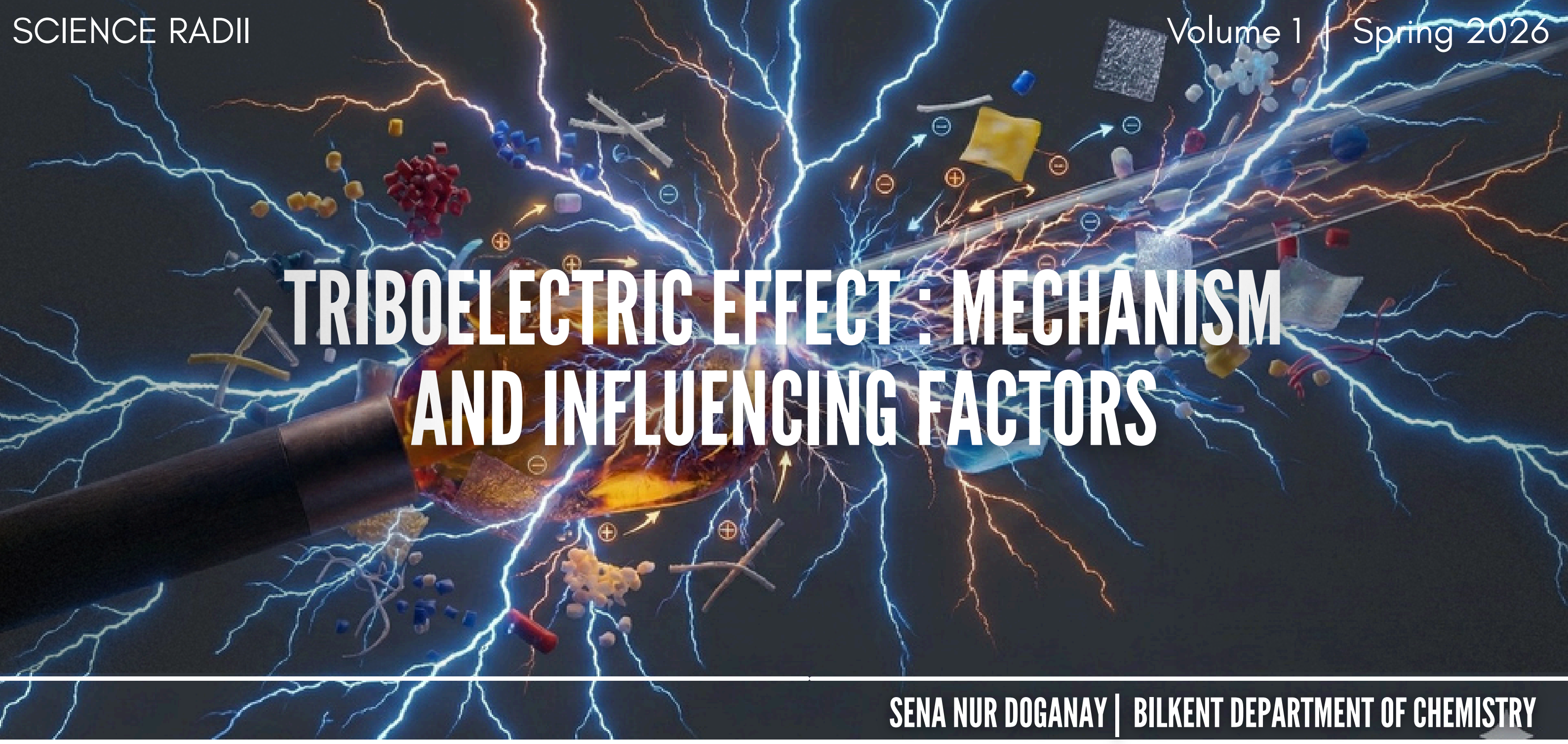

TRIBOELECTRIC EFFECT : MECHANISM AND INFLUENCING FACTORS

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T The riboelectric effect, which is generated by the connection and separation of materials, is a fundamental concept of daily life. There are various causes of tribo-electric effect like electron, ion, and material transfer. In addition, environmental and material properties can impact triboelectric charges.

Introduction

When two different surfaces are contacted and then separated, transfer of electrons creates surface charges. This is called the “triboelectric effect”. The concept of triboelectricity dates back to ancient times. One of the Greek philosophers, Thales of Miletus, realized that rubbing amber against wool was creating charges on the substances. Moreover, “tribo” means “rubbing,” and “electric” comes from the Greek word for amber, “elektra”. Thus, “triboelectric” in Greek literally means “rubbing amber” [1].

