

Ceramic dielectrics for space applications

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Ceramic materials play a vital role in space-related systems such as satellites, space-borne weapons, etc. The behaviour of ceramic dielectrics in space, particularly under electric field, is known to be different from that in earth. The present article presents a brief overview on ceramic dielectrics in space and the factors associated with the performance, with particular reference to surface electrical discharge.

Introduction

ADVANCEMENT in space research and development programmes has led to several benefits to mankind, e.g. faster/accurate communications and weather forecasting, through space satellites. Since the space programmes are realized to offer several benefits, many countries, particularly the developed nations, have expanded their space R&D activities many folds in all the disciplines. Presently, the major discipline that receives more attention is materials science and engineering, in which two categories of space R&D efforts are being made around the world: (a) processing or development of materials that are suitable for space applications, and (b) processing of materials in space environment itself as it differs vastly from that of the earth due to microgravity and vacuum. A major task involved in the design of any space-related equipment or system is the combination of compactness and light weight and, hence, the same is considered from the component/device levels. As the ceramic materials are generally known to offer the desired combination of one or more properties, i.e. mechanical, thermal and electrical/electronic properties, they receive more attention in almost all engineering/technology disciplines that are related to space. Among the ceramic materials, the dielectric materials are known to play vital roles in any space-borne systems (e.g. satellites). However, the ceramic dielectrics used in electrical/electronic circuits are found to display poor performance under space environments. A brief overview on the ceramic dielectrics in space-related applications and the problems associated with the same are presented in this article.

Ceramic space-dielectrics

The performance of components/devices used in the electrical or electronic circuits are expected to be better in

space compared to that on the earth. This is primarily because of the fact that the components, devices or circuits are, in general, surrounded by a good insulating/dielectric medium (i.e. vacuum) in space. Although space is known to be the best dielectric in the universe, the solid dielectrics display poor performance in space, particularly when subjected to medium to high electric field. The poor performance of the dielectric is believed to be due to the electrostatic charging that could lead to the failure of dielectrics, which in turn minimizes the reliability of electrical/electronic circuits of the space satellites. The electrostatic charge formation essentially causes high electric field formation within the dielectric, leading to electrostatic discharge. More than 90% of such discharges are found to occur along the dielectric surface. Hence, the electrostatic discharge along the dielectric surface is believed to be one of the major factors that impedes the exploitation of several technologies in space applications: (i) high voltage pulsed power systems, (ii) lasers for electric drive systems, (iii) particle beam technology and (iv) electrically driven kinetic energy weapons, etc. to name a few. Besides, more emphasis is given recently on miniaturization of components/devices such as sensors, actuators and controls, i.e. smart sensors or smart materials, and packaging of all in a single entity, smart structures, which essentially results in small size and light weight. A wide variety of dielectric materials are used in the smart sensors and structures. The smart structures, known as micro-system technology, essentially exploit various physical properties of ceramic dielectrics such as piezoelectric, ferroelectric, electrostrictive and magnetostrictive, etc. The driving force for some of these dielectrics is the electric field. The involvement of electric field in the miniaturized dielectrics may lead to electrostatic charge build-up in space.

Surface electrostatic discharge

As stated earlier, the ceramic dielectrics are expected to perform better in space, compared to other dielectric media. This is primarily because vacuum/space is known to be the best dielectric and the electrical withstand strength (i.e. breakdown) is more than 300 kV/cm and the bulk breakdown strength of a ceramic dielectric (e.g. alumina) is known to be ~ 250 kV/cm. However, the breakdown strength of a composite system (i.e. alumina in vacuum) is reduced by a factor of 3 to 5 compared to

the individual component's withstand level (i.e. vacuum or alumina). The premature failure of the composite system is attributed to the electrostatic discharge along the dielectric surface. Earlier, investigations on the dielectric failure along the surface were directed towards electrophysics¹ and until the early 1990s the materials science aspect did not receive adequate attention.

The electrostatic charge build-up along the surface of any dielectric, under electric field, usually originates from the interaction of electrons with the dielectric surface. Initially, the electrons, emitted from the cathode by field emission process, are accelerated by the electric field near the cathode as shown in Figure 1. The interaction of field emitted high-energy electrons with the dielectric surface causes electrostatic charge formation. The nature/type and magnitude of the electrostatic charge largely depend on the secondary electron emission characteristics of the dielectric surface. The ceramic dielectrics would be charged negatively during the interaction of higher energy (> 10 keV) electrons. In other words, the secondary electron yield of dielectrics at higher energy electron interaction is less than 1 as shown in Figure 1 (inset). The negative charge formation on the ceramic dielectric surface is essentially attributed to the phenomenon of electron trapping in defect centres. The type and concentration of surface defects are in turn affected by the surface properties, which are usually characterized through (a) surface roughness/finish, (b) surface residual stress, and (c) surface microstructural and lattice damages. The author has already demonstrated the influence of the above surface parameters on the electrostatic discharge behaviour of ceramic dielectrics elsewhere². In order to establish the relationship between the charge accumulation and the electrostatic discharge, an experiment is simulated by using a scanning electron microscope (SEM)³.

