Nano Energy (2012) 1, 418–423

Available online at www.sciencedirect.com

SciVerse ScienceDirect

journal homepage: www.elsevier.com/locate/nanoenergy

RAPID COMMUNICATION

Nanogenerator as self-powered vibration sensor

Aifang Yu[a], Peng Jiang[a], Zhong Lin Wang[a,b,*]

[a]National Center for Nanoscience and Technology, No.11 Beiyitiao, Zhongguancun, Beijing 100190, PR China
[b]School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

Received 15 December 2011; received in revised form 28 December 2011; accepted 28 December 2011
Available online 10 January 2012

KEYWORDS
Self-powering;
Nanogenerator;
Vibration sensor;
ZnO

Abstract
Vibration is one of the most popular phenomena that exists in our daily life. Detection of mechanical vibration usually uses laser technology. Here, we demonstrated the first application of a piezoelectric nanogenerator (NG) as a self-powered sensor for detecting the vibration status of a cantilever. By attaching a NG at the surface of a cantilever near the fixed end, the resonance frequency and amplitude damping have been quantified using the output voltage of the NG without a power source. This study proves another exciting application of NG in the self-powered vibration detection systems.

Introduction

Vibration is one of the most popular phenomena that exists in our daily life, which is everywhere and at all the time. Vibration is generated as a result of mechanical disturbance from sources such as music/sound, noise, engine, wind and many more. Detection of vibration is an important sensor technology for monitoring the operation of machines, bridges and buildings, warrant of security, prediction of natural disasters and more [1–3]. Almost all of the sensors used for vibration detection needs to be driven by electric power, either through optical approach or electrical approach. Such power is usually provided by battery or any other energy storage/supply systems. As the development of sensor network that contain huge amounts of small sensors, it is mostly desirable to use the energy harvested from the environment for driving the sensors to form self-powered sensors [4–7]. This is one of important applications in sensors especially with their power consumption extremely small.

Vibrations are an important source of energy, which can be harvested for driving small electronic components. Cantilever based piezoelectric resonators are the most typical generator for harvesting mechanical energy [8–11]. Nanogenerators (NG) using piezoelectric nanowires (NWs) have been developed as a key technology for converting mechanical energy into electricity [12–15]. Innovative researches based ZnO NWs have successfully converted external periodic dynamic mechanical stimuli into electricity and built self-powered nanosystems, such as ultraviolet (UV) sensor, wireless data transmission and Hg^{2+} ion sensor [16–19]. Mechanical vibration results in a periodic creation of piezoelectric potential in ZnO NWs, which drives the back and forth flow of electrons in the external load as an output

*Corresponding author. Tel.: +14048948008; fax: +14043853852.
E-mail address: zhong.wang@mse.gatech.edu (Z. Lin Wang).

2211-2855/$ - see front matter
doi:10.1016/j.nanoen.2011.12.006

electric signal about the vibration. This means that we can use the NG as a self-powered sensor that automatically detects mechanical vibration without using battery as the power source. The objective of this paper is to illustrate the application of NG for detecting low-frequency vibrations.

Experimental

Our experimental setup is made of a cantilever that respond to the vibration occuring in nature (Fig. 1a). The cantilever is a rectangular beryllium copper beam. At the root of the cantilever, a small and thin NG is affixed onto the cantilever, where the cantilever produces the maximum strain. With considering the position of the NG on the cantilever and its small size and mass, it has negligible effect on the resonance frequency of the cantilever. The NG is fabricated using the approach previously reported by Hu et al. [18], and it is a metal electrode sandwiched ZnO film that is made of textured NWs with their *c*-axis normal to the film. Once the film is mechanically strained in parallel to the plane of the film, a piezopotential drop is generated across the thickness of the film, which serves as the driving force for the flow of electrons from the top and bottom electrodes to "screen" the piezopotential. The generated piezopotential oscillate following the vibration of the cantilever. Therefore, the output voltage/current signal of the NG is a direct measure of the vibration of the cantilever. Therefore, no battery is needed for driving such a sensor.

