Faraday Discussions

Cite this: DOI: 10.1039/c4fd00159a

PERSPECTIVE

View Article Online
View Journal

Triboelectric nanogenerators as new energy technology and self-powered sensors – Principles, problems and perspectives

Zhong Lin Wang*[ab]

Received 17th August 2014, Accepted 8th September 2014

DOI: 10.1039/c4fd00159a

Triboelectrification is one of the most common effects in our daily life, but it is usually taken as a negative effect with very limited positive applications. Here, we invented a triboelectric nanogenerator (TENG) based on organic materials that is used to convert mechanical energy into electricity. The TENG is based on the conjunction of triboelectrification and electrostatic induction, and it utilizes the most common materials available in our daily life, such as papers, fabrics, PTFE, PDMS, Al, PVC *etc.* In this short review, we first introduce the four most fundamental modes of TENG, based on which a range of applications have been demonstrated. The area power density reaches 1200 W m^{-2}, volume density reaches 490 kW m^{-3}, and an energy conversion efficiency of ~50–85% has been demonstrated. The TENG can be applied to harvest all kinds of mechanical energy that is available in our daily life, such as human motion, walking, vibration, mechanical triggering, rotation energy, wind, a moving automobile, flowing water, rain drops, tide and ocean waves. Therefore, it is a new paradigm for energy harvesting. Furthermore, TENG can be a sensor that directly converts a mechanical triggering into a self-generated electric signal for detection of motion, vibration, mechanical stimuli, physical touching, and biological movement. After a summary of TENG for micro-scale energy harvesting, mega-scale energy harvesting, and self-powered systems, we will present a set of questions that need to be discussed and explored for applications of the TENG. Lastly, since the energy conversion efficiencies for each mode can be different although the materials are the same, depending on the triggering conditions and design geometry. But one common factor that determines the performance of all the TENGs is the charge density on the two surfaces, the saturation value of which may independent of the triggering configurations of the TENG. Therefore, the triboelectric charge density or the relative charge density in reference to a standard material (such as polytetrafluoroethylene (PTFE)) can be taken as a measuring matrix for characterizing the performance of the material for the TENG.

[a]*School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332-0245, USA. E-mail: zlwang@gatech.edu*

[b]*Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing, China*

1. Introduction

A drastic change occurring in the world in the last two decades is the fast development of portable and personal electronics, which is now even shifting toward wearable electronics. A unique character of this technology trend is the huge increase in the number of electronic devices/systems, in a total of billions to trillions, each of which requires a mobile power source. The most traditional approach is to use batteries to power these electronics, which is likely to face a few possible consequences. First, a battery has a limited lifetime, replacing the battery for each component becomes a huge task, especially, how do we know it is out of power, when should we replace the battery, who will replace the battery, *etc.* This is not a problem if the number of batteries is limited, but the situation drastically changes if the number of batteries to be replaced becomes huge. Secondly, with the use of huge amount of batteries, recycling of these batteries become a major task, because widely distributed batteries will inevitably cause environmental issues if the chemicals for making the batteries leak out.

The trend in the development of portable electronics is toward low power consumption, which makes it possible to use the energy harvested from the working environment of the device to power directly the device, forming a trend of self-powered systems[1] for application in ultrasensitive chemical and bimolecular sensors, nanorobotics, micro-electromechanical systems, remote and mobile environmental sensors, homeland security and even portable/wearable personal electronics. New technologies that can harvest energy from the environment as sustainable self-sufficient micro/nano-power sources are the newly emerging field of nanoenergy, which is concerned with the application of nanomaterials and nanotechnology for harvesting energy to power micro/nano-systems.[2] The objective of this paper is to give a review of the fundamentals of the triboelectric nanogenerator (TENG)[3] and its updated progress and potential applications as a new energy technology and in self-powered active sensors.[4]

2. Fundamental principle modes of triboelectric nanogenerators

The triboelectric effect is the phenomenon that a material becomes electrically charged after it contacts a different material through friction, and has been known for thousands of years. Although this is one of the most frequently experienced effects that each and every one of us inevitably sees every day, the mechanism behind triboelectrification is still being studied, possibly with debate. It is generally believed that after two different materials come into contact, a chemical bond is formed between some parts of the two surfaces, called adhesion, and charges move from one material to the other to equalize their electrochemical potential. The transferred charges can be electrons or may be ions/molecules. When separated, some of the bonded atoms have a tendency to keep extra electrons, and some a tendency to give them away, possibly producing triboelectric charges on the surfaces. The presence of triboelectric charges on dielectric surfaces can be a force for driving electrons in the electrode to flow in order to balance the electric potential drop created. Based on such a principle, we have invented four different modes of TENGs, as elaborated in the following.

