Dielectric Interfaces in HV Technology: Overview and Theoretical Approaches to the Modelling of Functional and Breakdown Behaviour

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INTRODUCTION

In virtually all modern electronic and electrical systems, the understanding of dielectric materials is imperative to the design, operation, and performance of system components. The use of dielectrics in solid, gas, and liquid phases is commonplace within the electrical engineering discipline, where the exact choice of material will be application-dependent, based on the specific requirements of the system being designed. It is common for different dielectrics of different phases to be found in a single system. For instance, phase-specific properties of dielectrics are often crucial for the operation of power equipment, and their inclusion is therefore unavoidable. In these cases, interfaces are generally undesirable. With ever-increasing system complexity, situations where interfaces are formed between different materials often becomes a necessity. While solid, gas, and liquid dielectrics have been extensively studied in isolation, the behaviour of dielectric interfaces and composite insulation, in general, has historically received far less attention.

However, challenges driven by shifts in global electricity generation, transmission, and distribution have shone a spotlight on the subject of dielectric interfaces. The growing demand on global electricity networks has led to a push toward higher capacity and higher voltage apparatus, yet limitations in terms of cost and space disallows any substantial increase in component dimensions. Simultaneously, the requirement for HVDC links for long distance transmission, and for the integration of renewable generation, has placed emphasis on the hazardous effects of space-charge accumulation in extruded HV cable insulation, which may arise due to the existence of dielectric interfaces [1]–[3]. Meanwhile, past studies on the failure of existing equipment suggest that interfaces can be potential points of weakness in electrical insulation systems [4]–[7], and if design issues are not addressed, they may severely compromise the integrity of future apparatus. The combination of these factors has also substantially increased the interest in novel insulation technologies such as dielectric composites [8], [9], functionally graded materials (FGM) [10]–[12], and nanodielectrics [13]–[15], all of which feature dielectric interfaces in some form.

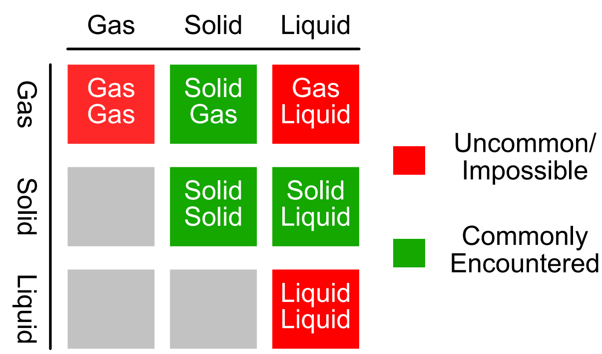

Figure 1: Matrix representing the types of dielectric interfaces formed of different phases – those in green are the most industrially relevant, and the focus of this article.

While the power industry may have placed a new significance on interfaces, their prevalence is far from limited to power systems apparatus, and any advancements in the direction of dielectric interfaces would be highly relevant for a plethora of other technologies. Some notable examples of interfaces in various systems are described in more detail within the next section titled 'Interfaces in the Wild'.

With these current trends and issues in mind, this article is broad in scope, and aims to provide a general theoretical overview of dielectric interfaces. Considering interfaces formed of adjacent dielectrics in potentially different phases of matter, Figure 1 shows a matrix of the possible combination of interface types (vacuum-insulated equipment is considered outside the scope of this article). Interfaces highlighted in green form the focus of this article, due to their prevalence in, and relevance to, industrial electrical systems (solid-gas, solid-solid, and solid-liquid). As for those highlighted in red, they are either non-existent (gas-gas interfaces) or are seldom found by design in the scenarios discussed here (liquid-gas interfaces, liquid-liquid interfaces). This article firstly discusses where these interfaces commonly arise, the role that they may play in various systems, and their associated design issues. The electrical characteristics of interfaces according to classical

