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Full paper

Intelligently detecting and identifying liquids leakage combining triboelectric nanogenerator based self-powered sensor with machine learning

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ABSTRACT

Self-powered, rapidly-responding and cost-effective sensor is greatly needed in liquids leakage detection. Here, a single electrode liquid-solid (SELS) triboelectric nanogenerator (TENG) with a triboelectric layer of p-type silicon was designed and its performances for liquids leakage detecting and identifying were studied. The results demonstrated that the designed SELS TENG was sensitive to very small liquids leakage and could qualitatively characterize the leakage rate of liquid. The difference between the short-circuit output currents of the SELS TENG responding to several liquids was mainly considered as from their different conductivity and wettability. In addition, the short-circuit output currents of SELS TENG responding to different liquids were considered as their fingerprint and used to identify liquids. A great deal of sensors in practical application generated a great of data and an intelligent detecting and identifying system was designed to identify different liquids based on big data and machine learning technologies. High classification accuracies over 90% were obtained for each two liquids in most of cases. These findings shed light on the application of TENG based self-powered sensors in liquid leakage detecting and environment monitoring fields. Most importantly, the great potential application of TENG combined with big data and machine learning technologies was successfully explored and exhibited.

1. Introduction

Pipelines are considered as the safest and a cost-effective way for liquids transportation, especially for the hazardous and flammable liquids. Liquid leakage is an inevitable problem for a pipeline system, which was a result of wear and corrosion of pipeline infrastructure, natural disasters or human sabotage [1,2]. The monitoring and detecting the liquid leakage is the first line priority for many companies and governments [2]. This is due to a fact that not only the liquid leakage causes huge amounts of economic losses every year [3], but also the leakage, especially the leakage of dangerous chemical liquids and nuclear fluids is highly harmful to human safety, environment and instruments. Many approaches have been proposed and are available for detecting and positioning leakages in pipeline systems. Hardware based methods for leakage detecting require special sensors including acoustic devices [4], fiber optic sensors [5], infrared sensors [6], soil monitoring sensors [1] and ultrasonic flow meters [7]. In practical operation, the detection of pipeline leakage was based on the pressure, temperature, density, flow rate or sonic velocity [8] information acquired by a plenty of sensors. However, it is difficult to detect the very small amount of liquid leakage by the above sensors owing to their insensitivities regarding to the low level amount of liquid. Moreover, a great deal of decentralized sensors are powered by traditional power supply units, which demands a complex energy supply system thus limited their potential applications in some cases. Therefore, a highly-sensitive, rapidly-responding, self-powered and cost-effective sensor is strongly expected to solving these problems for liquid leakage detecting.

Triboelectric nanogenerator (TENG) was firstly invented by Wang et al. in 2012 [9], and soon has drawn the world-wide attention due to its high output performance, cost-effective, diverse choice of materials and flexibility [10–15]. The working principle of TENG is based on the coupling of triboelectrification and electrostatic induction. The fundamental theory of nanogenerators starting from Maxwell equations and nanogenerators are the applications of Maxwell's displacement current in energy and sensors [16–18]. Researchers have widely demonstrated

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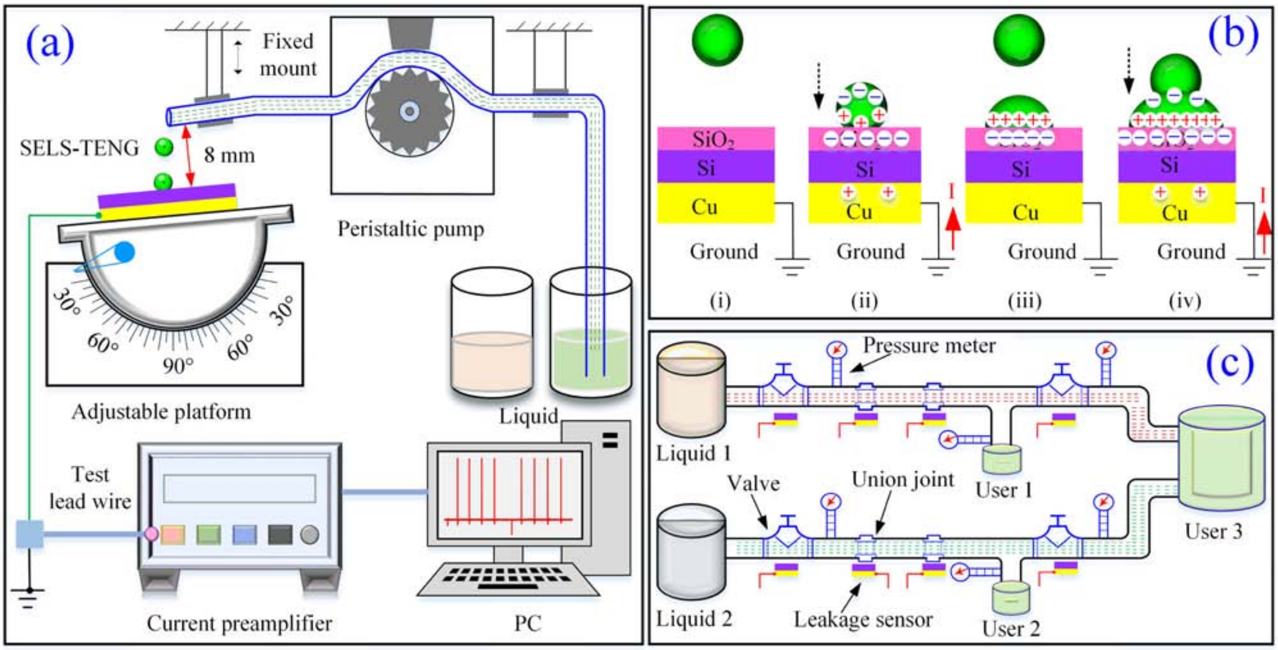

