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Characteristics of output voltage and current of integrated nanogenerators

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Owing to the anisotropic property and small output signals of the piezoelectric nanogenerators (NGs) and the influence of the measurement system and environment, identification of the true signal generated by the NG is critical. We have developed three criteria: Schottky behavior test, switching-polarity tests, and linear superposition of current and voltage tests. The 11 tests can effectively rule out the system artifacts, whose sign does not change with the switching measurement polarity, and random signals, which might change signs but cannot consistently add up or cancel out under designed connection configurations. This study establishes the standards for designing and scale up of integrated nanogenerators. © 2009 American Institute of Physics. [DOI: 10.1063/1.3072362]

Harvesting energy from environment is important for an independent, wireless, and sustainable operation of nanodevices.¹ This is a critical step toward self-powered nanosystems. We have developed a nanogenerator (NG) that utilizes piezoelectric nanowires for converting mechanical energy into electricity.²⁻⁵ The NG takes advantage of the piezoelectric and semiconducting coupled properties of ZnO nanowires. The piezoelectric effect converts mechanical strain into ionic polarization charges that generate a piezoelectric potential; the Schottky barrier at the interface between the electrode and the nanowires gates and directs the flow of electrons under the driving of the piezoelectric potential. We have demonstrated several approaches for the NGs, one of which is the single-wire generator (SWG).⁶

The SWG consists of a single ZnO microwire/nanowire lying on a flexible substrate, with its two ends firmly fixed by metal contacts. Bending of the substrate results in stretching or compression of the microwire and develops a piezoelectric-potential drop along the microwire. A Schottky contact at one end is required to prevent the flow of electrons through the microwire and enables the deformed wire to be a “charge pump” and a “capacitor.” The charging and discharging process when the ZnO microwire is stretched and released creates an oscillating electric current in the external load. The working mechanism has been presented in detail in Ref. 6, which is the prior work of the current paper.

The output of the SWG may be affected by the measurement system, change in capacitance of the microwire, and electric circuit during mechanical deformation, and the coupling of the SWG with the measurement system; it is thus easy to observe false signals. To differentiate the electric power that is generated by the SWG from possible artifacts, we have developed three criteria consisting of 11 tests to rule out artifacts. The generator must satisfy not only the Schottky behavior test (1) and switching polarity tests (2) but also a linear superposition of current and voltage for eight configurations as well. A true signal (current and voltage)

generated from a generator must pass each and all of the tests. Those criteria and configurations are applicable to all types of NGs and can serve as standard tests for general purpose.

A piezoelectric fine wire (PFW) was placed laterally on a Kapton polyimide film [Fig. 1(a)]. Because the film thickness is much greater than the diameter of the ZnO PFW, the ZnO PFW experiences a pure tensile strain when the substrate is bent inward, as shown in Fig. 1(b). The transport property of a working device, which generates good electricity output, always shows asymmetric behavior, as shown in Figs. 1(c) and 1(d) for two different SWGs. The nonlinear Schottky-like transport behavior is a necessity for a working NG. The asymmetric characteristic of Schottky barrier divides each cycle of driving action into two steps, charge accumulation and charge release, resulting in an electric output pulse. In the case of SWG, the Schottky contact serves as a one-way gate to prevent the flow of electrons through the microwire such that the electric power can be effectively outputted. Without the presence of the Schottky barrier, there will be no charge accumulation, thus, no charge release. This criterion can easily eliminate those defective devices which

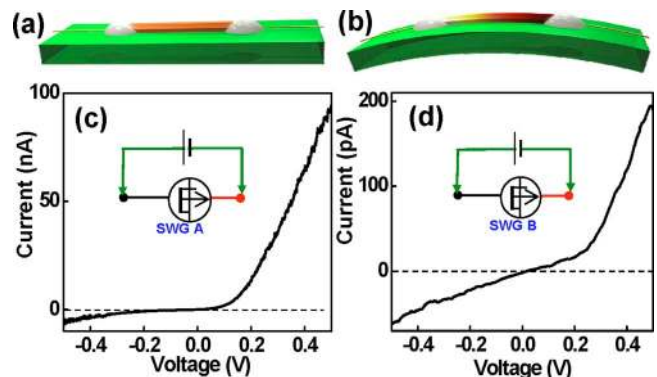


FIG. 1. (Color online) (a) A PFW lying on a polymer Kapton film substrate with two ends tightly bonded to the substrate. The leading wires connect to the measuring instrument. (b) Bending of the substrate results in the axial tensile strain and corresponding piezoelectric potential drop along the PFW. [(c) and (d)] I - V characteristic of SWG A and SWG B, respectively, which will be used for the studies presented in Figs. 2-4.

