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Trends onPhysics of Triboelectric Effect and Applications

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Abstract. Physics of triboelectric effect has been known for thousands of years. Since the invention of the triboelectric nanogenerator (TENG) in 2012, it has become one of the most vital innovations in energy harvesting technologies. This is one of the most frequently experienced effects that each and every one inevitably uses every day. Fundamentally friction driven static electrification is familiar, but its basics have long been unknown mysteriously and have continually perplexed the best scientists from ancient Greece to the modern high-tech era. Triboelectric effect is a general cause of every day's electrostatics. The phenomenon itself is obvious as in combing hair or lightning in daily life, and humanity discovered electricity from it and came to understand almost every aspect of electricity and magnetism through Maxwell's equations. But why do we not yet rigorously know which material is charged positively or negatively when two materials are rubbed? What is the fundamental origin of the mysteriousness of triboelectric charging? In view of the above, this paper discusses the physics behind of it, its trends and applications and so on.

1. Introduction

Triboelectrification aka contacts electrification as a physical phenomenon appeared for the first time in a dialogue by Plato around 400 B.C. With the advent of science, engineering and technology over past centuries bring along rapidly increasing high-energy consumption. As per world energy council report ninety percent of world energy consumption is based on non- renewable sources. There are variety forms of high voltage are present around us. Lightning discharges are the only known "natural" form of high voltage. In the global scenarios, lightning discharges transfer positive charge upward to restore the system's dynamic balance. The regular current flow between the positively charged ionosphere and the negatively charged earth is thus controlled by global thunderstorm activity. General characteristics of a technology for macro-scale energy are the total power output, stability, conversion efficiency and cost. In many cases, cost is the most important measure, such as for solar cell, Figure 1.

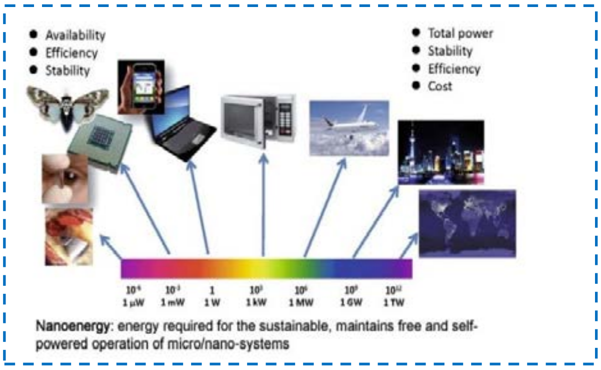

Figure 1: Magnitude of Power and its Applications

One of the biggest challenges ahead massive advancement of electronic technology trends towards miniaturization, portability and functionality. The development of computer systems, its peripherals and related subsystems are a typical example of miniaturization, from the vacuum tube based huge-size machine, to solid state metal-oxide-semiconductor field- effect transistor (MOSFET) based main frame computer and later laptop computer systems.

The tremendous increase of popularity of handhold cell phones is a typical example of portable/mobile electronics. The next few decades will be about building functionality on existing electronics, which inevitably involves developing a range of sensors including but not limited to navigation, motion, chemical, biological and gas sensors. The near future development is about electronics that are much smaller than the size of a cell phone, so that each person on average can have at least dozens to hundreds of such small electronics.

Such small size electronics operates at ultralow power consumption, making it possible to be powered by the energy harvested from our living environment. It will become impractical if sensor networks have to be powered entirely by batteries because of the huge number of devices, large scope of distribution, and difficulty to track and recycle to minimize environmental impact and possibly health hazardous. Therefore, power sources are desperately needed for independent and continuous operations of such small electronics, which could be used widely for ultrasensitive chemical and bimolecular sensors, nanorobotics, micro-electromechanical systems, remote and mobile environmental sensors, homeland security and even portable/wearable personal electronics.

2. Concept of Triboelectric Effect

2.1 The Power of Static Physics

Figure 1: Schematic of Static Power.

