

Mechanical—Electrical Triggers and Sensors Using Piezoelectric Micowires/Nanowires

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Received April 12, 2008; Revised Manuscript Received June 23, 2008

ABSTRACT

We demonstrate a mechanical—electrical trigger using a ZnO piezoelectric fine-wire (PFW) (microwire, nanowire). Once subjected to mechanical impact, a bent PFW creates a voltage drop across its width, with the tensile and compressive surfaces showing positive and negative voltages, respectively. The voltage and current created by the piezoelectric effect could trigger an external electronic system, thus, the impact force/pressure can be detected. The response time of the trigger/sensor is ~ 10 ms. The piezoelectric potential across the PFW has a lifetime of ~ 100 s, which is long enough for effectively “gating” the transport current along the wire; thus a piezoelectric field effect transistor is possible based on the piezotronic effect.

One-dimensional semiconducting nanomaterials have profound applications in nanosensors,^{1–4} nano-optoelectronics,⁵ nanoelectronics, and nanophotonics.^{6–11} Most of the existing nanodevices are made of individual nanowires/nanotubes/nanobelts, which typically have diameters of 20–100 nm and lengths of a few micrometers. The largely reduced device size, much improved performance, and the extremely small power consumption make them very attractive for applications in implantable biological devices, nanorobotics, security monitoring, and defense technology. A near future transition in paradigm from fabricating individual nanodevices to building complete nanosystems will revolutionize the applications of nanosensors, nanoelectronics, and nanophotonics. Although a large effort has been devoted to the fabrication of a diverse range of nanodevices,^{12,13} batteries are generally required to power them. The size of a battery is usually much larger than that of the nanodevice. Therefore, the size of a multicomponent nanosystem is mainly dictated by the size of the battery. The lifetime, size, weight, and toxicity of the battery become critical issues, especially for in vivo biomedical applications. Therefore, there is an urgent need to develop a self-powered nanosystem that harvests

energy from the environment so that it operates wirelessly, remotely, and independently with a sustainable energy supply.

In this paper, we report a force/pressure trigger built using a piezoelectric fine-wire (PFW) (microwire, nanowire) that electrically self-ignites once subjected to an external applied impact/displacement. No external power source is required to excite the trigger. The design of the “zero power” trigger is based on piezotronics¹⁴ that relies on the piezoelectric—semiconducting coupled properties of the PFW.

The design of the trigger is based on the principle of piezotronics.^{15–17} For a vertical ZnO wire, once it is bent by an external force, a potential drop is created across the PFW, with the stretched surface being positive and the compressed surface being negative.¹⁵ On the basis of a static model calculation for a case in which the force is uniformly applied to the PFW along its length, and without considering the conductivity of ZnO, the piezoelectric potential at the surface can be calculated as follows.¹⁸ We assume that all the external forces are surface forces with no body force acting on the wire; therefore,

$$\nabla \cdot \sigma = 0 \quad (1)$$

where σ is the stress tensor, which is related to strain ϵ , electric field E and electric displacement D by constitutive equations:

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$$\begin{cases} \sigma_p = c_{pq} \varepsilon_q - e_{kp} E_k \\ D_i = e_{iq} \varepsilon_q - \kappa_{ik} E_k \end{cases} \quad (2)$$

Here c_{pq} is the linear elastic constant, e_{kp} is the linear piezoelectric coefficient, and κ_{ik} is the dielectric constant. In our calculation, we only need to consider the direct piezoelectric effect, and the converse piezoelectric effect can be neglected. Under an approximation of ignoring the electric conductivity of ZnO, the Gauss equation is satisfied:

