ISSN 1330-3651(Print), ISSN 1848-6339 (Online)

https://doi.org/10.17559/TV-20160126093335

Original scientific paper

Triboelectric Nanogenerator Based Self-Powered Tilt Sensor

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Abstract: This work focuses on the fabrication and evaluation of triboelectric nanogenerator (TENG) based self-powered tilt sensor. The proposed fabricated structure is composed of polydimethylsiloxane (PDMS), steel ball, gold (Au) as electrode and circular ring housing. A specific configuration of electrodes was used to measure the tilt at different angles. FEM simulations were used to verify the electric potential at the electrodes at different angles. The outputs of the fabricated sensor were measured at different angles from 0 to 360°. A sensitivity of 254 mV/rad is obtained in single axis. The TENG based tilt sensor generates an open circuit voltage of 450 mV at 10 MΩ.

Keywords: self-powered; tilt sensor; triboelectric nanogenerator

1 INTRODUCTION

The focus from low power consumption devices to self-powered devices has recently received a large attention from the researchers. Triboelectric nanogenerator (TENG) developed by Wang's group could be a promising technology for the future self-powered electronic devices and sensors. TENG can be used as a power source [1, 2] as well as self-powered active physical or chemical sensor [3, 4-8] . The advantages of TENG are the low cost, usage of polymer and simple fabrication process.

TENG uses triboelectric effect for charge generation and electrostatic induction for separation and flow [8]. Generally, TENG can be used in three modes: vertical contact mode [9], sliding mode [10] and single electrode mode [11].

In motion detection application, tilt is an important parameter used in variety of applications like robots, consumer electronics, construction, toys, and military applications [8].Tilt sensor can be used to measure the slope/inclination with any reference usually gravity. Different approaches have been used to develop MEMS based tilt sensors like capacitive [9, 12, 13], electrolyte [21, 14,15], resistive [10], thermal [11], optical [16, 17] and inductive [18].

All these sensors have some merits and demerits. Fiber optic based tilt sensors have the highest resolution and accuracy but are expensive and need additional light source and detector, hence making the design more complex [16]. Electrolyte tilt sensor uses KOH which is toxic. Thermal tilt sensor has the disadvantage of high power consumption whereas resistive type sensor could be easily affected by the noise. Moreover, they need an external power source. To further broaden the application of the tilt sensor, self-powered piezoelectric based tilt sensor [19] was proposed. The piezoelectric based self-powered tilt sensor has low sensitivity which can be altered by TENG based tilt sensor proposed in [17]. The reported self-powered tilt sensors have the inclination measurement range of $\pm$ 90° in single axis.

This work focuses on SETENG based self-powered tilt sensor. The sensor is capable of measuring tilt angle with high range. The high sensitivity of the sensor reveals that it could not be affected by the noise. We discuss the characteristics of the proposed device using simulation and experimental results. The detailed contents are organized as follow. The design and fabrication of the SETENG tilt sensor are discussed in Section 2. Section 3 focuses on the experimental and simulation results while in Section 4 conclusions are driven.

2 DESIGN AND FABRICATION

2.1 Working principle

The charges on the surface of the material depend on the material selection and the contact between the two materials. To enhance the triboelectric effect the surface of the PDMS was modified, using soft lithography and micromachining of silicon, shown in SEM image Fig. 1. Due to triboelectric effect some materials have the potential to become more positively charged (donate electron) compared with other materials, which become negatively charged (accept electron). To accept or donate electron it depends upon the work function of the material [9].

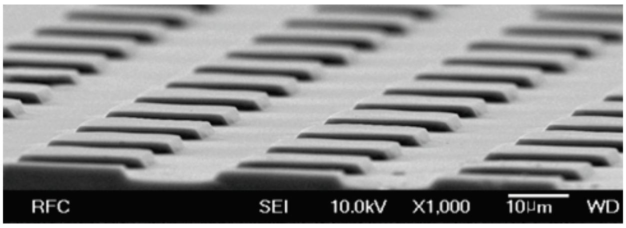

Figure 1 SEM image of modified PDMS

Steel ball and PDMS were selected as triboelectric materials because they are far away from each other in triboelectric series. It is well known that when a steel ball rolls on the surface of the PDMS surface negative charges will be developed on PDMS and positive charges on the steel ball due to triboelectric effect [8] . When the ball moves away from the electrode, equal and opposite amount of charges on the back side of electrode are developed due to electro static induction [20]. These charges are developed due to the movement of charges between the electrode and the ground. The potential difference between the electrode and the ground was measured for detecting the tilt angle.

2.2 DESIGN AND FABRICATION OF TILT SENSOR

The device fabrication was started with the surface modification of PDMS using soft lithography. A silicon (100) mold was patterned by using lithography. After removing the oxide layer by buffer oxide etchant (BOE), wet etching using TMAH at 80 °C for 20 minutes was carried out to make pyramid groves. Since the Si and PDMS have high adhesion, to overcome this, the master Si was treated with TMCS using vapor phase salinization.