Results and discussion

The NG is a five-layer structure using densely packed ZnO NWs textured films. Fig. 1b is a scanning electron microscopy (SEM) image of the as-grown ZnO NWs on the substrate. The diameter and length of the nanowires is about 300 nm and 2 μm, respectively. The size of the effective working area of the NG was 16 mm × 14 mm, much smaller than the size of the cantilever. The nanogenerator is attached at the root of the cantilever, where the maximum strain is induced owing to the vibration of the cantilever. The size of the nanogenerator is much smaller than the size of the cantilever so that its presence at the root does not affect the vibration behavior of the cantilever. Fig. 1c shows optical images of a NG when it was at static and was vibrating as excited by a mechanical triggering/impact.

The working principle of the NG is illustrated in Fig. 1d-f. When the cantilever is subjected to a downward deflection (Fig. 1e), a tensile stress is produced along the film. Owing to the presence of the d_{31} component, the ZnO NWs textured film subjects to a compressive strain along the normal direction of the film, which produces a piezopotential drop across the film. If the film is *c*-axis textured, the top and bottom surfaces of the film have negative and

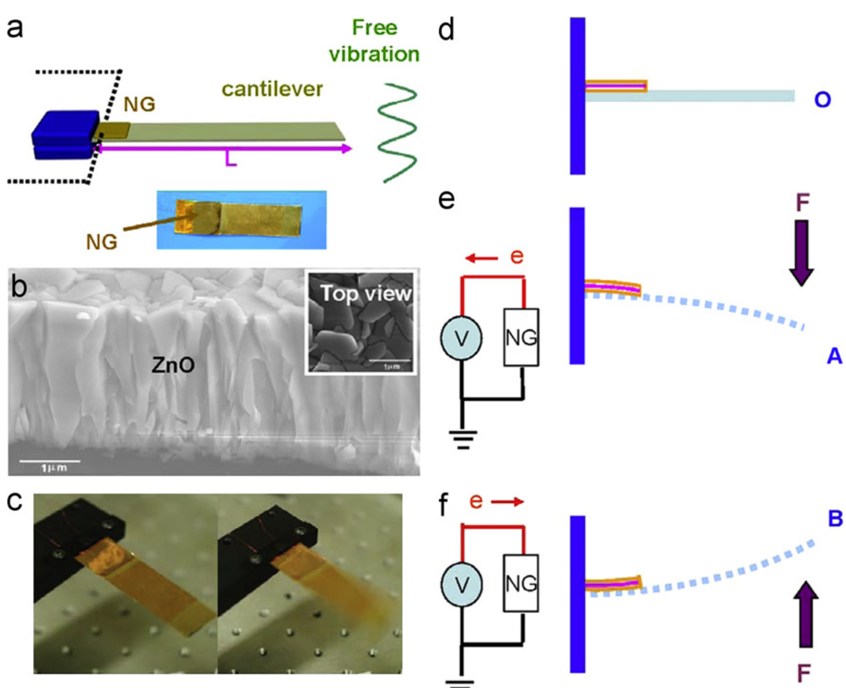

Figure 1 Fabrication of NG and its working mechanism. (a) Schematic of the experimental setup. The lower part is a photo of a NG attached to a cantilever. (b) Cross section SEM image of the as-grown NWs textured film on the PI substrate. The insert is the top view of film. (c) Optical images of a NG when it was static and was being excited by mechanical triggering/impact at the tip. (d) The NG with no vibration application. (e) Electrons flow from the top electrode to the bottom electrode through the external circuit driven by the negative piezoelectric potential generated between the top and bottom ZnO NWs film when the cantilever is subjected to a downward deflection. (f) Electrons flow from the bottom electrode to top electrode through the external circuit driven by the positive piezoelectric potential generated between the top and bottom ZnO NWs film when the cantilever is subjected to an upward deflection.

