Performance enhancement of the triboelectric energy harvester by forming rough surface polymer film using poly-dimethyl-siloxane +25 wt% water solution

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Abstract: In this paper, an experimental study of performance enhancement of the triboelectric energy harvester (TEH) by using rough surface poly-dimethyl-siloxane (PDMS) polymer film as one of the tribo layer has been presented. A parallel plate vertical-separation mode type TEH has been fabricated with rough surface morphology PDMS polymer film. Rough surface morphology is formed by spin coating diluted PDMS formed of Dow Corning 10:1 PDMS solution +25wt% water on the FR4 PCB board. FR4 substrate with single side copper clad has been utilised to realise bottom electrode. A cantilever structure is implemented utilising 50 µm thin copper foil, as top electrode, attached beneath a Kapton film. The device performance measurements showed the peak output voltage of 39.69 V and peak to peak voltage of 53.75 V. As a proof of concept, self-powered light emitting diodes (LED) system with 26 serially connected LEDs has been demonstrated with manual tapping on the TEH device.

Keywords: triboelectric; tribo-pair; energy harvester; poly-dimethyl-siloxane; PDMS; self-powered.

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1 Introduction

The technological advancements in microelectronics fabrication has drastically miniaturised the devices as well as systems, which made ultra-low power operation of electronic systems (Dieffenderfer et al., 2016; Han et al., 2016) for example pacemaker and cardioverter defibrillator requires < 10 μW power (Wong et al., 2004), hearing aid requires 100–2,000 μW of power (Kim et al., 2006; Neuteboom et al., 1997). As the power storage devices (e.g., batteries) has also evolved in their performance and cost reduction, these ultra-low power electronics can be operated for the more extended period. But the problem with batteries is the disposal of discharged batteries as these are hazardous for our health and the environment. Developments of self-powered systems could be a solution, because power required for ultra-low power electronics devices can be generated from the energy available in the surrounding in the form of sound, light, heat, vibration or movement using energy harvesters. These energy harvesters can be integrated with sensors to implement self-powered system. In this paper, we have presented kinetic energy harvester which converts available kinetic mechanical energy, in the form of vibrations, into electrical energy. There are three conventional mechanisms most commonly used for kinetic energy harvesters, i.e., piezoelectric (Janphuang et al., 2015; Kim et al., 2011; Ranton and Sodano, 2007), electromagnetic (Cepnik et al., 2013; Podder et al., 2016) and capacitive (Khan and Qadir, 2016). Recently in 2012, Fan et al. reported a new kinetic energy harvesting approach based on conjunction of triboelectrification (contact electrification) (Davies, 1969; Williams, 2012) and electrostatic induction mechanism called triboelectric energy harvesters (TEHs). TEHs have unique advantages of large output power, high efficiency, lightweight, cost effective materials, simple fabrication (Fan et al., 2012). TEHs can be configured in four modes, i.e., vertical contact-separation mode, lateral sliding mode, single-electrode mode and freestanding triboelectric-layer mode (Wang et al., 2016; Wang, 2014).

In this paper, we have presented a device configured to operate in vertical contact-separation mode because of its inherited advantage of simple design, durability as no large-scale frictions during operation. Energy harvesters based on vertical contact-separation mode have been reported (Zhu et al., 2012; Wang et al., 2012). Zhu et al. (2012), in which polymer dielectric poly (methyl methacrylate) (PMMA) and

Kapton has been used as tribo-pair which generated maximum open circuit voltage of 110 V and instantaneous electric power density of 31.2 mW/cm^3. Wang et al. (2012) reported an arch shaped design with tribo-pair of poly-dimethyl-siloxane (PDMS) and aluminium. They could obtain 230 V output voltage, 15.5 μA/cm^2 current density with 128 mW/cm^3 energy volume density. The conversion efficiency reported was 10%–39%. But these TEH have been fabricated using cleanroom processes such as in Zhu et al. (2012) electron beam evaporator to deposit aluminium (Al) at one side of the Kapton while dry etching fabricated the nanowire on the other side. These nanowires were created in order to increase the contact area. The plasma-enhanced chemical vapour deposition (PECVD), lithography, wet etching, lift-off processes were used to create squares and pyramid structures in Wang et al. (2012) on PDMS layer. In order to achieve the patterned PDMS surface in other works (Lin et al., 2013) the lithography and wet etching have been used to make silicon mould, in Dudem et al. (2017) and Yang et al. (2013), nano porous anodic aluminium oxide templates have been used. In contrast to these, we are presenting the design and fabrication of TEH without using any cleanroom process to achieve the rough surface morphology of PDMS.

