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A Flexible Pressure Sensor Based on Poly(dimethylsiloxane) Nanostructures Film

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Abstract: This paper proposed a flexible pressure sensor based on poly(dimethylsiloxane) nanostructures film and report an efficient, simple, and low-cost fabrication strategy via soft nanoimprint lithography. The pressure sensor can convert external pressure or mechanical deformation into electrical signal to detect pressure and strain changes based on the coupling of triboelectrification and electrostatic induction. To enhance the performance of the pressure sensor, it consists of sub-500 nm resolution on the surface of elastic poly(dimethylsiloxane) sensitive layer and an indium tin oxide electrode thin film. When the pressure applied on the nanostructures layer, triboelectrostatic charges are induced. In the experiment, it measures up to sensitivity of 0.8 V/kPa at frequency of 5 Hz. This study results in potential applications such as wearable smart devices and skin-attachable diagnostics sensing systems.

Keywords: Flexible, pressure sensor, poly(dimethylsiloxane), soft nanoimprint lithography, triboelectrostatic charges.

1. Introduction

As the key of flexible electronic devices, flexible sensing devices can transducer physical or environmental stimuli into detectable electrical signals, which have attracted increasing attention due to their great potential applications in displays, robotics, advanced therapies, and energy harvesting devices [1-5]. In particular, flexible sensing devices can be wearable on human body or clothing to continuously monitor body signals, such as temperature, pulse, heart rate, motions, and respiration [6-8]. To obtain various functions, wearable flexible sensors should have some special characteristics, for example, good flexibility, desirable stretch ability, biocompatibility, good stability, and high sensitivity [9-11].

Pressure is ubiquitous in the nature and human body, so flexible pressure sensors can be used to detect low and medium pressure (1-100 kPa) to track human activity and monitor personal health [12-14]. Typically, flexible pressure sensors consist of active pressure or strain sensing components, flexible substrates, and conductive electrodes. Generally, elastic polymers, such as poly(dimethlsiloxane) (PDMS), polyethylene terephthalate (PET), polyimide (PI), and rubber, are commonly used as the flexible substrates. Due to the good flexibility, strechability, stability, and biocompatibility, PDMS is the best choice. The suitable active sensing components materials play an important role in fabricating sensors with good performance, which include carbon nanotubes (CNTs), graphene, carbon black, conductive polymers, and nanostructures (nanoparticles, nanowires, nanograting). In some conditions, the flexible substrates and active components will be integrated into one layer [15-18].

Based on wording mechanism, the flexible pressure sensors can be classified into capacitive-type [19,20], piezoelectricity-type [21,22], and piezoresistive-type sensors [23,24], which can convert pressure signals into resistance, voltage, or current changes with advantages of simple sensing process, easy read-out system, and large detection range. However, the sensitivity, limit of detection, detection range, response time, stability, reliability, and complicated and high cost fabrication process are still a challenge for flexible wearable sensing systems.

In 2006, Z. L. Wang et al. proposed triboelectric nanogenerator (TENG) based on couple effects of electrification and electrostatic induction, which can

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achieve remarkable electric output under the external mechanical pressure at low cost and relatively simple structure [25-28]. The related researches about TENG with good performance of energy harvesting, electrical properties, high power density, and rapid response are conducted, which has potential applications in high sensitivity and self-powered sensing systems.

Here, we have constructed a flexible PDMS pressure sensor based on TENG, in which the PDMS nanostructures thin film serve as the triboelectric layer to fabricate high sensitivity and self-powered wearable sensors. A simple and low-cost fabrication method for PDMS nanostructures film based on soft nanoimprint lithography is developed. When the pressure in applied on the nanostructures layer, triboelectrostatic charges are induced. The experimental measurement of the electrical performance of TENG sensors is up to sensitivity of 0.8 V/kPa at frequency of 5 Hz. This study results provide an approach for self-powered sensing, with potential applications in military surveillance, artificial intelligence, health care.

