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STATIC ELECTRICITY: FROM FUNDAMENTAL PRINCIPLES TO MODERN APPLICATIONS

Static electricity arises as a result of the accumulation of electric charges on the surface of dielectrics or conductors isolated from the ground. This phenomenon is caused by an imbalance between positive and negative charges due to processes such as friction, contact, or induction. It is widely used in engineering: touch screens, air purification systems, photocopiers, microelectronics, aerospace industry and medicine.

One promising idea is the use of static electricity for energy generation in micro- and nanodevices. In recent years, triboelectric nanogenerators (TENGs) have been actively developed to convert mechanical friction energy into electrical energy. Such devices can power wearable electronics, sensors and even medical implants. The working principle of TENGs is based on the combination of the triboelectric effect and electrostatic induction. For example, when a polymer film rubs against a metal surface, a potential difference of hundreds of volts can arise [1]. This paves the way for autonomous power sources independent of external batteries.

The phenomenon of static electricity has long been of interest to the scientific community, yet it also poses significant practical challenges. In the field of electronics, electrostatic discharge (ESD) has the potential to compromise the integrity of sensitive components, such as semiconductor chips. Contemporary research has proposed the utilisation of metamaterials (composites) with regulated dielectric properties for the purpose of suppressing undesirable charges.

Metamaterials consist of periodically arranged elements (e.g., micro- or nanostructures) whose dimensions are smaller than the wavelength of the interacting electromagnetic radiation. In the context of static electricity, metamaterials are notable for their ability to control dielectric properties, such as

permittivity ϵ and conductivity σ , enabling the management of charge distribution and accumulation [2].

The employment of metamaterials facilitates an augmentation in system capacitance due to their high permittivity, thereby diminishing the potential at a given charge. This has the effect of minimising the risk of breakdown.

Metamaterials with conductive inclusions or gradient conductivity have been shown to be capable of directing charges to the ground through low-resistance paths. For instance, metamaterial structures comprising carbon nanotubes within a dielectric matrix facilitate "soft" charge dissipation, thereby preventing sudden discharges. Hybrid coatings with graphene inclusions represent a class of composite materials, wherein graphene (a single atomic layer of carbon with a hexagonal lattice) is integrated into a dielectric matrix, thereby combining high permittivity with controlled conductivity [3].

The dielectric matrix provides high permittivity, denoted by ϵ . The matrix materials that are most commonly utilised include polymers such as polyvinylidene fluoride (PVDF) or polymethyl methacrylate (PMMA), with permittivity values ϵ ranging from 5 to 50, and ceramic materials such as aluminium oxide (Al_2O_3 , $\epsilon = 10$) or barium titanate (BaTiO_3 , $\epsilon = 1000$ and higher).

Graphene exhibits unique properties. It is an excellent conductor due to its high electron mobility ($\sim 200,000 \text{ cm}^2/\text{V}\cdot\text{s}$). Its structure makes graphene incredibly strong and flexible. Graphene is resistant to corrosion and oxidation. A single graphene layer is $\sim 0.34 \text{ nm}$ thick, enabling ultra-thin coatings.

In hybrid coatings, graphene is typically used as nanoplatelets, nanotubes, or graphene oxide dispersed in a dielectric matrix (e.g., polymers, ceramics, or epoxy resins). This structure combines graphene's conductive properties with the matrix's insulating characteristics. For example, PVDF-based coatings with 1% graphene achieve $\epsilon \approx 50$ and conductivity $\sim 10^{-6} \text{ S/m}$ [3].

The presence of graphene inclusions generates pathways that exhibit moderate conductivity, thereby facilitating the safe dissipation of charges into the grounding system. This prevents the occurrence of abrupt discharges, which have the potential to cause damage to electronic devices or ignition. The presence of graphene nanoplatelets has been shown to mitigate local electric fields, thereby preventing the accumulation of charge at specific locations.

To evaluate hybrid coating parameters, consider a flat surface with area $S = 0.01 \text{ m}^2$ accumulating charge $Q = 10^{-7} \text{ C}$. Without coating ($\epsilon = 1$, distance to ground $d = 0.001 \text{ m}$), capacitance and potential are:

$$C_0 = \epsilon_0 \epsilon \frac{S}{d} = 8,85 \cdot 10^{-11} \text{ F}. \quad V_0 = \frac{Q}{C_0} = 1129 \text{ V}. \quad (1)$$

Applying a hybrid coating with $\varepsilon = 200$ (achieved via graphene inclusions in a polymer matrix) yields new capacitance $C_1 = 4.45 \times 10^{-9}$ F and potential $V_1 = 22.6$ V.

The coating's resistivity is $\rho = 10^6 \Omega \cdot \text{m}$. The effective resistance for charge dissipation through a coating of thickness $d = 0.001$ m is:

$$R = \rho \frac{d}{S} = 10^5 \Omega. \quad (2)$$

The charge dissipation time can be determined by measuring the relaxation time, $\tau = RC_1 = 1.77$ ms. It can thus be concluded that the coating reduces potential by 200 times and ensures safe charge dissipation within milliseconds, thereby preventing sparking.

Static electricity is not merely a curious physical effect; rather, it is a field in which fundamental science intersects with innovative technologies. Innovative ideas, such as triboelectric generators, and precise calculations pave the way for effective solutions – from autonomous energy sources to the protection of high-tech equipment.

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