Supplementary materials

Power generation with laterally-packaged piezoelectric fine wires

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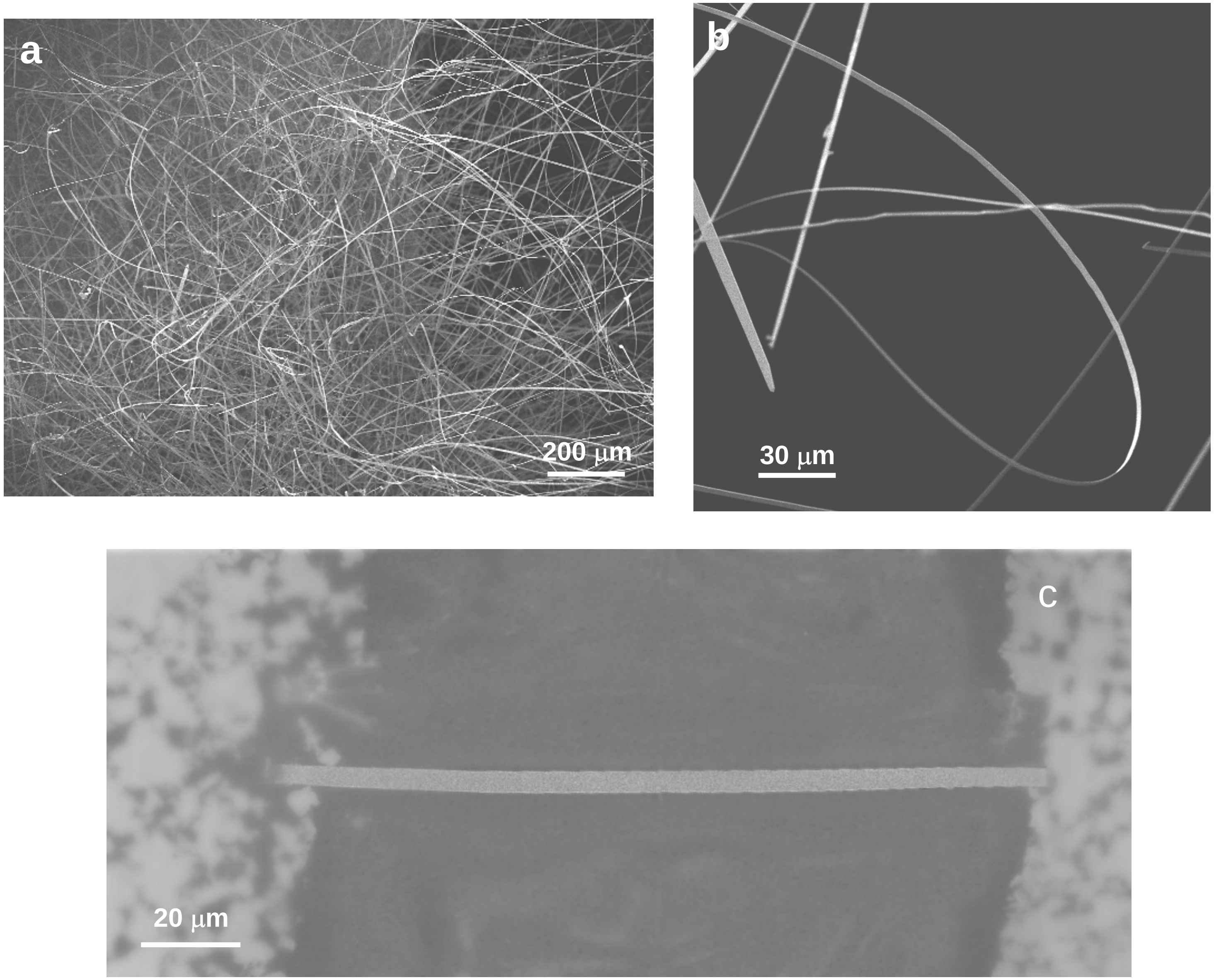
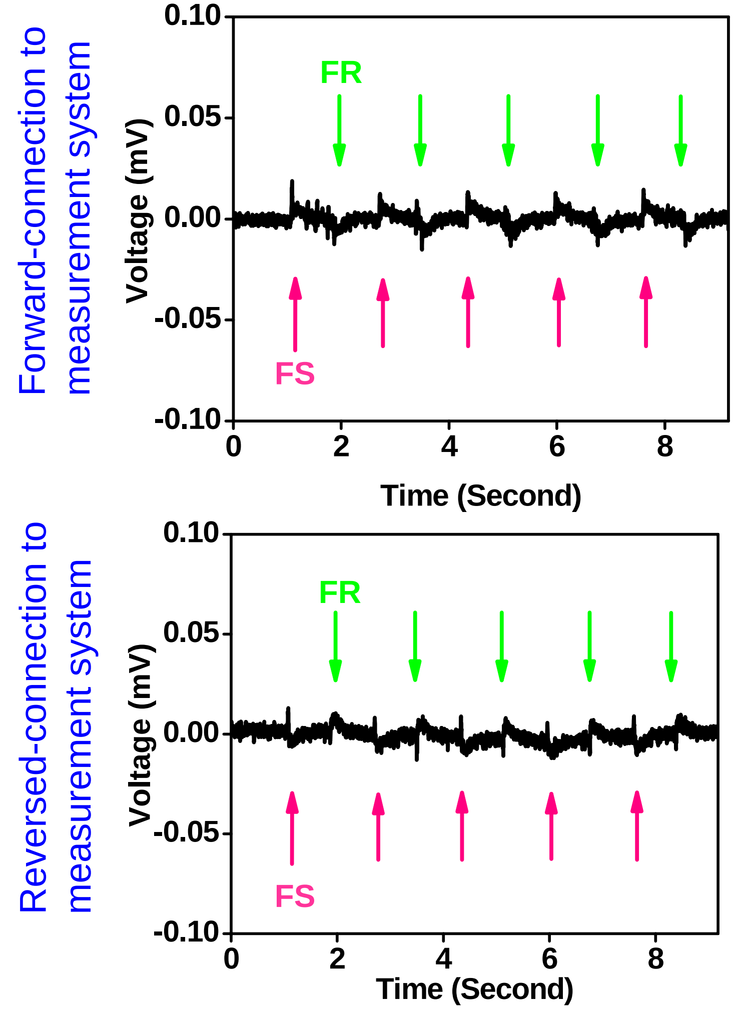


Figure. S1 | a, b Low- and high-magnification SEM images of ZnO fine-wires used for fabricating AC generators. **b,** An SEM image of a fabricated AC generator supported by a Kapton polyimide film.

Peaks of output current	Total generated charge when fast stretched (C x 10^{-11})	Total generated charge when fast released (C x 10^{-11})
First	1.49	−1.88
Second	1.73	−1.87
Third	1.76	−1.86
Fourth	1.74	−1.94
Fifth	1.85	−1.72
Sixth	1.67	−1.92
Seventh	1.86	−1.77
Eighth	1.90	−1.87
Ninth	1.90	−1.69
Tenth	1.79	−1.85
Average	1.77	−1.84

Table S1 | Total charge generated when the SWG was fast stretched and fast released by integrating the area of the peak in the I-t curve shown in Fig. 2a. The negative sign means the charges flow in an opposite direction.