2.1 Vertical contact-separation mode

We use the simplest design of TENG as an example (Fig. 1a).[5,6] Two dissimilar dielectric films face with each other, and there are electrodes deposited on the top and the bottom surfaces of the stacked structure. A physical contact between the two dielectric films creates oppositely charged surfaces. Once the two surfaces are separated by a small gap by the lifting of an external force, a potential drop is created. If the two electrodes are electrically connected by a load, free electrons in one electrode would flow to the other electrode to build an opposite potential in order to balance the electrostatic field. Once the gap is closed, the triboelectric-charge-created potential disappears and the electrons flow back.[7]

2.2 Lateral sliding mode

The structure to start with is the same as that for the vertical contact-separation mode. When two dielectric films are in contact, a relative sliding in parallel to the surface also creates triboelectric charges on the two surfaces (Fig. 1b).[8,9] A lateral polarization is thus introduced along the sliding direction, which drives the electrons on the top and bottom electrodes to flow in order to fully balance the field created by the triboelectric charges. A periodic sliding apart and closing generates an AC output. This is the sliding mode TENG. The sliding can be a planar motion, a cylindrical rotation,[10] or disc rotation.[11] Related theoretical studies have been carried out for understanding the basic mode and grating structured TENG.[12,13]

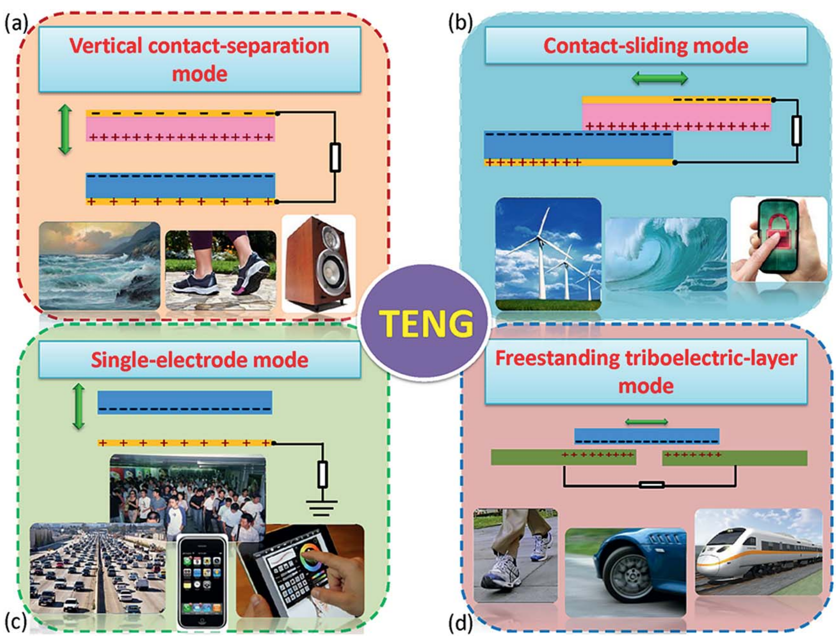

Fig. 1 The four fundamental modes of triboelectric nanogenerators: (a) vertical contact-separation mode; (b) in-plane contact-sliding mode; (c) single-electrode mode; and (d) freestanding triboelectric-layer mode.

2.3 Single-electrode mode

The two modes introduced in Sections 2.1 and 2.2 have two electrodes interconnected by a load. Such TENGs can freely move so that they can work for mobile cases. In some cases, the object that is part of the TENG cannot be electrically connected to the load because it is a mobile object, such as a human walking on a floor. In order to harvest energy from such a case, we introduced a single electrode TENG, in which the electrode on the bottom part of the TENG is grounded (Fig. 1c). If the size of the TENG is finite, an approaching or departing of the top object from the bottom one would change the local electrical field distribution, so that there are electron exchanges between the bottom electrode and the ground to maintain the potential change of the electrode. This energy harvesting strategy can be in both contact-separation mode[14] and contact-sliding mode.[15,16]

2.4 Freestanding triboelectric-layer mode

In nature, a moving object is naturally charged due to its contact with air or other object, such as our shoes walking on floors that are usually charged. The charges remain on the surface for hours and contact or friction is unnecessary within this period of time because the charge density reaches a maximum. If we make a pair of symmetric electrodes underneath a dielectric layer, and the size of the electrodes and the gap distance between the two are of the same order as the size of the moving object, the object's approach to and/or departure from the electrodes creates an asymmetric charge distribution in the media, which causes the electrons to flow between the two electrodes to balance the local potential distribution (Fig. 1d).[17] The oscillation of the electrons between the paired electrodes produces power. The moving object does not have to touch directly the top dielectric layer of the electrodes so that, in rotation mode, free rotation is possible without direct mechanical contact; wear of the surfaces can be drastically reduced. This is a good approach for extending the durability of the TENGs. Using such a design, we have demonstrated the harvesting of energy from human walking and a mobile automobile,[13] showing the potential for harvesting energy from a freely moving object without an electric connection.

