Nano Energy 51 (2018) 721–727

Contents lists available at ScienceDirect

Nano Energy

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

Full paper

Triboelectric nanogenerator as a highly sensitive self-powered sensor for driver behavior monitoring

Xiaoyi Meng[a,b,1], Qian Cheng[c,1], Xiaobei Jiang[c,1], Zhen Fang[d], Xianxiang Chen[d], Shaoqing Li[a,b], Chenggang Li[c,1], Chunwen Sun[a,b,e,*], Wuhong Wang[c,**], Zhong Lin Wang[a,b,e,f,*]

[a] CAS Center for Excellence in Nanoscience, Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 100083, PR China
[b] School of Nanoscience and Technology, University of Chinese Academy of Sciences, Beijing 100049, PR China
[c] Department of Transportation Engineering, Beijing Institute of Technology, Beijing 100081, PR China
[d] Institute of Electronics, Chinese Academy of Sciences, Beijing 100090, PR China
[e] Center on Nanoenergy Research, School of Physical Science and Technology, Guangxi University, Nanning 530004, PR China
[f] School of Material Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0245, USA

ARTICLE INFO

Keywords:
Triboelectric nanogenerator
Self-powered sensor
Driver behavior monitoring
Intelligent traffic

ABSTRACT

Driver behavior is important for traffic safety and status monitoring. Major parameters in driving behavioral analysis are generally acquired by utilizing some mirror or sensitive but expensive sensors, such as eye tracker, electroencephalograph, etc. Here, we report for the first time a pressure-sensitive, flexible and robust triboelectric nanogenerator (TENG) consisting of Al foil and Kapton materials as a cost-effective sensing device for self-powered driver behavior monitoring. The sensitivity of TENG was evaluated preliminarily by detecting its open-circuit voltage signal in responding to externally enforced perturbation. A real-time monitoring system is demonstrated with TENGs, data-collecting unit and a driving simulator. A preliminary assessment of the real-time collected data demonstrates that the self-powered sensor is feasible for monitoring a driver's behavior. This work provides a promising strategy for monitoring driver's behavior and will extend TENG-based sensors for practical applications in vehicles as well as aeronautical and space technologies.

1. Introduction

Road traffic injuries (RITs) are reported to be the eighth-leading cause of death across the world [1]. Poor driver behavior, especially driver distraction, is believed to be directly responsible for the traffic accidents. The National Highway Traffic Safety Administration (NHTSA) made a thorough evaluation by conducting the 100-car Naturalistic Driving Study [2], and indicated that driver inattention was a factor of 78% crashes/near crashes, and most of the inattention phenomena are related to driver distraction. Actually, the primary task of driving only takes about 46% of total time in vehicle [3], the rest of the time is taken up by secondary tasks, for example, texting, navigating or adjusting radio channels. However, these kinds of activities require drivers to deviate their eyes from the road, which is extremely hazardous that the risk of crashing increases three times if the eyes-off-road-time exceeds 2 s [3,4]. The analysis of drivers' driving behaviors could be used in many fields, such as researches on traffic safety [5–8], researches on traffic flow [9,10]. Thus, driver monitoring is of great importance and has been a research focus.

Bright pupil effect based on near-infrared (IR) illuminators is a widely-used approach to monitor driver behavior [11,12]. For example, DD850 Driver Fatigue Monitor (DFM) provides a real-time measurement of eye position and eyelid closure to detect drowsiness [13]. This system is based on a single camera which takes two pictures, one bright-pupil image and one dark-pupil image using IR illumination sources with different wavelength. And the two images are processed further to produce a third image in which drivers' eyes are identified, and the key point of this image is to enhance the bright eyes and exclude all image features except for the bright pupil [14]. In despite of the effectiveness and simplicity of this bright pupil method, several factors impose negative influences on the application such as sunlight, eyeglasses as well as brightness and size of pupils. This method uses an infrared light

* Corresponding authors at: CAS Center for Excellence in Nanoscience, Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 100083, PR China.
** Corresponding author.
E-mail addresses: sunchunwen@binn.cas.cn (C. Sun), wangwuhong@bit.edu.cn (W. Wang), Zhong.wang@mse.gatech.edu (Z.L. Wang).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.nanoen.2018.07.026
Received 25 May 2018; Received in revised form 4 July 2018; Accepted 12 July 2018
Available online 17 July 2018
2211-2855/

