Flashover Characteristic of Epoxy Composites Filled with Different Micro Inorganic Oxide Particles under Nanosecond Pulse in Vacuum

Yu Chen, Yonghong Cheng, Kai Wu, J. Keith Nelson, Leonard A. Dissado and Shengtao Li

Abstract—Research on the vacuum surface flashover mechanisms of insulating material under nanosecond pulses is important for the design and manufacture of high power pulse generators. Here the vacuum surface flashover characteristic of epoxy composites filled with different micro-fillers, \(\text{Al}_2\text{O}_3\cdot3\text{H}_2\text{O}, \text{Al}_2\text{O}_3, \text{BaTiO}_3, \text{and TiO}_2\), is investigated using a unipolar pulse generator (50 ns rise time and 600 ns full width at half maximum). In addition, their thermally stimulated depolarization current (TSDC) and secondary electron emission (SEE) coefficients are measured. The results show that the flashover performance does not depend just on the SEE coefficient, but that the different effects of shallow and deep traps must also be taken into account.

Index Terms—Micro-scale inorganic oxide particles, Epoxy composites, Pulsed vacuum flashover, Thermally stimulated current, Secondary electron emission

I. INTRODUCTION

Experiments conducted on pulsed-power equipment and particle accelerators typically require that a high-voltage pulse be transmitted across a vacuum-insulator interface [1-6]. Surface flashover in vacuum is a primary limitation to the interface distance over which the voltage is applied. Furthermore, it typically takes place on the surface region of an insulating material at an applied electric stress much lower than the bulk breakdown strength of the material. Two design requirements for vacuum insulators must be considered. One is that the insulator should not flashover during the main power pulse. This usually implies a large electrode separation, however the interface is inductive, and large distances reduce the power to the load. The second design requirement is that the insulator must be durable enough to survive for many shots before needing replacement. The material can suffer dendrite damage caused by discharge of electrons deposited in the insulator. There can also be "worm-hole" discharges through the bulk of the material. Therefore, it is of interest to develop a dendrite-resistant coating with greater flashover strength. I.S. Roth [5,6] has produced a dendrite-resistant vacuum insulator coating, called Dendresist, which is an epoxy loaded with hydrated alumina (\(\text{Al}_2\text{O}_3\cdot3\text{H}_2\text{O}, \text{ATH}\)) powder. The coating has extended the insulator lifetime on the PITHON and Double-EAGLE pulse generators. The alumina powder gives the coating a transient conductivity that allows deposited charge to be conducted away without causing dendrite damage. Such inorganic oxide fillers are also used as a voltage-stabilizing agent in the polymer insulation of DC transmission systems. The epoxy resin is filled with a large amount of micro-scale fillers, e.g. silica (\(\text{SiO}_2\)) or aluminum oxide (\(\text{Al}_2\text{O}_3\)) [7,8], to achieve the same low thermal expansion coefficient as the associated conductors. T. Imai [7] at Toshiba Corporation proposed titanium oxide nano-filler and silica micro-filler mixed composites as the industrial insulating materials for HVDC/DC GIS equipment due to the excellent tree resistance. J.K.Nelson studied the electric strength of epoxy composites loaded with micro or nano titanium oxide (\(\text{TiO}_2\)) fillers [9,10]. His papers show that the use of nanometric particles results in a substantial change in the behaviour of the composite, which can be traced to the mitigation of internal charge when a comparison is made with conventional \(\text{TiO}_2\) fillers. Dang Zhimin studied the barium titanate oxide (\(\text{BaTiO}_3/\text{epoxy}\) composites for high dielectric constant [11]. However, it is important here to distinguish between the effects on bulk electric strength and those on the surface flashover (or "creep" failure).

The question is what effect the fillers that are added to inhibit dendrite formation have on surface flashover. The initiation of a surface flashover is usually induced by the emission of electrons (generally by field emission or thermal-field emission) from the cathode triple-point junction (the interface where the insulator, cathode, and vacuum are in close proximity). While there is general agreement on the initiating mechanism of surface flashover, there is considerable disagreement concerning the details of the intermediate or development stage of the discharge [12-19]. It is usually assumed that the final stages of surface flashover occur in desorbed surface gas or in vaporized insulator or electrode material. Two theories have been put forward to describe the intermediate stage. One involves an electron cascade along the surfaces of the insulator, or a Secondary Electron Emission Avalanche (SEEA), and the other relies on an Electron Triggered Polarization Relaxation (ETPR) model. However, neither of these seem to be capable of explaining all cases of surface flashover in vacuum. Most SEEA theories predict that a SEEA will result in surface charging of the insulator. ETPR is attributed to rapid charge detrapping from localized sites and corresponding relaxation of energy of polarization.

