Transparent glass based single electrode mode triboelectric tracking sensor array

Jinkai Chen, Peng Ding, Ruizheng Pan, Weipeng Xuan, Dapeng Guo, Wuliang Yin and Jikui Luo

Abstract: Glass based single electrode mode triboelectric generator (SETEG) has been made and PDMS negative charge material is used to cyclically contact with it under different contact forces, frequencies and spacers. There will be higher electric output under higher contact force, frequency and spacer. The SETEG shows a better electric output performance with a thinner glass positive charge material under lower ambient humidity condition. An open circuit voltage, short circuit current and power up to 318 V, 8.3 μA and 427 μW has been obtained with only 5×5 cm contact area. The sensor array wafer is then made with 9 separated 5mm×5mm SETEG on it and the voltage output can easily reach 2 V under ~1 N PDMS covered stylus touch. A LabVIEW based automatic measure system is built to record, calculate and display the voltage output of the sensing array under the stylus contact. The recorded output voltage shows good independence and can easily be calculated to track the motion of the stylus, demonstrating the great potential of the glass based SETEG to be made into sensing applications in our daily life.

Keywords: transparent, glass based, sensor array, automatic measure system

1. Introduction

With the rapid development of the Internet of things (IoT), the complementary energy sources and self-powered sensors are attracting more and more attentions. There are plenty of potential choices for complementary energy sources, which are based on piezoelectric[1, 2], pyroelectric[3, 4] and triboelectric[5, 6] effect etc. The triboelectric generator (TEG) uses the contact of two materials with opposite charge affinities to convert the mechanical energy into electric energy and it is considered to
be one of the most promising complementary energy sources due to its simpler device structure, lower cost, easiness for large-scale fabrication and most importantly, the higher electrical output compared with other microgenerators. Besides, TEG can generate electric energy through the mostly used three types of contact modes, which are the vertical contact, lateral slide and single electrode mode. As only one of the charge material is connected to the circuit, the SETEG is not the best choice for generator due to its smallest quantity of generated electricity[7]. However, this structure is more suitable to be used in the daily life as a self-powered sensor because the other unconnected material can be anything such as rain drop[8], finger[9, 10] and pavement[11] etc.

Glass has the advantages of high transparency, excellent corrosion and wear resistance, thermal reliability and hardness etc. It has been widely used in our daily life from the satellites in the universe to the mobile phones in our hands. For the usage in the contact mode TEG, it has showed good electrical output and excellent mechanical reliability in our previous work[12]. But there is no actual practical TEG application made from glass has been reported.

Here we report a further development of the transparent SETEG tracking sensor array based on commercially available glass and polydimethylsiloxane (PDMS) covered touch stylus. And the preliminary test with 5 cm×5 cm glass and PDMS charge materials shows an open circuit voltage, short circuit current and power up to 318 V, 8.3 $\mu$A and 427 $\mu$W, respectively. And the following test performed on the sensor array has a voltage output larger than 2 V with a 5 mm×5mm device size and ~1 N contact force, which can be easily detected by a commercial analog to digital converter (ADC). The glass based sensor array demonstrates its great potential for the integration of the enormous existed glass application and the promising newly developing TEG.

2. Fabrication and experiment setup
Figure 1 the 3D illustration of the SETEG with the glass and PDMS parts (a) and the sensing array wafer (b). The sensing array wafer was connected to a central hollowed printed circuit board (PCB) using conductive tape, showing good optical transparency (c). (d) A stylus with a PDMS covered head was touching and sliding on the glass side of the sensing array wafer during the test. (e) The voltage data from 9 independent SETEGs on the sensing array wafer were collected using a DAQ card.

Before fabricating the sensing array wafer, we firstly need to systematically estimate the performance of the SETEG using glass and PDMS as the charge material. The complete 5 cm × 5 cm structure with the upper PDMS part and the lower glass part is shown in Fig. 1(a). The PDMS (184 Silicone Elastomer, Dow corning Co. Ltd.) solution, which was a mixture of the base PDMS and the crosslinker at a ratio of 10:1 by mass, was spun on the commercially available 1 mm soda lime glass at 1100 rpm for 10 seconds to obtain a PDMS thin film with a thickness of ~100 μm. Then the PDMS layer on the glass substrate (the upper PDMS part) was crosslinked on a hot plate at 100 °C for 25 minutes. The lower glass part consists of a commercially available soda lime glass with different thicknesses (0.55 mm, 1 mm, 2 mm and 3 mm), a transparent indium tin oxide (ITO) conductive thin layer (750 nm, Resistivity = 3.525×10⁻⁴ Ω·cm) and an acrylic protective layer. The ITO layer was deposited on
the soda lime glass by the direct-current reactive magnetron sputtering with 150 W power, 0.7 Pa pressure and -75 V bias voltage[13]. For a better transparency and conductivity, the ITO was then annealed using a rapid thermal annealing machine (RTP-CT100M) at 300 °C for 5 minutes in N₂ atmospheric pressure. Finally, the protective acrylic layer was glued to the ITO layer. These samples were made for the preliminary test to demonstrate its capability to be used as TEG sensor array. A dynamic fatigue tester (Popwill Model YPS-1) was utilized to control the cyclic contact force, frequency and space of two TEG charge pairs, which was the same as the experiment setup in our previous work[12]. The voltage and current output were collected using an oscilloscope (Tektronix MDO3022) and a picometer (Keysight B2981A), respectively.