People frequently encounter examples of the triboelectric effect in their daily lives. When a plastic balloon is rubbed against hair, the hair becomes statically charged, causing it to lift and stick to the balloon. A pencil that has been rubbed on hair beforehand can attract small pieces of paper. These are just a few daily life examples of the triboelectric effect.

Although the triboelectric effect may seem very simple at first, this concept involves deep knowledge of chemistry and physics. Atoms do not lose electrons easily, and gaining an electron from one neutral atom needs energy. However, electron transfer occurs with the triboelectric effect by contact and separation rather than requiring high amounts of thermal or electrical energy. This raises the question of how simple rubbing can lead to electron transfer, resulting in the triboelectric effect.

Atoms consist of protons, neutrons, and electrons. Protons have positive and electrons have negative charges. Electrons are not localized, so they can transport charges, which means an excess or a deficiency of electrons [2]. Electrons move from one surface to another, and this leads to one surface having an excess of electrons and the other being deficient of electrons for triboelectricity. The excess and lack of electrons create a negative and a positive charge, respectively. This makes up the core mechanism behind the triboelectric effect. Rubbing is not essential for this effect to occur; the connection and separation are enough to create a triboelectric charge between the two surfaces. Generally, the potential differences between surfaces are extremely small.

However, a potential difference in a very close range can create an electric field large enough to move electrons through the electric breakdown of air, which causes sparks associated with static electricity [3]. Although the physical mechanism of electron transfer is widely discussed in the physics literature, several alternative interpretations exist. Different perspectives highlight that triboelectricity cannot be fully explained by a single discipline.

Electron

Electrons play a significant role in the triboelectric process because they create charges. surface W is an important factor which determines the minimum thermodynamic work that is needed to be done in order to remove an electron from the surface to the vacuum level. Surface W demonstrates the ease of losing or gaining electrons during contact and separation.

$$W = E_{vacuum} - E_{fermi} \quad (1)$$

E_{fermi} shows the "Fermi level". The Fermi level demonstrates the highest occupied electron energy level in the solid at 0 K [4]. It represents the top of the filled electronic states and acts as the reference point in the work-function formula. When two materials with different work functions are contacted, electrons move from the material that has a smaller work function to the material that has a larger work function. Fermi levels of both surfaces go to an equilibrium, and the differences become zero. After separation, the physical electron path is broken, so electrons cannot go back to their original positions. Two materials have opposite charges [5].

The primary force that leads to electron transfer in triboelectricity is the difference in work function. The secondary effect can be explained by the phonon-electron system [6].

The phonon-electron system demonstrates the phonons' impacts on electron behaviours through solids. In solids, electrons go through a crystal lattice, which consists of vibrating atoms. Vibrations are called "phonons".

When electrons move, they interact with these vibrations, phonons, and it is called phonon-electron interaction. Electrons make interactions with phonons through probabilistic scattering. It states electrons do not interact with vibrations at fixed. Each interaction occurs with a certain probability, which depends on temperature and lattice vibrations. Phonons influence the likelihood of electron transfer to occur by raising or lowering the barrier locally. In the triboelectric effect, electron-phonon interaction can resist or allow charge transfer between surfaces [7].

An electron can move through a small tunnel by absorbing or emitting phonons, thereby overcoming energy barriers. This is called "quantum tunneling". Phonon interactions can assist or hinder quantum tunneling at specific moments by lowering or raising the energy barrier, but they do not necessarily cause it. Quantum tunneling occurs because the wavefunction of the electron extends to the other side of the barrier; therefore, it also has a probability to exist on that side. Thanks to quantum tunneling, electrons can transfer from one surface to the other even if they do not have enough energy to overcome the energy barrier required for the transfer [8]. Both phonon-electron interaction and quantum tunneling might provide electrons to move from one surface to another surface with less energy and significant factors on the triboelectric effect, especially at the nanoscale.