When a primary electron strikes a solid material, it may penetrate the surface and generate secondary electrons. The secondary electron emission occurs in the following three
steps [20]: (1) production of internal electrons through bombardment by the primary electrons; (2) transport of the internal secondary electrons toward the surface, which is accompanied by some energy loss due to inelastic scattering; and (3) escape of the electrons through the solid-vacuum interface. In flashover, some of the electrons emitted from the triple junction impact the surface of the insulator, producing additional electrons by secondary emission. Some of these secondary electrons will again strike the surface, producing tertiary electrons. Continuation of this process results in the development of an SEEA. Therefore there will be a lower flashover voltage for a material with higher Secondary Electron Yield (SEY).

The Thermally Stimulated Depolarisation Current (TSDC) technique has been used as a powerful tool in numerous investigations of dipolar and dc relaxation phenomena. The method has been extensively documented by van Turnhout [21,22] and the experimental details are provided later in Section II. TSDC refers to the external current produced by heating a variety of objects over a wide temperature range of 15-600K after polarization by an electrostatic field (intensity $F_p \sim 10^4$ kV/m) at a defined polarization temperature ($T_p$). This charge separation includes the charging of internal interfaces via the Maxwell-Wagner-Sillars (MWS) mechanism, and polarization due to space charge generation. The relaxation of these dipoles and charges after removal of the field is governed by their natural relaxation times, which are temperature dependent. Cooling the sample down with the field still applied maintains the polarization imposed by the applied fields. When the field is removed at a lower temperature than that at which the poling takes place the relaxation times for the dipoles and charges are much longer than at the polarization temperature. Heating the sample reduces the relaxation times to the timescale of the temperature ramp, and a current peak will occur at a temperature corresponding to the instantaneous relaxation time of the specific species contributing to the polarization. The current peaks that are observed therefore, give information as to the activation energies required to relax the different classes of contribution to the polarization and the integral of the current under the peak gives the amount of charge involved in the specific contribution. The relaxation times are determined by the morphology and chemistry of the material and the types of charge/dipole being studied. A good example of this is seen in the glass transition process in many polymers where changes in chain mobility produce a strong TSDC response. However, in the context of the present study, it is the ability of the TSDC technique to quantify the charge trapping in the polymer at the interfacial sites created by embedded particulates that is the primary motivation (see later). Examples may be found in other studies of composite materials [23]. The relaxation processes occurring in the bulk and at the interfaces can differ greatly because the interfacial relaxations (as well as any interfacial phenomena) depend on the characteristics of a material and a medium surrounding this material, as well as on the topology (fractality, porosity) of the material. The TSDC technique can be applied to study the effects occurring both in the bulk and at the surface of any material.

In this paper, a comparative study of the flashover characteristics of epoxy composites with different kinds of micron-scale filler particles is carried out. In addition, the TSDC and SEY are measured.

II. EXPERIMENTAL APPARATUS & TECHNIQUES

A. Sample Preparation

Diglycidyl ether of bisphenol A type epoxy resin (EPON-828) was cured by a methyltetrahydrophthalic anhydride curing agent and N, N-dimethylbenzylamine accelerator to form a crosslinked structure. The fillers were treated by 3 Aminopropyltrithoxy Silane coupling agent and fumed silica (Degussa, Aerosil380, $D_{50} = 7$ nm) as the thixotropic agent were mixed in order to prevent filler sedimentation. The mass ratio of the epoxy resin and the curing agent was 100:78. Typically, the preprocessed mixture of epoxy, curing agent, and micro-scale filler is placed in a vacuum agitator, heated to 40°C and kept at 100 Pa pressure. The final curing process was performed at 100°C for 20 min, then at 120°C for 12 h. Four kinds of epoxy composite materials filled with ATH, $\mathrm{Al_2O_3}$, $\mathrm{BaTiO_3}$ and $\mathrm{TiO_2}$ micro powders with a size of 1–10 $\mu$m were prepared at the 20% weight proportion. SEM micrographs of the epoxy composite samples are shown in Fig.1. It can be seen that the micro-particles are dispersed homogeneously.