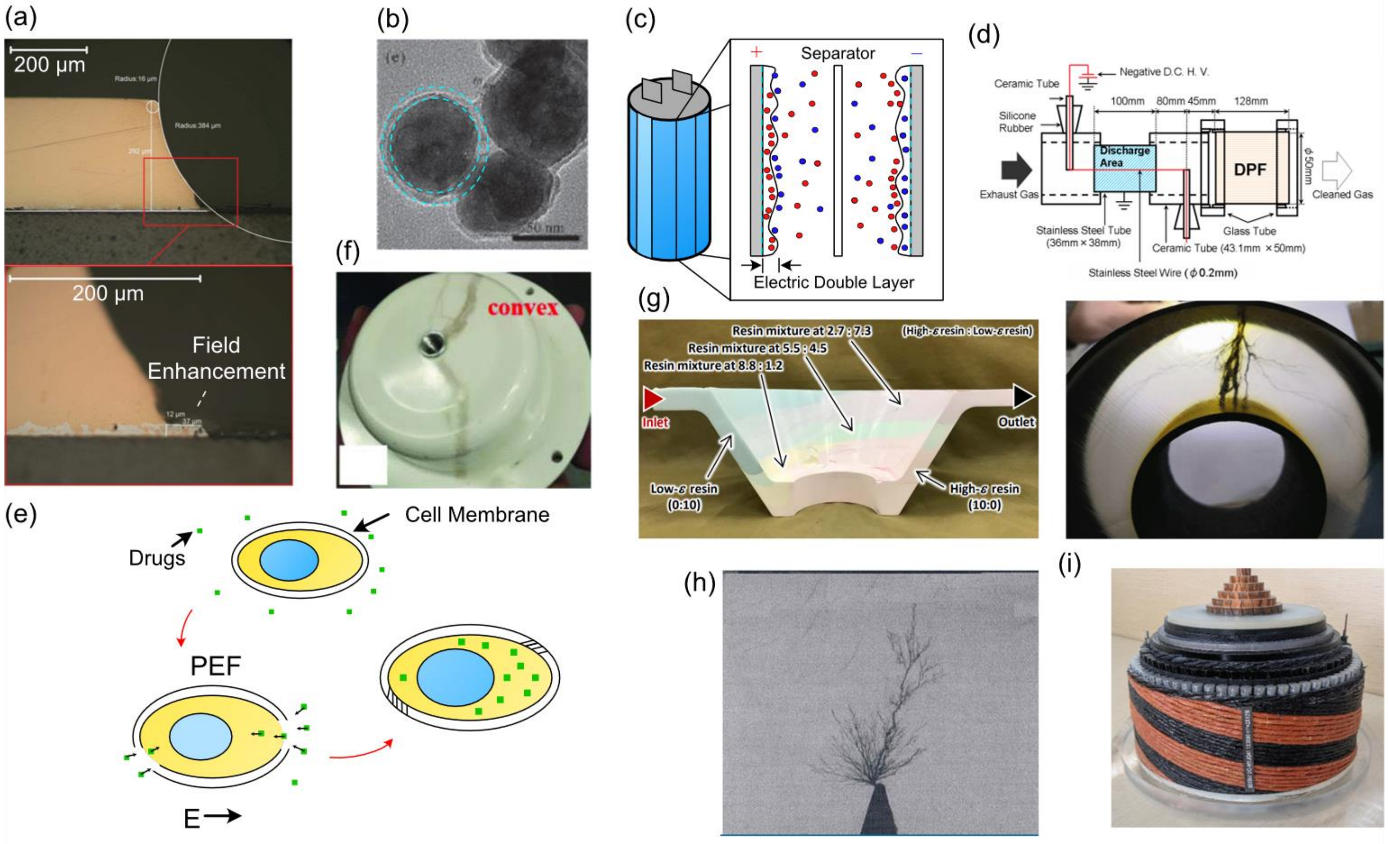

Figure 2: Graphic depicting the widespread occurrence of dielectric interfaces in many electrical systems, large or small - (a) triple junction between copper trace, ceramic and encapsulant in an active metal brazed (AMB) semiconductor substrate, adapted from [113]; (b) transmission electron microscopy (TEM) images of $BaTiO_3$-polydopamine nanoparticles from [115]; (c) diagram of an electrochemical capacitor and its construction; (d) ESP and filter system for diesel soot from [116]; (e) diagram of the principle of reversible electroporation for drug delivery using PEF; (f) post-flashover trace over GIS spacer from [120]; (g) novel FGM GIS spacer fabricated using resin-injection methods presented in [35]; (h) discharge in cable mineral oil initiated from a point electrode as part of tests conducted in [119]; (i) (top) breakdown channel in cable insulation during tests conducted in [117], (bottom) section of a ±535 kV HVDC cable shown in [118].(All images apart from (c), (d), (e) are © IEEE.)

macroscopic theory is the focus of this article, with a brief discussion of microscopic theories that are outside the scope of this article. Approaches that allow relevant dielectric phenomena to be modelled are outlined. Then, considering the increasing prevalence of high-field conditions within many applications, dedicated sections discuss the theory behind electrical pre-breakdown and breakdown phenomena across solid-gas, solid-solid, and solid-liquid interfaces, separately. The ultimate objective of this article is to raise awareness for the issues surrounding dielectric interfaces, from their purposeful application to potentially hazardous characteristics. For the system designer, engineer, and researcher: this article aims to be a guide to interfaces and how they may affect system operation; to describe critical aspects that may dictate the performance (or failure) of equipment; to provide a theoretical basis for the modelling and analysis of dielectric interfaces; and to identify key areas where further study could lead to significant technological advancement.

INTERFACES IN THE WILD

The graphic in Figure 2 provides several important example scenarios where dielectric interfaces feature in existing and emerging technologies. These vary greatly in terms of size, scale, and application, yet all share some form of interface as a common feature. The examples of Figure 2 have been categorized according to the types of interfaces indicated by Figure 1, and are briefly discussed in the following section. It is remarked that this list is far from exhaustive but provides a general idea of the prevalence of dielectric interfaces across a range of modern technology.

Solid-Gas Interfaces

Gas Insulated Systems (GIS) (f) – Gas insulated transmission lines, switchgear, and circuit breakers are essential parts of modern power transmission, distribution, and protection infrastructure. The interactions between gases and solid supports at solid-gas interfaces continue to be of high interest. For example, the interfaces formed from the inclusion of solid spacers in gas insulated transmission lines, may induce surface flashover across a spacer. This may be due to field enhancement at the spacer-electrode-gas triple junction, or by discharge initiation due to various other imperfections, such as the adherence of contaminant particles onto the spacer surface [16]. Another major issue is charge accumulation, more details of which are provided in the next section entitled 'Dielectric

Phenomena at Interfaces'. There have been significant and recent efforts to use various charge-tailoring methods with the aim to control interfacial charges [17], [18]. Other work has further identified field-dependent regions of charge accumulation characteristics [19], as part of the ongoing effort to develop effective HVDC transmission technologies.

Semiconductor Technology (a) – Significant research continues on the topic of miniaturisation for next-generation electronic devices, where 'high-*k*' (*k* referring to the relative permittivity, typically ε_r in other fields) materials show promise for the reduction of leakage current and power consumption, among other benefits [20], [21]. However, field enhancement at internal- or air-exposed-contacts caused by high-*k* materials has also been shown to be a cause for concern, potentially leading to a significant reduction of the device breakdown voltage [20], [22], and thereby limiting its operational range.

Electrostatic Precipitation (ESP) – (d) Effective capture of particulate matter in precipitators, driven by repetitive pulsed power systems, has been demonstrated in the past [23]–[25], achieving close to 100% efficiency in some cases. The accumulated charge on a particle can be estimated by considering interfacial charging between the solid particulates and the gas in which they are suspended [24]. Optimisation of the precipitation efficiency may help progress toward the reduction of harmful airborne pollutants which have potentially severe impacts on human health [26].

Solid-Solid Interfaces

HV Transmission Cables (i) – Extruded polymeric cables have featured in power transmission for several decades [27], and have demonstrated their durability and reliability during this time. However, challenges arising from the use of the same cables with emerging HVDC transmission are primarily associated with long-term charge accumulation at layered insulation interfaces or conductivity gradients, leading to degradation and premature failure [1], [2], [28]. Solid interfaces formed at cable connectors and terminations have also been identified as potential weak points [6], [29].

Nanocomposites (b) – By embedding nanoparticles (or nanofiller material) into a host matrix, experimental studies have found numerous benefits, including higher dielectric strength of nanocomposite insulation [14], [15], among many others. Several studies have suggested that the interphase region formed at the interface, between the filler particles and the matrix, appears to be critical to the enhancement of the composite properties, e.g., [30].

High Energy Density Storage (c) – A challenge relating to capacitive energy storage systems involves maintaining suitably fast charge-discharge rate, high power density, and good processability, while maintaining low dielectric losses [31], [32]. Possible solutions explored include multi-layered dielectrics or combining traditional dielectrics with novel materials such as nanocomposites [32], where the space charge accumulation at interfacial boundary regions appears to contribute to improved performance [31].

Functionally Graded Insulation (g) – Functionally graded materials (FGM) employ nonuniform distributions of permittivity or electrical conductivity, for electric field grading and control [33], [34]. One such method is to use layered dielectric composites [35], [36], which naturally results in the formation of interfaces between each layer.

Solid-Liquid Interfaces

Liquid Insulated Systems (h) – Power and pulsed power components (e.g., transformers, capacitors, cables) often use liquid dielectrics on account of their phase-specific attributes, such as their self-healing properties, or role as a coolant, among others [37], [38]. In many cases, mechanical support is provided using solid dielectric spacers, which create liquid-solid interfaces. There also exists the possibility of bubbles or contaminant particles within dielectric liquids, which have been suggested to be possible sites for breakdown initiation [39]–[41]. Moreover, the theoretical treatment of contaminant regions often involves modelling these inclusions as solid-liquid or liquid-gas interfaces [42], [43].

Pulsed Electric Field (PEF) Technology (e) – The PEF process induces electroporation in cells [44], which can be controlled to be reversible for drug delivery, or irreversible to affect cell rupture and death [45], [46]. In the food industry, the same principle may be exploited for disinfection or pasteurisation [47], [48]. The multi-layer cell structure (i.e., nucleus, cytoplasm, membrane, etc.) has often been modelled as separate dielectric regions forming a layered structure [44], [49], [50], where the transmembrane voltages are of great interest, as they may dictate the treatment type and efficacy [48]. The external (fluid) suspending medium may further have consequences for the efficacy of PEF treatment, such as in applications targeting cell lysis.