ION

Although electron transfer is the primary source of triboelectric effect in the solids, ion transfer also provides triboelectricity, particularly in a liquid interface. In such a case, ions contribute to triboelectricity rather than electrons. In insulating materials charge formation is limited because of a lack of free charges, but can still occur. While the surface is strongly bound by one charge polarity, it is loosely bound by other ions with the opposite charge on the insulator surface. This circumstance leads to an imbalance of affinity with various ions. During tribological contact, a particular type of ions is transferred so charge accumulates on the insulator surface [6]. In the case of conductors, free electrons exist on and inside the surface; therefore, ions are not the dominant charge carriers. However, if the interface between the conductor and the environment is a liquid or a polymer, triboelectric charging can occur. Ion transfer occurs at the interface between the conductor and environment (or another surface). During the connection, ions can be attached to (adsorption) or detached from (desorption) the conductor's surface. Two layers form between the surface and environment, where one layer of ions is present on the conductor surface, and the other layer, which carries ions of an opposite charge, is formed on the opposing surface. Two different layers occur, which are called the "electric double layer (EDL)". While a layer of ions exists on the liquid surface, the opposing surface acquires the opposite charge. When the surfaces are separated, some ions remain trapped, which creates a triboelectric potential [9].

Material

Besides ion and electron transfer, material transfer may also contribute to the formation of triboelectric charges. Strongly rubbing both surfaces against one another and applying pressure on the surfaces can transfer small pieces of both surfaces to the other. Transferred material might provide a charge imbalance. Therefore, dynamic changes such as strain can cause the material transfer because substances tend to exist in lower energy states. Dynamical factors change the potential energy of the surface, and the materials that tend to go to lower energy states might be transferred [6]. This contributes to the triboelectric effect. Additionally, studies on polymers such as PDMS have shown that triboelectric contact can involve homolytic and heterolytic bond breaking [10]. A chemical bond consists of two electrons. While a bond is breaking, bond electrons can separate equally, which is called "homolytic bond cleavage or unequally, which is called "heterolytic bond cleavage". After homolytic and heterolytic bond breaking, some ends of the polymer chain open. These open chain ends are more chemically reactive and can react with new functional groups, resulting in a surface charge.

Consequently, contact electrification may involve the transfer of these charged material patches between surfaces. This situation contributes to the formation and persistence of triboelectric charges [10].

Triboelectric Series

In 1757, the Swedish physicist J. C. Wilcke created an empirical list of materials. He ordered materials according to their tendency to acquire positive/negative charges by mechanical connection. After that, many scientists prepared their material lists according to the willingness of each material to acquire charges.

In 1917, Shawn first used the term "Triboelectric Series (TS)". It is a simplified material table that shows their tendencies to gain or lose electrons after physical connection. It is still a controversial matter, and there is no universal version that is accepted by all scientists. Although this table is empirical and context-dependent, it contributes significantly to the knowledge we have about solid surface properties and experiments about triboelectricity [11].

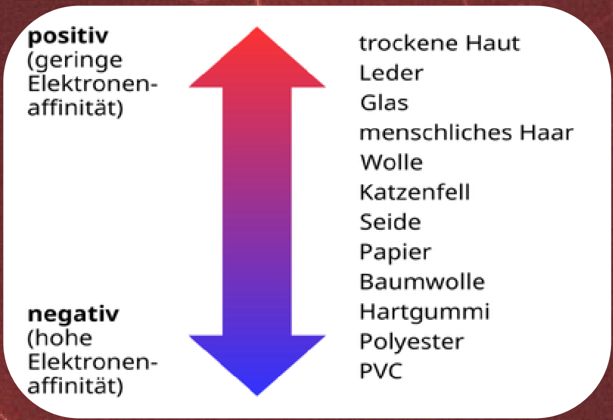

Fig 1. Triboelectric series showing materials ordered by their tendency to gain or lose electrons. Adapted from MikeRun, Wikimedia Commons, CC BY-SA 4.0. [12]

Factors Impacting Triboelectric Effect

Both surface properties and medium are the main factors that can influence the triboelectric effect. Although the type of material is the most noteworthy contributor to the triboelectric effect, there are other contributors. Surface roughness determines the contact area between the materials; rougher surfaces increase the area of contact, which in turn increases charge transfer. Additionally, particle size is also a significant factor. When two particles are contacted, they gain opposite charges. Latest studies demonstrate that statistically, while larger particles tend to have positive charges, smaller particles tend to gain negative charges. Stress, humidity, and acidity are environmental changes. The ability to create ions and electrons by stress is proven. Furthermore, stress load can change charge transfer mechanism and their behaviours, so the triboelectric effect is impacted by stress directly. Both acidity and humidity can create ions, so they can change electrical conductivity. During tribo-contact, salt or water molecules are attracted to the surfaces and create a conductive layer. This conductive layer or film allows charge leakage to occur between the two surfaces, therefore the overall charge decreases. [6].