3. Applications of TENGs

Based on the four modes illustrated above, we have fabricated various TENGs depending on specific applications. Fig. 2 shows a collection of photographs of TENGs we have fabricated for harvesting various types of energy. These structures are the fundamental units for providing micro-scale power for small electronics, their assembly and integration can be the basis for harvesting mega-scale energy.

3.1 TENGs as micro-scale power source

The first goal of developing TENGs is to power small electronics for sensor networks. Using the four modes demonstrated above and their combinations, a range of energy harvesting methods has been demonstrated from cases such as body motion,[18] fabrics,[19,20] vibrations from human walking,[21] hand pressing,[22,23] shoe insole,[24,25] vibration of a string or tree branch,[26] vibration of a machine,[27,28] elastic energy in sponge structure,[29] sound wave in air[30] and in water.[31]

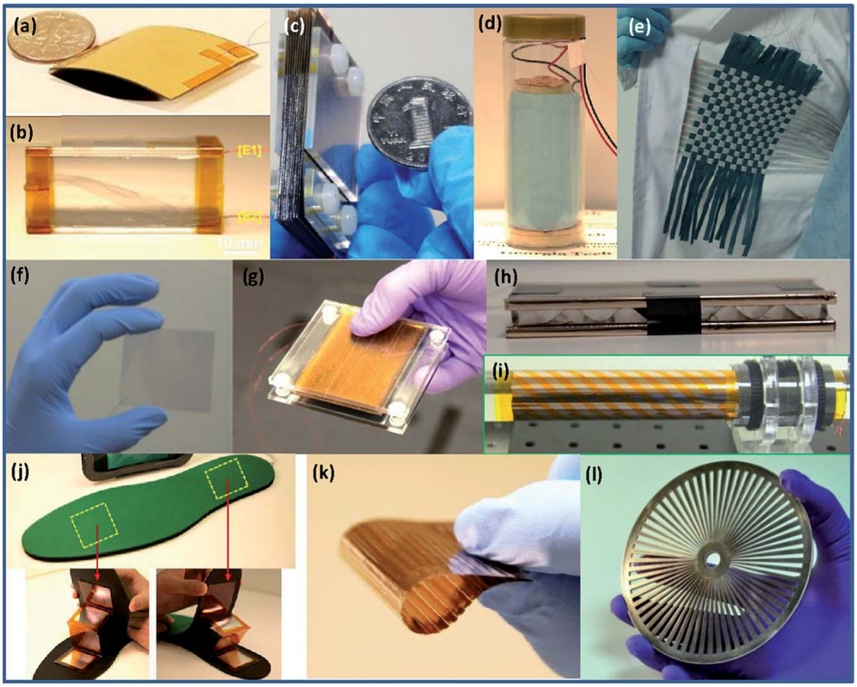

Fig. 2 Typical photographs of some triboelectric nanogenerators fabricated for harvesting: (a) finger tapping energy; (b) air-flow/wind energy; (c) relative in-plane sliding energy; (d) enclosed cage for harvesting oscillating/disturbing energy in water or mechanical vibration; (e) fabric for harvesting body motion energy; (f) transparent TENG for harvesting energy in touch pad; (g) foot/hand pressing energy; (h) water impact energy; (i) cylindrical rotation energy; (j) shoe insole for walking energy; (k) flexible grating structure for harvesting sliding energy; and (l) disc shape rotation energy.

The mechanical action can be either linear or in rotation mode. By designing a grating structure, we can lower effectively the output voltage and greatly increase the output current, which is required for high efficiency of charging of an energy storage unit. An energy conversion efficiency of 50% has been demonstrated for a sliding mode TENG[32] and 24% for a rotation based TENG,[33] and the output power density reaches as high as 1200 W m^{-2}. Such a power output is high enough to power small electronics, establishing a solid foundation for self-powered systems.