Fig. 1. The test platform, working mechanism and potential practical application of the SELS TENG based self-powered liquid leakage detection sensor. a) Schematic illustration of test platform. b) The working mechanism of SELS TENG based sensor. i: the first liquid drop falling down; ii: the first liquid drop contacts with silicon wafer; iii: second liquid drop falling down; iv: the second liquid drop contact with the first liquid drop. c) The potential practical application situation of SELS TENG based liquid leakage detection sensor.

that TENG can harvest energy from various sources such as wind [19], human motion [20,21], vibration [22] and water flow [23,24]. More importantly, TENG can act as self-powered sensor because the relevant input parameters such as force, frequency, surface charge density and wind speed directly affects its output electrical signals. By far, a series of TENGs based self-powered sensors were successfully developed, including pressure sensor [25,26], velocity sensor [27], chemical sensor [28–30], acoustic sensor [31], temperature and humidity sensor [32], touch sensor [33,34], angle sensor [35], vibration sensor [36], motion vector sensor [37], amenity sensor [38], and gesture sensor [39]. Self-powered sensor for liquid leakage detection and identification is strongly needed but has not received enough attention yet. Theoretically, the contact electrification between liquid and solid can make solid-liquid TENG act as active self-powered sensor used in the field of environment monitor, liquid leakage detecting and identifying.

In this paper, we developed a single electrode liquid-solid (SELS) TENG for detecting and identifying different kinds of liquids by using contact electrification and electrostatic induction between solid and liquid. The p-type silicon wafer was selected as the triboelectric layer, which is cost-effective and can withstand harsh environment. The effects of liquid leakage rate and slope angle of triboelecric layer on the output current of the SELS TENG were studied, which demonstrated that SELS TENG can act as a self-powered sensor for liquid leakage detecting. The output currents of different kinds of liquids dropped on the silicon wafer were studied, which has the capability to identify liquids. In industrial application, a great deal of decentralized SELS TENG based self-powered sensors were used and huge amounts of data generated. Therefore, an intelligent detecting and identifying system was designed based on big data and machine learning technologies in this study. Due to the stability of the short-circuit output current of SELS TENG and the robust of the intelligent detecting and identifying system, liquid leakage was successfully detected and different liquids were classified. High classification accuracies nearly all over 90% were obtained for each two liquids based on the data collected by the SELS TENG based self-powered sensors.

2. Experiments

2.1. Fabrication of silicon TENG

P-type silicon wafer (thickness: 525 μm, resistivity: < 0.0015 Ω cm) was cut into 2.6 cm × 2.6 cm and cleaned in the ethyl alcohol and deionized water bath successively by ultrasonic wave. Then a layer of conductive copper tape (thickness: 0.01 cm) with the same size was attached on the unpolished side of silicon as electrode for electrical connection. The digital photograph of the device was shown in Fig. S1, Supporting Information.

2.2. Preparation of liquids

The tap water, ethyl alcohol with a mass concentration of 99.7%, 60%, 40%, 20%, NaCl liquid and NaOH liquid both with a mass concentration of 15% were prepared and used as the test liquids.

2.3. Characterization and electrical measurement

The conductivity and total dissolved solids (TDS) of the test liquids were tested by using a conductivity meter (DDS-307A, Shanghai INESA & Science Instrument CO. LTD). The PH of the liquids was tested by using a PH meter (PHS-3C, Shanghai INESA & Science Instrument CO. LTD). These tests were conducted under a condition with the temperature of 25 ± 0.2 °C, and the relative humidity of 60 ± 2%. The contact angle between test liquids and silicon surface was tested by using a drop shape analyzer (DSA-100, KRÜSS) under droplet mode with a liquid drop volume of 2.0 μl. For evaluating the performance of the single electrode liquid-solid TENG based self-powered leakage detection sensor, a peristaltic pump (BT100J-1A, HuiYuWeiYe (Beijing) Fluid Equipment CO. LTD) was used to pump the liquids for simulating the liquid leakage. The height of the liquids dropping is 7 mm and the rate of leakage was controlled by adjusting the speed of peristaltic pump. Twenty-five identical SELS TENGs were fabricated and divided into 5 groups to acquire the currents of tap water, alcohol, acetone, NaCl and NaOH liquids for further demonstrating its stability and

