Influence of deep traps on charge transport in nanodielectrics

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Abstract – Nanodielectrics have attracted significant attention due to their potential applications as the improved dielectrics in high voltage direct current (HVDC) power transmission. One of the improved properties widely reported is the suppression of space charge of nanodielectrics when subject to DC electric fields. The proposed mechanism for the reduction in space charge is the introduction of deep traps due to the interaction between nanoparticles and polymer matrix. The supporting experimental results that leads to the deep trap formation, however, are not rigorously examined. In this letter, a simple and more direct approach has been designed based on isothermal surface potential decay measurements. The observation of surface potential and its time evolution immediately after polarization of DC electric fields have been used to prove the existence of deep traps. By comparing the surface potential results from nanodielelctrics with different nanoparticles loading concentrations, 0, 1wt% and 5wt%, the concept of deep traps introduced by nanoparticles can easily explained the observed results and its impact on charge transport processes in nanodielectrics.

Keywords: nanodielectrics, space charge, surface potential, tunneling process, deep traps.

I. INTRODUCTION

The benefits of nanotechnology have spread in the different areas such as aerospace and medicines. Although the research on nanodielectrics started relatively later [1], there is a rapid growing trend in research publications due to its potential applications in engineering [2]. It has been widely reported that both thermal and electrical properties of nanodielectrics can be improved. One of the major improved electrical properties of nanodielectrics is its ability to suppress the formation of space charge when subject to the high electric fields [3]. This feature is particularly useful for HVDC applications as the easy formation of space charge in dielectric materials is a major obstacle to the reliable operation of the HVDC transmission systems.

The explanation put forward for the reduction in space charge is the formation of deep traps due to the interaction between the nanoparticles and matrix. This has been supported by the thermally stimulated discharge current measurements [4] and pulse electroacoustic technique [5]. The simulation of a model based on quantum mechanics [6] showed the existence of strong interaction between nanoparticles and matrix, resulting in deep traps. By using the concept of deep traps associated with nanodielectrics, the charge transport processes have been explained [7], especially when the loading concentration varies. However, the supporting experimental evidence that shows the existence of the deep traps in nanodielectrics is not satisfactory. For the TSDC measurements as the temperature changes may result in morphological changes in nanodieelctrics, meaning the TSDC measurement itself may bring change to the material trapping characteristics. The magnitude of the applied electric field and the duration during the polarization stage can also affect the discharge current. Whether the bias voltage during TSDC measurement is applied during the depolarization stage significantly affect the current due to the effect of charge combination. Most importantly, the TSDC results do not give spatial distribution of traps in the sample. On the other hand, the PEA technique can give spatial charge distribution across the sample but with limited resolution (typically 5 to 10 μm). If charges distribute very close to the two surfaces of the sample, i.e. next to the two electrodes, the measurement results can hardly distinguish them from the capacitive charges on the electrodes. Therefore, no space charge observed by the PEA method in the nanodielectrics does not guarantee there is no space charge in the sample. It has been illustrated in the schematic model for the nanodielectrics with a low loading concentration [4] that the charge injection may take place but be deeply trapped in the region close to the surface. The electric field produced by the injected/trapped charges is in the opposite direction of the applied field, resulting in reduction of the total electric field at the interface. The weakened electric field leads to the reduced charge or negligible injection if the electric field produced by the trapped charges. The concept has been

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successfully implemented to explain conduction current observed in the nanodielectrics [4, 5]. However, the trapped charges closed to the surface in the case of lower nanoparticle concentration has never been experimentally verified. It is important to validate the existence of deeply trapped charges close to the surface of the nanodielectrics, hence the formation of deep traps brought in by nanoparticles in the nanodielectrics. A novel/simple experimental procedure has been designed based on isothermal surface potential decay (ISPD) and PEA measurements.

In this paper, a series of PEA and isothermal surface potential decay (ISPD) combined measurements are designed and applied to a same type of nanodielectrics with different loading concentrations from 0 wt% (none nanoparticles), 0.5 wt% to 5 wt%, in order to validate the deep traps caused by the characteristics of nanoparticles and the proposed nanodielectrics charge transport model.