positive piezopotential, respectively. The piezopotential drives the external electrons to flow from the top electrode to the bottom electrode through an external load that has a much smaller resistance than the NWs film, which is the output electric signal. Owing to the mechanical property of the entire system (NG+cantilever) is dominated by the cantilever, the top layer of the NG and the bottom layer of NG are subjected to different degrees of strain, thus, different outputs of piezopotential. The measured output signal is the difference of the piezopotential from the top and bottom layers. If we define the positive output voltage is the case of electrons flowing from bottom electrode to top electrode in our experiments, a negative voltage is first obtained. By the same token, when the cantilever is deflected upward (Fig. 1f), the film will suffer compressive strain and generates an opposite sign of potential. So, a positive voltage is first received.

The dynamics of the vibration is approximately divided into two phases. Phase I is the initial mechanical triggering that deflects the cantilever to a deflection Z_0 at the tip. Phase II is a free vibration process under elastic restoring force and damping force. Because of the damping force, the vibration will ultimately stop after a certain time. Fig. 2a gives the output voltage vs. time of the NG after triggering. The inset is the output of the cantilever after several period of triggering. It can be seen that once the cantilever is subjected to a triggering at its tip, it will vibrate and generate alternating current voltage signal. The insert is the output voltage of the NG after several excitations, which demonstrates the stability of this structure. All of the output voltage signals have the same waveform. The waveforms of the voltage signals consist of two parts: the first part is that immediately after deflection (phase I), which is followed by the second part of free vibration and decaying oscillation (phase II) [20]. In phase I, the cantilever is displaced to a fixed distance Z_0 by a mechanical trigger for initiating the vibration, after which the cantilever is set to free vibration in ambient condition. Then the vibration of the cantilever is damped after the triggering, showing an exponential attenuation in the generated output voltage from the NG. Fig. 2d is a Fourier transform of the vibration amplitude, clearly displaying the first harmonic and second harmonic resonance frequencies.

Synchronization of the output voltage with the motion of the cantilever could be observed, and the amplitude decayed to zero after approximately 0.4 s. The response of voltage signals to vibration shows that the NG can act as a self-powered vibration sensor. The sensor not only may be used in detecting some sudden triggering/vibration and give alarm, but also used in process control and detection in some vibration environment. Voltage signals were also measured when a triggering in opposite direction was applied at the tip of cantilever. Fig. 2b gives the experiment results, which well agree with the above analysis about the vibration process. One can judge the direction of the triggering according to initial output voltage. If the positive voltage corresponds to upward movement and negative voltage corresponds to downward movement, when negative initial voltage is observed, one will clearly know the direction of the initial impact. So, the NG also can be used as a self-powered directional sensor.

Based on the piezoelectric constitutive equation and Euler–Bernoulli beam theory, we can calculate the open-circuit voltage at different phases [21–24]. In phase I, the force is concentrated at the tip of the cantilever and the movement is similar to a static process. So, the maximum initial open-circuit output voltage is approximately

$$V_0 \sim -CZ_0 \tag{1}$$

where C is a constant, which is determined by the material parameters of cantilever and ZnO NWs textured film. Z_0 is the tip displacement of cantilever. For the phase II, it is a