B. Electrode Preparation

Finger electrodes as shown in Fig.2 were made of stainless steel, and polished to attain a mirror finish. The radius of curvature in the front of electrode was 10 mm. Laminar samples were 1 mm thick and 60 mm in diameter. The electrode gap spacing was set to $d = 10$ mm and remained unchanged throughout the experiments. Samples were placed between the two electrodes on a holder made of PTFE. After polishing, the electrodes were conditioned by passing a current of 2 kA for 10 min, so as to remove emission sites, surface gas or surface contaminants. The electrodes were cleaned ultrasonically in carbon tetrachloride for 10 min, then in deionized water for 10 min, and then baked at a temperature of 300°C for 12h. The samples were cleaned ultrasonically in...
absolute ethyl alcohol for 10 min, then in deionized water for 10 min, and then baked at a temperature of 100°C for 6 h.

C. Pulsed Vacuum Flashover Testing

The unipolar pulse generator was set up with six stage switches and capacitors, having a charging capacitance, \( C = 5.6 \text{ nF} \). The wave front control resistance was \( R_{\text{load}} = 1.1 \text{ kΩ} \), and the wave tail resistance was \( R_{\text{limit}} = 530 \text{ Ω} \), and a loop inductance of 21 \( \mu \text{H} \) were used (Fig. 3a). A typical applied voltage waveform and flashover waveform obtained from the system are displayed in Fig. 3b. During the flashover experiments on different insulation materials, the vacuum level of \( 5 \times 10^{-3} \text{ Pa} \) was kept unchanged. The vacuum flashover characteristics of the epoxy composites were investigated using the same fast pulse front and full width at half maximum times (50/600ns) derived from the 78 kV Max peak output. In the experiments, twenty consecutive flashover voltage measurements at the time interval of 2 min were recorded, and their average value and standard deviation was calculated from the instantaneous voltages recorded.

D. Secondary Electron Yield Measurement

Direct measurements of the yield of SEE at low energies of primary electrons are difficult because of the charging of the sample surface. Indeed, the surface will acquire a positive charge if the flux of secondary electrons is higher than primary flux, and negative in the opposite case. The electric field due to the surface charge changes the energy of the primary electrons. This electric field may also impede or facilitate the yield of low energy “true” secondary electrons.

An experimental apparatus based on a two electron gun technique [24] was used for the SEY measurement. The principal features of this technique are 1) use of a balance gun to place the target surface at some fixed voltage, and 2) the use of an amplitude modulated measuring gun beam and a narrow-band amplifier centered at the probing beam modulating frequency, to measure the collected probing current at the target. Fig.4 is a schematic of the basic experimental setup. The primary current, \( I_p \), measured with a Faraday cup, the target current, \( I_t \), and the secondary electron current, \( I_s \), can be expressed as

\[
\delta = I_s / I_p = (I_p + I_t) / I_p = 1 + I_t / I_p
\]

E. Thermally Stimulated Depolarization Current Measurement

TSDC measurements were conducted using a device made by TOYO SEIKI in Japan. Typically, when TSDC investigations were carried out, the system was heated to a given temperature, \( T_p \), and a static electric field, \( F_p \), was applied for a time, \( t_p \), that is long enough to permit the different mobile entities of the material to orient themselves within the field. A rapid decrease in temperature to a value \( T_0 \) low enough to freeze the configuration (typically \( T_0 < 100 \text{ K} \)) follows. At \( T_0 \), the field is switched off and the sample is short-circuited for a time \( t_0 = 30 \text{ s} \) to eliminate the rapid space charge relaxation and stabilize the sample at this temperature. During a linear temperature increase at rate, \( \beta \), the return to equilibrium of the previously oriented entities generates a depolarization current (\( I_d \)) which is recorded as a function of temperature with a high sensitivity electrometer Keithley 6517A.

