International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:3, No:5, 2009

Modeling Electric Field Distribution on Insulator under Electron Bombardment in Vacuum

A.G.E. Sutjipto, Jufriadi, R. Muhida, Afzeri, and E.Y. Adesta

***Abstract*—**Charging and discharging phenomenon on the surface of materials can be found in plasma display panel, spacecraft charging, high voltage insulator, etc. This report gives a simple explanation on this phenomenon. A scanning electron microscope was used not only as a tool to produce energetic electron beam to charge an insulator without metallic coating and to produce a surface discharging (surface breakdown/flashover) but also to observe the visible charging and discharging on the sample surface. A model of electric field distribution on the surface was developed in order to explain charging and discharging phenomena. Since charging and discharging process involves incubation time, therefore this process can be used to evaluate the insulation property of materials under electron bombardment.

***Keywords*—**Flashover, SEM, Electron Bombardment, Electric Field.

I. Introduction

MATERIAL behavior under stress up to failure conditions is an important issue due to the development of new and high performance materials to meet a wide variety of industrial needs. In harsh environment such as high lightning strike density [1] the reliable insulator for overhead high voltage transmission line is needed. In space technology, it was reported [2] that materials under space radiation for large power applications need to be developed for spacecraft and space station. In an electrostatic separator, it was [3] shown that materials under electron beam bombardment to prevent breakdown are needed. These entire situations are considered to be very severe to the insulation since they may cause a material failure when the field stress exceeds a critical value.

Studies and models for electron-irradiated insulators have been reported intensively by Sessler, et al. [4] and Liu et al. [5] and references therein. The phenomenon that involves surface charging, discharging and surface breakdown (flashover) 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 [6]. On the other hand, a number of experiments [7-11] 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 and Hirt [9, 10] 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 materials. They proposed that the incubation of an accumulated charge at submerged layer may lead to the occurrence of a discharge (flashover). Later, Le Gressus and Blaise [11] 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 a scanning electron microscope (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. Sutjipto et al. [12] investigated the effect of electron bombardment on a measured optically-visible flashover treeing (tree-like structure) for a high purity polycrystalline MgO ceramic. Fig. 1 shows a treeing appeared after about 7 min (hereinafter as a bombardment-time to flashover treeing or *TTF*) of 25 keV electrons bombardment. It was considered that a flashover treeing may happened when the electric field at the surface exceeding a critical value. The increase of electric field is proportional with bombardment-time [13, 14]. It was also found that the *TTF* was reduced to 3 min after the material was exposed in air for three days. Therefore, it can be considered to evaluate surface breakdown property of an insulator by using energetic electrons produced in an SEM [15-18]. However the phenomenon of the appearance of optically flashover treeing has not been explained in detail. This paper gives the explanation about the origin of flashover based on the distribution of electric field on an insulator surface under electron beam bombardment by employing a scanning electron microscope.

II. Electric Field Distribution under Electron Bombardment

When an incident electron bombards an insulating material, it causes the emission of secondary electrons. Secondary

A.G.E. Sutjipto, Afzeri and E.Y. Adesta are with the Dept. of Manufacturing and Materials Engineering, International Islamic University Malaysia, Kuala Lumpur 53100, Malaysia (phone: +60361964541; fax: +60361964541; e-mail: agus@iiu.edu.my).

R. Muhida is with the Dept. of Mechatronics, International Islamic University Malaysia (e-mail: muhida@iiu.edu.my).

Jufriadi is PhD student with the Dept. of Manufacturing and Materials Engineering, International Islamic University Malaysia.

electrons are electrons which are ejected from the sample during electron beam bombardment. The total secondary electron emission yield δ is given by

$$\delta = \frac{n_{SE}}{n_B} \tag{1}$$

where n_{SE} is the number of secondary electrons emitted from a sample bombarded by n_B. When δ is greater than one, the sample surface becomes positively charged. Secondary electrons are generated from a shallow escape depth of D. The electrons are produced along the entirely of the beam electron trajectories within the specimen. The thickness, D, of this region is not well known, but is less than about 50 nm for insulator [19].

