Origin of the Contact Force-Dependent Response of Triboelectric Nanogenerators

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Abstract. Triboelectric nanogenerators (TENGs) have attracted significant interest as the alternative source of renewable energy. Their performance is believed to depend on the contact force, but its origin is yet to be established. Herein, we show that the origin lies in the real contact area Ar, probed with novel experiments specifically designed for this purpose. The open circuit voltage Voc, short circuit current Isc and A_r for a TENG, having two nominally flat tribo-contact surfaces, were found to increase with contact force/pressure. The A_r is notably small at low pressures (0.25% at 16 kPa) that are typically experienced in wearable applications. However, it increases 328-fold to as much as 82% when it saturates beyond about 1.12 MPa pressure. Critically, V_{oc} and I_{sc} saturate at the same contact pressure as A_r suggesting that electrical output follows the evolution of the A_r. Assuming that tribo-charges can only transfer across the interface at areas of real contact, it follows that an increasing $Ar$with contact pressure should produce a corresponding increase in the electrical output. These results underline the importance of accounting for real contact area in TENG design to boost their performance, the distinction between real and nominal contact area in tribo-charge density definition, and the possibility of using TENGs as a self-powered pressure/load sensors.

Introduction

Triboelectric nanogenerators (TENGs) are newly emerging renewable energy harvesters that rely one the triboelectric effect to convert mechanical energy (e.g. vibration, contacting and sliding) to electricity. Owning to their versatility, TENGs have been proposed for harnessing kinetic energy from a wide variety of mechanical sources [1-4]. In order to boost TENG performance, most of the focus has been on optimising the material selections [5] and engineering the contact surfaces [6, 7] and most of the work conducted to date has involved relatively low contact forces/pressures (such as with wearables). Output performance depends on a number of factors: materials, contact force, surface topography, frequency and separation distance. Surprisingly, the role of some of these aspects is still rather poorly characterised and understood in TENG design. A recent analytical model in [9] has shown how accounting for a contact force-dependent real contact area produces the commonly observed force-dependent TENG electrical performance, but this has yet to be explored experimentally until this work. We investigate why TENG output increases with contact pressure by investigating both electrical outputs and real contact area (testing by pressure sensitive film) at a large range of applied pressure.

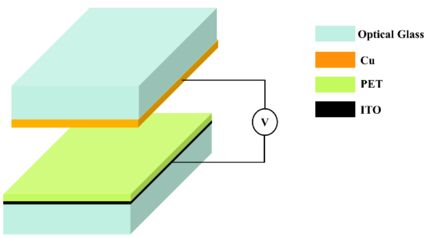

Fig. 1: Schematic of the CS-TENG having copper (Cu) in contact with polyethylene terephthalate (PET)

Result and Discussion

Fig. 1 shows the schematic of the experimental TENG device, including a copper sheet (50μm thickness) and indium tin oxide (ITO, 60Ω/sq resistivity) coated polyethylene terephthalate (PET) sheet (127μm thickness) as the tribo-positive and negative layer, respectively. Note, the tribo-layers were both fixed to optical glass plates. Device dimensions (active tribo-contact surface) were 6.25cm^2. The roughness scans for both Cu and PET are $6.1\mu m$ and $0.0095\mu m$. An example of real contact area A_r results, which tested by pressure sensitive film (SPF-A, Pressure Sensors Inc., USA) via a wide contact pressure range (from 32 to 1488 kPa), is shown in Fig. 2(a). The pink spots and white points in the left and right images represent the A_r between the TENG interface pair. It is to note that the sum of the white areas is the Ar which is defined as the ratio of A_r/A_n. Simultaneously, the Ar at each contact pressure was quantified; the contact area ratio against contact pressure is plotted in Fig. 2(b). It can be noted that the A_r increases linearly in the lower pressure regime, and then saturates at higher pressures. For instance, the contact area ratio saturates at about 82% when pressured reached about 1200 kPa. In accordance with the principle of contact electrification, the tribo-charges could only be transferred at the areas of real contact. This is because tribo-charges generation via electron tunnelling (i.e. contact electrification) requires the interatomic distance between atoms across an interface smaller than the equilibrium bond distance (i.e. within repulsive regime) [10]. Assuming tribo-charges can only transfer through the real contact area A_r, and defining σ_T as the areal density of tribo-charge transfer through A_r, we can write:

$$Q_T = \sigma_T A_r \qquad (1)$$

According to the parallel plate capacitor model, the Voc for the device is given by:

$$V_{oc} = \frac{Q_T x(t)}{A_n \varepsilon_0} \qquad (2)$$

where, σ_T is a constant from the tribo-material pair, x(t) is separation distance, ε_0 is the permittivity of air and A_n is the nominal contact area. Since these parameters are constant in our experiment, we can conclude that the total tribo-charge Q_T is increasing with the applied contact pressure. Therefore, Eqs. (1) and (2) show that V_{oc} is dependent on A_r. Meanwhile, A_r between interface pair is related to the normal contact pressure remarkably. Fig. 2(c) plots the TENG open circuit voltage signals used for device characterisation. A signal is shown for 12 contact forces between 20 and 930 N corresponding to nominal contact pressures of 32 to 1488 kPa. In Fig. 2(d), open circuit voltage increases with contact pressure and the upper end of the pressure range here is also sufficient to saturate the open circuit voltage: i.e. beyond about 1176 kPa (753 N), the voltage levels off at around 88 V. This is in-line with previous studies [7, 11] who have noted a similar response. Fig. 2(d) also indicates a very similar response for short circuit current. Therefore, due to both V_{oc} and I_{sc} saturated at almost same contact pressure as A_r, suggesting that electrical output follows the evolution of the real contact area.

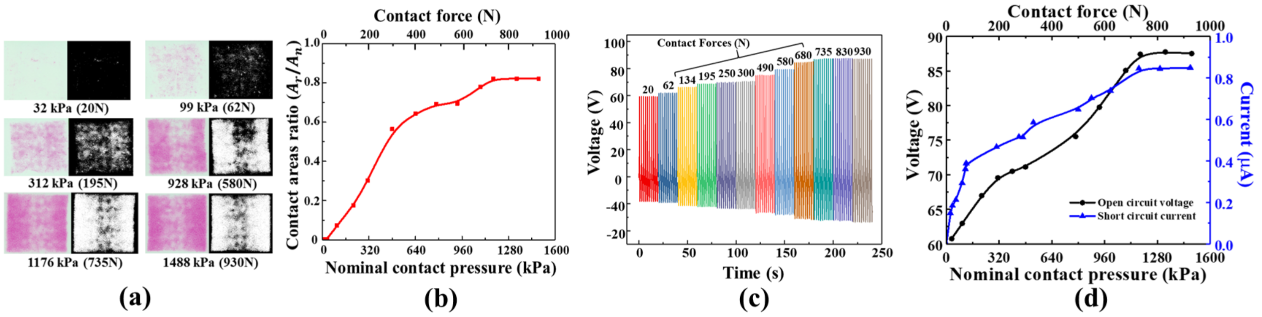

Fig. 2: (a) Real contact area as detected by pressure sensitive film with increasing contact pressure showing as-scanned film with pink indicating solid contact and binarized image with white indicating solid contact and (b) Contact area ratio vs. nominal contact pressure. (c) Sample of TENG V_{oc} signals for increasing contact force and (d) Peak V_{oc} and I_{sc} vs. nominal contact pressure.

Conclusion

The results investigated the origin of the contact force-dependent performance of TENGs. Experiments were carried out where open circuit voltage and short circuit current were measured together with real contact area under increasing contact force/pressure with identical test conditions for a TENG involving two nominally flat surfaces. Digitised pressure sensitive film was used to directly measure the real contact area, this is the first-time both real contact area and electrical output have been measured between two nominally flat surfaces in a TENG device. Results show that open circuit voltage, short circuit current and real contact area all increase with contact pressure. For example, at 16 kPa the percentage of A_r was only 0.25% of the active device area. Voltage, current and contact area increase roughly linearly at first and later saturate to a converged value at higher contact pressures. Real contact area at saturation was about 82% - this represents an enormous increase in contact area over the pressure range investigated. Critically, both open circuit voltage and short circuit current saturated at almost the same contact pressure as the real contact area suggesting that electrical output follows the evolution of the real contact area.

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