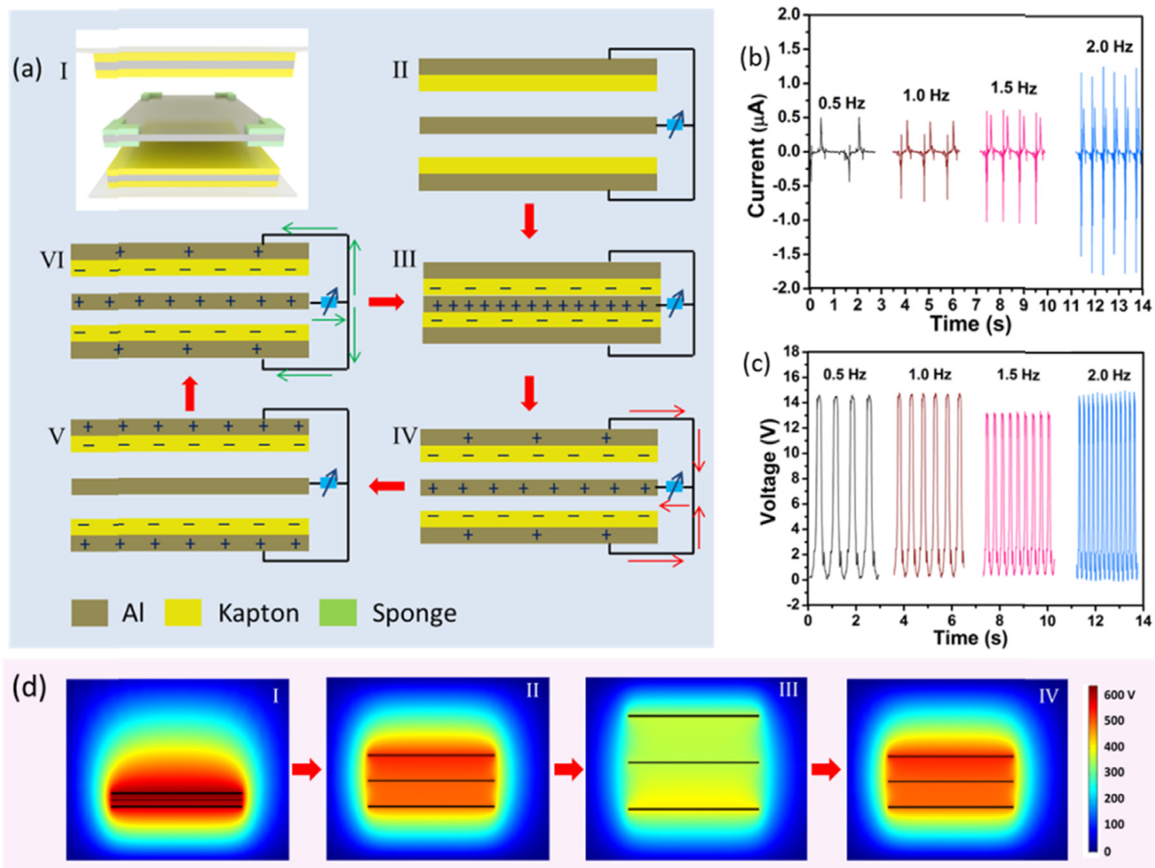


Fig. 1. (a) The electricity signal generation process of TENG. The direction of arrow in (a) represents the direction of electron flow. (b) Short-circuit current of the TENG generated at different test frequencies. (c) Open-circuit voltage of the TENG at different test frequencies. (d) The calculated electric potential distributions corresponding to III , IV, V and VI in (a), respectively.

source to illuminate the human eye and form a bright spot on the cornea. The center of the bright spot and center of the pupil would make up a vector, which has a corresponding relationship with the eye gaze point. Then we can find the position of the eye point of view through this vector, sunlight, eyeglasses as well as brightness; and size of pupils will definitely have a bad influence on the formation of bright spot. Nonetheless, systems based on bright pupil effect are the most common in industry. Several auto companies have designed such systems to observe drivers' drowsiness and distraction. Other auto companies also attempt to monitor driver distraction by observing eye movements. Moreover, this system provides a wide field of view that enables analysis of naturalistic behavior, thus it has been extensively employed in simulators and applied in some inattention systems [15–17]. However, the stereo-based systems exploiting infrared light source are too expensive especially considering mass production. Another widely used method, named magnetic fields based search coil, has many disadvantages over TENG sensing method. It holds a larger area in participants' face. The mapping structure from waveforms to states of eyes might be more complicated, robustness of this method might be weak. Overall, the existing products are not very sensitive to blinking which is also an important parameter to detect driver drowsiness. So far, bright pupil approach is widely accepted while the effectiveness could be easily impaired by some external factors.

Triboelectric nanogenerators (TENGs) are a newly developed energy-harvesting devices that can convert various forms of mechanical energy, ranging from human motion, wind power to ocean waves into electric power by coupling between the contact-electrification effect and electrostatic induction effect [18,19]. It has been developed to harvest these energy used to power electric appliances, including LED light activation and personal wearable electronics [20,21]. Moreover, TENG can be applied to various self-powered sensing units for environmental monitoring and pollution treatment [22–26], medical service [27,28], health monitoring [29–31], positioning sensors [32,33], and other fields [34,35]. In particular, utilization of the TENG as a self-powered pressure sensing component, is being intensively explored because the TENG generates electrical signals based on triboelectric charges induced by physical contact and electrostatic induction resulting from external mechanical excitations like touch or contact collision [36]. To date, various TENG-based sensors with different configurations have been fabricated. Table S1 (Supporting information) summarizes TENG-based sensors and their applications reported recently.

Herein, self-powered TENG-based sensor composed of Kapton and Al foil is introduced for the first time to monitor driver's behavior with a driving simulator, which is of high sensitivity, high stability and low cost compared with the traditional near-infrared illustrator. Importantly, this sensor is capable of capturing eye blink motion with a super-high signal level (~750 mV) and enables real-time measurement. Furthermore, the driver's behavior is well correlated with the collected signals. This work paves a way to explore highly sensitive TENG sensors for monitoring drivers' behavior in various vehicles and improving the traffic safety.

