Nano Energy (∎∎∎∎) ∎, ∎∎∎–∎∎∎

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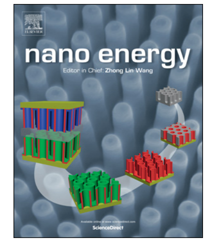

Recent progress in piezoelectric nanogenerators as a sustainable power source in self-powered systems and active sensors

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Received 14 October 2014; accepted 7 November 2014

KEYWORDS
Piezoelectric nanogenerator;
Sandwich structure;
Self-powered systems;
Active sensors

Abstract
Mechanical energy sources are abundant in our living environment, such as body motion, vehicle transportation, engine vibrations and breezy wind, which have been underestimated in many cases. They could be converted into electrical energy and utilized for many purposes, including driving small electronic devices or even constructing an integrated system operated without bulky batteries and power cables. Many progresses have been made recently in the mechanical energy harvesting technology based on piezoelectric nanogenerators (PENGs). By introducing a new sandwich structure design, high performance PENGs can be achieved through very simple fabrication process with good mechanical stability by utilizing ZnO nanowires (NWs). By further optimizing the nanomaterials' properties and device structure, the PENG's open circuit (OC) voltage can be elevated to over 37 V. Two important applications of this technology are that the nanogenerator can be used as a sustainable power source for self-powered system and can worked as active sensors. Several demonstrations are reviewed here. Finally, perspectives of this mechanical energy harvesting technology are discussed. Co-operation with power management circuit, capability of integrating with a system, and low cost large-scale manufacturing processing are suggested to be the key points toward commercialization of PENGs.

Introduction

The development of technology brings us a smarter world, and also makes us to be more dependent on electronic equipment. As the size and power consumption shrinks day by day, harvesting energy from the working environment to power

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http://dx.doi.org/10.1016/j.nanoen.2014.11.038
2211-2855/

Please cite this article as: Y. Hu, Z.L. Wang, Recent progress in piezoelectric nanogenerators as a sustainable power source in self-powered systems and active sensors, Nano Energy (2015), http://dx.doi.org/10.1016/j.nanoen.2014.11.038

electronic devices is a promising way. It is especially feasible for the applications in sensor networks and personal consumer electronics, which can extend their capability by getting rid of batteries and power cables. There are many kinds of energy sources in the environment, such as mechanical energy, thermal energy, chemical energy, solar energy, nuclear energy, *etc.*, which are all represented in various forms, as shown in Figure 1. Distinguished from others, mechanical energy is the one that is available almost everywhere and at all the time. It can come from gentle airflow, ambient noise, vibration, human body activity, *etc.*, which is suitable for the purpose we mentioned above. But, the amplitude and frequency of the mechanical energy source in the environment are usually random. That means we need to find a proper energy harvesting approach that has a tolerance for variable environments which is differ from the traditional cantilever based resonators [1] and [2] and electromagnetic induction based electrical generator [3] and [4]. The technology of piezoelectric nanogenerator (PENG) [5] was first proposed in 2006. It converts random mechanical energy into electric energy by using piezoelectric ZnO nanowires (NWs), which can be triggered by tiny physical motions and work in a large frequency range. Also ZnO is non-toxic and biocompatible, which is very critical for the sustainable energy technology used in our living environment. At the very beginning, we are more focused on the science behind the phenomenon [6-10], and it took a long journey to bring this technology from a scientific concept to a practical technology. For example, it took 4 years to raise the open circuit (OC) voltage from the original 9 mV to over 1 V [11-14]. Even so, the sophisticated device fabrication process sets up a barrier for the further development of this technology. Recently, new device design based on a sandwich structure was proposed, by which high performance PENG can be achieved with greatly simplified fabrication process and high mechanical stability by utilizing ZnO NWs. we will review two representative sandwich structure device designs and compare the working mechanism with previous devices based on Schottky contact structure. One very important application of the PENGs is that they can be used to construct self-powered systems, which harvest energy from the working environment and convert it into electricity to realize maintenance-free and sustainable operation of the system. PENGs can also work as active sensors. It is triggered by the mechanical deformation from the environment, and an electrical signal will be generated. That means no extra power source is needed here at least for the sensor tip [15]. In this review, several demonstrations of self-powered systems and active sensors by integrating PENGs will be illustrated. At the end, perspectives of this mechanical energy harvesting technology are discussed.

High output PENGs with new design

Sandwich structure vs. the Schottky contact structure in PENGs

At the early stage, the Schottky contact formed at the metal-ZnO interface is considered to play an important role on the output performance of PENGs [5], [9], [10] and [13]. In such a device design, two metal-semiconductor contacts form at the

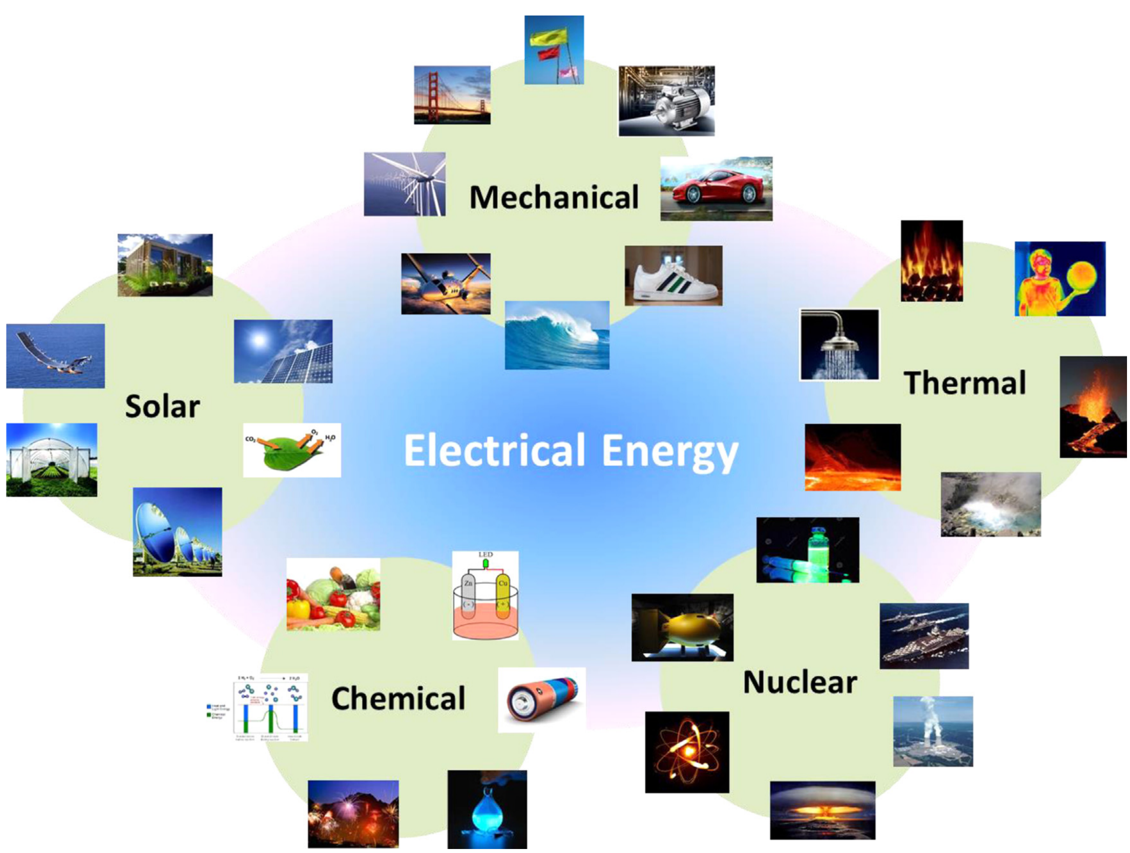

Fig. 1 Various available energy sources in the environment and their representative forms.