When a scanning electron microscope is used as a source of energetic electrons, a rectangular charged area will be formed. This study begins by evaluating the field created by such a model of rectangular charged area (thickness D, length L, wide W, and charge density ρ) in an infinite medium of dielectric constant ε. The study evaluates only the field for that in the direction parallel with the surface since this component plays important role in the surface breakdown.

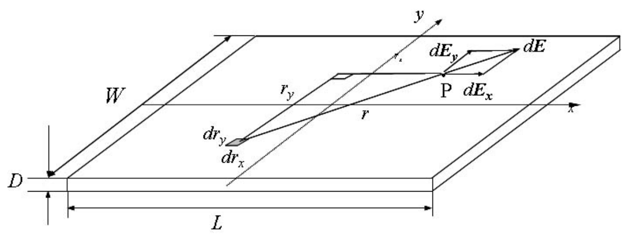


Fig. 1 Model of a rectangular charged area

Fig. 1 shows the model of a rectangular charged area. The electric field at any point due to a group of point charges is found by *(a)* calculating the potential E_i due to each charge, as if the other charges were not present, and *(b)* adding the obtained quantities as

$$\mathrm{E_i}(x,y,z) = \sum_i E_i = \frac{1}{4\pi\varepsilon}\sum_i \frac{q_i}{r_i^2} \tag{2}$$

where q_i is the value of the ith charge and r_i is the distance of this charge from the point P (the point at the area at which E is to be calculated). If the charge distribution is continues, rather than being a collection of points, the sum in eq. (2) must be replaced by an integral, or

$$E(x,y,z) = \int dE = \frac{1}{4\pi\varepsilon}\int \frac{dq}{r^2} \tag{3}$$

where dq is a differential element of the charge distribution, r is its distance from the point P, and dE is the electric field it establishes at that point.

By considering a charge element dq consisting of a flat rectangular strip of r_i , depth D, and width dr_x and dr_y at a point (x_q,y_q) for x and y direction, respectively, the element dq on the surface (z=0) is

$$dq = \rho D(dr_x dr_y) \tag{4}$$

where $dr_x dr_y$ is the area of the strip andρ is a charge density that corresponds to the charge density ρ as

$$\rho(t) = \frac{J_0\delta}{D}t \tag{5}$$

where J_0 is the final current density[16].

The charge element dq has the distance r_i $(=(r_x^2+r_y^2)^{1/2})$ from point P so that their contribution dE to the electric potential at P is given by *Coulomb's law* as

$$dE\ (x,y,0) = \frac{1}{4\pi\varepsilon}\frac{dq}{r^2} = \frac{1}{4\pi\varepsilon}\frac{\rho D(dr_x dr_y)}{r_x^2 + r_y^2} \tag{6}$$

The potential dE consists of component dE_x and dE_y., where $\mathrm{dE=dE_x+ dE_y}$ (Note that the sum is a *vector sum*).

The component strip of electric field $dE(x,y,0)$ is found by multiplying $dE(x,y,0)$ and $\sin\alpha$, where

$$\sin\alpha = \frac{r_x}{\sqrt{r_x^{\ 2} + r_y^{\ 2}}},$$ or

$$dE_x(x,y,0) = \frac{1}{4\pi\varepsilon}\frac{\rho D(dr_x dr_y)}{r_x^2 + r_y^2}\sin\alpha = \frac{1}{4\pi\varepsilon}\frac{D\rho r_x(dr_x dr_y)}{\left(r_x^2 + r_y^2\right)^{3/2}} \tag{7}$$