$$\nabla \cdot \bar{D} = 0 \quad (3)$$

With eqs 1–3 and the geometrical compatibility equations, the electric field generated by the microwire can be calculated when a proper boundary condition is given. In our model, we approximate the nanowire to be a beam with a square-shaped cross section. The bottom of the nanowire is assumed to be affixed on a well-grounded substrate. We assume that the nanowire is subjected to a force uniformly distributed on one of its four lateral sides. The mechanical property of ZnO is $E = 129.0$ GPa and $\nu = 0.349$,¹⁸ the relative dielectric constants are $\kappa_{11}^r = 7.77$ and $\kappa_{11}^i = 8.91$ for bulk ZnO,¹⁹ and the piezoelectric constants are $e_{31} = -0.51$ C/m², $e_{33} = 1.22$ C/m², and $e_{15} = -0.45$ C/m².²⁰ The length of the microwire is taken to be 1 mm, the size of the square-shape cross section is taken to be $6 \mu\text{m} \times 6 \mu\text{m}$, and the the total force exerted on the lateral side is 2 mN, giving a pressure of 0.33 MPa. The maximum potential generated at the surface is $(V_s^\pm)_{\text{max}} \approx \pm 0.2$ V at both the stretched side and the compressed side, respectively (Figure 1a,b). For an air-flow-triggered piezoelectric microwire, the electric field is weaker at places further from the substrate, which suggests that one should put the probe closer to the substrate in the experiments to get better signals.

Ultralong ZnO PFWs used in our experiments were synthesized by a thermal evaporation technique.²¹ An experimental design to measure the voltage and current output by a PFW is shown in Figure 1c. All of the experiments were carried out at room temperature and normal atmosphere pressure. A PFW was placed on the edge of a Si substrate, with one end fixed to the substrate, which was electrically grounded, and the other end was left free. A tungsten needle coated with $\sim 2 \mu\text{m}$ thick Au was connected to an external measurement circuit. The needle was placed at one side of the PFW, and Ar gas was blowing from the other side along a direction perpendicular to the orientation of the needle. Figure 1d shows a scanning electron microscopy (SEM) image of a single ZnO PFW ~ 1 mm in length. Figure 1e,f shows optical images of a ZnO wire when it was static and was being blown by a flowing gas, indicating that the ZnO wire was vibrating/resonating as excited by flowing gas. The role played by the flowing gas was to simulate an external mechanical impact.

We anticipated that an output signal would be produced by the PFW when the needle contacted the compressed surface of the PFW. The short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) were measured separately. No external voltage was applied at any stage of the experiment. To avoid possible artifacts from static charges, the tip and ZnO wire were grounded every time before we conduct the output measurement. Voltage output was detected (red curve in Figure 1g) when a flowing gas pulse was blown at the ZnO

wire, which was distinctly higher than the baseline (green curve in Figure 1g). A “switch polarity” testing method was applied to eliminate possible artifacts from the measurement system.²² By switching the connection of the two outlets from the PFW system to the electrical measurement system without changing any other conditions, the output voltage and current signals had the same magnitude but reversal in sign (Figures 1h and 1i). The voltage signal was easier to measure than the current because it was less sensitive to the instantaneous contact between the needle and the PFW, while the current signal was very sensitive to the contact between the needle and the PFW. This measurement result confirmed that the voltage and current signals were indeed generated by the ZnO wire. It is worth noting that our measurement system was unable to resolve the pulses produced by each contact between the wire and the tip. A high bandwidth amplifier is required to improve the measurement system, which is planned for near future work.

The measured voltage signal in our experiment is much lower than that predicted by the static calculation. The following reasons may account for this difference. First of all, the contact resistance can be very large as a result of the small contact area between the ZnO wire and Au-coated tungsten tip. Therefore, the voltage created by the piezoelectric effect of the ZnO wire was largely consumed at the contact because of the contact resistance, and only a small portion was received as the output. Second, the capacitance of the measurement system could be much larger than the capacitance of the ZnO wire. The large system capacitance consumes most of the charges produced by the ZnO wire and results in a low voltage output. More importantly, the finite conductivity of ZnO greatly may reduce the magnitude of the piezoelectric potential,²³ which was not included in theoretical calculation. Beyond the static model, the dynamic discharge process has to be considered as well.