2.2 Triboelectric: How does it work?

When two different materials come in contact with each other, they exchange subatomic particles that cover their surfaces. Rubbing the two materials together causes friction and can cause a buildup of oppositely charged particles on one or both surfaces. This can lead to the materials becoming "charged," creating static electricity, Figure 2.

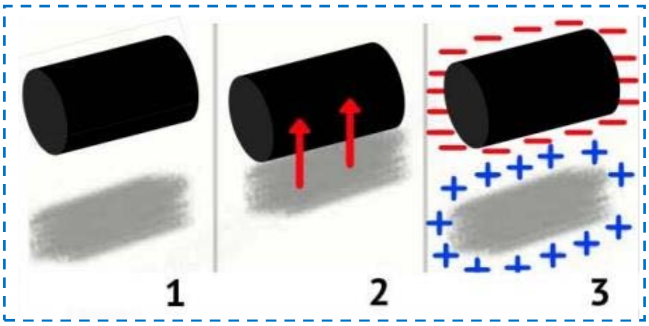

Figure 2: Schematic of Triboelectric Effect.

The buildup of charge is called the triboelectric effect and has been known since the times of Ancient Greece. Without nanotechnology; however, the Greeks could never harness this energy. Now, triboelectric nanogenerators (TANGs) use the triboelectric effect between two different materials to generate power. TANGs consist of two circuits: an inner circuit containing two oppositely charged materials and an outer circuit of electrodes that stimulate electrons to flow.

TANGs could potentially provide a clean alternative to power electronics; however, the energy produced by the triboelectric effect is unpredictable and not easily understood. To better understand the unpredictable nature of the tribelectric effect, scientists use computational models to perform large-scale simulations. These have revealed that the fundamental mechanism behind the triboelectric effect are the molecular structural changes that occur at the suface of materials when they come into contact with each other.

The triboelectric effect is a contact induced electrification in which a material becomes electrically charged after it is contacted with a different material through friction. The signed of the charges to be carried by a material depends on its relative polarity in comparison to the material to which it will contact. Figure 2 shows trivial solutions of temperature profiles of finite-size materials for thermoelectricity and triboelectricity at the steady state.

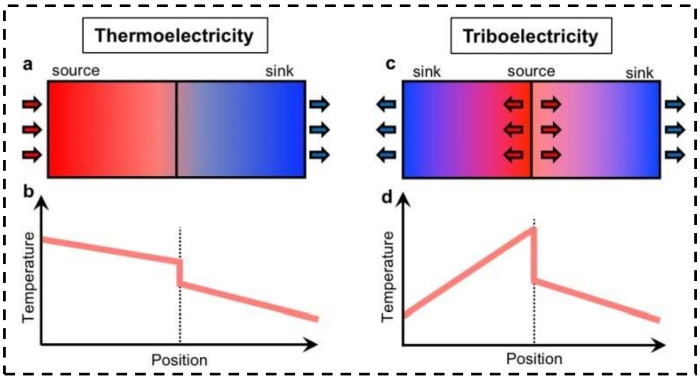

Figure 3: Thermoelectricity vs. Triboelectricity.

Triboelectric effect is probably the only a few effects that have been known for thousands of years. Although this is one of the most frequently experienced effects that each and every one of us inevitably uses every day, the mechanism behind triboelectrification is still being studied possibly with debate. It is generally believed that after two different materials coming into contact, a chemical bond is formed between some parts of the two surfaces, called adhesion, and charges move from one material to the other to equalize their electrochemical potential. The transferred charges can be electrons or may be ions/molecules. When separated, some of the bonded atoms have a tendency to keep extra electrons, and some a tendency to give them away, possibly producing triboelectric charges on surfaces.