3.2 TENG as macro-scale power source

By using the contact-electrification between a liquid and a solid surface as well as the packaged TENGs,[34] we have shown that TENGs can be used for harvesting energy from flowing water in river, rain drops,[35,36] tide and ocean waves. Using the four fundamental modes presented above, we have successfully harvested the kinetic energy such as the up and down fluctuation of a water surface,[37] water waves, water streams and the impact of water to the shore.[38] Such structures can be used to harvest water energy from creeks without building a dam. Looking into the future, by constructing a three-dimensional network of the TENGs, such as a 3D fishing net, as schematically shown in Fig. 3, if the output of each unit is 1 mW

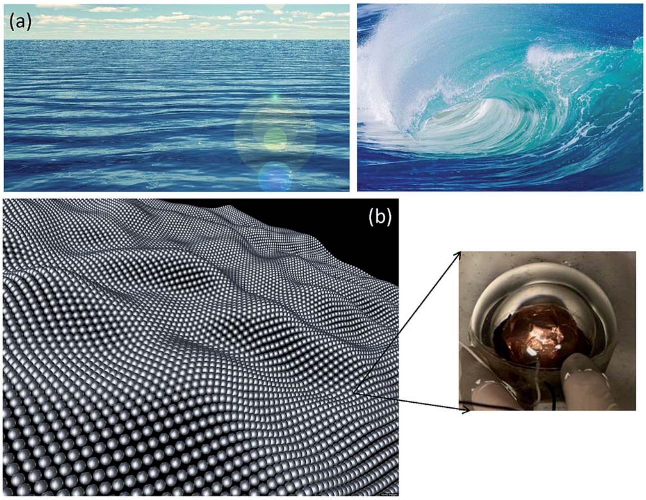

Fig. 3 A proposed idea for harvesting water energy from ocean using an integrated assembly of small unit TENGs in a 3D network.

on average,[39,40] our calculation shows that 1 MW power can be generated using 1 km square of surface area in ocean, possibly provides a feasible blue energy for large-scale energy needs of the world in the near future.

Using the contact-separation mode, a mechanical resonance of a polymer film between two dielectrics can be used to harvest wind energy.[41] If we can build a wall and solve the problem of surface wetting, we can effectively harvest energy from wild wind.

3.3 TENG as self-powered sensors

TENG is a device that converts a mechanical trigger into an electric output signal (voltage and current), which means that it can be used to direct sensing a dynamic mechanical action without applying a power unit to the device. This is a self-powering sensor. We have applied TENGs for a range of sensing types such as finger touch,[42–44] vibration detection,[19] tracking of a moving object (location, velocity and acceleration),[45–47] fine displacement in MEMS,[48] rotation sensors[49] and even chemical sensors.[50]

4. Problems to be discussed

Since their first demonstration in 2012,[3] TENGs have experienced a very rapid development both in fundamental understanding and technological improvements. As toward the future applications, there are a number of issues and problems need to be addressed, as listed in the following.

4.1 Fundamental mechanism of contact-electrification

Although triboelectrification is a phenomenon known to everyone, the basic mechanism of why two materials become charged once in physical contact remain to be investigated extensively. It has been debated that the charging is due to electron transfer as a result of energy level misalignment, ion transfer and/or materials species transfer. We have used AFM to study the charge density that a surface can be charged to, how long does it take for the charges to dissipate on an insulator surface (which can be hours), and how fast the charge diffuses on the surface.[51] We also used a conductive AFM tip to manipulate the sign of charges to be delivered to a surface by applying a preset bias, so that the surface charge can be positive, null or negative.[52] More detailed measurements have to be made in order to fully understand the electrostatic charging on surfaces.

4.2 Quantitative understanding the surface charge density

A key factor that dictates the performance of the TENGs is the surface charge density, which can be taken as a standard to characterize the matrix of performance of a material for a TENG. Quantitative techniques have to be developed to measure accurately the surface charge density. It is unclear how the surface structures, such as roughness, dielectric properties and the presence of nanoparticles/nanowires, would affect the magnitude of the charge density. More fundamental studies are required.

4.3 Measurement matrix – a standard for calibrating the performance of a material for a TENG

We have presented four modes of TENGs. The design and operation conditions of these TENGs are vastly different and it is important to find a parameter that can be used to quantify the performance of the TENG, similar to defining the efficiency for a solar cell, and a *ZT* factor for thermoelectrics. The energy conversion efficiencies for each mode can be different although the materials are the same, depending on the triggering conditions and design geometry. But one common factor that determines the performance of all the TENGs is the charge density on the two surfaces, the saturation value of which may independent of the triggering configurations of the TENG. Therefore, the triboelectric charge density or the relative charge density in reference to a standard material (such as polytetrafluoroethylene (PTFE)), can be taken as a measuring matrix for characterizing the performance of the material for the TENG.