When the two-end-contacts of a ZnO microwire are symmetrically Ohmic, the SWG does not generate output voltage



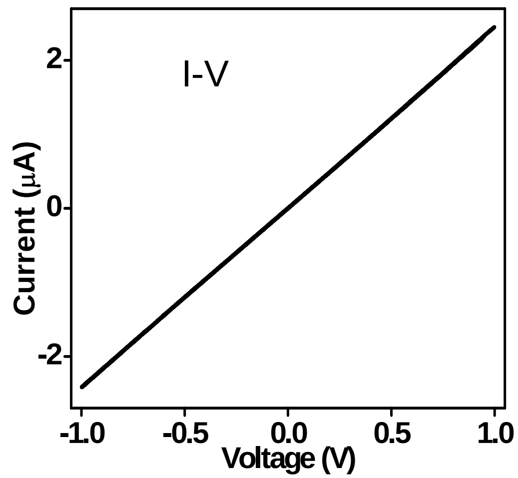


Figure S2 | By using metal In as electrodes, the I-V characteristic of the ZnO microwire showed Ohmic behavior. In such a case, the output current and voltage did not have a good correspondence to the frequency and magnitude of the stretching and releasing applied to the substrate. The signals showed no reversal with the reversion of the connection polarity. The data show that symmetric Ohmic contacts are not the choice for SWG.

No current or voltage generated using carbon fiber

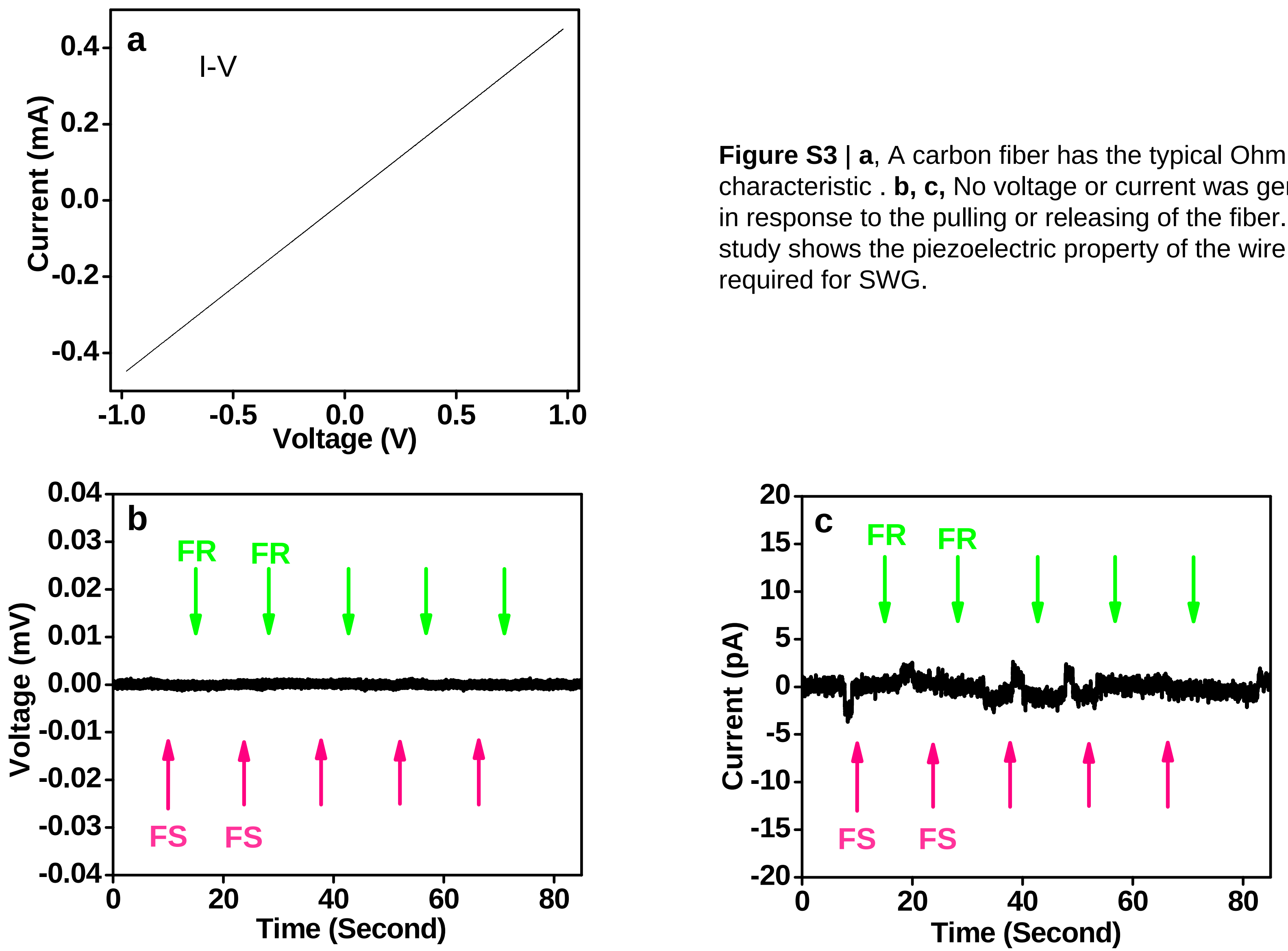


Figure S3 | **a**, A carbon fiber has the typical Ohmic I-V characteristic . **b, c,** No voltage or current was generated in response to the pulling or releasing of the fiber. This study shows the piezoelectric property of the wire is required for SWG.