II. EXPERIMENT DETAILS

A. Specimen Preparation

Nanosilica produced by Sigma-Aldrich is used in this study. The range of its diameters is from 10nm to 20nm. For revealing the effect of the nanosilica loading ratios, three weight percentages including 0 wt% (without adding nanoparticles, named as BPE), 0.5wt% and 5wt% were used in this work. The host polymer used was 20wt% HDPE (Rigidex HD5813A BP Chemical) blend with 80wt% LDPE (LD100BW ExxonMobil Chemicals). The thickness of specimen is ~120 ± 5 µm. The process of specimen manufacturing is the same as that introduced in the previous work [9]. The manufacturing procedures were strictly followed from batch to batch, the nanoparticle loading ratio was the only variation for untreated nanosilica.

B. Experiment setup

The PEA system as shown in Fig. 2 has been widely used for the space charge profile measurement. The fundamental principle of the PEA system is that the accumulated charges within the sample can be excited and generating acoustic signal under the applied pulse field, the acoustic signals are detected and processed into space charge distribution within the sample. In the present PEA system, the applied pulse voltage is 600 V with 5ns pulse width. The semiconducting polymer was used as a top electrode for obtaining better acoustic impedance match and aluminum was used as a bottom electrode. The sample was firmly pressed between the top and bottom electrode. For all the measurements, the calibration was conducted at 10kV/mm.

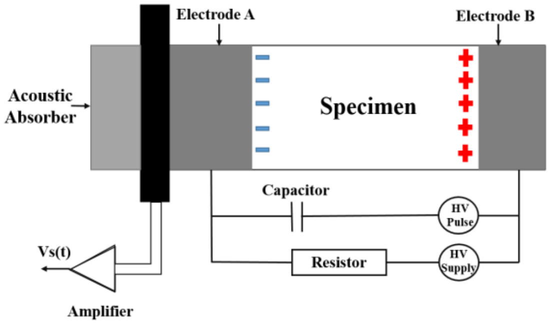

FIG. 2. The schematic diagram of the PEA system.

The ISPD system, as shown in Fig. 3, is applied to measure the surface potential and its decay caused by the charges captured by the deep traps in the nanodielectrics. The specimen was stressed within the PEA system at 50kV/mm, room temperature for 1hours. After that, the specimen was transferred to the ISPD system for measuring the remained potential caused by the trapped charges as soon as possible. By doing this, although those charges captured by the deep traps at the sub-surfaces of the specimen are hardly observed and distinguished by the PEA measurement system, their effects on surface potential can be detected by ISPD measurement system. Therefore, the presence of these deep traps introduced by the nanoparticles at the sub-surfaces of the nanodielectrics can be verified.

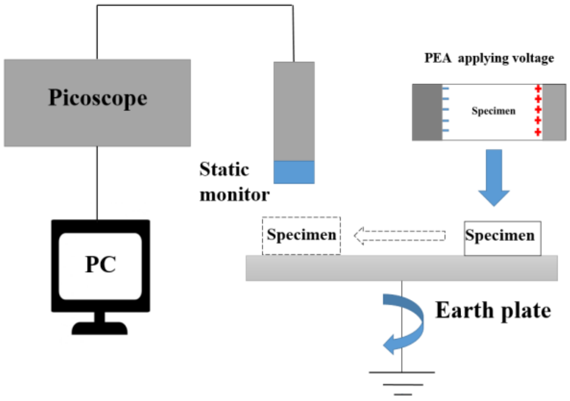

FIG. 3. The designed experimental setup for combining PEA method and ISPD method.

IV. RESULTS AND ANALYSIS

When the nanodielectrics samples with different loading concentrations are stressed under 50 kV/mm, the space charge profiles are shown in Fig. 4, Fig. 5, and Fig. 6. When no nanoparticles are loaded in the sample (named as BPE sample), as shown in Fig. 4, it can be found that large amount of positive charges are quickly accumulated in the bulk of the sample near the cathode (from 0 µm to about 50 µm) within the first 2 mins of the voltage application. After that, until 2 hours, the charge distribution is only slightly changing. These accumulated positive charges can induce more negative charges on the cathode and anode. Therefore, the magnitude of the negative cathode peak is increasing, while the magnitude of the positive anode peak is decreasing.