DIELECTRIC PHENOMENA AT INTERFACES

Dielectric phenomena are inherently multi-scalar and can be analysed at several different levels of abstraction, depending on the processes of interest. The rough outline from Figure 3 illustrates the physical processes which are present over a range of dimensional scales, starting from atomic properties at the nanoscale, such as the chemical structure of dielectrics and charge transport processes; through microscale features, like material roughness at solid surfaces, or flow characteristics in liquids and gases; which then ultimately drive macroscale phenomena, including net electric field distributions, space charge, or complete discharge and breakdown events. This article does not aim to provide intricate details on any particular dimensional scale, but rather, an overview of important phenomena across the spectrum of dimensions. This section deals with the basic theoretical characteristics of dielectric interfaces, as dictated by classical electromagnetism in the meso- to macro-scale. The contents of this section are applicable to all types of dielectric interface, regardless of phase. Phase-specific properties necessitate a shift towards micro- and atomic-scale processes, which are briefly discussed, but detailed description lies outside the scope of this article.

For the applications discussed here, inductive effects can be assumed to be negligible, as signal wavelengths are generally far longer than that of the characteristic geometric length of the system. Thus, the electric field $\vec{\boldsymbol{E}}$ and magnetic field $\vec{\boldsymbol{B}}$ in linear isotropic dielectric materials are governed by Gauss's Law (1)

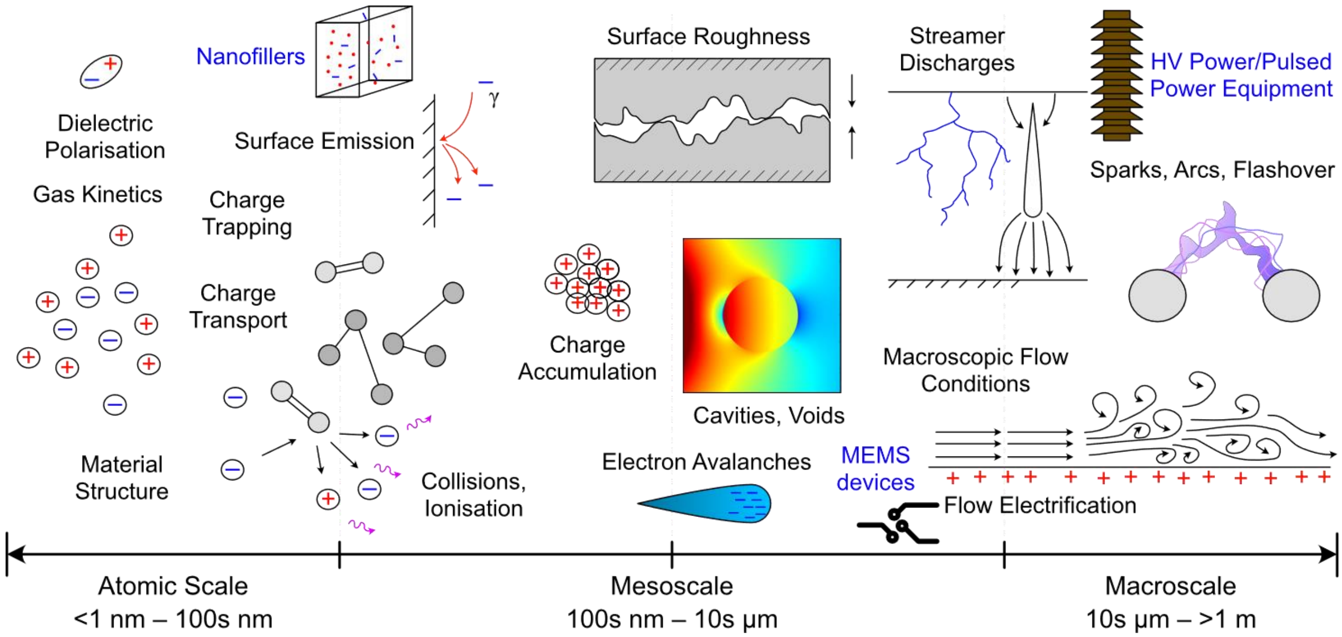

Figure 3: Physical processes relating to dielectric and dielectric interfaces at various dimensions/scales of interest. Macroscopic behaviours are driven by mesoscopic electrical phenomena, which themselves stem from atomic interactions between charges, atoms, and molecules. Indicated in blue text are the relative positions of some technologies discussed in Figure 2 on this scale.

and by the Ampére-Maxwell Law (2):

$$\varepsilon\vec{\nabla}\cdot\vec{E} = \rho, \tag{1}$$

$$\vec{\nabla}\times\vec{B} = \mu\left(\vec{J} + \varepsilon\frac{\partial\vec{E}}{\partial t}\right), \tag{2}$$

where $\vec{J} = \sigma\vec{E}$ is the conduction current density (in Am^{-2}) relating to free charge carriers in the medium, with σ denoting the electrical conductivity in Sm^{-1}; $\vec{B}$ is the magnetic field (also known as *magnetic flux density*) in Wbm^{-2}; and ρ is the volumetric charge density in Cm^{-3}. The electric field $\vec{E}$ is linked to the electric field flux density, $\vec{D}$ (or *electric displacement*) in Cm^{-2} by $\vec{D} = \varepsilon\vec{E}$. The permittivity, ε, and permeability, μ, are generally expressed as $\varepsilon = \varepsilon_0\varepsilon_r$ and $\mu = \mu_0\mu_r$ respectively, where the subscript r denotes the nondimensional *relative* values, with $\varepsilon_0 \approx 10^{-9}/36\pi$ Fm $^{-1}$ and $\mu_0 \approx 4\pi\times10^{-7}$ Hm^{-1} in vacuum. Combining (1) and (2), one recovers the equation for the conservation of charge,

$$\vec{\nabla}\cdot\vec{J} = -\frac{\partial\rho}{\partial t}, \tag{3}$$

which indicates that space charge accumulates at points inside a dielectric where the change in current flux with position is nonzero. It follows from (3) and (2) that the space-charge-induced electric field will lead to field distortion, and the net electric field may thus deviate from the Laplacian field. From (3) therefore, space-charge accumulation will occur if the current density $\vec{J}$ is spatially nonuniform, which may be induced by the nonuniformity of the electric field $\vec{E}$, or the electrical conductivity σ. The nonuniformity of $\vec{E}$ can be a result of the geometry of the system (nonuniform $\vec{D}$) or resulting from nonuniformity in the relative permittivity ε_r. At interfaces formed by two materials with different permittivity and electrical conductivity, the current density becomes discontinuous, and electric charge will accumulate at the interface in accordance with the Maxwell-Wagner effect. The simplest case of a one-dimensional, double-layer dielectric system is customarily used to illustrate this effect, where the interfacial contact is assumed to be perfectly flat, as shown in Figure 4. Application of (2) allows the Maxwell-Wagner relaxation time to be derived for this basic system, which describes the necessary time for interfacial charge to build up:

$$\tau_{MW} = \frac{\varepsilon_2 d_1 + \varepsilon_1 d_2}{d_1\sigma_2 + d_2\sigma_1}. \tag{4}$$

If the conduction current is dominant and the space-charge-induced field is sufficient to cause field distortion, τ_{MW} is the characteristic time for the developed electric field in the dielectric layers to reach its steady-state condition, upon the application or removal of an external electric field. Consequently, the ability for a system to react to transient fields is strongly impacted by the Maxwell-Wagner effect, which becomes a factor of critical importance for applications which may be sensitive to the applied voltage wave-shape, or in general, the temporal characteristics of the developed electric field.

