Journal of Electrostatics 90 (2017) 147–152

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

Relationship between triboelectric charge and contact force for two triboelectric layers

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ARTICLE INFO

Keywords:
Contact charging
Contact mechanics
Insulator
Triboelectrification
Triboelectric nanogenerators

ABSTRACT

A relationship between triboelectric charge and contact force for two triboelectric layers is presented, by combining the theories of insulator contact charging and contact mechanics. Experimental verification has been successfully performed using contact-mode triboelectric nanogenerators (TENGs) in two cases: (a) under varying contact forces while keeping the surface roughness profile constant, and (b) under varying surface roughness profiles while keeping the contact force constant. The theory presented here can serve as an important guide in the design of triboelectric systems, particularly of a contact-mode TENG structure for specific applications and self-powered systems.

1. Introduction

Contact force plays an important role in the triboelectric charge generation process between two triboelectric layers. This phenomenon is clearly evident in a contact-mode triboelectric nanogenerator (TENG). A larger contact force increases the triboelectric charge density and thereby results in a higher current and voltage. An instance of this can be seen in the experiments conducted on a flexible zig-zag shaped multilayered TENG, with Kapton and Polytetrafluoroethylene (PTFE) as its dielectric/triboelectric materials, and Aluminum as the electrode material [1]. Another instance is seen in the experiments on a human skin based TENG that is based on periodic contact-separation between human skin and a micropyramid patterned polydimethylsiloxane (PDMS) film deposited with Indium tin oxide (ITO) electrode, wherein, the magnitude of the output voltage is proportional to the applied pressure [2]. Although contact force is a critical factor that affects the triboelectric charge generation process, a theoretical relationship between transferred triboelectric charge and contact force is not reported in literature. Consider the well-accepted theoretical $V-Q-x$ relationship given in equation (1), developed to provide guidance for rational design of contact-mode TENGs [3], which does not explicitly consider the impact of contact force.

$$V = -\frac{Q}{A\varepsilon_0}\left(\frac{d_1}{\varepsilon_{r1}} + \frac{d_2}{\varepsilon_{r2}} + x(t)\right) + \frac{\sigma\ x(t)}{\varepsilon_0} \tag{1}$$

where V is voltage between the electrodes, Q is the amount of transferred charge between the electrodes, A is the apparent area of contact, x is the separation distance between the dielectric or triboelectric layers, σ is the triboelectric charge density, d_1 and d_2 represent the thickness, while ε_{r1} and ε_{r2} are the relative dielectric constants of the two layers, and ε_0 is permittivity of free space.

The TENG structures that the above $V-Q-x$ relationship is derived for are shown in Fig. 1(a). Briefly, the contact side of the triboelectric layers are stacked facing each other, with the non-contact side deposited with a metal electrode. Once an external mechanical force is applied to the structure, the two dielectric layers make contact. Owing to surface charge transfer due to contact electrification, the contacting surfaces will have equal and opposite triboelectric charge density σ.When the force is removed, the separation between the triboelectric layers increases, and a potential difference (V) is induced between the electrodes. This potential is responsible for driving charges Q between the two electrodes via an external load, when connected. In Fig. 1(b), contact occurs between a metal and a dielectric layer, i.e., the metal acts as the triboelectric layer of the TENG. The $V-Q-x$ relationship for the conductor-to-dielectric contact-mode can thus be obtained by simply substituting $d_1 = 0$ in equation (1).

From the discussion above, the TENG output is dependent on the development of surface triboelectric charge density (σ) and is directly proportional to it. This charge is only developed when the two triboelectric layers are brought into contact by an external force, as

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https://doi.org/10.1016/j.elstat.2017.11.001
Received 16 October 2017; Received in revised form 5 November 2017; Accepted 5 November 2017
Available online 14 November 2017
0304-3886/