The pattern was transferred to the PDMS by pouring liquid PDMS on the Si master. A PDMS solution was prepared by mixing PDMS and sylgard at 10:1 at room temperature. The solution was degased in vacuum desiccator to completely remove the water bubbles. For uniform distribution the poured PDMS on the Si was spin coated at 800 rpm for 50 seconds. After heating at 90° for 45 minutes, the PDMS was peeled off easily.

Gold electrode was deposited on the back side of the PDMS using RF magnetron sputter. RF power source of 150 W, at 13 K temperature and low pressure was used. Ar gas was used to create plasma between the target and substrate. Ar ions cause the atoms or molecules to be ejected from the target. These molecules or atoms travel to the substrate to form a thin layer of Gold on PDMS.

In SETENG, only one electrode is used, which is directly connected to the triboelectric part. The second electrode is used as a reference electrode which could be directly connected to the ground to keep the potential balance [9]. The proposed tilt sensor also uses SETENG. A special configuration of the electrodes was used to cover complete 360° in a single axis. Four electrodes named A, B, C and D were placed 90° apart. The output can be measured across each electrode for measurement of different tilt angles. Fig. 2 shows the schematic diagram of the proposed device. A circular housing of 2 cm radius, a commercial steel ball of 1 cm diameter and PDMS with thickness of 300 μm were used.

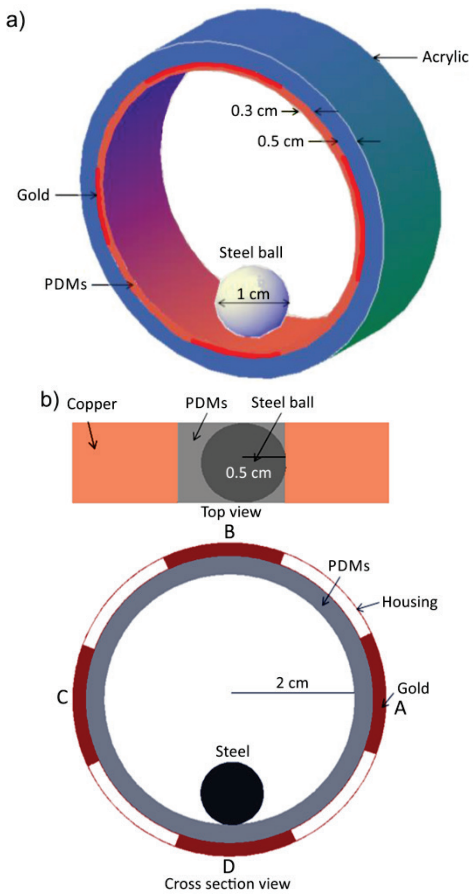

Figure 2 a) Schematic diagram, b) top and cross section of self-powered tilt sensor

Circular ring housing was used for assembling the device. The PDMs was attached to the ring using adhesive tape. The resolution of the sensor depends on the number of electrodes and the distance between the electrodes. By following the well-known equation

$$S = r \cdot \theta \tag{1}$$

we can find the resolution of the sensor where θ is the minimum detectable range, S is the length of arc, in this case is the length of electrode and r is the radius of the housing.

3 SIMULATIONS AND EXPERIMENTAL RESULTS

To understand the basic principle of the SETENG based tilt sensor electric potential distribution was studied using COMSOL. The proposed model is illustrated in Fig. 3. A surface charge density of 8 μC/cm^2 was used for the simulation. When the ball rolls across the electrode back and forth, the electric potential changes.

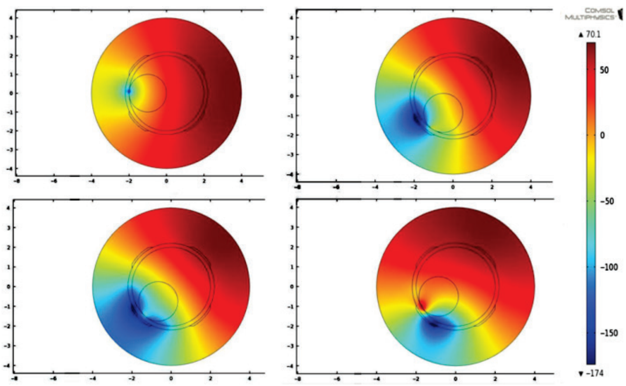

Figure 3 Comsol simulation for electric potential distributions of tilt sensor

Fig. 4 shows the experimental setup. The electrodes at the back side of the PDMS were connected to the LeCory oscilloscope positive terminal while the negative terminal was connected to the ground. The steel ball moves back and forth on the PDMS surface, to generate static charges due to triboelectric effect. An opposite charge is also generated on the back side of the electrode. The potential difference on the electrode was measured.