The voltages at the stretched and compressed sides of the PFW were measured, respectively. When a periodic gas flow pulse was applied to a ZnO wire, the wire was vibrating and a corresponding periodic negative voltage output (Figure 2a) was detected by connecting the surface of compressed side of the PFW with an external measurement circuit. This is an electrically self-activated triggering/sensing process that is initiated from an external impact (gas flow in current case), immediately accompanied with power generation and a simultaneous triggering of external circuit. The largest voltage output detected here was -25 mV. Correspondingly, a periodic positive voltage output (Figure 2b) was detected at the stretched side of the PFW using the Au-coated needle. The observed results are entirely consistent with the principle proposed for piezotronics.¹⁵

The response of the piezoelectric trigger to an external impact can be estimated from the shape of the output voltage. We have applied a deconvolution technique to retrieve the voltage response function of the PFW.²⁴ From the as observed raw data in Figure 2c, a processed signal after removing the response function of the measurement system is shown in Figure 2d. The voltage response time of the PFW

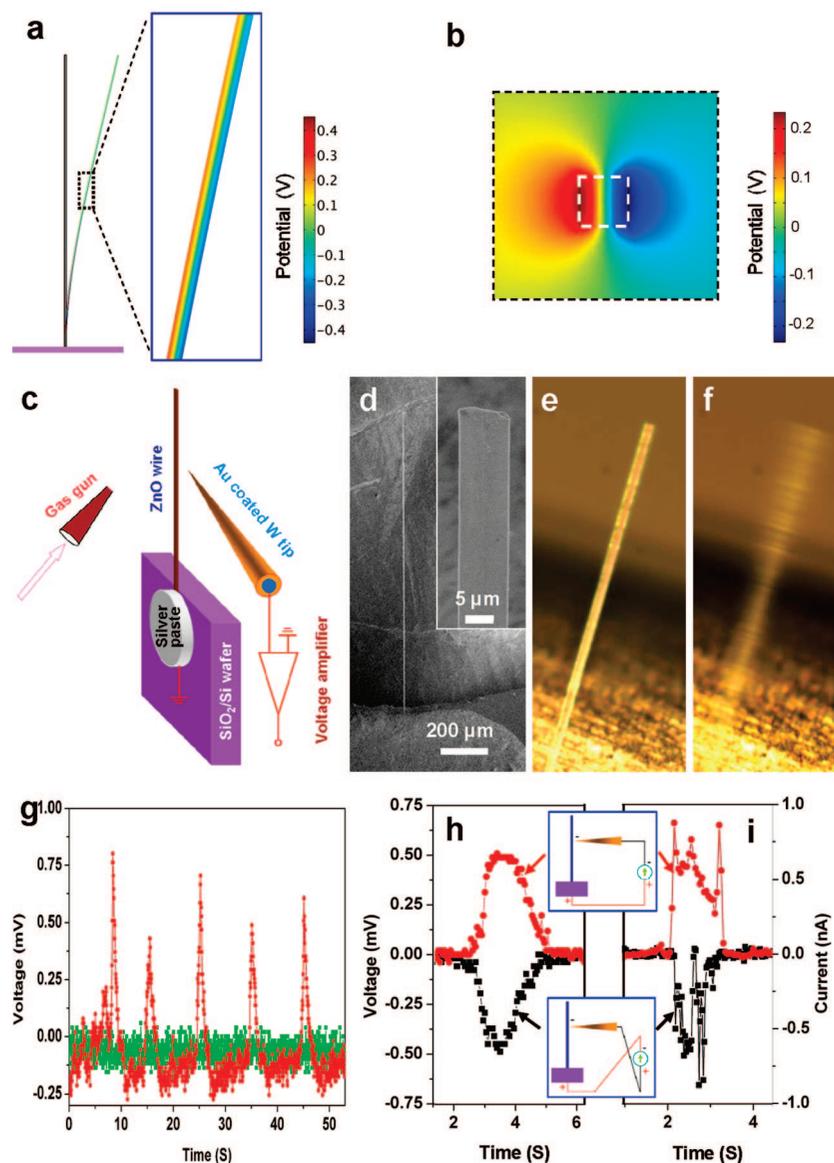


Figure 1. Modeling and measurements of piezoelectric power generation from a ZnO wire once subjected to gas impact, for demonstrating the principle of a force/pressure-driven electric trigger. (a) Calculated piezoelectric potential distribution in a rectangular ZnO wire using a static model, showing the positive and negative potential distribution across the wire at the tensile and compressive sides, respectively, once bent by an external force. (b) A cross-sectional output of the potential distribution perpendicular to the wire. (c) Schematic experimental set up of the self-activated triggers and sensors. An external force/impact creates a deformation of the wire, which generates a piezoelectric potential that triggers the measurement system. (d) SEM image of a