2. Experimental Details

Figure 1 illustrates the scheme mechanism of the flexible TENG senor based on couple of electrification and electrostatic induction. The principle is based on single-electrode based TENG that is more practical and feasible design for some applications such as wearable and finger-tip-driven TENG [29-31]. Two kinds of polymers have distinctly different triboelectric characteristics with one easy to gain electrons and the other one easy to lose electrons. By contacting the skin or cloth with the PDMS triboelectric layer, two insulating materials are touched and rubbed with each other when deformed by an external mechanical deformation. Therefore, triboelectric charges with opposite signs are generated and distributed on the PDMS surface. When the deformation starts to be released, the opposite charges are separated with an air gap and form dipole moment. Electrons are injected from skin or cloth to the PDMS surface, leading to establish an electric potential difference between the flexible PDMS surface and electrode. To achieve equilibrium, electron flow from the electrode with lower potential to ground, resulting in accumulation of electrostatically inducted positive charges on the electrode. When the deformation is then reapplied and the two materials surfaces are again contact, the dipole moment disappears or reduced in magnitude. Thus, the reduced electric potential difference leads to the electrons to flow from ground to the electrode in the opposite direction, and the accumulated induced charges vanish. With repeated bending and releasing of the contact layers, electrons are driven flow between electron and ground. This is a full cycle of the electricity generation process for the single-electrode-based TENG in contact-separation mode. According to the basic principle of the TENG, micro/nano-structures are fabricated onto the triboelectric surface to increase the contact area to increase electrostatically inducted charges.

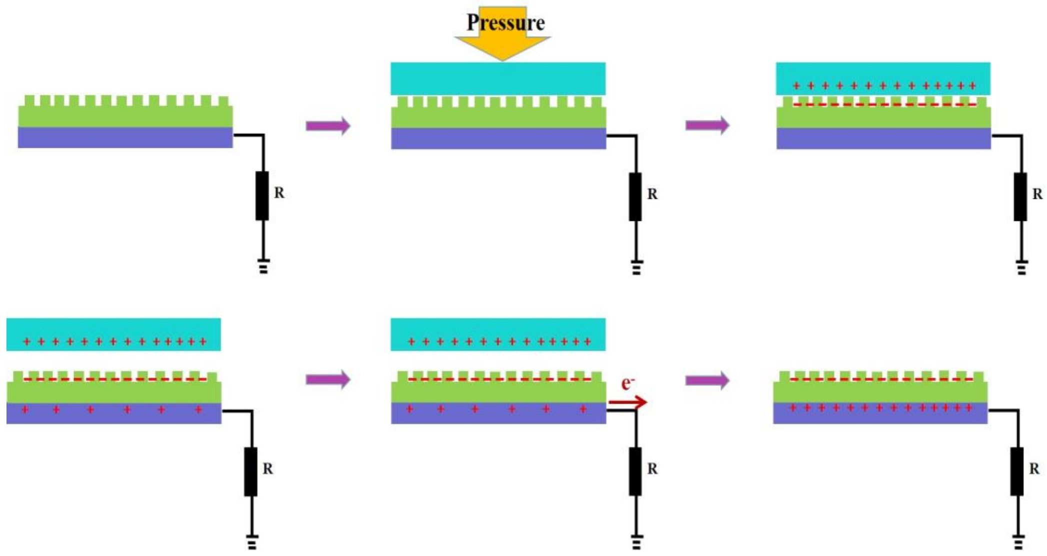


Figure 1. Sketches that illustrate the electrical signal generation process of single-electrode-based TENG sensor.