No current or voltage generated using ZnO nanocrystal coated fiber

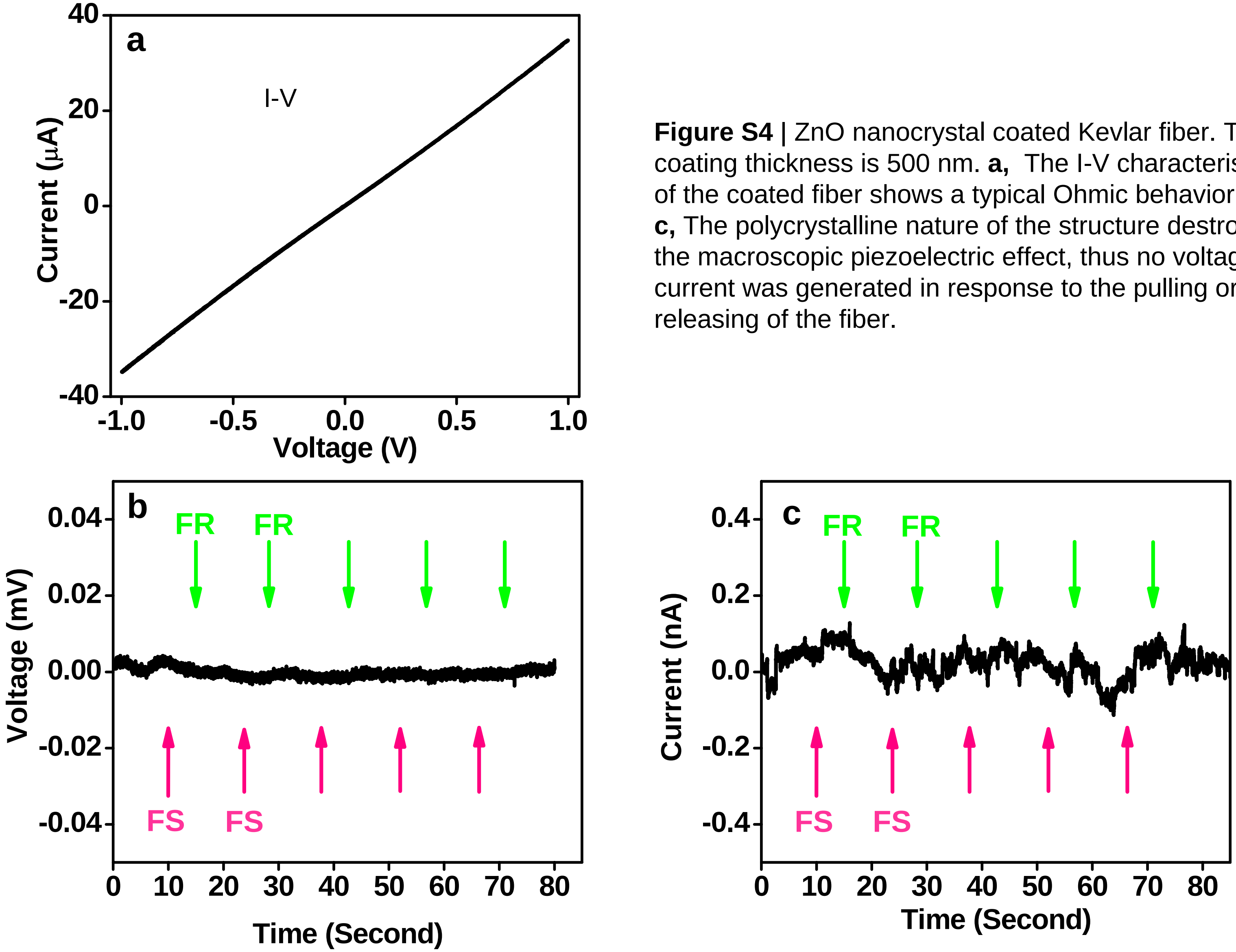
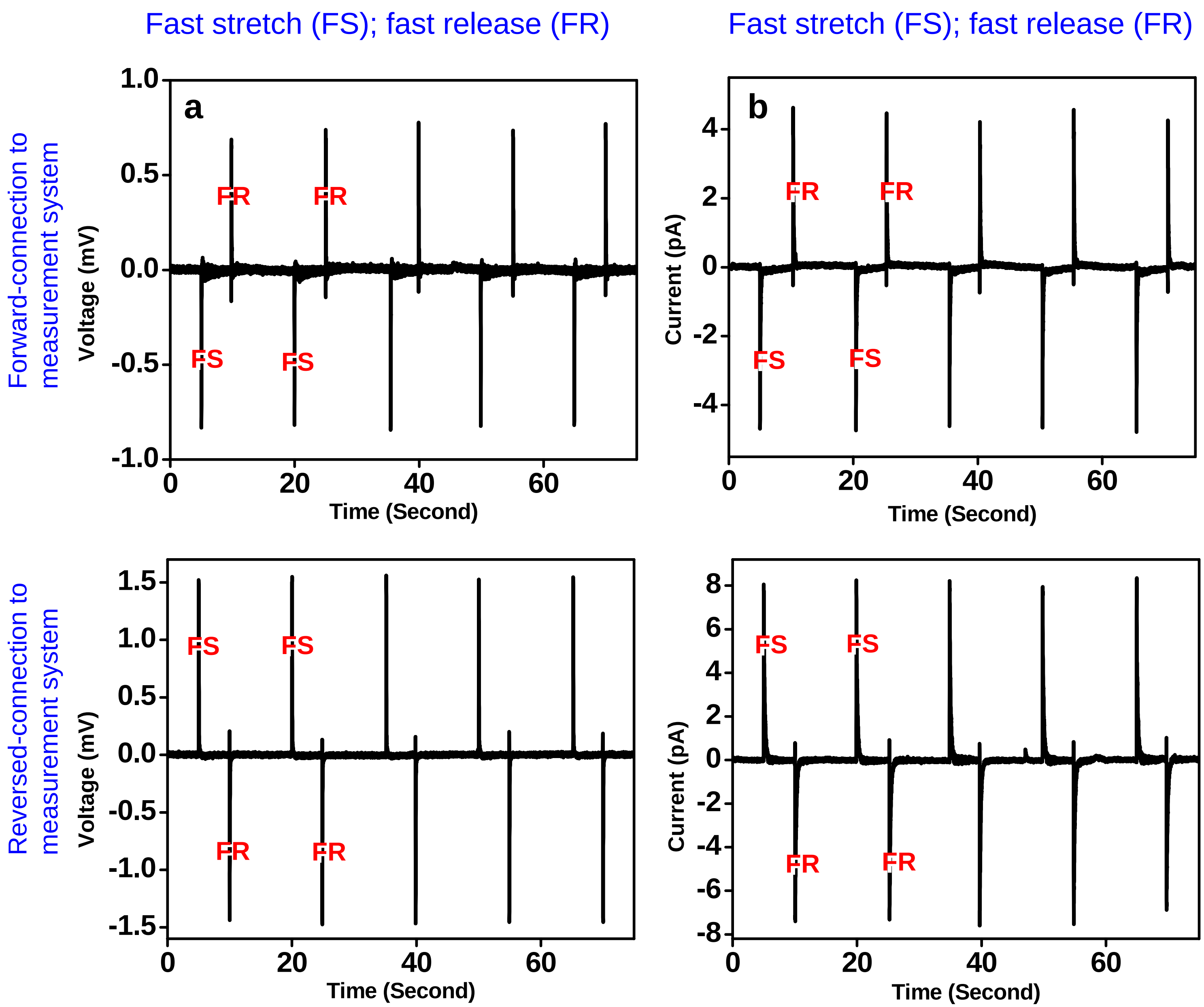


Figure S4 | ZnO nanocrystal coated Kevlar fiber. The coating thickness is 500 nm. **a,** The I-V characteristic of the coated fiber shows a typical Ohmic behavior. **b, c,** The polycrystalline nature of the structure destroys the macroscopic piezoelectric effect, thus no voltage or current was generated in response to the pulling or releasing of the fiber.