The 3D illustration of the sensing array wafer (0.55 mm thickness, 5 cm ×5 cm) with 9 SETEGs (5 mm×5mm) is shown in Fig. (b). The ITO pattern on the glass wafer was fabricated using the conventional ultraviolet light photolithography and lift-off process and it was then deposited and annealed using the same conditions mentioned above. The central 9 squares of the ITO pattern were the electrodes for the 9 SETEGs, and the relatively smaller 9 squares around were designed for the connection of the sensor array wafer and the PCB using the conductive tape, which was shown in Fig. 1(c). The good transparency of ITO and glass structure has been reported in our previous work[12]. The PCB was designed to have a hollowed square window to demonstrate the good optical transparency of the sensor array wafer, the image on the computer screen can be seen clearly with the sensor array wafer on it.

Fig. 1(d) shows the test situation of the sensor array, a stylus with a PDMS covered head was touching or sliding on the front side (glass side) of the sensing array wafer and Fig. 1(b) is captured exactly from the back side (ITO side) of the sensing array wafer. The voltage signals are collected using a data acquisition (DAQ) USB card (Adlink USB 1902) connected to the computer, as shown in Fig. 1(e). A self-developed LabVIEW program is then used to calculate the voltage data from 9 independent SETEGs to display the real-time voltage curve and tracking animation on the computer screen.
3. Results and discussion

Before developing the SETEG sensor array, it is very important to thoroughly investigate the electric output performance and the reliability of the SETEG first. The SETEG with 0.55 mm glass were cyclically tested under different contact forces, frequencies, spacers. Fig. 2(a) and (b) show the open circuit voltage and short circuit current of the 0.55 mm TEG with 4 mm spacer and 5 Hz contact frequency under different contact forces, respectively. The open circuit voltage steadily increases from 146 V (20 N) to 238 V (60 N), and then slightly goes up to 250 V when the contact force reaches 80 N. The short circuit current experiences a same trend, which increases from 4.3 μA to 6.6 μA when the contact force increases from 20 N to 80 N. There are mainly two reasons that enhance the electric output improvement of the contact mode glass based TEG under higher contact force according to our previous work[12], which are the increase of the contact area and the total capacity of the TEG[14]. And the capacity increase of the PDMS part in the contact mode TEG is the
primary reason that results in the total capacity increase of the TEG, because glass is a rigid material and higher contact force will only compress the PDMS triboelectric layer, leading to a smaller thickness, which means a larger flat panel capacity of the PDMS part. For SETEG, the PDMS part has not electrically linked to the TEG, so the total capacity of the TEG actually remains almost unchanged. Only the increasing contact area is enhancing the electric output performance under higher contact force, and that’s the reason why the electric output improvement of the glass based SETEG under higher contact force was not as good as that of glass based contact mode TEG[12]. The open circuit voltage and short circuit current with 50 N contact force and 4 mm spacer under different contact frequencies are shown in Fig. 2(c) and (d). The open circuit voltage gradually increases from 74 V to 238 V when the frequency increases from 1 Hz to 5 Hz, while the short circuit current shows the same trend, gradually increasing from 1.9 μA (1 Hz) to 7 μA (5 Hz). The rising trend of the electric output can be attributed to the rapider contact under higher frequency, which leads to a faster induction and movement of charges. Fig. 2(e) and (f) illustrate the open circuit voltage and short circuit current with 50 N contact force and 5 Hz contact frequency under different spacers, respectively. It is clear from these two figures that the electric output saturate when the spacer is larger than 8 mm. The open circuit voltage and short circuit current is 75 V and 1.9 μA at 2 mm spacer, followed by a sharp increase to 254 V and 6.6 μA when the spacer gets to 4 mm, then slightly increase to 318 V and 8.3 μA at 8 mm spacer. As the contact frequency is the same for different spacer conditions, higher spacer means higher relative velocity of the PDMS and glass triboelectric layers, which will lead to a faster charge transferring speed thus a better electric output performance.
Figure 3 (a) open circuit voltage, (b) short circuit current and (c) power of SETEG with different glass thicknesses (0.55 mm, 1 mm, 2 mm and 3 mm), decreasing with the increasing glass thickness. (d) open circuit voltage, (e) short circuit current and (f) power under different humidity levels, decreasing with the increasing humidity.