At this stage, it is important to further discuss the role of electrical conductivity σ. In the ideal case of nonconductive materials (i.e., $\sigma \to 0$), the Maxwell-Wagner relaxation time tends toward infinity, such that there will be zero interfacial charge accumulation. If there is also an absence of volumetric

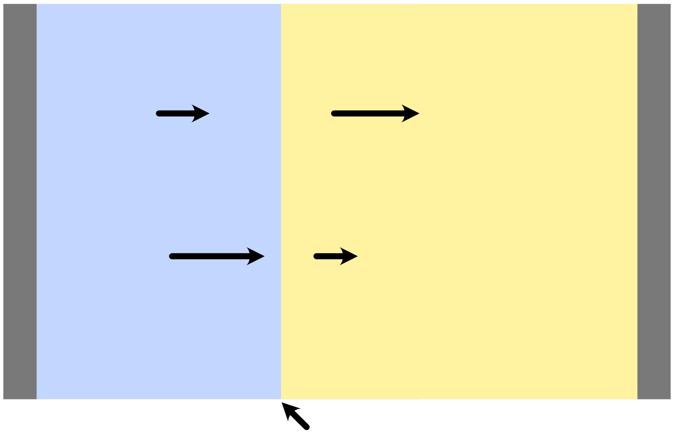

Figure 4: Simple double-layer dielectric system. Surface charge is accumulated at the boundary between materials due to conductivity mismatch, according to the Maxwell-Wagner effect.

charge, then the electric field becomes purely electrostatic and is governed by the Laplace equation (5). However, practical dielectrics possess low - but non-zero - electrical conductivity, and are often classified as "poorly conducting", since their non-negligible conductivity leads to a finite relaxation time. The consideration of field relaxation and charge accumulation processes when designing practical systems is, therefore, necessary. Charge control and tailoring techniques continue to be an open question, where a multitude of potential techniques have been discussed, see for instance, [17], [18]. These encompass charge source suppression, methods for controlled charge decay, and the structural/chemical modification of involved dielectrics. The ultimate goal is to eradicate the issue of charge accumulation and any related, undesirable, phenomena.

Furthermore, conductivity generally depends on the electric field and on the temperature, $\sigma(|\vec{\boldsymbol{E}}|, T)$. The example above assumes that σ is constant, isotropic, and independent of any external parameter, which may be a valid assumption in certain systems, e.g., applications where the electric field is sufficiently low (the exact threshold being material-dependent) and has lesser effect on σ, or in fast-rising pulsed applications where the temperature change over the duration of the voltage wave-form is negligible. In applications such as HVDC transmission, however, $\sigma(|\vec{\boldsymbol{E}}|, T)$ dependence can cause significant charge accumulation during long-term operation, as a result of the temperature- and field-induced spatial nonuniformity of σ [1], [2], [28], leading to field distortion. The latter case, when compounded with charge accumulation at interfaces, introduces significant complexity for theoretical modelling. As such, these two limiting cases are discussed separately below.

Isotropic, linear materials, low-field, or fast transient conditions

For some materials, the degree of nonlinearity (referring here to the deviation from an Ohmic relation – the nonlinearity in $\sigma(|\vec{\boldsymbol{E}}|)$) only becomes significant past a threshold field

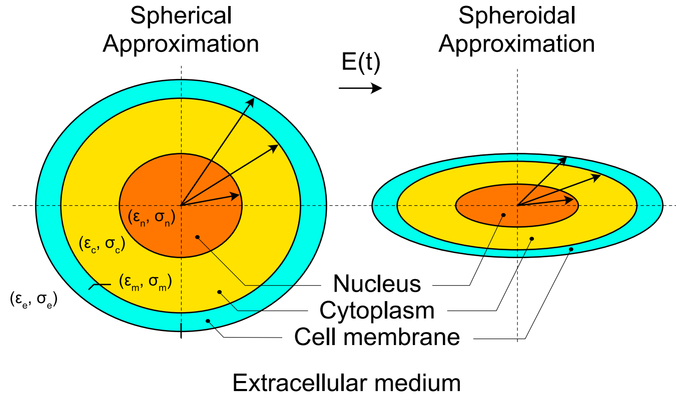

Figure 5: Multilayer dielectric models often used to analyse microbial cells in electromedical applications. Each layer is electrically characterised by (ε, σ) parameter pairs.

magnitude, which is unique to the material in question. For example, for existing field-grading materials, an approximate threshold range within 10^5 - 10^6 V/m is typical [34]. Similarly, applications in pulsed power systems, which typically operate with pulse durations in the microsecond- to nanosecond range, will experience negligible temperature increase over such short timescales. At interfaces formed between dielectrics which satisfy the above conditions, it may be appropriate to assume constant electrical conductivity, which significantly reduces the complexity of analytical modelling.

The application of such an approximation gives rise to a particular class of multi-layered dielectric models, which has seen particularly strong adoption in the fields of biophysics and bio-electromagnetics, due to the ability to arrive at closed-form analytical solutions. This is advantageous for the analysis of simple geometries resembling various microbial cells under time-dependent electric fields for PEF applications [44]. The methodology employed under this approach involves the establishment of a boundary value problem governed by the Laplace equation,

$$\nabla^2 \varphi = 0, \tag{5}$$

where φ is the scalar potential of the electric field in a domain composed of several subdomains, such as the cell model shown in Figure 5. In this approach, an appropriate coordinate system that allows for each interfacial layer to align with curves described by a single spatial coordinate should naturally be used. Each layer is characterised by a unique value of relative permittivity and electrical conductivity, forming an ideal interface with its neighbouring layers. To account for the Maxwell-Wagner effect, appropriate boundary conditions should be prescribed at each of the layer interfaces in accordance with classical electromagnetic theory. The first involves the continuity of potential at the interface:

$$\varphi_a(\boldsymbol{r}, t) = \varphi_b(\boldsymbol{r}, t), \tag{6}$$

where $\boldsymbol{r}$ is the coordinate describing the interface between layers a and b, and t is time. The second follows from the current continuity equation (2); however, in the framework of these models, it is assumed that there is zero volumetric space

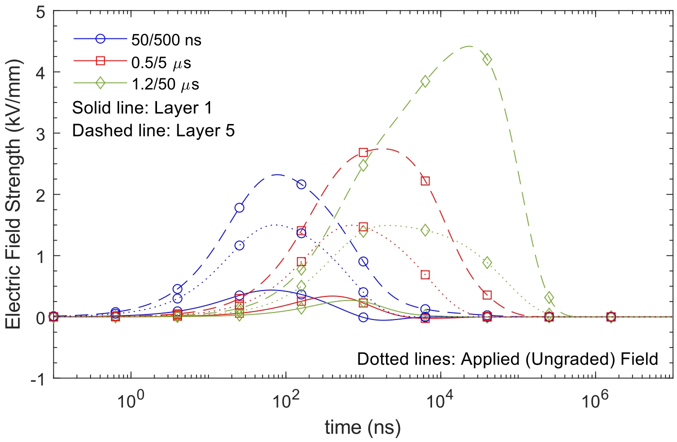

Figure 6: Transient electric field developed in a 10-layer composite graded using the model and profiles from [52], under three different voltage waveforms. The transient fields are measured near the electrodes (layer 1) and in the middle of the composite (layer 5). The peak developed field magnitude and time-to-peak is dependent on the applied signal and of the composite parameters.

