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Triboelectrification of a Metal by Repeated Impacts on A Dielectric Film : Analytical and Numerical Study

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ABSTRACT

Theoretically, the impact triboelectrification between metal and dielectric films has been studied. We analyze the $V - Q - z_0$ relationship for the contact mode TENG at the impacts to investigate how the charge moves in the short-circuit state. The total charge of triboelectricity due to a number of impacts is analytically derived under short circuit conditions, taking into account the initial charge and the time-dependent charge relaxation.
Keywords: Repeated impacts, dielectric constant, triboelectrification

I. INTRODUCTION

AFM tip-induced triboelectrification is a type of impact electrification [1] and is normally explained by the potential difference between the triboelectric bodies [2, 3]. Changes in the amount of charge over time, defined as charge relaxation, can also affect the electrification [4, 5]. In order to understand the mechanism of triboelectrification in numerous impacts, the triboelectric charge density induced at the contact interface is analytically derived to account for charge transfer under short-circuit conditions. However, since the previous reference [1] mainly focuses on the charge transfer in the impact in the open circuit condition, it is important to analyze the temporal charge flow analysis in the contact mode TENG in which the external circuit is closed.

II. RESULTS AND DISCUSSION

When the metal impacts on the dielectric film, each gets the same and opposite charge. After the external circuit is connected to the contact mode TENG as shown in FIG. 1, the charge is redistributed on the metal and dielectric surfaces, and some charge is transferred from the upper electrode onto the lower electrode. Based on the theory of impact electrification [6], the initial charge for metal under short-circuit conditions in contact mode TENG [7] is

$$\mathrm{q} = \mathrm{s}\sigma - \mathrm{Q} \quad \cdots\cdots\cdots(1)$$

$$\frac{dq_c}{dn} = k_1 \cdot C \cdot V \quad \cdots\cdots\cdots(2)$$

$$= k_1 \cdot C \cdot (V_c - V_e) \quad \cdots\cdots\cdots(3)$$

$$= k_1 \cdot C \cdot (V_c - k_0 q) \quad \cdots\cdots\cdots(4)$$

$$= k_1 \cdot C \cdot (V_c - k_0(\mathrm{s}\sigma - \mathrm{Q})) \quad \cdots\cdots\cdots(5)$$

The quantity $\frac{dq_c}{dn}$ is approximated using an equivalent rate process in which $\frac{dq_c}{dn}$ is proportional to the residual charge.

$$\frac{dq_r}{dt} = -\frac{k_2}{f} q \quad \cdots\cdots\cdots(6)$$

$$= -\frac{k_2}{f}(\mathrm{s}\sigma - \mathrm{Q}) \quad \cdots\cdots\cdots(7)$$

The quantity $\frac{dq_r}{dt}$ is the charge relaxation over time approximated by [4]

Therefore,

$$\frac{dq}{dn} = \frac{dq_c}{dn} + \frac{dq_r}{dn} \quad \cdots\cdots\cdots (8)$$

$$= s\frac{d\sigma}{dn} - \frac{dQ}{dn} \quad \cdots\cdots\cdots (9)$$

$$= k_1 \cdot C \cdot (V_c - k_0(s\sigma - Q)) - \frac{k_2}{f}(s\sigma - Q) \quad \cdots\cdots\cdots (10)$$

The Q is calculated as follows [7]

$$Q = \frac{\sigma \cdot s \cdot z_0}{t/_{\varepsilon} + z_o} \quad \cdots\cdots\cdots (11)$$