The component E_x can be obtained by integrating over all strips into which the area can be divided, or

$$E_x(x,y,0) = \int dE_x = \frac{\rho D}{4\pi\varepsilon}\iint \frac{r_x dr_x dr_y}{\left(r_x^2 + r_y^2\right)^{3/2}}$$

$$= \frac{\rho D}{4\pi\varepsilon} f_x(x,y,0) \tag{8}$$

The electric field at the surface, $E_x(x,y,0)$ corresponds to the sum of the electric field created by charge distributionρ in the dielectric (ε) and the images, $K\rho$, situated in the vacuum. Where K characterizes the image weight and is given [20] by

$$K = \frac{\varepsilon - \varepsilon_0}{\varepsilon + \varepsilon_0}.$$

The direction of the field created by the image effects is the same as the direction of the field created by the real charges themselves.

$$E_x(x,y,0) = \frac{\rho d_s}{4\pi\varepsilon} f_x(x,y,0) + K\frac{\rho d_s}{4\pi\varepsilon} f_x(x,y,0)$$

$$= \frac{\rho d_s}{4\pi\varepsilon}(1+K) f_x(x,y,0) \tag{9}$$

With the same process, by considering image weight, the component $E_y(x,y,0)$ is as follows

$$E_y(x,y,0) = \frac{\rho D}{4\pi\varepsilon}(1+K) f_y(x,y,0) \tag{10}$$

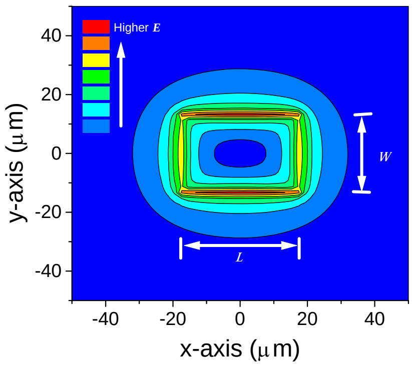
Finally the electric field **E** can be obtained as the vector sum of the component $\mathbf{E_x}$ and $\mathbf{E_y}$. Then the scalar of electric field **E** is E, or $E^2(x,y) = E_x^2 + E_y^2$ and

$$E(x,y) = \sqrt{E_x^2 + E_y^2} \tag{11}$$

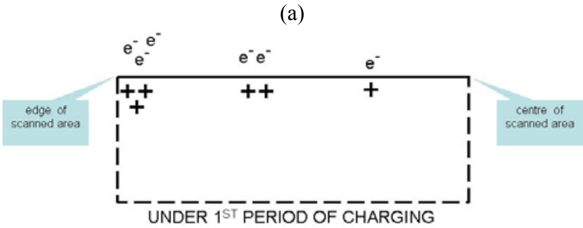
III. SURFACE BREADOWN (OPTICALLY-VISIBLE FLASHOVER TREEING)

The mechanism of a surface flashover (optically-visible flashover treeing) is as follows. Under the period of charging, by using Eq. 8-11 above, the highest electric field is created at the edge of the scanned area (shown in Fig. 2(*a*)). Consequently, the highest field may cause more electrons which are emitted from the subsurface region around the edge (Fig. 2(*b*)). The increase of period of charging may increase the number of electrons above the surface (containing secondary electrons and field-emitted electrons) and cause a potential difference between the edge (more negative charges) and the centre (less negative charges or zero) of the scanned area.

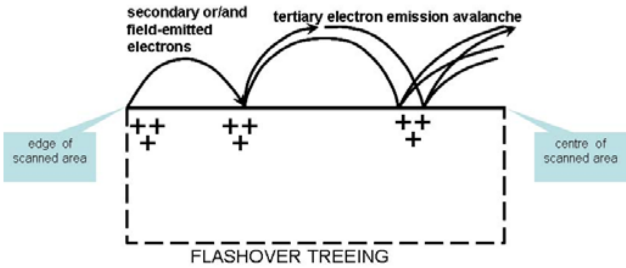
When the potential difference reaches a critical value, some of the electrons from the edge region may be accelerated and attracted towards the centre (Fig. 2(**c**)). The electrons impact upon the surface producing additional electrons by tertiary emission. Some of these tertiary electrons will again 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 as an optically-visible flashover treeing. Once a flashover treeing is completed, the potential difference between the scanned area edge and the centre becomes zero (see Fig. 3). In this stage, the surface becomes positively charged (Fig. 2(*d*)).



