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The use of SEM to investigate the effect of an electron beam on the optically-visible flashover treeing of MgO ceramic

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Abstract This paper introduces the use of a scanning electron microscope (SEM) to evaluate the insulation property of insulators under electron bombardment. An SEM may be used not only to observe a surface image but also to provide a fine electron beam for charging an insulator surface simultaneously. The distribution of electric field created by the surface charging can be developed by a simple model. The increase of electric field at the surface may exceed a critical value to experience a surface breakdown/optically-visible flashover. The insulation property is evaluated by measuring the period of charging/electron bombardment, which is needed to initiate a treeing-formation (hereinafter time to flashover treeing/*TTF*). In this paper, under a 25 keV primary electron beam energy and for a magnification of 5000×, a 99.95% purity polycrystalline MgO specimen resulted in 7 min *TTF*. It was also observed that increasing the primary beam energy and the SEM's magnification decreased the TTF. Therefore, at for a given energy and magnification, this method can be used to evaluate the insulation property of insulators under an electron beam environment.

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Introduction

The ability of insulators to withstand high voltage is of great importance knowledge in modern technology. The phenomenon that involves surface charging, discharging and flashover (surface breakdown) may damage the instrument and lead to material degradation. The flashover mechanism has been studied for many years, and it is believed that a flashover is initiated at a triple junction of metal, insulator and vacuum [1]. On the other hand, a number of experiments [2–5] have stressed the role of surface charging that lead to a flashover. In later theories, electron bombardment is often used to make charge accumulation on an insulator surface. Balmain [4] observed subsequent breakdown on the electron flux irradiated specimen by measuring the specimen peak current. This method was used to evaluate the surface discharge property of Kapton, Milar and Teflon. He proposed that the incubation of an accumulated charge at submerged layer may lead to the occurrence of a discharge (flashover). Later, Le Gressus [5] observed optically-visible flashover (tree-like structure) when a wide-band-gap polycrystalline Y_2O_3 sample was first charged with a 30 keV beam and then discharged with a low beam energy of 3 keV. The accepted idea of this observation is that the flashover is due to the space charge destabilization under low energy electron irradiation. Since an SEM can produce a controlled electron beam, research utilizing the beam to produce a measured optically-visible flashover treeing for material characterization has been left unexplored so far.

In the current work, the effect of increasing the period of scanning on an insulator surface leading to optically-visible flashover treeing (hereinafter as *TTF*) was studied. It was reported [6] that a *TTF* of 7 min was measured for 30 samples of 99.95% purity polycrystalline MgO during

evaluation in an SEM with 25 keV electron beam energy, 25 mm work distance, 200 μm diameter of final aperture, 5000× magnification and 0° tilt angle. In order to obtain additional information concerning the applicability of using this method for insulator characterization, the following sections present a model of electric field distribution on a rectangular charged area created by scanning the incident electron beam in the SEM. The model is then used to explain a flashover treeing mechanism. The effect of primary beam energy U_0 and magnification (which defines the charged area) on *TTF* are also given. These data are essential in order to select the appropriate SEM's operating conditions for further observation on doped MgO ceramics.

Experimental procedure

Samples were prepared from 0.15 g of fine 99.95% purity MgO powder less than 1-micron diameter. The powder was then pressed into a disk of 10 mm diameter at the pressure of 200 MPa. The green samples of MgO were sintered at 1,650 °C for 7.5 h. Prior to examination in the scanning electron microscope (SEM JEOL T220A), the most of the sample surface was metal-coated with the exception of a small-uncoated area of 500 μm in diameter at the center. Silver paste was used to mount the sample onto the sample holder. The sample was placed inside the SEM vacuum chamber (4×10^{-7} Pa). The SEM's operating conditions (200 μm diameter of final aperture, 0° tilt angle and 25 mm work distance) were kept constant during the experiment. A video camera was connected to the SEM for recording the charging process and measuring the *TTF*. The experiment was initially conducted on a sample with a 25 keV electron energy and at a magnification 5000× (charged area 27×36 μm^2). Additional experiments were also performed at different accelerating voltages and magnifications to observe the effects of primary beam energy and charged area on *TTF*. In this stage, the experiments would be extremely time-consuming, so that the number and ranges of the parameters selected would have to be limited. Therefore, it was decided to select only high accelerating voltages and magnifications to permit the measured *TTFs* in a reasonable time. Thus from the selected voltages and magnifications, if a flashover would not appear up to 50 min the test should be terminated.

