Nano Energy 76 (2020) 105051

Contents lists available at ScienceDirect

Nano Energy

journal homepage: http://www.elsevier.com/locate/nanoen

Novel wireless power transmission based on Maxwell displacement current

Yandong Chen [a,b,1], Yang Jie [a,b,1], Ning Wang [d,**], Zhong Lin Wang [a,b,e,***], Xia Cao [a,b,c,d,*]

[a] CAS Center for Excellence in Nanoscience, Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, National Center for Nanoscience and Technology(NCNST), Beijing, 100083, China

[b] College of Nanoscience and Technology, University of Chinese Academy of Sciences, Beijing, 100049, China

[c] Center on Nanoenergy Research, School of Physical Science and Technology, Guangxi University, China

[d] Research Center for Bioengineering and Sensing Technology, Beijing Key Laboratory for Bioengineering and Sensing Technology, School of Chemistry and Biological Engineering, And Beijing Municipal Key Laboratory of New Energy Materials and Technologies, University of Science and Technology Beijing, Beijing, 100083, China

[e] School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, 30332-0245, GA, United States

ARTICLE INFO

Keywords:
Wireless power transmission
Maxwell displacement current
Triboelectric nanogenerator
High frequency electric field

ABSTRACT

Wireless power transmission (WPT) is vitally important for portable electronics. Recently, wireless energy delivery via Maxwell displacement current from triboelectric nanogenerator may open new routes to develop novel technologies especially for implantable medical devices and sensor network due to its flexibility, adaption, convenience and safety. In this paper, the propagation characteristics of WPT are explored, which are based on displacement current from a spherical high frequency electric field. The results showed that the spherical surfaces with the same radius from the center have equal value of electric field intensity. When the receiver has a larger area or workload, the output has a higher value, which is subject to the electric field intensity. However, the current is almost unchanged with increasing output power below 15 kΩ of load resistance in series, which may have potential applications for sensors. Furthermore, the receiver circuit of wireless energy is in accordance with the traditional serial and parallel circuit regularity. Based on these, we are going to assume that the electric field source is a reservoir, and water flow is analogous to current. The assumption is suitable for studying propagation characteristics. This new discovery may also offer a new research direction for WPT based on Maxwell displacement electric field.

1. Introduction

Energy is the foundation of today's society. Electromagnetic generator (EMG) has been the dominant technology to generate commercial power since the first discovery of the electromagnetic induction phenomenon [1]. Electricity has propelled the world-wide economical development and changed the world. However, it is desperately needed to find new energy sources as alternatives to fossil fuels due to energy shortage, environmental pollution and depletion of the fossil fuel increasing. Recently, triboelectric nanogenerator (TENG) has attracted more and more attention owing to its lightweight, low cost and environmentally friendliness [1–5]. It has been proved to be a new energy harvesting device to efficiently scavenge ambient mechanical energy for self-powered micro/nanosystem applications, blue energy and even big data [6–16]. Unlike the EMG, TENG is based on the coupling of the contact-electrification effect and electrostatic induction to convert the ambient mechanical energy into electricity [17,18]. Moreover, the fundamental theory of the TENG starts from the Maxwell equations [19,20], which are among the top 10 most important equations for physics. Displacement current as one of the most greatest creative ideas was first postulated by Maxwell in 1861 [21]. The displacement current is a time-varying electric field (vacuum or media), plus a contribution from the slight motion of charge bound in atoms, dielectric polarization in materials, which differs from conduction current depending on moving free charges. It is defined as:

* Corresponding author. CAS Center for Excellence in Nanoscience, Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, National Center for Nanoscience and Technology(NCNST), Beijing, 100083, China.

** Corresponding author.

*** Corresponding author. College of Nanoscience and Technology, University of Chinese Academy of Sciences, Beijing, 100049, China.

E-mail addresses: wangning@ustb.edu.cn (N. Wang), zlwang@gatech.edu (Z.L. Wang), caoxia@ustb.edu.cn (X. Cao).