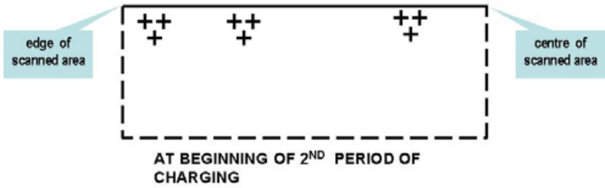
(a)



(b)



(c)



(d)

Fig. 2 Model of electric field distribution on the charged (scanned) area surface

Fig. 3 shows a scanning electron microscope image of an optically-visible flashover treeing on the surface of a high purity (99.99%) polycrystalline MgO under an electron beam bombardment with the incubation time (period of charging) as long as 7 min with the electron energy 25 keV (the SEM operation voltage 25 kV). The treeing was initiated from the edge and propagated into the center of the charged area.

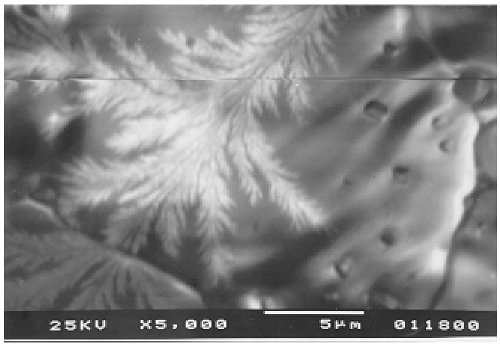


Fig. 3 An optically-visible flashover treeing on an insulator (MgO) surface [11, 16]

The second and the following optically-visible flashovers may occur when the further period of charging is extended. Fig. 4 shows the repeated optically-visible flashovers under continuous period of charging for several SEM's magnifications (i.e.: 10,000x, 7,500x, 5,000x and 3,500x).

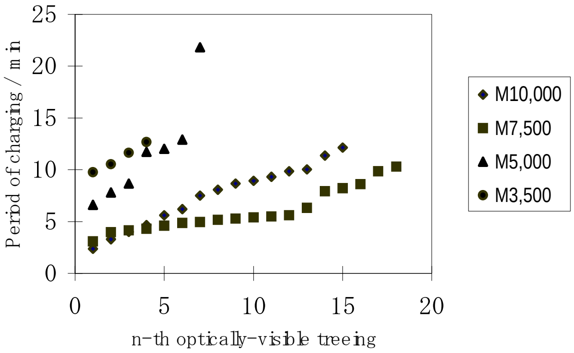


Fig. 4 The repeated flashover treeing for several SEM magnification on the surface of MgO under 25 keV electron beam bombardment using an SEM

IV. Conclusion

The distribution of electric field on the insulator surface such as MgO under electron beam bombardment in vacuum has been demonstrated by using a simple model. From this model, the phenomenon of surface breakdown under electron bombardment could be explained. Scanning using a scanning electron microscope forms a rectangular charged area. The highest electric field is created at the edge of the charged area. This region becomes a critical place for treeing initiation. The treeing can be observed from the monitor of the SEM as optically-visible flashover treeing. Since incubation time is a parameter to increase electric field at an insulator surface, this parameter can be used to evaluate insulation property of an insulator to withstand the appearance of surface breakdown under electron bombardment. Therefore, the better insulation placed in harsh environment such as in space, in tropical countries with high density lightning, in nuclear reactor could be evaluated.

Acknowledgment

The authors would like to thank IIUM and Ministry of Higher Education Malaysia for providing research grant under LT-40 and FRGS 0106-21, respectively.