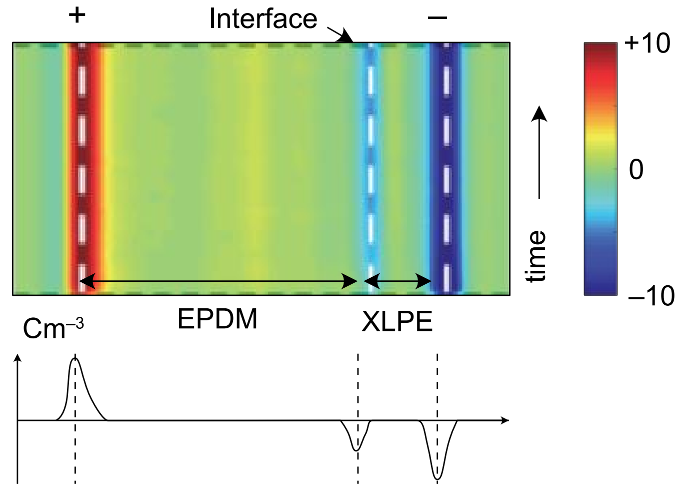

Figure 7: Typical profiles of space-charge accumulation measured using the PEA method. Image adapted from [55] which conducted experiments on EPDM-XLPE interfaces. Original image © 2021 IEEE.

charge, and only a surface charge density $\gamma(t)$ is developed at the interfaces, given by:

$$-\frac{\partial \gamma(t)}{\partial t} = \left[\vec{\boldsymbol{J}}_b(\boldsymbol{r}) - \vec{\boldsymbol{J}}_a(\boldsymbol{r})\right] \cdot \hat{\boldsymbol{n}}, \qquad (7)$$

where $\hat{\boldsymbol{n}}$ is the unit normal. The opposing field generated by $\gamma(t)$ is then incorporated as an interfacial boundary condition between each subdomain, by introducing the discontinuity into the electric displacement:

$$\left[\vec{\boldsymbol{D}}_b(\boldsymbol{r}) - \vec{\boldsymbol{D}}_a(\boldsymbol{r})\right] \cdot \hat{\boldsymbol{n}} = \gamma(t). \qquad (8)$$

By the additional application of an external potential or electrode boundary condition, self-consistent solutions for φ (hence also for the electric field $\vec{\boldsymbol{E}} = -\vec{\boldsymbol{\nabla}}\varphi$) can be found analytically for simple geometries, e.g., in [50], [51]. Using this approach, it was additionally shown in [52] that analytical solutions can be found for an arbitrary number of layers within simple one-dimensional planar and cylindrical geometries, and that there exists an upper limit to the number of layers where closed-form solutions are possible [52]. The model was applied to multilayer graded spacers in gas insulated lines under impulsive stress, demonstrating the ability to rapidly estimate the field redistribution at the gas-spacer interface, which exhibited good correlation with simulated results [52]. For applications using fast-rising signals, these types of models were able to further demonstrate the coupling effects between composite relaxation times and the signal rise time. As shown in Figure 6, the temporal characteristics of the field developed within a layered composite vary significantly, depending upon the applied signal rise and fall time, which may affect field-grading effectiveness during fast system transients, or be of importance in the development of novel pulsed-power systems. Similar models with an arbitrary number of layers were extended to axisymmetric spherical and spheroidal geometries in [53], where detailed analysis under impulsive energisation showed that the surface charge dynamics played a major role in significantly modifying the transient response of the developed intra-layer fields, resulting from the Maxwell-Wagner effect.

This approach is not without its limitations, however. In practice, space charge does not accumulate solely on the interface, for a number of reasons. Interfaces are imperfect due to factors such as surface roughness, so that locally, the electric field is highly nonuniform, resulting in space charge build-up in the form of charge trapping or charge injection near the interfacial region [54]. The use of the macroscopic approach also fails to consider atomic-scale interactions and parameters. For instance, it neglects the differing types of charge carriers undergoing various processes which may affect their mobility, or account for local inhomogeneities within the material bulk. This was made evident in numerous experimental studies reporting on space-charge measurements at dielectric interfaces, e.g., [2], [55], which showed clear spatial distributions of charge around the interfacial region, with values that often disagreed with those obtained using the Maxwell-Wagner approach. Figure 7 illustrates a typical profile of space charge at an XLPE-EPDM interface, measured using the pulsed electro-acoustic (PEA) method. Nevertheless, under conditions where the assumptions stated above are valid, or where the approximation achieved is sufficiently accurate for the application, this approach can provide rapid results, is convenient for analysis, and is not constrained by the resolution of spatial or temporal discretisation used in popular computational methods.

Anisotropic, nonlinear materials, high-field, or long-term DC steady-state conditions

Under conditions where there exists a strongly nonlinear dependency of conductivity on the electric field, or if the spatial/temporal variation of temperature is sufficiently nonuniform, the application of the assumptions made in the previous section will generally result in a significant degree of inaccuracy. Examples of particular relevance are problems within HVDC transmission, whereby the exposure of conventional extruded polymeric cables to prolonged unipolar DC conduction currents may give rise to hazardous levels of space charge inside the insulation bulk, and at interfaces [1], [2], [28], [56]. This behaviour is due to a combination of: (i) the nonzero electrical conductivity of the solid insulation, (ii) uneven heating of insulation due to joule heating, inhomogeneities, or external heating, and (iii) interfaces between the different types of dielectrics used in cable construction. Space charge not only accumulates and leads to field distortion but may also rapidly accelerate the rate of insulation degradation [57], resulting in the shorter operational lifetime of critical infrastructure. Under DC polarity reversal conditions, the sudden alignment of the applied field to the direction of the space-charge-induced field can lead to spikes in field magnitude, potentially leading to insulation failure [58], [59].

Inclusion of the $\sigma(|\vec{\boldsymbol{E}}|, T)$ dependency into the analysis adds considerable complexity to physical modelling, made even more difficult by the need for material-dependent parameters to be determined. In solids, semi-empirical relations are often used to describe these effects: an exponential relation (9) or hyperbolic sine relation (10) is used for the field dependence, while the temperature component is adequately described using the Arrhenius law, often combined like:

$$\sigma(|\vec{\boldsymbol{E}}|, T) = \sigma_0 \exp\left(-\frac{W}{k_B T}\right) \exp\left(\alpha|\vec{\boldsymbol{E}}|\right), \qquad (9)$$

$$\sigma(|\vec{\boldsymbol{E}}|, T) = \sigma_0 \exp\left(-\frac{W}{k_B T}\right) \frac{\sinh\left(B|\vec{\boldsymbol{E}}|\right)}{|\vec{\boldsymbol{E}}|}, \qquad (10)$$

where k_B is the Boltzmann constant, and σ_0, W, B and α are constants unique to the material. In liquids, Onsager [60] dealt similarly with the field-dependence of electrical conductivity, and provided corresponding techniques to estimate the relationship based on electrochemical principles. An additional layer of complexity may be introduced by the explicit modelling of the temperature, T, by considering heat conduction:

$$\rho_m C_p \frac{\partial T}{\partial t} = \vec{\boldsymbol{\nabla}} \cdot \left(k \vec{\boldsymbol{\nabla}} T\right) + S_T, \qquad (11)$$

where ρ_m is the mass density in kgm^{-3}, C_p is the specific heat capacity in Jkg^{-1}K^{-1}, k is the thermal conductivity in Wm^{-1}K^{-1}, and S_T (in Jm^{-3}s^{-1}) represents the effects of heat sources and sinks, e.g., heat influx due to joule losses, or heat outflux due to active or passive heat management.