ZnO wire. The inset is an enlarged image. (e,f) Resonance of a wire once blown by flowing Ar gas. The amplitude of the bending depends on the speed and pressure of the flowing gas. (g) Voltage output (red line) of the wire measured using the set up in panel c when the Ar gas was periodically turned on and off. The green line is the background signal. (h,i) Voltage and current outputs generated by the wire when it was blown by Ar gas, where a polarity-test was adopted to verify the inversion of output signal once the connection to the measurement system was switched. This is a critical test to ensure that the voltage and current were generated by the piezoelectric wire rather than the measurement system. The positive and negative connections of the system are shown in the inset.

is ~ 10 ms, which is the reaction time of the trigger and sensor. A sophisticated data processing technique has to be applied to fully quantify the performance of the trigger.

A continuous output voltage was received if the gas blowing was continuous. By extending the gas flow to a periodicity of 5 s in each cycle, the output voltage detected by the needle from the compressive surface of the PFW gives the corresponding pattern (Figure 3). Specially, the voltage output in the earliest stage of the contact in each blowing cycle has the highest amplitude, followed by a slow decay. This might be due to the fact that the gas flow has the highest

pressure when the gas gun was first turned on. This high pressure might introduce good contact between the ZnO wire and the Au-coated tungsten needle and a larger deflection of the PFW at the very beginning of the impact.

Piezoelectric potential is created by the piezoelectric charges produced in the PFW when it is subject to mechanical deformation or strain. The piezoelectric charges are ionic charges associated with cations and anions in the crystal, and they cannot freely move. The external electrons can screen the piezoelectric charges, but they cannot deplete the piezoelectric charges. This means that, with the consideration

