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Effect of Environmental Temperature on the Insulating Performance of Epoxy/MgO Nanocomposites

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Abstract: This article reports on the development of nano-MgO/epoxy resin composites with various mass ratios via a solution blending method. The influence of MgO nanofillers on the thermal properties and the effect of environmental temperature on the insulating properties of the composite material were analyzed. The results show that the thermal conductivity of the composites increased with an increasing MgO nanofiller content. Compared with the pure epoxy resin, the thermal conductivity increased by 75% when the content of MgO nanoparticles was 7%. The volume resistivity first increased and then decreased with an increasing doping concentration. The volume resistivity increased by 26.8% in comparison with the pure epoxy resin when the content of MgO nanoparticles was 1%, while its dielectric constant and dielectric loss increased with temperature. In addition, the dielectric constant increased and the dielectric loss first decreased and then increased with an increasing MgO nanoparticle content. Moreover, the MgO composites changed from a glassy to a rubbery state, and the breakdown strength was significantly reduced with an increased temperature. When the temperature was higher than the glass transition temperature, the breakdown strength decreased by 51.3% compared with the maximum breakdown strength at 20 °C. As the content of MgO nanoparticles increased, the breakdown strength of the composite first increased and then decreased. The highest breakdown strength was achieved when the content of MgO nanoparticles was 1%, which was 11.1% higher than that of the pure epoxy resin. It was concluded that the MgO nanofillers can significantly improve the thermal properties of epoxy composites and their insulation performance at high temperatures.

Keywords: epoxy resin; thermal conductivity; volume resistivity; dielectric constant; dielectric loss; breakdown strength

1. Introduction

Epoxy resins are widely used in electronics due to their good electrical, thermal, and processing properties, being one of the main materials used in electrical equipment [1,2]. However, epoxy resins exhibit poor heat dissipation, which significantly shortens the service life of insulating equipment [3,4]. In recent years, higher requirements have been demanded on the electrical and thermal properties of epoxy resins owing to the development of the power industry toward high voltage and large capacities [5,6]. The improvement of the performance of polymer matrix composites using inorganic particles has been thoroughly investigated [7,8]. In 1994, Lewis first proposed the concept of nanocomposite dielectrics, which refers to a material composed of organic particles with a diameter of 1–100 nm in the polymer matrix [9]. Since then, nanocomposite dielectrics have become an electrical insulating material and a focus of extensive research for device applications and other fields. Studies have demonstrated that the thermal conductivity, dielectric, breakdown, and other main electrical properties of epoxy resins can be improved by doping with different kinds of nanoparticles, such as silicon dioxide, titanium dioxide, aluminum oxide, and magnesium oxide, among others. At present, the influence of nanoparticles on the thermal properties and dielectric performance of epoxy resins has been studied extensively [10–17]. It has been demonstrated that the introduction of micron-modified particles can increase the dielectric constant of epoxy resins, because of the higher dielectric constant of the organic particles compared with the epoxy matrix. Furthermore, Maxwell–Wagner-type interfaces can be introduced by micro-particles to increase the dielectric constant [11]. Imai et al. demonstrated that titanium dioxide epoxy composites exhibit better insulation performances than epoxy resins [12]. Hu et al. have shown that the electrical strength of nano-TiO_2 and epoxy resin composites was much higher than that of the pure epoxy resin and the micro-doped samples, at a frequency of 60 Hz [13]. Takahiro et al. found that the glass transition temperature of epoxy resins was higher than that of epoxy resins with nanolayered silicate at 20 °C, which effectively reduced the dielectric constant and dielectric loss at a high temperature [16]. Li et al. reported that the electrical strength of epoxy resins doped with nano-Al_2O_3 and TiO_2 increased when the nanoparticle content was 1% [17]. Nelson et al. investigated the dielectric performance of nanotitanium dioxide epoxy resins, demonstrating that nanofillers can reduce the interface polarization characteristics of traditional materials and reduce the accumulation of internal electric fields [18]. Imai et al. developed a method for obtaining nanofiller and micro-filler mixture composites, which improved their insulation properties while maintaining a low thermal expansion [19]. Nano-MgO is used in the field of high voltage insulation due to its high thermal conductivity, good thermal stability, and suppression of space charge accumulation. Majeed et al. investigated the effect of nano-MgO on the thermal conductivity and dielectric performance of epoxy and found that doped nano-MgO can effectively improve the relative dielectric constant, dielectric loss, and thermal conductivity and the improvement of the thermal conductivity was much greater than that of micron-doped Epoxy (EP) with the same mass fraction [20]. Agari et al. proposed a thermal conductivity model for nanothermal conductive materials. The model states that if the conductive block formed by the filler particles and the polymer conductive block is parallel to the direction of the heat flow, the thermal conductivity is the highest if the filler particles are distributed in parallel with the polymer matrix, and if the filler particles are distributed in series with the polymer matrix, the thermal conductivity is the lowest [21]. Thomas et al. focused on the effect of nano-MgO on the space charge, Direct Current (DC) conductance, and dielectric properties of epoxy resins [22]. Du et al. found that nano-MgO can improve the DC tracking resistance of the epoxy matrix [23]. Moreover, Guo et al. demonstrated that the addition of MgO nanoparticles can improve the tracking resistance of epoxy resins, and the best improvement was obtained when the nanoparticle content was 5 wt% [24]. Andritsch et al. conducted a broadband dielectric response test in a wide temperature range (−20 to 120 °C) and found that the relative dielectric constant of nano-doped epoxy was lower than that of pure EP. When the content of MgO nanoparticles was 2%, the relative dielectric constant was the smallest [25]. Kochetov et al. cured an MgO/EP composite at 160 °C for two days and measured its dielectric properties. It was found that the dielectric loss of the samples decreased to varying degrees [26]. Hinata et al. studied the dielectric performance of Low Density Polyethylene/MgO (LDPE/MgO) nanocomposites under a high Alternating Current (AC) voltage and estimated the content of MgO nanoparticles under an application of 50 and 200 Hz LDPE based on the dissipation current waveform under a high electric field. It was observed that the MgO nanoparticle content was dependent on the volume resistivity and relative dielectric constant under 50 and 200 Hz AC electric fields [27]. Maezawa et al. studied the space charge behavior of LDPE/nano-MgO composites containing MgO particles of different particle sizes at a high temperature and electric field. The results showed that between 30 and 60 °C, the electric field increased with an increasing amount of MgO nanoparticles. In terms of suppressing the injection of packet-like charges and reducing electric field distortion, MgO nanoparticles have a better effect than MgO micro-particles, especially when they contain a small amount of MgO nanoparticles [28]. Murakami et al. studied the electrical properties of LDPE/MgO nanocomposites under DC voltage, including volume resistivity and breakdown strength, and found that the DC breakdown strength and volume resistivity of the composites increased when adding MgO nanofillers [29]. Kawano et al. studied the electrical properties of magnesium oxide nanocomposites under DC voltage. Due to the addition of MgO nanofillers, the space charge of the composites under high electric fields was reduced. The mechanism by which MgO nanofillers improve the DC characteristics of LDPE has also been discussed [30].