The necessity to include these additional effects either restricts the possible analytical solutions to very basic, one-dimensional cases, which are seldom of use in practice, or often completely removes the possibility of deriving analytical solutions. Additionally, the introduction of spatially-varying parameters, e.g., temperature, which are inherently three-dimensional, further places severe limitations on the applicability of one- or even two-dimensional approximations to many practical system topologies. Fortunately, advancements in computational power have facilitated the use of numerical mesh-based methods, such as the finite element method (FEM) or finite volume method (FVM), to solve complex multi-dimensional and strongly-coupled multi-physical systems. Accessibility has been further increased with commercially-available, or various open-source frameworks, which are free to modify [61], [62]. These are a class of numerical methods which allow boundary-value problems to be solved in arbitrary geometries, given the governing equations and an appropriate set of boundary conditions, and/or initial conditions. The spatial discretisation of the domain under analysis allows the global, continuous solution of equations to be locally approximated, and when assembled, provides an approximation of the global solution with an error which decreases with the resolution of the discretisation. The generality and versatility of these methods have helped to firmly establish their place in science and engineering, contributing to their widespread usage. Studies conducted using these methods have strongly contributed to the understanding of electrical phenomena, particularly within complex geometries of practical interest.

Charge Transport Modelling

The introduction of computational modelling perhaps leads naturally into the discussion of advanced charge transport models, growing usage of which has largely been made possible only with the advent of accessible high-speed computing. These models generally aim to describe macroscopic behaviour by simulating collective atomic-scale behaviour, incorporating principles of statistical mechanics or solid-state physics. Their approach is multi-scale in nature, reflecting the multi-scalar reality as shown in Figure 3, making them among the most complex models currently in use. For composite systems with mixed phases, charge transport processes differ across interfaces, but can be combined using the above-stated computational techniques. A detailed description of these models is outside the scope of the present article, however, a brief summary nevertheless follows, since they form an unavoidable and important part of modern charge modelling techniques.

Broadly, there are two approaches: (i) particle methods, or (ii) continuum methods. Generally, continuum methods require less computational resources, and have therefore seen wider adoption and usage. On the other hand, particle methods are based on more fundamental principles, allowing the modelling of behaviours which lie outside the region of validity for continuum methods. In both cases, the main limitation to models of such complexity is the need for experimentally-determined material parameters, such that the accuracy of the simulation is then intrinsically tied to the uncertainty in the measurement. These techniques can nevertheless provide insights unattainable through experimental means, and act to confirm or refute the presence of physical mechanisms, through comparison with experimental data. Simulation models of this nature will likely become increasingly widespread with the increase in processing capabilities, and the fidelity of physical models will become far higher than ever before. Readers are referred to works such as [63]–[65] for solid charge transport modelling, [66]–[68] for gas discharge modelling, or [69] for mechanisms pertaining to ion transport in liquids.

ELECTRICAL PRE-BREAKDOWN AND BREAKDOWN

In some applications, for example, spark-gap switches [70], [71], electrostatic precipitators (ESP) [24], [25], nonthermal plasma related applications [72], [73], and plasma drilling processes [74], [75], the formation of partial (or complete) discharges are essential to system functionality. In others, namely in insulating systems, electrical breakdown is a hazard to be avoided, as its occurrence may mean the catastrophic failure of equipment, potentially leading to major economic and environmental costs. In electronic devices, the drive for miniaturisation of parts fabricated from semiconductors and MEMS, for example, make the development of electric fields approaching the breakdown field possible, despite their low operational voltages. The need, therefore, to understand pre-breakdown and breakdown processes cannot be understated, and the problem only becomes more complex when interfaces become involved. In the next three subsections, some of the basic breakdown mechanisms at solid-gas, solid-solid, and solid-liquid interfaces are treated separately.

Solid-Gas Interfaces

In the case of solid-gas interfaces, the gaseous medium is likely to have significantly lower breakdown strength than that of its solid counterpart. In consequence, the breakdown strength of the system is largely determined by gaseous breakdown processes, the fundamentals of which will not be discussed here. Noteworthy advancements, however, include the usage of drift-diffusion modelling to simulate gas discharge processes. Authors have since built upon these models by including the effects of recombination and photoionization [76], [77], nonuniform electric fields [78], [79], plasma chemistry [80], [81], and, importantly for this article, solid dielectric surfaces [82]–[84].

The inclusion of solid dielectrics to form solid-gas interfaces modifies the breakdown physics in several different ways. Primarily, field distortion and enhancement can arise due to several factors. Illustrated in Figure 8, these include:

a) Formation of electrode-dielectric-gas triple junctions, which significantly enhances the local electric field in the gas, due to the polarisation of the dielectric.
b) Possible adherence of (conductive) contaminant particles to the solid surface, which lead to local field enhancement. These areas become possible sites for discharge initiation.
c) Presence of highly divergent local electric fields at the uneven and rough surfaces of solid dielectrics, possibly leading to charge injection or local charge accumulation.

Local enhancement of the electric field is highly undesirable, acting as a likely location for electron avalanches to form. All three of the above cases can lead to the development of partial

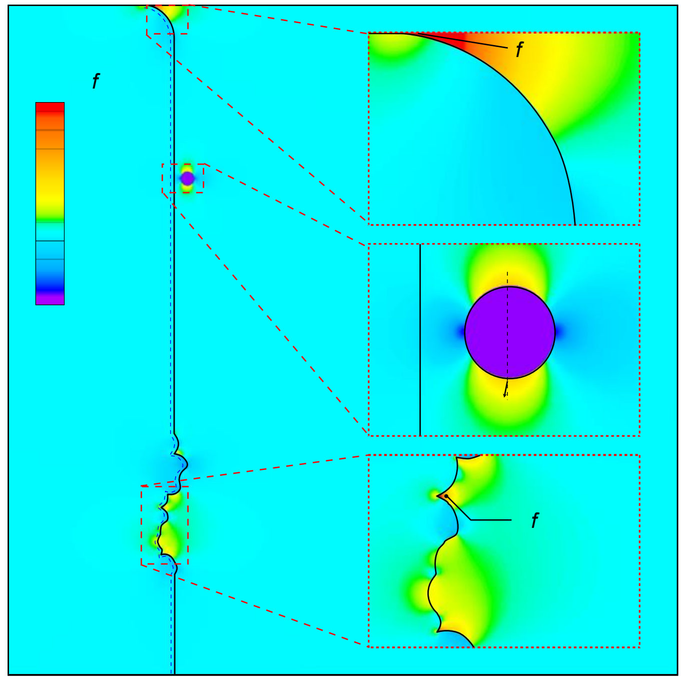

Figure 8: Illustration of some possible sources of field distortion/enhancement at solid-gas interfaces, which may impact on their dielectric strength. Descriptions given in main text.

or full discharges should the maximum local field strength exceed the breakdown threshold of the gas. The presence of solid interfaces also allows surface charge to accumulate, either through bulk conduction, or from the particle influx due to the occurrence of partial discharges in the gas. This may further contribute to local field enhancement, and as shown in [84], may facilitate or inhibit streamer discharge formation, depending on the polarity.