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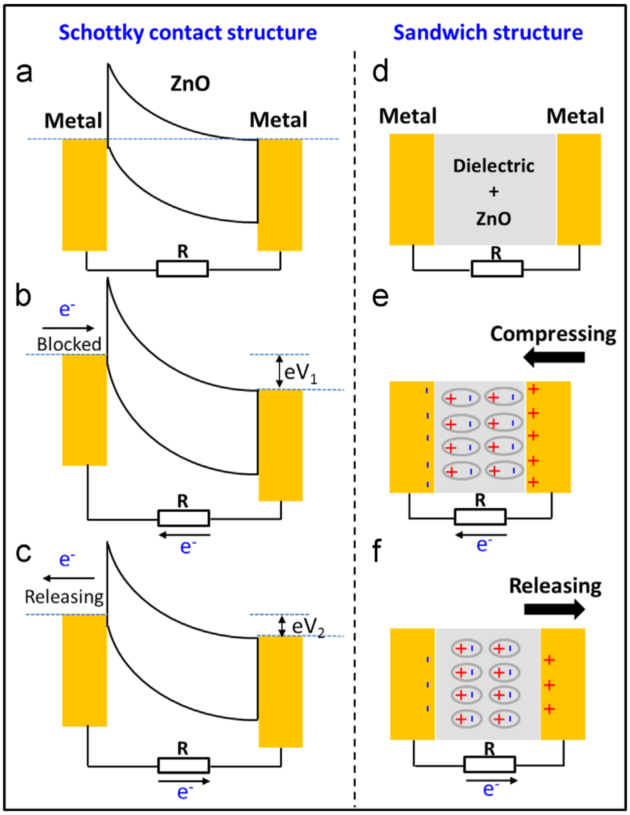

Fig. 2 Comparison of working mechanism between PENG based on Schottky contact structure (a)–(c) and sandwich structure (d)–(f).

two ends of a ZnO NW. By choosing metals with appropriate work functions, PENGs are constructed to form a Schottky contact at one end, and an ohmic contact at the other end, as shown in Figure 2(a). When the ZnO NW experiences mechanical deformation, the introduced piezoelectric potential in the NW changes the relative positions of Fermi levels in two metal electrodes, and electrons flow from the right electrode to the left electrode through the external circuit, as shown in Figure 2(b). They will be blocked by the Schottky barrier at the left contact area, and accumulated in ZnO near the interface. When the mechanical deformation is released, the difference between two Fermi levels vanishes, and the accumulated electrons will flow back to the right electrode through the external circuit, as shown in Figure 2(c). In each deforming-releasing cycle, a positive and a negative current pulse will be detected. The integral areas under these two peaks should be the same, which represent the charges transferred between two electrodes during these two processes. For this device design, the first issue needed to be handled is to produce a stable and reproducible Schottky contact at the metal–ZnO interface. As we know that, the Schottky barrier formed at a metal-semiconductor interface depends not only on the work function difference between these two materials, but also determined by the interface states. Sometimes, the later one even dominates. And, the Schottky barrier is sensitive to the surrounding environment, like the atmosphere, humidity, *etc*. So it is hard to get stable, reproducible and uniform Schottky contacts at different metal–ZnO interfaces. This will be a problem if we consider the uniformity between different devices, or when arrays of NWs are integrated to work together in one device. Secondly, there is a hard contact formed between the nanowire and the electrode. The mechanical stability under repeated deformation would be a problem in practical applications. Thirdly, when we try to improve the output performance of PENG by integrating arrays of nanowires working together in such a device design, the fabrication process becomes more and more complicated, which is not acceptable for the mass production [12] and [14].

Considering all of the issues we mentioned above, a new device design is needed to push this technology moving forward. In 2010, PENGs based on a sandwich structure were introduced [16]. For such a new design, the key point is that well organized ZnO NWs are mixed with dielectric, and sandwiched between two electrodes, as shown in Figure 2(d). When the structure is compressed, the strain on ZnO NWs introduces aligned electric dipole moments in the dielectric matrix. In response, electrons transfer between two electrodes as induced charges to screen the built-in electric field, as shown in Figure 2(e). When the strain is released, the electric dipole moments vanish, and electrons flow back, as sketched in Figure 2(f).

Representative device designs

The first example of the sandwich structure based PENG is shown in Figure 3 [16]. When checking the morphology of NWs grown by the vapor phase deposition method, we find that under certain growth conditions, the diameter of a ZnO NW can be changed uniformly along its growing direction, forming a conical shape. Figure 3(a) shows a conical shaped ZnO NW is dispersed on a flat silicon substrate surface. The white arrow indicates the *c* axis orientation of the nanowire, and its conical angle is measured to be 0.87°. In order to take advantage of this special morphology characteristic, the PENG is constructed in the following way. The ZnO and dielectric mix is formed by spin-coating of a thin polymethyl methacrylate (PMMA) layer (100 nm) and dropping-on ZnO conical shaped NW solution alternately several times on a Kapton film substrate, and is sandwiched between two Cr/Au films, as sketched in Figure 3 (b). In each layer, the conical shaped NWs were fairly uniformly distributed with their lateral orientations random and bottom surface paralleled. The working mechanism is revealed in Figure 3(c). A pair of conical shaped NWs with opposite *c* axes is put in a PMMA matrix to represent the random distribution of NWs in each layer. When a mechanical deformation is applied, a very high piezopotential is generated in the NW, and an induced electric potential difference is obtained between top and bottom electrodes. The conical shape plays an important role here. The *c* axis orientation in each NW can be divided into two components: the one parallel to the substrate surface and the one perpendicular to the substrate surface. The parallel components will be canceled with each other due to the random distribution of NWs in each layer. While the perpendicular components will be added up all through the NWs. So the conical shaped ZnO NWs and PMMA mix can be regarded as a piezoelectric bulk with an effective *c* axis orientated vertically to the substrate surface. The potential difference built up between two electrodes is proportional to the thickness projected density of NWs. At the density of 7500 NWs/cm^2,