The thermally stimulated current, \( I_d \), can be described by the following equation

\[
I = A \exp[-(E / kT) - B \int_{T_0}^T \exp(-E / kT) \,dT']
\]

Here \( T \) is absolute temperature and \( k \) is Boltzmann’s constant. If the current arises from de-trapping of electrons, \( E \) is the energy depth of the traps. \( A' \) and \( B \) are coefficients independent of \( T \) and \( E \), but dependent on the model one uses to analyze the TSC.

We use the following equations [25] to calculate the activation energy.
Here \( A = a_1 + \sum_{n=0}^{n} \left(1 - a_2^{-1} e^{-a_3 n} \right) (n+1)! A^n a_3^{-n} (1) \) 

(3)

Here \( a_1 = \ln\left(\frac{I_p}{I_i}\right) \), \( a_2 = T_i / T_p \), \( a_3 = \left(\frac{T_p - T_i}{T_i}\right) \). Obviously, after calculating \( a_1 \), \( a_2 \) and \( a_3 \) from \( T_p, T_i \) and \( I_p, I_i \), introducing them into Eq.(3), and choosing a proper value of \( n \) (here, \( n=8 \)), we can calculate \( A \), and estimate the activation energy of the relaxation process from the following expression.

\[ E = A \frac{kT_i T_p}{T_p - T_i} \]  

(4)

The importance of Eq.(4) consists in providing a method that not only estimates the value of \( E \) for a TSC curve with a distinct peak, but also identifies the real peak point for a TSC curve without a distinct peak. The electric charge, \( Q \), produced during the depolarization stage can be estimated by integration over the TSDC thermogram

\[ Q_{\text{TSC}} = \frac{1}{\beta} \int_0^\infty I(T)dT \]

where \( \beta \) is the heating rate.

III. RESULTS

A. Flashover Characteristic of Epoxy Composites filled with different micro-fillers

In the present study, the surface flashover characteristic of the composite materials filled with ATH, BaTiO\(_3\), Al\(_2\)O\(_3\), TiO\(_2\) filler at the 20% weight proportion is investigated. The characteristic values together with the associated error bars are shown in Fig.5. It can be seen that the flashover voltage of the ATH/epoxy composite is the lowest among the five kinds of material. TiO\(_2\)/epoxy composite is the lower than base resin but higher than others on flashover performance. Al\(_2\)O\(_3\)/epoxy composite is lower than TiO\(_2\)/epoxy composite, and BaTiO\(_3\)/epoxy composite is lower than Al\(_2\)O\(_3\)/epoxy composite.

B. SEE Characteristics

The SEY curves of various micro-composites are shown in Fig. 6. The SEY peak value and corresponding primary electron energy is as shown in Table I. In Fig. 6, the data is fitted to a curve described by the following empirical equation [20]:

\[ \delta(E_p) = \delta_{\text{peak}} \frac{E_p}{E_{\text{peak}}} \left( s - 1 + \left( \frac{E_p}{E_{\text{peak}}} \right)^s \right) \]

(6)

Here \( \delta(E_p) \) is the secondary electron emission yield depending on the energy of the primary electron, \( \delta_{\text{peak}} \) is the peak secondary yield, which occurs at the primary electron energy \( E_{\text{peak}} \), and \( s \) is a fit parameter (larger than 1) which describes the form of the secondary emission yield curve.

According to the SEE model, if the SEY of the material is high, the flashover voltage is low. Then we can judge that the flashover voltage of the 20% Al\(_2\)O\(_3\)/Epoxy material should be the highest, and the 20% BaTiO\(_3\)/Epoxy material should be the lowest. However, this does not fit the results in Fig. 5, which indicates that the ATH material is substantially weaker than all the others. Thus, the flashover performance of the material does not depend just on the SEY.

<table>
<thead>
<tr>
<th>TABLE I SEY OF DIFFERENT SAMPLES.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
</tr>
<tr>
<td>20% Al(_2)O(_3)-3H(_2)O</td>
</tr>
<tr>
<td>20% Al(_2)O(_3)</td>
</tr>
<tr>
<td>20% BaTiO(_3)</td>
</tr>
<tr>
<td>20% TiO(_2)</td>
</tr>
</tbody>
</table>

Fig.4. Experimental setup for secondary emission current measurement.

Fig.5. Flashover characteristic of epoxy composites filled with different fillers in comparison with the base resin measurement.