By modelling gas discharges, studies have additionally observed the electrostatic attraction of streamer heads toward solid dielectric surfaces [82]–[84], which then appear to induce a significant increase in propagation velocity, causing the discharge to rapidly accelerate across the surface. An example of such a simulation is shown in Figure 9 and compared to an experimental image of a spark during a flashover event. The reason for the observed behaviour can be illustrated using case (b) of Figure 8. If the sphere is instead considered as a model for the head of a streamer, one may observe that the enhanced electric field at its tip is shifted slightly toward the solid surface. Therefore, as the streamer propagates in time, it will gradually be attracted towards the dielectric, where the strength of the attraction appears to be dependent upon the permittivity of the solid material. In [85], streamers initiated from localised build-ups of surface charge on a solid surface were simulated, which were also morphologically similar to those imaged in experiments, and may explain some instances of the discharge seemingly detaching from a surface. It is likely for surface effects to also have some impact on discharge characteristics, e.g., secondary emission from the surface, photoemission, field emission, or surface chemistry. However, the ability to model

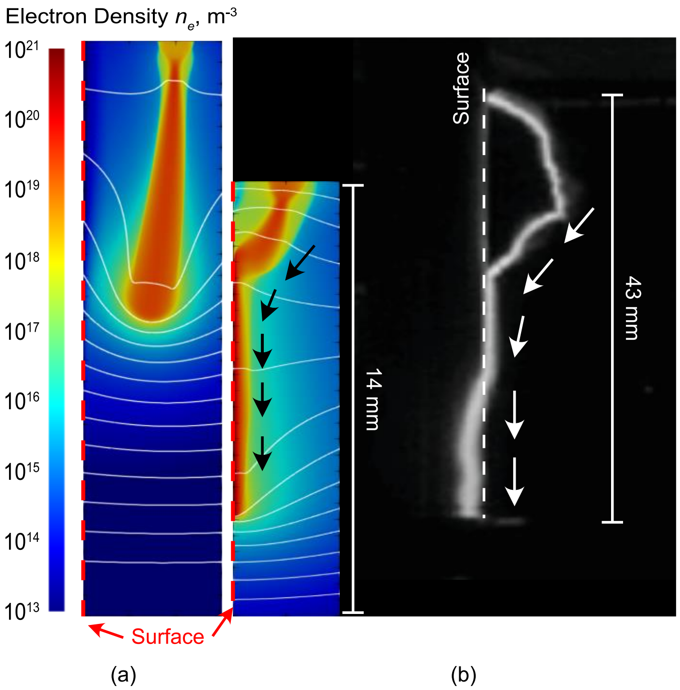

Figure 9: (a) Simulation of the electrostatic attachment of a positive streamer to a neighbouring dielectric surface in atmospheric air, adapted from [82]. (b) Comparison of a simulated surface streamer attaching and propagating across a solid surface with ε_r = 4, to the one possible breakdown path imaged experimentally in [114]. Original image © 2020 IEEE.

these phenomena is mainly limited by available data, and in turn, the availability of instrumentation capable of performing measurements of such data to be included as simulation parameters.

Streamer discharges are inherently multiscale [86], [87], stochastic, and three-dimensional processes, rendering them highly challenging to simulate. Thin geometrical features and steep field gradients near solid surfaces push computational algorithms to their very limits, while the curse of dimensionality makes three-dimensional simulations considerably more computationally expensive than two- or one-dimensional approximations. Progress has been made toward improving simulation feasibility with the advancements documented in [68], [88], or macroscopic models such as those described in [89], [90], but far more must be done if improvements upon design criteria such as the classical Meek criterion are to be made, particularly with regards to post-streamer discharge dynamics.

Solid-Solid Interfaces

Interfaces formed between two solid dielectrics have been known to reduce the tangential breakdown strength (when the dominant component of the electric field lies parallel to a connecting interface) across the insulator [4], [91], [92]. This is particularly important for undersea cable connections or terminations, where the electric field generated by the conductor core may be dominant in the direction parallel to a connecting solid-solid interface, for example, as illustrated in Figure 10. Leading theories which drive this reduction point toward the existence of microcavities, formed between the solid

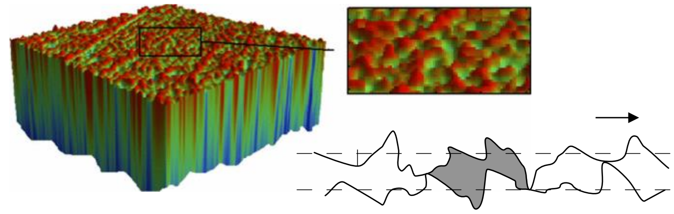

Figure 10: Optical profilometry data of a rough polymer surface, adapted from [98], and a depiction of cavities formed between similarly rough surface. Original image © 2021 IEEE.

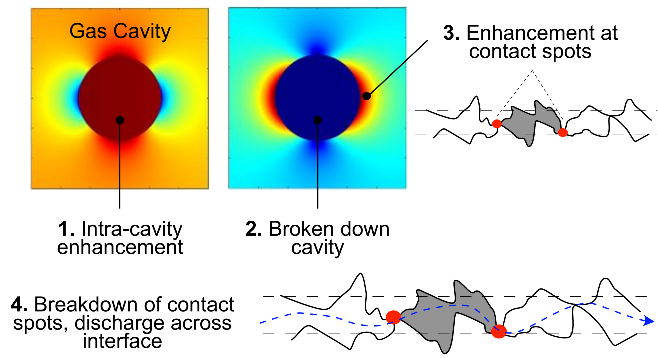

Figure 11: Simplified development of interfacial breakdown at a solid-solid interface, driven by gas discharge processes inside the interfacial cavities.

insulators due to the unavoidable surface roughness present on the contacting solids [93, 94]. A graphical depiction of these cavities is shown in Figure 10. Under dry-mate conditions (e.g., if the connection was made in air, or has not had any form of fluid penetration onto the contact), cavities will be gas-filled, and will exhibit field enhancement due to their low permittivity in comparison to the surrounding bulk solids. It is therefore suggested that the lowering of the dielectric strength is primarily due to initial discharge activity within these cavities, which eventually leads to breakdown across the length of the interface [95]. Naturally, gaseous breakdown mechanics apply, though, cavities along the interface with dimensions below 10's of μm begin to fall outside of the classical behaviour described by Paschen's law – what effect this has on the macro-scale interfacial discharge is currently unknown. The development of interfacial breakdown has been postulated to unfold following the process below (e.g., see [96], [97] and references therein). Corresponding to Figure 11:

a) Gas cavities formed at the solid-solid interface exhibit a significant degree of field enhancement, compounded by the highly irregular geometry of the rough surface.
b) As the field rises, the critical field inside the cavities is exceeded, initiating ionisation, and allowing the development of (partial) discharges inside the gas cavities, though the full interface has yet to fail.
c) The generation of space-charge raises the conductivity of the cavities and leads to field redistribution to the cavity edges, along the contact spots between neighbouring cavities.

d) With a sufficiently high field magnitude present at all of these contact spots along the interface, these eventually all break down, thereby connecting the discharged cavities in a chain along the full length of the interface.

e) A high current is able to flow through the conductive chain of connected cavities and broken-down contact spots, leading to full interfacial breakdown.