4.4 Choice of materials

Although all materials exhibit triboelectricity, finding the right paired materials can give maximum output. Although there is guidance from the triboelectric series, it is a qualitative indication on the capability of a material to gain or lose an electron but it lacks a quantitative standard of calibration. Choice of materials, surface structure configurations and patterning, surface functionalization and more need to be studied. By introducing nanomaterials and possibly nanocomposites, we can optimize the mechanical, dielectric and surface properties of materials to receive the maximum power output.

4.5 Power management

A typical characteristic of the TENGs is high output voltage but low output current, but general electronics require a regulated power of a few volts. Approaches have to be developed to lower the output voltage without sacrificing the output power. This can be done by designing TENGs with smaller size or thickness, but the entire package can integrate many units to increase the output current. As for rotation based TENGs with a periodic AC output, a transformer can be applied to lower the voltage, but finding a right match is required to maximize the efficiency of power transfer.

4.6 Durability and stability

Since the triboelectrification is a result of two materials in physical contact, especially in contact-sliding mode, the durability and stability of the TENGs must be continuously improved. We have tested a disc based rotation TENG for 10 million cycles in contact mode;[32] no degradation in output was observed. This may be good for low frequency applications. For practical application at high frequency, finding and using materials with a high durability is important.

4.7 Packaging

Since the TENG is based on the surface charging effect, its performance is largely affected by the environment such as humidity and surface adsorption layers. Packaging materials and technologies are required to protect the device from contamination or liquid infiltration but without reducing too much of the efficiency and output power. This is because the TENG is a device that converts mechanical energy into electricity; preserving its flexibility and elasticity is important for improving the energy conversion efficiency. Such packaging is different from conventional packaging because of the presence of mechanical triggering.

4.8 Energy storage

Energy harvesting from the environment is subject to the variation of the environment, which is time dependent, unstable and sometime unpredictable, but the power required to drive electronics is regulated with a fixed input voltage and power. It is important to store the generated energy in a battery or capacitor, so that it can be used to power a device in a regulated manner. Between the power generation unit and a storage unit, a power management circuit is required to maximize the efficiency of power storage; the integration of the three forms a self-charging power pack.[53]

4.9 Hybridized cell for harvesting all types of energies

The working environment of a sensor can vary and the energy available in its working environment can also vary, such as solar, thermal and mechanical. It is important to harvest all types of energy that are available for the sensor. Hybrid cells that simultaneously or individually harvest solar, thermal and/or mechanical energy have been developed,[54–57] but the performance and coupling among them are unsuitable, because the output characteristics of each type of energy harvester are drastically different; for example, solar is a constant DC signal, while a TENG provides a pulsed AC signal.

4.10 Hybridization with a traditional electromagnetic induction generator

Electromagnetic induction was first discovered by Faraday in 1831, and later becomes the dominant mechanism used to convert mechanical energy into electricity. The generator requires a strong magnet, a metal coin and a rotator. The electromagnetic generator (EMG) usually is heavy, fairly costly and has a large volume. EMG's output characteristic is low voltage but high output current. In contrast, TENGs use organic materials so that they are light, smaller and cost-effective. The output characteristics of TENGs are high voltage but low current. The disadvantage of the TENG is a likely lower durability. The power performances of the two approaches are quite compatible and each has its own unique advantages, but the two can be complementary according to the application concerned.[58,59]

5. Perspectives

The discovery of the triboelectric nanogenerator (TENG) is a major milestone in the field of converting mechanical energy into electricity for building self-powered systems. It offers a completely new paradigm for harvesting mechanical energy effectively using organic and inorganic materials. An energy conversion efficiency of 50% and a total energy conversion efficiency of 85% have been demonstrated, and an output power density of 1200 W m^{-2} has been realized. The TENG can not only serve as a micro-scale power source for mobile and portable electronics, but it also has the potential to harvest water energy from ocean and wind, opening a new field of *blue energy*, which is a new chapter beyond green energy. Fig. 4 shows a proposed technology development road map for nanogenerators and its commercial applications. Furthermore, TENGs can serve as a self-powered sensor for sensing mechanical triggering, pressure, muscle stretching and more, which may become commercially available sooner than energy harvesters.

