

Plasma Polymer-coated on Nanoparticles to Improve Dielectric and Electrical Insulation Properties of Nanocomposites

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ABSTRACT

Polymeric nanocomposites have been shown to possess superior electrical insulation properties compared to traditional filled-resins. However, poor dispersion uniformity and insufficient filler-matrix interaction can adversely affect insulation properties of nanocomposites. In this study, the use of plasma polymerization is proposed to coat poly(ethylene oxide) polymer layers on silica nanoparticles. It is shown that better dispersion is achieved and C–O bonds are created between the surface functional groups of the nanoparticles and the host epoxy polymer. Electrical insulation tests demonstrate that the nanocomposites with plasma polymerized silica nanoparticles feature better resistance against electrical treeing, lower dielectric constant, and also mitigated space charge built-up. Therefore, plasma polymerization offers a promising fabrication technique to further improve the synthesis of nanocomposite dielectrics with superior electrical insulation properties.

Index Terms – Nanocomposite dielectrics, electrical insulation, plasma polymerization, partial discharge, electrical treeing, space charge.

1 INTRODUCTION

NANOCOMPOSITES, which are synthesized by incorporating nanoscale inorganic particles into conventional polymers, are regarded as promising candidates of insulation materials in electrical power equipment [1, 2]. However, one of the main challenges in fabricating this type of materials is the incompatibility between the inorganic filler particles and the organic host polymers. This can give rise to inhomogeneous dispersion of the nanofillers and poor filler-matrix interactions, resulting in unsatisfactory electrical insulation properties. At present, wet-chemical methods are widely used to modify the surface of nanoparticles. Such methods involve grafting functional groups on nanoparticles, which can effectively alter the nature of surface properties and improve the affinity with the surrounding polymer matrices [3]. However, wet-chemical processes are generally complicated, time-consuming, energy inefficient, and environmentally hazardous.

Non-equilibrium plasmas have been widely demonstrated as versatile tools in surface modification of nanomaterials [4-6]. In most of the plasma processes, the electric field is applied in the reaction zone, where the working gases are dissociated and reactive species are formed to interact with the substrates. Recently, we reported the use of atmospheric-pressure plasmas (APP) with helium as the working gas to modify SiO₂ nanoparticles, which resulted in the improved electrical insulation properties of the epoxy/SiO₂ nanocomposites [7-9]. In this work, we explore the effect of plasma polymerization in the synthesis of optimized nanocomposite insulation materials. To this end, a plasma polymerization process was custom-designed for nanoparticle surface polymerization. With the use of this approach, poly(ethylene oxide)-like films were uniformly coated on SiO₂ nanoparticles, resulting in excellent dispersion and adhesion with an epoxy resin matrix. The surface chemistry of the functionalized nanoparticles and the interfacial region of the nanocomposites were thoroughly characterized. In addition, electrical tests demonstrated the substantially improved resistance against electrical treeing, decreased dielectric constant, and also mitigated space charge

built-up within the nanocomposites with plasma-polymerized nanoparticles.

2 Experimental

2.1 MATERIALS SELECTION

Silica nanoparticles (AEROSIL® 380) with specific surface area of $380 \pm 30 \text{ m}^2/\text{g}$ were adopted as the nanofillers. The average particle size was 7 nm. Epoxy resin was employed as the host polymer for the nanocomposites. The two-part epoxy set consisted of bisphenol-A diglycidyl ether (BADGE) (Robnor Resins Ltd.) as the pre-polymer resin and triethylenetetramine (TETA) (Huntsman Advanced Materials) as the curing agent. Bis(2-methoxyethyl) ether (Diglyme; Sigma Aldrich) was adopted as the monomer for the plasma polymerization. This monomer has been widely used for the plasma polymerization of poly(ethylene oxide) (PEO)-like films, which were well-known for their non-fouling properties and biocompatibility [10, 11].

2.2 PLASMA POLYMERIZATION

A custom-designed plasma polymerization reactor (Figure 1) was developed for modifying the nanoparticles prior to mixing them with the host polymers. First, a RF power generator (PDX 500, Advanced Energy) with a built-in matching network was connected to a customized RF step-up transformer (AL-T500-V200, Amp-Line Corporation). After that, high voltage was applied to a cylindrical electrode suspending in a stainless steel chamber through a current limiting resistor (R1, 500 Ω). Helium and the monomer vapour were introduced to the chamber as working gases. In particular, the monomer vapor was carried by a separate stream of helium through a bubbler as the monomer was liquid at room temperature.