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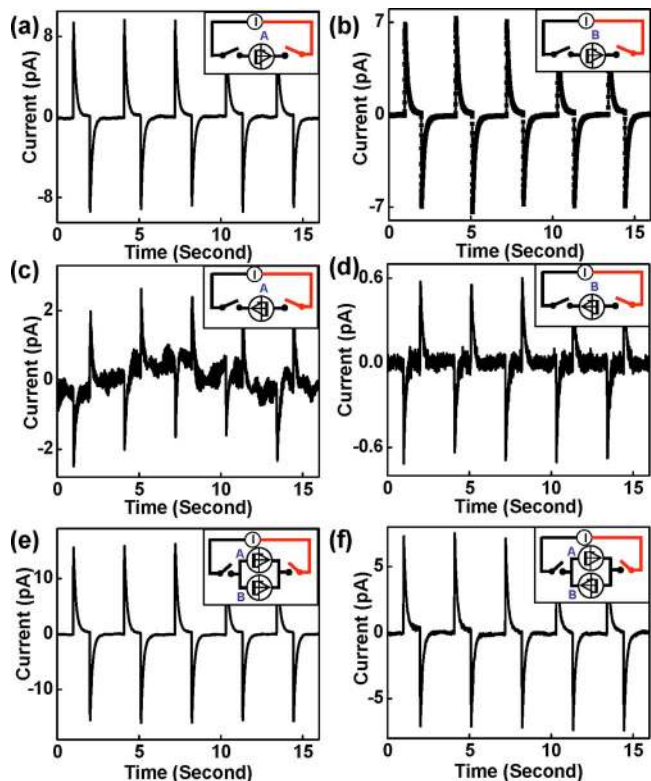


FIG. 2. (Color online) [(a) and (b)] Short-circuit current power output from SWG A and SWG B, respectively, under forward connection. [(c) and (d)] Short-circuit current power output from SWG A and SWG B, respectively, under reverse connection. [(e) and (f)] Parallel connection of SWG A and SWG B demonstrates SWG's ability to "add up" or "cancel out." All insets illustrate the connection configuration of the two SWGs in reference to the measurement system.

will not be able to harvest energy from the environment. A symbol has been created as shown in the insets of Figs. 1(c) and 1(d) to represent the SWG. For easy notation, we define the side that has a Schottky contact as the positive side. This will be referenced in the following tests.

For the short-circuit current measurement, we first measured the forward connection, in which the positive probe and negative probe of the measurement system are connected to the positive and negative ends of the generator, respectively. Figures 2(a) and 2(b) show the results for SWG A and SWG B. The insets give the connection configurations. The positive peaks correspond to the stretching states of the PFW when the underneath substrate is bent inward. When the substrate is released, the PFW returns to free state, resulting in a negative electric peak. The mechanism about the creation of the signal has been reported elsewhere.

In order to identify if the signal is the true electricity output due to piezoelectric property of the ZnO fine wire, we did the switching-polarity test, in which the positive and negative probes of the current meter are connected to the negative and positive ends of the SWG, respectively. The result is given in Figs. 2(c) and 2(d). The output signal is the reversal of that presented in Figs. 2(a) and 2(b). Stretching of the PFW produces a negative pulse, and a positive pulse is generated when released. The satisfaction of the switching-polarity test rules out the possible error from the system capacitor change. The change in contact resistance might produce a signal when the SWG is deformed, but such signal will not change its sign from positive to negative when the connection is reversed. Additionally, we also notice the mag-