Generated voltage and current by fast stretching (FS) and fast releasing (FR) microwire



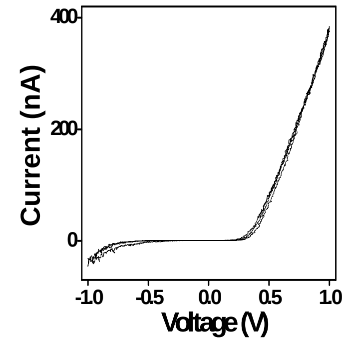
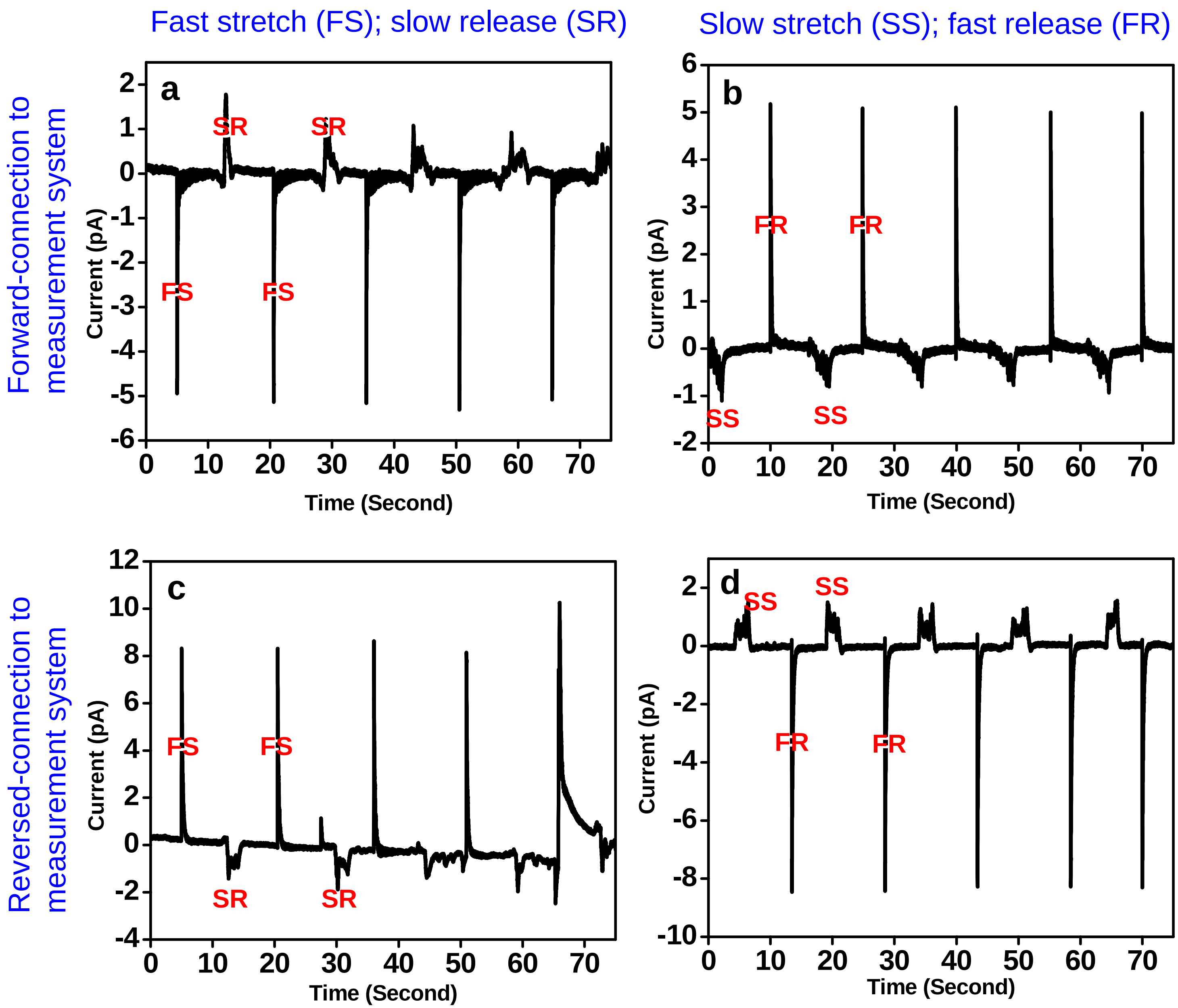


Figure S5 | For another nanogenerator, the sign of the output signal is the reverse of that shown in Figure 2 in the text although the I-V characteristic preserves the same. This is suggested due to the reversal in the piezoelectric field produced in the microwire as a result of switching microwire orientation.

Generated voltage and current by fast/slow stretching (FS, SS) and fast/slow releasing (FR, SR) a microwire



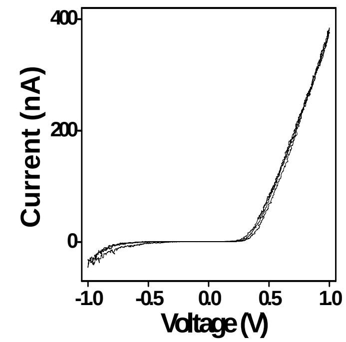


Figure S6 | For the same generator shown in supplementary Figure S5, reducing the pulling or releasing speed results in drastic decrease in the corresponding output signals. This is because the rate at which the charges were accumulated or released was greatly reduced, so that each process took quite long, resulting in weak output signal.

Total charge generated when the SWG was stretched and released by integrating the area of the peak in the I-t curve. The negative sign means the charge flow in opposite direction.

Table S2: From Fig. S6a

Peaks of output current	Total generated charge when slowly released (C x 10^{-13})	Total generated charge when fast stretched (C x 10^{-13})
First	8.02	-6.75
Second	6.95	-7.39
Third	7.49	-7.47
Fourth	7.39	-7.55
Fifth	8.97	-8.21
Average	7.76	-7.48

Table S3: From Fig. S6d

Peaks of output current	Total generated charge when slowly stretched (C x 10^{-13})	Total generated charge when fast released (C x 10^{-13})
First	14.9	-16.44
Second	15.44	-16.81
Third	16.695	-15.90
Fourth	17.795	-15.53
Fifth	17.89	-14.48
Average	16.54	-15.83