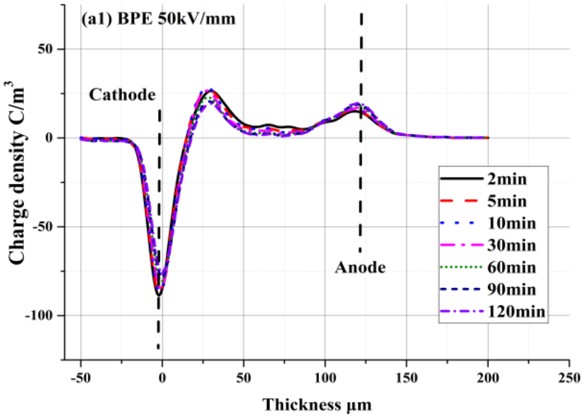

FIG. 4. The space charge distributions of the blended PE sample without adding nanoparticles under 50 kV/mm.

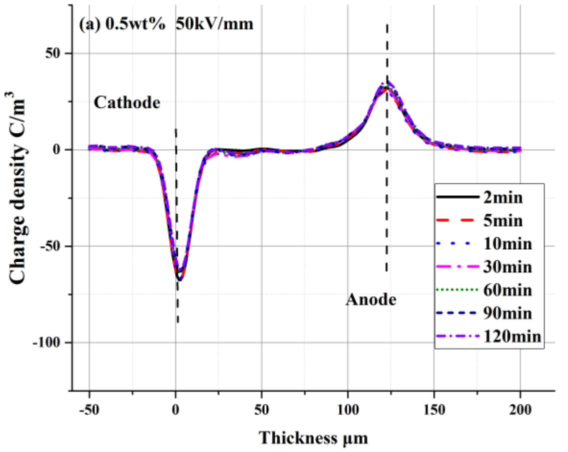

FIG. 5. The space charge distributions of the blended PE sample with a loading concentration of 0.5 wt% under 50 kV/mm.

When the nanodielecrtic sample with a low loading concentration (0.5 wt%) is stressed under 50 kV/mm, the obvious space charge suppression effect can be observed, as shown in Fig. 5, i.e. during the 2-hour voltage application period, very limited space charge accumulation can be observed within the bulk of the sample. Based on the proposed model in [2], the accumulated charges may locate in the regions very close to the two electrodes, i.e. the sub-surfaces of the sample. Therefore, the PEA measurement system cannot distinguish the accumulated charges from the capacitive electrode charges due to the limited spatial resolution. This will be further experimentally validated by the results of ISPD measurements in the following sections of this paper.

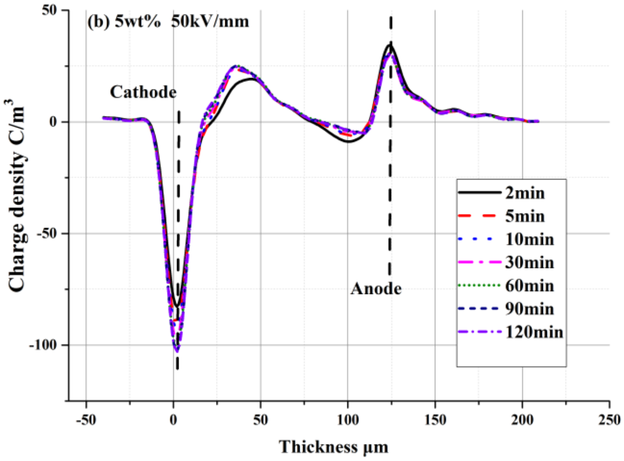

FIG. 6. The space charge distributions of the blended PE sample with a loading concentration of 5 wt% under 50 kV/mm.

When the loading concentration of the sample is increased to 5 wt%, the space charge profiles, as shown in Fig. 6, confirm that the space charge suppression effect is lost, i.e. large amount of space charges accumulate within the bulk of the sample. The charge dynamics in the sample with a high loading concentration are much more complicated compared with the previous two samples: large amount of hetero charges accumulate in the sample, i.e. positive charges accumulate near the cathode and negative charges accumulate near the anode. With the voltage application, the positive charge peak near the cathode keeps increasing, while the negative charge peak near the anode is gradually decreasing.