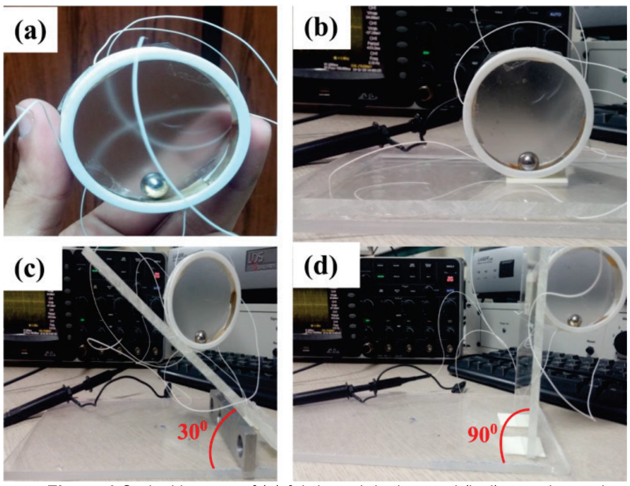

Figure 4 Optical images of (a) fabricated device, and (b-d) experimental setup at 0, 30 and 90 degrees, respectively

At 0° tilt the ball was at the center of electrode A and swings across the electrode. A maximum output voltage of the 450 mV was observed shown in Figs. 5 and 6. Since the open circuit voltage depends on the displacement distance and surface charge density σ given in Eq. (2) [20]

$$V = \frac{\sigma x}{\varepsilon_0}\left(\frac{d_1}{\varepsilon_{r1}} + \frac{d_2}{\varepsilon_{r2}}\right) \tag{2}$$

The output can be altered by changing the displacement distance and the surface charge density between the steel ball and back electrode. When the sensor was tilted at 30° the ball moves though only half of the electrode and an open circuit voltage of 375 mV were observed. The same trend was also observed for electrode B, C, D. At 45° tilt angle the ball was at the center of the electrode A and B and moves across both the electrodes, an output voltage of 375 V was observed across both electrodes. Tab. 1 summarizes the output voltages across electrode A, B, C and D.

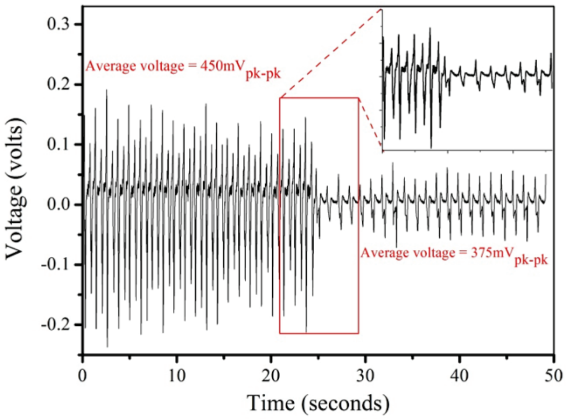

Figure 5 Open circuit voltage 0° and 30°/330° of electrode A

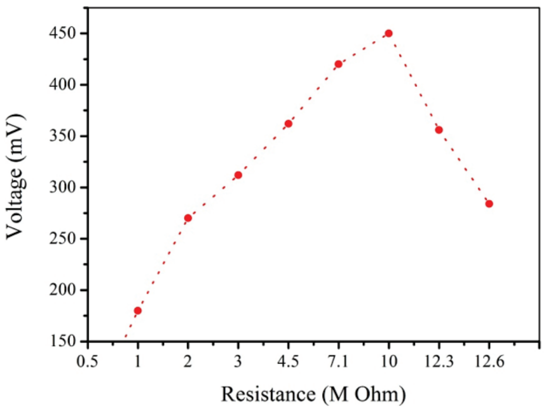

Figure 6 Output Voltage at different load resistances

Tab. 2 summarizes the comparison of the proposed device with the reported work. SETENG based Tilt sensor improves the range of the self-powered inclinometer in single axis. A maximum sensitivity of 152 mV/ rad was observed.

The output of the SETENG based tilt sensor was also measured across different resistances shown in [6]. The output was low and noisy below 0.5 MΩ and cannot be observed. The maximum output voltage of 450 mV was observed at 10 MΩ.

Table 1 Corresponding output voltages at different electrode

Angles (degree)	Output voltage at electrodes (mV)			
	A	B	C	D
0	450			
30	375			
45	375	375		
60		375		
90		450		
120		375		
135		375	375	
150			375	
180			450	
210			375	
225			375	375
240				375
270				450
300				375
315	375			375
330	375			

Table 2 Comparison with self-powered titlt sensors

Reference	Method	Resolution	Range (degree)	sensitivity
[9]	Piezoelectric	NA	0-90	200 µv/rad
[23]	Triboelectric	30 degree	0-90	450 mV/rad
This work	Triboelectric	30 degree	0-360	152 mV/rad

4 CONCLUSIONS

In this work we demonstrated a self-powered tilt sensor based on triboelectric nanogenerator. Since the resolution of the sensor depends on the number of electrodes used and the distance between the electrodes, the output of the sensor was checked at large angles. A maximum sensitivity of 154 mV/rad and an open circuit voltage of 450 mV was observed. The output of the SETENG tilt sensor was also measured at different resistances and the maximum output was observed at 10 MΩ.

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