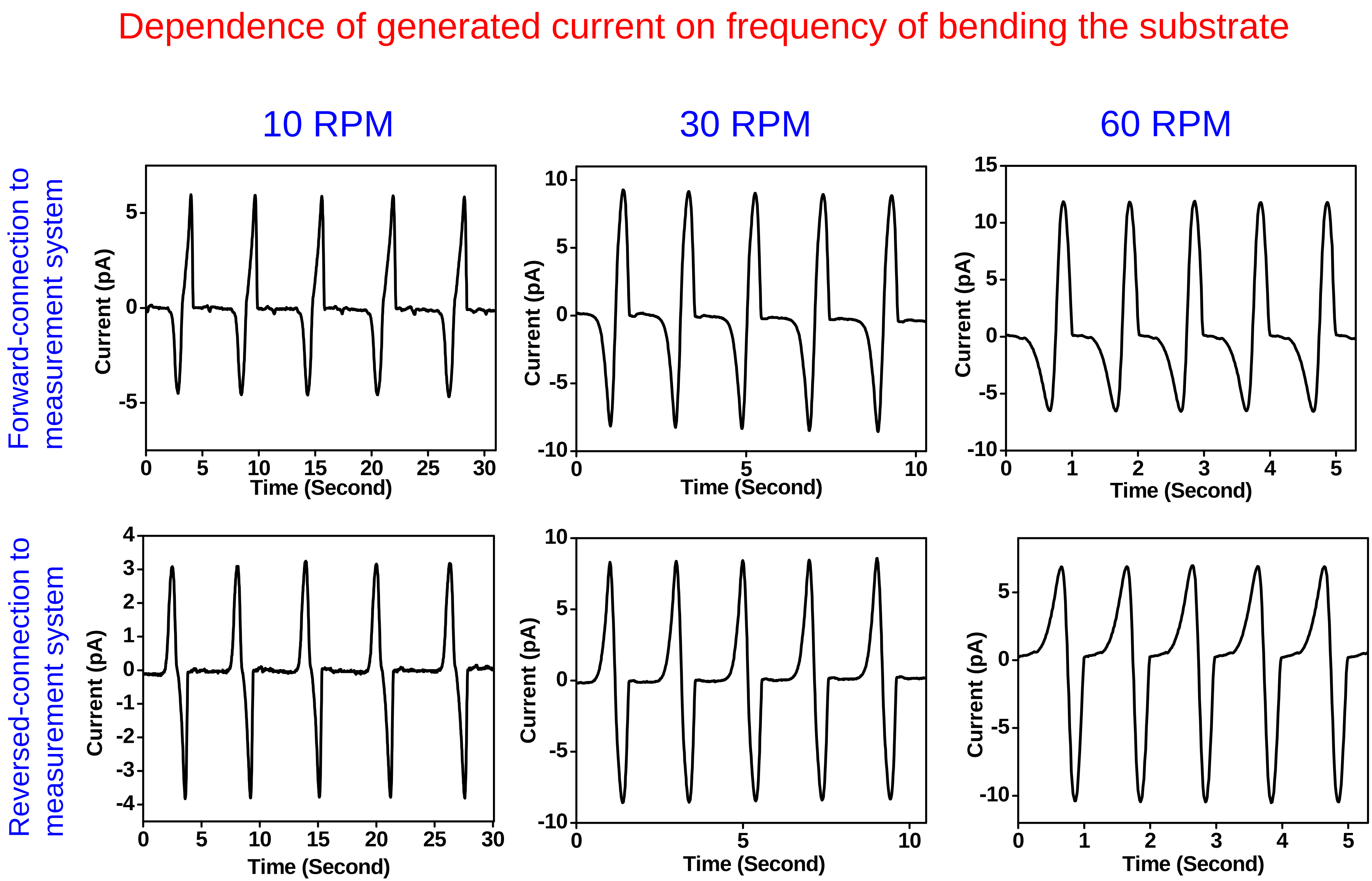


Figure S7 | An increase in bending frequency generally increases the magnitude of the output current signal.

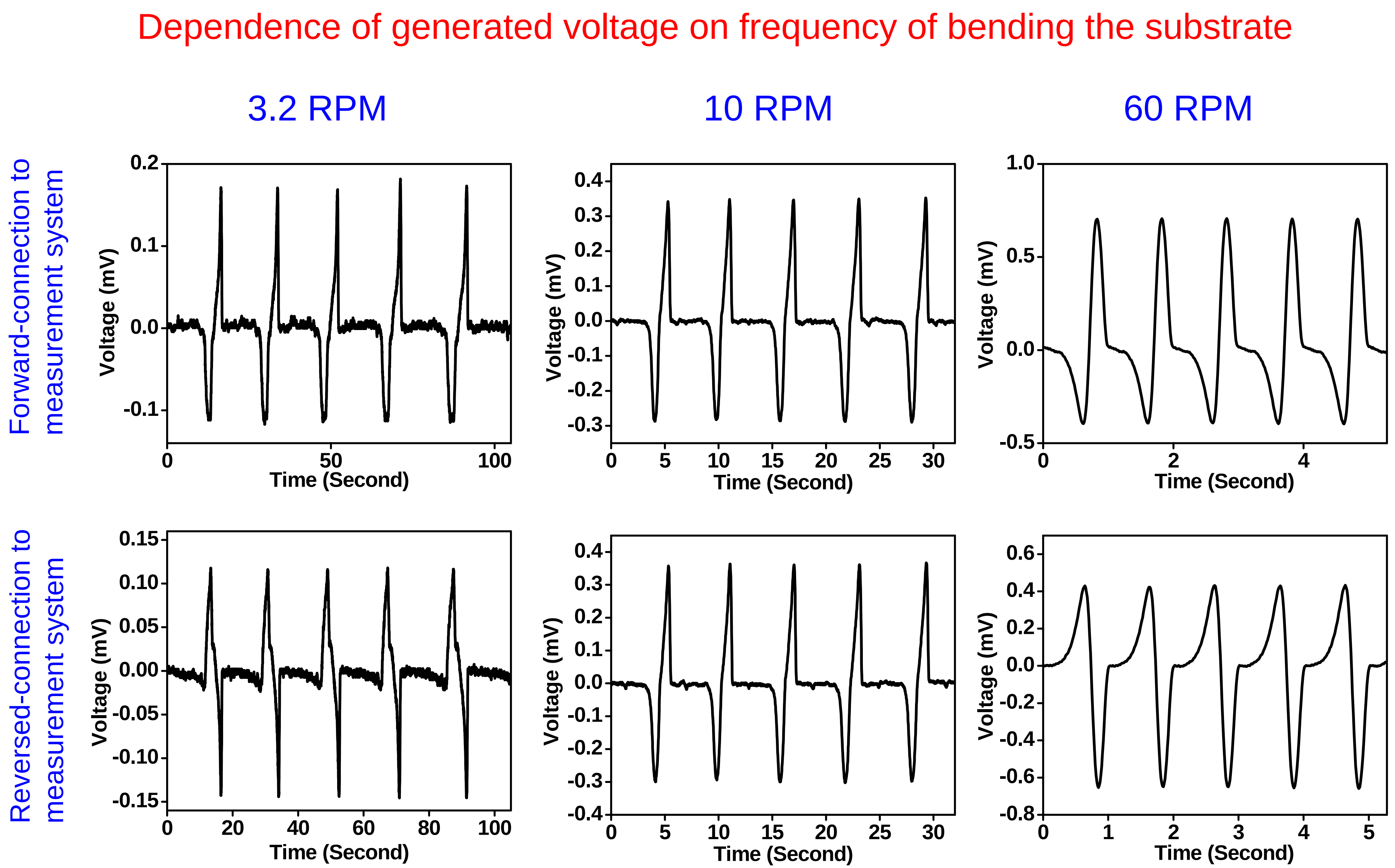


Figure S8 | An increase in bending frequency generally increases the magnitude of the output voltage signal.