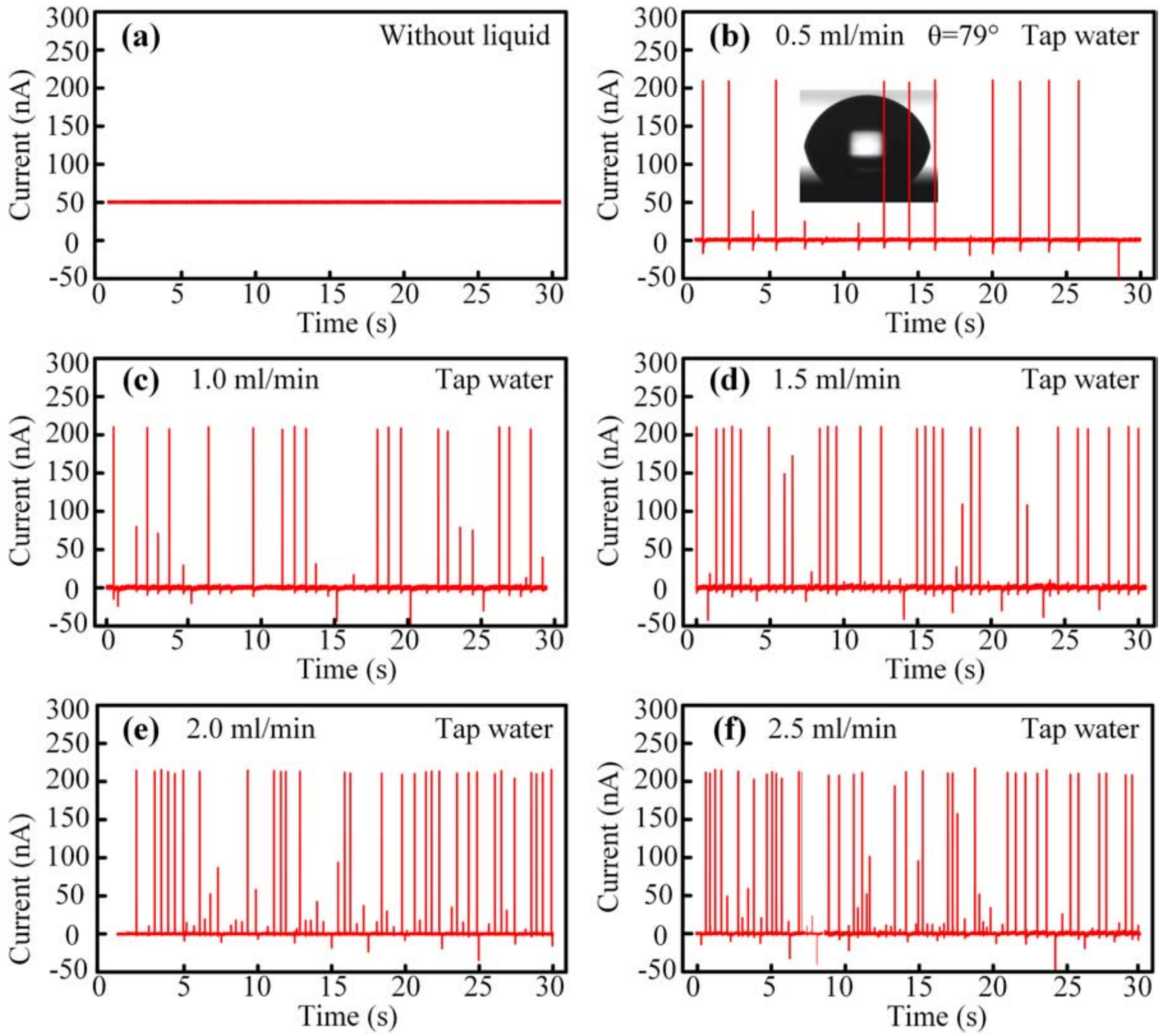

Fig. 2. The short-circuit output currents of the SELS TENG based self-powered sensor responding to tap water under different leakage rates. a) Background noise without liquid leakage. b-f) Short-circuit output current of the SELS TENG based self-powered sensor responding to tap water at a leakage rate of 0.5 ml/min, 1.0 ml/min, 1.5 ml/min, 2.0 ml/min and 2.5 ml/min, respectively.

capacity to identify various liquids. The measurement time was 80 s and each test was repeated 6 times. The short-circuit output current of the SELS TENG based self-powered sensor was measured by using a low-noise current preamplifier (SR570, Stanford Research System) with a frequency of 500 Hz. The tests were conducted under a condition with the temperature of 25 ± 1 °C, and the relative humidity of 60 ± 6%.

3. Results and discussion

Fig. 1(a) shows the test platform, working mechanism and potential practical application of the SELS TENG based sensor. The liquid was pumped by using a peristaltic pump to simulate the pipeline liquid leakage. The SELS TENG based sensor which was constructed by a piece of p-type silicon wafer as triboelectric layer and copper as the electrode and was fixed on a platform. Silicon wafer was selected as the triboelectric layer because its surface potential was stable and hard to change, which contributed to a stable output current. In addition, silicon was abundant on earth, low-cost and could withstand a harsh environment.

The working mechanism of the SELS TENG was explained by a sequential contact-electrification and electrostatic-induction process [24,40,41]. As a liquid leakage detection sensor, the generation of electrical signal was interpreted by using contact electrification process of liquid and solid combined with the electrostatic-induction process. The operation of the TENG based self-powered liquid leakage detection sensor will be explained as single-electrode mode. The charge on the triboelectric layer surface could be positive or negative depending on the counterpart the triboelectric layer interacts with [24] and tap water was used to illustrate it. As Fig. 1(b) shows, when the liquid pipeline worked under a normal condition, there was no liquid droplet fall down and contact with the silicon oxide (SiO_2) layer of silicon wafer which naturally formed due to the silicon wafer was exposed in air and there was no electrical signal generated. When the first liquid droplet contacted with SiO_2 layer, the liquid spread on the surface and SiO_2 would be negatively charged due to triboelectric effect. Meanwhile, the liquid droplet would be positively charged to maintain the electrical neutrality in the contact area. With the change of liquid-solid contact area, the potential difference would drive electrons flow from copper electrode to ground to keep a potential equilibrium (Fig. 1(b)-ii). In Fig. 1(b)-iii, the second liquid droplet falling down, but before contact with the first liquid droplet which remained on the SiO_2 layer due to no change of contact area and followed with a zero potential difference, there was no short-circuit output current generated. When the second liquid droplet contacted with the liquid remained on the SiO_2 layer of silicon wafer, the contact area between liquid and solid would be enlarged and the contact electrification process and electrostatic induction process would come into being sequential and electrons flow from copper electrode to ground under the drove of potential difference (Fig. 1(b)-iv). When the liquid droplet continuously fall down and contact with the liquid remained on the SiO_2