2. Experimental section

2.1. Fabrication of flexible TENGs

Two types of TENG sensors with sizes of 3 × 3 cm and 1.5 × 3 cm were fabricated with the same Al foil and Kapton. The thicknesses of Al foil and Kapton are 15 μm and 25 μm, respectively. The thickness of the

TENG is about 4 mm due to a space between the electrodes.

2.1.1. Characterization and measurement

The output voltage and current of TENG were measured by a Keithley 6514 system electrometer. The open-circuit voltage signals of the driving simulation were acquired with a multichannel data-acquisition equipment (Cdaq-9171 and NI 9239). Static driving simulator with UC Win/Road environmental design is used to record virtual driving in BIT.

3. Results and discussion

TENG was fabricated with Kapton and Al foil as two contact layers, as shown in I of Fig. 1a. The Al foil adhered to sponge at the corner works as one electrode to contact the front and back Kapton films, then another two Al foils stuck on the side of Kapton are used to transfer charge generated on the surface of the Kapton films. By virtue of the sponge adhered to the corner of Al foil in the center, and the ability of elastic Kapton film to recovery, so the TENG exhibits good contact-separation capability. The electricity signal of TENG is generated due to the coupling effect of contact electrification and electrostatic induction during contact-separation operation on the TENG [37]. Fig. 1a shows a cycle of electron flow process from the friction layers to an external load. To start, no charge is generated between the electrodes without externally applied force (II in Fig. 1a). When Al foil and Kapton are contacted with each other, charge transfer occurs at the interface due to their different electron affinities, resulting in positive charges at the Al foil surface and negative charges at the Kapton surface, respectively (III in Fig. 1a). Then, the separation motion induces a potential drop between the dielectric layers, which drives the electrons to transfer from Al on Kapton side to Al in the center (IV in Fig. 1a). The electrons will stop moving until the gap distance between the contact layers reaches the maximum and an electrical equilibrium achieves (V in Fig. 1a). When the active layers are approaching again, electrons will flow from Al electrode in the center to the Al on Kapton side (VI in Fig. 1a) to form an electrostatic equilibrium [38]. The cyclic generation of potential difference between the contact triboelectric electrodes is numerically simulated with a COMSOL Multiphysics software, which shows the electric potential distribution during the contact-separation process corresponding to III, IV, V and VI in (a) respectively, as shown in Fig. 1d. It can be seen that the potential difference between the two layers gradually becomes lower as Kapton electrode moves away from Al foil, but it increases with approaching each other. Therefore, the electricity is generated during potential difference changing.

The electric output of the TENG with a size of 3 × 3 cm was measured at different frequencies, from 0.5 Hz to 2.0 Hz, as shown in Fig. 1b and c. The short-circuit current (I_{sc}) basically increases with the increase of frequency at an open-circuit condition, from 0.5 μA at 0.5 Hz to 1.2 μA at 2.0 Hz. But the open-circuit voltage (V_{oc}) almost remains the same peak value of about 14 V. It is generally assumed that a higher flow rate of charges occurs with the increase of deformation frequency, giving rise to a higher response current. Since the value of V_{oc} is only determined by the triboelectric charge density and the separation distance between the contact layers, little change at different frequencies is thus observed [39]. As one of energy conversion devices, TENG is primarily applied to harvest mechanical energy in the environment, and coupled with some electronic devices, such as LEDs, batteries, supercapacitors, to assemble them into a self-powered system [40–42]. Moreover, TENG can be a sensor with high sensitivity due to the pulsed signal (I_{sc} or V_{oc}) generated by itself in response to external mechanical forces applied on it. So it is possible to get the feedback of the intensity and frequency of the force applied on TENG real time by transmitting and collecting the electric signal.

The sensitivity of the fabricated TENG with Al foil and Kapton was examined by a series of tests, including sound vibrations and different movement behaviors, as shown in Fig. 2. When one says a word, like "Hi", "Very", "Good" or "Very good", the TENG stuck on his/her throat will be subject to bending and deformation under the induction of vocal chords vibrating. Simultaneously, different pronunciation can be recorded with the characteristic voltage signal generated by the TENG, which indicates that the TENG served as a self-powered sensor has good sensitivity and reliability (Fig. 2a). Similarly, different movements are monitored by this TENG sensor as one perform some actions or apply pressure on it, as shown in Fig. 2b. For example, it is easy to judge one drop or a few consecutive drops of water falling on the TENG.

In this work, this Al-Kapton based TENG was also used as a self-powered sensor for monitoring the driver's behavior in automobiles for the first time. The monitoring system is consisting of TENGs as sensors, data-acquisition unit and a driving simulator, which is schematically illustrated in Fig. 3a. A photograph in Fig. S1 shows the real testing process. First, two TENG sensors are mounted on the accelerator and brake of a driving simulator, respectively. One side of another TENG sensor is contacted with the corner of driver's eye while the other side of this sensor is adhered to the driver's glasses frame. Then all the three sensors are linked to a multichannel data-acquisition device, which is connected with a laptop. During the testing process, a driver attentively watches a driving simulated scene in a projection screen when the virtual car is started. The driver can perform various driving behaviors when he is facing complex traffic road conditions, e.g. pressing the accelerator, braking or poor concentration. It is vital to analyze these driving performances in the vehicle test field.