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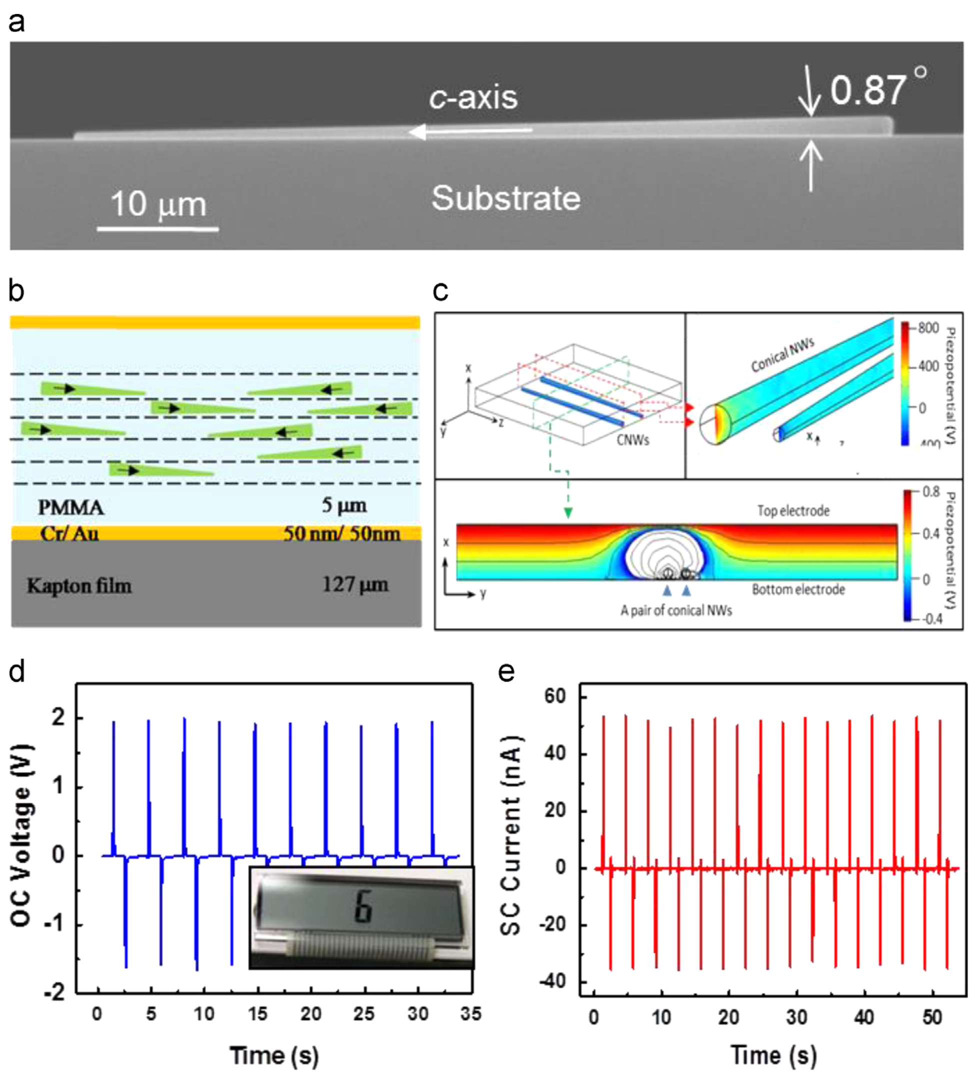

Fig. 3 The sandwich structure based PENG with rational unipolar assembly of conical shaped ZnO NWs in PMMA dielectric matrix. (a) A cross-section view SEM image of a conical shaped NW on a flat substrate. (b) The schematic diagram showing the device structure. (c) The model used for working mechanism simulation and the calculated potential distribution across the top and bottom electrodes of the PENG under deformation. (d) and (e) Measured OC voltage and SC current of the PENG. Inset of (d) is the picture of a LCD screen driven by a PENG [16].

under a compressive strain of 0.11% at a straining rate of 3.67% s^{-1}, the measured OC voltage reached 2 V, and the short-circuit (SC) current exceeded 50 nA, as shown in Figure 3(d) and (e). Based on such a good performance, an LCD screen taken from a calculator can be continuously lighted up by the PENG, as shown by the insert picture of Figure 3(d). Similar device design has also been realized on conical shaped GaN NWs [17].

Another representative sandwich structure device design is shown in Figure 4(a) [18]. First, densely packed ZnO NWs were grown on a polyester (PS) substrate's top and bottom surfaces by the hydrothermal method. Then, a thin layer of PMMA was spin coated on ZnO NW arrays to make insulating, followed by a Cr/Au layer deposition serving as the electrode of the PENG. Finally, the whole device was fully packaged with polydimethylsiloxane (PDMS) to enhance the mechanical stability. The left part in Figure 4(b) shows a scanning electron microscope (SEM) image of the cross-section view of the as grown NWs on PS substrate. The NW arrays were grown vertically from the substrate with a diameter about 150 nm, and a length around 2 μm. The NWs' bottom surfaces are connected through the ZnO seed layer, while their top surfaces are also bonded together to form a film. Thus, the whole ZnO structure could be regarded as a textured film that consisted of fully packed ZnO NW arrays between two parallel ZnO films. The right part in Figure 4 (b) shows pictures of a real device. When the device is bended, the textured film on the substrate's top surface will be stretched, while the textured film on the bottom surface will be compressed. According to the *c* axes, orientations of ZnO textured films are determined by the growth process, as indicated by the arrows in Figure 4(a), the calculated potentials distribution in the device is displayed in Figure 4 (d), and the potential differences across the top and bottom electrodes are enlarged in Figure 4(c) and (e). Induced charges will be introduced in the two electrodes to screen the built-in electric field generated by piezoelectric material in the dielectric matrix under strain. When the PENG was strained to 0.12% at a strain rate of 3.56% s^{-1}, the