Fig.6. SEY curves of four micro-composites fitted to a curve described by the following empirical equation [20].
C. TSDC Results

Laminar samples of various micro-filled resin in two thickness, having been poled at 120°C at a stress of 3 kV mm\(^{-1}\) for 1 mm thickness and poled at 180°C at a stress of 15 kV mm\(^{-1}\) for 0.25 mm thickness, were subjected to TSDC measurement. The temperature ramp rate was 5°C min\(^{-1}\). Evaporated Au electrodes with 100 nm thickness, 20 mm diameter were used. Typical TSDC thermograms for five different types of material at -80 to 160°C are shown in Fig. 7 and Fig. 8. The electric charge \(Q\) produced during three depolarization stages, and the associated relaxation parameters within different relaxation process have been calculated, and depicted in Table II, III and IV.

<table>
<thead>
<tr>
<th>Samples</th>
<th>(Q_{\text{TSC}}) (nC) (-80 - 0) °C</th>
<th>(Q_{\text{TSC}}) (nC) (0 - 100) °C</th>
<th>(Q_{\text{TSC}}) (nC) (100 - 160) °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base resin</td>
<td>0.40</td>
<td>0.55</td>
<td>6.73</td>
</tr>
<tr>
<td>20% Al(_2)O(_3)·3H(_2)O</td>
<td>0.42</td>
<td>1.06</td>
<td>5.23</td>
</tr>
<tr>
<td>20% Al(_2)O(_3)</td>
<td>0.57</td>
<td>0.48</td>
<td>4.48</td>
</tr>
<tr>
<td>20% BaTiO(_3)</td>
<td>0.24</td>
<td>0.22</td>
<td>1.74</td>
</tr>
<tr>
<td>20% TiO(_2)</td>
<td>2.11</td>
<td>2.60</td>
<td>11.03</td>
</tr>
</tbody>
</table>

Table II: \(Q_{\text{TSC}}\) of different samples in Fig. 7.

<table>
<thead>
<tr>
<th>Samples</th>
<th>(T_p) (°C)</th>
<th>(E_p) (kV/mm)</th>
<th>(T_{g} (°C))</th>
<th>(E_{g} (kV/mm))</th>
<th>(E_p (°C))</th>
<th>(E_{g} (°C))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base resin</td>
<td>-69.27</td>
<td>0.57</td>
<td>141.08</td>
<td>2.32</td>
<td>154.25</td>
<td>3.52</td>
</tr>
<tr>
<td>20% Al(_2)O(_3)·3H(_2)O</td>
<td>-69.54</td>
<td>0.67</td>
<td>125.82</td>
<td>1.63</td>
<td>157.94</td>
<td>1.94</td>
</tr>
<tr>
<td>20% Al(_2)O(_3)</td>
<td>-67.51</td>
<td>0.53</td>
<td>136.66</td>
<td>1.76</td>
<td>154.00</td>
<td>2.48</td>
</tr>
<tr>
<td>20% BaTiO(_3)</td>
<td>-68.65</td>
<td>0.57</td>
<td>126.23</td>
<td>1.85</td>
<td>154.54</td>
<td>2.48</td>
</tr>
<tr>
<td>20% TiO(_2)</td>
<td>-68.56</td>
<td>0.30</td>
<td>135.12</td>
<td>2.29</td>
<td>158.49</td>
<td>2.34</td>
</tr>
</tbody>
</table>

Table III: Different relaxation parameters.

Typically, several relaxations such as \(\gamma\), \(\beta\), \(\alpha\), \(\rho\), and MWS are considered for polymers. The glass transition temperature, \(T_g\), for the base resin is 141°C. Although differential scanning calorimetry measurements have already demonstrated that \(T_g\) can change slightly with the filler type, the different TSC peaks below 141°C are associated with the main chain relaxation (the \(\alpha\) relaxation) involved in the glass transition, as is shown in Fig. 7(c). However, the characteristics above 141°C are very different indeed for these fillers, as is also shown in Fig. 7(c). This is the region identified as the \(\rho\) relaxation due to the release of space charge in epoxy resins [26]. The relaxation peaks in low temperature region are...
observed as β relaxation peaks (due to local segmental motion) shown in Fig.7(b). When we increase the poling electric field strength and poling temperature, the TSDC spectra of ATH sample shows one obvious relaxation peak at 77.68°C, and its activation energy is 0.40 eV.