Results and discussion

Figure 1 shows the process of appearing a visible-optically flashover treeing (tree-like structure) on a surface of 99.95% purity MgO sample. The tree is initiated from a scanned area edge and propagates towards the centre. This phenomenon can be explained as follows. When the incident electron beam in the SEM scans a sample, the primary energetic electrons interact with the sample surface and form a rectangular charged area. The electron-sample interaction causes backscattered and secondary electrons emission. By extending the period of scanning, the scanned area experiences an accumulation of charge, which results in raising its surface potential or electric field. The electric field E at any point $P(x,y)$ can be deduced from its component dE. Taking into account a contribution of a charge element dq of a small strip dr_xdr_y at a point (x_q, y_q) and by applying Coulomb's law, the field component d$E(x, y, t)$ is given in Eq. 1.

$$\mathrm{d}E(x,y,t) = \frac{1}{4\pi\varepsilon}\frac{\mathrm{d}q}{r^2} = \frac{1}{4\pi\varepsilon}\frac{\rho(t)D\mathrm{d}r_x\mathrm{d}r_y}{r_x^2 + r_y^2} \tag{1}$$

where $\rho(t)$ is a time dependent charge density of the rectangular charged area, D is a depth of the electron beam impinges the surface and r is the distance between P and the charge element where $r_x = x–x_q$ and $r_y = y–y_q$. The charge density $\rho(t)$, as given by Cazaux [7], is

$$\rho(t) = \frac{J_0\delta}{D}t \tag{2}$$

where J_0 is the current density at the surface and δ is secondary electron emission constant and is defined as

$$\delta = \frac{n_{\mathrm{SE}}}{n_{\mathrm{B}}} \tag{3}$$

where n_{SE} is the number of secondary electrons emitted from a sample bombarded by n_{B}, and J_0 is given by [8] as

$$J_0 = J_c U_0 \alpha^2 k^{-1} T^{-1} \tag{4}$$

where

J_c: emission current density (A/m^2)

U_0: electron beam energy (keV) = eV_0; e: electron charge = 1.60219×10^{-19}C, V_0: accelerating voltage (Kv)

a: beam divergence at final aperture

k: Boltzman constant = 1.38062×10^{-23} JK^{-1}

T: operating temperature of tungsten (K)

The emission current density, J_c is expressed by Richardson equation:

$$J_c = A_c T^2 \exp(-U_w/kT) \tag{5}$$

where A_c = 120 A/cm^{2}K^2 is the constant for all thermionic emitters and U_w is the work function of the filament material.

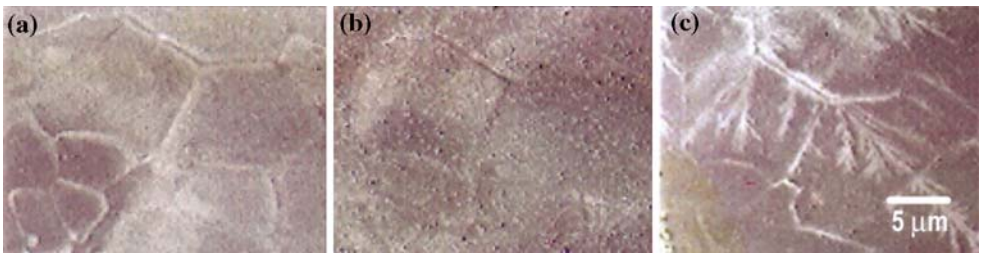

Fig. 1 Flashover treeing produced at the surface of a high purity polycrystalline MgO. The sample was charged by an incident electron beam of 25 keV at a magnification of 5000×. The extended period of charging (i.e. time to flashover treeing) was about 7 min. (**a**) shows start charging, (**b**) charging process and (**c**) optically-visible flashover treeing

