Research Article

Mohsen Keykha* and Mohsen Hosseni

Multi capacitor modeling for triboelectric nanogenerators with multiple effective parameters

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Abstract: Considering the ever-increasing human need for energy resources and on the other hand, the reduction of fossil fuel resources, the use of renewable energy has become one of the attractive topics of researchers. One of the available and ambient sources in nature is mechanical energy in nature, such as the energy of body movements, wind energy, energy in sea waves, etc. One of the methods of converting and extracting energy from the mentioned forms is the use of triboelectric nano generators. Triboelectric nanogenerators have various structures. In the current research, the contact mode and two electrodes of triboelectric nanogenerators have been discussed and also the relationships governing the nano generator have been calculated. By comparing the response of the nano generator in ideal and non-ideal state, it can be understood that considering the effects of edge capacitors will be effective on the final response of the nano generator. Finally, the effect of various parameters on the performance of the triboelectric nano generator has also been investigated.

Keywords: edge capacitor; renewable energy; triboelectric nanogenerators.

Introduction

In today's societies, energy has become a very important factor in economics and societies (Trancik 2014; Wang 2017). On the other hand, due to the limitations of fossil fuels, the possibility of using energy has become a very important challenge. As a result, the tendency to use renewable energy such as sunlight, wind and sea waves has increased. The importance of converting these types of energies to electrical energy lies in their renewability, permanence and freeness (Beeby et al. 2006; Cottone et al. 2009). One of the types of renewable energy that has recently attracted a lot of attention is the energy of mechanical vibrations in nature, which can be used to run triboelectric nanogenerators. The basis of triboelectric nanogenerators based on the movement of electrons is the effect of triboelectric effect on two surfaces that have different triboelectric properties (Zhu et al. 2012). Simultaneously with the progress made in the integration of electronic circuits, the need to design a fully integrated mechanism including energy storage, circuit including triboelectric nano generator, signal processing circuits and external load circuit was felt to be able to convert and transfer energy to other applications. Integrated parts perform with high accuracy (Niu et al. 2013, 2014a). Finally, integrated circuit models of this type of circuits were constructed using SPICE software. It was also observed that the external impedance connected to the triboelectric nano generator could greatly affect its performance and output power (Niu et al. 2014b). It was observed that matching the external impedance with the impedance of the nano generator itself will cause the optimal performance of the nano generator. Triboelectric nanogenerators have a variety of structures, and this variation in structure makes them have their own analytical methods. One of the types of nanogenerator structures is conductor-conductor contact mode in which two dielectrics are used as triboelectric layers and on both sides of these layers two electrodes are used to transfer the electric charge and the current generated to the external charge (Yu et al. 2016). Among the researches conducted in order to study the effect of the capacitive property of triboelectric nano generates, the use of this structure in the human body for an implantable sensor. It can be used by using ultrasound to transfer mechanical energy under the skin and through liquids in such a way that with this nano generator you can charge a lithium ion battery at a speed of 166 microcoulombs and to a voltage of 2.4 voltage and current. 156. Find microamps (Hinchet et al.

***Corresponding author: Mohsen Keykha**, Department of Electrical and Computer Engineering, University of Sistan and Baluchestan, Zahedan, Iran, E-mail: mohsen.keykha@gmail.com
Mohsen Hosseni, Department of Electrical Engineering, University of Tehran, Tehran, Iran

2019). In another study, researchers investigated the electron transfer coefficient in order to understand the triboelectric properties of PTFE. In this study, they investigated the change in the triboelectric properties of PTFE by changing its molecular structure by applying an external force based on density functional theory (DFT) and finally concluded that the deformation caused by the contact force is its negative triboelectric property (that is, it increased the property of accepting electrons in it) (Kang et al. 2022). Although analytical models and formulas have been proposed for this structure, but so far in the proposed models, the final edge effect has not been considered (Li et al. 2019). Therefore, a comprehensive analytical model is needed to fully cover the structures of triboelectric nanogenerators, taking into account all the effective side effects on external characteristics. In this paper, we want to investigate the conductor-conductor contact mode using the equivalent edge capacitor approximation (EDAEC) method and examine the effect of the non-ideal nano generator on its outputs.