layer of silicon wafer, a continuous and periodic electrical pulses would be generated on account of the diffusion and fluctuation process of liquid on a horizontal triboelectric layer. It was worth noting that the working mechanism of SESL TENG worked under a large leakage rate a little different and bidirectional current generated due to the diffusion and contraction of liquid and flow away from the surface of triboelectric layer, (the bidirectional short-circuit output current under high leakage rate was shown in Fig. S2, Supporting Information), which was same to the working mechanism proposed in [24,41]. Fig. 1(c) shows a potential practical application of the SELS TENG based self-powered liquid leakage detection sensor. In a pipeline system the union joints, valves and flanges were the easier leakage positions due to the corrosion, friction, wear. The SELS TENG based self-powered sensors were fixed on these positions for detecting leakage, especially for the dangerous liquids due to their high sensitivity and adaptation to harsh environment.

In order to prove the SELS TENG could be used to detect the liquid leakage in daily life and industry field, a peristaltic pump was used to pump tap water to simulate the liquid leakage of a pipeline. The volume of each drop was about 25 μl, fall from a distance of 7 mm, and the slope angle (β) between the triboelectric layer and horizontal plane was 0°. Fig. 2 shows the short-circuit output currents of the SELS TENG based self-powered sensor under different dripping rates. When the pipeline worked under a normal condition there was no liquid droplet fall down and the signal was the background noise (Fig. 2(a)). Fig. 2(b-f) show the short-circuit output currents of the SELS TENG based self-powered sensor under a liquid leakage rate ranged from 0.5 ml/min to 2.5 ml/min and the short-circuit output current of tap water consisted of pulses with a maximum value about 200 nA. The working mechanism of the SELS TENG based self-powered sensor was proposed in Fig. 1(b). Especially, the SELS TENG based self-powered sensor exhibited a high sensitive to leakage and was able to make a fast respond to a very small leakage rate of 0.5 ml/min. The test process of tap water leakage was shown in Video S1, Supporting information. The SELS TENG based sensor also exhibited a very important behavior that the values of the short-circuit output current pulses were independent on the leakage rate at a low leakage rate whereas the number of current pulses was positive correlation to the leakage rate. The results demonstrated that a leakage rate ranged from 0.025 ml/min to 25 ml/min could be successfully detected by the SELS TENG based sensor, as shown in Fig. S2 (Supporting Information). Moreover, it was referred that a leakage less than 0.025 ml/min or larger than 25 ml/min also could be detected. In practical application, the SELS TENG based self-powered sensor not only could use to detect the leakage but also could characterize the liquid leakage rate by the frequency of the short-circuit output current. The new measure principle of SELS TENG based self-powered liquid leakage detection sensor would have a huge impact on the evolution of liquid leakage detection technology and bring huge benefits both on economic development and environmental protection.

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For evaluating the reliability and adaptability of the SELS TENG based self-powered sensor, it was worth further exploring the effect of the slope angle (β) on the output current of SELS TENG. Fig. 3 shows the output current of the SELS TENG based self-powered sensor at different angles β ranged from 5° to 15° under a liquid leakage rate of 0.5 ml/min. A slight increase in the short-circuit output current value from about 200–220 nA could be observed when the slope angle ranging from 0° (Fig. 2(b)) to 15° (Fig. 3). It also could be found several current pulses over 220 nA with the angle increased from 0° to 15°. Moreover, the frequency of the output current exhibited a slight decrease trend with the increase of slope angle. Based on the observation in experiments, we considered that the increase in current value was induced by the enlarged contact area between liquid droplet and triboelectric layer of SELS TENG with the increase of slope angle β. The appearance of short-circuit output current pulses over 220 nA and the decrease of short-circuit output current frequency attributed to the accumulation and flow away instantaneously of water droplet on the surface of triboelectric layer.