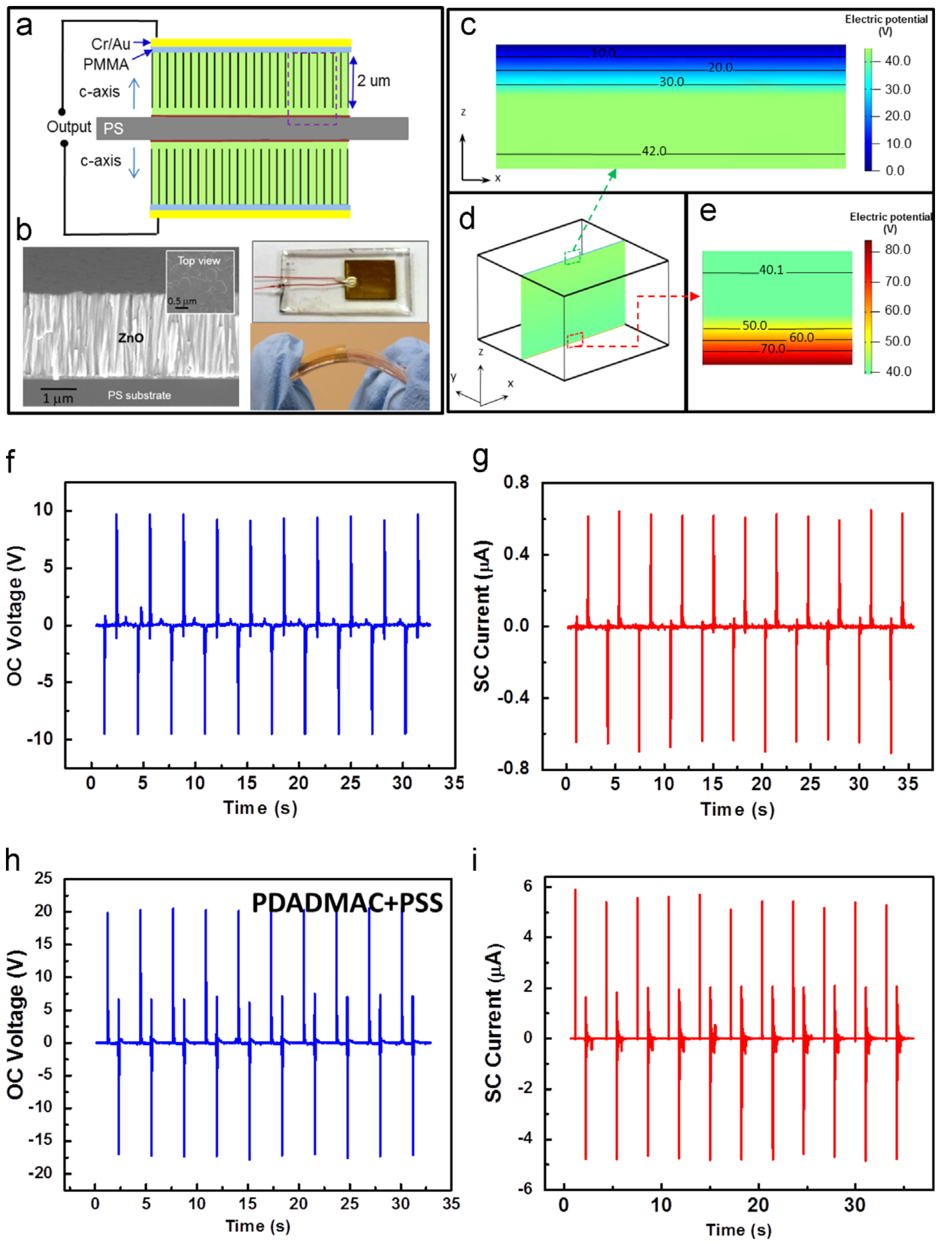

Fig. 4 The sandwich structure based PENGs with ZnO NW textured films on a PS substrate's top and bottom surfaces. (a) Schematic diagram showing the device structure. (b) Left: Cross section SEM image of the as-grown nanowire textured film on the substrate. The insert is the top view of the nanowire film. Right: Photos of a fabricated PENG after packaging and its flexibility under bending. (d) The model used for working mechanism simulation and the calculated potential distribution across the (c) top electrode and (e) bottom electrode under deformation. (f) and (g) Measured OC voltage and SC current of the PENG. (h) and (i) Measured OC voltage and SC current of the PENG after passivated with PDAMAC and PSS [18] and [20].

measured OC voltage reached 10 V, and the SC current exceeded 0.6 μA, as shown in Figure 4(f) and (g).

Optimization

Optimizing the materials' properties can improve PENGs' performance. According to former results [9] and [19], a higher carrier density in ZnO NWs will result in a lower OC voltage and SC current. The PENGs' performance can be improved by pretreatment of the ZnO NWs to reduce conductivity by oxygen plasma, annealing in air, and surface passivation with certain polymers [20]. The most effective way we got is passivating the NWs' surfaces with positively charged poly (diallydimethylammonium chloride) (PDADMAC) and negative charged poly (sodium 4-styrenesulfonate) (PSS) in sequent, which may eliminate the oxygen vacancies and introducing a depletion layer at the ZnO NWs' surface. After passivation, the OC voltage reached 20 V, and the SC current exceeded 6 μA, as shown in Figure 4(h) and (i).

The device design was further optimized for higher output performance and to be more compatible with batch fabrication techniques for easier scale up [21]. First, a silicon substrate was consecutively deposited with an ITO layer

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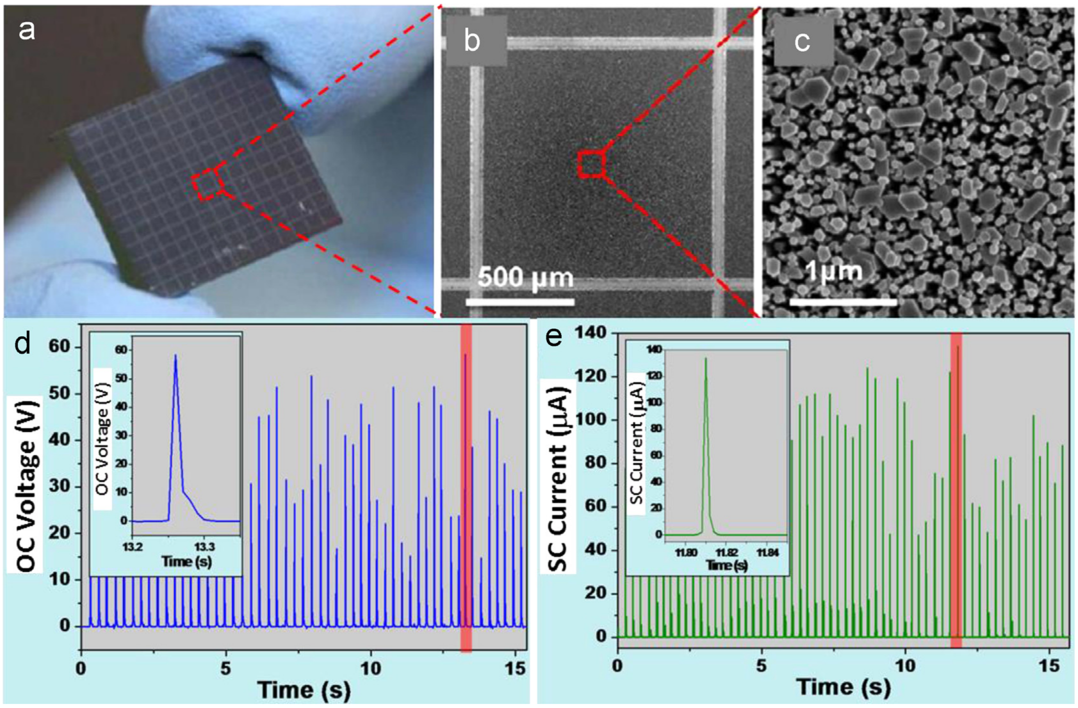

Fig. 5 PENGs with optimized device design for easy scale up. (a) Picture of the real device. Position-controlled ZnO NWs were grown on a silicon substrate. SEM image of (a) one segment on the substrate and (c) corresponding enlarged top view. (d) OC voltage and (e) SC current of nine nanogenerators connected in parallel [21].

and a ZnO seed layer. This ITO layer works as the bottom electrode in the PENG. By the hydrothermal method, ZnO NWs were grown on exposed seed layer surface on silicon, which is an array of square windows with narrow spacing in between opened by photolithography on photoresist. Then, the NWs were thermally annealed, and covered by a layer of PMMA. Finally, a layer of aluminum was deposited as the top electrode, and the whole device was packaged with another layer of PMMA. Figure 5(a) is a picture of the device. It shows well-defined segments on the silicon substrate. Each segment contains densely grown vertically aligned ZnO NW arrays, as shown in Figure 5(b) and (c). By using a rigid substrate and the PMMA as a capping layer, when a force is applied along the vertical direction, the stress can be transferred to the ZnO NWs more efficient. For a NG with an effective dimension of 1 cm by 1 cm by 10 μm occupied by ZnO NWs, the OC voltage and the SC current reached up to 37 V and 12 μA under a stress of 1 MPa, respectively. The output performance can be further scaled up by linear superposition. Under impact by a human palm, the peak value of open-circuit voltage and the short-circuit current of nine nanogenerators connected in parallel exceeded 58 V and 134 μA, respectively (Figure 5(d) and (e)).