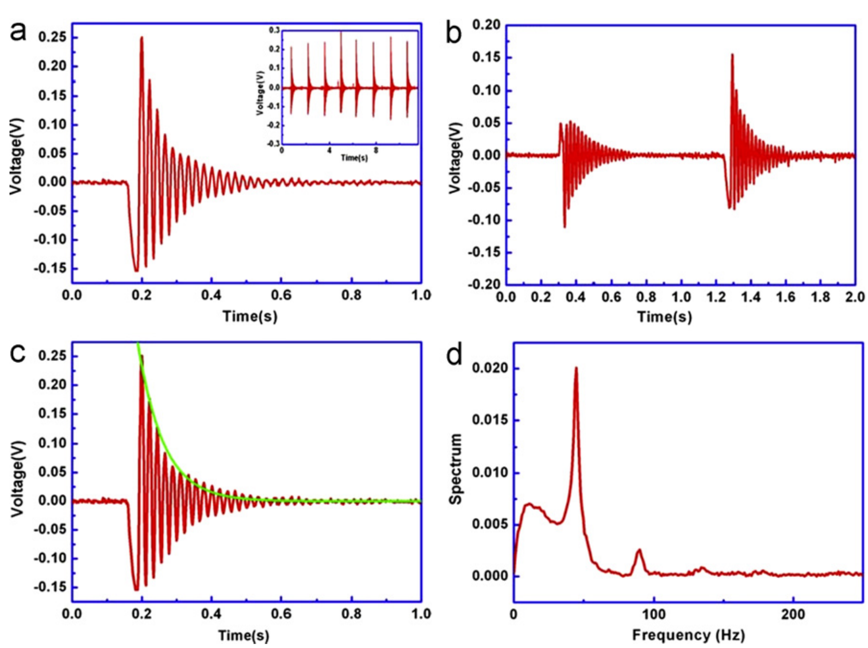

Figure 2 (a) A close view of output voltage of the NG after excitation. The insert is the output voltage of the NG after several excitations. (b) Self-powered directional sensors (left: upward deflection, right: downward deflection). (c) Fitted amplitude of output voltage used exponentially function. (d) Frequency spectrum of (a).

dynamic process. The generated voltage can be written as a function of time t as

$$V \sim C_0 T_0 e^{-\beta t} \cos(\omega t + \varphi) \quad (2)$$

where C_0 and ω are constant, which are all determined by the material parameters of the cantilever and ZnO NWs textured film. T_0 and φ is determined by the initial condition of triggering.

Fitting the amplitude of output voltage used exponential function $A_0 e^{-\beta t}$ yielding damping factor β of 13 as shown in Fig. 2c. A Fourier transform of Fig. 2a gives the first order resonance frequency f of 44.1 Hz. Using the relationship of $\zeta \approx \beta/2\pi f$ and $Q = 1/2\zeta\sqrt{1-\zeta^2}$, the first order damping ratio ζ of 0.047 and Q-factor of 10.6 were also obtained [9]. According to the Bernoulli–Euler theory of beams [24], the resonance frequency of the fundamental bending vibration of the cantilever is expressed by

$$f = \frac{3.52}{2\pi L^2}\sqrt{\frac{EI}{\rho A}},$$

where E is the Young's modulus of the beam material, I is the geometrical moment of inertia, A is the cross-sectional area, ρ is the mass density per unit volume, and L is the length of the cantilever. In reference to the material parameters and the geometrical shape of the cantilever: L=47.1 mm, W=23 mm, T=0.15 mm, E=127 GPa, and ρ=8260 kG/m^3, the resonance frequency was calculated to be 42.6 Hz, and the experimentally measured resonance frequency was 44.1 Hz. The result indicates the effect of the attached ZnO NWs textured film to the first order resonance frequency was extremely small and the first order resonance frequency of output electrical signals was mainly determined by cantilever. The vibration of cantilever is well reflected by the electrical signals. So, the NG can be used as a self-powered vibration sensor to detect vibration frequency.

Fig. 3a gives characteristic parameters of the variation with different lengths of cantilever. When the length of the cantilever is 30 mm, its first order frequency is over 100 Hz. Moreover, the relation between frequency and length meets $f \propto L^{-2}$. By the same token, β and ζ were deduced by fitting the voltage curve. The relationship is shown in Fig. 3b. With the decreasing of length, β increases. But the ζ is not proportional to the length of cantilever (see Fig. 5), which is likely caused by the nonlinear of the vibration and dependence of the output voltage on the straining rate.