Fig. 3b displays a single-channel blinking signal in the simulation. In general, an unaffected eye blink action of one person lasts about 0.2–0.4 s on average, experiencing a short blink-release process, as

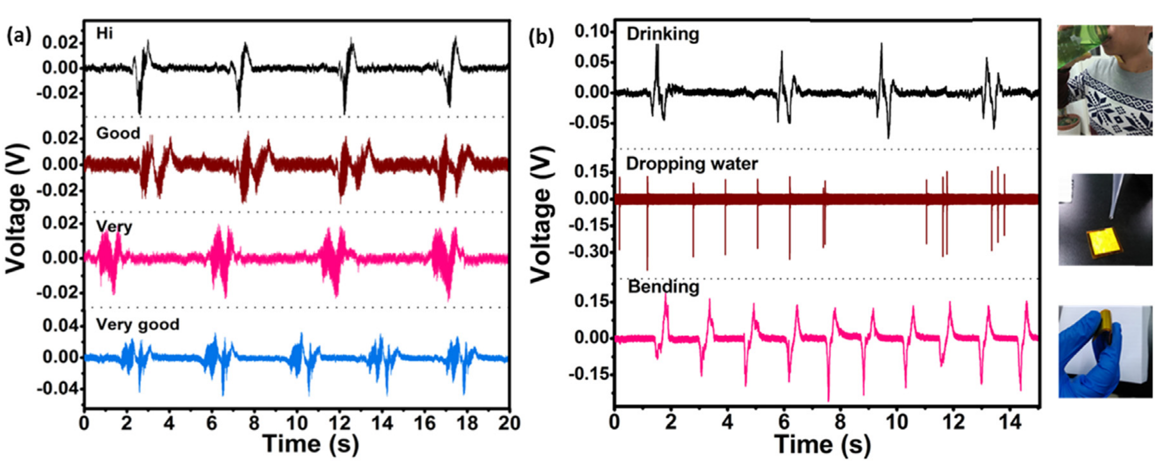


Fig. 2. (a) The sensing signal response to different speaking voice. (b) The sensing signal response to different movements.