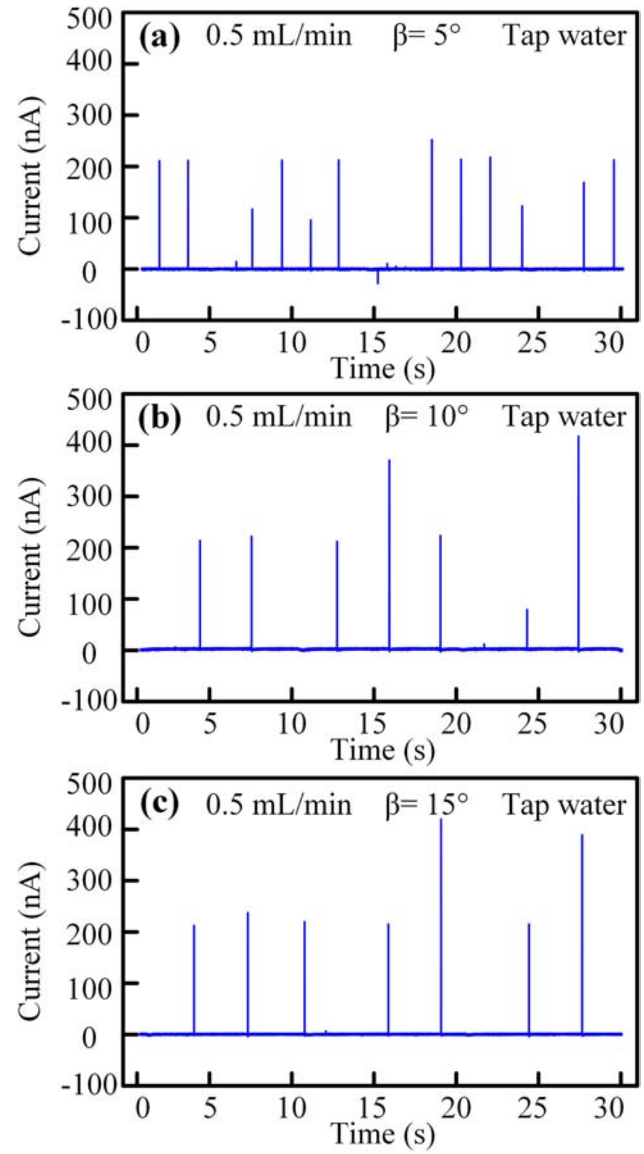

Fig. 3. The short-circuit output currents of the SELS TENG based self-powered sensor at different slope angles (β) ranged from 5° to 15° under a liquid leakage rate of 0.5 ml/min.

When the slope angle β was 0°, continuously dripped liquid droplets accumulated on the surface of silicon wafer and fluctuated with subsequent droplet dripped. Almost every dripped liquid droplet would induced a diffusion area induced by the drop of droplet due to the liquid could spread out from center, therefore, the short-circuit output current pulse keep a stable value. While, with an increase of slope angle β and the liquid droplet continuously dripped, the previous droplets would not leave away immediately and accumulated with subsequent droplet at the bottom position of triboelectric layer due to the surface tension of liquid, but the drop of some droplets couldn't change the contact area so there was no current generated. When the surface tension was broken due to the accumulation of liquid and the liquid flow away instantaneously and a larger area change was occurred naturally, which resulted in short-circuit output current pulses over 220 nA.

The short-circuit output current of SELS TENG responding to different kind liquids can considered as the fingerprint of the liquids and has a potential used to identify the liquid. Here, the alcohol, acetone, NaOH and NaCl liquids with a mass concentration of 99.7%, 99.5%, 15% and 15%, respectively were used as test liquids. Fig. 4 shows the short-circuit output current of SELS TENG based self-powered sensor respond to

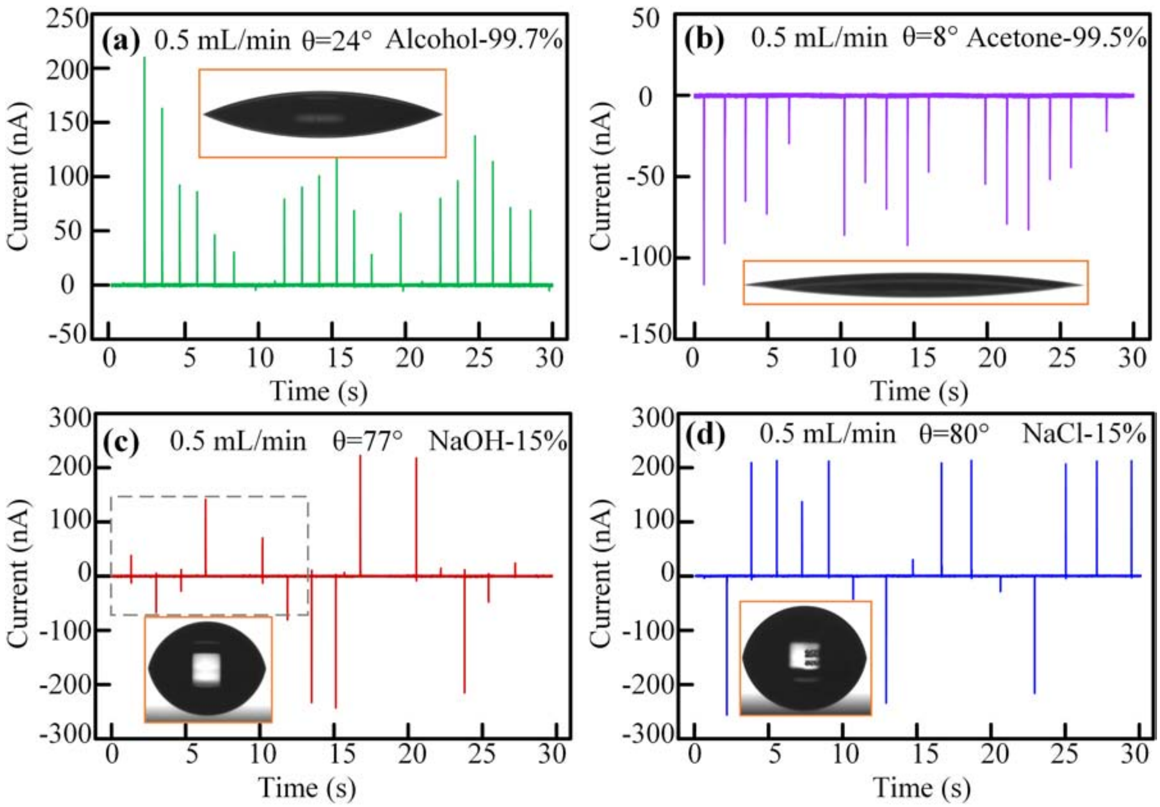

Fig. 4. The short-circuit output currents of SELS TENG based self-powered sensor responding to different liquids a) Short-circuit output current responding to alcohol. b) Short-circuit output current responding to acetone. c) Short-circuit output current responding to NaOH liquid. d) Short-circuit output current responding to NaCl liquid.