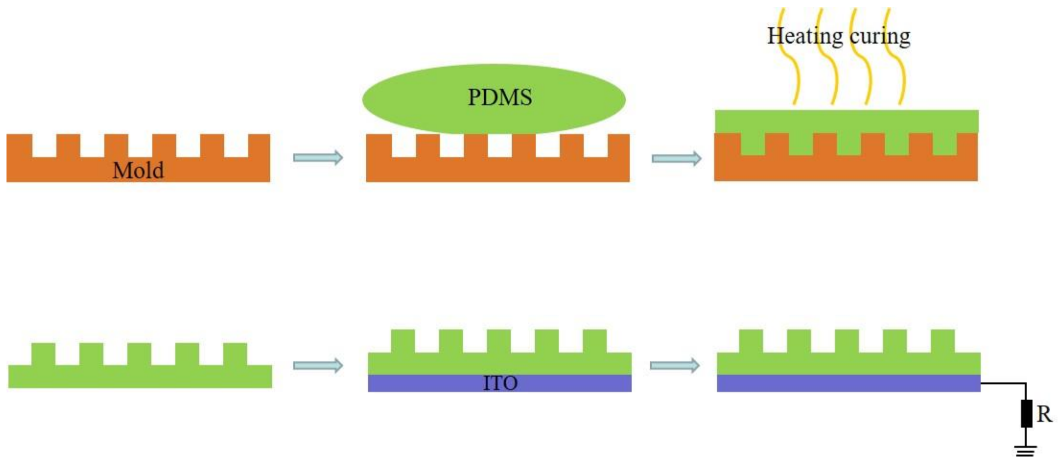


Figure 2. Schematic illustration of the fabrication process of TENG pressure sensor devices..

In order to increase the triboelectric power output, we have fabricated nanoscale structures on the PDMS surfaces via casting replication and coating technique. Figure 2 shows the detailed fabrication process of our flexible pressure sensor based on PDMS nanostructures film. The quartz wafer molds with nanostructures were first fabricated by the traditional photolithography method, followed by dry etching process. The liquid PDMS (Sylgard 184, Dow coating) is prepared by mixing base and curing agent with the ratio of 10:1, which is uniformly coated onto the surface of nanostructure mold to form a thin film. It is kept at room temperature for 30 min to remove the air bubbles, then curing thermally cured at 90 ℃ for 1 h. A uniform PDMS layer was peeled off and contained nanostructures onto the surfaces. Finally, the PDMS film was fixed on the conductive ITO electrode form the sensor device. The entire preparation process of the device is simple and low-cost, making it possible to be scaled-up for large-scale production and practical applications.

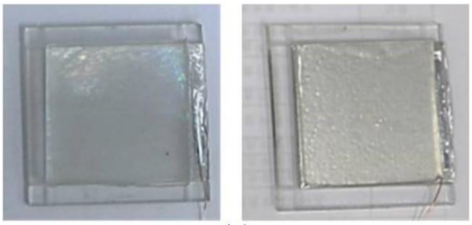
The fabricated flexible TENG sensor is fixed on a measurement platform and the nanostructures surface contact with a linear motor (E1100-RS-HC) that can apply adjustable pressure force within the range of from 5 N to 50 N. The measurement frequency is from 1Hz to 5Hz. The morphology and nanostructures of the PDMS substrate are characterized by scanning electron microscopy (SEM). The output electrical signal of the sensor is measured using Keithley 6514 and low noise amplifier (Stanford SR570) to record the voltage, current, and sensitivity. The photograph of the fabricated sensor sample and the measurement equipment are shown in Figure 3. Based on the elasticity, the prepared PDMS sensors are flexible, stretchable, and transparent.

3. Results and Discussions

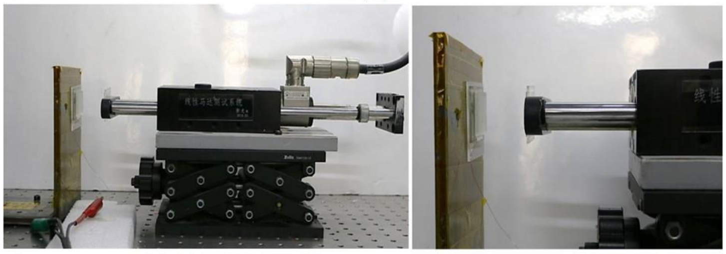
The fabricated single-electrode-based TENG sensor based on PDMS nanostructures film is displayed in Figure 4, including scanning electron microscope (SEM) and atomic force microscope (AFM) images of nanostructure that is random Daman grating. The shape and dimensions of the PDMS structure are well controlled by the initial patterns on the surface of the wafer mold. The feature size of PDMS Daman grating is about 500 nm and the structural configuration is similar to ridge. High-magnification SEM images illustrate that the feature is regular and remarkably uniform in large area of about 2 * 2 cm^2, showing that the fabrication process is an efficient method. The ridge-shaped structure has sharp protrusions and corners, which is beneficial for increasing the friction area and the efficiency in the electrical signal generation process of the TENG sensor.

The high density closed-packed and regularized nanostructures allow the PDMS Daman grating better electrical performance, compared to other nanostructures. The major reason is that the high-resolution uniform sharp nanostructures improve the friction contact area and surface roughness to increase the generate more triboelectric charges under the same pressure force.

