Voltage-Induced Nonlinear Conduction Properties of Epoxy Resin/Micron-Silver Particles Composites

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Abstract. The nonlinear conduction properties of epoxy resin (ER)/micron-silver particles (MP) composites were investigated. Under sufficient high intensity applied constant voltage, the obvious nonlinear conduction properties of the samples with volume fraction 25% were found. With increments in the voltage, the conductive switching effect was observed. The nonlinear conduction mechanism of the ER/MP composites under high applied voltages could be attributed to the electrical current conducted via discrete paths of conductive particles induced by the electric field. The test results show that the ER/MP composites with nonlinear conduction properties are of great potential application in electromagnetic protection of electron devices and systems.

1. Introduction
Heterogeneous conductor-insulator composites, subjects of both theoretical and experimental studies, have a wide range of applications, including self-controlled heaters, overcurrent protectors, and sensors [1-5]. The nonlinear conduction properties of composites made from conducting powders dispersed in polymeric materials has been the subject of many previous investigations. In many of these studies [6-8], carbon black is employed as the conducting phase because it is chemically inert and readily available, and because such composites have wide industrial applications. In general, two sorts of nonlinear transport in such conductive binary mixtures of an insulator and a conducting component can be classified. One is electrical failure which takes place irreversibly in extreme conditions either owing to application of high voltage (dielectric breakdown [9, 10]) or current (burning of thermal fuse [11, 12]), namely, irreversible nonlinearity. The other sort corresponds to the reversible nonohmic (nonlinear) electrical conduction due to application of weak bias or current [13], that is, reversible nonlinearity.

Epoxy resin with excellent mechanical properties, thermal stability and chemical resistance has been widely used as a thermosetting polymer matrix for the preparation of the conductive composites [14-17]. In this paper, the voltage-induced nonlinear conduction properties of ER/MP composites were investigated. The obvious nonlinear conduction properties of the samples were found under sufficient high intensity applied voltage. With increments in the voltage, the conductive switching effect was observed. The results of this work indicate that electric current is conducted via discrete paths of conductive particles induced by the electric field. The test results show that the ER/MP composites with nonlinear conduction properties are of great potential application in electromagnetic protection of electron devices and systems.
2. Experimental Procedures

2.1. Materials
The conducting filler utilized here is composed of micron-silver particles (Baijujie Science and Technology Instrument Co., Ltd, Shenyang, China) with purity not less than 99.99% and a mean diameter of roughly 0.82 um (Fig.1). Insulating epoxy resin is supplied by Hui-Sheng Electronic Materials Co., Ltd., Chuzhou, China.

![Figure 1](image1.jpg)

**Figure 1.** Scanning electron micrograph of silver particles.

2.2. Preparation of ER/MP Composites
The composites comprising epoxy resin and conducting charge of micron-silver particles were synthesized in the form of cylindrical shape. The detail of procedures and conditions for fabrication were described briefly as follow: the desired filling volume concentration of the micron-silver particles was incorporated into the epoxy resin. The silane coupling agent was added and stirred for 30min for surface modification. The pretreated particles were vacuum-dried, incorporated into the epoxy resin in an oil bath at 60°C, and then stirred for 2 hours. The polyamide resin was added to the mixture and then stirred for 10min. The mixed material was placed in vacuum oven for 10min for removing bubbles. The mixture was then transferred to a sample mold mounted on a rotating holder in an oven. The diameter of round samples was about 40mm and the thickness was about 5 mm. The scanning electron micrograph of ER/MP composite with 25% filling volume concentration is shown in Fig.2.

![Figure 2](image2.jpg)

**Figure 2.** Scanning electron micrograph of ER/MP composite with 25% filling volume concentration.
2.3. Measuring Circuit
Measurements of the I–V characteristics were tested in the axial orientation. An NHWY6000-2 DC power supply (Nova Power Instruments Ltd., China) was utilized as the constant voltage source. Conducting paint was also coated on the two circular surfaces of the specimens held between two circular brass electrodes slightly larger in diameter than those of specimens in order to ensure good electrical contact. The improved test system based on voltmeter-ammeter (V-I) method was developed (see Fig.3). K1, K2 and K3 are remote control switches. For protecting the DC power, a large capacitor is used as the voltage source. The sample (S) and sample holder were placed inside a glass box filled with SF6 for avoiding discharge between electrodes (holder).

Figure 3. Measuring circuit for conductive property under applied voltage: R1-current limiting resistor, R2-sampling resistor, R3-discharge resistor, S-sample and DC-regulated power supply.

3. Results and Discussions
The relationship between current and applied voltage of the sample with 25% filling volume concentration was shown in Fig.4. The current-voltage curves of the composite material exhibited two regions. Under low voltages, the current of the sample show nonlinear with the increase of the applied voltage, which implies that free electrons are very few and conductive pathway is not formed in composites. The current of the sample sharply changes and shows conductive switching effect when the applied voltage is about 2.5 kV.

Actually, once a current is flowing, the following may then happen. In the first stage, the electrons bombarding a silver particle may be energetic enough to break some metallic bonds, thus setting free some silver ions which are then driven by the local field in a direction opposite to the electron flow. The net result is that silver is sputtered along some path forming a "filament", which is the "discrete conduction path". The samples investigated here also exhibit switching effects though with quite irregular switch-on voltage.

4. Conclusions
In this paper, the ER/ MP composites were fabricated. The nonlinear conduction properties of the samples were investigated under applied voltage, the obvious nonlinear conduction properties of the samples with volume fraction 25% were found and the conductive switching effect was observed when the applied voltage is about 2.5 kV. The test results show that the ER/MP composites are of great potential application in electromagnetic protection of electron devices and systems.
Figure 4. Current-voltage curve of ER/MP composites with 25% filling volume concentration.

5. References
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