Materials that usually have strong triboelectrification effect are likely less conductive or insulators, thus, they usually capture the transferred charges and retain them for an extended period of time, building up the electrostatic charges, which are usually attributed to as negative effect in our daily life and technology developments. We can use the following examples to illustrate the damages that can be caused by triboelectrification. Aircraft flying will develop static charges from air friction on the airframe, which will interfere with radio frequency communication. Electrostatic charges are an important concern for safety, due to the fact that it can cause explosion and ignite flammable vapours. Carts/cars that may carry volatile liquids, flammable gasses, or explosive chemicals have to be discharged properly to avoid fire. Some electronic devices, most notably complementary metal-oxide semiconductor (CMOS) integrated circuits and the solid state metal–oxide–semiconductor field-effect transistor (MOSFET) transistors can be accidentally destroyed by high-voltage static discharge that may be carried by gloves. Therefore, triboelectrification is mostly taken as a negative effect in our daily life, industrial manufacturing and transportation. Therefore, by surprise, although triboelectrification is known for thousands of years, it has not been used for many positive applications. It is until recently that triboelectric effect has been widely used for converting mechanical energy into electricity and as self-powered active mechanical sensors. Therefore, power sources are desperately needed for independent and continuous operations of such small electronics, which could be used widely for ultrasensitive chemical and bimolecular sensors, nanorobotics, micro-electromechanical systems, remote and mobile environmental sensors, homeland security and even portable/wearable personal electronics, Figure 4 and Figure 5.

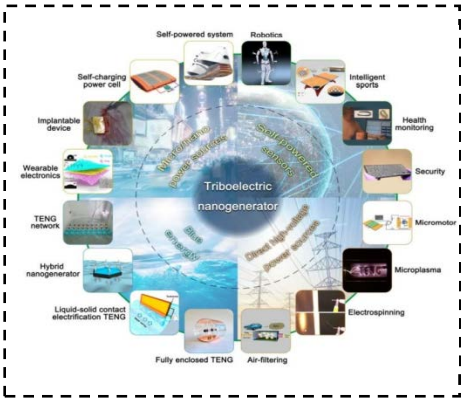

Figure 4: Major Application fields of TENGs as micro/nano power sources, active self- powered sensors, blue energy, and direct high-voltage power sources.

Figure 5: Diverse Applications of TENG for mechanical-to electrical energy conversion (enabled smart shoes).

2.3 Model vs. Simulation

The top block is made up of one material and the bottom block another. When the materials are not touching they have little to no charge (1 & 2). As they get closer, tiny structural changes at their surfaces lead to a buildup of charges (3&4). These charges are highest when the two come into contact at which point they can exchange charges (5&6). Check out these simulations based on the triboelectric effect to understand why we get a shock after walking across a carpet in socks to touch a doorknob, or why a balloon sticks to the wall after touching a sweater, Figure 6.

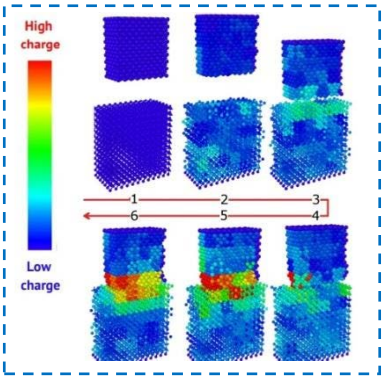

Figure 6: Schematic of Model vs. Simulation

3. History of Triboelectric Effect

The first description of the triboelectric phenomenon, “the marvels that are observed about the attraction of amber”, appeared in Plato’s dialogue Timaeus, which dates to approximately 400 B.C. The “attraction of amber" refers to the attraction of amber to dry hair that is a result of the electrostatic interaction in which electrostatic charges are generated by the triboelectrification between the amber and human skin or hair. Around 300 A.D., a Chinese Philosopher, Pu Guo, described the "amber effect" in his poem "Ci Shi Zan (Eulogy of the magnet)." The English translation of the poem in Dr. Frank Nordhage's thesis "The magnet draws the iron, and the amber attracts mustard seed. There is a breath which penetrates secretly and with velocity and which communicates itself imperceptibly to that which corresponds to it in the other object. It is an inexplicable thing." The harvesting and conversion of mechanical energy is one of the main ways in which mankind obtains electricity. As shown in Figure 7, the electromagnetic generator invented by Faraday has been the dominant mechanical energy harvesting technology from 1831 until now.