[1] These authors contributed equally to this work

https://doi.org/10.1016/j.nanoen.2020.105051
Received 30 April 2020; Received in revised form 1 June 2020; Accepted 2 June 2020
Available online 17 June 2020
2211-2855/

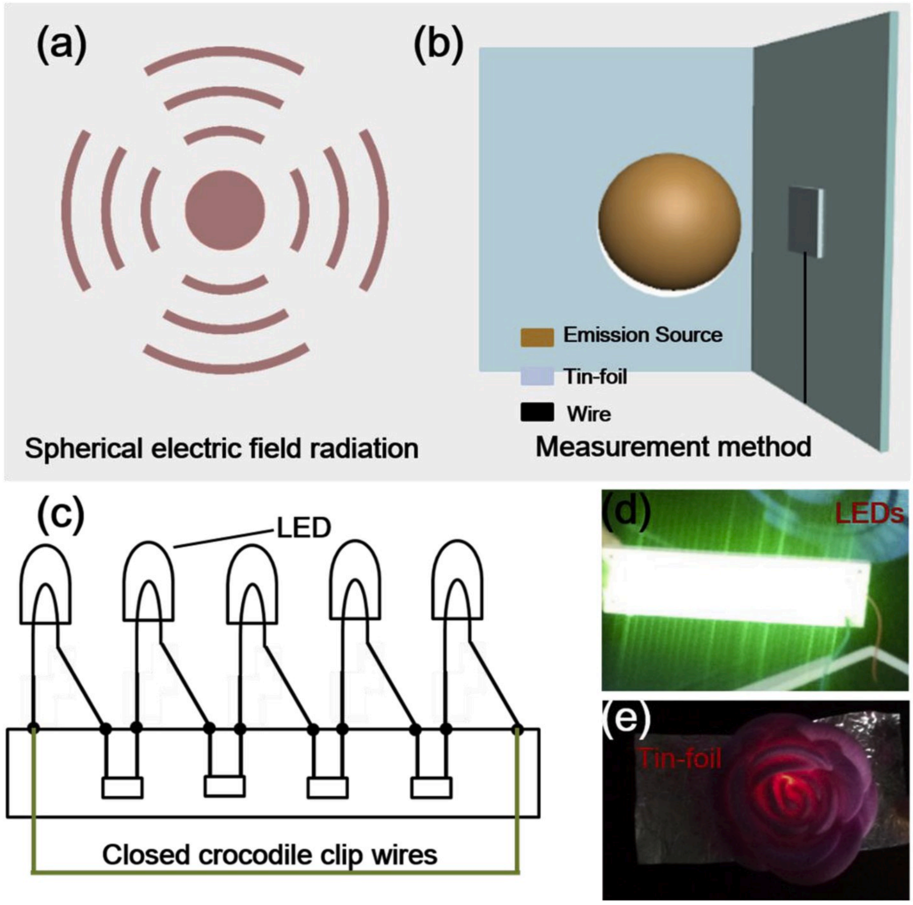

Fig. 1. Wireless power delivery of spherical electric field. (a) Schematic diagram of electric field radiation. (b) Test method of electric field for wireless power. (c) The schematic diagram of circuit connection for lighting LEDs (d, e) Photograph of the wireless power for driving LEDs (d) and rose lamp (e).

$$J_D = \frac{\partial \boldsymbol{D}}{\partial t} = \varepsilon \frac{\partial \boldsymbol{E}}{\partial t} + \frac{\partial \boldsymbol{P}_s}{\partial t} \quad (1)$$

where the $\boldsymbol{\varepsilon}$ is the permittivity of free space, $\boldsymbol{D}$ is displacement field, $\boldsymbol{E}$ is the electric field intensity, and $\boldsymbol{P_s}$ is the polarization density introduced by the surface electrostatic charges owing to contact-electrification effect.

In Eq. (1), the first component $\varepsilon \frac{\partial E}{\partial t}$ gives the birth of electromagnetic wave, which establishes foundation to develop wireless communication, radio, radar, TV, microwave, light theory, space technology, photonics, and many more [21]. It has driven the development of world in communication and laser technology in the last century, which has changed people's way of life. Meanwhile, the newly added term $\partial \boldsymbol{Ps}/\partial t$ is the application of Maxwell displacement current in energy and sensors, which was first proposed by Wang for the nanogenerators [22]. It is important to note that the $\boldsymbol{P_s}$ term is different from medium polarization $\boldsymbol{P}$ which induced by the electric field. The $\boldsymbol{P_s}$ is the polarization created by the electrostatic surface charges owing to mechanical triggering, and is simply called Wang term. This excellent work provides the theoretical rational for further study of piezoelectric nanogenerator and triboelectric nanogenerator. It can quantify the nanogenerators' output and provide theoretical guidance for performance improvements [20,21,23]. Furthermore, the electromagnetic radiation from nanogenerator systems can be calculated if they have high operating frequency [21]. Therefore, it may expand the scope of nanogenerators' application in wireless power transmission using displacement current.