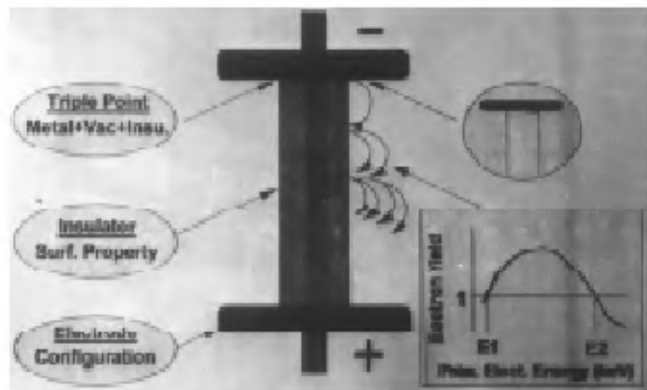


Figure 1. Secondary electron emission avalanche process. (Inset) Secondary electron yield of a dielectric.

Electrostatic discharge in SEM

It is well known that examination of an insulating solid by the SEM usually requires a thin conducting coating on the surface to avoid any spurious charging effect. The charging effect is primarily dictated by the secondary electron emission yield (δ). Under normal SEM operating conditions (i.e. > 10 keV beam), the δ of the insulators is usually less than unity, an indication that the electron bombarded surface is negatively charged. The extent of

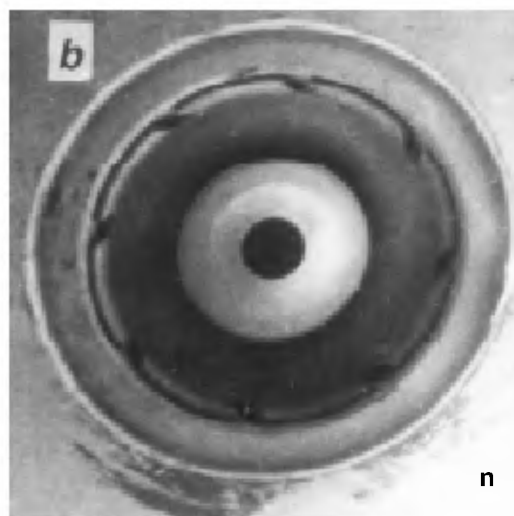
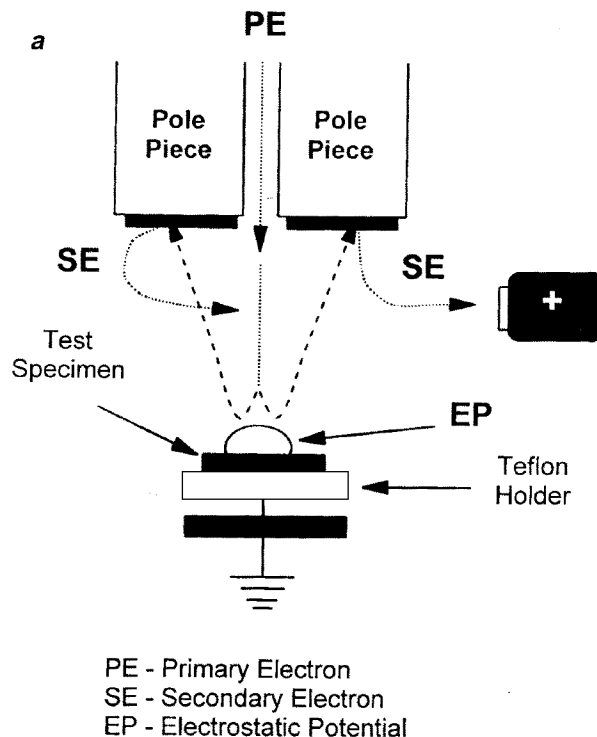


Figure 2. *a*, Electrostatic mirror image formation in SEM; *b*, Electron mirror image of SEM pole piece.

charging is directly related to the concentration of defects that act as electron trapping centres. The electron-bombarded surface would therefore exhibit an electrostatic negative potential within the vicinity of the charged region that repels the electrons. Note that the electrostatic charging of dielectric in SEM is similar to that of the dielectric charging under electric field where the electrons are emitted from the cathode.

After a thorough cleaning and drying of the insulator surface, the dielectric specimen is fixed firmly on an insulating (e.g. Teflon) holder and placed in the SEM. The purpose of the insulating holder is to isolate the specimen from the ground metallic stub used in SEM. After evacuating the specimen chamber, the insulator surface was bombarded with high-energy electrons (10 to 15 keV beams) for 3 min in spot mode to charge the desired location negatively. After 3 min exposure, the e-beam is turned off and subsequently, the charged region is probed with low energy beam (< 2 keV beam) in normal/spread mode. The low energy electrons would obviously be reflected at the charged region due to the repulsive force and do not interact with the insulator surface as shown in Figure 2 *a*. The reflected electrons would in turn impinge the components of the SEM, predominantly the

