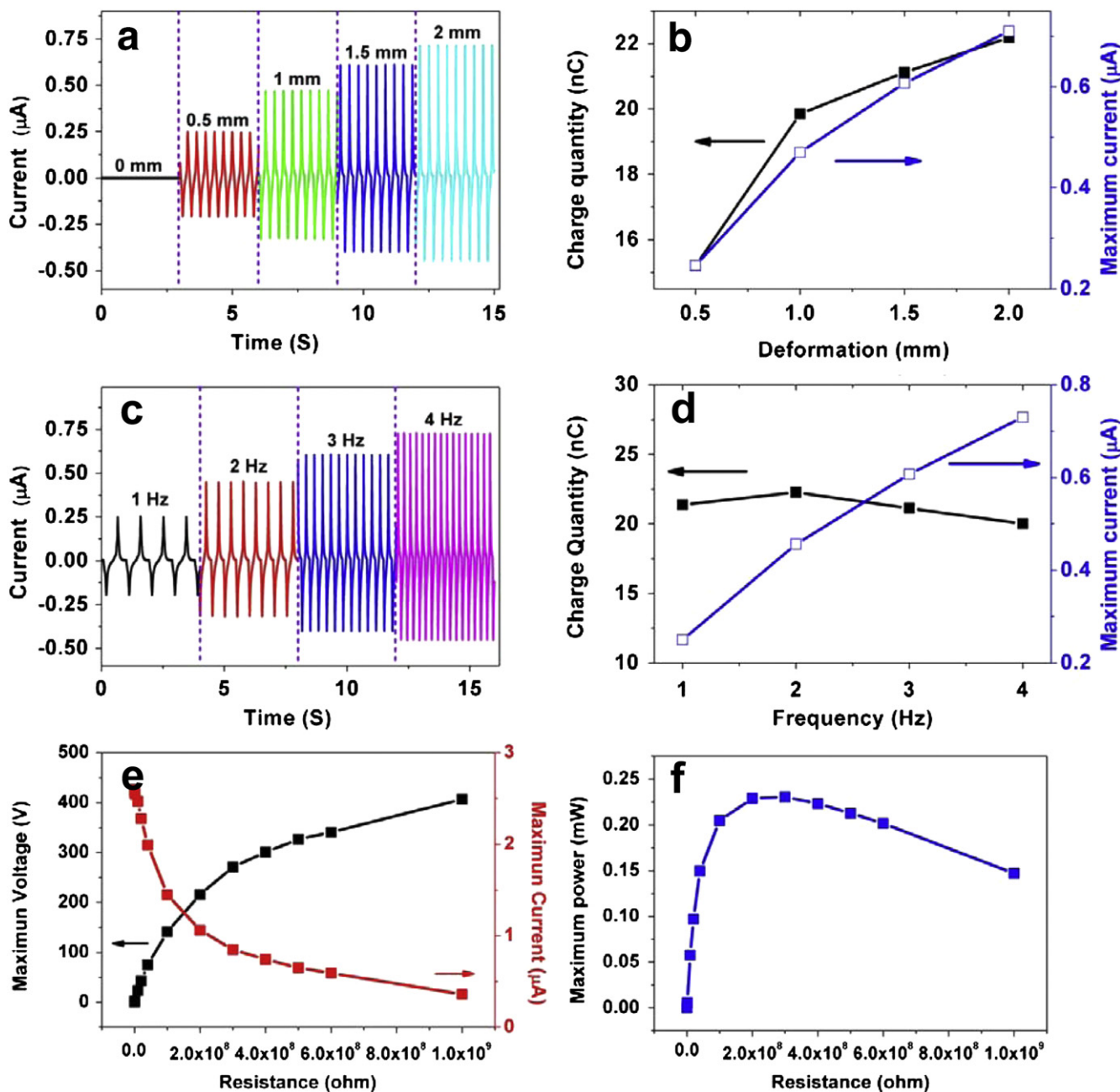


Figure 2 Electrical performance characterization measurement of a TENG under different experiment conditions. (a) Output current-time curve and (b) maximum output current as well as the total charges transported at different deformations for a given frequency of 3 Hz and external load resistance of 500 MΩ. (c) Output current-time curve and (d) maximum output current as well as total charges transported at different stimulation frequencies at a given deformation of 1.5 mm and external load resistance of 500 MΩ. (e) Stimulation and variation with different degrees of deformation provided by the mechanical trigger to the TENG. (f) Maximum output current and instantaneous peak power as a function of the external load resistance at a given bending frequency of 3 Hz and deformation of 1.5 mm.