It is generally known that metal wires are the primary medium of power transmission. However, with the development and improvement of the technology in recent years, wireless power transmission (WPT) technology is getting more concern because of its advantages of its high flexibility, adaption, convenience and safety for charging handhold electronics and devices for the internet of things [24–26]. At present, wireless transmission mainly includes electromagnetic induction, magnetic resonance, and radio wave, which mainly depends on the EMG relying on the Lorentz force driven flow of free electrons in a metal coil. As a new environmental energies harvester, TENG based on the Maxwell displacement current has also been designed for wireless energy delivery [27–29]. These studies show the applications of wireless energy delivery by TENG in areas of portable and wearable electronics. As depicted in previous studies [20,21], nanogenerator systems can produce electromagnetic radiation when the nanogenerator systems operating at high frequency. So, it is significant to explore the propagation characteristics based on Maxwell displacement current at high operating frequency.

Here, a high frequency electric field was applied to explore the wireless power transmission characteristics based on displacement current. Tin-foils with different areas are served as receivers for receiving wireless power from the electric field. Meanwhile, oscilloscopes are applied to measure the receiving-end voltages. It shows that the test points with same radius from the center have the equal value of electric field intensity. The receiving voltage and power from spherical electric field will nonlinearly increase along with the increase of receiving area and workload. However, the current is almost unchanged below 15 kΩ of load resistance. It may have potential applications for sensors. Most importantly, we have presented a new model inspired by reservoir for explaining the propagation characteristics of WPT based on displacement current.