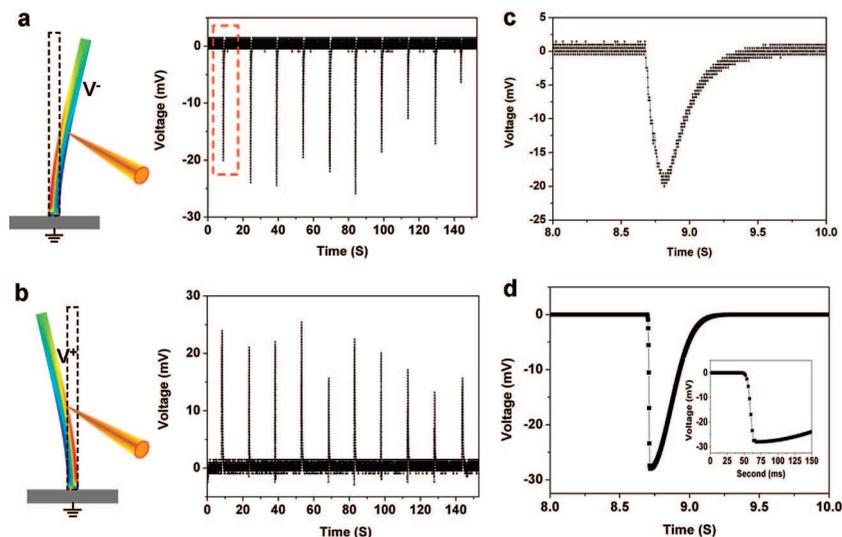


Figure 2. Self-generated voltages as directional triggers based on a single piezoelectric wire. Direct measurements of the asymmetric voltage distribution on the tensile and compressive side surfaces of a ZnO wire. (a) By placing a metal tip at the right-hand side and blowing Ar pulses at the left-hand side, negative voltage peaks of ~ 25 mV were observed once the pulse was on. (b) By quickly pushing and releasing the wire at the right-hand side by a metal tip, a positive voltage peak of ~ 25 mV was observed for each cycle of the deflection. The frequency of the deflection was once every 15 s. (c) An enlarged negative voltage peak from panel a, which is a convoluted result of the responses from the wire and the measurement system. (d) By removing the response of the measurement system, the signal displayed in panel c was processed to reveal the true response function of the trigger. The inset is an enlargement of the rising part of the signal. A response time of ~ 10 ms is demonstrated.

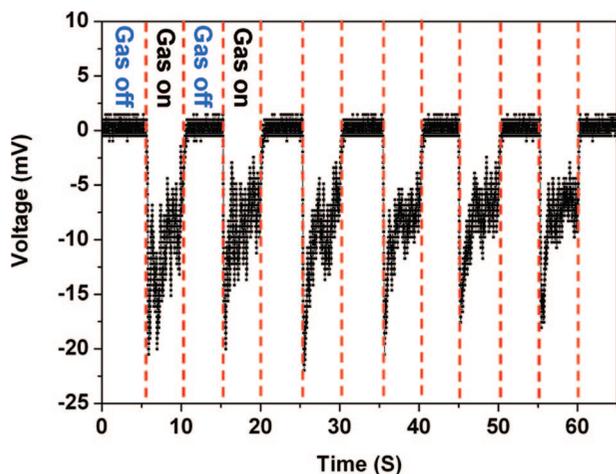


Figure 3. Piezoelectric voltage output of a ZnO wire measured by periodically blowing Ar gas at a ZnO wire. The gas was on and off at an interval of 5 s. The voltage output not only acts as a force/pressure-induced electric trigger/sensor, but also generates power that may be high enough to drive the electrical measurement nanoelectronics if its power consumption is very small.

of free electron carriers in ZnO, the magnitude of the piezoelectric potential may be reduced by the electrons, but they cannot totally neutralize the piezoelectric charges. From our previous study of ZnO, the carriers generated in ZnO under the excitation of UV light are trapped by the surface/defect states,²⁵ so that the conductivity of a ZnO took a long time, over several hundreds of seconds, to recover. A question that we would like to address here is how long the piezoelectric potential will be preserved after a PFW is bent and held still by the metal needle. We have designed an experiment to measure the lifetime of the piezoelectric potential.

The piezoelectric potential created in a PFW across its width behaves like an electric field distribution across a parallel-plate capacitor (see Figure 1a). Once connected at the two ends to electrodes, the role played by the piezoelectric potential is likely the gate voltage for a nanowire-based field effect transistor, which will trap the charge carriers in the PFW. This is the principle of the piezoelectric field effect transistor (PE-FET).³ A method to detect the presence and decay of the piezoelectric field as soon as the PFW is bent is to continuously monitor the source-drain current–voltage (I – V) transport properties of the PE-FET as a function of time. This experiment was carried out by continuously applying a sweeping voltage through the PFW and measuring its electric current.