This work is expanded version of Sharma and Agarwal (2018a), and here we are reporting the simultaneously measured voltage, current, and instantaneous power unlike only measured voltage with calculated current and instantaneous power in Sharma and Agarwal (2018a) from the measured voltage across 1 MΩ internal resistance of the oscilloscope, with modification in mechanical support in top electrode configuration. Details of the working principle of TEH have been reported in Sharma and Agarwal (2018a). The fabricated TEH device has been integrated in a 26 light emitting diode (LED) system to demonstrate a self-powered system. This paper is organised in four sections. Under Section 1, the introduction is given, Section 2 discusses about the design and fabrication, Section 3 provides the experimental results, Section 4 is the self-powered system demonstration followed by the conclusions in Section 5.

2 Design and fabrication

Here TEH has been designed with tribo-pair of copper as metal and diluted PDMS polymer layer as a dielectric. Commercially available FR4 substrate with single side copper clad has been used to realise the bottom electrode. The PDMS polymer dielectric layer of tribo-pair has been implemented by spin coating on the bottom electrode. The top electrode has been configured as cantilever structure realised using 50 μm thin copper foil attached beneath a piece of cardboard (Sharma and Agarwal, 2018a) to make it mechanically strong as top electrode is the moving structure in this design. In the top electrode configuration, the cardboard has been replaced by the Kapton film of thickness 180 μm to make this design more durable as the cardboard loses its flexibility over the time with repetitive tapping over it. This top electrode copper foil will act as an electrode as well as a tribo layer. The TEH device has been assembled as shown in the schematic view in Figure 1. TEH device with design parameters listed in Table 1 has been fabricated and experimentally tested.

PDMS-Copper tribo-pair design with pure PDMS has been fabricated and tested (Sharma and Agarwal, 2018b) as well as device with changed surface morphology by incorporating roughness to see the impact of rough surface on TEH performance. The surface morphology of PDMS polymer layer has been altered by diluting the

Dow Corning 10:1 PDMS solution by adding 25 wt% DI water. The PDMS-water solution has been mixed thoroughly and spin coated on bottom electrode. Coated PDMS was cured at 90°C for one hour. The cured PDMS has been closely observed and wavy surface has been achieved, as shown in Figure 2(a). It was observed that there are no entrapped water droplets in the PDMS film which may be due to bigger water droplet size compared to spin coated film thickness which is of the order of 44–44.6 µm, as shown in Figure 2(b) (microscopic image of cross-sectional view). These bigger water droplets got evaporated from the surface in the course of curing process and left voids, which were not fully filled by surrounding PDMS, resulting to wavy rough surface. Fabricated TEH device is shown in Figure 3 and Figure 4. Here, the device with Kapton cantilever structure has been experimentally characterised for output voltage, current and instantaneous power as discussed in next section.

Figure 1 Schematic view of TEH device (see online version for colours)

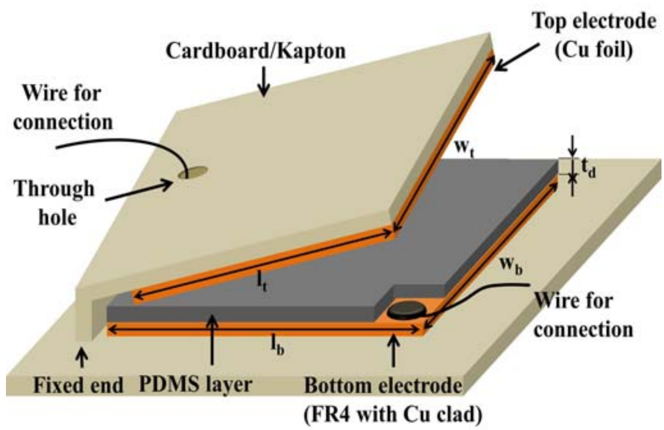
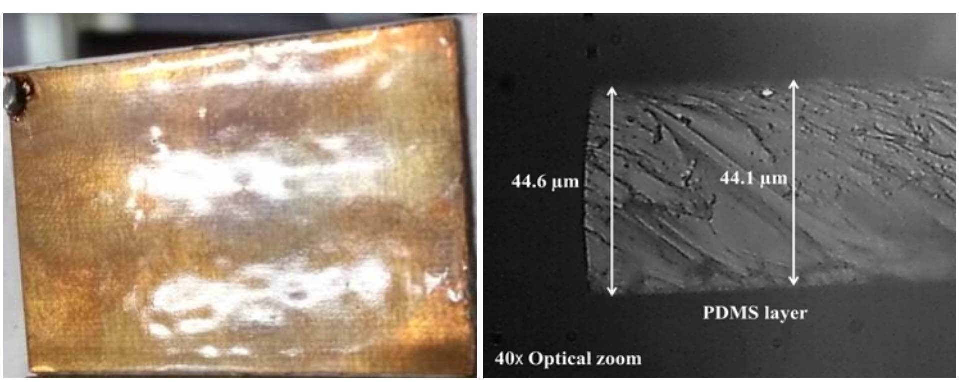