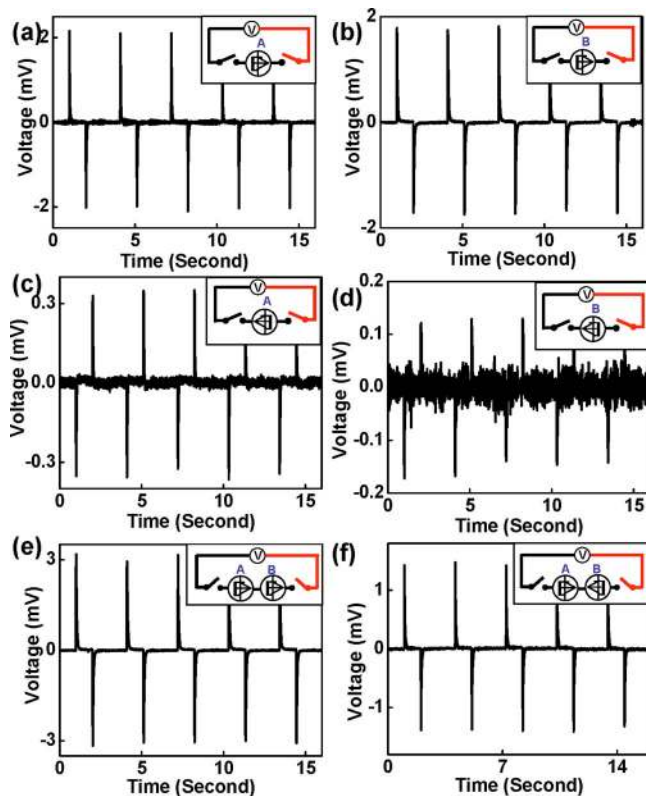


FIG. 3. (Color online) [(a) and (b)] Open-circuit voltage output from SWG A and SWG B, respectively, under forward connection. [(c) and (d)] Open-circuit voltage power output from SWG A and SWG B, respectively, under reversal connection. [(e) and (f)] Serial connection of SWG A and SWG B demonstrates the add up or cancel out effect. All insets illustrate the connection configurations of the SWGs in reference to the measurement system.

nitude difference between the signals with forward connection and with the reverse connection. The nonsymmetric output of the SWG prior and after switching the polarity is likely caused by the measurement system that has a bias current. If this bias current adds up to the current generated by the SWG at forward connection configuration, it will be subtracted from the generated current at reversely connected configuration. The true signal generated by the SWG is an average of the magnitudes observed under forward and reverse connection configurations.

Due to the presence of Schottky at one end of the SWG, the switching-polarity test is not sufficient to rule out some of the artifacts. The linear superposition is thus applied. We did the current measurement when two SWGs were connected in parallel to examine the linear superposition of currents. Since there is a Schottky contact at one end of the SWG, we need to pay attention to their connection direction. Figure 2(e) presents the result when two SWGs are in the same direction, in which output current is enhanced and approximately equal to the sum of signal from Figs. 2(a) and 2(b). In comparison, when two SWGs were connected in reversed directions as shown in Fig. 2(f), the output current is decreased and approximately equal to the sum of the signal from Figs. 1(a) and 1(d). As a result, a linear superposition of current is satisfied for the two SWGs. In addition, the parallel connection of the two SWGs also satisfies the switching-polarity test.

The voltage output of the SWGs is presented in Fig. 3. SWG A and SWG B generate a positive voltage signal when

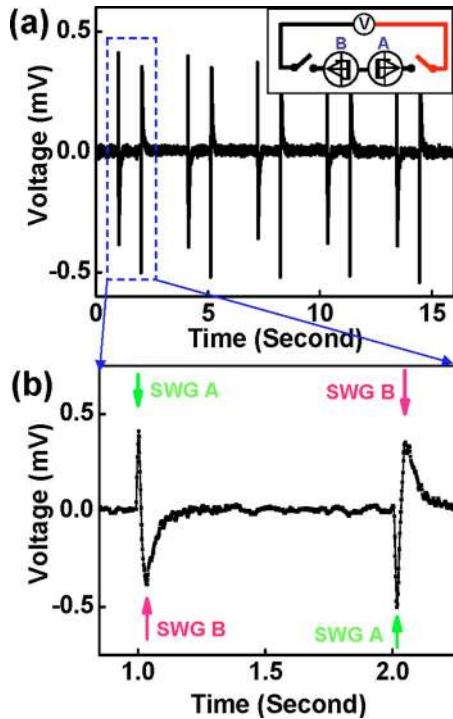


FIG. 4. (Color online) (a) Voltage output of two reversely connected SWGs in serial when the deformation of the two were slightly off synchronization. The inset illustrates the connection configuration of the SWGs. (b) An expanded output of two double peaks in (a) to illustrate the sharp switch in output voltage.