To investigate the electrical performance of the polymer nanostructures film, we made a detailed measurement and analysis. Figure 5a, b and c, d show the open-circuit voltage and short-circuit current output of the PDMS sensor at different



(a)



(b)

Figure 3. (a) Photograph of PDMS sensor samples, (b) measurement experimental setup based on linear motor for applying external pressure.

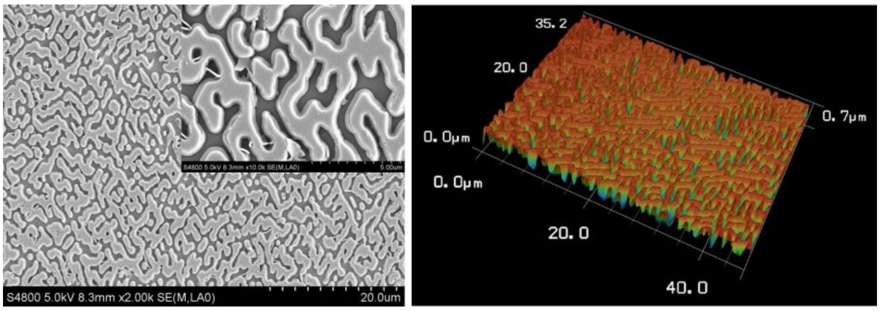


Figure 4. (a) SEM image and (b) AFM image of PDMS random Daman grating.

frequency and at different pressure force, respectively. We used a linear motor to pressure onto the surface of the PDMS film with the force between 5 N and 50 N at frequency from 1 Hz to 5 Hz. The result clearly shows that the electrical output performance increases with the increasing of the frequency from 1 Hz to 5 Hz and the pressure force from 9.8 N to 39.97 N. As the frequency increases, the open-circuit voltage has no obvious changes, yet the short-circuit current has significant increase. The possible reason is that the triboelectric effect did not increase significantly with the increase of frequency. As the force increases, the open-circuit voltage and short-circuit current obviously increase. The maximum output voltage and current signal for the PDMS sensor are up to about 80 V and 1.5 μA at the frequency of 5 Hz and the force of 39.97 N, respectively, which can compare with sensing system based on piezoelectric materials or other more complicated designs. The corresponding pressure sensitivity is 0.8 V/kPa, which is almost three or four times as high as the sensor using flat films.

4. Conclusion

In summary, we have demonstrated a flexible pressure sensor based on PDMS nanostructures film. The working mechanism of the pressure sensor is based on the couple of triboelectrification and electrostatic induction, which is used as the single-electrode-based TENG. We combine casting replication process and coating technique to fabricate the PDMS sensor with ITO electrode layer. The random Daman grating nanostructures with feature size of 500 nm increase the friction area to improve the output electrical performance of the sensor. The experimental results show that the pressure sensitivity of the PDMS sensor is up to 0.8 V/kPa at frequency of 5 Hz, which has potential applications in flexible smart electronics devices, wearable nanogenerator, and skin-attachable diagnostics sensing systems