The discovery of TENGs opens a new field for materials scientists and chemists for using organic nanogenerators to convert mechanical energy at a high

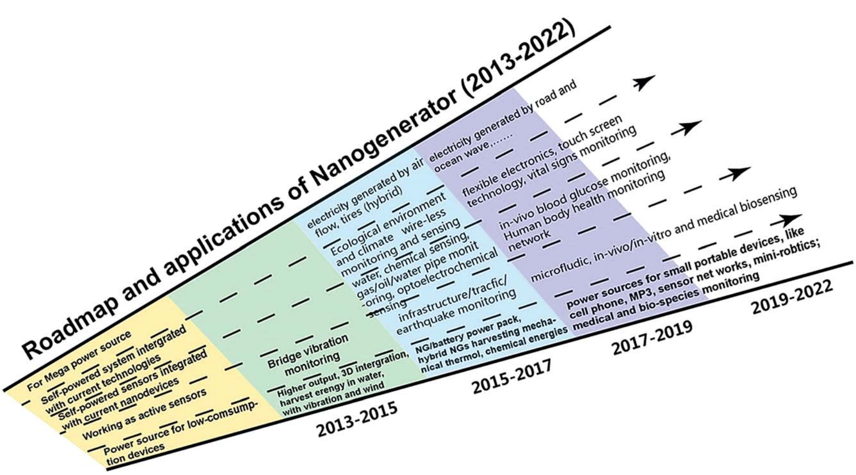

Fig. 4 Proposed technology roadmap for nanogenerators (2012).

efficiency, a so called organic nanogenerator, which is a disruptive technology for energy. We anticipate that much more enhancement of the output power density will be demonstrated in the next few years. We anticipate a worldwide study of TENG in the next few years, and soon some industrial products and applications will be demonstrated.

Acknowledgements

Research was supported by BES DOE, NSF, Airforce, Samsung, SKKU (Korea), MANA NIMS (Japan), and the Knowledge Innovation Program of the Chinese Academy of Sciences (KJCX2-YW-M13), the Hightower Chair foundation, and the "thousands talents" program for pioneer researcher and his innovation team, China. I thank my group members and my collaborators for their contributions to the work reviewed here, especially to those ones: Fengru Fan, Guang Zhu, Sihong Wang, Ya Yang, Zong-Hong Lin, Long Lin, Simiao Niu, Jun Chen, Yusheng Zhou, Weiqing Yang, Gang Cheng, Jin Yang, Hulin Zhang, Yannan Xie, Peng Bai, Cao-feng Pan, Qingshen Jing, Ying Liu, Yuanjie Su, Chi Zhang, Changbao Han, Wei Tang, Aifang Yu, Zhong-Qun Tian, Mengxiao Chen, Limin Zhang, and Weiming Du.

References

1 Z. L. Wang, *Sci. Am.*, 2008, **298**, 82.
2 Z. L. Wang and W. Z. Wu, *Angew. Chem.*, 2012, **51**, 11700.
3 F. R. Fan, Z. Q. Tian and Z. L. Wang, *Nano Energy*, 2012, **1**, 328.
4 Z. L. Wang, *ACS Nano*, 2013, **7**, 9533.
5 G. Zhu, C. F. Pan, W. X. Guo, C. Y. Chen, Y. S. Zhou, R. M. Yu and Z. L. Wang, *Nano Lett.*, 2012, **12**, 4960.
6 S. H. Wang, L. Lin and Z. L. Wang, *Nano Lett.*, 2012, **12**, 6339.
7 S. M. Niu, S. H. Wang, L. Lin, Y. Liu, Y. S. Zhou, Y. F. Hu and Z. L. Wang, *Energy Environ. Sci.*, 2013, **6**, 3576.
8 S. H. Wang, L. Lin, Y. N. Xie, Q. S. Jing, S. M. Niu and Z. L. Wang, *Nano Lett.*, 2013, **13**, 2226.
9 G. Zhu, J. Chen, Y. Liu, P. Bai, Y. S. Zhou, Q. S. Jing, C. F. Pan and Z. L. Wang, *Nano Lett.*, 2013, **13**, 2282.
10 Q. S. Jing, G. Zhu, P. Bai, Y. N. Xie, J. Chen, R. P. S. Han and Z. L. Wang, *ACS Nano*, 2013, **7**, 10424.
11 L. Lin, S. H. Wang, Y. N. Xie, Q. S. Jing, S. M. Niu, Y. F. Hu and Z. L. Wang, *Nano Lett.*, 2013, **13**, 2916.
12 S. M. Niu, Y. Liu, S. H. Wang, L. Lin, Y. S. Zhou, Y. F. Hu and Z. L. Wang, *Adv. Mater.*, 2013, **25**, 6184.
13 S. M. Niu, S. H. Wang, Y. Liu, Y. S. Zhou, L. Lin, Y. F. Hu and Z. L. Wang, *Energy Environ. Sci.*, 2014, **7**, 2339.
14 Y. Yang, Y. S. Zhou, H. L. Zhang, Y. Liu, S. Lee and Z. L. Wang, *Adv. Mater.*, 2013, **25**, 6594.
15 Y. Yang, H. L. Zhang, J. Chen, Q. S. Jing, Y. S. Zhou, X. N. Wen and Z. L. Wang, *ACS Nano*, 2013, **7**, 7342.
16 S. M. Niu, Y. Liu, S. H. Wang, L. Lin, Y. S. Zhou, Y. F. Hu and Z. L. Wang, *Adv. Funct. Mater.*, 2014, **24**, 3332.