It should be mentioned that, here, PMMA works not only as the dielectric material to make insulating, but also as the medium to transfer mechanical deformation from external source to the piezoelectric materials. It should have proper mechanical properties to match ZnO for effective mechanical deformation transfer. Researchers carried out simulations to replace PMMA with different materials, and optimized the device design by using different geometry [22] and [23]. It shows that there are still rooms for devices' output performance optimization.

From these device designs represented above we can see that the piezoelectric materials are enclosed by polymer and no hard electric contacts are needed between NWs and metal electrodes, which can produce robust PENGs with high mechanical stability. Also these characteristics make the fabrication process greatly simplified, which is likely to be adaptable for industrial mass production. So far, this new device design based on sandwich structure has been well adopted by researchers in this field [24-27].

Applications in self-powered systems and active sensors

A self-powered system with wireless data transmission for photon detecting

When the research of PENG technology started, one original idea proposed is to construct a self-powered system [5]. For such a system, generally several modules with different functions are included, such as energy harvester module, energy storage module, sensors, data processor and controller module, data transmitter and receiver module, *etc.*, as shown in Figure 6(a). The system can harvest energy from its working environment and store it. Then the energy is used to power sensors, process the detected signal, transmit the information out, and make response. A prototype self-powered system is demonstrated by integrating a PENG as mechanical energy harvester, a capacitor for storing the energy, an infrared photodetector as sensor, and a wireless data transmitter for signal transmission, which is sketched in Figure 6(b) and diagramed in Figure 6(c). The photodetector is a NPN silicon phototransistor with an infrared

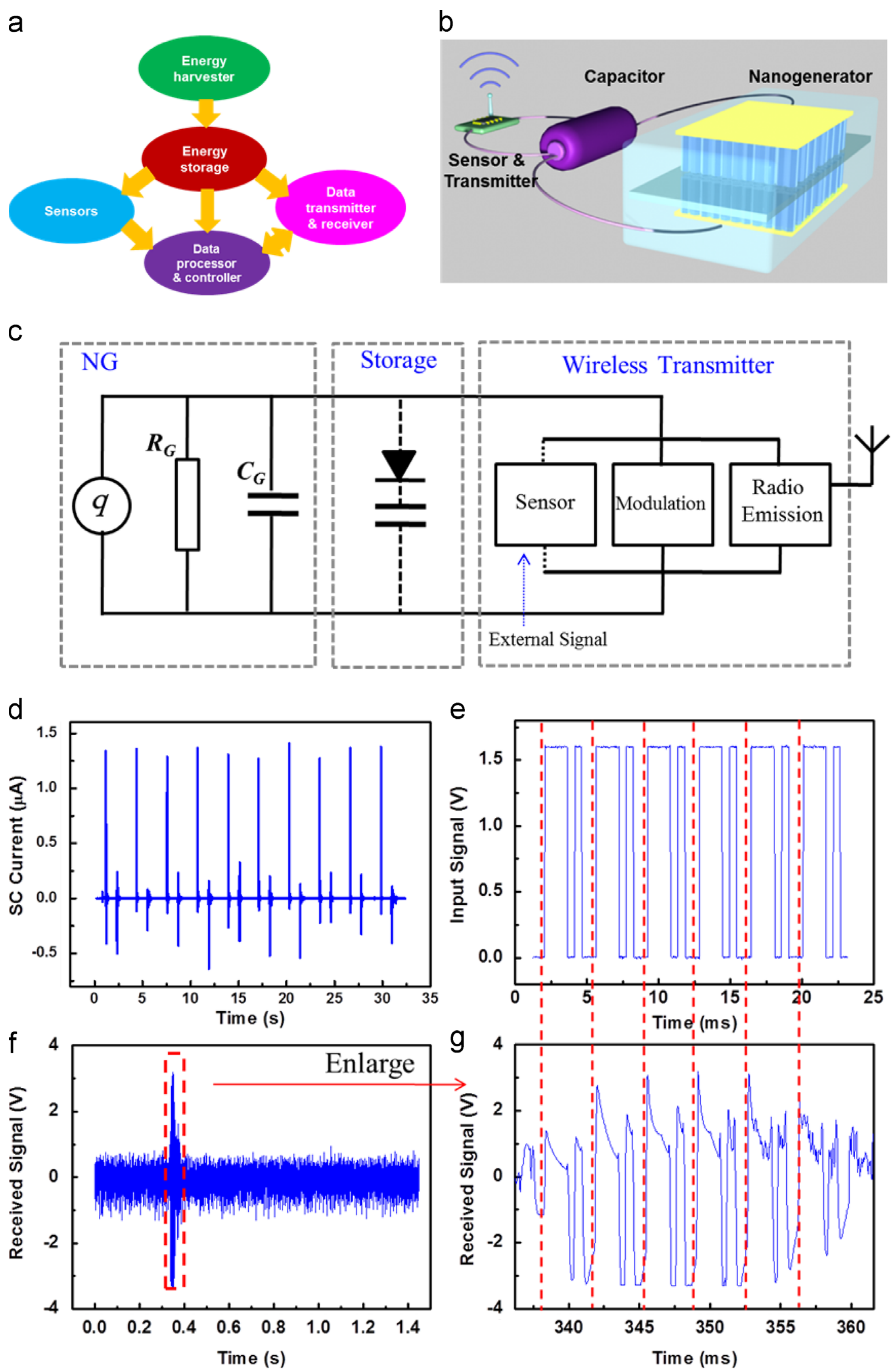

Fig. 6 Self-powered system with wireless data transmission for photon detecting. (a) Schematic diagram of the integrated self-powered system. (b) The prototype of an integrated self-powered system by using a PENG as the mechanical energy harvester. (c) Schematic diagram of the designed self-powered system. (d) Performance of the PENG used in the test. (e) The voltage sequence used to trigger the LED. (f) Recorded signal from the headphone jack of the radio. (g) Enlargement of the pulse in (f) [18].

light-emitting diode (LED) mounted 4 mm away in a slotted optical switch (OPB 825, OPTEK Technology). Figure 6 (d) shows the PENG's performance used in this demonstration. The LED was triggered with a programmed voltage sequence to shine light onto the phototransistor as an external signal to be detected. The phototransistor and transmitter were periodically triggered by using the energy stored in the capacitor. Each time, the signal transmitted out was modulated by the photocurrent generated by the phototransistor. The transmitted wireless signal was