the PFWs are stretched and a negative signal when the PFWs are released, as shown in Figs. 3(a) and 3(b). The switching polarity is also satisfied for output voltage, as shown in Figs. 3(c) and 3(d). In order to testify the signal and further characterize the generator, it is necessary to measure the voltage when the two SWGs are in serial, as shown in Figs. 3(e) and 3(f). When two SWGs are connected in the same direction, the final output is apparently increased. In comparison, when two SWGs are connected in opposite directions, the final output is reduced. As a result, the superposition of voltage is also satisfied for those two SWGs. Further more, the SWGs connected in serial also satisfy switching-polarity test.

In order to observe the superposition phenomena, two SWGs must be deformed and released simultaneously. In a case that there is a slight delay in the deformation, the distinct outputs of the two SWGs are revealed. Figure 4(a) shows a case where two SWGs are being oppositely connected in serial. A pair of positive-negative peaks is observed one following immediately the other when PFWs are stretched or released. The double peaks that are opposite in sign and one closely following the other correspond to the signals from two SWGs, respectively [Fig. 4(b)]. Before the bending of SWG A is completed, bending of SWG B starts, which results in a negative peak in the first double peak owing to its reversal connection. Similarly, before the releasing of SWG A is completed, the release of SWG B starts, which results in a positive peak due to its reversal connection. The two positive-negative peaks in Fig. 4 further confirmed that the generated voltages satisfy the linear superposition rule, and any discharge artifacts, if any, cannot generate signal as presented in Fig. 4(b).

TABLE I. Summary of current and voltage output when the SWG A and SWG B were connected under various configurations illustrated in Figs. 2 and 3.

	Current (pA)		Voltage (mV)	
	Forward connection	Reverse connection	Forward connection	Reverse connection
SWG A	9.54	-2.42	2.13	-0.36
SWG B	7.31	-0.7	1.81	-0.15
SWG A+SWG B	16.2	-3.76	3.18	-0.37
SWG A-SWG B	7.33	4.65	1.46	1.5

By taking the average value from the output signals when the SWGs are bent, the output current and voltage for Figs. 2 and 3 are tabulated in Table I. In order to simplify the discussion, we define V_A^+ and I_A^+ as the voltage and current measured from SWG A under forward connection, and V_A^- and I_A^- when reversely connected. The same definitions apply to SWG B. In an ideal case, we should have $V_A^- = -V_A^+$ and $I_A^- = -I_A^+$. However, with consideration of the contribution from the bias current from the measurement system, the measured voltage/current may not have the same magnitude. In any case, a true electricity output from an SWG must change its sign when the SWG is reversely connected. The first two rows in Table I fully support that the SWG A and SWG B satisfy the first criteria of switching-polarity test for both output current and voltage.

The last two rows in Table I demonstrate the second criteria of linear superposition of current and voltage under eight connection configurations. When the SWG A and SWG B are connected in parallel, as shown in the insets in Figs. 2(e) and 2(f), the measured currents (last two rows in Current columns) obey the following requirements:

$$I_{A+B}^+ = I_A^+ + I_B^+, \quad I_{A+B}^- = I_A^- + I_B^-, \quad I_{A-B}^+ = I_A^+ + I_B^-, \\ I_{A-B}^- = I_A^- + I_B^+.$$

When the SWG A and SWG B are connected in series, as shown in the insets in Figs. 3(e) and 3(f), the measured voltage (last rows in voltage columns) obey the following requirements:

$$V_{A+B}^+ = V_A^+ + V_B^+, \quad V_{A+B}^- = V_A^- + V_B^-, \quad V_{A-B}^+ = V_A^+ + V_B^-, \\ V_{A-B}^- = V_A^- + V_B^+.$$

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