Governing theory and equations

In the ideal model, which presents a triboelectric nano generator in contact mode in terms of air distance changes (Q, v, I), the effect of edge capacitors is not considered. As shown in Figure 1 (Trancik 2014; Wang 2017), in the ideal descriptive model, the nanogenerator capacitor depends only on the effect of capacitor changes between the two electrodes and the dielectrics. l is the length of the electrodes and d_1, d_2 is the thickness of the dielectrics and x is the air gap between the electrodes.

The equation of the total capacitor between the plates is ideally calculated from Equation (1):

$$C_{\text{total}}(x) = \frac{\varepsilon_0 wl}{\frac{d_1}{\varepsilon_{r1}} + \frac{d_2}{\varepsilon_{r2}} + x(t)} \tag{1}$$

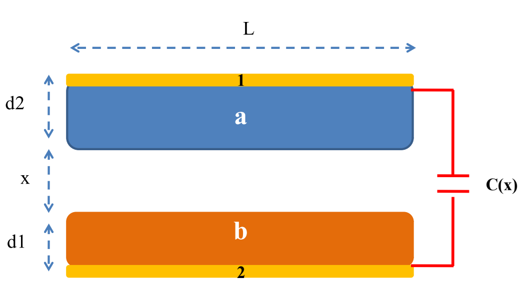

Figure 1: Nanogenerator structure in conductor-conductor mode.

Also, the Q_{sc} and V_{oc} relationships are ideally described by the following relationships

$$Q_{sc}(x) = \frac{\sigma x(t) wl}{\frac{d_1}{\varepsilon_{r1}} + \frac{d_2}{\varepsilon_{r2}} + x(t)} \tag{2}$$

$$V_{oc}(x) = \frac{\sigma x(t)}{\varepsilon_0} \tag{3}$$

In the equivalent capacitor-based edge capacitor approximation (EDAEC) model, the effects of edge capacitors on the nanogenerator outputs are also considered, so the C_{total} relationship must be modified. The total capacitor relationship consists of three parts. The first part of the capacitor is formed between dielectric No. 1 and the first electrode ($C_{a1}(x)$) and the second electrode ($C_{a2}(x)$), which is shown in Equation (4):

$$\begin{cases} C_{a1}(x) = \dfrac{\varepsilon_0 lw}{\dfrac{d_1}{\varepsilon_{r1}}} \\ \mathrm{C}_{a2}(\mathrm{x}) = \dfrac{\varepsilon_0 lw}{x(t) + \dfrac{d_2}{\varepsilon_{r2}}} \end{cases} \tag{4}$$

The second part consists of a capacitor between dielectric two and electrode number 1 ($C_{b1}(x)$) and the second electrode ($C_{b2}(x)$) shown in Equation (5):

$$\begin{cases} C_{b1}(x) = \dfrac{\varepsilon_0 lw}{\dfrac{d_1}{\varepsilon_{r1}} + x(t)} \\ C_{b2}(x) = \dfrac{\varepsilon_0 lw}{\dfrac{d_2}{\varepsilon_{r2}}} \end{cases} \tag{5}$$

Finally, the third part, which contains the capacitor between the two electrodes, is called C_{12d}. Schematics of capacitors and their circuit model and how they are connected are shown in Figure 2.

Therefore, the C_{total} relation can be written in relation form (6):

$$\begin{aligned} C_{\text{total}} &= C_{1a2} + C_{1b2} + C_{12d} \\ &= \frac{2\varepsilon_0 \varepsilon_{r1} \varepsilon_{r2} lw}{\varepsilon_{r1} d_2 + \varepsilon_{r2} d_1 + \varepsilon_{r1} \varepsilon_{r2} x(t)} + C_{12d} \end{aligned} \tag{6}$$

The electric charge formed on the plates of the triboelectric nanogenerator is equal, but their sign is opposite to each other, so using σ, which is the sum of the electric charges collected on the electrode plates of the triboelectric nanogenerator, the electric charge distributed on the plates can be written as follows:

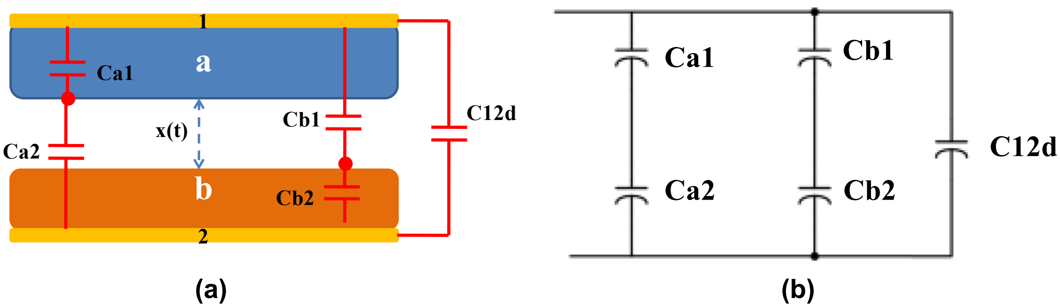

Figure 2: Triboelectric nanogenerator model in EDAEC model (a) nanogenerator with capacitors formed between conductors and electrodes (b) equivalent capacitor circuit of nanogenerator.

$$\begin{cases} q_{a1}(x) = \dfrac{C_{a1}}{C_{a1}+C_{a2}} Q_a = \dfrac{\varepsilon_{r2}(d_2 + \varepsilon_{r2} x(t))}{\varepsilon_{r1} d_2 + \varepsilon_{r2} d_1 + \varepsilon_{r1}\varepsilon_{r2} x(t)} \sigma w l \\ q_{a2}(x) = \dfrac{C_{a2}}{C_{a1}+C_{a2}} Q_a = \dfrac{\varepsilon_{r2}}{\varepsilon_{r1} d_2 + \varepsilon_{r2} d_1 + \varepsilon_{r1}\varepsilon_{r2} x(t)} \sigma w l \end{cases} \quad (7)$$

$$\begin{cases} q_{a1}(x) = \dfrac{C_{a1}}{C_{a1}+C_{a2}} Q_b = \dfrac{\varepsilon_{r1} d_2}{\varepsilon_{r1} d_2 + \varepsilon_{r2} d_1 + \varepsilon_{r1}\varepsilon_{r2} x(t)} \sigma w l \\ q_{a2}(x) = \dfrac{C_{a2}}{C_{a1}+C_{a2}} Q_b = \dfrac{\varepsilon_{r2}(\varepsilon_{r1} x(t) + d_1)}{\varepsilon_{r1} d_2 + \varepsilon_{r2} d_1 + \varepsilon_{r1}\varepsilon_{r2} x(t)} \sigma w l \end{cases} \quad (8)$$

Therefore, the sum of the charges formed on electrode 1, called q_1, can be written as Equation (9):

$$q_1(x) = q_{a1}(x) + q_{b1}(x) = \frac{2\varepsilon_{r1} d_2 + \varepsilon_{r1}\varepsilon_{r2} x(t)}{\varepsilon_{r1} d_2 + \varepsilon_{r2} d_1 + \varepsilon_{r1}\varepsilon_{r2} x(t)} \sigma w l \quad (9)$$

at position $x = 0$, the initial load on the capacitor plate can be calculated:

$$q_1(0) = \frac{2\varepsilon_{r1} d_2}{\varepsilon_{r1} d_2 + \varepsilon_{r2} d_1} \sigma w l \quad (10)$$

The displaced loads Q_{sc} are equal to the loads accumulated on the electrode 1, so Q_{sc} can be calculated from the difference $q1(x)$ and $q1(0)$. The Q_{sc} relation is written as follows:

$$\begin{aligned} Q_{sc}(x) &= |q_1(x) - q_1(0)| \\ &= \frac{\varepsilon_{r1}\varepsilon_{r2} x(t)(\varepsilon_{r2} d_1 - \varepsilon_{r1} d_2)}{(\varepsilon_{r1} d_2 + \varepsilon_{r2} d_1 + \varepsilon_{r1}\varepsilon_{r2} x(t))(\varepsilon_{r1} d_2 + \varepsilon_{r2} d_1)} \sigma w l \end{aligned} \quad (11)$$

Finally, the following relation can be written for V_{oc}:

$$V_{oc}(x) = \frac{Q_{sc}(x)}{C_{total}} \quad (12)$$

Table 1: Parameters of the nanogenerator tested.

C_{12} (nF)	v (m/s)	σ (μC/cm²)	l (m)	w (m)	d_2 (mm)	d_1 (mm)	ε_{r2}	ε_{r1}	R (MΩ)
1	0.1	10^{-4}	0.05	0.05	0.1	0.1	1.2	3.6	10^3

Result and discussion

Table 1 shows the components and parameters of a nanogenerator in test mode. Based on the values of this table, two nanogenerators in two modes without considering the edge capacitors and considering the edge capacitors in Simulink MATLAB are simulated. And compare the outputs of two nanogenerators.

