Electronic Supplementary Material (ESI) for Nanoscale

Flexible Electrostatic Nanogenerator Using Graphene Oxide Film

—Supplementary Information

He Tian,[1,2,†] Shuo Ma,[1,2,†] Hai-Ming Zhao,[1,2,†] Can Wu,[1,2] Jie Ge,[1,2] Dan Xie,[1,2] Yi Yang,[1,2] Tian-Ling Ren[1,2,*]

[1]Institute of Microelectronics, Tsinghua University, Beijing 100084, China

[2]Tsinghua National Laboratory for Information Science and Technology (TNList), Tsinghua University, Beijing 100084, China

†These authors contributed equally to this work

*Corresponding Author E-mail: RenTL@tsinghua.edu.cn

Supplementary Figures

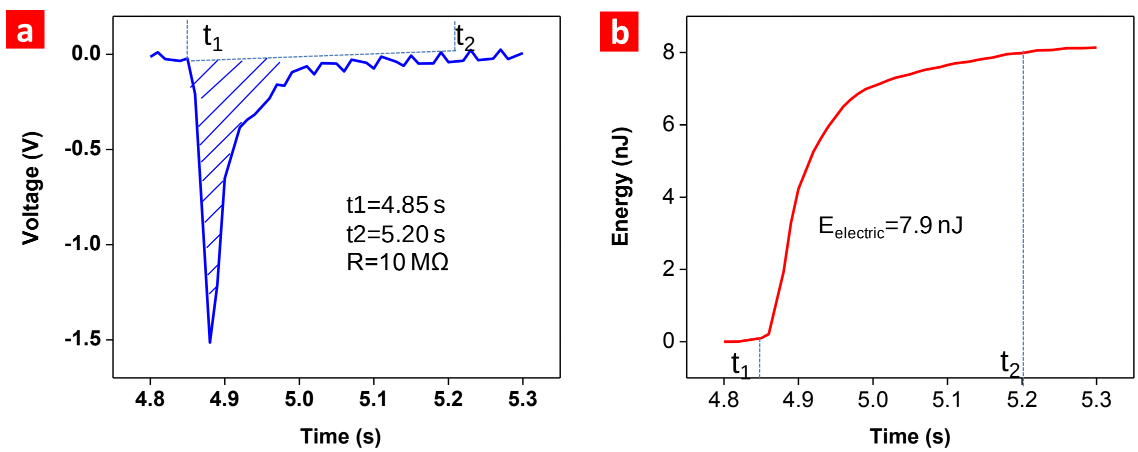

Figure S1. (a) A output voltage produced at load resistance of 10 MΩ. (b) Electric energy generated by the voltage pulse.

As shown in figure S1, the output electric energy is 0.79 nJ. The input mechanical energy is 375 μJ. The efficiency could be 0.00021%. The energy conversion density is 22.57 nW/cm^2.

Electronic Supplementary Material (ESI) for Nanoscale
This journal is © The Royal Society of Chemistry 2013

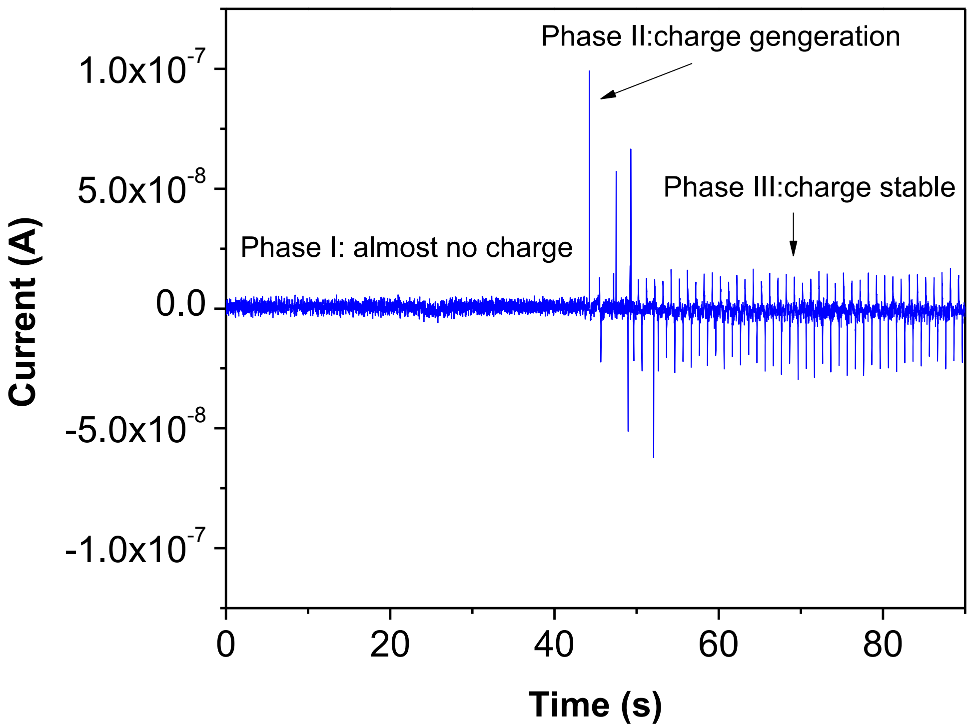

Figure S2. The detail phase change vs. time in the control sample without GO film

As shown in figure S2, there are three phases in the control sample without GO film. In phase I, there is almost no charge in the PI film. As a result, no current generated. In phase II, there is sharp peak generated, which could be attributed to the triboelectric effects. In phase III, there is stable current output, which means that the charge is stable.