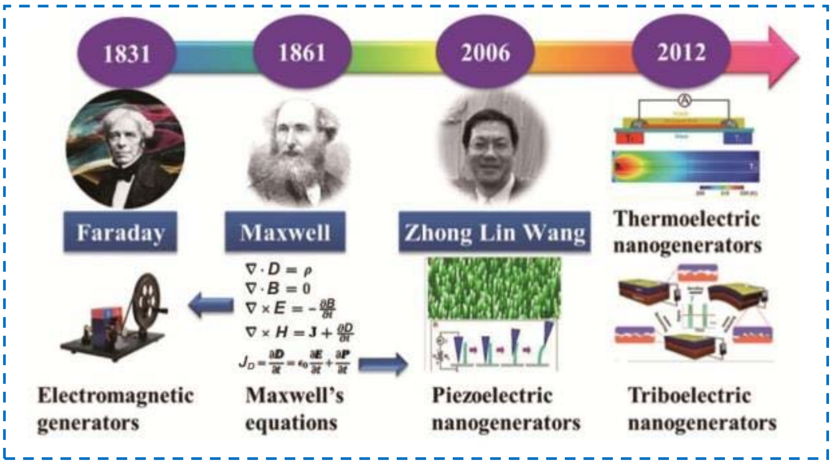

Figure 7: The Birth of the TENG and related major historical events.

"The amber attracts mustard seed" indicates the same physical principle as amber attracting dry hair. The "breath" describes the electric fields created by the triboelectric charges on the surface of the amber. The "which communicates itself imperceptibly to that which corresponds to it in the other object" explains how the charged object interacts with other objects.

William Gilbert experimentally proved the generation of triboelectric charge by rubbing contact, written about in his book "deMagnete" in 1600. Such findings indicated the commonness of the generation of triboelectric charges between two surfaces in physical contact. The Swedish physicist J. C. Wilcke made the first triboelectric series that showed the charge affinity of materials. The charge affinity indicates the charge transfer during the triboelectrification process, Figure 8**.** During the triboelectrification process, the charge generation was recognized as being the result of rubbing two materials together for a very long time. It was not until 1789 when Alessandro Volta noted that it is contact, rather than rubbing, that leads to charge transfer; people started to realize that the actual mechanism was not that simple.

There is no single theory can explain this mysterious but fundamental phenomenon. The failure has been reluctantly attributed to the unknown complexity of interfacial interaction between two contacting materials. Many researchers have proposed various may explain phenomenologically a specific case or more, but none can satisfactorily explain the above general observations. A collection of even more puzzling facts about triboelectric charging, gleaned after thousands of years of observations summarized as:

(a) Triboelectric charging occurs universally. It occurs not only at solid-solid contacts, but also at various solid-liquid, solid-gas, and gas-gas systems. Lateral friction dominantly induces a charging effect called triboelectrification, but normal contact also causes electrification to a large extent, in a process called contact electrification.

(b) Generally, triboelectric charging effects are negligible for metallic systems, but maximized for insulating polymeric systems.

(c) Triboelectric series do exist. Surprisingly, there is no consistent triboelectric series from experiment. A general tendency was observed, but reproducibility is not settled at the level of science. Middle-school textbooks have started to remove the triboelectric series from the contents, simply because it is not accurate enough.

(d) Even more peculiar triboelectric effects have been routinely observed; identical materials exhibit charging effects when rubbed together; dust particles are charged depending on their size; and groups of materials exhibit cyclic triboelectric charging.