where σ is the charge density of PTFE surface, σ_1 is charge density of Cu surface which is contacted with PTFE and σ_2 is charge density of Ag upper surface (Figure 1d). If we define electric potential of the top electrode as U_{TE} and electric potential of bottom electrode as U_{BE} , then at any equilibrium state (Figure 2b) U_{BE} can be presented as follows [20]:

$$U_{BE} = \frac{\sigma_2}{2\epsilon_0} d_2 + \frac{\sigma_2}{2\epsilon_{rp}\epsilon_0} d_1 + \frac{\sigma}{2\epsilon_{rp}\epsilon_0} d_1 - \frac{\sigma}{2\epsilon_0} d_2 - \frac{\sigma_1}{2\epsilon_0\epsilon_{rp}} d_1 - \frac{\sigma_1}{2\epsilon_0} d_2 = U_{TE} = 0 \quad (2)$$

where ϵ_0 is the vacuum permittivity, and ϵ_{rp} is the relative permittivity of PTFE, d_1 is the thickness of PTFE film, d_2 is the distance between the two electrodes. Put Eq. (1) into Eq. (2), we can get

$$\sigma d_2 + \sigma_1 d_2 + \frac{\sigma_1}{\epsilon_{rp}} d_1 = 0 \quad (3)$$

$$\sigma_1 = -\frac{\sigma}{1 + d_1/d_2\epsilon_{rp}} \quad (4)$$

As d_1 and ϵ_{rp} are constant with value of 0.2 mm and ~ 1.93 , [25] respectively, and charge Q is stable for a relatively long time on the PTFE surface, thus σ_1 is dictated by the gap distance d_2 (See Figure S2). The variation of d_2 will result in the redistribution of the charges between Cu and Ag electrodes through the load R which generates a current through the load, so that mechanical energy is converted into electricity. The working mechanism of the TENG is similar to a variable-capacitance generator [26-28] except that the bias is provided by the triboelectric charges rather than an external voltage source. Once the TENG was being pressed (Figure 1e), a reduction of the interlayer distance of d_2 would make the decrease σ_1 according to

Eq. (4) (See Figure S1), which results in an instantaneous positive current (Figure 1g) (here we defined a forward connection for the measurement as a configuration with positive end of the electrometer connected to the top electrode). Upon the TENG was being released (Figure 1f), the device would revert back to its original arch shape due to resilience, the interlayer distance d_2 would increase, and the surface charge σ_1 increased as well, resulting in an instantaneous negative current (Figure 1g).

The output performance of TENG

The output of the TENG was carefully studied by periodically bending and releasing at a controlled frequency and amplitude. The measuring system is schematically shown in Figure S2. One end of the TENG was fixed on a x - y - z mechanical stage that was fixed tightly on an optical air table, with another end free to be bend. To rule out the possible artifacts, we did the measurement of the output current when two TENG were connected in parallel with an external load of 500 M Ω and the results are shown in Figure 1h. When two TENGs were connected in the same direction, the total output current was enhanced. In comparison, when two TENGs were connected in antiparallel, the total output current was decreased. The results indicated that the electrical output of the TENGs satisfied linear superposition criterion in the basic circuit connections [18].

The output current of a TENG variation with different degree of deformations (the amplitude of the pushing down distance of the mechanical trigger) are depicted in the Figure 2a. Correspondingly, for a given frequency of 3 Hz and external load resistance of 500 M Ω , an increase of