The figure 3a is given for the device in phase III condition. We have observed the triboelectric effect in phase II. However, after the charge store in the dielectric, it is more likely to be electrostatic effect rather than the triboelectric effect.

In the previously reported literature, triboelectric effects are more likely to be happened between two different kinds of polymer materials such as PET and PI, PET and PDMS, PMMA and PI. In our control sample without graphene oxide, we use two layers of PI, which could minimize the triboelectric effects. Moreover, for our device with graphene oxide, the GO is pre-charged with negative charges. So the device with GO film is worked based on electrostatic effect rather than the triboelectric effect.

Supplementary Equations

The output current I could be expressed as following:

$$\mathrm{I} = dQ_1/dt = Q_0 C_2 C_1 * (d_1^{'} / d_1) / (C_1 + C_2)^2$$

As the I=30 nA, the impact speed of $d_1^{'}$ could be 0.02 m/s.

In our experimental condition, the $d_1^{'} = d/t = 10^{-4}/0.005 = 0.02\ \mathrm{m/s}$, so the calculated $d_1^{'}$ is in a good agreement with the experimental results.

For the GONG without release structure,

The initial capacitor could be

$$C_1 = \mathrm{C}_2 = \varepsilon_r \varepsilon_0 S/d = 8.85 \times 10^{-12} \times 3.5 * 10^{-4} / 10^{-4} = 3.1 \times 10^{-11} F$$

The theoretical output voltage could be

$$\begin{aligned} V &= RI = R * \mathrm{dQ}_1/\mathrm{dt} = R * Q_0 C_2 C_1 * (d_1^{'} / d_1) / (C_1 + C_2)^2 \\ &= 10^7 * 1.5 * 10^{-9} * (3.1 * 10^{-11})^2 * 0.02 / 10^{-4} / (3.1 * 10^{-11} + 3.1 * 10^{-11})^2 \\ &= 0.75 (V) \end{aligned}$$

As shown in Figure 3b, the experimental output voltage is 0.7 V. So the theoretical value is reasonable.

For the GO device with release structure:

The initial capacitor could be

$$C_1 = {}_r \varepsilon_0 S/d = 8.85 \times 10^{-12} \times 10^{-4} / 10^{-4} = 8.85 \times 10^{-12} F$$

$$\mathrm{C}_2 = \varepsilon_r \varepsilon_0 S/d = 8.85 \times 10^{-12} \times 3.5 * 10^{-4} / 10^{-4} = 3.1 \times 10^{-11} F$$

The theoretical output voltage could be

$$V = RI = R*\mathrm{d}Q_1/\mathrm{d}t = R*Q_0 C_2 C_1 *(d_1^{'}/d_1)/(C_1+C_2)^2$$
$$= 10^7 *1.5*10^{-9} *(3.1*10^{-11})*(8.85*10^{-12})*0.06/10^{-4}/(8.85*10^{-12}+3.1*10^{-11})^2$$
$$= 1.55(V)$$

As shown in Figure 3c, the experimental output voltage is 1.5 V. So the theoretical value is reasonable.

Based on the equation that $I = \mathrm{d}Q_1/\mathrm{d}t = Q_0 C_2 C_1 *(d_1^{'}/d_1)/(C_1+C_2)^2$ where d_1 is the thickness of the top parallel plate capacitor. When pressure frequency increases from 1 Hz to 10 Hz, the impact speed of d_1' could increase 10 times. As a result, the I could increase 10 times and the output voltage V = RI will be also increase 10 times. In our experimental observation, the voltage is increase almost 17 times. The over increase of 1.7 times in experimental results could be attributed to the increase of the Q_{GO} due to the triboelectric effects. As shown in Figure S2, there is charge generation in the control sample without GO film. So the triboelectric effects could be happened in phase II and become stable in phase III for GONG. We carefully estimate the Q_{GO} increase versus frequency through the reference.

We check the output current versus frequency based on triboelectric effects from Zhongling Wang's group results (**F.-R.Fan,etal.,Flexible triboelectric generator, NanoEnergy(2012), doi:10.1016/j.nanoen.2012.01.004**). There is almost 1.5 times increasing of output current when the frequency increasing from 0.5 Hz to 5 Hz. So the over increase 1.7 times could be attributed to the increase of the Q_{GO} due to the triboelectric effects.

Supplementary Table

Table S1. Comparison of the GONG performance with other reported data.

Material	**Type**	**Geometry**	**Output Voltage**	**Output Power**	**Reference**
ZnO	Wurtzite	D:50 nm L:600 nm	90 mV	16.2 pW	[S1]
GaN	Wurtzite	D:50 nm L:10 μm	35 mV	0.8 pW	[S2]
PVDF	Polymer	D: 5 μm L:0.5 mm	30 mV	90 pW	[S3]
GO	**Derivative of Graphene**	**D:20 μm L:10 mm**	**2 V**	**60 nW**	**This Work**

Table I shows the comparison of GONG performance with recent literature data.[S1-S3] The output power 60 nW per cycle is three orders of magnitudes larger than the previously reports.

Supplementary References

S1. M.-P. Lu, J. Song, M.-Y. Lu, M.-T. Chen, Y. Gao, L.-J. Chen and Z. L. Wang, Nano Lett, 2009, 9, 1223-1227.

S2. C.-T. Huang, J. Song, W.-F. Lee, Y. Ding, Z. Gao, Y. Hao, L.-J. Chen and Z. L. Wang, Journal of the American Chemical Society, 2010, 132, 4766-4771.

S3. C. Chang, V. H. Tran, J. Wang, Y.-K. Fuh and L. Lin, Nano Lett, 2010, 10, 726-731.