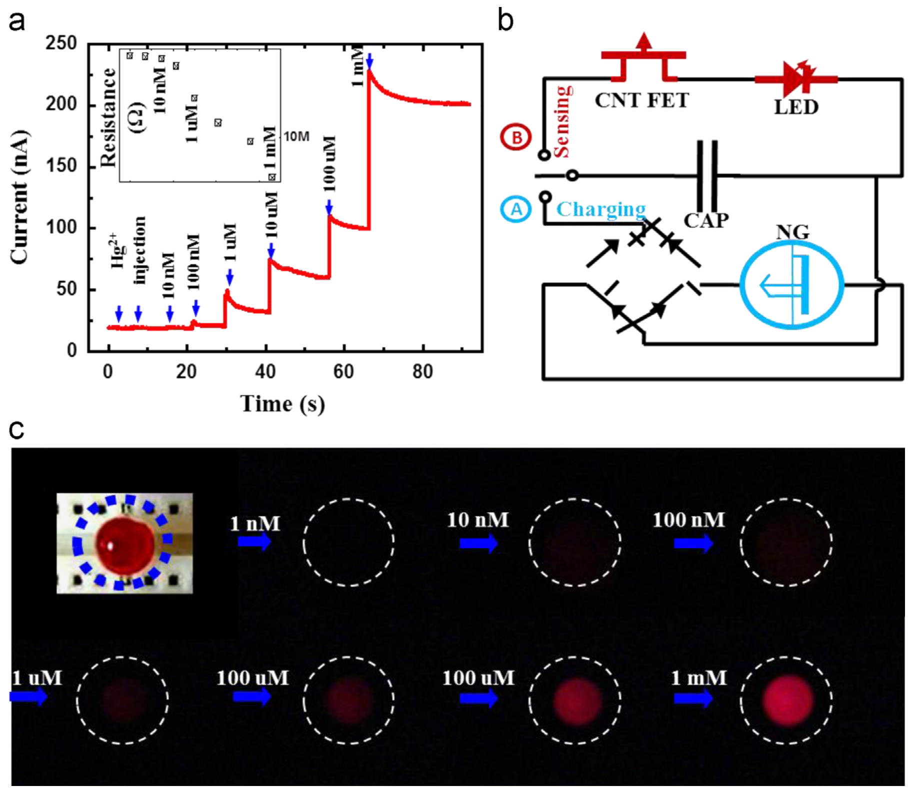

Fig. 7 A self-powered system for environmental monitoring. (a) Sensing behavior of the detector with different Hg^{2+} ions concentrations in water solution. The inset shows the plot of resistance changing corresponding to different Hg^{2+} ions concentrations. (b) Circuit diagram of the self-powered system, including PENG, rectifying bridge, capacitor, SWNT FET based Hg2+ detector, and LED. (c) Serial images of a LED representing intensity changes due to resistance changes in the detector depending on the concentration of Hg^{2+} ions in water solution [28].

received by a commercial portable AM/FM radio, and the demodulated signal was recorded from the headphone jack. The voltage sequence used to trigger the LED is shown in Figure 6(e). Figure 6(f) shows the recorded signal from headphone jack, and the peak from the background is enlarged in Figure 6(g). It has the same waveform envelope as the triggering voltage sequence of the LED. It indicates that we realized a self-powered system with wireless data transmission capability for photon detecting.

A self-powered system for environmental monitoring

Another application for the high output performance PENG we have demonstrated is the self-powered system for environmental monitoring, which can detect Hg^{2+} ions and indicate their concentration via the emitting intensity of an LED [28]. In this system, a field effect transistor (FET) based on a single-walled carbon nanotube (SWNT) served as the Hg^{2+} sensor. First, when water droplets with various concentrations of Hg^{2+} ions were dropped on, the source-drain current of the FET was recorded to characterize the sensing behaviors. Figure 7(a) shows the change of measured current and sensor's resistance at different concentrations. Initially, we chose the SWNT FET to work in enhancement mode, and a current less than 10^{-8} A was observed. When the concentration of Hg^{2+} ions in solution reached about 10 nM, which is the allowable limit of Hg^{2+} ions in drinking water set by most government environmental protection agencies, a noticeable change of resistance appeared. The circuits we constructed for the self-powered system are depicted in Figure 7(b). It is composed of a PENG, rectifying bridge, capacitor, Hg^{2+} detector, and a LED as an indicator. The circuit was designed with two independent loops. In the energy-harvesting process, the circuit was switched to loop 'A' (Figure 7(b)) with PENG and rectifying bridge to store generated charges in the capacitor. After a sufficient charging period, the connection was switched to loop 'B'. The sensor was powered to detect Hg^{2+} ions and an LED was lit up with the emission intensity depending on the concentration of pollutants in the water droplet. Figure 7(c) shows serial images of a LED lit up under various concentrations of Hg^{2+} ions. A noticeable LED light was recorded starting from the 10 nM concentration, and it got brighter gradually to a concentration of 1 mM. As a proof of concept, we demonstrated an environmental sensor circuit fully powered by PENGs which also can give us the result of detection simultaneously without any supporting equipment.

Active sensors for vehicle monitoring

PENGs can also work as active sensors, which convert the mechanical inputs into electrical output signals without the need of an external power source. One demonstration we made based on this idea is integrating PENG with a tire for pressure and speed monitoring [29]. In general, when a vehicle is moving, tires are rotating. The shape change of

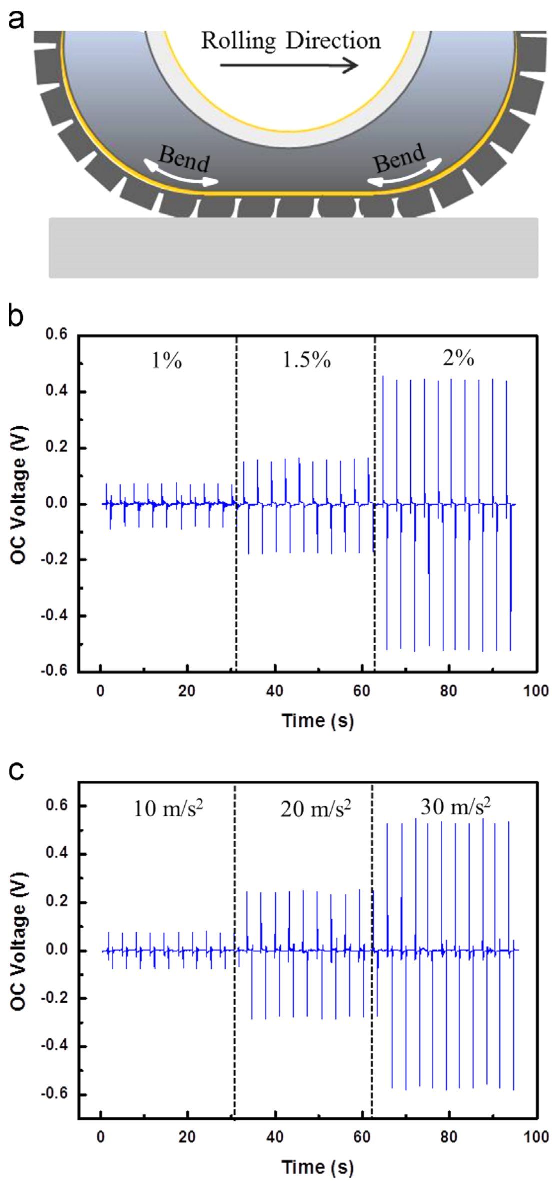

Fig. 8 Active sensors for vehicle monitoring. (a) Schematic image to show the shape change of a tire during the vehicle's movement. The OC voltage of PENG increased as (b) the strain increased which represents a decreased tire pressure or (c) the trigger speed increased which represents an increased vehicle speed [29].