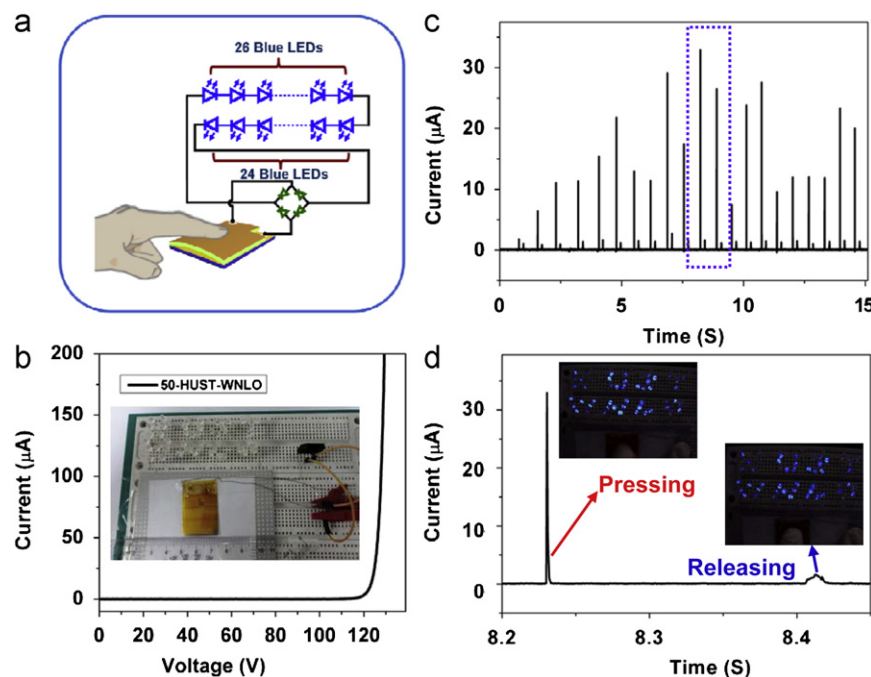


Figure 3 TENG as a direct power source to drive 50 commercialized blue light emitting diodes. (a) Schematic of the energy harvesting circuit and LED display. (b) Current-voltage curve of the 50 LEDs connected in series. Inset shows the digital photography of the prototype energy harvesting circuit and LED display. (c) The rectified output current through 50 LEDs driven by the TENG with a finger typing. (f) The magnified current peak and the corresponding snapshots of the TENG-driven flashing LED display.

deformation generally increased the magnitude of the maximum current, from $0.25 \mu\text{A}$ at 0.5 mm to $0.72 \mu\text{A}$ at 2 mm . The integration of each current peak can give the total charges transferred between the electrodes, as shown in Figure 2b, indicating that the total amount of charges transferred increased with the increase of distance change between the two electrodes, which is consistent with our model discussed above.

Figure 2c shows the output current of the TENG under stimulation frequencies ranging from 1 to 4 Hz for a given deformation distance (1.5 mm) and external load resistance ($500 \text{ M}\Omega$), revealing a clear increasing trend with the increase of frequency. For a given deformation, as the deformation rate increases with stimulation frequency, which leads to a higher flow rate of charges, resulting in a higher current peak value, however the total amount of the charges transferred is constant. The integration of each current peak from each of the 4 different stimulation frequencies are shown in Figure 2d, indicating that the total amount of the charges transferred almost keep constant of $\sim 21 \text{ nC}$ at a given deformation. Therefore, the instantaneous power output increases with the increase of stimulation frequency.

The output current and voltage of a TENG variation with different external load for a given frequency of 3 Hz and degree of deformation (1.5 mm) are depicted in Figure 2e. With an increase in the load resistance, the maximum current decreases, while the voltage across the following an opposite trend with the maximum value of $\sim 407 \text{ V}$.

The output power exhibits an instantaneous peak value of 0.23 mW with an external load of $300 \text{ M}\Omega$ (Figure 2f). The measurement results reveal that the TENG is particularly efficient provided that the load has a resistance on the order of hundreds of megaohm. The electric energy produced by our TENG can be stored and using a rectifier and capacitor, and also can be used as a direct power source without electric storage to power commercial LEDs (Video 1 and Figure S3).

Supplementary material related to this article can be found online at <http://dx.doi.org/10.1016/j.nanoen.2012.11.015>.

Powering 50 LEDs in series by TENG directly

As a demonstration of converting irregular mechanical energy, such as human motion into electricity to power electronics, our TENG was successfully used as a direct power source without an energy storage system to instantly power 50 commercial blue LEDs (3B45C) connected in series with a finger typing! Figure 3a and inset of Figure 3b show the schematic and digital photography of the prototype energy harvesting circuit and LED display. A bridge rectifier is used to convert the AC output signals into DC signals. 50 LEDs are connected in series, and 26 LEDs in the first row forms characters of "HUST", while 24 LEDs in the second row forms characters of "WNLO". Figure 3b shows the current-voltage (I - V) curve of the 50 LEDs connected in