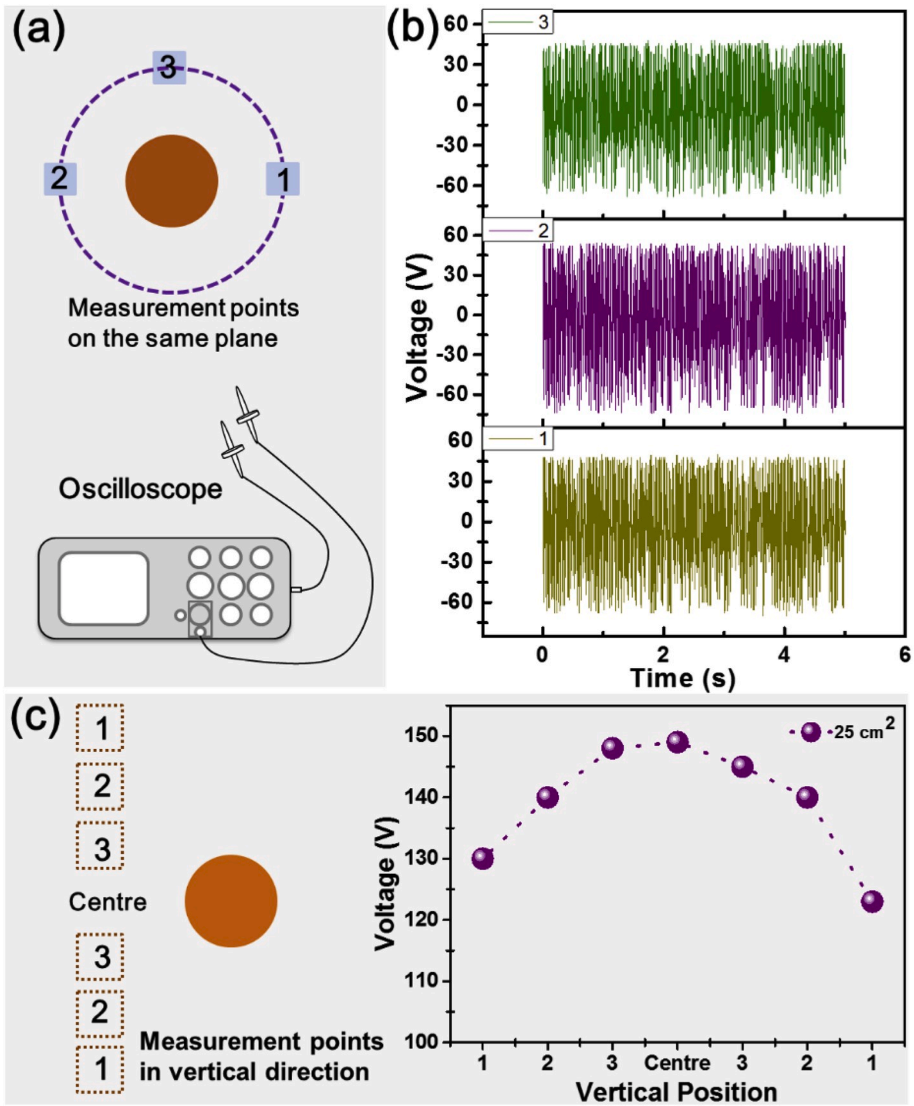

Fig. 2. (a) Schematic diagram of oscilloscopes for measuring voltages. (b) The voltages of receivers. (c) The receiver at different locations of symmetric distribution in the vertical direction.

2. Results and discussion

As schematically shown in Fig. 1a, a spherical electric field radiation is adopted to explore the propagation characteristics of WPT based on displacement current. A piece of tinfoil as the receiver is attached to the Poly (methyl methacrylates) (PMMAs) for measuring radiant energy from the electric field in following study in Fig. 1b. As exhibited in Fig. 1d, numbers of LEDs in series can be lit up by using the circuit connection in Fig. 1c, and the bottom of crocodile clip wires as the receiver are 10 cm away from the electric field center. Similarly, a mobile phone can be driven only through connecting mobile phone charger, which is illustrated in Fig. S1. More interestingly, the rose lamp placed on a piece of tin-foil can also be illuminated at the same distance in Fig. 1e. It makes us surprised and excited. These interesting phenomena are similar as the previous studies about wireless capacitive energy transfer by Thomas [30–32]. Therefore, it is significant to explore the propagation characteristics of WPT depending on displacement current.

As presented in Fig. 2a, three pieces of tinfoil with 5 cm × 5 cm size are placed at the same height but in different positions. Meanwhile, three oscilloscopes are simultaneously applied to measure the voltages. The output performances of three receivers with 10 cm away from the electric field center at 100 kΩ of resistance are displayed in Fig. 2b. The average output peak-to-peak open-circuit voltage is about 105 V for each of receivers. The results show that they are on equipotential line which means the spherical surfaces with the same radius from the center have the equal value of electric field intensity. Similarly, a receiver in two different locations of symmetric distribution may have the same values in the vertical direction. As depicted in Fig. 2c, a receiver with 5 cm × 5 cm size for receiving electric field energy has been used for explore this regulation. Line charts indicate that the results basically correlated with the characteristic. These results suggest that the radiant energy from the electric field is uniformly distributed in the space. Then the propagation characteristics were also studied.

Fig. 3a shows the receiving-end voltage decreases with increasing distance while the load resistor is 100 kΩ at the receiving area 5 cm × 5 cm. When the distances ranged from 0 cm to 20 cm, the voltage across the load decreases rapidly. The voltage reduces from 220 V to 65 V. It suggests that the propagation of electric field radiation will be damping when flying in the air due to air attenuation. Furthermore, the receiving voltage increases with the increase of receiving area at 100 kΩ of resistance (Fig. 3b). However, it will not increase infinitely along with the increase of receiving area when the electric field density is constant. Meanwhile, workload is a vital factor for receiving voltage amplitude. As