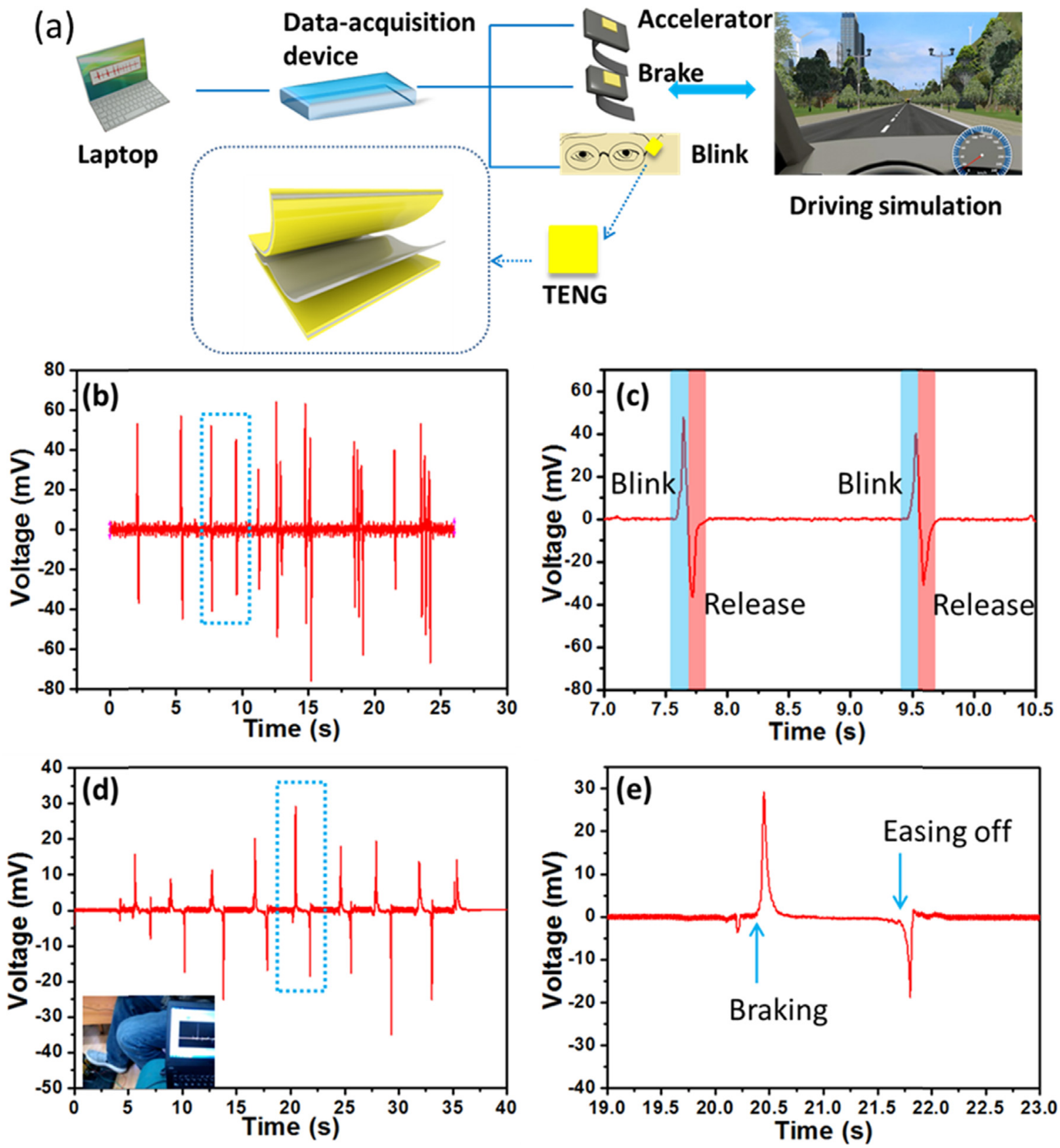


Fig. 3. (a) Schematic illustration of self-powered triboelectric sensors for driver behavior monitoring. (b) The voltage signals from blinking and (c) The corresponding enlarged curves of the area marked in (b). (d) The voltage signals from braking process and the photograph showing braking (inset); (e) The corresponding enlarged curve.

shown in Fig. 3c. At the same time, the motion and frequency of blinking are accurately recorded by a voltage signal. During the driving process, driver's eye blinking information can be used for distraction detection, fatigue warning, drunken state detection, etc [43,44]. Video S1 shows the blinking movement can be real-time monitored. Similarly, the braking motion from a driver can be transmitted and reflected by touching the TENG in one motion because the TENG devices generally show press-sensor characteristics (Fig. 3d and video S2). Driver intention can be detected by the actions on brake and gas pedal [45,46], which can be used for implement of some sub-systems of ADAS such as Autonomous Emergency Braking (AEB) and Emergency Alert System (EAS) [47].

Supplementary material related to this article can be found online at doi:10.1016/j.nanoen.2018.07.026.

The simultaneous three-channel data-acquisition results are shown in the Fig. 4. Two TENG sensors with a size of 3 × 3 cm were used to collect the signals of “pressing the accelerator”, “braking” motions, while “blinking” signal from the driver is acquired by a TENG with a size of 1.5 × 3 cm, as shown in Fig. 4b and c. Fig. 4a displays three voltage signals with a cut-off of 98 s, and a part of the corresponding driving motions and simulated scenes were recorded in video S3 and S4. Drivers would experience virtual driving with the driving simulator. Common traffic scenes including highway driving, signalized and unsignalized intersections were created. Percentage of Eyelid Closure Over the Pupil Over Time (PERCLOS) was the ocular closure degree in unit time. Eye blinking frequency was numbers of blinks in unit time. They can be obtained from the TENG signals through simple algorithm and used to identify the state of drivers. A longer PERCLOS may result from drivers’ drowsiness. A higher eye blinking frequency may result from discomfort of drivers’ eyes. Type of pedal action (fast/slow) and duration time can be easily extracted from the TENG signals, which can be used in the process of identifying acceleration/deceleration

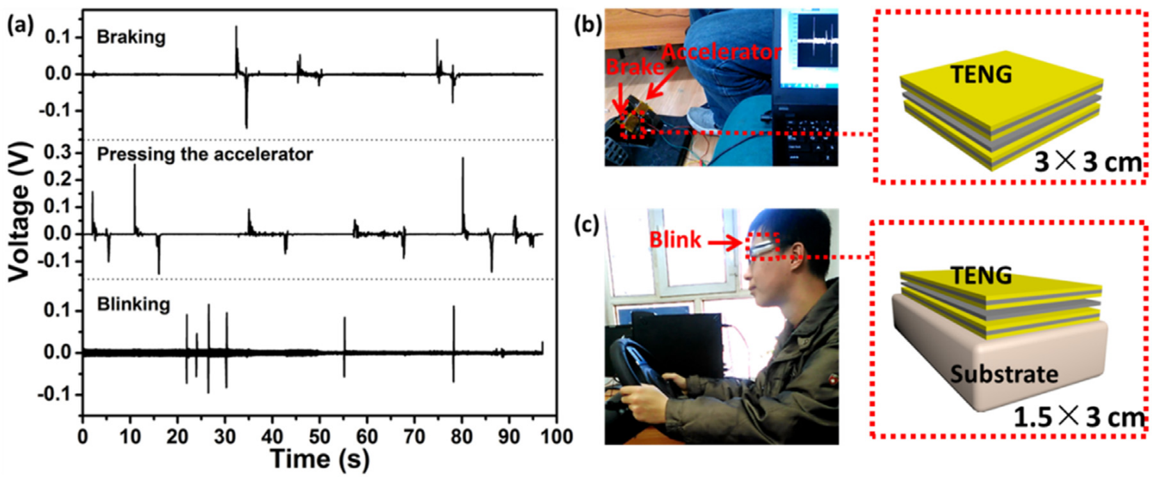


Fig. 4. (a) The recorded voltage signals of "braking process", "pressing the accelerator" and "blinking" acquiring data simultaneously with three-channels data-acquisition device. (b) Two TENGs with a size of 3 × 3 cm placed on brake and accelerator, respectively. (c) A TENG with a size of 1.5 × 3 cm mounted on a driver's spectacle frame.

attentions of drivers. Bad driving behaviors including impulse or drowsiness driving could be monitored. Sound and light warning can be implemented according to the TENG signals. Although the real road conditions are more complex than the simulation cases, the present results provide a feasible strategy for analyzing the drivers' behaviors. It can also be extended to real-time monitoring other driving behavior in various vehicles and aeronautical and space fields. This work also sheds light on the clues for constructing an intelligent traffic network (Fig. S2).