In the table above, the external load R connected to the nanogenerator, ε_{r1}, ε_{r2}, the coefficients of the triboelectric layers, d_1, d_2, the thicknesses of the triboelectric layer, w, the width of the triboelectric layer, l, the length of the triboelectric plate, σ, the surface charge density, v, the velocity of the plates; Are formed between two electrodes. By small considering the air distance between the two dielectric materials of equations (2) and (3), it can be understood that in both ideal cases and also in the EDAEC model, they have a linear relationship with the air distance between the nanogenerator plates. The two parameters Q_{sc} and C_{total} are compared. Figure 3a shows that ideally, regardless of the effect of edge capacitors, the amount of load stored on the plates is slightly higher than the EDAEC model. It can also be seen in Figure 3b, considering the edge capacitors, the

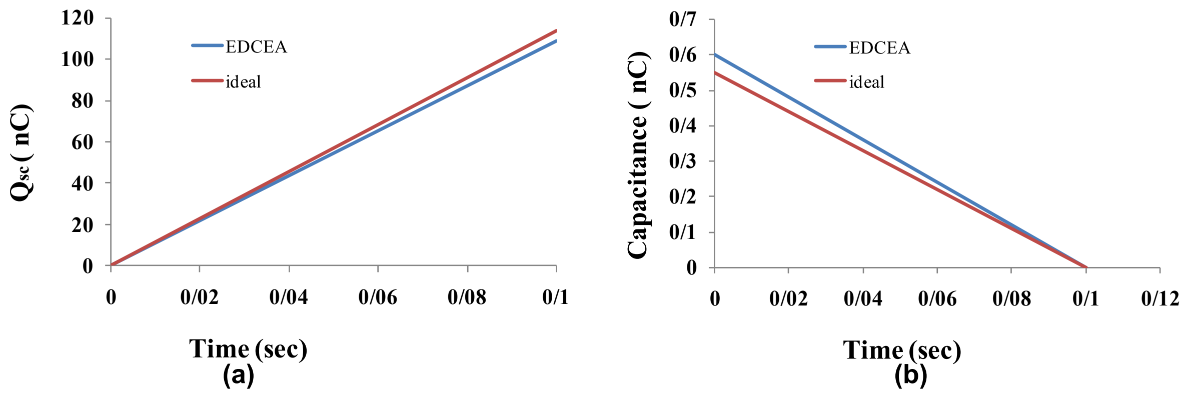

Figure 3: Comparison of triboelectric nanogenerator specifications in both ideal and non-ideal modes (a) The load stored on the nanogenerator capacitor plates (b) the capacitive behavior of the nanogenerator in both ideal and non-ideal modes.

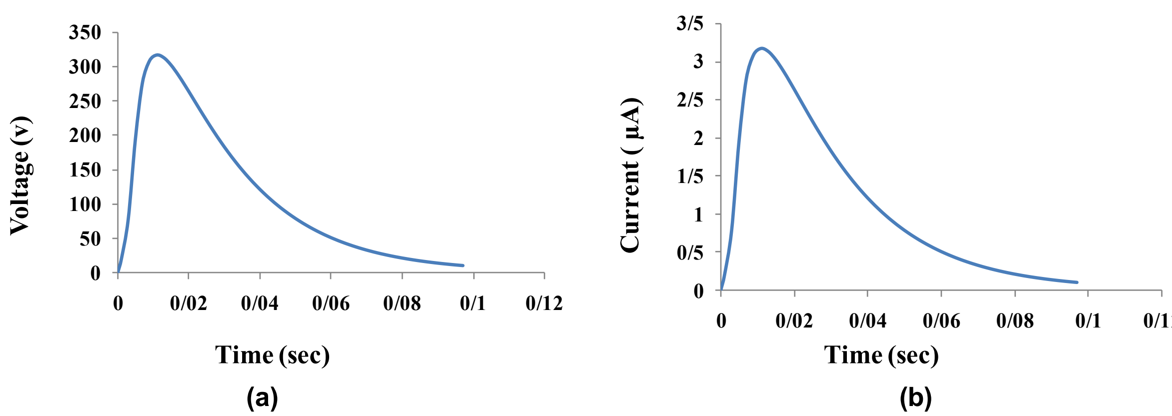

Figure 4: Outputs generated by triboelectric nanogenerators in EDAEC mode (a) output voltage (b) output current.

amount of capacitor of the nanogenerator model is more than the ideal state.

