DIELECTRIC MATERIALS AND DEVICES

Steven A. Boggs
Electrical Insulation Research Center, Departments of Physics and Electrical Engineering, University of Connecticut, Storrs, CT, USA.

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Summary

A dielectric refers to the class of materials which are poor conductors of electricity. Such materials can be used for energy storage as in capacitors, for charge storage as in the photosensitive materials used in laser printers and copying machines, for mechanical actuation, sound generation, etc. as in materials which change their dimension as a result of an applied voltage (piezoelectrics), for transducers as in condenser, electret, and piezoelectric microphones, for detecting changes in temperature as in pyroelectrics, and as liquid crystals employed for alphanumeric displays. A wide range of other display technologies is also based on dielectrics.

In addition, dielectrics are used for electrical insulation to provide for transfer of electrical energy through electric power systems. Vacuum, gases, liquids, and solids are all used in this context. In addition, power circuit breakers have been based on gases, liquids and vacuum used as interrupting media.

The present chapter first considers dielectric materials and then devices based on such materials.

1. Dielectric Materials

A dielectric material is:

1. A material which is not used to transfer electrical energy through conduction but which can be used to transfer electrical energy through displacement current.

2. A material whose primary function depends on its inability to conduct useful electrical currents under the conditions of use.

Note that these definitions are functional. A material can be a dielectric under some conditions of use but a conductor under other conductions of use. For example, any gas can be made conducting through appropriate ionization, but can usually recover back to a dielectric after the ionizing condition is removed.

Dielectrics can have many useful properties, including piezoelectricity (dimensional change as a function of electric field), nonlinearity (change in conductivity and/or dielectric constant as a function of electric field), photosensitivity (change of conductivity or other properties as a function of exposure to electromagnetic radiation), etc. Further, dielectrics can be used to "store" charge, as in EEPROM's.

If we compare gases, liquids and solids as dielectrics, gases and liquids have the advantage of mobility, i.e., if a region of gas or liquid is "damaged" through electric field-induced degradation, it can mix into the medium and be replaced with "fresh" dielectric. This is not true of solids, where field-induced damage will accumulate to the point of eventual total failure. Gases have the advantage over liquids that conducting impurities, such as metallic contaminants, will not "float" in the medium but will fall to the bottom of the enclosure, where a low field region can be provided to render them harmless. Bulk liquids tend to be poor dielectrics because impurities can float and line up in the liquid to provide a breakdown path. The disadvantage of gases over liquids is ease of containment. A gas will diffuse out of an enclosure through any opening. Also, the density of gases is low, and they are often used at elevated pressure which brings additional difficulties in containment. The presence of a gas cannot be observed - is the enclosure full of SF_6, or has it all diffused out and been replaced with air? This question cannot be answered with simple observation as it can be for a liquid with a visible meniscus.

1.1. Dielectric Gases

When a gas is placed in an electric field, any electron which appears in the gas is accelerated in the field. If the electron can gain enough energy to knock electrons off of gas atoms or molecules and the electrons are not attached by those molecules, then the electron density will start to grow exponentially and breakdown will typically ensue.

Some gases, such as nitrogen, are nonattaching, i.e., an electron will not be attached to a nitrogen molecule (N_2). Other gases, such as oxygen, are weakly attaching (electronegative), and a few gases, such as SF_6, are strongly attaching. The advantage of electron attachment is that it converts a very light, highly mobile electron, which can pick up energy very quickly from the electric field, into a much heavier negative ion, which picks up energy from the electric field much more slowly.

The breakdown of gases is a strong function of pressure. In the range of atmospheric pressure, the breakdown electric field is usually roughly proportional to pressure. However as the pressure is reduced, the breakdown field reaches a minimum and then starts to increase as vacuum is approached. The curve of breakdown field vs the product of pressure times the gap distance between uniform field electrodes is known as the Paschen curve. The distance comes into the picture because electrons must have sufficient distance over which to multiply before a critical number is reached which creates a conducting "channel". The withstand of gases near the Paschen minimum is extremely low and can be several hundred times less than the breakdown field at atmospheric pressure. Ironically, the pressure in near space orbit, where space stations and low altitude satellites operate, is near the Paschen minimum. As a result, employing voltages above a few tens of volts is difficult without the use of heavy solid dielectric insulation. Commercial airliner power systems suffer from the same types of problems, and the maximum distribution voltage is generally in the range of 100 V.