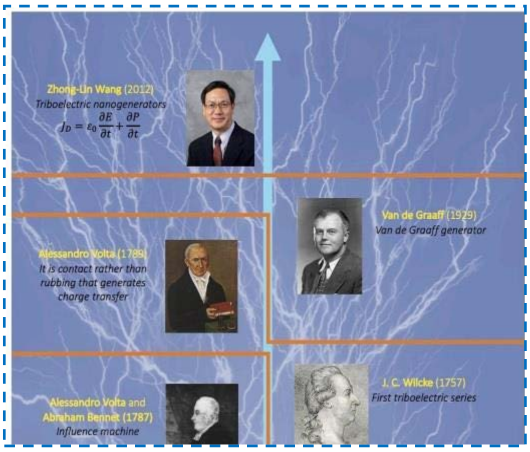

Figure 8: A brief history of triboelectrification.

[All photos and pictures are copied from wikipedia.com.]

4. Theory of Thermoelectric Effects

The study of basic theory lays an essential foundation for the establishment. In the recent two years, some significant breakthroughs in the fundamental physics of the TENG have been achieved. Let us discuss the mathematics of fundamental theory and basic knowledge of the TENG. When two materials are rubbed together, the mechanical energy dissipates into frictional heat. Microscopically, frictional heat is generated via a bond-breaking process at the interface. If the relative speed of the two contacting materials is about v = 10 cm/s, or 1

Å/ns, approximately Q_0=0.01 J/m^2 of heat is generated at the interface per, τ=1 ns. To make the problem simple, we replace the frictional motion with a stationary heat source $\dot{Q}(x,t) = Q_0 \delta(x) \sum_n^N \delta(t - n\tau)$ at the interface that generates successive N heat pulses. The δ-function-like heat pulse is a reasonable assumption because bond breaking and phonon excitation typically occurs very quickly, on the time scale of femto-seconds. Also, the stationary heat generator model is naturally applicable to contact electrification, in which similar bond-breaking energy dissipation occurs at the interface.

Generally, heat flows away from a heat source, and heat conduction is governed by Fourier's law $\dot{Q} = -k\nabla T$. Here, $\dot{Q}$ is the heat density flux and ∇T is temperature gradient. Once a temperature profile *T* is settled in a longer timescale, a thermo-electromotive force instantaneously develops due to the thermoelectric effect according to, $J = \sigma(E - S\nabla T)$, where J is the current density ; the electrical conductivity, and < the electric field. At the steady state, the open-circuit condition *J* = 0 is applied throughout the materials. Then, the electrostatic potential *V* is simply described by

$$V = -ST \tag{1}$$

since $-Q = -k\nabla T.$, and the accordingly redistributed charge density is expressed as $\rho_e = \varepsilon S\nabla^2 T$ from Gauss' law, where ε is the dielectric constant. Therefore, if we can determine the temperature profile *T* from the heat conduction equation, we can obtain the electrostatic potential profile *V* and the charge density profile ρ_e with information ε and *S*. In this way, any thermal electrification between two contacting materials can be evaluated.

In a thermoelectric experiment with two contacting materials, heat flows from one material to the other. While temperature gradually varies within the materials, it suddenly drops at the interface. The abrupt interfacial temperature drop is known to be determined by the interfacial thermal conductance A. In our triboelectric model, the heat source is located at the interface of two materials. Therefore, the interfacial temperature will be high, with a certain temperature difference between the two materials, and the temperatures will gradually decrease to the ambient temperature T_0.

5. Conclusions

The TENG, since its first invention in 2012, has experienced a very rapid development with its technological improvements particularly in applications for energy harvesting and self-powered sensing. For over 2000 years, physics of turboelectric effect, its generality and interesting phenomena attract significant research interests. Finally, the future directions and perspectives of the TENG have been outlined in briefly. The TENG is not only a sustainable micro-power source for small devices, but also serves as a potential macro-scale generator of power from water waves in the future. Also, the TENG will make great breakthroughs in key technologies for the Internet of Things, which is an unavoidable tool connecting everyday objects for facilitating human life progress and so on. In brief, triboelectricity is the wave of the future.

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