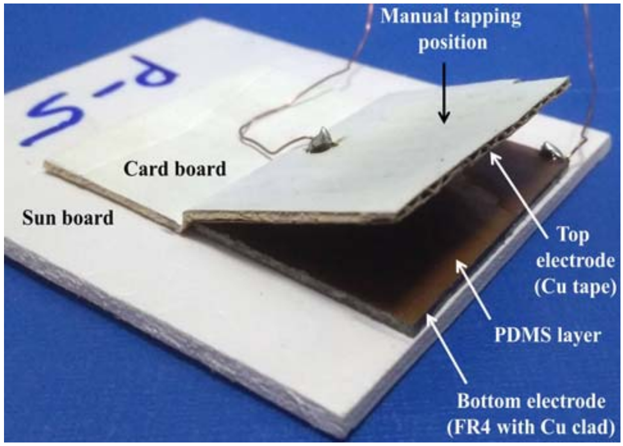
Figure 2 Spin coated PDMS layer, (a) optical image showing wavy surface (b) microscopic image showing cross-sectional view (see online version for colours)



(a) (b)

Source: Sharma and Agarwal (2018a)

Figure 3 Fabricated TEH device with cardboard cantilever structure (see online version for colours)



Source: Sharma and Agarwal (2018a)

Figure 4 Fabricated TEH device with Kapton cantilever structure (see online version for colours)

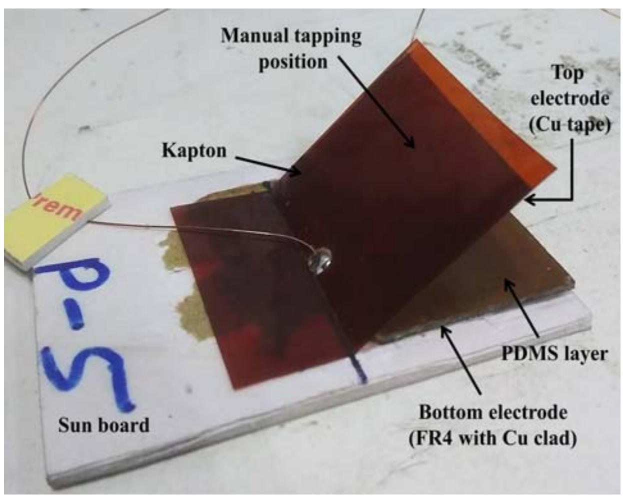


Table 1 Design parameters of TEH device

Parameters	*Dimensions*
Top electrode length, l_t (mm)	25
Top electrode width, w_t (mm)	35
Bottom electrode length, l_b (mm)	30
Bottom electrode width, w_b (mm)	40
Overlap area, A (mm^2)	875
Measured PDMS thickness, t_d (µm)	44–44.6
Tribo-pair	PDMS-Cu