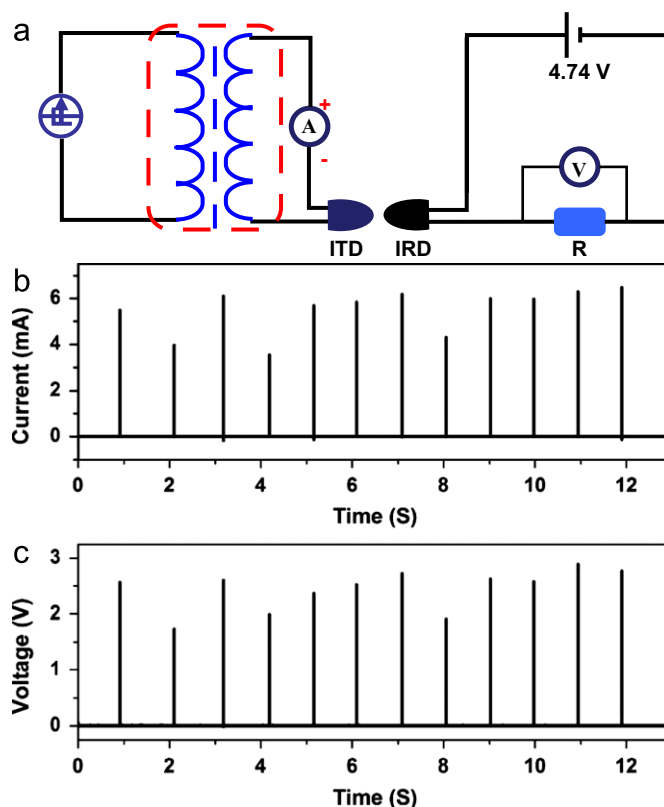


Figure 4 (a) Schematic of an infrared transmitter-receiver system in which the infrared transmitter diode (ITD, L1) was driven by a TENG in conjunction with a transformer. L2 is the infrared receiver diode (IRD) as a receiver to detect the light from the ITD. R is external load connected with IRD with a value of 20 M . (b) The output current through the ITD and (c) the voltage drop across R with time when ITD was driven by TENG in conjunction with a transformer under finger typing.

series, revealing the forward turn-on voltage of ~ 125 V. In our study, both the finger pressing and releasing process could light the LEDs (See Video 2 and inset of Figure 3d), and the corresponding output current through the LEDs were simultaneously recorded and shown in Figure 3c. It is observed that the current peak corresponding to releasing process has a smaller magnitude but lasts longer than that for pressing process (Figure 3d). Such an observation can be explained by the fact that pressing is caused by finger typing, while it is the resilience of the arch-shaped PTFE film that leads to the releasing. Therefore, it is very likely that releasing corresponds to a slower process and thus a smaller but wider current signal. The highest peak current went across the LEDs was $\sim 33 \mu\text{A}$, corresponding to an instantaneous output power of ~ 4.125 mW.

TENG used in wireless system

In addition, by conjunction with a transformer that is a passive device, high output current in the order of milliamperes was generated by our TENG that could be used to power those electronic devices which work with high current. Figure 4a shows the schematic of an infrared transmitter-receiver system (ST188, L4). The infrared transmitter diode (ITD) (forward turn-on voltage of ~ 1 V, Figure S4) was powered by a TENG conjunct with a transformer, while infrared receiver diode (IRD) and external load R ($20 \text{ M}\Omega$) were powered by a constant power source. When the ITD was driven by TENG which was triggered by finger typing, a strong infrared signal would emitted from the ITD, as the IRD received the infrared signal, the resistance of the IRD would decrease and leading to an obvious change of voltage across the external load R . In our study, the output current through the ITD and the voltage drop across R with time was monitored simultaneously, and are shown in Figure 4b and c, respectively. Figure 4b depicts the output current after applying the transformer can reach as high as ~ 6 mA. The change of the voltage across the external load R has the same trend with the output current (Figure 4c).

Conclusions

In summary, a novel and simple arch-shaped TENG is invented that can efficiently used for harvesting irregular mechanical energy. The instantaneous output power of single TENG device can reach as high as ~ 4.125 mW, which is high enough to instantaneously drive 50 commercial blue LEDs connected in series. By conjunct with a transformer, the TENG can power a commercial infrared transmitter with an output current of ~ 6 mA. The TENGs have potential of harvesting energy from human motion, mechanical vibration and more, with great applications in self-powered systems for wearable electronics, sensors and security.

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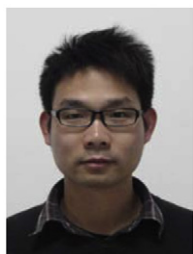
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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.nanoen.2012.11.015>.

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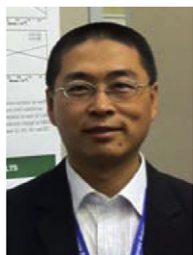


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semiconductor hybrid novel nanostructures with functional materials.

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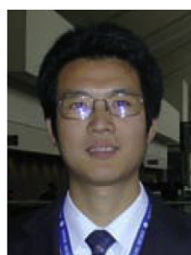
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