Should the cavities be filled with something other than a gas, e.g., under wet-mate conditions, water ingress, or the use of oil lubrication, the breakdown characteristics of the interface become dependent on the properties of the filling medium. If the cavities are water-filled, for example, steps (a), (b), and (c) are assumed not to take place, but rather, the high permittivity of water will immediately redistribute the field to the contact spots, and the discharge evolution begins at step (d). Step (d) also explains why the breakdown strength in direction normal to the interface is higher, as the field enhancement in such a case would be directed into the solid bulk rather than the contact spots, which possess the dielectric strength of the original (bulk) solid material. In an oil-mate scenario, experimental evidence shows substantial improvement of the AC interfacial breakdown strength [93], attributed to the higher strength of the oil itself, and of the closer match between the permittivity of the oil and that of the solid, which decreases the degree of field nonuniformity at the interface.

Further evidence of cavity-driven breakdown comes from studies on the effects of mechanical properties on the interfacial breakdown strength. The mating pressure at the contact, elastic moduli of the materials, and the surface roughness of the contacting surfaces [95], [98] affect the measured AC breakdown strength. Their effects are attributed to their respective modifications to the size and distribution of the interfacial cavities. Higher contact pressure, softer materials, and smoother surfaces lead to the reduction of average cavity size and leads to the increase of the effective contact area [93], [95], [98], giving rise to higher dielectric strength. In recent work [96], the above phenomena were consolidated into predictive models for AC interfacial breakdown, which blended approaches from the fields of tribology and high-voltage engineering to successfully provide estimates which mostly followed experimental trends. Techniques included statistical [97] and deterministic [99] models for estimating cavity distribution and average cavity dimensions, while cavity discharge voltage was predicted using Paschen's law. A review of solid-solid interfaces under AC conditions has further been conducted in [100]. Overall, the present literature emphasises the importance of material selection, avoidance of water ingress, and the dangers of losing mating pressure at solid interfaces, as they may pose a threat to the longevity of electrical equipment.

There remain unexplored avenues relating to solid-solid interfaces, for instance, under long-term steady-state DC, or fast-rising pulsed fields. Space-charge accumulation has previously been discussed and is crucial for the development of HVDC transmission. How interfacial cavities couple with charge transport and space-charge accumulation is currently unknown. Similarly, since the impulsive breakdown of solid-solid interfaces has relevance to power equipment under fast-transient stresses, for pulsed-power applications, and for the prevention of flashover in modern semiconducting devices, all would benefit immensely from the further theoretical or experimental study of solid-solid interfaces.

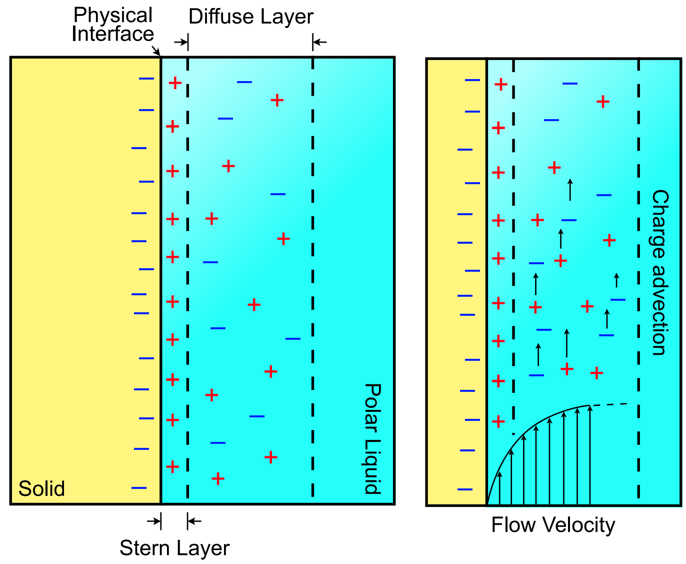

Figure 12: Depiction of electric double layer (referring to the parallel charge layers on opposite sides of the interface) at solid-liquid interfaces, and the process of flow electrification.

Solid-Liquid Interfaces

Of the interface types discussed within this article, solid-liquid interfaces are by far the least understood. This results mainly from the lack of understanding of liquid breakdown mechanisms themselves, which are complex multiphysical processes that exhibit a wide range of unexplained behaviours [101]. In the past, effort has been made to determine Paschen- or Meek-like laws for liquid breakdown, with limited success for simple (non-polar) liquids, but generally to no avail in practical polar liquids such as water, mineral oil, or esters. Intricate computational studies of significant complexity using drift-diffusion laws and fluid dynamic equations [102]–[104] have been conducted, owing to their success in modelling pre-breakdown processes in gases. However, as suggested in a review by Lesaint [101], comparison to gaseous processes should be "*made with great caution*" because of how fundamentally different the governing processes in the two media are. Leading theories for liquid breakdown involve liquid-to-gas phase change dynamics, bubble generation and expansion, impurities, contaminants, electrohydrodynamics, and electrochemical processes [39], [40], [101]. The sheer complexity, stochasticity, and difficulty of obtaining material parameters has understandably mostly limited the investigation of liquid breakdown and related phenomena to experimental characterisation.

Despite this, there exists some theoretical understanding of processes taking place at solid-liquid interfaces. Like solid-gas interfaces, similar behaviour of attachment and subsequent transition into a surface discharge has been simulated using drift-diffusion approaches [105], [106], once again predicting an increased post-transition velocity. As this effect appears to be electrostatic in nature, it is unlikely to be drastically different if more advanced modelling were to be conducted. An additional aspect unique to liquid-solid interfaces is the formation of electric double-layers (EDL) resulting from physicochemical processes which generate opposing charge layers at the interface [107], [108]. The nature of this interaction varies based upon the chemical composition of the solid and liquid pair. In the presence of fluid flow, space charge may be advected and accumulate at points of weakest flow, known as flow electrification; a process which has some significance to technologies dealing with surface treatment or energy harvesting [109], [110], and is illustrated in Figure 12. However, as previously established, long-term build-up of space-charge in insulators is potentially hazardous, and some authors believe that streaming currents generated from flow electrification may be a contributing factor to the failure of oil-cooled or oil-insulated systems [111], [112]. For a more comprehensive review of charge transport in polar liquids, readers are referred to [69].

Overall, the knowledge of composite solid-liquid insulation systems is lacking, and the current state of theoretical techniques for analysis appear to be generally insufficient due to the complexity of the processes involved. With the aging of existing oil-insulated power equipment, the push toward environmentally-friendly liquid alternatives, and the number of emerging technologies that are dependent on liquid-phase materials, the importance of further theoretical study and experimental characterisation of liquid dielectrics has never been higher.

CONCLUSION

Composite dielectric systems are everywhere, and their numbers will only grow as technology moves rapidly towards goals such as miniaturisation, higher speed, higher capacity, or lessened environmental impact. Whether dielectric interfaces are critical to functionality and performance, or manifest as an electrical failure hazard, they undeniably have a massive impact on how systems should be designed, constructed, and analysed.

In this article, a general theoretical overview of solid-gas, solid-solid, and solid-liquid dielectric interfaces has been presented, to give readers an appreciation of the variety of technologies that depend on interfacial processes, and to highlight the design issues and challenges associated with the incorporation of dielectric interfaces into engineering systems. A range of theoretical models have been described and discussed, which should provide a solid foundation for engineers and researchers to model phenomena relevant to composite insulating systems found in modern technology.

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