In the first step, we set a reference for the initial transport characteristic of the ZnO wire, which was measured when the needle was first in contact with the ZnO wire but without bending (black curve in Figure 4a). Then, the ZnO wire was bent by the needle from the side to create a mechanical deformation, during which the I – V curve of the ZnO wire was continuously measured (red curve in Figure 4a). Finally, the ZnO wire was firmly held and maintained at the maximum bent position by the needle; meanwhile, a sweeping voltage from -2 to 2 V was applied to the ZnO wire for more than 14 min. A series of I – V curves were recorded (left inset of Figure 4a). The conductivity of the ZnO wire slowly recovered and finally reached a steady state (Figure 4b). Our experimental observation also showed the full recovery of the I – V curve after the release of the strain (Figure 5).

A changed I – V characterization after the ZnO wire was bent is likely contributed by two factors. One is the gating effect of the piezoelectric potential across the wire,³ and the

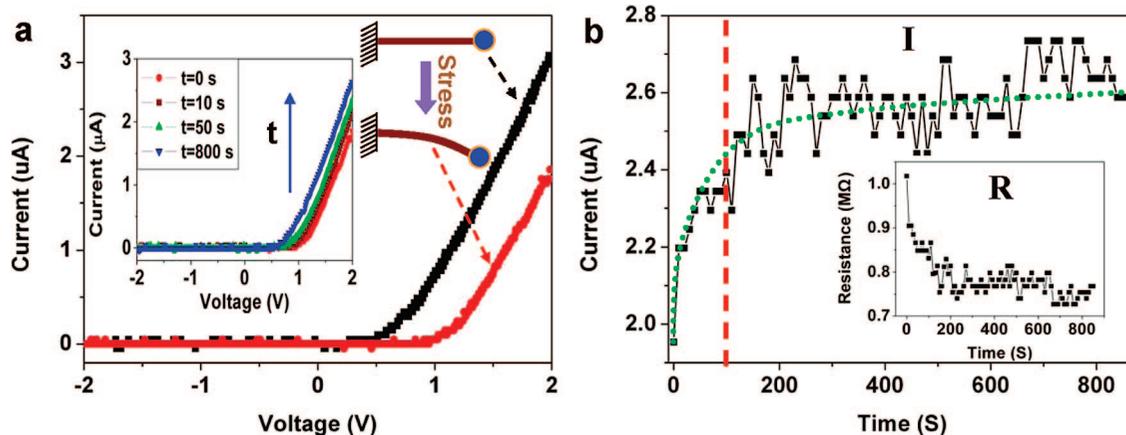


Figure 4. Measuring the lifetime of the piezoelectric potential created in a ZnO wire after straining. (a) I – V transport property of a ZnO wire before and after being bent by a metal tip at the free end. A great reduction in conductance is observed. By holding the bent wire stationary and continuously measuring the transport property as a function of time (inset), the I – V curve eventually reached a steady state, in which the piezoelectric potential created by the rigid ionic charges in the crystal was finally fully screened by the free carriers in the circuit. (b) For a fixed bias of 2 V, the current flowing through the bent wire was measured as a function of time. The current reached a steady state after ~ 100 s. The inset is an equivalent plot of the resistance R – t plot in corresponding to the I – t curve.