Thus,

$$\frac{dq}{dn} = s\frac{d\sigma}{dn} - \frac{d}{dn}\left(\frac{\sigma \cdot s \cdot z_0}{t/_{\varepsilon} + z_o}\right) \quad \cdots\cdots\cdots (12)$$

$$= s\left(\frac{t/_{\varepsilon}}{t/_{\varepsilon} + z_o}\right) \cdot \frac{d\sigma}{dn} \quad \cdots\cdots\cdots (13)$$

$$= k_1 \cdot C \cdot \left(V_c - k_0\left(s\sigma - \sigma\left(\frac{s \cdot z_0}{t/_{\varepsilon} + z_o}\right)\right)\right) - \frac{k_2}{f}\left(s\sigma - \sigma\left(\frac{s \cdot z_0}{t/_{\varepsilon} + z_o}\right)\right) \quad \cdots (14)$$

$$= k_1 \cdot C \cdot \left(V_c - k_0 \cdot s \cdot \sigma\left(\frac{t/_{\varepsilon}}{t/_{\varepsilon} + z_o}\right)\right) - \frac{k_2}{f}\left(s \cdot \sigma\left(\frac{t/_{\varepsilon}}{t/_{\varepsilon} + z_o}\right)\right) \quad \cdots\cdots\cdots (15)$$

To summarize,

$$\frac{d\sigma}{dn} = \frac{k_1 \cdot C \cdot V_c}{s\left(\frac{t/_{\varepsilon}}{t/_{\varepsilon}+z_0}\right)} - \sigma\left(k_1 \cdot k_0 \cdot C + \frac{k_2}{f}\right) \quad \cdots\cdots\cdots (16)$$

If $C = \frac{\varepsilon \cdot \varepsilon_0 \cdot s}{z_0}$, capacitance is inserted into Eq (16)

$$\frac{d\sigma}{dn} = \frac{k_1 \cdot \frac{\varepsilon \cdot \varepsilon_0 \cdot s}{z_0} \cdot V_c}{s\left(\frac{t/_{\varepsilon}}{t/_{\varepsilon}+z_0}\right)} - \sigma\left\{k_1 \cdot k_0 \cdot \frac{\varepsilon \cdot \varepsilon_0 \cdot s}{z_0} + \frac{k_2}{f}\right\} \quad \cdots\cdots\cdots (17)$$

The Eq (17) can be rewritten as

$$\frac{d\sigma}{dn} = \frac{k_1 \cdot \varepsilon^2 \cdot \varepsilon_0 \cdot V_c(t/_{\varepsilon} + z_0)}{z_0 \cdot t} - \sigma\left\{\frac{k_1 \cdot k_0 \cdot \varepsilon \cdot \varepsilon_0 \cdot s}{z_0} + \frac{k_2}{f}\right\} \quad \cdots\cdots\cdots (18)$$

In order to solve Eq (18) with initial condition ($\sigma(n = 0) = 0$), following simplified equations were used.

$$\left(\frac{d\sigma}{dn}\right) = A - B \cdot \sigma \quad \cdots\cdots\cdots (19)$$

with $A \equiv \frac{k_1 \cdot \varepsilon^2 \cdot \varepsilon_0 \cdot V_c(t/_{\varepsilon}+z_0)}{z_0 \cdot t}$

$$B \equiv \frac{k_1 \cdot k_0 \cdot \varepsilon \cdot \varepsilon_0 \cdot s}{z_0} + \frac{k_2}{f}$$

Thus, the solution is written as

$$\sigma(n) = \frac{\frac{k_1 \cdot \varepsilon^2 \cdot \varepsilon_0 \cdot V_c(t/_{\varepsilon}+z_0)}{z_0 \cdot t}\left[1 - \exp\left[-n \cdot \left(\frac{k_1 \cdot k_0 \cdot \varepsilon \cdot \varepsilon_0 \cdot s}{z_0} + \frac{k_2}{f}\right)\right]\right]}{\frac{k_1 \cdot k_0 \cdot \varepsilon \cdot \varepsilon_0 \cdot s}{z_0} + \frac{k_2}{f}} \quad \cdots\cdots\cdots (20)$$

In order to see the effect of dielectric constant, ε on σ(n), some parameters are fixed as constants: f =5, $k_1 = k_0 = k_2$ =1, V_c =1, s =1, ε_0 =8.85 × 10^{-12} $F/_m$, z_0=10 nm, and t= 100 μm.