different liquids. The current pulses induced by the drop of liquid droplets and natural standstills appeared during the process of liquid drop, which can be observed in video S1 in supporting information, therefore, the periodic currents were caused by the periodic natural standstills of liquid drop. The short-circuit output current of the SLES TENG based self-powered sensor to alcohol was positive current pulse with different value and mainly around 100 nA, as showed in Fig. 4(a). On the contrary, the short-circuit output current of the SLES TENG based self-powered sensor to acetone was negative current pulse with different value and mainly around − 80 nA, as showed in Fig. 4(b). The short-circuit output currents of the SLES TENG based self-powered sensor to NaOH and NaCl liquids consisted of current pulses about + 200 nA and − 250 nA, respectively. Moreover, several positive current pulses less than 100 nA and negative current pulses greater than − 100 nA appeared in the response current of SELS TENG based self-powered sensor to NaOH liquid, as the gray dashed rectangle indicted in Fig. 4(c). The contact angle θ was used to characterize the level of wettability of the surface, which could directly affect the contact area between wafer surface and liquids. The wettability of liquids directly affected contact area and the conductivity directly affected the potential difference. For a certain triboelectric layer, a large wettability liquid lead to a larger contact area and more electrons was flow through the circuit corresponding to a higher current. Moreover, the conductivity directly affected the potential difference between triboelectric layer and liquid, which determined the electrons flow in circuit. In addition, the ions in liquid also have effect on the output current. In summary, the output current of SELS TENG was affected by the wettability, conductivity and ions content of liquid. The different diffusion and fluctuation properties of tap water and alcohol were obviously found in Video S2 and Video S3 in Supporting Information. The insert pictures in Fig. 4(a-d) give the contact angles of alcohol, acetone, NaOH and NaCl liquid between the triboelectric layer (p-type silicon), which was about 24°, 8°, 77° and 81°, respectively.

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Fig. 5 shows the short-circuit output currents of SELS TENG based self-powered sensor to different mass concentrations alcohol under a leakage rate was 0.5 ml/min. Fig. 5(a) shows that three current pulses nearly 200 nA, which was more than those of alcohol liquid with a mass concentration of 99.7% (Fig. 4(a)). Compared the short-circuit output currents of alcohol liquids with different mass concentration in Fig. 5 and Fig. 4(a), it could be found that with the decrease of mass concentration, the number of current pulses approximated 200 nA increased and gradually close to the response current of tap water as shown in Fig. 2(b). The inset pictures in Fig. 5 were the contact angles (θ) of alcohol liquids with a different mass concentration. The contact angles θ was 40°, 48° and 68° for alcohol liquids with a mass concentration of 60%, 40% and 20%, respectively. With the decrease of alcohol mass concentration, the contact angle exhibited an increase trend and would directly affect the contact area, which was an important factor affected the current.

The study about the currents of SELS TENG based sensor responding to tap water, acetone, NaCl, NaOH and alcohol with different mass concentration exhibited different features. The attributes of the liquids involved in this study were shown in Table 1. The mechanism of the difference between the currents respond to a variety of liquids is very complex and a possible reasonable explanation was mainly considered in the difference of the contact angel and conductivity of the liquids. The electrical output performance of SELS TENG was directly determined by the total transferred charges, whose equation is given by

$$Q = \sigma \times A \tag{1}$$

In Eq. (1), Q is the total transferred charges, σ is the charge density and A is the actual contact area. The triboelectric layer was identical in this study so that the contact electrification charge density σ was