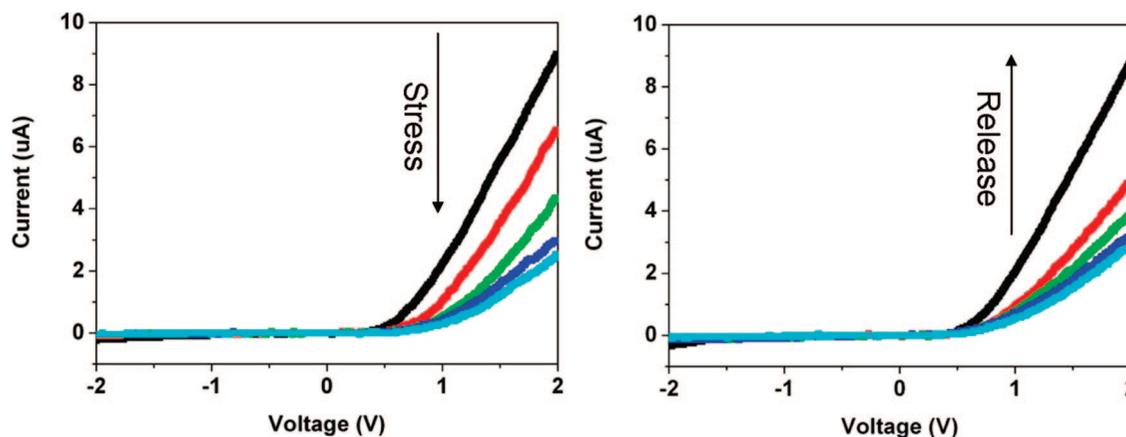


Figure 5. Transport measurements of a single ZnO wire when it was (a) bent and (b) released, showing the change in electronic properties under strain and the full recovery after releasing the strain.

other is the strain-induced piezoresistance²⁶ or change in barrier height.²⁷ With the consideration of asymmetric strain distribution across the wire at the stretched and compressed sides, the effect caused by an increased bandgap at the compressive side is likely balanced by that of a decreased bandgap at the tensile side. Moreover, a strained ZnO most likely has an increased conductivity,²⁶ which is in contrast to what we have observed here. Thus, the contribution from piezoresistance is negligible. On the other hand, the first factor is a time-dependent component, while the second factor is stationary as long as the deformation shape of the wire is preserved. Therefore, any change in conductance when the wire was held in static position was due to the piezoelectric effect.

By plotting the current measured at a fixed bias of 2 V as a function of time, as shown in Figure 4b, a clear trend is seen about the recovery of conductance in the current–time (I – t) curve. The long lasting recovery of the current possibly indicates that ZnO could hold the piezoelectric potential for as long as ~ 100 s before they are fully screened by external electrons to reach a steady state. This slow screening process is likely due to the strong trapping effect of the electrons by

vacancy/impurity/surface states in ZnO, which results in a slow release of the trapped charge, similar to the recovery of photoconductivity after UV light excitation.²⁵ One may suggest that the piezoelectric charges and potential created in a ZnO wire may hold for an equivalent length of time before being screened by external electrons, so that it can effectively gate the charge carriers as proposed for piezotronics and give sufficient time for experimental observation of the relevant effect.

In summary, we have demonstrated a mechanical–electrical trigger using a ZnO PFW. Once subjected to mechanical impact, a bent PFW creates a voltage drop across its width, with the tensile and compressive surfaces showing positive and negative voltages, respectively. The voltage and current created by the piezoelectric effect could trigger an external electronic system; thus, the impact force/pressure can be detected. The response time of the trigger/sensor is ~ 10 ms. The voltage across the PFW has a lifetime of ~ 100 s, which is long enough for effectively “gating” the transport current along the wire; thus a PE-FET is possible based on the piezotronic effect.

Acknowledgment. This research was supported by DAR-PA, BES DOE, NSF, and Emory–Georgia Tech CCNE funded by the NIH. P.F. and Y.D.G. thank the partial fellowship support by the China Scholarship Council (CSC) (No. 20073020).