Figure 4 also shows the voltage and current outputs generated by the nanogenerator in an alternating velocity of nanogenerator operation and air distance motion from $x = 0$ to $x = 1$ cm at a constant speed of 0.1 m/s in EDAEC mode.

According to Equation (11), Q_{sc} is also influenced by the structural parameters of the nanogenerator including the components (dielectric coefficients), the thickness of the dielectrics as well as the dimensions of the plates. Figure 5 shows the effect of changes in plate area and dielectric thickness on the output voltage and electrical charge stored on the plates. Figure 5a shows that increasing the area of the dielectric plates increases the output voltage of the nanogenerator and the generated voltage increases from about 50 to 310 V. Also, according to Figure 5b, increasing the thickness of the dielectric layers used in the structure of the nanogenerator reduces the output voltage of the nanogenerator, so it can be understood that the thinner layers of dielectrics will have a more favorable effect on the performance of the nanogenerator. In the following and in Figure 5c, we have investigated the effect of increasing the thickness of dielectrics on the load produced on the nanogenerator plates, which is consistent with the previous results.

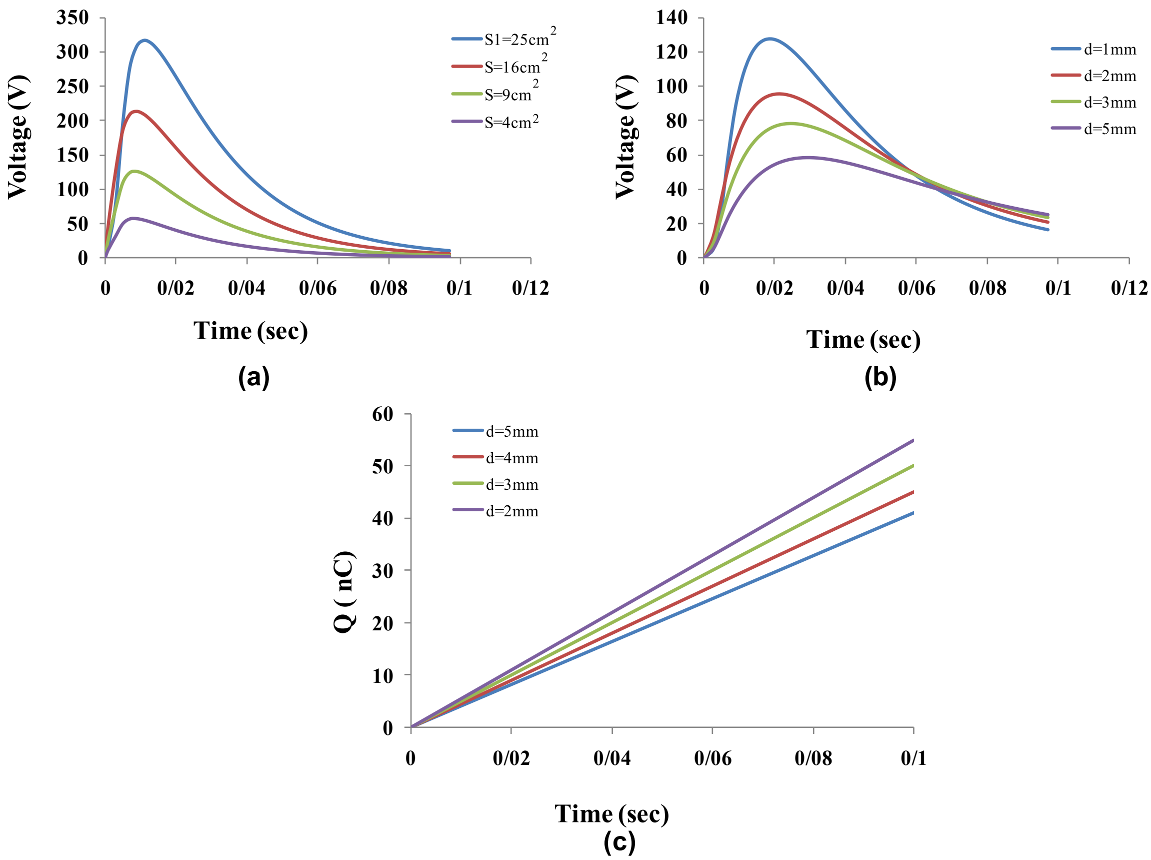

Figure 5: Effect of changes in nanogenerator structural parameters on nanogenerator performance (a) the effect of increasing the area of dielectrics on the output voltage (b) the effect of increasing the thickness of dielectrics on the output voltage (c) the effect of increasing the thickness of dielectrics on the generated electric charge.