tires at the position where they touch or detouch the road surface is large, as shown in Figure 8(a). If a PENG is attached on the inner surface of a tire, an electric signal is generated at the moment when it passes through such a position. As we know that the magnitude of OC voltage is proportional to both the applied strain and the strain rate, but has different slopes. For a tire, lower pressure results in a flatter tire, which leads to an increased magnitude of deformation experienced by the attached PENG. Figure 8 (b) shows the OC voltage measured from the PENG increases when the strain experienced by the NG increased, which represents the pressure in the tire is lowered. When the vehicle runs fast, the strain rate experienced by the PENG will increase, which also result in an increased OC voltage. Here we showed that PENGs can work as active sensors for vehicle monitoring in this way.

Active sensors for deformation detection

Most of our PENGs are fabricated on flexible substrate, which is suitable to work as a supersensitive sensor to detect small physical motions. Here we showed a demonstration by using a highly flexible PENG fabricated on an ultrathin Al-foil to work as an active deformation sensor to detect the wrinkling of a human face and tracking eye ball motion without the needs of extra power supply [30] and [31]. First, in Figure 9(a), a PENG with a size of 5 mm × 13 mm was attached to the skin next to a human eye with eyelash glue, which can be used to detect small amount of skin wrinkling, as shown in Figure 9 (b). When the eye was blinking, the PENG deformed following the dynamic wrinkles due to its super-flexibility and high conformability, and corresponding signal was detected. Figure 9(c) shows that PENG with the active area of 3 mm × 10 mm was attached to a right eyelid on the center. The PENG was triggered by the movement of the eye ball from side to side. The OC voltage of the PENG was recorded under slow and rapid eye ball movement, as shown in Figure 9(d) and (e), respectively. The PENG is strained when the eye ball travels under it, and released when the eye ball has passed it. As a result, a positive and a negative peak are detected when the eye ball moves from one side to the other side. A quicker movement of the eye ball produces a larger strain rate, and results in a larger OC voltage signal generated from the TENG, which is clear when we comparing Figure 9(e) with 9(d). If the design of PENG is further optimized by considering the shape and the size of a target surface, the sensor with an enhanced sensitivity can be achieved due to the increased output performance.

Vortex capture and ambient wind-velocity detection

Due to its high flexibility, PENGs can also be used to capture ambient vortex-energy and detect gas/liquid flow [32]. Figure 10(a) shows the working principle of the vortex generation and capture. There are two parts in the experimental setup. The first one is a bluff body, which is a triangular prism with a plate at its end. According to the Karman vortex street principle, a row of vortices will be generated on both sides of the bluff body when the Reynolds number of the flow is in a certain range. A PENG fixed on a glass strip substrate is placed in the wake of the bluff body to work as an active sensor. We can measure the vortex induced local pressure variation by the PENG probe. The relationship between the input airflow velocity ν and the detected vibration frequency f can be expressed as as follows:

$$\nu = \frac{fd}{St}$$

where St is the Strouhal number, and d is the width of the bluff body. Figure 10(b) shows the signal detected by the PENG, and the estimated air-flow velocity is 0.6 m/S, which is provided by compressed air through a tube in front of the bluff body to simulate the ambient wind. Inset of Figure 10(b) is the practical experimental setup. When the input airflow velocity changed,

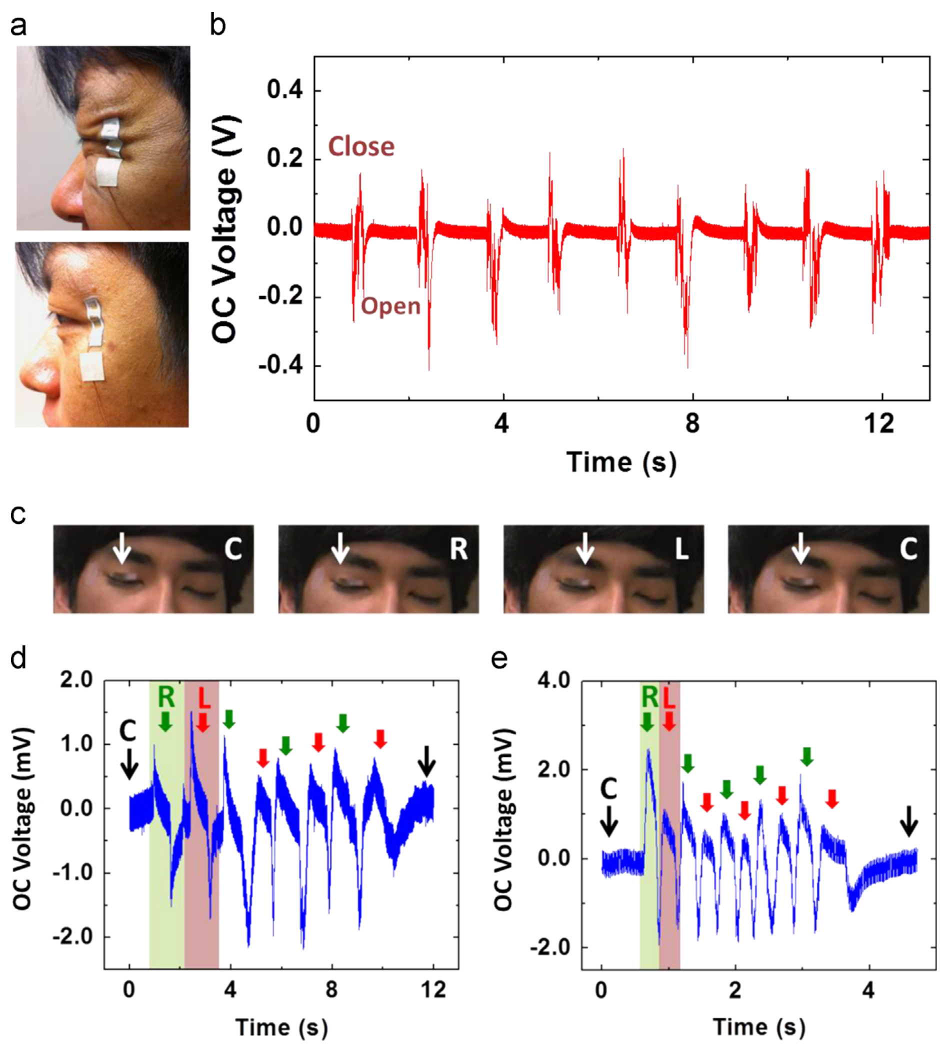

Fig. 9 Active sensors for deformation detection. (a) A PENG is attached on the skin near a human eye for detecting wrinkling of a human face. (b) Output signal recorded when the eye is blinking. (c) A PENG is attached on a right eyelid to detect the eye ball movement. Measured OC voltage under (d) slow and (e) rapid eye movement [30] and [31].

the detected vibration frequency by PENG also changed. We can get a linear relationship between these two parameters as shown in Figure 10(c), which is consistent with the Karman vortex street principle predication. Then we utilize the setup to measure the real ambient wind velocity, as shown in Figure 10 (d). The setup was enclosed in a glass passage to reduce the influence of air-flow direction variation. When the passage was opened, signal was detected by the PENG, and the ambient wind-velocity could be deduced.