References

- (1) Cui, Y.; Wei, Q.; Park, H.; Lieber, C. M. *Science* **2001**, *293*, 1289.
- (2) Patolsky, F.; Timko, B. P.; Yu, G.; Fang, Y.; Greytak, A. B.; Zheng, G.; Lieber, C. M. *Science* **2006**, *313*, 1100.
- (3) Wang, X. D.; Zhou, J.; Song, J. H.; Liu, J.; Xu, N. S.; Wang, Z. L. *Nano Lett.* **2006**, *6*, 2768.
- (4) Senesac, L.; Thundat, T. G. *Mater. Today* **2008**, *11*, 28.
- (5) Duan, X. F.; Huang, Y.; Agarwal, R.; Lieber, C. M. *Nature* **2003**, *421*, 241.
- (6) Gudiksen, M. S.; Lathon, L. J.; Wang, J.; Smith, D. C.; Lieber, C. M. *Nature* **2002**, *415*, 617.
- (7) Tans, S. J.; Verschueren, A. R. M.; Dekker, C. *Nature* **1998**, *393*, 49.
- (8) Bachtold, A.; Hadley, P.; Nakanishi, T.; Dekker, C. *Science* **2001**, *294*, 1317.
- (9) Javey, A.; Guo, J.; Wang, Q.; Lundstrom, M.; Dai, H. J. *Nature* **2003**, *424*, 654.
- (10) Huang, M.; Mao, S.; Feick, H.; Yan, H.; Wu, Y.; Kind, H.; Weber, E.; Russo, R.; Yang, P. *Science* **2001**, *292*, 1897.
- (11) Fasth, C.; Fuhrer, A.; Samuelson, L.; Golovach, V. N.; Loss, D. *Phys. Rev. Lett.* **2007**, *98*, 266801.
- (12) Chang, C. W.; Okawa, D.; Majumdar, A.; Zettl, A. *Science* **2006**, *314*, 1121.
- (13) Hochbaum, A. L.; Chen, R. K.; Delgado, R. D.; Liang, W. J.; Garnett, E. C.; Najarian, M.; Majumdar, A.; Yang, P. D. *Nature* **2008**, *451*, 163.
- (14) Wang, Z. L. *Adv. Mater.* **2007**, *9*, 889.
- (15) Wang, Z. L.; Song, J. H. *Science* **2006**, *312*, 242.
- (16) Wang, X. D.; Song, J. H.; Liu, J.; Wang, Z. L. *Science* **2007**, *316*, 102.
- (17) Qin, Y.; Wang, X. D.; Wang, Z. L. *Nature* **2008**, *451*, 809.
- (18) Gao, Y. F.; Wang, Z. L. *Nano Lett.* **2007**, *7*, 2499.
- (19) Ashkenov, N.; Mbenkum, B. N.; Bundesmann, C.; Riede, V.; Lorenz, M.; Spemann, D.; Kaidashev, E. M.; Kasic, A.; Schubert, M.; Grundmann, M.; Wagner, G.; Neumann, H.; Darakchieva, V.; Arwin, H.; Monemar, B. *J. Appl. Phys.* **2003**, *93*, 126.
- (20) Carlotti, G.; Socino, G.; Petri, A.; Verona, E. *Appl. Phys. Lett.* **1987**, *51*, 1889.
- (21) Pan, Z. W.; Dai, Z. R.; Wang, Z. L. *Science* **2001**, *291*, 1947.
- (22) Wang, X. D.; Song, J. H.; Liu, J.; Wang, Z. L. *Nano Lett.* **2007**, *7*, 2475.
- (23) Gao, Y. F.; Wang, Z. L. Unpublished data.
- (24) The response of the trigger/sensor has two components: the response of the PFW itself, and the response of the electronic measurement system used in the experiments. To remove the response of the measurement system, we have applied a standard square wave to the electronic system; from the deconvolution of the output signal with the input signal, the response function of the measurement system was received. Then, the response of the PFW was received by deconvoluting the response function of the measurement system from the raw data displayed in Figure 2c.
- (25) Liu, J.; Fei, P.; Song, J. H.; Wang, X. D.; Lao, C. S.; Tummala, R.; Wang, Z. L. *Nano Lett.* **2008**, *8*, 328.
- (26) He, R. R.; Yang, P. D. *Nat. Nanotechnol.* **2006**, *1*, 42.
- (27) Chung, K. W.; Wang, Z.; Costa, J. C.; Williamson, F.; Ruden, P. P.; Nathan, M. I. *Appl. Phys. Lett.* **1991**, *59*, 1191.

NL8010484