Conclusions

The importance of EADCA analytical method is that it can be used to study and analyze all structures of triboelectric nanogenerators. In this research, we have investigated and modified the relationships of the ideal dielectric-to-dielectric attached-electrode parallel-plate contact-mode nanogenerator, and it has been observed that including edge capacitors in the capacitor formula equivalent to the nanogenerator are effective in load distribution and nanogenerator outputs. Also, according to the capacitor relationship obtained in EADCA method, it was observed that structural parameters including dielectric thicknesses and plate area affect its performance and production power so that the selection of larger surfaces with lower thicknesses of triboelectric layers leads to performance. They will be more desirable. To ensure the accuracy of the obtained relationships, simulation was performed using simulated MATLAB for the analyzed models in both ideal and non-ideal modes, and it was observed that the results obtained are consistent with EDAEC theory.

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Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

References

Beeby, S. P., M. J. Tudor, and N. M. White. 2006. Energy Harvesting Vibration Sources for Microsystems Applications. *Measurement Science and Technology* 17 (12): R175.

Cottone, F., H. Vocca, and L. Gammaitoni. 2009. Nonlinear Energy Harvesting. *Physical Review Letters* 102 (8): 080601.

Hinchet, R., H. J. Yoon, H. Ryu, M. K. Kim, E. K. Choi, D. S. Kim, and S. W. Kim. 2019. "Transcutaneous Ultrasound Energy Harvesting Using Capacitive Triboelectric Technology." *Science* 365 (6452): 491–94.

Kang, D., H. Y. Lee, J. H. Hwang, S. Jeon, S. Kim, D. Kim, S. Kim, and S. W. Kim. 2022. "Deformation-Contributed Negative Triboelectric Property of Polytetrafluoroethylene: A Density Functional Theory Calculation." *Nano Energy* 100: 107531.

Li, X., T. H. Lau, D. Guan, and Y. Zi. 2019. A Universal Method for Quantitative Analysis of Triboelectric Nanogenerators. *Journal of Materials Chemistry* 7 (33): 19485–94.

Niu, S., Y. S. Zhou, S. Wang, Y. Liu, L. Lin, Y. Bando, and Z. L. Wang. 2014. Simulation Method for Optimizing the Performance of an Integrated Triboelectric Nanogenerator Energy Harvesting System. *Nano Energy* 8: 150–6.

Niu, S., Y. Liu, S. Wang, L. Lin, Y. S. Zhou, Y. Hu, and Z. L. Wang. 2013. Theory of Sliding-mode Triboelectric Nanogenerators. *Advanced Materials* 25 (43): 6184–93.

Niu, S., Y. Liu, Y. S. Zhou, S. Wang, L. Lin, and Z. L. Wang. 2014. Optimization of Triboelectric Nanogenerator Charging Systems for Efficient Energy Harvesting and Storage. *IEEE Transactions on Electron Devices* 62 (2): 641–7.

Trancik, J. E. 2014. Renewable Energy: Back the Renewables boom. *Nature News* 507 (7492): 300.

Wang, Z. L. 2017. New wave power. *Nature* 542 (7640): 159–160.

Yu, A., X. Chen, R. Wang, J. Liu, J. Luo, L. Chen, Y. Zhang, W. Wu, C. Liu, H. Yuan, and M. Peng. 2016. Triboelectric Nanogenerator as a Self-Powered Communication Unit for Processing and Transmitting Information. *ACS Nano* 10 (4): 3944–50.

Zhu, G., C. Pan, W. Guo, C.-Y. Chen, Y. Zhou, R. Yu, and Z. L. Wang. 2012. "Triboelectric-generator-driven Pulse. Electrodeposition for Micropatterning." *Nano Letters* 12 (9): 4960–5.