Charge Transfer Between Identical Materials

When two identical materials are contacted, common sense does not expect charge transfer between them. However, charge transfer does occur. A significant factor that impacts charge transfer is symmetry. If identical materials are also perfectly symmetrical, the charge transfer direction is completely random, so surfaces may have the same or opposite charges. If substances are not symmetrical, charge transfer tends to occur in a preferred direction and surfaces become oppositely charged [13]. If the charges of surfaces are not in equilibrium, charge transfer occurs from the higher non-equilibrium charge surface to the lower non-equilibrium charge surface. Additionally, the net charge transferred is proportional to the difference in surface charge density [6].

From a chemical perspective, small differences in surface composition can create regions that act like a charge acceptor or a charge donor. During contact, chemical bonds can break either equally (homolytic cleavage) or unequally (heterolytic cleavage). Breaking bonds can generate open-chain ends on polymers. Reactive open ends can provide ions or radicals by reacting with these. Open ends, radicals, and ions cause electron density differences.
Electrons can accumulate at particular regions, and other regions may have an electron deficiency. This leads to the formation of local charge regions, which are called "charge mosaics" [10]. These charge mosaics allow charge transfer between identical materials.

Conclusion

The triboelectric effect arises from electron, ion, and material transfer, which causes a charge imbalance. Several factors can impact triboelectricity by decreasing or increasing the amount of charge transferred. Interestingly, triboelectric charge transfer occurs between identical materials when the surfaces are asymmetric or the charges are not in equilibrium, but also between materials that have different work functions or surface properties. The triboelectric effect and its mechanism provide scientists with valuable insights into material behaviour, which leads to practical applications and experiments, so the triboelectric effect is one of the most significant concepts in material science.

Works Cited

1. Williams MW. What creates static electricity. Am Sci. 2012;100(4):316. Available from: https://www.jstor.org/stable/23223132

2.Lüttgens G, Lüttgens S, Schubert W. Static electricity: understanding, controlling, applying [Internet]. 2017. Available from: http://www.wiley-vch.de/publish/dt/books/ISBN978-3-527-34128-3/

3.Silsbee FB. Static electricity. Circular of the National Bureau of Standards. 1942;(438):10.

4.Kahn A. Fermi level, work function and vacuum level. Materials Horizons [Internet]. 2015 Oct 13;3(1):7–10. Available from: https://doi.org/10.1039/c5mh00160a

5.Bailey AG. The charging of insulator surfaces. Journal of Electrostatics [Internet]. 2001 May 1;51–52:82–90. Available from: https://doi.org/10.1016/s0304-3886(01)00106-1

6.Pan S, Zhang Z. Fundamental theories and basic principles of triboelectric effect: A review. Friction [Internet]. 2018 Aug 10;7(1):2–17. Available from: https://doi.org/10.1007/s40544-018-0217-7

7.Giustino F. Electron-phonon interactions from first principles. Reviews of Modern Physics [Internet]. 2017 Feb 16;89(1):7. Available from: https://doi.org/10.1103/revmodphys.89.015003

8.Electron-Phonon interactions in Low-Dimensional structures [Internet]. 2003. Available from: https://doi.org/10.1093/acprof:oso/9780198507321.001.0001

9.Park SJ, Seo MK. Interface Science and Composites. In: Interface science and technology [Internet]. 2011. p. 46. Available from: https://doi.org/10.1016/b978-0-12-375049-5.00011-6

10.Baytekin HT, Patashinski AZ, Branicki M, Baytekin B, Soh S, Grzybowski BA. The mosaic of surface charge in contact electrification. Science [Internet]. 2011 Jun 24;333(6040):308–12. Available from: https://doi.org/10.1126/science.1201512

11.Galembeck F, Burgo T a. L, Balestrin LBS, Gouveia RF, Silva CA, Galembeck A. Friction, tribochemistry and triboelectricity: recent progress and perspectives. RSC Advances [Internet]. 2014 Jan 1;4(109):64280–98. Available from: https://doi.org/10.1039/c4ra09604e

12.MikeRun. Triboelectric series (English labels) [image]. Wikimedia Commons; 2022 Mar 24 [cited 2025 Dec 14]. Available from: https://en.wikipedia.org/wiki/Triboelectric_effect#/media/File:Triboelectric-series_EN.svg

13.Wang AE, Gil PS, Holonga M, Yavuz Z, Baytekin HT, Sankaran RM, et al. Dependence of triboelectric charging behavior on material microstructure. Physical Review Materials [Internet]. 2017 Aug 23;1(3). Available from: https://doi.org/10.1103/physrevmaterials.1.035605