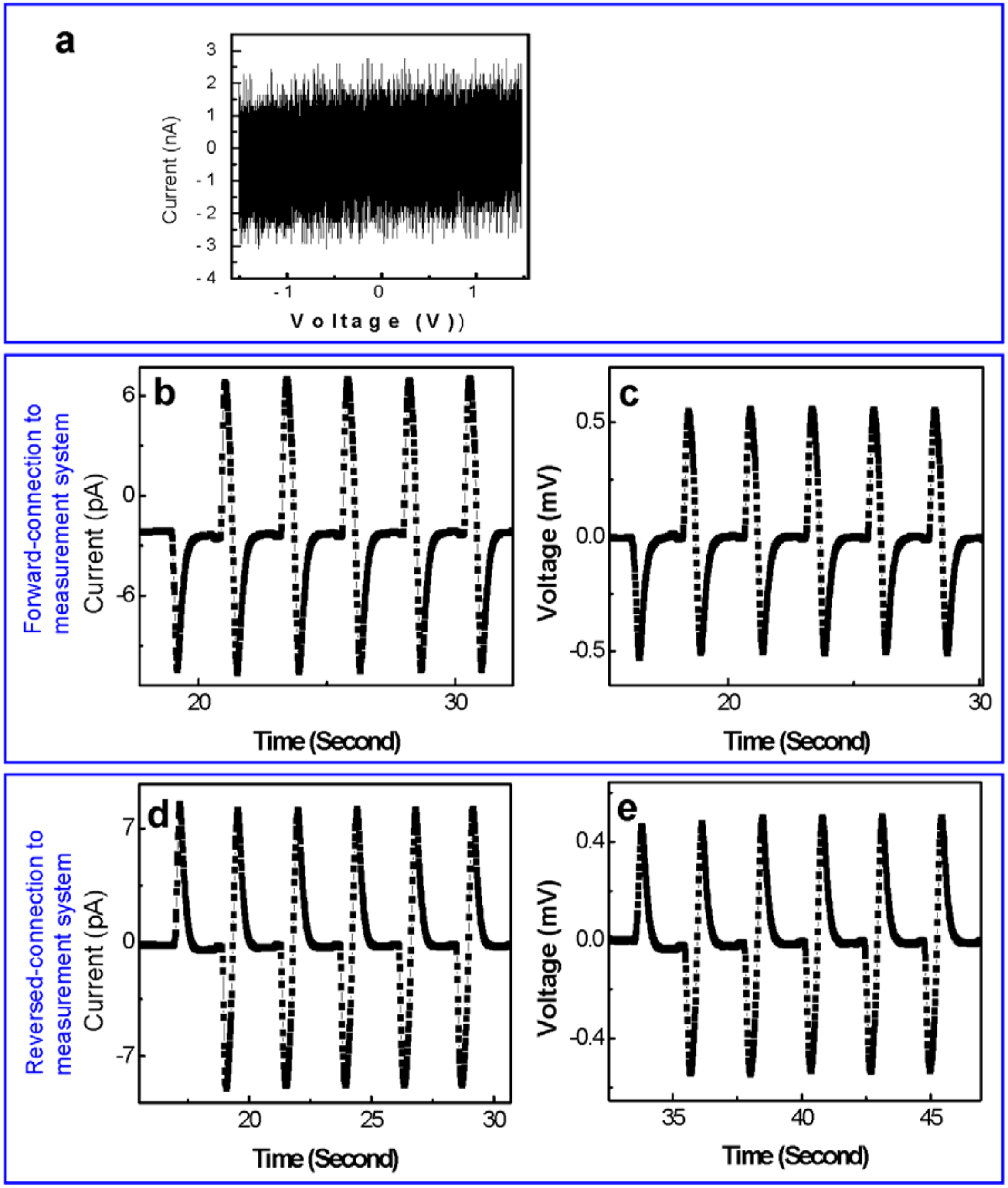


Figure S9. For a case that there is an insulator layer between ZnO microwire and the electrode, the resistance of the interface is in the order of ~2 GΩ, the interface serves as a “gate”, which can also be used to generate the AC electricity as a result of piezopotential driven flow of electrons. (a) The I-V property of the device. (b, c) and (d, e) The output current and voltage under forward- and reversed connections, respectively.

Mechanical flexibility and toughness of a ZnO microwire

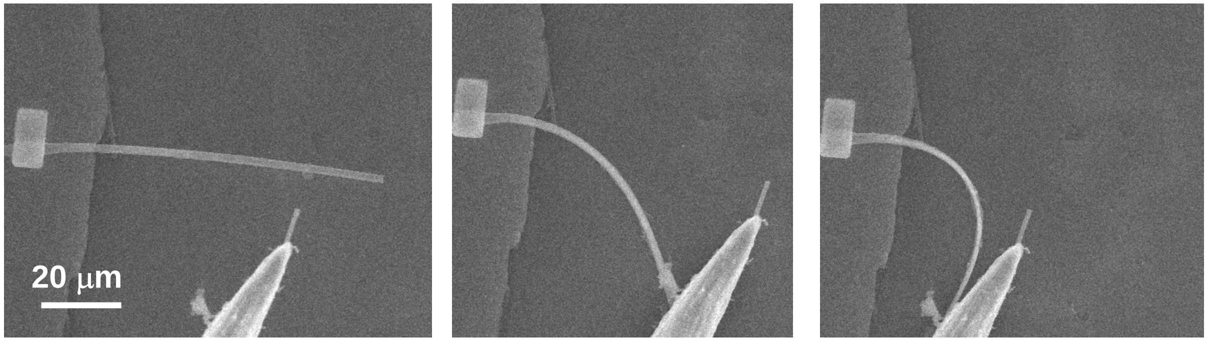


Figure. S10 **|** Manipulation of a ZnO microwire by a W-tip in SEM, showing its extremely large mechanical flexibility, elasticity and toughness (Hsin, C.L., Mai, W.J. & Wang, Z.L. unpublished)

Supplementary A: Identification of true signals vs artifacts

Artifacts may occur in the measurements due to various sources, such as a change in system capacitance as a result of sample mechanical deformation, movement of wires, coupling with measurement system. Caution must be exercised to identify true signals vs artifacts. We have developed two criteria and 8 connecting configurations to rule out artifacts.

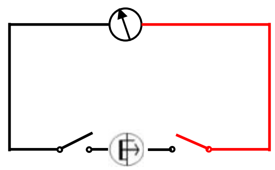


Figure Ia

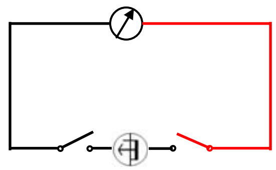


Figure Ib

Before and after our measurements, the IV curve of NG must be measured to make sure the connection between the electrodes and ZnO nanowire is Schottky contact. The real current signal and voltage signal must obey the following two principles.

Criteria 1. Switching polarity test.

When the current meter is forward connected to the NG, which means that the positive and negative probes are connected to the positive and negative electrodes of the NG as defined in Fig. Ia, firstly positive current pulse can be measured during the process that the NG is bent from the free position to the stretching position, and then negative current pulse can be detected during its releasing process. When the current meter was reversely connected, which means the positive and negative probes connected to negative and positive electrodes of the NG respectively, negative current pulse and positive pulse can be received in sequence in the same moving cycle. This testing method rules out the artifacts from the vibration of conductive wire. For the artifacts from the conductive wire, they won't reverse their polarity even we switch the connection mode.

Identification of true signals vs artifacts (Cont.)

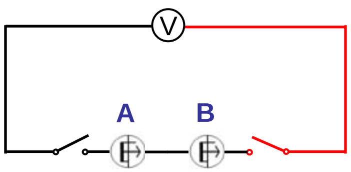


Figure IIa

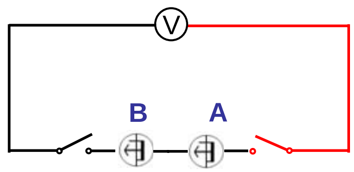


Figure IIb

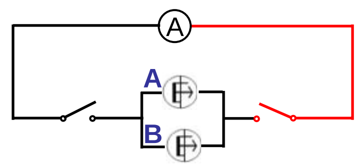


Figure IIIa

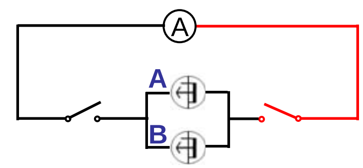


Figure IIIb

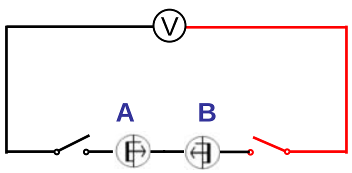


Figure IIc

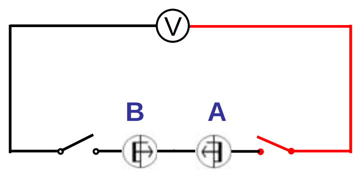


Figure IId

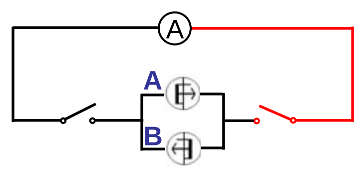


Figure IIIc

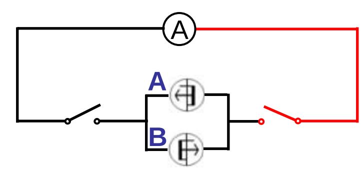


Figure IIId

Criteria 2. Linear superposition of current and voltage in 8 configurations.