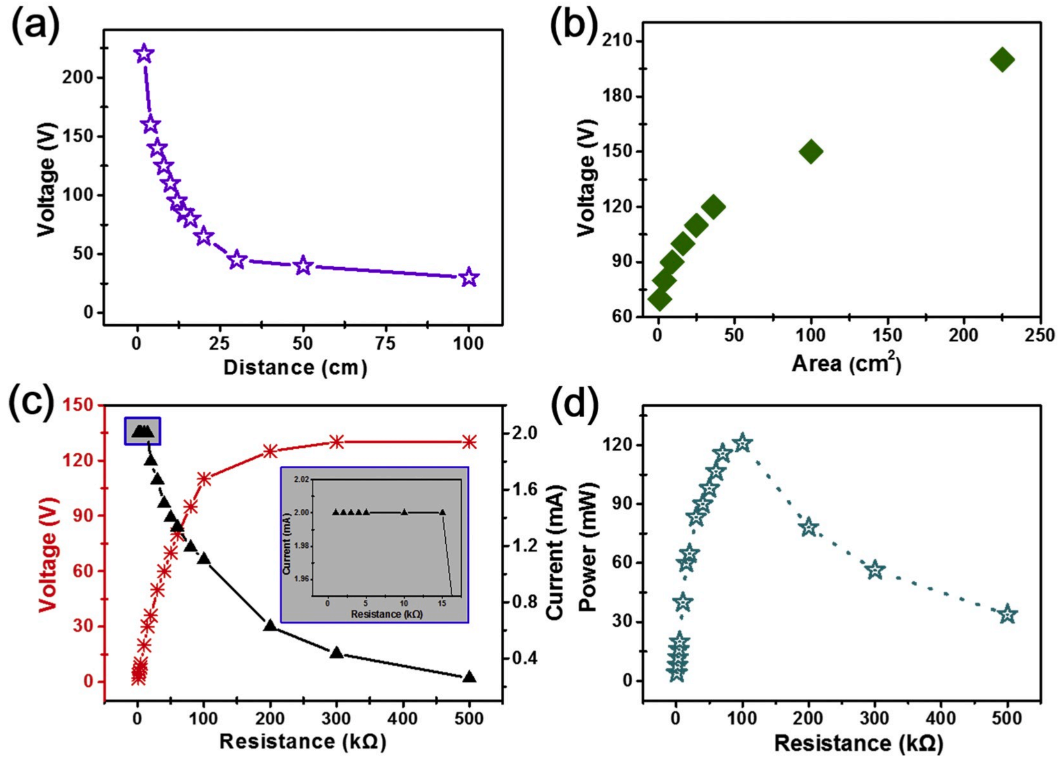

Fig. 3. (a) Voltage decreases with increasing distance at the receiving area 5 cm × 5 cm. (b) Receiving voltage increases with the increase of area at 100 kΩ of resistance. (c) Voltage and current of receiver increases with increasing loading resistance, inserts: unchanged current below 15 kΩ of load resistance. (d) The output power with loading resistance.

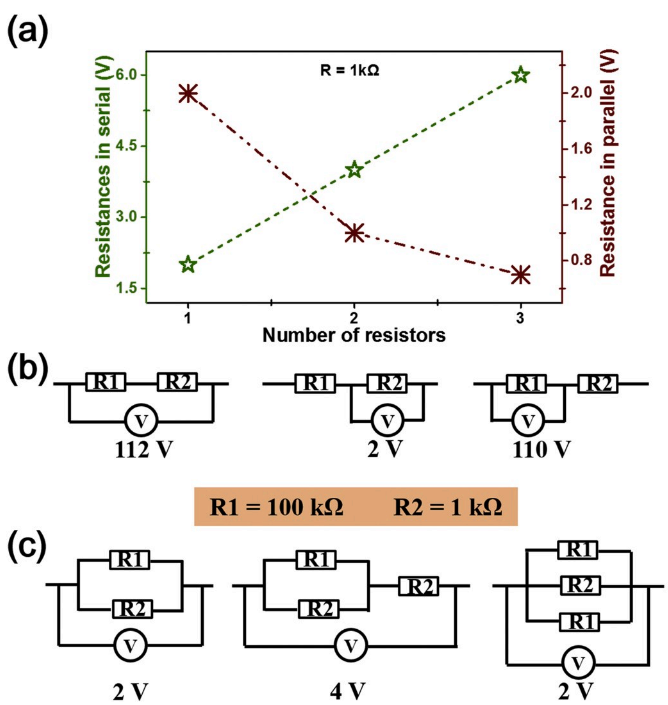

Fig. 4. (a) The voltage changes of resistors in series and in parallel using 1 kΩ. (b, c) Exploration of (b) serial and (c) parallel circuit regularity using 1 kΩ and 100 kΩ resistors.

is illustrated in Fig. 3c, the voltage of receiver increases with increasing loading resistance under the same receiving area (5 cm × 5 cm) and distance (10 cm) before 100 kΩ, subsequently increased slowly. Most interestingly, the current is almost unchanged below 15 kΩ of load resistance (Fig. 3c, inserts). The results indicate that the ratio of resistor to voltage is constant in a certain range, which may have promising potentials for wireless sensing network. In addition, Fig. 3d shows the output power of the receiving end increases in the resistance region from 1 kΩ to 100 kΩ and then decreases with the resistance above 100 kΩ. Consequently, the power reaches the maximum value of 121 mW at a resistance of 100 kΩ. Therefore, it is essential to select matched components to get the maximum wireless power from the electric field.