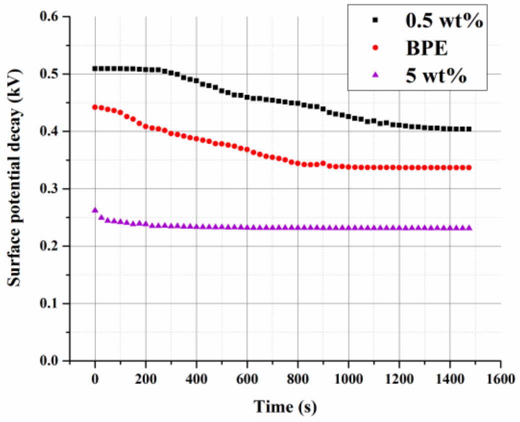

FIG. 7. The surface potential decay results for the three samples after stressing in the PEA system and a reference sample without stressing.

The space charge results shown above clearly demonstrate the influence of loading concentrations of nanoparticles on the space charge characteristics. The results confirm that the space charge suppression only occurs in the sample with a low loading concentration, which is consistent with the reports in literatures. To validate the deep traps introduced by the nanoparticles in the sample with a low load concentration and the proposed charge transport mechanism in nanodielectrics, the stressed samples in the PEA measurement system was quickly transferred to ISPD measurements.

The results of surface potential decay measurements of the stressed samples are shown in Fig. 7. After 2-hour 50kV/mm stressing, the surface potential of the sample with 0.5 wt% loading concentration show the highest value (0.51 kV), compared with the other samples, though no space charge accumulation can be observed in the bulk of the sample in PEA measurement. Therefore, the potential decay result clearly validates that the charges are trapped by the deep traps at the sub-surfaces of the sample. It is also observed that the potential decay rate of the sample with 0.5 wt% is slowest, i.e. about 1400s to reach a steady state, suggesting the trap depth within the low loading concentration sample is very large. The potential decay of the BPE sample starts from 0.45 kV, and gradually decreases to steady state in the period of 1000s. Compared with the result of the BPE sample, the higher surface potential voltage and longer time period to reach the steady state clearly validate that the deep traps are introduced into the sample by adding nanoparticles. And these trapped charges are located in the sub-surface region that can be hardly distinguished by the PEA measurement.

Compared with the result of the sample with a low loading concentration, the surface potential voltage of the sample with a high loading concentration (5 wt%) is much lower, i.e. potential decay starts from about 0.25 kV and quickly reaches the steady state (about 0.24 kV) within a much short period, 200s. The different electrical performances between the samples with different loading concentrations can be well explained by the proposed nanodielectrics charge transport model in [2]. The trapped charges can quickly and easily transport between deep traps with short distances generated by the high loading concentration of nanoparticles, and decay through the ground electrode via tunneling process.

Moreover, to evaluate the accuracy of the surface potential decay, the sample without stressing under HVDC voltage is also tested, as a benchmark to show the surface potential of the sample due to the electrification during the experimental setup processes. The surface potential is generally less than 0.08 kV, which is far less than the results of the stressed samples.

V. CONCLUSION

In this paper, the “deep trap” mechanism for nanodielectrics are experimentally validated by a series of combined PEA and ISPD measurements. The proposed and applied experimental method can overcome the drawbacks of the conventional TSC method and PEA method. The results clearly demonstrate that the suppressed space charge accumulation are observed in the sample with a low loading concentration by PEA method, while a high surface potential voltage can be measured by ISPD method. Compared with the results of the sample without adding nanoparticles, these results indicate that 1) the deep traps are introduced in the sample by adding nanoparticles; 2) charges are trapped in the sub-surface of the sample, though these charges cannot be observed by the PEA method. The comparisons between the samples with 0.5wt% and 5wt% nanoparticles well support the proposed charge transport model in nanodielectrics. The high loading concentration leads to strong space charge accumulations and low surface potential voltages, which may result from the tunneling process between deep traps.

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