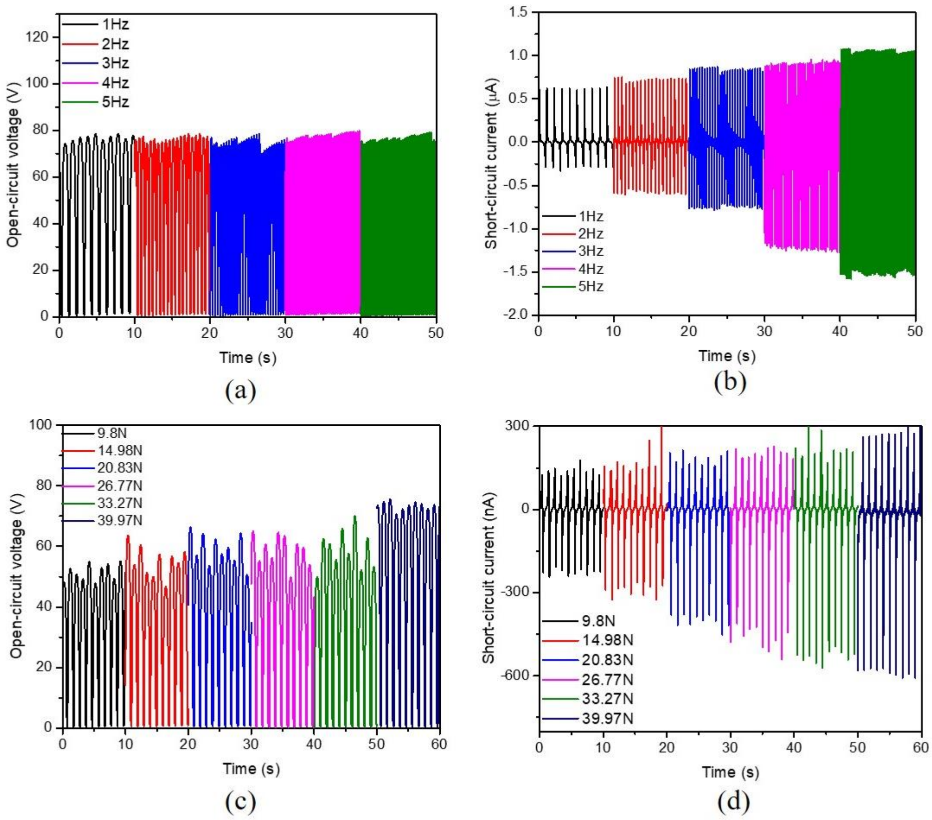


Figure 5. Electrical output measurement of the PDMS nanostructures film. (a) Open-circuit voltage and (b) short-circuit current at different frequency from 1 Hz to 5 Hz. (c) Open-circuit voltage and (d) short-circuit current at different pressure force from 9.8 N to 39.97 N.

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References

[1] C. Pang, C. Lee, and K. Suh, "Recent advances in flexible sensors for wearable and implantable devices," *J. Appl. Polym. Sci.* **130**(3), 1429 (2013).

[2] K. N. Kim, S. M. Lee, A. Mishra et al., "Atmospheric pressure plasmas for surface modification of flexible and printed electronic devices: A review," *Thin. Solid. Films.* **598**, 315 (2016).

[3] W. C. Shu, C. Xia, W. Ning et al., "An ultrathin flexible single-electrode triboelectric-nanogenerator for mechanical energy harvesting and instantaneous force sensing," *Adv. Energy. Mater.* **7**(1), 1601255 (2016).

[4] M. Zarek, M. Layani, and I. Cooperstein, "3D printing 3D printing of shape memory polymers for flexible electronic devices," *Adv. Mater.* **28**(22), 4166 (2016).

[5] J. Hou, M. Liu, H. Zhang et al., "Healable green hydrogen bonded networks for circuit repair, wearable sensor and flexible electronic devices," *J. Mater. Chem. A* **5**(25), 13138 (2017).

[6] W. Gao, S. Emaminejad, H. Y. Nyein et al., "Fully integrated wearable sensor arrays for multiplexed in situ perspiration analysis," *Nature* **529**(7587), 509 (2016).

[7] Y. Liu, H. Wang, W. Zhao et al., "Flexible, stretchable sensors for wearable health monitoring: sensing mechanisms, materials, fabrication strategies and features," *Sensors* **18**(2), 645 (2018).

[8] U. R. M. Habib, C. S. Liew, T. Y. Wah et al., "Mining personal data using smartphones and wearable devices: a survey," *Sensors* **15**(2), 4430 (2015).

[9] J. Park, S. Wang, L. Ming et al., "Three-dimensional nanonetworks for giant stretchability in dielectrics and conductors," *Nat. Commun.* **3**(2), 916 (2016).