In practical application, workloads may take different circuit connections. Therefore, resistors in series and in parallel have also been preliminary studied by using 1 kΩ and 100 kΩ resistors, as is depicted in Fig. 4. The results indicate that the receiver circuit of wireless energy is in accordance with the traditional serial and parallel circuit regularity when the workload and receiving area at a certain range of values.

3. Conclusion

In summary, the receiving voltage and power from spherical electric field will nonlinearly increase along with the increase of receiving area and workload. Moreover, it is limited by the electric field density. Most interestingly, the current is almost unchanged below 15 kΩ of load resistance, which may have promising potentials for sensors. Furthermore, the receiver circuit of wireless energy is in accordance with the traditional serial and parallel circuit regularity. Based on these, we can assume that the electric field source is a reservoir. Water has the equivalently potential energy with a different location in the same altitude position. When there is a hole in the dam, water will flow out of the reservoir. Moreover, the larger cave mouth size, the greater flow of water. Similarly, when the receiver has a larger area or workload, the output has a higher value. However, if the hole reaches a considerable size, water flow will not further increase because of the finite storage. Of course, when the hole size increase below a certain value, water flow will remain unchanged due to the reduced velocity. If this value is above a certain threshold, reduced velocity rate will be less than the rate of increased hole size. Then total water flow is nonlinearly increasing with the hole size. The model is suitable for explaining the propagation characteristics of WPT based on displacement current. Therefore, it is hoped that this research can be helpful to related studies in this field.

4. Experimental section

Spherical electric field radiation is adopted to explore the propagation characteristics of WPT based on displacement current. Tinfoils as the energy receiver are attached to the PMMAs. Oscilloscopes are applied to measure the receiving-end voltages.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Yandong Chen: Methodology, Formal analysis, Investigation, Data curation, Writing - original draft. **Yang Jie:** Methodology, Investigation, Writing - original draft. **Ning Wang:** Writing - review & editing. **Zhong Lin Wang:** Writing - review & editing. **Xia Cao:** Conceptualization, Supervision, Writing - review & editing.

Acknowledgements

We thank the financial support from the National key R and D project from Minister of Science and Technology, China (2016YFA0202702, 2016YFA0202701). The National Postdoctoral Program for Innovative Talents (No. BX20180081), and China Postdoctoral Science Foundation (No. 2019M650604). Patents have been filed to protect the reported inventions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.nanoen.2020.105051.