References

[1] K.T. Sirait, 18th International Conference on Lightning, Munchen, pp. 16-20, Sept.1985.
[2] Y. Yamano, A. Ohashi, K. Kato, H. Okubo, and Y. Hakamata, Y.," "Charging Characteristics on Dielectric Surface by Different Charging Processes in Vacuum", IEEE Trans. Diel. Elect.Insul., Vol.6, No.4, pp.464-468, 1999.
[3] W. Kalbreier and B. Goddard; "Radiation-triggered breakdown phenomena in high energy e+e- colliders", IEEE Trans. Elec. Insul., vol. 28 (4), pp. 444-453, 1993.
[4] G.M. Sessler, M.T. Figueiredo, G.F Leal. and Frreira, IEEE Trans. on Dielectr. Electr. Insul., vol.11(2), pp.192-202, 2004.
[5] Y.S. Liu, G.J. Zhang, W.B. Zhao, and Z. Yan, Appl. Surf. Sci., vol. 230(1-4), pp.12-17, 2004.
[6] H.C. Miller, IEEE Trans. Electr. Insul., Vol. 24(5), pp. 765-788, 1989.
[7] A. Neuber, M. Butcher, L.L. Hatfield, H. Krompholz, J. Appl. Phys., Vol. 85, p. 3084, 1999.
[8] Y.S. Choi, H.J. Kim, and B.J. Shin, EEE Trans. Electron Devices, vol. 51(8), pp. 1241-1244, 2004.
[9] K.G. Balmain, and W. Hirt, IEEE Trans. On Nuclear Science, Vol. NS-27(6), pp.1770-1775, 1980.
[10] K.G. Balmain, and W. Hirt, IEEE Trans. Electr. Insul., Vol. EI. 18(5), pp. 498-503, 1983.
[11] C. Le Gressus, and G. Blaise, IEEE Trans. on Electr. Insulation, vol. 27(3), pp. 472-481, 1992.
[12] A.G.E. Sutjipto, T. Okamoto, and M. Takata, Key Eng. Mater., vol. 181-182, pp.231-234, 2000.
[13] A.G.E. Sutjipto, T. Okamoto, and M. Takata, Trans. Mater. Res. Soc. Jpn., vol. 25(1), pp. 193-196, 2000.
[14] J. Cazaux, J. Appl. Phys., vol. 85(2), pp.1137-1147, 1999.
[15] A.G.E. Sutjipto, R. Muhida, and M. Takata, Proceeding of 8th International Conference on Properties and Application of Dielectric Materials, pp.216-219, 2006.
[16] A.G.E. Sutjipto, and M. Takata, Journal of Materials Science, Springer, vol. 42, pp.6036-6040, 2007.
[17] A.G.E. Sutjipto, Canadian Journal of Pure and Applied Sciences, vol. 1(1), pp. 73-77, 2007.
[18] A.G.E. Sutjipto, Key Engineering Materials, vol. 345-346, p. 1609, 2007.
[19] H. Niedrig, J. Appl. Phys., vol. 53R15, 1982.
[20] J. Cazaux, J. Appl. Phys., vol. 59(5), pp.1418-1430, 1986.

Agus G.E. Sutjipto was born at Klaten, Indonesia 27 August 1964. The author got B.Eng in Electrical Engineering from Bandung Institute of Technology, Indonesia in 1989, M.Eng. in Electronics and Dr.Eng in Materials Science and Engineering from Nagaoka University of Techology, Japan in 1999 and 2002, respectively.

He is now as an Associate Professor at Department of Manufacturing and Materials Engineering, International Islamic University Malaysia (IIUM). He joined IIUM since 2004. He is interested in charging and discharging phenomena of dielectric materials under electron bombardment, crystal growth, thin film and green nanotechnology.

Dr. Sutjipto is a member of IEEE and dedicated with many awards from INNOVA exhibition in 2007 at Brussel and got a Promising Researcher Awards in Quality Day 2008 at IIUM.