By integrating Eq. 1 over all strips composing the scanned area, the distribution of electric field results in Fig. 2. The electric field takes its highest value at the edge of the scanned area, reduces outward from the scanned area and gets to be zero at the center. Further increases in the period of charging may lead to surface breakdown. Though the secondary electron emission constant at primary beam of 25 keV has not been reported, it might be predicted [9] to be greater than 1. This means that the charging can be expected to be positive. The distribution of electric field gives its highest value at the edge of the scanned area. Consequently, more electrons, which consist of secondary and field-emitted electrons, will be accumulated at the edge region. Therefore, the subsurface region around the edge behaves as a positive electrode and the subsurface region around the center as a negative electrode (less positive charge). On the other hand, the region above the edge behaves as a negative electrode and the positive one at the center because of the less negative charge. When the potential difference between the edge and the centre reaches a critical value, some of the electrons from the edge region will be accelerated towards the centre. The accelerated electrons impact upon the surface producing additional electrons by tertiary emission. Some of these tertiary electrons will again strike the surface producing second-tertiary electrons. Continuation of this process results in a cascade along the surface that develops into a tertiary electron emission avalanche. This avalanche, in turn, can lead to a complete breakdown. Some of these electrons will be detected by the Everhart-Thornley (E-T) detector and form an image as an optically-visible flashover treeing.

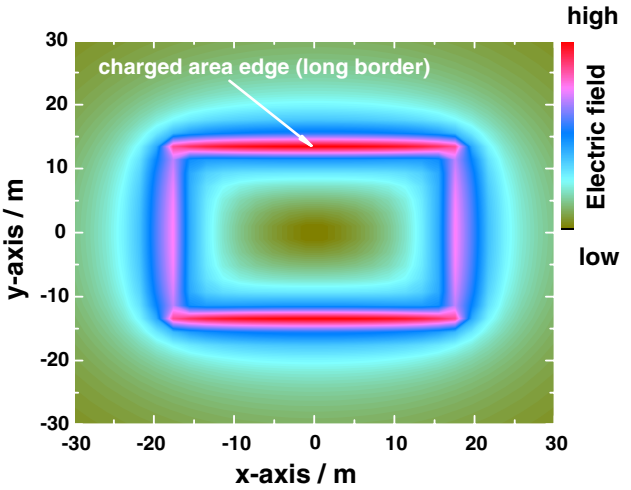

Fig. 2 Electric field distributions for a scanned area of 27 × 36 μm^2 (magnification 5000×). The electric field takes its highest value at the edge of the scanned area, reduces outward from the scanned area and gets to be zero at the center

Figure 3 shows the possibility of treeing initiation and propagation. The initiation of a flashover treeing initiated from the four possible regions where the electric field has the highest value: (1) a grain boundary of the long edge of the rectangular scanned area, (2) at a grain of the long edge, (3) at the grain boundary of the short border, (4) at the grain of the short edge. Observations were obtained for 30 identical samples of 99.95% polycrystalline MgO [10]. The number of treeing initiation events from the long edge grain was found to be 1.4 times higher than that from short one, and 1.6 times higher at grain boundary at the same region. These results show that the treeing tends to be initiated more easily from the long border region. This result agrees with the above electric field analysis that the region at the middle of long edge has the shortest distance to the center and is the critical place for the initiation of a treeing event. It is also clear that the number of treeing initiation events at the grain boundary is higher than that within the grain. It is known that grain boundaries generally contain higher concentration of contaminants than the grain. Therefore, it can be considered that the grain boundary at the long edge of scanned area would be the most critical place of treeing initiation.

Figure 4 shows the relationship between primary beam energy and *TTF*. *TTF* tends to increase with lower electron beam energy. For the selected primary beam of 30, 25 and 20 keV, the average *TTF* was 6, 7 and 9 min, respectively. However, it was difficult for flashover treeing to occur at

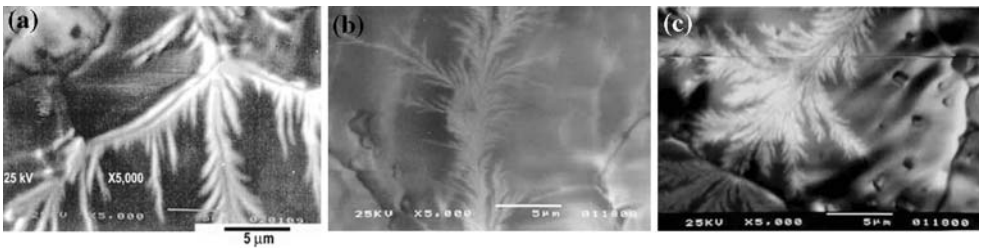

Fig. 3 Some possibilities of treeing initiation at the surface of high purity polycrystalline MgO under 25 keV electron beam energy. (**a**) and (**b**) show two kinds of treeings initiated at a grain boundary of long border of scanned area edge, and at grain for (**c**)