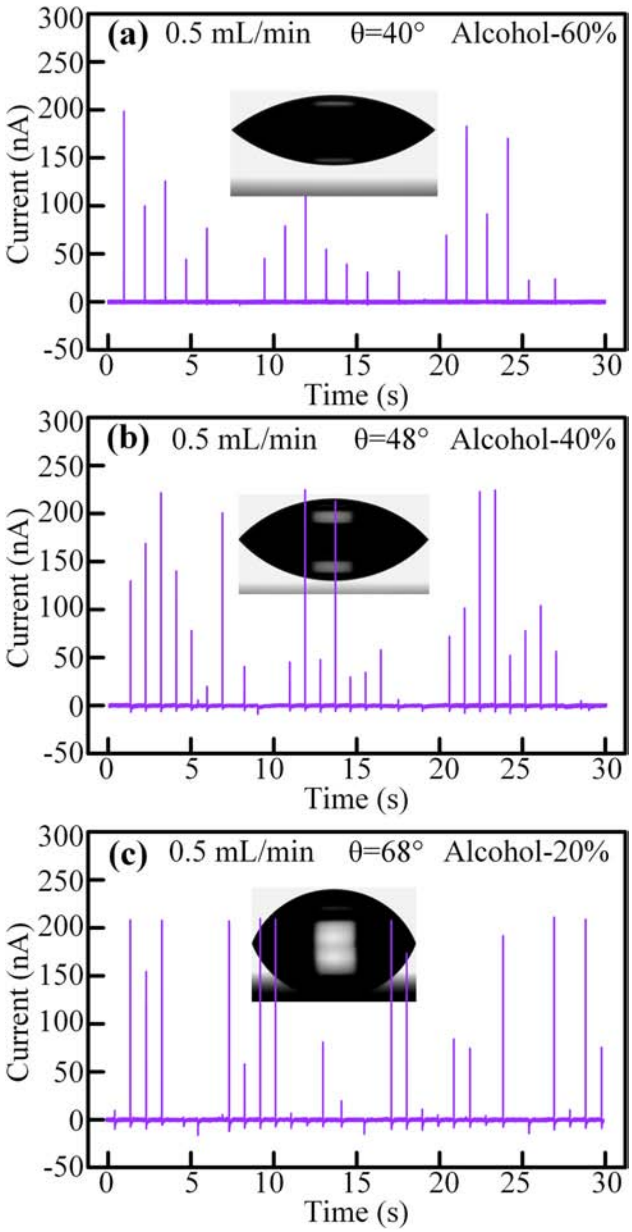

Fig. 5. The short-circuit output currents of SELS TENG based self-powered sensor responding to alcohol with a different mass concentration. a) Short-circuit output currents responding to alcohol with a mass concentration of 60%. b) Short-circuit output current responding to alcohol with a mass concentration of 40%. c) Short-circuit output current responding to alcohol with a mass concentration of 20%.

Table 1
The attributes of liquids.

Liquids	Conductivity(uS/cm)	TDS(mg/L)	PH
Acetone-99.5%	0.77	0.39	6.59
Alcohol-99.7%	0.37	0.18	6.93
Alcohol-60%	20.52	10.29	7.28
Alcohol-40%	52.76	26.31	7.35
Alcohol-20%	120.31	60.26	7.41
Tap water	157.62	78.82	7.47
NaCl-15%	2120.00	1064.00	6.86
NaOH-15%	2110.00	1057.00	13.98

mainly affected by the electrical properties of the liquids. The conductivities of liquids were the key factor for the contact electrification charge density and reflected in their currents. Moreover, the actual area between liquid and triboelectric layer was also a crucial factor for the output current of SELS TENG. The contact angle between liquid and triboelectric layer represented the wettability of the surface which determined the actual contact area. In addition, the total dissolved solids in liquid induced the positive ions and negative ions, and the fluctuation of ions along with liquid may also has influence on the current to some extent. But at all events, the distinct properties of different liquids contributed to identify and classify them by using the current of SELS TENG based sensor.

The detection and identification of various liquids involved a lot of human resources and the great deal of decentralized sensors would generate huge amounts of data. An intelligent detecting and identifying system based on big data and machine learning maybe a killer for practical applications. Fig. 6 shows the schematic illustration of the intelligent detecting and identifying system based on big data technology and machine learning technologies, the data samples for identifying and the classified results of tap water and NaOH liquids by using the system. Fig. 6(a) shows the illustration of the system, firstly, the SLES TENG based sensor detected the liquid leakage and a mass of data (here was the current) were acquired. The current signal data were partitioned at regular time intervals and the sample data were built. Due to the sample frequency was generally over 50 Hz and the dimensions of data sample would be very large, therefore the principle component analysis (PCA) method was used to extract the main feature information and reduce dimensions of data. Herein, the contributing rate of principal component was set a value of 85%. As a machine learning method, support vector machines (SVM) have been widely used as classifiers in various settings including pattern recognition [42], handwritten signature recognition [43], breast cancer diagnosis [44], dynamic texture recognition [45] and machine fault diagnosis [46]. In this system, a one-versus-one SVM was used to recognize the liquids [47]. The radial basis function was set as the kernel function. The penalty parameter c and kernel function parameter g were optimized by using K-fold cross validation (K-CV) method and K was set a value of 5. 120 data samples were gained by partitioning the acquired data at a fixed time interval of 20 s (part of the data sample was shown in Fig. 6(b)) and normalized in the range of [0, 1]. Afterwards, 60 data samples were used as training data to train the SVM and the other 60 data samples acted as testing data to verify the performance of the system and SELS TENG based sensor for liquids classification. All the data samples of the five kinds of liquids were shown in Fig. S3, Supporting Information. Fig. 6(c) shows the classification result of tap water and NaOH liquid. It was obviously found that the classification accuracy of tap water and NaOH liquid was 95% and 6 data samples were wrongly recognized, which marked with red cycle. The classification results of the other each two kinds liquid and the parameter optimization process were shown in Fig. S4 and Fig. S5, respectively.

Table 2 shows the classification results by the intelligent detection and identifying system based on the data acquired by SELS TENG based self-powered sensor. All the training set accuracies over 98% and the testing accuracies were all exceeded 90% except the tap water and NaCl liquid with an accuracy of 78.3%. We thought the lower accuracy of 78.3% possibly caused by the minor difference characteristic in their current or the defects of the detection and identifying system to some extent, which could further improved by optimizing the feature extraction method and pattern recognition algorithm. The application of TENG combining with big data and machine learning technologies was an important trend in the near future.

The SELS TENG based self-powered sensor didn't need a complex distributed energy supply system compared with traditional leakage detection sensors and showed a good performance in liquid leakage detection, which was beneficial to expand the practical application range of liquid leakage detection. Besides, the SELS TENG based self-powered liquid leakage detection sensor was considered working under an active mode which was