3 Experimental results

The fabricated energy harvester device has been experimentally tested for output voltage, current and instantaneous power using digital oscilloscope and current-to-voltage converter circuit (Mallineni et al., 2017) by proving mechanical vibration with manual finger tapping on the top of cantilever electrode structure as labelled in Figure 4. With manual tapping, we could achieve peak voltage output of 39.69 V. Measured output voltage waveform is shown in Figure 5. The negative peak of output voltage waveform is at –14.06 V, therefore measured peak-to-peak output voltage is 53.75 V. The frequency of output voltage waveform shows the tapping frequency which is 6.3 Hz; therefore the time interval between two consecutive peaks is 158 ms. For current measurement we have used current-to-voltage converter circuit (Mallineni et al., 2017) and customised it for conversion ratio of 100 mV/µA (Sharma and Agarwal, 2019). Simultaneously measured peak current and instantaneous power is 4.79 µA and 170.4 µW respectively. The waveforms for output current and instantaneous power, measured simultaneously with voltage are shown in Figure 6 and Figure 7. The experimental results of this device are compared with the device fabricated with pure PDMS film (Sharma and Agarwal, 2018b) (without dilution), as depicted in Table 2. In Sharma and Agarwal (2018a, 2018b) the voltage has been experimentally measured but current and instantaneous power has been calculated from the measured voltage across 1 MΩ internal resistance of the digital oscilloscope. In Table 2 the calculated peak current and instantaneous power for the device reported in this paper has also been listed along with the experimentally measured values. The comparison for device performance enhancement has been carried out with respect to the voltage output. It is observed that diluted PDMS rough surface has enhanced the performance with peak-to-peak output voltage from 36.7 V (Sharma and Agarwal, 2018b) to 53.75 V by around 46%. Therefore, rough surface morphology of PDMS layer causes increase in surface area which enhances the performance of TEH device (Yang et al., 2018; Jin et al., 2016). There is also an increase in the performance as compared to the design discussed in Sharma and Agarwal (2018a) because cantilever configured with the Kapton film provides good contact between PDMS and top copper electrode.

Table 2 Experimental results

Parameters	*Experimental results*			
	Rough surface PDMS device 25 wt% water + PDMS			*For pure PDMS device (Sharma and Agarwal, 2018b) PDMS only*
	This work		*Sharma and Agarwal (2018a)*	
Peak voltage (V)	39.69		33.6	29.6
Peak-to-peak voltage (V)	53.75		50.2	36.7
Peak current (µA)	4.79	39.69 (calculated)	33.6 (calculated)	29.6 (calculated)
Instantaneous power (µW)	170.4	1,575.30 (calculated)	1,128.96 (calculated)	876.16 (calculated)
Instantaneous power density (µW/cm^2)	19.5	180.03 (calculated)	129.02 (calculated)	100.13 (calculated)

Figure 5 Output voltage waveform of TEH device with Kapton cantilever structure (see online version for colours)

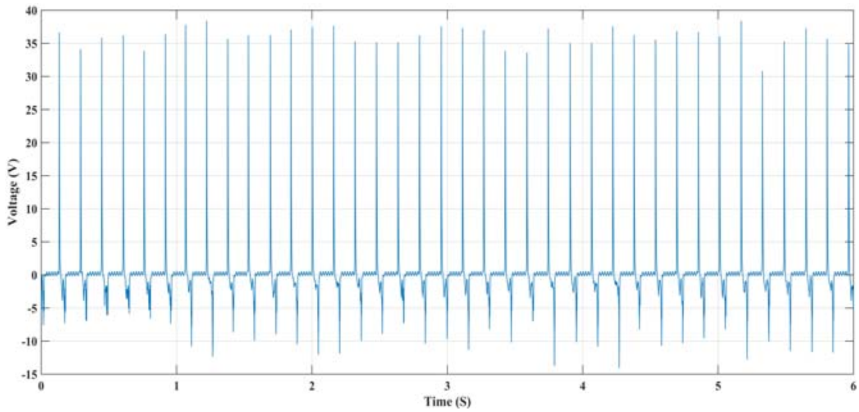


Figure 6 Output current waveform of TEH device with Kapton cantilever structure (see online version for colours)