17 S. H. Wang, Y. N. Xie, S. M. Niu, L. Lin and Z. L. Wang, *Adv. Mater.*, 2014, **26**, 2818.
18 W. Q. Yang, J. Chen, X. N. Wen, Q. S. Jing, J. Yang, Y. J. Su, G. Zhu, W. Z. Wu and Z. L. Wang, *ACS Appl. Mater. Interfaces*, 2014, **6**, 7479.
19 J. W. Zhong, Y. Zhang, Q. Z. Zhong, Q. Y. Hu, B. Hu, Z. L. Wang and J. Zhou, *ACS Nano*, 2014, **8**, 6273.
20 T. Zhou, C. Zhang, C. B. Han, F. R. Fan, W. Tang and Z. L. Wang, *ACS Appl. Mater. Interfaces*, 2014, **6**, 14695–14701.
21 W. Q. Yang, J. Chen, G. Zhu, J. Yang, P. Bai, Y. J. Su, Q. S. Jing and Z. L. Wang, *ACS Nano*, 2013, **7**, 11317.
22 X. S. Zhang, M. D. Han, R. X. Wang, F. Y. Zhu, Z. H. Li, W. Wang and H. X. Zhang, *Nano Lett.*, 2013, **13**, 1168.
23 S. Kim, M. K. Gupta, K. Y. Lee, A. Sohn, T. Y. Kim, K. S Shin, D. Kim, S. K. Kim, K. H. Lee, H. J. Shin, D. W. Kim and S. W. Kim, *Adv. Mater.*, 2014, **26**, 3778.
24 G. Zhu, P. Bai, J. Chen and Z. L. Wang, *Nano Energy*, 2013, **2**, 688.
25 B. Meng, W. Tang, X. S. Zhang, M. D. Han, W. Liu and H. X. Zhang, *Nano Energy*, 2013, **2**, 1101.
26 J. Yang, Y. Yang, J. Chen, H. L. Zhang, W. Q. Yang, P. Bai, Y. J. Su and Z. L. Wang, *Adv. Energy Mater.*, 2014, **4**, 1301322.
27 W. Q. Yang, J. Chen, Q. S. Jing, J. Yang, X. N. Wen, Y. J. Su, G. Zhu, P. Bai and Z. L. Wang, *Adv. Funct. Mater.*, 2014, **24**, 4090.
28 J. Chen, G. Zhu, W. Q. Yang, Q. S. Jin, P. Bai, Y. Yang, T. C. Hou and Z. L. Wang, *Adv. Mater.*, 2013, **25**, 6094.
29 K. Y. Lee, J. Chun, J. H. Lee, K. N. Kim, N. R. Kang, J. Y. Kim, M. H. Kim, K. S. Shin, M. K. Gupta, J. M. Baik and S. W. Kim, *Adv. Mater.*, 2014, **26**, 5037.
30 J. Yang, J. Chen, Y. Liu, W. Q. Yang, Y. J. Su and Z. L. Wang, *ACS Nano*, 2014, **8**, 2649.
31 A. F. Yu, M. Song, Y. Zhang, Y. Zhang, L. B. Chen, J. Y. Zhai and Z. L. Wang, *Nano Res.*, 2014, DOI: 10.1007/s12274-014-0559-z.
32 G. Zhu, Y. S. Zhou, P. Bai, X. S. Meng, Q. S. Jing, J. Chen and Z. L. Wang, *Adv. Mater.*, 2014, **26**, 3788.
33 G. Zhu, J. Chen, T. J. Zhang, Q. S. Jing and Z. L. Wang, *Nat. Commun.*, 2014, **5**, 3456.
34 Z. H. Lin, G. Cheng, L. Lin, S. Lee and Z. L. Wang, *Angew. Chem., Int. Ed.*, 2013, **52**, 12545.
35 Z. H. Lin, G. Cheng, S. Lee and Z. L. Wang, *Adv. Mater.*, 2014, **26**, 4690.
36 Z. H. Lin, G. Cheng, W. Z. Wu, K. C. Pradel and Z. L. Wang, *ACS Nano*, 2014, **8**, 64.
37 G. Zhu, Y. J. Su, P. Bai, J. Chen, Q. S. Jing, W. Q. Yang and Z. L. Wang, *ACS Nano*, 2014, **8**, 6031–6037.
38 X. N. Wen, W. Q. Yang, Q. S. Jing and Z. L. Wang, *ACS Nano*, 2014, **8**, 7405.
39 Y. F. Hu, J. Yang, Q. S. Jing, S. M. Niu, W. Z. Wu and Z. L. Wang, *ACS Nano*, 2013, **7**, 10424.
40 Y. Yang, H. L. Zhang, R. Y. Liu, X. N. Wen, T. C. Hou and Z. L. Wang, *Adv. Energy Mater.*, 2013, **3**, 1563.
41 Y. Yang, G. Zhu, H. L. Zhang, J. Chen, X. D. Zhong, Z. H. Lin, Y. J. Su, P. Bai, X. N. Wen and Z. L. Wang, *ACS Nano*, 2013, **7**, 9461.
42 Y. Yang, H. L. Zhang, X. D. Zhong, F. Yi, R. M. Yu, Y. Zhang and Z. L. Wang, *ACS Appl. Mater. Interfaces*, 2014, **6**, 3680.