Besides testing the SETEG performance under different contact conditions, we have also measured the electric output performance of the glass based SETEG with different environment humidities and thicknesses of glass. Fig. 3(a), (b) and (c) show the open circuit voltage, short circuit current and power of the SETEG with 4 different glass thicknesses under 50 N contact force, 5 Hz contact frequency and 4 mm spacer, respectively. The open circuit voltage gradually decreases from 238 V to 135 V when the glass thickness increases from 0.55 mm to 3 mm. The short circuit shows a same trend, which decreases from 7.1 μA to 3.5 μA while the glass thickness increases from 0.55 mm to 3 mm. It can be seen clearly from Fig. 3(c) that the peak power is close when the glass thickness is less than 1 mm, which is 359.1 μW and 331.7 μW for 0.55 mm and 1 mm glass thickness, respectively. With a further increase of the glass thickness, the peak power declines dramatically to 159.3 μW when the glass thickness reaches 2 mm. And then the decrease trend becomes smooth again, and the peak power of the TEG with 3 mm glass slightly drops to 149.1 μW. The downturn of the peak power might be attributed to the larger portion of charges lost...
during the propagation from the surface of a thicker glass to the ITO electrode. The glass based SETEG is designed to be used in our daily life and as the previously works reported, higher humidity level will lead to the electric output deterioration due to the inducted charge leakage on the surface of the triboelectric material[15], so the measurement of the open circuit voltage, short circuit current and power under different humidities, which have been shown in Fig. 3(d), (e) and (f) respectively, is extremely important. The open circuit voltage decreases from 282 V at 38 % to 61 V at 73 %, and the short circuit current declines from 6.6 μA to 1.6 μA when the humidity increases from 38 % to 73 %. For the peak power, it is only 21.4 μW at 73 % humidity, and dramatically increases to 427 μW at 38 %. The power output at high humidity level is undoubted too small for the energy harvesting applications, but it is sufficient for the sensing applications as the commercial ADC can easily measure voltage signal in millivolt scale.

Figure 4 The open circuit voltage of a SE TEG with a 0.55 mm glass cyclically tested for more than 10000 periods, demonstrating its excellent stability.

![Figure 4](image)

The stability is one of the most important criterions to decide if the sensors are good or not. Fig. 4 is the open circuit voltage of a SETEG with a 0.55 mm glass cyclically tested for more than 10000 periods. The initially tested open circuit voltage is 322 V, and it slightly rises to 350 V after 3000 periods' contact. After that, the open circuit voltage keeps stable until the end of the test. The increment of the open circuit voltage can be explained by the better contact of the PDMS and glass, which leads to
a larger contact area.

Figure 5 (a) 3D illustration captured from front side (glass side) of the sensing array wafer and the 9 separated SETEG sensors have been numbered from Port 1 to Port 9. (b) DAQ device collected voltage output of Port 1. The negative and positive voltage is generated when the stylus presses on and release from the glass surface, respectively.

Figure 6 stacked voltage pictures for 9 ports touch independently (a) and being slided with Z type (b) by a stylus, showing a good independence of these 9 SETEG sensors.

All the experiments above have demonstrated the feasibility of using the commercial glass to make the sensor array application. Fig. 5(a) is the 3D illustration captured from the front side (glass side) of the sensor array wafer. There are 9
independent SETEG sensors made in 1 complete glass wafer and they have been numbered from Port 1 to 9. After the fabrication of the sensor array, an automatic measure system is built to record, calculate and display the voltage output of the sensing array under the contacting of the PDMS covered stylus. Fig. 5(b) shows the voltage output of port 1 under the stylus touching recorded by the DAQ. A negative and positive voltage is generated when the stylus presses on and releases from the glass surface, respectively. The generated voltage is not as large as the results tested under the dynamic fatigue tester as the contact force of stylus is very small force (~1 N), but it is large enough for a commercial DAQ to collect.