Further, the initial open-circuit output voltage under different excited displacement was also studied in Fig. 4. Changing the tip displacement of the cantilever, serials of damping curve was obtained (Fig. 4a). As the tip displacement increased from 2 mm to 16 mm, the deformation of the cantilever increased, or, in other words, the strain applied on the ZnO NWs textured film increased, which resulted in an increase in the output voltage from 0.03 V to

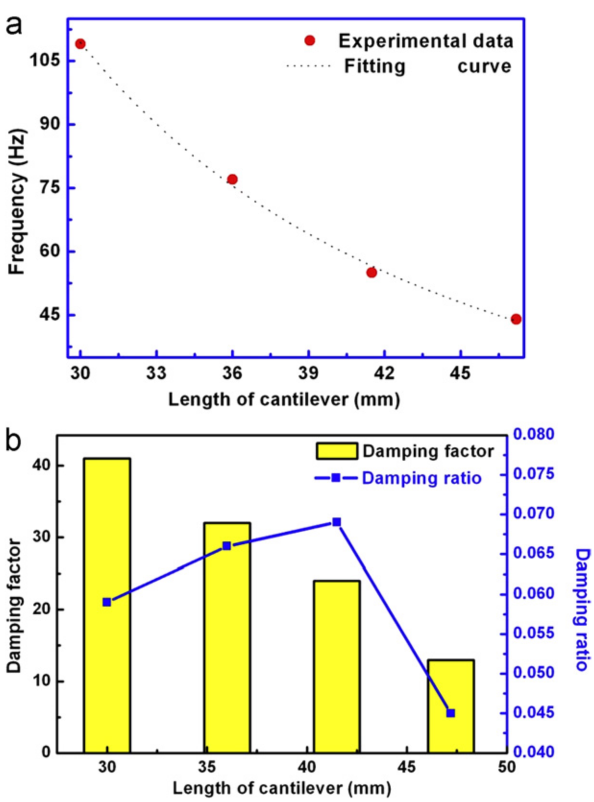

Figure 3 (a) The relationship between frequency of output voltage and length of cantilever. Experimental data (red circle) and fitting data (dashed black curve). (b) Damping factor and damping ratio under different cantilever length.

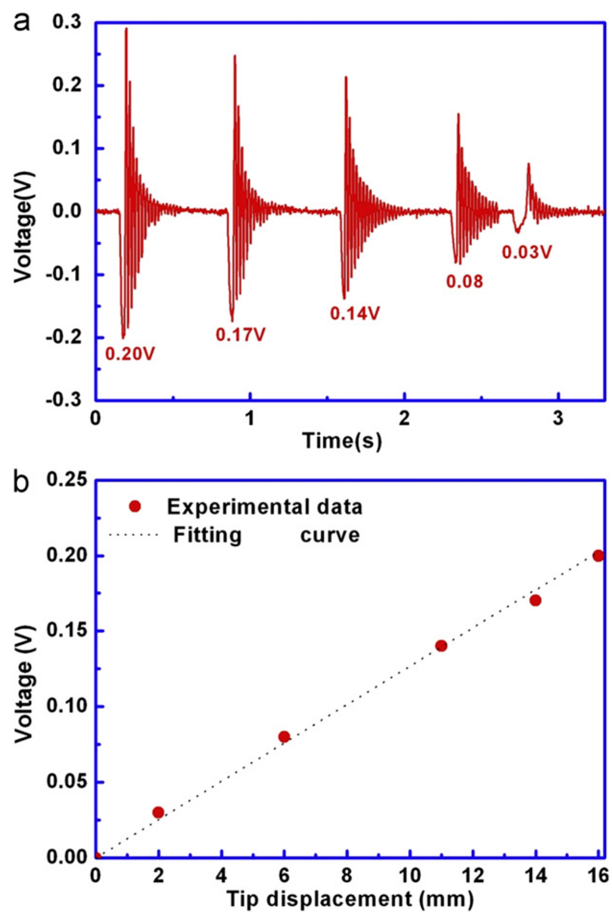

Figure 4 (a) Damping curve of output voltage at different tip displacement. (b) The relationship between initial open-circuit voltage of NG and tip displacement of cantilever. Experimental data (red circle) and fitting data (dashed black curve).