On the other hand, the nanoparticles were loaded in a quartz vial, which the HV electrode was extended to. The distance between the HV electrode and the bottom of the vial was 30 mm. Furthermore, magnetic stirring was maintained throughout the plasma polymerization process to ensure uniform exposure. To perform plasma polymerization on nanoparticles, the chamber first pumped down to a base vacuum of 13.3 Pa (0.1 Torr). Then, the Diglyme vapour was fed to the chamber at a rate of 100 standard cubic centimetres per minute (SCCM). By keeping the pressure of the reactor at 1.4 Torr, the plasma was ignited at the power of 10 W. 200 mg of silica nanoparticles was treated each time for 20 minutes.

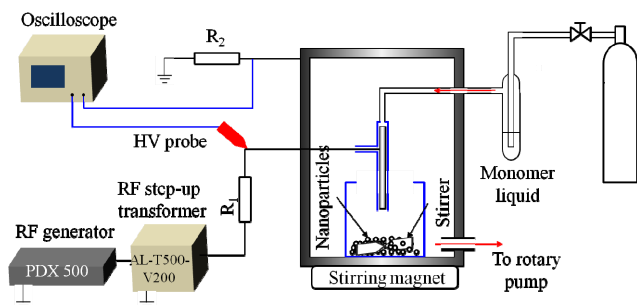


Figure 1. Configuration of the low-pressure plasma polymerization system.

2.3 NANOCOMPOSITE PREPARATION

First, 420 mg plasma-polymerized nanoparticles were dispensed into 10 g pre-polymer resin. The mixture then underwent ultrasonication for 30 minutes. Next, mechanical mixing was performed for 30 minutes by using an overhead blender. After that, 4g curing agent was added into the mixture, followed by mechanical mixing for another 30 minutes. The mixture was then degassed at 1 Torr until all bubbles disappeared. Afterwards, the nanocomposite liquid was dispensed into the pre-made moulds, followed by another degassing process. The casting was done under room temperature for 48 hours. The filler loading rate of the obtained nanocomposites was 3 wt%. Nanocomposites with as-received SiO_2 nanoparticles and the pure epoxy resin samples were also prepared as controls. The samples and their compositions are listed in Table 1.

Table 1. The notations and compositions of the samples.

Sample	Composition
PER	Pure epoxy resin
ER-380	Nanocomposite: epoxy resin / 3 wt % as-received SiO_2 nanoparticles
ER-PP380	Nanocomposite: epoxy resin / 3 wt % plasma polymerized SiO_2 nanoparticles

2.4 MATERIAL CHARACTERIZATION AND ELECTRICAL TESTS

X-ray photoelectron spectroscopy (XPS; SPECS SAGE 150) was utilized to analyze the surface chemistry of the plasma polymerized nanoparticles and nanocomposites. Scanning electron microscope (SEM; Zeiss Auriga) was used for investigating the dispersion of the nanoparticles. The nanocomposite samples for SEM imaging were coated with Au to avoid surface charging. The glass transition temperature of the nanocomposites was measured by a differential scanning calorimeter (DSC; Perkins Elmer STA6000). Each measurement was taken on 50 mg of the sample materials and repeated for 4 times.

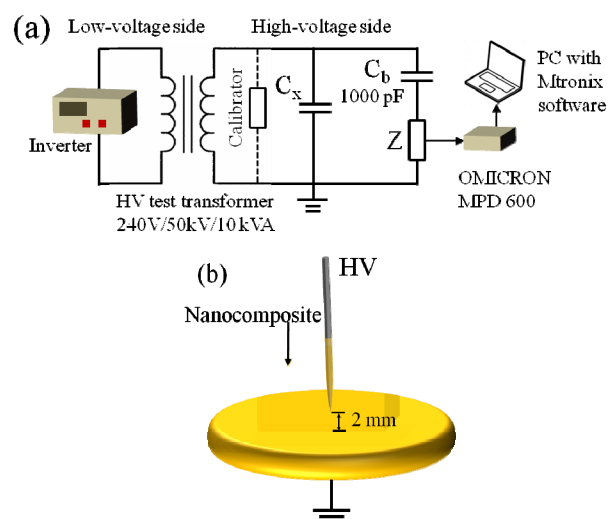


Figure 2. (a) Electrical treeing and partial discharge measurement circuit. (b) The needle-to-plane electrode.

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