![Figure 7 Schematic diagram of the multi-channel DAQ device collecting data from 9 independent TEG sensors. The over-large input impedance of SETEG will lead to a ghosting effect.](image)

The stack illustrations of 9 ports contacted one by one is shown in Fig. 6(a). Fig. 6(b) shows the voltage output when the stylus sliding on the sensing array with a Z type. It moves with a sequence of Port 1, Port 2, Port 3, Port 3, Port 5, Port 7, Port 7, Port 8 and Port 9. It is clear that when one port is being touched, the voltage signal can also be generated from other ports. For example, when port 9 is touched around 30s in Fig. 6(a), there is a small peak also occurred in Port 1. This phenomenon can be
called as ghosting effect and explained using the measure principal of a commercial DAQ device. As shown in Fig. 7, for a commercial economic DAQ, it usually only has one ADC and a multiplexer is used to switch from one channel to another according to sampling rate when doing a multi-channel measurement, which means only one channel can be recorded at a time even for multi-channel setup. When the multi-channel analog signals come into the DAQ device, the multiplexer will first choose one of this signals and then let it charge the capacitor C in the front of the ADC to reach the voltage of the source analog signal. The time used for the capacitor charging from the initial voltage to the source signal voltage is called the setting time. After the convert of the first channel finished, the multiplexer will switch to next channel, and the capacitor C starts to charge from the voltage of the previous channel to the voltage of the channel connected. For common analog source, the DAQ device works perfectly, but it is well known that TEG has a very large input impedance (R₁ to R₉ as shown in Fig. 7) at tens or even hundreds of MΩ, which means it will take much more time for TEG source to charge or discharge the capacitor C (higher setting time). For instance, after the voltage convert of Port 9, the capacitor C has a high voltage and when the multiplexer switches to Port 1, as the source analog signal of Port 1 is 0 V, the capacitor C will tend to discharge to 0 voltage, but the high input impedance leads to a longer setting time, which means it can not be discharged to 0 V before the next channel switching action comes and the ADC records a voltage higher than 0 V for Port 1. The ghosting effect can be weakened by using a DAQ device with multiple ADCs or just set the sampling rate as low as possible for the capacitor C having enough time to charge or discharge to source voltage. Here we set the sampling rate (~ 250 ms per point or 4 Hz) lower for weakening the ghosting effect, which can be nearly neglected as shown in Fig. 6(a) and (b), showing a good independence of these 9 TEG ports.
Figure 8 Voltage output under 9 independent touch (a) and Z type sliding (b), showing the capability of the sensing array to track motion on the glass surface.

Figure 9 LabVIEW Graphic interface is used to display the real-time voltage output (left) and the trace (right) of the moving stylus.

The contact sequence and voltage amplitude can be seen more clearly in Fig. 8(a) and (b), which are the voltage output under 9 independent touch and Z type sliding, respectively. The peak voltage output in Fig. 8(a) is 2.03 V, 2.81 V, 2.99 V, 2.33 V, 3.46 V, 2.55 V, 3.66 V, 2.45 V and 4.53 V for Port 1 to 9, respectively. The voltage outputs are not the same because human hand controlled stylus touching have different contact conditions every time, but all the voltage amplitudes of 9 ports are large enough for any commercial DAQ devices to collect. The move sequence can be
easily obtained from Fig. 8(b) and the average moving velocity of the stylus can be calculated using the distance divide time between peaks. The Z type sliding consists of 3 strokes and the average sliding speed is 4 cm/s, 2.75 cm/s and 3.92 cm/s for these 3 strokes, respectively.

Besides the data recording function of the automatic measure system, a real-time tracking display is also developed to see the trace of the stylus on LabVIEW program, which has been shown in Fig. 9. The left 9 stacked pictures are for the real-time voltage output displaying and the right part is used to display the real-time stylus moving, which have 9 squares corresponding to 9 ports on the sensing array. When the stylus touches one of the sensors, the corresponding black square will turn to white and a higher voltage output will lead to a whiter square. Two videos (see supplement video touch.mp4 and slide.mp4) are recorded to demonstrate the feasibility of tracking stylus movement using the sensing array.

4. Conclusion

Transparent glass based SETEG has been made and it was firstly tested under different contact forces, frequencies and spacers. Higher contact force, frequency and spacer lead to a higher SETEG electric output. SETEGs with different glass thicknesses are tested under different humidities and show a larger electric output with a thinner glass and a lower humidity. An open-circuit voltage, short-circuit current and power up to 318 V, 8.3 μA and 427 μW has been achieved, respectively. At last, this SETEG is cyclically tested for more than 10000 cycles without performance deterioration, showing its good stability. After the preliminary tests that have verified the possibility of the glass based SETEG to be made into sensor applications, a sensor array glass wafer with 9 separated SETEG sensors has been made to tracking the motion of a stylus with PDMS covered head. Furthermore, A LabVIEW program is developed to calculate and display the real-time voltage output and stylus motion. The 9 separated sensors show good independence with each other while doing single port touch test and the following sliding test demonstrates its capability to track stylus motion. All the above experiments exhibit the great potential
of the glass based SETEG to be utilized in our daily life for sensing applications.

Acknowledgement:

References