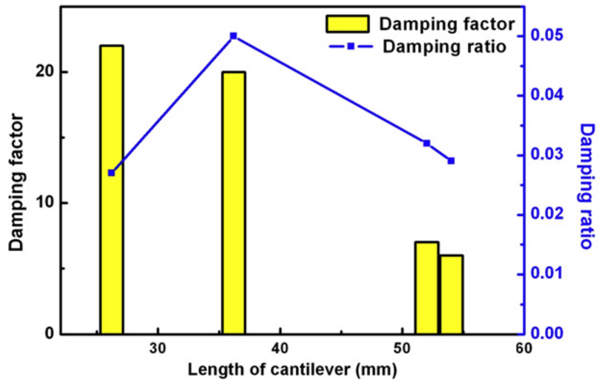

Figure 5 Damping factor and damping ratio of another device with different cantilever parameters.

0.2 V. The generated output voltage from the NG is proportional to the Z_0 applied to the cantilever (Fig. 4b). The V_0 value increased linearly with Z_0, which have good consistence with the formula (1). This relationship clearly supports the evidence that the piezoelectric output generated by the vibration system follows mechanical-piezoelectric energy conversion. Based on the relationship between V_0 and Z_0, the NG shows the potential as self-powered shock sensor for safety and security.

Conclusions

In summary, we demonstrated the first application of a piezoelectric NG as a self-powered sensor for detecting the vibration status of a cantilever. Once the cantilever vibrates, the ZnO NWs textured film will be bent and create transverse strain, which induces a potential drop between the top and bottom electrodes of the NG. The frequency of electrical signal is proportional to L^{-2} and the amplitude of its initial open-circuit voltage increased linearly with Z_0. The synchronization between the output voltage and the motion of the cantilever and the linear relationship between initial V_0 and Z_0 shows that the NG can be used as self-powered vibration sensors. These sensors not only may be used in detecting some sudden triggering/vibration and give alarm, process control and detection in some vibration environment, but also act as self-powered directional sensor and frequency detector of a vibration system for security and safety applications.

Acknowledgment

This research was supported by Knowledge Innovation Program of Chinese Academy of Sciences (KJCX2-YW-M13). Thanks to Dr. Youfan Hu for helpful assistances and discussions, and Jianming Zhang, Haoying Tang and Tengjiao Liu for technical assistance.

Appendix A. Supplementary information

Damping factor and damping ratio of another device with different cantilever parameters, and video of output voltage of a NG after excitation online version at doi:10.1016/j.nanoen.2011.12.006.