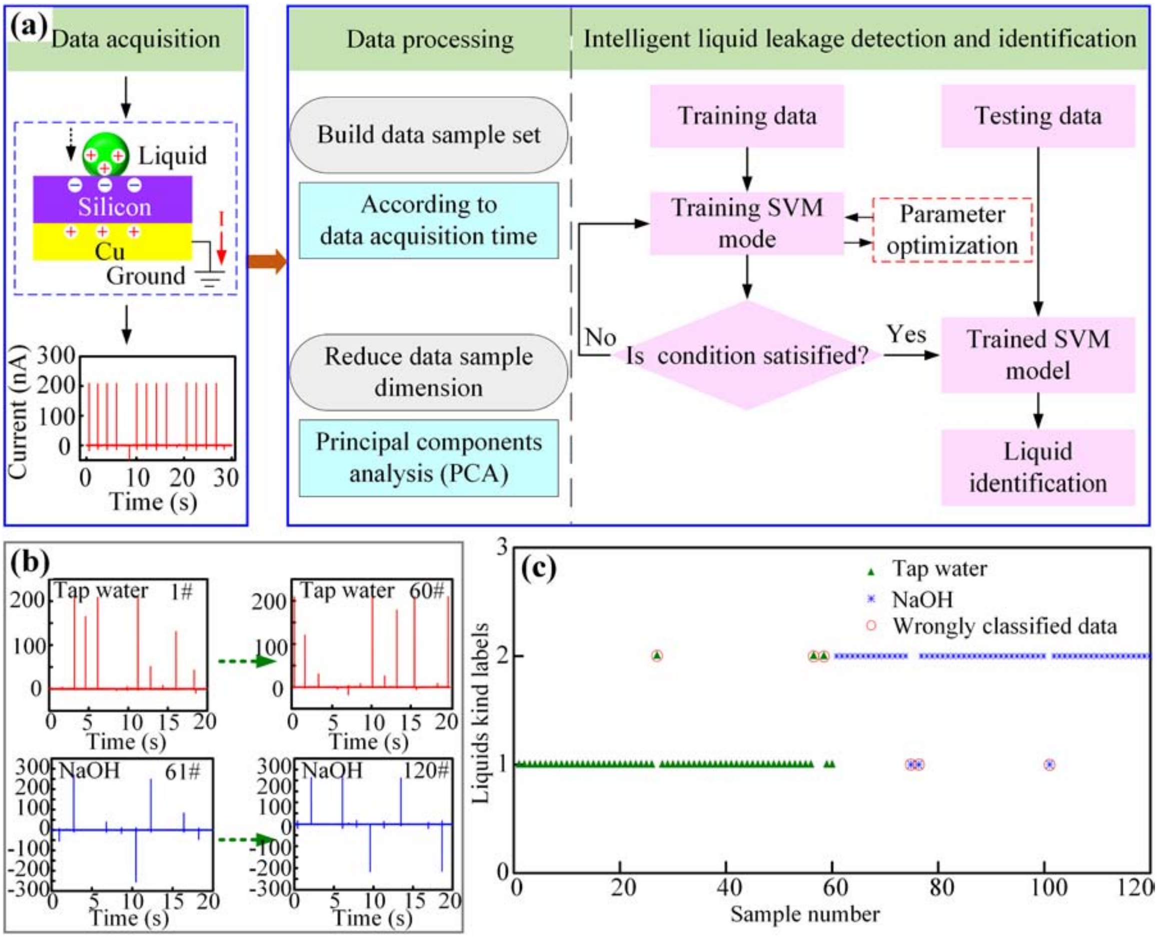

Fig. 6. The schematic illustration of the detecting and identifying system, data samples and the result of classification. a) Schematic illustration of the intelligent detecting and identifying system based on big data and machine learning technologies. b) Graphical representation of data samples. c) Classification result of tap water and NaOH liquid.

Table 2
The classification results of the data.

Liquid	Train set accuracy	Test set accuracy
Water-NaOH	100%(120/120)	95%(114/120)
Water-acetone	100%(120/120)	98.3%(118/120)
Water-NaCl	98.3%(118/120)	78.3%(94/120)
Water-alcohol	100%(120/120)	100%(120/120)
Acetone-NaCl	99.2%(119/120)	90%(108/120)
Acetone-NaOH	100%(120/120)	92.5%(111/120)
Acetone-alcohol	100%(120/120)	100%(120/120)
NaOH-NaCl	100%(120/120)	94.2%(113/120)
NaOH-alcohol	98.3%(120/120)	98.3%(118/120)
NaCl-alcohol	98.3%(118/120)	98.3%(118/120)
Average	99.4%	94.5%

triggered only when leakage occurred in a liquid pipeline. Compared with the TENG based chemical sensor [30] considered working under a passive mode which needs the TENG continuously working to detect liquid/gaseous and the lifetime would limited, therefore, the active detection mode design in this study has great superiority in lifetime and cost. Most importantly, the successful combination of TENG with big data and machine learning technologies laid a foundation for the exploration of the potential applications of combination TENG with big data and machine learning in the future.

4. Conclusions

In summary, a SELS TENG based self-powered sensor which could be used for liquids leakage detecting and identifying was designed and studied. The results showed that the design not only sensitive to small amount liquid leakage but also qualitatively characterize the leakage rate in practical application. In addition, the study indicated that the short-circuit output currents of SELS TENG based self-powered sensor responding to liquids can considered as the fingerprint of liquids and has a potential in the application of different liquids identifying. An intelligent detecting and identifying system was established based on big data and machine learning technologies for identifying different kinds of liquids by using the data acquired by the SELS TENG based self-powered sensor. High classification accuracies exceeded 90% were obtained for each two kinds of liquids in most of cases. Most importantly, the great potential application of TENG combined with big data and machine learning was successfully explored and exhibited.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nanoen.2018.11.058.

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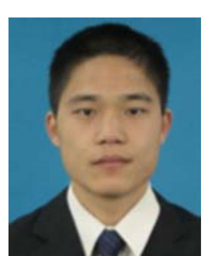

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