43 Y. Yang, H. L. Zhang, Z. H. Lin, Y. S. Zhou, Q. S. Jing, Y. J. Su, J. Yang, J. Chen, C. G. Hu and Z. L. Wang, *ACS Nano*, 2013, **7**, 9213.
44 B. Meng, W. Tang, Z. H. Too, X. S. Zhang, M. D. Han, W. Liu and H. X. Zhang, *Energy Environ. Sci.*, 2013, **6**, 3235.
45 M. X. Chen, X. Y. Li, L. Lin, W. M. Du, X. Han, J. Zhu, C. F. Pan and Z. L. Wang, *Adv. Funct. Mater.*, 2014, **24**, 5059–5066.
46 C. B. Han, C. Zhang, X. H. Li, L. M. Zhang, T. Zhou, W. G. Hu and Z. L. Wang, *Nano Energy*, 2014, **9**, 325–333.
47 Y. J. Su, G. Zhu, W. Q. Yang, J. Yang, J. Chen, Q. S. Jing, Z. M. wu, Y. D. Jiang and Z. L. Wang, *ACS Nano*, 2014, **8**, 3843.
48 Y. S. Zhou, G. Zhu, S. M. Niu, Y. Liu, P. Bai, Q. S. Jing and Z. L. Wang, *Adv. Mater.*, 2014, **26**, 1719.
49 Q. S. Jing, G. Zhu, W. Z. Wu, P. Bai, Y. N. Xie, R. P. S. Han and Z. L. Wang, *Nano Energy*, **10**, 305–312.
50 Z. H. Lin, G. Zhu, Y. S. Zhou, Y. Yang, P. Bai, J. Chen and Z. L. Wang, *Angew. Chem., Int. Ed.*, 2013, **52**, 5065.
51 Y. S. Zhou, Y. Liu, G. Zhu, Z. H. Lin, C. F. Pan, Q. S. Jing and Z. L. Wang, *Nano Lett.*, 2013, **13**, 2771.
52 Y. S. Zhou, S. H. Wang, Y. Yang, G. Zhu, S. M. Niu, Z. H. Lin, Y. Liu and Z. L. Wang, *Nano Lett.*, 2014, **14**, 1567.
53 S. H. Wang, Z. H. Lin, S. M. Niu, L. Lin, Y. N. Xie and Z. L. Wang, *ACS Nano*, 2013, **7**, 11263.
54 S. Lee, S. H. Bae, L. Lin, S. Ahn, C. Park, S. N. Cha, Y. J. Park, H. Chang, S. W. Kim and Z. L. Wang, *Nano Energy*, 2013, **2**, 817.
55 Y. Yang, H. L. Zhang, S. Lee, T. C. Hou and Z. L. Wang, *Energy Environ. Sci.*, 2013, **6**, 1744.
56 Y. Yang, H. L. Zhang, Z. H. Lin, Y. Liu, J. Chen, Z. Y. Lin, Y. S. Zhou, C. P. Wong and Z. L. Wang, *Energy Environ. Sci.*, 2013, **6**, 2429.
57 Y. Yang, H. L. Zhang, S. Lee, D. Kim, W. Hwang and Z. L. Wang, *Nano Lett.*, 2013, **13**, 803.
58 C. Zhang, W. Tang, C. B. Han, F. R. Fan and Z. L. Wang, *Adv. Mater.*, 2014, **26**, 3580.
59 F. R. Fan, W. Tang, Y. Yao, J. J. Luo, C. Zhang and Z. L. Wang, *Nanotechnology*, 2014, **25**, 135402.