For generator A, define V_A^+ and I_A^+ are measured current and voltage for positive connection according to figure 1a, and V_A^-, I_A^- are measured current and voltage for negative connection according to figure 1b [In an ideal case $V_A^- = - V_A^+$, $I_A^- = - I_A^+$]. The same symbols stand for generator B.

When generator A and B are connected in series as shown in figure II, the measured voltage should obey:
(1) $V_{A+B}^+ = V_A^+ + V_B^+$ (figure IIa)
(2) $V_{A+B}^- = V_A^- + V_B^-$ (figure IIb)
(3) $V_{A-B}^+ = V_A^+ + V_B^-$ (figure IIc)
(4) $V_{A-B}^- = V_A^- + V_B^+$ (figure IId)

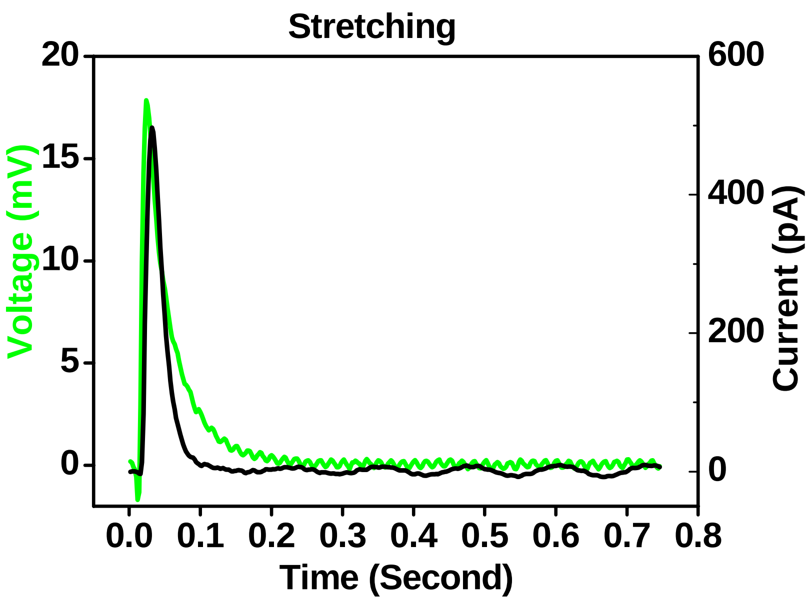
When generator A and B are connected in parallel as shown in figure III, the measured current should obey:
(5) $I_{A+B}^+ = I_A^+ + I_B^+$ (figure IIIa)
(6) $I_{A+B}^- = I_A^- + I_B^-$ (figure IIIb)
(7) $I_{A-B}^+ = I_A^+ + I_B^-$ (figure IIIc)
(8) $I_{A-B}^- = I_A^- + I_B^+$ (figure IIId)

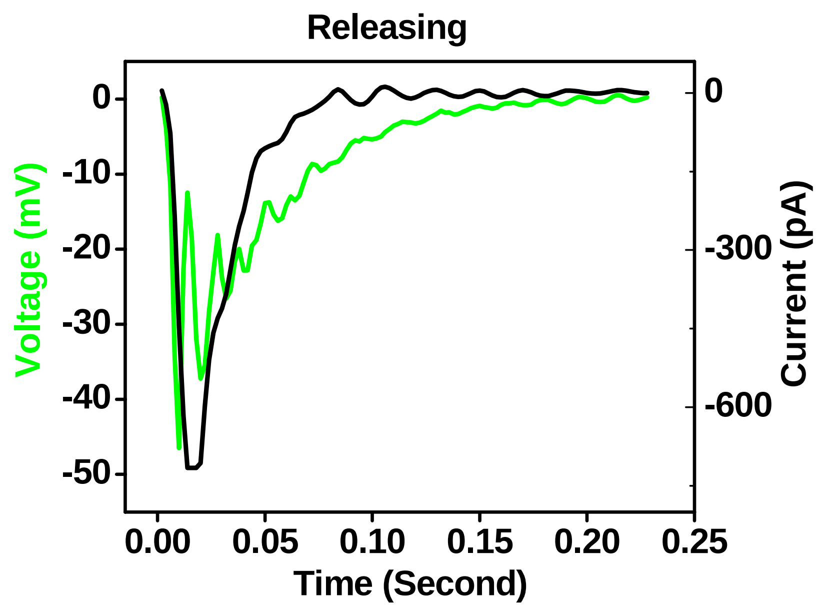
Supplementary B:

Calculation of energy conversion efficiency of the PFW

When the ZnO fine wire is stretched or released, the electric energy generated can be estimated with the following formula

$$W_e = \int VIdt$$





Total electric energy generated per cycle of stretching and releasing is: W_e = 6.48E-13J

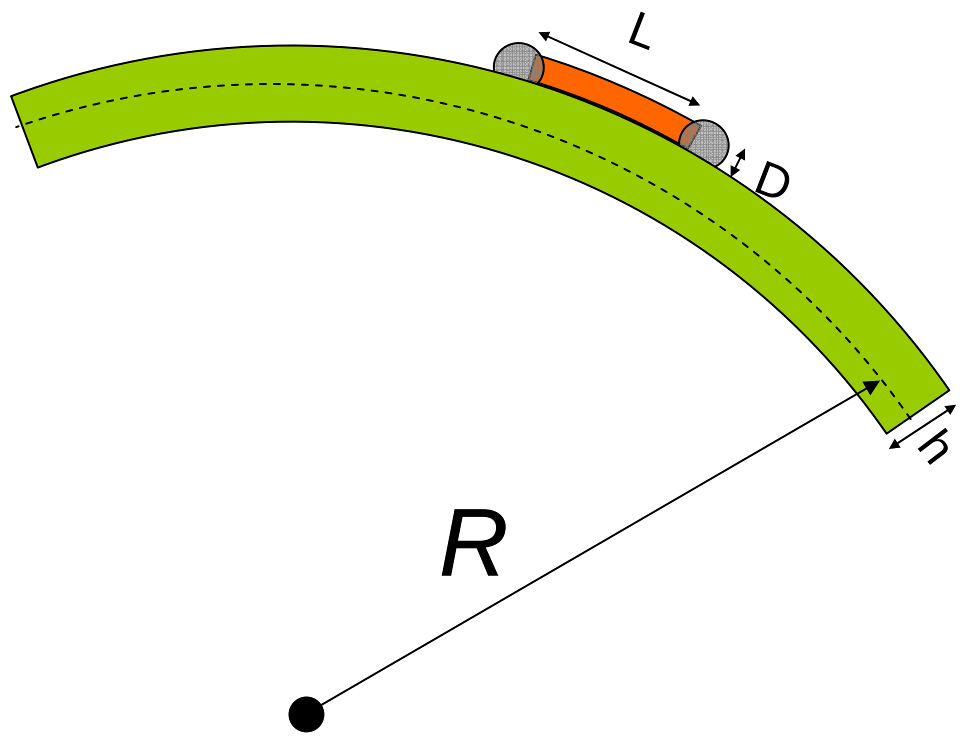
Elastic energy stored in the bent wire

Strain

Assume the Kapton substrate was bent with a radius of R. The thickness of Kapton substrate is h. The ZnO fine wire has a length of L and diameter of D. Because R >>h and h>>D, the strain of ZnO nanowire is approximately equal to the strain of the outer surface of Kapton film, which is equal to

$$\varepsilon = \frac{h}{2R}$$

The thickness of the Kapton substrate is 50 μm, and the radius R is between 2.0-3.0 cm. According to above formula and the value of h and R, the strain of ZnO fine wires is ε =**0.05%-0.1%**