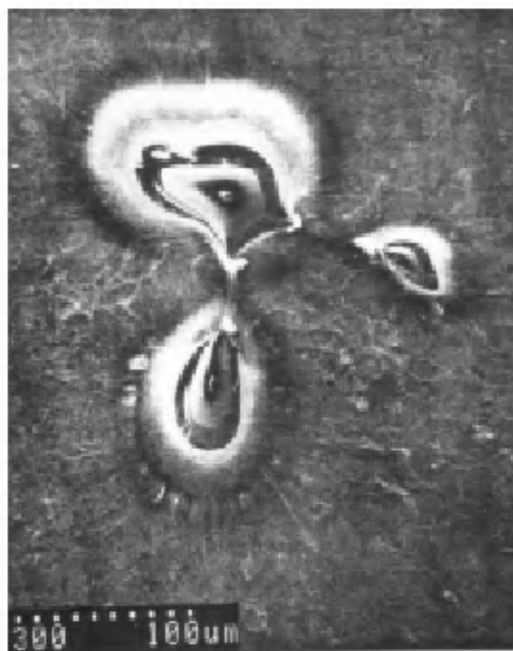


Figure 3. Fragmentation of charged region under high-energy electron interaction.

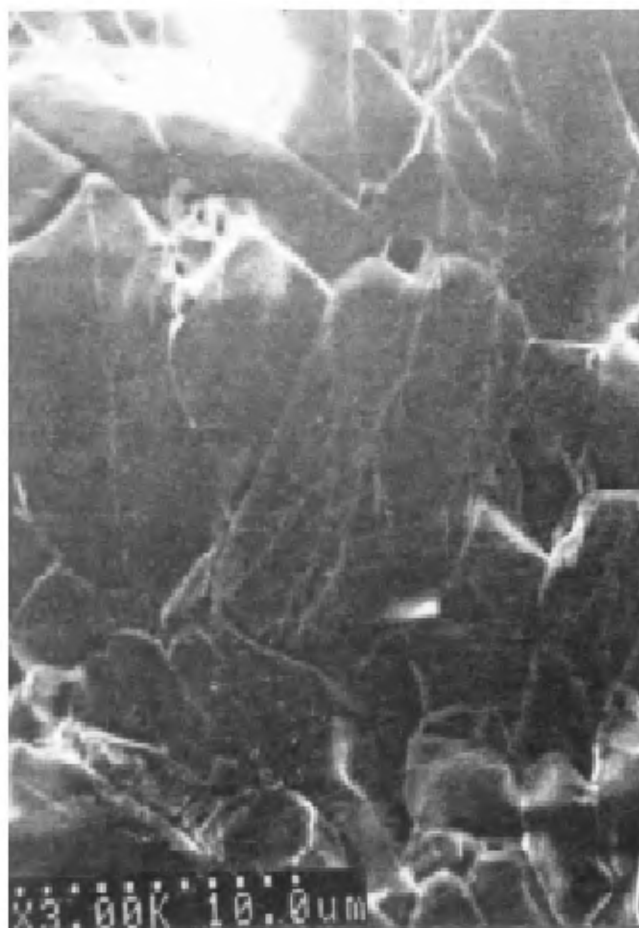


Figure 4. Tree-like discharge pattern along the surface of dielectric.

pole pieces³. The interaction of the reflected electrons with the pole pieces essentially produces secondary electrons that are detected by the secondary electron detector, resulting in the formation of a pole piece image instead of insulator surface. A typical pole piece image obtained using alumina ceramics is shown in Figure 2 *b*. In order to understand the stability of the negatively charged region, the energy of the probing beam is increased in steps of 1 keV. The stability of the charged region is judged based on the mirror image. Interestingly, as the energy of probing beam is increased above 5 keV, distortion in the pole piece image is observed. Further increase of beam energy resulted in fragmentation of the charged regions as evidenced in Figure 3. Around 8 keV, the pole piece image could not be formed. Instead, the surface is found to charge again as before, an indication that the charges were de-trapped by the high-energy electrons. In order to confirm the above view, the charging of the dielectric was repeated in spot mode as before. However, the energy of the probing beam was increased to 20 keV. Interestingly, as soon as the high-energy beam is turned on a bright flash is observed near the region where the charges are implanted. The flash is essentially due to the rapid discharge/de-trapping of charges. Figure 4 evidences tree-like pattern of the discharge near the region where the flash is observed.

The SEM simulation of electrostatic discharge suggests that the charge accumulation and discharge of the same, caused by the electron interaction, is responsible for the

dielectric failure in space environments. However, it is important to note that the above simulation is performed in vacuum, which is one of the major features of space. The study under microgravity condition is yet to be performed to establish the phenomenon unambiguously. As the energy of the electron involved in the bombardment is very high, the effect observed in vacuum is believed to be nearly the same in space environment that involves both vacuum and microgravity.

Conclusion

The electrostatic charge accumulation is one of the major problems associated with the application of ceramic dielectrics in space. The dielectric failure is believed to be due to the electrostatic charging and discharging phenomena, caused by the interaction of high energy electrons with the dielectric surface. The increased reliability of ceramic dielectrics for space applications could be achieved by reducing the concentration of surface defects, which in turn reduces the charge accumulation. The investigation, however, is to be extended to the microgravity environment.

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