Challenges and opportunities

A fast development of PENGs shows a bright future of these mechanical energy harvesting technologies. To overcome the final barriers toward commercialization, there are several issues that need to be handled first. Properly designed power management circuits is highly demanded to make the PENGs to work as the practical power source. Generally, the output signal from the PENG is fluctuating with high dependence on the changes in the environment. The power management circuit should be designed to have very good tolerance, including working at a large frequency range and handling input signals with very different amplitudes. As the output impedance of PENGs is very large, generally in the range of 10^6–10^7 Ω level, special design of the power management circuit is needed to insure high energy transfer efficiency when they are connected. To realize the integrated self-powered system, the fabrication process of PENGs should be compatible with the current mainstream process in the industry. When the cost factor is taken into account, cheap, highly repeatable, and large-scale manufacturing process should be developed for PENGs. Other issues including the packaging technique, system design, fatigue test, aging test, *etc.*, need researchers from different backgrounds to put their efforts in. There are big challenges here for the final steps, while big opportunities are also just ahead.

Conclusion

In this article, we reviewed some recent progresses in the mechanical energy harvesting technology of PENGs based on ZnO NWs. The new introduced PENGs based on sandwich

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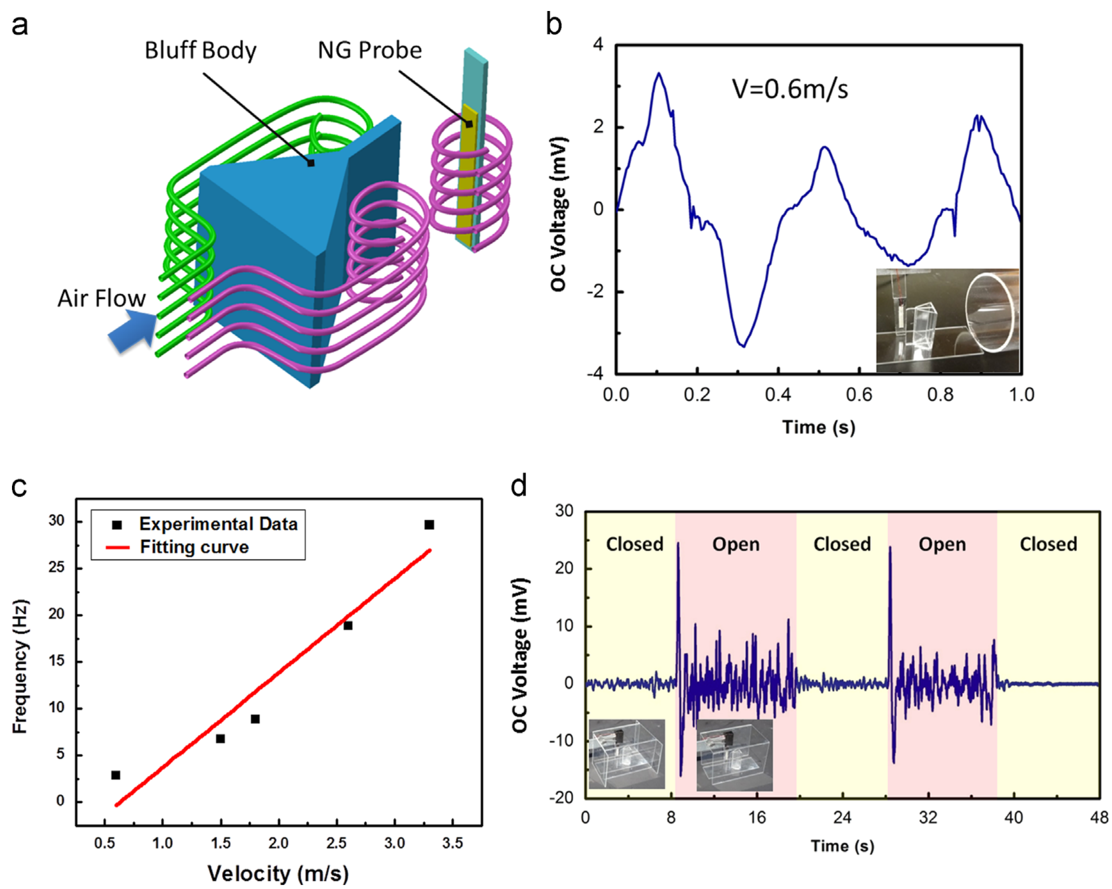

Fig. 10 Active sensors for vortex capture and ambient wind-velocity detection. (a) PENG as an active sensor for detecting air flow. (b) OC Voltage of the PENG under very slow air-flow velocity to show its high sensitivity. (c) There is a linear relationship between the vortex shedding frequency and air-flow velocity as expected in the Karman vortex street principle. (d) A PENG worked as an active sensor for ambient wind-speed detection [32].

structure show very good output performance and mechanical stability with simple fabrication process. The working mechanism difference between PENGs based on Schottky contact and sandwich structure is presented for the first time. Representative device designs for PENGs with sandwich structures are reviewed. Improvement of the output performance is realized by reducing ZnO NWs' conductivity and optimizing devices' structure. A maximum OC voltage from an individual PENG of 37 V is achieved. Several demonstrations of PENGs applications in self-powered systems and active sensors for photon detecting, environment monitoring, vehicle monitoring, deformation detecting, and ambient wind-velocity detection are summarized. At the end, challenges and opportunities for the technology of PENGs are discussed from the aspect of the author.

Acknowledgment

Research was supported by the BES DOE (DE-FG02-07ER46394), DARPA (HR0011-09-C-0142), NSF (CMMI 0403671), MURI from the Airforce, the Knowledge Innovation Program of the Chinese Academy of Sciences (KJCX2-YW-M13). We thank the contribution made by the following people to the work reviewed here: Drs. Yan Zhang, Chen Xu, Guang Zhu, Minbaek Lee, Sangmin Lee, Rui Zhang, Mrs. Long Lin, Qingshen Jing, and Miss. A.C. Wang

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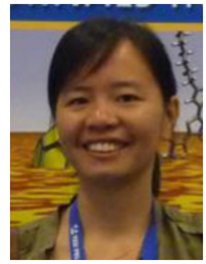

Dr. Youfan Hu received her Ph.D. from the Peking University in Physical Electronics in 2008, and then worked as a postdoctoral research fellow and as a research scientist at the School of Materials Science and Engineering in Georgia Institute of Technology. Currently, she is an Assistant Professor at the Department of Electronics in Peking University. Her primary interests are integrated multifunction sensor system, energy harvesting technology, and the coupling effect in nanomaterials. She has published over 40 peer-reviewed papers in highly reputable journals and holds 5 patents on nanodevices design and energy harvesting technology. Her work has been cited over 1300 times, and 7 publications are ESI papers.

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