IV. DISCUSSION

When oxide fillers are loaded into the epoxy, there are two possibilities for a change in trap distribution, i.e. addition of a new trap distribution to original traps and replacement of original traps by a new trap distribution [27]. Many defects existing in some regions, producing deep traps, are effective to make an electron mean free path shorter and lower its energy, existing in some regions, producing deep traps, are effective to make an electron mean free path shorter and lower its energy, resulting in the increase in breakdown strength.

Silane is commonly used to couple an organic polymer with an inorganic filler particle. The Si-O bonding would constrain the motion of polymer outside the monolayer to bring about the bound states or the extended regions of immobile polymer at the interface. According to the multi-core model for polymer nanocomposite dielectrics proposed by T. Tanaka[28], polymer morphology becomes less ordered from the first layer to the third one. It is then postulated that carrier traps are distributed from deep to shallow. It might be a good picture that deep traps are present in the first and second layers, whereas shallow traps are available in the third layer. Hence, one may speculate that water of crystallization on the surface of ATH particle generate a relaxation process caused by reorientation of water molecules. Moreover, they can impede the formation of good Si-O bonding, and thus is shown in Fig.9. On the other hand, Al2O3, TiO2 and BaTiO3 particles coupled by silane can form good Si-O bonding, that is to say, they are more watertight [10]. In this way, the interface of the ATH particle filled composites is “looser” than the others, so its activation energy should also be lower, as is shown in TABLE III.

In Table III, we can see that the activation energies for molecular movement in the range -80 to 100°C are less than 1 eV. This relative ease of chain motion can be associated with the regions away from the particles and hence with shallow charge traps, according to Tanaka’s [28] model. The activation energies in the interval 100 - 160°C are larger than 1 eV, and this stiffer region of polymer will be influenced by the inner interface and hence be associated with deep charge traps. The activation energies in the high temperature region show that the ATH composite is the lowest and base epoxy resin is the highest. Moreover, ATH composite shows one relaxation peak with 0.40 eV trap depth at 77.68°C. In Table II and IV, Q_{TSC} produced in the temperature range of -80 - 100°C and 100 - 160°C correspond approximately to the amount of shallow and deep traps respectively insofar as the activation energy for molecular dipoles can be related to trap density. However only the p-peak corresponds to the amount of charge trapped during the poling period of the TSC experiment, and consequently gives its trap depth. Carriers in shallow traps may easily escape and contribute to the flashover process through release and migration. We call this the “shallow trap phenomena”. However, the deep traps may prevent the internal secondary electrons from escaping onto the surface and thus restrain the flashover plasma development, and make electron injection difficult. We call this the “deep trap phenomena”. A surface flashover model is proposed and is shown in Fig.10.

By considering the different effects of shallow and deep traps, the experimental results shown in Fig. 5 can be explained as follows. As shown in Table II and IV, there is copious deep trap charge for pure epoxy and for TiO2 composite, so the flashover voltages for these materials are also high. However the sample with 20% BaTiO3/Epoxy composite has the lower deep trap charge quantity, but its flashover voltage is larger than the sample of 20% ATH/ Epoxy composite. This difference cannot be due to their SEY as they are almost the same, but it may be due to the effect of the large quantity of shallow traps in ATH composite.

As the role of deep electron traps during the flashover has been emphasized [29,30], deeper electron traps can restrain the emission of internal secondary electrons inside the surface layer of material, and the surface flashover voltage can be possibly increased by enhancing the density of deeper traps. However, the effect of deep traps alone does not seem able to explain all our experimental results. We suggest that the effects of shallow and deep traps are different, and that the surface flashover in vacuum is related not only to the trap concentration but also their energy distribution.

Here, it is also important to recognize that these experiments were conducted using a pulse voltage having a front time of only 50 ns. The effect of discharge time lag may also play an important role in determining the flashover voltage. Shallow traps tend to reduce the time lag as electrons can easily escape from the shallow traps. However, deep traps may prevent electron emission and thus enhance the flashover voltage. These may also contribute to the experimental phenomena in Fig. 5.