As gas pressure is increased, the withstand field tends to become less than proportional to pressure as a result of electrode effects, i.e., microscopic roughness of the electrodes initiates breakdown, and such roughness-induced breakdown is not proportional to pressure.

The breakdown mechanism of gases varies depending on the nature of the gas (degree of electronegativity) and the polarity of the electrode from which the breakdown starts. In the case of breakdown from the negative electrode, the electrode can be the source of initiatory electrons which can accelerate in the field, generate net electron multiplication, and cause breakdown.

In the case of breakdown from a positive electrode, the initiatory electron must come from within the gas. Cosmic rays generate electrons in air at a rate of about 3 e-/cm^3-s-bar and in SF_6 at a rate of about 10 e-/cm^3-s-bar. In air and SF_6, some of the electrons are "stored" as negative ions to which the electrons are relatively weakly bound, and the ion density builds up in the gas to a value determined by field-induced migration and recombination of positive and negative ions. These negative ions are a source of free electrons under high field conditions. Once a free electron occurs somewhere close to a high field, positive electrode, the electron accelerates toward the electrode, generating photons in the process of collisions, ionization, etc. These photons move ahead of the electron cloud, creating additional electrons through photoionization, and this is the mechanism by which a conducting channel is initiated.

A small sharp "point" in a gas can cause breakdown of the entire gas gap even though most of the gap is well below the breakdown field. This occurs as a result of step-wise breakdown processes. The general idea is that corona (low energy discharge which results in relatively cool, weakly ionized gas channels) form around the point. If the field is high enough, one of these channels will covert to conducting. The mechanism by which this occurs depends on the nature of the gas. In the case of SF_6, for example, the region which fills with corona extends out to the point at which the field falls below the "critical field" (the field above which net electron multiplication occurs). This corona-filled region contains substantial numbers of positive and negative ions which separate in the field. The ion separation at the boundary of the corona region causes the field to increase. Since the field was already at the critical field, any increase in field causes the field to go above the critical field which results in a breakdown from this boundary region back to the "point" through one of the corona channels. This breakdown causes the temperature in the channel to rise to the point that the channel becomes substantially conducting. In other words, shorting of some of the electric field by the conducting channel reduces the energy in the electric field, and some of that energy heats the channel. The conducting channel now acts as a stress enhancement in the gas, and the process repeats. In this manner, a small defect can cause breakdown of the entire gap in a step-wise manner.

1.1.1. Air

Air is undoubtedly the most widely employed of dielectric materials. It is used as an insulator for overhead transmission lines which presently operate up to 800 kV, in television picture tubes and computer monitors working in the 10 kV range, and as an insulator for printed circuit boards operating at anything from a few volts to a few hundred volts.

Air has a breakdown field of about 3 kV/mm. As air is usually employed uncontained, apparatus operating in air can be in intermittent or even continuous corona. Utility apparatus takes advantage of this, and corona can often be heard from medium voltage (5 kV to 69 kV) utility apparatus on a damp morning, typically as a result of the interaction of the moisture and polluted insulator surfaces. However, utility apparatus is designed to be corona free under "normal" operating conditions, as corona activity causes electromagnetic interference, annoying noise, ozone generation, and power loss.

The ability to operate in occasional corona is a big advantage over other dielectric media in which corona activity almost inevitably results in gradual degradation of the contained dielectric medium. However, apparatus which operates in ambient air must tolerate the combination of pollution which settles from the air, varying weather conditions, and lightning induced voltage transients. This requires extended creepage distances between the high voltage electrode and ground which are usually obtained through the use of convoluted surfaces (the sheds on an insulator).