Figure 2 shows the numerical results of the triboelectric charge density as a function of various dielectric constants and number of impacts, such as ε = 3, 10 and 20. As the dielectric constant increases, the triboelectric charge density also increases and the repeated impacts clearly demonstrate the genetic impact on charge density. The higher the dielectric constant, the higher the saturation of the triboelectric charge density.

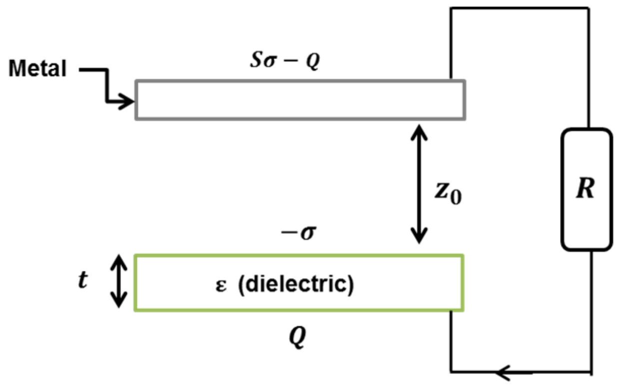
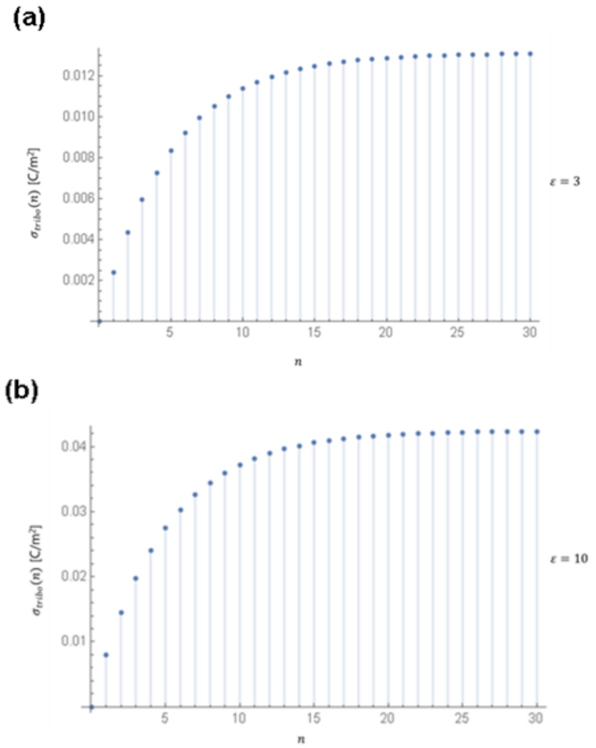


Figure 1: A schematic diagram of a metal to dielectric contact-mode TENG



(c)

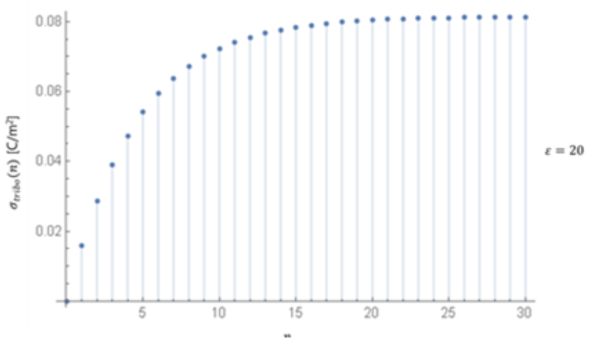


Figure 2 : σ_{tribo} as a function of number of impacts for (a) ε = 3, (b) ε = 10, and (c) ε = 20, respectively

III. CONCLUSION

Triboelectrification of metal films by numerous impacts on dielectric films has been studied analytically and numerically based on contact mode TENG frame work. The results obtained are as follows. The triboelectric charge density with repeated impact is closely related to the dielectric constant as a triboelectrical property. The higher the dielectric constant, the greater the saturation of the triboelectric charge and the more affected.

IV. ACKNOWLEDGMENTS

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