Supplementary material related to this article can be found online at doi:10.1016/j.nanoen.2018.07.026.

4. Conclusions

In summary, a facile TENG-based pressure sensor was realized by utilizing the contact triboelectrification between an Al foil and two Kapton film materials. The working mechanism and the output performance of the TENGs were studied. TENGs are effective pressure sensors because of their sensitive response to external presses. For the first time, we demonstrate the application of sensitive TENG-based sensors in driving field by collecting and analyzing the V_{oc} signals with the assistance of multichannel data-acquisition device. The collected data during braking, pressing the accelerator and even blinking are well correlated with the driving behaviors, which is of vital importance for traffic safety and intelligent driving. The TENG sensors may be extended to monitor other driving behaviors. This work opens up new avenue for designing intelligent traffic network by means of the cost-effective pressure-sensing functionalities of TENGs.

Acknowledgements

The authors acknowledge the financial support of National Key R & D Project from Ministry of Science and Technology, China (2016YFA0202702) and the National Science Foundation of China (Nos. 51672029, 51372271 and 51378062). ZLW thanks the support form MANA, NIMS, Japan. This work was also supported by the *Thousands Talents Program* for the pioneer researcher and his innovation team in China. This work was supported by the *Thousands Talents Program* for the pioneer researcher and his innovation team in China.

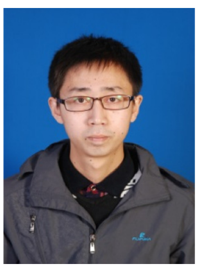
Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nanoen.2018.07.026.

References

[1] A. Patel, E. Krebs, L. Andrade, S. Rulisa, J.R.N. Vissoci, C.A. Staton, BMC Public Health 16 (2016) 1–10.
[2] T.A. Dingus, S.G. Klauer, V.L. Neale, A. Petersen, S.E. Lee, J. Sudweeks, R.R. Knipling, Behavior 8 (2006) 8–72.
[3] J.E.B. Tornros, A.K. Bolling, Accid. Anal. Prev. 37 (2005) 902–909.
[4] NHTSA, Fed. Regist. 77 (2012) 12907–12908.
[5] X. Jiang, W. Wang, H. Guo, Q. Cheng, K. Bengler, Transp. Res. D-Transp. Environ. (2018), https://doi.org/10.1016/j.trd.2018.05.004.
[6] W. Wang, W. Zhang, H. Guo, H. Bubb, K. Ikeuchi, Transp. Res. C- Emerg. Technol. 19 (2011) 1202–1214.
[7] X. Jiang, W. Wang, K. Bengler, IEEE Trans. Intell. Transp. Syst. 16 (2015) 1048–1053.
[8] Y. Mao, W. Wang, C. Ding, W. Guo, M. Baumann, G. Wets, Transp. Res. D-Transp. Environ. 62 (2018) 739–747.
[9] T. Qu, S. Yu, Z. Shi, H. Chen, Control Conference, 2018, pp. 114–119.
[10] A. Khodayari, R. Kazemi, A. Ghaffari, R. Braunstingl, IEEE International Conference on Mechatronics, 2011, pp. 200–205.
[11] J.P. Batista, Lect. Notes Eng. Comput. Sci. 3522 (2005) 200–208.
[12] Q. Ji, X. Yang, Real-Time Imaging 8 (2002) 357–377.
[13] S. Hu, G. Zheng, B. Peters, IET Intell. Transp. Syst. 7 (2013) 105–113.
[14] Y. Dong, Z. Hu, K. Uchimura, N. Murayama, IEEE Trans. Intell. Transp. 12 (2011) 596–614.
[15] L. Fletcher, N. Apostoloff, L. Petersson, A. Zelinsky, IEEE Intell. Syst. 18 (2003) 12–17.
[16] L. Fletcher, G. Loy, N. Barnes, A. Zelinsky, Robot. Auton. Syst. 52 (2005) 71–84.
[17] L. Fletcher, A. Zelinsky, Int. J. Robot. Res. 28 (2009) 774–801.
[18] X. Pu, W. Hu, Z.L. Wang, Small 14 (2018) 1702817.
[19] S. Niu, Y. Liu, X. Chen, S. Wang, Y.S. Zhou, L. Lin, Y. Xie, Z.L. Wang, Nano Energy 12 (2015) 760–774.
[20] J. Deng, X. Kuang, R. Liu, W. Ding, A.C. Wang, Y.-C. Lai, K. Dong, Z. Wen, Y. Wang, L. Wang, H.J. Qi, T. Zhang, Z.L. Wang, Adv. Mater. 30 (2018) 1705918.
[21] Y. Yang, N. Sun, Z. Wen, P. Cheng, H. Zheng, H. Shao, Y. Xia, C. Chen, H. Lan, X. Xie, C. Zhou, J. Zhong, X. Sun, S.-T. Lee, ACS Nano 12 (2018) 2027–2034.
[22] S. Gao, Y. Chen, J. Su, M. Wang, X. Wei, T. Jiang, Z.L. Wang, ACS Nano 11 (2017) 3965–3972.
[23] S. Gao, M. Wang, Y. Chen, M. Tian, Y. Zhu, X. Wei, T. Jiang, Nano Energy 45 (2018) 21–27.
[24] S. Gao, J. Su, X. Wei, M. Wang, M. Tian, T. Jiang, Z.L. Wang, ACS Nano 11 (2017) 770–778.
[25] M. Lee, J. Bae, J. Lee, C.-S. Lee, S. Hong, Z.L. Wang, Energy Environ. Sci. 4 (2011) 3359–3363.
[26] H. Zhang, Y. Yang, Y. Su, J. Chen, C. Hu, Z. Wu, Y. Liu, C.P. Wong, Y. Bando, Z.L. Wang, Nano Energy 2 (2013) 693–701.
[27] M.A.P. Mahmud, N. Huda, S.H. Farjana, M. Asadnia, C. Lang, Adv. Energy Mater. 8 (2018) 1701210.
[28] Q. Zheng, H. Zhang, B. Shi, X. Xue, Z. Liu, Y. Jin, Y. Ma, Y. Zou, X. Wang, Z. An, W. Tang, W. Zhang, F. Yang, Y. Liu, X. Lang, Z. Xu, Z. Li, Z.L. Wang, ACS Nano 10 (2016) 6510–6518.
[29] W. Song, B. Gan, T. Jiang, Y. Zhang, A. Yu, H. Yuan, N. Chen, C. Sun, Z.L. Wang, ACS Nano 10 (2016) 8097–8103.
[30] Z. Lin, J. Yang, X. Li, Y. Wu, W. Wei, J. Liu, J. Chen, J. Yang, Adv. Funct. Mater. 28 (2018) 1704112.
[31] Q. Zhang, Q. Liang, Z. Zhang, Z. Kang, Q. Liao, Y. Ding, M. Ma, F. Gao, X. Zhao, Y. Zhang, Adv. Funct. Mater. 28 (2018) 1703801.
[32] P. Maharjan, R.M. Toyabur, J.Y. Park, Nano Energy 46 (2018) 383–395.