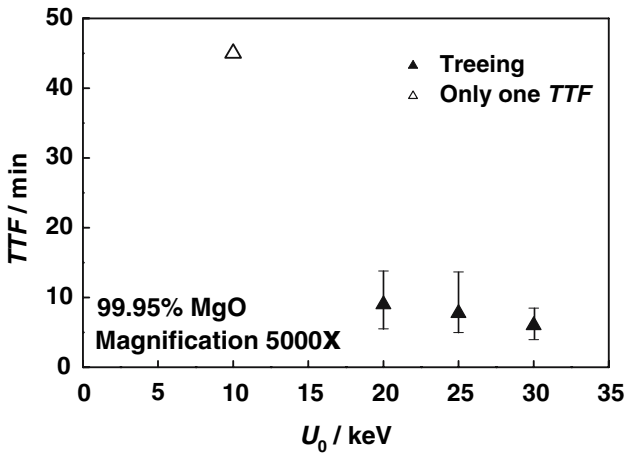

Fig. 4 Time to flashover treeing versus primary beam energy. The low beam energy might cause the primary electrons can not impinge the surface due to the surface potential and results in the difficulty to make a flashover treeing

low primary beam energy. From 10 investigated samples the only one *TTF* of 45 min was recorded (see an open triangle in Fig. 4). One reason of this is the other *TTF*s might be over 50 min, or the electric field created on the specimen surface at low accelerating voltages may not exceed the critical value to initiate flashover treeing. The effect of varying charge area by changing the magnification of the SEM on *TTF* at 25 keV primary beam energy was observed. Increasing the area may increase the extended period of scanning to perform a treeing (Fig. 5) measurement. From the selected magnifications, the measured *TTF*s were in a reasonable time. These data are important prior to evaluate insulation property to withstand flashover of an insulator. Therefore, for an example, the primary beam energy of 25 keV and the magnification of 5000× may be selected as the optimum SEM's parameters to evaluate doped MgO ceramics. Thus the *TTF* of the doped MgO ceramics may occur in around 7 min.

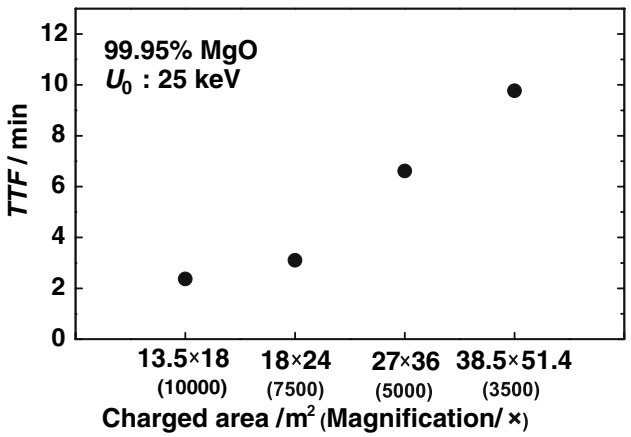

Fig. 5 Time to flashover treeing versus charged area (SEM's magnification)

MgO is a wide band gap insulator (8 eV). Elemental additions (dopants) might change the insulation property of MgO. Due to its high secondary electron emission constant, this material is important in electronic applications such as a protective layer in plasma display panels. In order to have a better protective layer, the doped MgO ceramics could make a surface discharge easily or in another word the *TTF* should be less than 7 min. In addition, for space technology application as an insulator, MgO could be used to protect devices from discharge appearance under space irradiation. In this case, the dopants should cause the *TTF* greater than 7 min.

Conclusion

It has been demonstrated that an SEM can be used not only to image but also to produce an optically-visible flashover treeing on the high purity (99.95%) polycrystalline MgO. The treeing appearance is attributed to the limitation of the sample surface to withstand electric field created by extending period of scanning/charging. It was found that *TTF* of 99.95% MgO was 7 min when its charged-area of $27 \times 36\ \mu m^2$ was bombarded by 25 keV electron beam energy. *TTF* is also varied by changing primary beam energies and magnification. It can be predicted that *TTF* of MgO ceramic might be changed by material addition. Since MgO is an important material for applications, lowering or increasing *TTF* of MgO by material addition should be studied.

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