The geometry, insulator material, gap distance, surface condition of the electrode and insulator, etc. can also influence the progress and development of the flashover. In the experiments, the geometry and gap distance were fixed accurately. The surface condition of the electrode and
were kept perfect by mechanical, electrical, and chemical processing. Although the static permittivities of these specimens are appreciably different, a previous study on the field distribution indicated that the change in permittivity only weakly affects the strong tangential component of the field along the surface of our specimen [31].

Here, we suggest that the model of shallow and deep traps may not only explain our experimental results, but also reflects some detailed information of the interface zone in the composites.

V. CONCLUSIONS

The flashover voltage of the ATH/Epoxy composite is substantially lower than that for samples filled with different 20% 1μm micro-fillers, whereas the TiO2/Epoxy composite is the highest. In both cases their flashover voltages are lower than the base resin. The flashover performance does not depend just on the SEE coefficient, but also on the trap distribution in quantity and energy, and can be explained in terms of the different effects of shallow and deep traps based on a surface flashover conceptual model.

ACKNOWLEDGEMENT


REFERENCES

[6] Yu Chen (S’05-M’07) was born in Hebei, China in 1977. He received the M.S. and Ph.D. degrees in electrical engineering from Xi’an Jiaotong University, China in 2003 and 2008, respectively. Now, he is a visiting lecturer of graduate school of information, production and system, Waseda University.

[11] Yu Chen (S’05-M’07) was born in Hebei, China in 1977. He received the M.S. and Ph.D. degrees in electrical engineering from Xi’an Jiaotong University, China in 2003 and 2008, respectively. Now, he is a visiting lecturer of graduate school of information, production and system, Waseda University.

Kai Wu (M’00) was born in Shaanxi, China in 1969. He received the M.S. and Ph.D. degrees in electrical engineering from Xi’an Jiaotong University, China in 1992 and 1998, respectively. He was a postdoctoral fellow from 1998 to 2000 and then joined the staff from 2000 to 2003 at Nagoya University, Japan. In 2003, he worked as a research associate at the University of Leicester, UK. In 2004 and 2005, he was a visiting researcher at the Central Research Institute of Electric Power Industry, Japan. Since 2006, he is a professor of Xi’an Jiaotong University.

J. Keith. Nelson (F’90) was born in Oldham, UK and received the B.Sc.(Eng.) and Ph.D. degrees from the University of London, UK. He is currently Philip Sporn Chair of Electric Power Engineering at the Rensselaer Polytechnic Institute. Prior to his appointment at Rensselaer, he was manager of Electric Field Technology Programs at the General Electric R & D Center in Schenectady, NY. He has held numerous IEEE appointments including that of the presidency of the IEEE Dielectrics and Electrical Insulation Society, 1995-6. He is a chartered electrical engineer, a Fellow of both the IEEE and IET and the recipient of the IEEE Millennium Medal.

Leonard A. Dissado (SM’96-F’06) graduated from University College London with a degree in chemistry in 1963, obtained a Ph.D. degree in theoretical chemistry in 1966 and a D.Sc. degree in 1990 from the same university. In 2007 he was honoured by the Universite Paul Sabatier, Toulouse, with the award of a Doctuer Honoris Causa. After rotating between Australia and England twice, he settled in Chelsea College in 1977 to carry out research in dielectrics. Since then he has published many papers and one book, together with John Fothergill, on breakdown and associated topics. In 1995 he moved to the University of Leicester and was promoted to professor in 1998. He has been a visiting professor at the University Pierre and Marie Curie in Paris, Paul Sabatier University in Toulouse, and Nagoya University, and a Senior Visiting Fellow at the Institute of Advanced Studies of the University of Bologna. He also has given numerous invited lectures, including the Whitehead Memorial Lecture in 2002. Currently he is an associate editor of the IEEE Transactions on DEI, co-chair of the Multifactor Aging Committee of DEIS, and a member of DEIS AdCom.

Shengtao Li (M’96) was born in Sichuan, China in 1963. He received the M.S. and Ph.D. degrees in electrical engineering from Xi’an Jiaotong University, China in 1986 and 1990, respectively. Since 1998, he is a professor of Xi’an Jiaotong University. He is the recipient of National Natural Science Funds for Distinguished Young Scholar. He is currently deputy director of state key laboratory of electrical insulation and power equipment.