Strain energy: Because the length of ZnO fine wire is much smaller than the radius R, the dominant strain in ZnO fine wire is the stretching strain along axial direction, and the shear strain can be safely neglected for the estimation purpose. Based on the basic solid mechanics, we can easily achieve the elastic energy of the stretched ZnO fine wire.

$$W_m = \frac{1}{8}\pi D^2 L_0 E \varepsilon^2$$

Where D is the diameter of the wire, L_0 is its original length, E is the Young's modulus, and ε is the strain of ZnO fine wire. The ZnO fine wire in this report has a diameter D about 4 μm, L_0 about 200 μm, E about 30-50 GPa, and ε about 0.05%. Based on those values and the electric energy W_e = 6.48E-13J, the ultimate energy conversion efficiency of the PFW itself, excluding the substrate film, is estimated as follows:

E (GPa)	50	30
ε	0.0005	0.0005
W_m (J)	1.57E-11	9.42E-12
Efficiency (%)	4.1	6.8

Statistical data about the resistance SWGs

We totally have made over 70 SWGs that can generate electricity. The resistance is sensitive to the batch of microwire samples we used. This could be related to the density of surface vacancies/impurities. For all of the SWGs that were active for electricity generation, 90% of them had Schottky contacts, and 10% had Ohmic behavior but with a resistance > 1 GΩ (see Supplementary Fig. 10). Details are given in Tables 4 and 5.

Table 4: Differential Resistance of SWG at different bias

We have quantified the resistance of the SWG under positive and negative biases. It is the local resistance that is important for “gating” and “preventing” the electrons to flow through the microwire. The resistance around zero volt bias is most essential for the energy generation.

$$R = \left.\frac{dV}{dI}\right|_{V=bias}$$

Figure \ Bias (V)	-1	-0.5	-0.2	0	0.2	0.5	1
Figure 2 a, b (Ω)	4.24E+07	2.13E+07	1.21E+08	2.49E+07	1.05E+06	5.15E+04	1.98E+04
Figure 2 c (Ω)	4.12E+09	5.00E+09	1.36E+09	7.41E+09	3.95E+07	3.62E+06	4.85E+05
Figure 2d (supp. Fig 5,6) (Ω)	5.56E+06	4.39E+07	7.58E+08	4.57E+09	4.78E+07	1.74E+06	1.49E+06
Figure 3a SWG1 (Ω)	8.55E+06	8.77E+07	1.21E+09	2.08E+09	2.79E+08	7.81E+06	3.52E+06
Figure 3a SWG2 (Ω)	2.13E+09	4.20E+09	2.15E+10	7.19E+08	5.99E+08	3.32E+09	2.57E+09
Supp. Figure S7, S8 (Ω)				5.18E+09			

Table 5: Resistance of SWG at different bias

We have quantified the resistance of the SWG under positive and negative biases. It is the local resistance that is important for “gating” and “preventing” the electrons to flow through the microwire. The resistance around zero volt bias is most essential for the energy generation.

$$R = \frac{V_{bias}}{I_{bias} - I_0}$$

I_0 is the current when bias $V = 0$, because I-V curve does not exactly pass (0,0)

I_{bias} and V_{bias} is the current value and bias value from the I-V curve

Figure / Bias (V)	-1	-0.5	-0.2	0	0.2	0.5	1
Figure 2 a, b (Ω)	1.02E+08	1.00E+09	1.18E+08	6.15E+07	5.35E+06	2.64E+05	4.06E+04
Figure 2 c (Ω)	6.21E+09	5.21E+09	2.08E+09	1.15E+09	2.22E+08	1.15E+07	1.62E+06
Figure 2d (supp. Fig 5,6) (Ω)	3.13E+07	1.98E+08	3.77E+09	1.97E+09	1.74E+08	6.55E+06	2.61E+06
Figure 3a SWG1 (Ω)	3.97E+07	3.54E+08	2.63E+09	1.99E+09	1.34E+09	3.39E+07	8.03E+06
Figure 3a SWG2 (Ω)	4.10E+09	4.04E+10	1.21E+09	9.95E+08	7.78E+08	7.87E+08	1.14E+09
Supp. Figure S7, S8 (Ω)				5.18E+09			

Note 1. The strain calculated by the formula given in the supplementary material over estimates the true strain because the fine-wire tends to be curved and attracted onto the surface of the substrate during device fabrication. An over estimation of strain results in smaller conversion efficiency.

Note 2. For slow stretching or releasing, the width of the output signal peak was smaller than the length of the straining process. This is likely due to that the small voltage at small strain might not be separable from the noise and background level. It became significant only when the degree of bending was significantly large.

Note 3. It was speculated by Harnack et al. that the factor that produces the Schottky behavior could be the alternating zinc and oxygen layers parallel to the basal plane, which produce a dipole moment that leads to a potential gradient and then introduce the asymmetry of current flow along the c axis [Harnack, O., Pacholski, C., Weller, H., Yasuda, A. & Wessels, J.M. Rectifying behavior of electrically aligned ZnO nanorods. *Nano Lett.* 3, 1097-1101 (2003)]. This assumption was proposed based on the noncentral symmetric and layered distribution of cations and anions in the wurtzite structure, and more importantly, the contact was assumed only at the basal plane surfaces. This is apparently not the case in our experiment because the contacts were at the same side-surface of the nanowire lying on the substrate and the cation- or anion-terminated surface had no effect unless the contacts are at the top and bottom ends of the nanowire. The formation of the Schottky diodes was suggested due to the asymmetric contacts between the nanowire and the electrodes as introduced in the fabrication process and may not have any relation to the orientation of the c-axis [Lao, C.S. et al. ZnO nanobelt/nanowire schottky diodes formed by dielectrophoresis alignment across Au electrodes *Nano Lett.* 6, 263-266 (2006)].

Note 4. The potential produced by a uniform tensile strain (ε))along a piezoelectric microwire can be estimated as follows. From the definition of the piezoelectric coefficient (d_{33}), the corresponding electric field parallel to the microwire is $E \approx \varepsilon / d_{33}$. The potential drop at the two sides $V^+ - V^- \approx EL = \varepsilon / d_{33}$, where L is the length of the microwire. This calculation can only be used for qualitative discussion. More rigorous calculation has to be made to get the real numbers by including the boundary conditions, conductivity and carrier density in the microwire.