1.1.2. SF_6

Sulfur hexafluoride is the mostly widely used dielectric gas other than air as a result of its outstanding dielectric strength, ability to be decomposed without forming any conducting compounds, and its rapid recombination and de-ionization after arcing ceases. The strong electronegativity of SF_6 gives it outstanding insulating properties, with a breakdown field of about 9 kV/mm-bar compared with air at about 3 kV/mm-bar. Essentially all high voltage circuit breakers made since the 1980's (69 kV and above) employ SF_6 as an insulating and interrupting medium. In much of the world, SF_6-insulated high voltage substations are the norm, as these can be placed in the basements of buildings and take up about 10% of the area of an equivalent air-insulated substation. Such substations take the form of coaxial Al tubes, with the inner tube supported on filled epoxy insulators, and SF_6 at a pressure of about 400 kPa filling the space between the conductors. The circuit breakers in such substations are also based on SF_6. Such substations are manufactured 69 kV to 800 kV. While the breakdown field of SF_6 is about 9 kV/mm-bar, the design stress is usually about 60% of the theoretical breakdown field at the rated lightning impulse withstand voltage for pressures in the range of 400 kPa.

The primary disadvantages of SF_6 are (i) its decomposition products (in the presence of trace quantities of oxygen and moisture) are highly toxic and corrosive and (ii) it is a very strong greenhouse gas with a long persistence in the atmosphere. The corrosiveness of SF_6 decomposition byproducts, primarily the result of HF formation, means that SF_6-insulated systems cannot operate with appreciable amounts of corona. As a result, the design rules for SF_6-insulated apparatus must differ from those used for nitrogen or air-insulated apparatus.

1.1.3. Vacuum

Vacuum is, of course, not a gas but the absence of matter. At very low pressures, the Paschen curve rises as a perfect vacuum is approached. As a dielectric medium, vacuum is used in x-ray, CRT (Cathode Ray Tube), and other "vacuum" tubes, in medium high voltage (5 to 35 kV) vacuum circuit breakers, etc. Because charges can accelerate very rapidly in a vacuum, x-ray emission is an issue. Breakdown can occur along dielectric surfaces as a result of secondary electron emission. Vacuum dielectric technology is a field unto itself, not strongly related to other dielectric technologies.

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Biographical Sketch

Dr. Steven Boggs is a Research Professor of Materials Science, Electrical Engineering and Physics as well as Director of the Electrical Insulation Research Center at the University of Connecticut, as well as an Adjunct Professor of Electrical Engineering at the University of Toronto. Although educated as a physicist and awarded his Ph.D. for a thesis on Quantum Diffusion in Solid Hydrogen, Dr. Boggs has over 20 years experience in managing and conducting research and development for the electric power industry. While employed in the Research Division of Ontario Hydro in the late 1970's, Dr. Boggs led development of the first product to be licensed by EPRI. In the late 1980's, he proposed and led a multimillion dollar EPRI project related to the reliability of solid dielectric castings for which ASEA, Brown Boveri, Alsthom, Siemens, the Technical University of Denmark, and the University of Connecticut were subcontractors working under his direction. He has led numerous utility-sponsored R&D projects and surveys of user experience. Dr. Boggs has developed a new design for high voltage cable terminations under EPRI sponsorship for which a patent has been granted, developed analytical models for various economic and technical aspects of high temperature superconducting (HTS) cable from which he conceived the room temperature dielectric HTS cable design which is presently under development by EPRI. Dr. Boggs is an expert at high voltage design through the use of such tools as finite element field analysis. In collaboration with one of his graduate students at the University of Toronto, he recently developed a finite element programs for solution of transient nonlinear field problems with coupled electric and thermal fields. He also holds an MBA and has experience conducting economic analyses including the application of the EPRI TAG™ protocol. Dr. Boggs has been elected a Fellow of the IEEE for his contributions to SF_6-insulated substation technology.