References

[1] Z.L. Wang, Nat. News 542 (2017) 159.
[2] F.-R. Fan, Z.-Q. Tian, Z.L. Wang, Nano Energy 1 (2012) 328–334.
[3] X. Cao, Y. Jie, N. Wang, Z.L. Wang, Adv. Energy Mater. 6 (2016), 1600665.
[4] Z.L. Wang, J. Chen, L. Lin, Energy Environ. Sci. 8 (2015) 2250–2282.
[5] A. Ahmed, I. Hassan, T. Ibn-Mohammed, H. Mostafa, I.M. Reaney, L.S. Koh, J. Zu, Z.L. Wang, Energy Environ. Sci. 10 (2017) 653–671.
[6] H. Fang, X. Wang, Q. Li, D. Peng, Q. Yan, C. Pan, Adv. Energy Mater. 6 (2016), 1600829.
[7] W. Xu, L.B. Huang, M.C. Wong, L. Chen, G. Bai, J. Hao, Adv. Energy Mater. 7 (2017) 1601529.
[8] S.Y. Shin, B. Saravanakumar, A. Ramadoss, S.J. Kim, Int. J. Energy Res. 40 (2016) 288–297.
[9] U. Shaislamov, Y. Kim, W.S. Kim, H. Jeong, H.J. Lee, W. Chun, Int. J. Energy Res. 41 (2017) 1412–1421.
[10] G. Zhu, J. Chen, T. Zhang, Q. Jing, Z.L. Wang, Nat. Commun. 5 (2014) 3426.
[11] B. Meng, W. Tang, Z.-h. Too, X. Zhang, M. Han, W. Liu, H. Zhang, Energy Environ. Sci. 6 (2013) 3235.
[12] W. Seung, M.K. Gupta, K.Y. Lee, K.-S. Shin, J.-H. Lee, T.Y. Kim, S. Kim, J. Lin, J. H. Kim, S.-W. Kim, ACS Nano 9 (2015) 3501–3509.
[13] J. Qian, D.-S. Kim, D.-W. Lee, Nano Energy 49 (2018) 126–136.
[14] W. Tang, T. Jiang, F.R. Fan, A.F. Yu, C. Zhang, X. Cao, Z.L. Wang, Adv. Funct. Mater. 25 (2015) 3718–3725.
[15] Z. Liu, H. Li, B. Shi, Y. Fan, Z.L. Wang, Z. Li, Adv. Funct. Mater. 29 (2019), 1808820.
[16] J. Sun, A. Yang, C. Zhao, F. Liu, Z. Li, Sci. Bull. 64 (2019) 1336–1347.
[17] Y. Chen, Y. Cheng, Y. Jie, X. Cao, N. Wang, Z.L. Wang, Energy Environ. Sci. 12 (2019) 2678–2684.
[18] Y. Guo, Y. Chen, J. Ma, H. Zhu, X. Cao, N. Wang, Z.L. Wang, Nano Energy 60 (2019) 641–648.
[19] D.-M. Shin, H.J. Han, W.-G. Kim, E. Kim, C. Kim, S.W. Hong, H.K. Kim, J.-W. Oh, Y.-H. Hwang, Energy Environ. Sci. 8 (2015) 3198–3203.
[20] Z.L. Wang, Mater. Today 20 (2017) 74–82.
[21] Z.L. Wang, Nano Energy (2019) 104272.
[22] Z.L. Wang, Nano Energy 58 (2019) 669–672.
[23] Z.L. Wang, T. Jiang, L. Xu, Nano Energy 39 (2017) 9–23.
[24] O.C. Onar, J.M. Miller, S.L. Campbell, C. Coomer, C.P. White, L.E. Seiber, Ieee, A novel wireless power transfer for in-motion EV/PHEV charging, in: Twenty-Eighth Annual Ieee Applied Power Electronics Conference and Exposition, Ieee, New York, 2013, pp. 3073–3080, 2013.
[25] D.H. Kim, H.J. Shin, H. Lee, C.K. Jeong, H. Park, G.T. Hwang, H.Y. Lee, D.J. Joe, J. H. Han, S.H. Lee, Adv. Funct. Mater. 27 (2017), 1700341.
[26] C.K. Jeong, J.H. Han, H. Palneedi, H. Park, G.-T. Hwang, B. Joung, S.-G. Kim, H. J. Shin, I.-S. Kang, J. Ryu, Apl. Mater. 5 (2017), 074102.
[27] Y. Jie, J. Ma, Y. Chen, X. Cao, N. Wang, Z.L. Wang, Adv. Energy Mater. 8 (2018), 1802084.
[28] L. Lin, S. Wang, S. Niu, C. Liu, Y. Xie, Z.L. Wang, ACS Appl. Mater. Interfaces 6 (2014) 3031–3038.
[29] X. Cao, M. Zhang, J. Huang, T. Jiang, J. Zou, N. Wang, Z.L. Wang, Adv. Mater. 30 (2018), 1704077.
[30] C. Van Neste, A. Phani, R. Hull, J. Hawk, T. Thundat, IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW), IEEE, 2016, pp. 196–199, 2016.
[31] C. Van Neste, A. Phani, A. Larocque, J. Hawk, R. Kalra, M. Banaag, M. Wu, T. Thundat, IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW), IEEE, 2017, pp. 229–234, 2017.
[32] C. Van Neste, J. Hawk, A. Phani, J. Backs, R. Hull, T. Abraham, S. Glassford, A. Pickering, T. Thundat, Wireless Power Transfer 1 (2014) 75–82.