[33] Y. Hu, J. Yang, Q. Jing, S. Niu, W. Wu, Z.L. Wang, ACS Nano 7 (2013) 10424–10432.
[34] Z.L. Wang, ACS Nano 7 (2013) 9533–9557.
[35] B. Wang, Y. Liu, Y. Zhou, Z. Wen, Nano Energy 46 (2018) 322–330.
[36] C. Xu, Y. Zi, A.C. Wang, H. Zou, Y. Dai, X. He, P. Wang, Y.C. Wang, P. Feng, D. Li, Z.L. Wang, Adv. Mater. 30 (2018) 1706790.
[37] X. Pu, L. Li, H. Song, C. Du, Z. Zhao, C. Jiang, G. Cao, W. Hu, Z.L. Wang, Adv. Mater. 27 (2015) 2472–2478.
[38] Y.S. Choi, Q. Jing, A. Datta, C. Boughey, S. Kar-Narayan, Energy Environ. Sci. 10 (2017) 2180–2189.
[39] L. Lin, Y. Xie, S. Wang, W. Wu, S. Niu, X. Wen, Z.L. Wang, ACS Nano 7 (2013) 8266–8274.
[40] K. Zhao, Y. Yang, X. Liu, Z.L. Wang, Adv. Energy Mater. 7 (2017) 1700103.
[41] H. Hou, Q. Xu, Y. Pang, L. Li, J. Wang, C. Zhang, C. Sun, Adv. Sci. 4 (2017) 1700072.
[42] S.Q. Li, D. Zhang, X.Y. Meng, Q.A. Huang, C.W. Sun, Z.L. Wang, Energy Storage Mater. 12 (2018) 17–22.
[43] L. Jin, Q. Niu, Y. Jiang, H. Xian, Y. Qin, M. Xu, Adv. Mech. Eng. (2013) 648431.
[44] P. Ebrahim, W. Stolzmann, B. Yang, IEEE International Conference on Systems, Man, and Cybernetics. IEEE Computer Society, 2013, pp. 4142–4148.
[45] S.B. Amsalu, A. Homaifar, A. Karimoddini, A. Kurt, IEEE International Conference on Systems, Man, and Cybernetics. IEEE, 2017, pp. 2712–2717.
[46] J. Heine, M. Sylla, I. Langer, T. Schramm, B. Abendroth, IEEE, International Conference on Intelligent Transportation Systems. IEEE, 2015, pp. 1022–1027.
[47] C. Su, W. Deng, H. Sun, J. Wu, B. Sun, Intelligent Vehicles Symposium. IEEE, 2017, pp. 535–540.



Xiaoyi Meng received his Bachelor's Degree in Chemical Biology from Tianjin Normal University. He is currently a Ph.D candidate under the supervision of Professor Chunwen Sun at Beijing Institute of Nanoenergy and Nanosystems (BINN), Chinese Academy of Sciences (CAS). His current research interests focus on high performance metal-air batteries, electrochemical catalysis, TENG-based sensors.