References

[1] Y. Itakura, N. Fujii, T. Sawada, Physics and Chemistry of the Earth (B) 25 (2000) 717–720.
[2] E.P. James, M.J. Tudor, S.P. Beeby, N.R. Harris, P. Glynne-Jones, J.N. Ross, N.M. White, Sensors and Actuators A 110 (2004) 171–176.
[3] K. Fischer, S.G. Mayr, Advanced Materials 23 (2011) 3838–3841.
[4] P. Glynne-Jones, N.M. White, Sensor Review 21 (2001) 91–98.
[5] Z.L. Wang, Self-Powering Nanotechnology Scientific American 298 (2008) 82–87.
[6] R. Bogue, Sensor Review 29 (2009) 194–199.
[7] R. Byrne, D. Diamond, Nature Materials 5 (2000) 421–424.
[8] K.A. Cook-Chennault, N. Thambi, A.M. Sastry, Smart Materials and Structures 17 (2008) 043001.
[9] L. Gu, C. Livermore, Smart Materials and Structures 20 (2011) 045004.
[10] F. Cottone, H. Vocca, L. Gammaitoni, Physical Review Letters 102 (2009) 080601-1-080601-4.
[11] K. Morimoto, I. Kanno, K. Wasa, H. Kotera, Sensors and Actuators A 163 (2010) 428–432.
[12] Z.L. Wang, J. Song, Science 312 (2006) 242–246.
[13] R. Yang, Y. Qin, L. Dai, Z.L. Wang, Nature Nanotechnology 4 (2009) 34–39.
[14] D. Choi, M.Y. Choi, W.M. Choi, H.J. Shin, J.S. Seo, J. Park, S.M. Yoon, S.J. Chae, Y.H. Lee, S.W. Kim, J.Y. Choi, S.Y. Lee, J.M. Kim, Advanced Materials 22 (2010) 2187–2192.
[15] X.Y. Wang, K. Kim, Y.M. Wang, M. Stadermann, A. Noy, A.V. Hamza, J.H. Yang, D.J. Sirbuly, Nano Letters 10 (2010) 4901–4907.
[16] S. Xu, Y. Qin, C. Xu, Y. Wei, R. Yang, Z.L. Wang, Nature Nanotechnology 5 (2010) 366–373.
[17] M. Lee, J. Bae, J. Lee, C.S. Lee, S. Hong, Z.L. Wang, Energy and Environmental Science 4 (2011) 3359–3363.
[18] Y.F. Hu, Y. Zhang, C. Xu, L. Lin, R.L. Snyder, Z.L. Wang, Nano Letters 11 (2011) 2572–2577.
[19] B.J. Hansen, Y. Liu, R.S. Yang, Z.L. Wang, ACS Nano 4 (2010) 3647–3652.
[20] M. Umeda, K. Nakamura, S. Ueha, Japanese Journal of Applied Physics 35 (1996) 3267–3273.
[21] W.G. Cady, Piezoelectricity, McGraw-Hill, New York, 1946.
[22] J. Twiefel, B. Richter, T. Hemsel, J. Wallaschek, Proceedings of the SPIE 6169 (2006) 45–54.
[23] S. Timoshenko, Optical Society of America 11 (1925) 233–255.
[24] K.F. Graff, Wave Motion in Elastic Solids, Dover, New York, 1991.

Aifang Yu obtained her Ph.D degree (2007) from Technical Institute of Physics and Chemistry, Chinese Academy of Science. She joined the group of Professor Zhong Lin at National Center for Nanoscience and Technology of China in 2009. Her main research interests focus on the fields of nanogenerators and self-powered nanosystems.

Peng Jiang received BS and MS degrees in Chemistry from Lanzhou University, China, in 1990 and 1993, respectively. After that, he obtained a PhD degree in physical chemistry from Peking University in 1999, and was then a postdoctoral researcher in Institute of Physics, Chinese Academy of Sciences, from 1999 to 2001. He joined Fritz-Haber-Institut der Max-Planck-Gesellschaft, Germany, as a postdoctoral associate from 2001 to 2003. In 2004, he

became an associate professor in the National Center for Nanoscience and Technology of China. He was a visiting scholar at CEA, CNRS, Lab Organ Nanostruct & Semicond, France, from 2005 to 2006. He currently is a full professor in the National Center for Nanoscience and Technology of China. His research interests include synthesis, physical and chemical properties of metal and semiconductor nanomaterials.

Zhong Lin (ZL) Wang received his PhD from Arizona State University in transmission electron microscopy. He now is the Hightower Chair in Materials Science and Engineering, Regents' Professor, Engineering Distinguished Professor and Director, Center for Nanostructure Characterization, at Georgia Tech. Dr. Wang's publications have been cited for over 46,000 times. The H-index of his citations is 103. Dr. Wang was elected as a foreign member of the Chinese Academy of Sciences in 2009, member of European Academy of Sciences in 2002, fellow of American Physical Society in 2005, fellow of AAAS in 2006, fellow of Materials Research Society in 2008, fellow of Microscopy Society of America in 2010, and fellow of the World Innovation Foundation in 2002. He is an honorable professor of over 10 universities in China and Europe. He received 2011 MRS Medal from the Materials Research Society, 1999 Burton Medal from Microscopy Society of America, 2001 S.T. Li prize for Outstanding Contribution in Nanoscience and Nanotechnology, and the 2009 Purdy Award from American Ceramic Society. Details can be found at: http://www.nanoscience.gatech.edu.