[10] T. Q. Trung and N. E. Lee, "Flexible and stretchable physical sensor integrated platforms for wearable human-

activity monitoring and personal healthcare," *Adv. Mater.* **28**(22), 4338 (2016).
[11] S. Zhao, J. Li, D. Cao et al., "Recent advancements in flexible and dtretchable electrodes for electromechanical sensors: strategies, materials, and features," *ACS Appl. Mater. Imter.* **9**(14), 12147 (2017).
[12] G. Schwartz, B. C. K. Tee, J. Mei et al., "Flexible polymer transistors with high pressure sensitivity for application in electronic skin and health monitoring," *Nat. Commun.* **4**(5), 1859 (2013).
[13] F. Santoso and S. J. Redmond, "Indoor location-aware medical systems for smart homecare and telehealth monitoring: state-of-the-art," *Physiol. Meas.* **36**(10), R53 (2015).
[14] Y. Nam and J. W. Park, "Child activity recognition based on cooperative fusion model of a triaxial accelerometer and a barometric pressure sensor," *IEEE J. Biomed. Health. Inform.* **17**(2), 420 (2013).
[15] S. C. B. Mannsfeld, C. K. Tee, R. M. Stoltenberg et al., "Highly sensitive flexible pressure sensors with microstructured rubber dielectric layers," *Nat. Mater.* **9**(10), 859 (2010).
[16] S. Gong, W. Schwalb, Y. Wang et al., "A wearable and highly sensitive pressure sensor with ultrathin gold nanowires," *Nat. Commun.* **5**, 3132 (2014).
[17] D. J. Lipomi, M. Vosgueritchian, C. K. Tee et al., "Skin-like pressure and strain sensors based on transparent elastic films of carbon nanotubes," *Nat. Nanotechnol.* **6**(12), 788 (2011).
[18] X. Jin, X. D. Chang, W. Y. Wang et al., "Research progress in flexible wearable strain sensors based on polydimethylsiloxane," *J. Mater. Eng.* **6**(11), 17 (2018).
[19] B. Y. Lee, J. Kim, H. Kim et al., "Low-cost flexible pressure sensor based on dielectric elastomer film with micro-pores," *Sensor. Actuat. A-Phys.*, **240**, 103 (2016).
[20] L. Ma, X. Shuai, Y. Hu et al., "A highly sensitive and flexible capacitive pressure sensor based on a micro-arrayed polydimethylsiloxane dielectric layer," *J. Mater. Chem. C* **6**(48),13232 (2018).
[21] C. T. Wang, K. Y. Huang, D. T. Lin et al., "A flexible proximity sensor fully fabricated by inkjet printing," *Sensors* **10**(5), 5054 (2010).
[22] Z. Wang, X. Pan, Y. He et al., "Piezoelectric nanowires in energy harvesting applications," *Adv. Mater. Sci. Eng.* **2015**, 1 (2015).
[23] N. Dong, W. Jiang, G. Ye et al., "Graphene-elastomer nanocomposites based flexible piezoresistive sensors for strain and pressure detection," *Mater. Res. Bull.* **102**, 92 (2018).
[24] S. M. Doshi and E. T. Thostenson, "Thin and flexible carbon nanotube-based pressure sensors with ultrawide sensing range," *Acs Sensors* **3**(7), 1276 (2018).
[25] H. Zhang, Y. Yang, Y. Su et al., "Triboelectric nanogenerator as self-powered active sensors for detecting liquid/gaseous water/ethanol," *Nano Energy* **2**(5), 693 (2013).
[26] S. Wang, L. Long, and L. W. Zhong, "Triboelectric nanogenerators as self-powered active sensors," *Nano Energy* **11**, 436 (2015).
[27] G. Zhu, Z. H. Lin, Q. Jing et al., "Toward large-scale energy harvesting by a nanoparticle-enhanced triboelectric nanogenerator," *Nano Lett.* **13**(2), 847 (2013).
[28] J. Chen, G. Zhu, W. Yang et al., "Harmonic-resonator-based triboelectric nanogenerator as a sustainable power source and a self-powered active vibration sensor," *Adv. Mater.* **25**(42):6094 (2013).
[29] H. Zhang, Y. Yang, X. Zhong et al., "Single-Electrode-Based Rotating Triboelectric Nanogenerator for Harvesting Energy from Tires," *Acs Nano* **8**(1), 680 (2014).
[30] N. Kaur, J. Bahadur, V. Panwar et al., "Effective energy harvesting from a single electrode based triboelectric nanogenerator," *Sci. Rep-UK* **6**(1), 38835 (2016).
[31] J. Park, A. Y. Choi, J. L. Chang et al., "Highly stretchable fiber-based single-electrode triboelectric nanogenerator for wearable devices," *Rsc Adv.* **7**(86), 54829 (2017).