Qian Cheng received Bachelor degree in Transportation System from the Beijing Institute of Technology 2015, and continued as a Ph.D candidate since then. From 2016 to 2017, he worked on the project of Intercultural analysis of driver behavior in a cognitive architecture based on driving simulator and on-road experiments with the Chair of Ergonomics from Technical University of Munich. His current research interests include driver's risk perception, identification of drivers' driving intention.

Xiaobei Jiang received the M.E. degree in traffic engineering from Beijing Institute of Technology, China in 2008 and the Dr.-Ing. in traffic technology from Institute of Ergonomics, Technische Universität München in 2012. She is now a research fellow in Beijing Institute of Technology-Technische Universität München Joint Laboratory for Driver Behavior and Traffic Safety. Her major study fields include driver behavior, ADAS and traffic safety. Dr.-Ing. Xiaobei JIANG's awards include the second prize of Invention in Science & Technology, Beijing, China (2012) and the second prize of the Award of Ministry of Education China (2017).

Zhen Fang, Born in 1976, Professor and PhD supervisor of Institute of Electronics, Chinese Academy of Sciences and University of Chinese Academy of Sciences, associate director of State Key Laboratory of Transducer Technology. His research interests include medical electronics and Internet of Things for Healthcare, made great contribution in wearable technology, now principle medical detection technology and health big data technology. He is PI of more than 10 national projects of China. He has published over 150 peer reviewed papers, 135 of which are referenced by SCI or EI. He has over 50 filed patents, 27 of which got authorized.

Xianxiang Chen, Born in 1979 , Associate Professor of Institute of Electronics, Chinese Academy of Sciences. He received his PhD degree in Physical Electronics from Institute of Electronics, CAS in 2007. His research interests include wearable health monitoring sensors, biomedical signal processing and Internet of Things for Healthcare etc. He is co-author of more than 60 papers which are indexed by SCI or EI, two book chapters, one authorized US patents and 12 authorized Chinese patents. He is PI of 4 Chinese National High Technology Research and Development (863) Project and 1 Chinese National Natural Science Foundation Project. He was a recipient of the first prize of Science and Technology Award awarded by Beijing Municipal Government, in 2015 and a recipient of Best Paper Award of IEEE Ubi-HealthTech 2015.

Shaoqing Li received his Bachelor's Degree from Beijing Institute of Technology in 2015. He is currently a Master candidate in Condensed Matter Physics under the supervision of Professor Chunwen Sun from Beijing Institute of Nanoenergy and Nanosystems (BINN), Chinese Academy of Sciences (CAS). His current research interests focus on flexible rechargeable batteries.

Chenggang Li received Bachelor degree in Transportation Engineering from the Beijing Institute of Technology 2013, and continued as a Ph.D candidate since then. From 2016 to 2017, he worked on the project of Intercultural analysis of driver behavior in a cognitive architecture based on driving simulator and on-road experiments with the Chair of Ergonomics from Technical University of Munich. His current research interests include driver's risk perception, influences of secondary tasks on driver behavior and collision avoidance strategies.

Chunwen Sun received his Ph.D. degree in Condensed Matter Physics from the Institute of Physics (IOP), Chinese Academy of Sciences (CAS) in 2006. He is a full professor and group leader of Energy Storage Materials and Devices at Beijing Institute of Nanoenergy and Nanosystems (BINN), CAS. His research interests include energy storage and conversion, e.g., lithium-ion batteries, metal-air batteries, all-solid-state batteries, fuel cells and self-powered systems. He has published 90 peer-reviewed papers with a citation more than 4000 times, edited 5 book chapters and filed 15 Chinese patents. He has also received a number of awards, including the Outstanding Overseas Talents by the Institute of Physics CAS (2011), the Second Prize of Military Progress Prize in Science and Technology Advancement in China (2013) and the International Association of Advanced Materials (IAAM) Scientist Medal (2017).

Wuhong Wang spent two years as a postdoctoral fellow at Beihang University from 1997 to 1999 after finished his Ph.D studies from Southwest Jiaotong University, and then he joined Beijing Institute of Technology since 1999 first as an associate professor then a full professor. He stayed at computer vision laboratory, Institute of Industrial Science, the University of Tokyo, Japan, as a JSPS Research Fellow in 2002–2004 and Visiting Professor in 2005. From 2005 to 2007 he had been affiliated with Lehrstuhl für Ergonomie, Technische Universität München, serviced as Humboldt Research Fellow. He conducted research at Transportation Research Institute, Hasselt University, Belgium in 2014. His areas of research interest include Intelligent connected vehicles and assisted driving, Green transportation behavior and safety, Human factors and human-machine interaction.

Zhong Lin (ZL) Wang received his Ph.D from Arizona State University in physics. 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 has made original and innovative contributions to the synthesis, discovery, characterization and understanding of fundamental physical properties of oxide nanobelts and nanowires, as well as applications of nanowires in energy sciences, electronics, optoelectronics and biological science. His discovery and breakthroughs in developing nanogenerators established the principle and technological road map for harvesting mechanical energy from environment and biological systems for powering a personal electronics. His research on self-powered nanosystems has inspired the worldwide effort in academia and industry for studying energy for micro-nano-systems, which is now a distinct disciplinary in energy research and future sensor networks. He coined and pioneered the field of piezotronics and piezo-phototronics by introducing piezoelectric potential gated charge transport process in fabricating new electronic and optoelectronic devices.