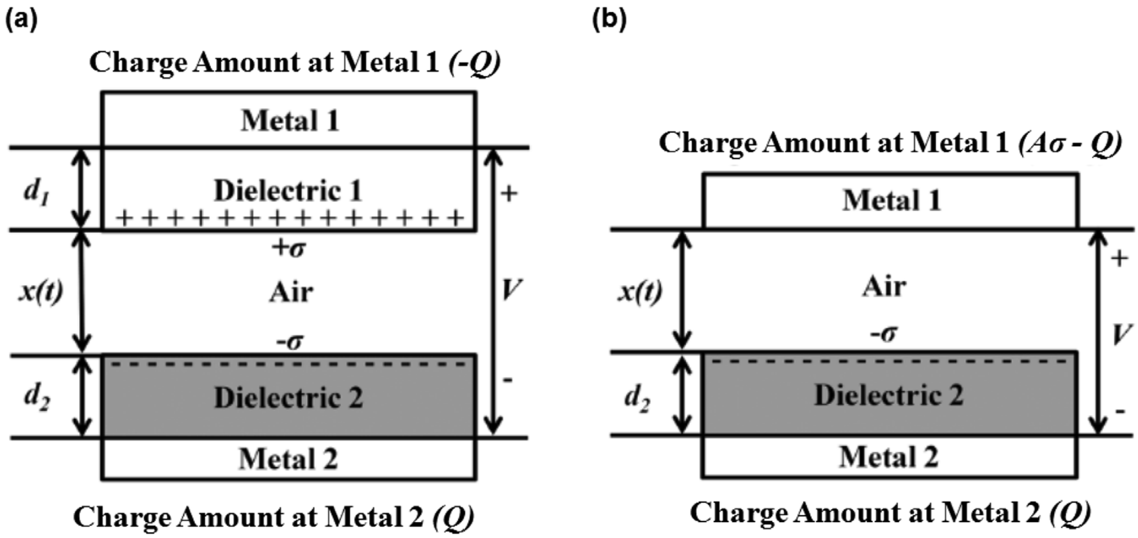

Fig. 1. Contact-mode TENG structures for (a) dielectric-to-dielectric contact, and (b) conductor-to-dielectric contact. Image from Ref. [3].

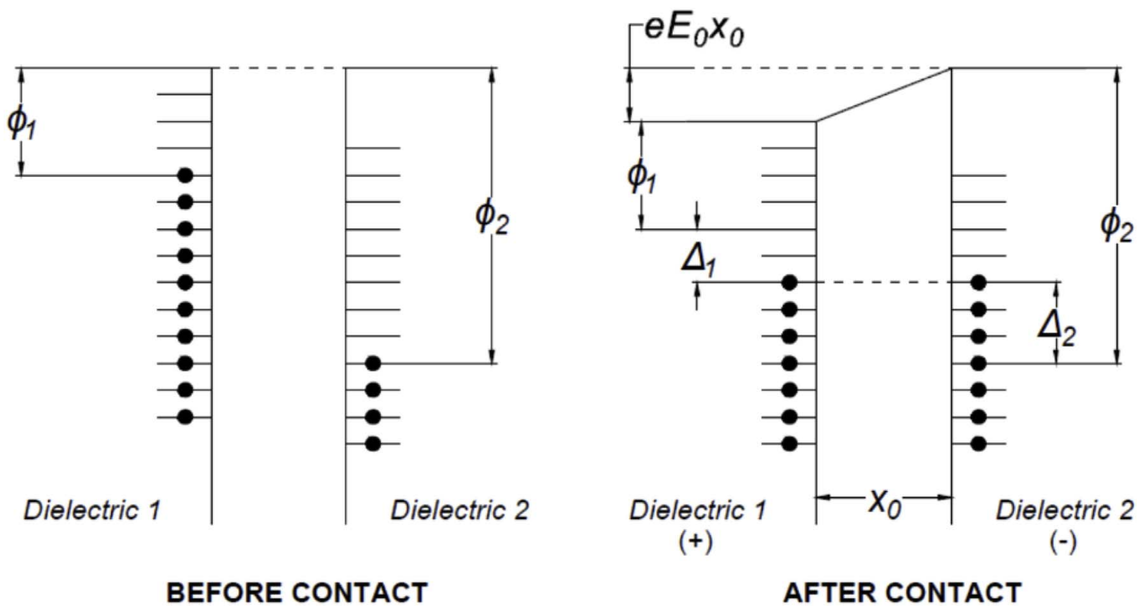

Fig. 2. Energy level diagram for insulator-insulator contact. Figure modified from Ref. [15].

mentioned above. Therefore, understanding the relationship between triboelectric charge and contact force is important. Accordingly, a theoretical relationship between the transferred triboelectric charge (q) and contact force (F) is presented, by combining the theories of contact electrification and contact mechanics (briefly described in sections 1.1 and 1.2, respectively). Subsequently, using the calculated triboelectric charge, open circuit voltage (V_{oc}) of a TENG is predicted for varying contact forces. Furthermore, to show that the effect of different surface morphologies is captured by the $q - F$ relationship, V_{oc} of TENGs made with triboelectric layers having different surface roughness characteristics is assessed.

1.1. Contact charging involving insulators

The triboelectric effect or contact electrification is universal and has attracted many investigations, but due to the variations in the structure and morphology of insulator materials, there has been no conclusive mechanism for all triboelectric phenomena. The mechanism of charge exchange between two contacting surfaces when at least one of them is insulating, is one of the oldest unresolved problems in physics [4–6]. Reports proposing mechanisms involving electron transfer, ion transfer, and material transfer exist in literature [7,8]. On the other hand, metal-to-metal contact charging is well understood. Charge transfer in this case is explained using the mechanism of electron transfer that results from the difference in work function (φ) between the contacting metal surfaces to equalize their energy levels. This is used to explain metal-to-insulator contact charging, by assigning an effective work function to the insulator. Electron transfer is proposed to occur between the metals' fermi level and localized energy levels in the band gap of the insulator [9]. Several charge transfer models for insulator-to-insulator contacts are presented which are similar to those for metal-insulator contact, except that the available energy levels are at the surface instead of the bulk, and these levels are called “surface states”. The surface state theory is used to explain the charge transfer between the surface states of the two contacting materials, driven by the “surface work function” difference between the materials, and conceptually applies equally to [10–12]. This theory has two limits. In the low-density limit, a finite number of states on the dielectric surface are filled or emptied. In the high-density limit, an electric field is created between the dielectric surfaces by charge exchange to equalize the fermi levels of the