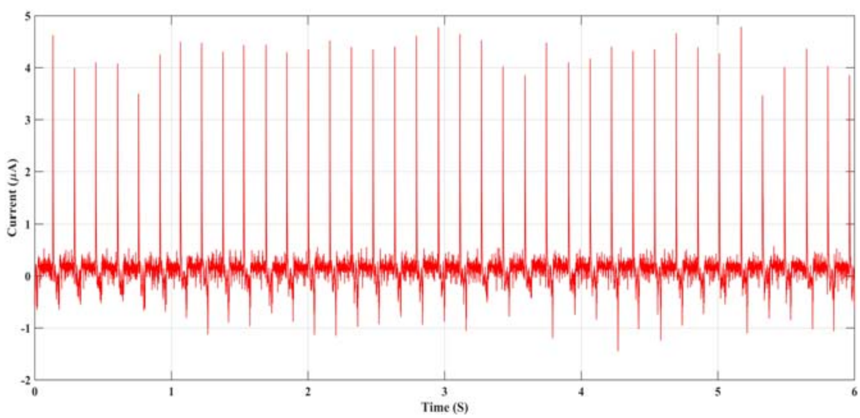
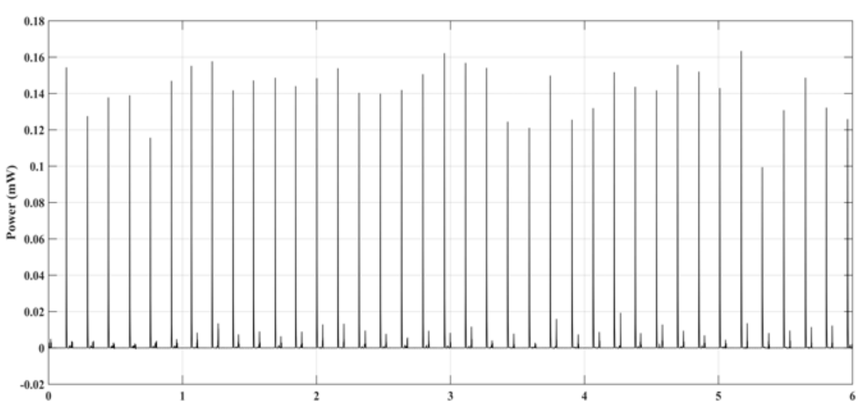


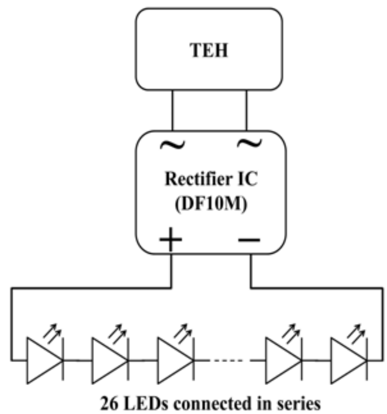
Figure 7 Output power waveform of TEH device with Kapton cantilever structure



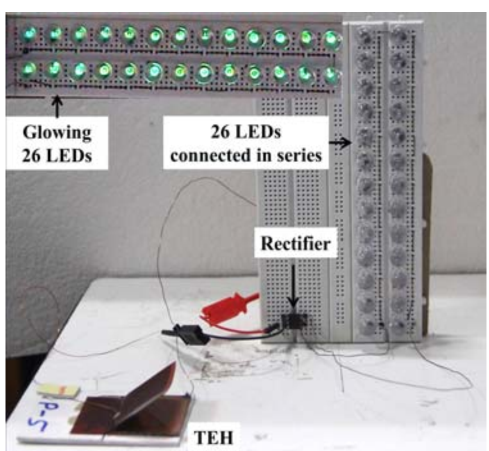
4 Self-powered system demonstration

The developed energy harvester device with Kapton cantilever structure is demonstrated in a self-powered LEDs system as same as the device with cardboard cantilever structure reported in Lin et al. (2013). The Kapton cantilever structured TEH is connected to serially connect 26 green LEDs (each of size 10 mm) on a breadboard through a full bridge rectifier IC (DF10M), as presented in Figure 8. On top of the cantilever, mechanical vibrational energy is provided by manual tapping which led to glow LEDs as shown in inset view of Figure 8(b). Therefore, a self-powered 26 LED working system is presented using in-house fabricated TEH.

Figure 8 Self-powered system demonstration, (a) block diagram of TEH integrated with LEDs and (b) the self-powered LEDs systems circuitry setup (see online version for colours)



(a)



(b)

Note: Inset: Glowing 26 green LEDs.

5 Conclusions

In this paper, an in-house developed parallel plate mode type TEH device has been demonstrated. The TEH device fabrication process does not include any complex cleanroom process. The surface morphology of the PDMS layer has been altered with a simple cost-effective method. The altered surface morphology has increased the total surface area of the PDMS polymer film and enhanced the device performance. In the top electrode configuration cardboard has been replaced with the Kapton which gives more durability, flexibility and better contact between tribo layers. For verification we have demonstrated TEH device working in a self-powered LED system, in which 26 LEDs were glowing with TEH output.

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