At present, there is an urgent need for high-temperature and high-pressure insulating materials, and there are few reports on the insulation properties of nano-MgO/EP composites at different environmental temperatures. The insulation performance of nano-MgO/EP composite dielectrics at different temperatures has important practical applications. Therefore, this article studied the dielectric and breakdown characteristics of nano-MgO/epoxy composites at different temperatures. A blended solution method was used to prepare nano-MgO/epoxy composites (named epoxy-MgO composites) with different mass fractions, and the thermal conductivity and volume resistivity performance were analyzed. The influence of temperature on the electrical performance of nano-MgO/epoxy composites (epoxy-h-BN composites) with different mass fractions, including the dielectric performance and breakdown performance, was studied.

2. Materials and Methods

2.1. Materials

Bisphenol epoxy resin (Eponex 1513) E-51 was obtained from Changzhou Runxiang Chemical Co., Ltd., Changzhou, China. Methyltetrahydrophthalic anhydride (anhydride curing agent), an accelerator, was produced by Shanghai Aladdin Biochemical Technology Co., Ltd., Shanghai, China. 2, 4, 6-Tris (dimethyl amino) phenol DMP-30, MgO nanoparticles (500 nm) were acquired from Wuxi Zehui Chemical Co., Ltd., Wuxi, China.

2.2. Preparation of MgO/EP Composites

The epoxy resin was first weighed and the weight m1 was recorded. According to such a measurement, the weight of the curing agent, m2, and the weight of the accelerator, m3, were calculated to obtain a ratio of m1:m2:m3 of 100:80:1. The mass of the MgO fillers was calculated as $m4 = (m1 + m2 + m3) * n$, where n is the desired mass percentage. The resin was placed in an oil bath at 60 °C with electric stirring at 1000 rpm for 30 min. Then, the curing agent was added, and the mixture was stirred for 1 h before adding the phenol accelerator (DMP-30) (m3) and was stirred for an additional 30 min. The mixture was transferred to a vacuum box for 1 h until no bubbles were observed in the sample. The mixture was then poured into the molds, which were placed in a vacuum box and heated using the following procedure: 80 °C for 1 h, 120 °C for 1 h, and 150 °C for 2 h. After curing, the sample was left cooling to room temperature naturally.

2.3. Characterization and Testing

2.3.1. Characterization by Scanning Electron Microscopy

Scanning electron microscopy (SEM) was used to observe the surface morphology of the experimental samples. The samples were first placed in a vacuum drying oven at 60 °C for 2 to 4 h and then cleaned with ethanol. After drying, a conductive adhesive was applied evenly, and the dried sample was placed on the surface. The prepared sample was sprayed with gold and placed on the SEM at an accelerating voltage of 10 kV for 20 min. Finally, sample images were collected.

2.3.2. Thermal Conductivity

A multifunctional thermal conductivity tester (Xiangyi Instrument Co., Ltd., DRE-111, Xiangtan, China) was used to measure the thermal conductivity of the composites, and the heating current was set to 2A or 3A.

2.3.3. Volume Resistivity

An AZC36 high insulation resistance measuring instrument (Shanghai Anbiao Electronics Co., Ltd., Shanghai, China) was used to measure the volume resistivity of the composites.

2.3.4. Dielectric Performance

A high-frequency LCP digital bridge (Tonghui Electronics Co., Ltd., TH2826, Guangzhou, China) was used to measure the dielectric performance of the composites with different mass fractions at different temperatures. A three-electrode connection method was used to measure the capacitance and dielectric loss of the sample, and the dielectric constant of the sample was obtained according to Equation (1):

$$\varepsilon_{\mathrm{r}} = \frac{4 * C * h}{\pi(\mathrm{d}_1 + \mathrm{g})^2 \varepsilon_0} \tag{1}$$

where C is the capacitance of the sample, h is the thickness, d_1 is the diameter of the protected electrode, g is the electrode gap, and ε_0 is the dielectric constant of the vacuum.

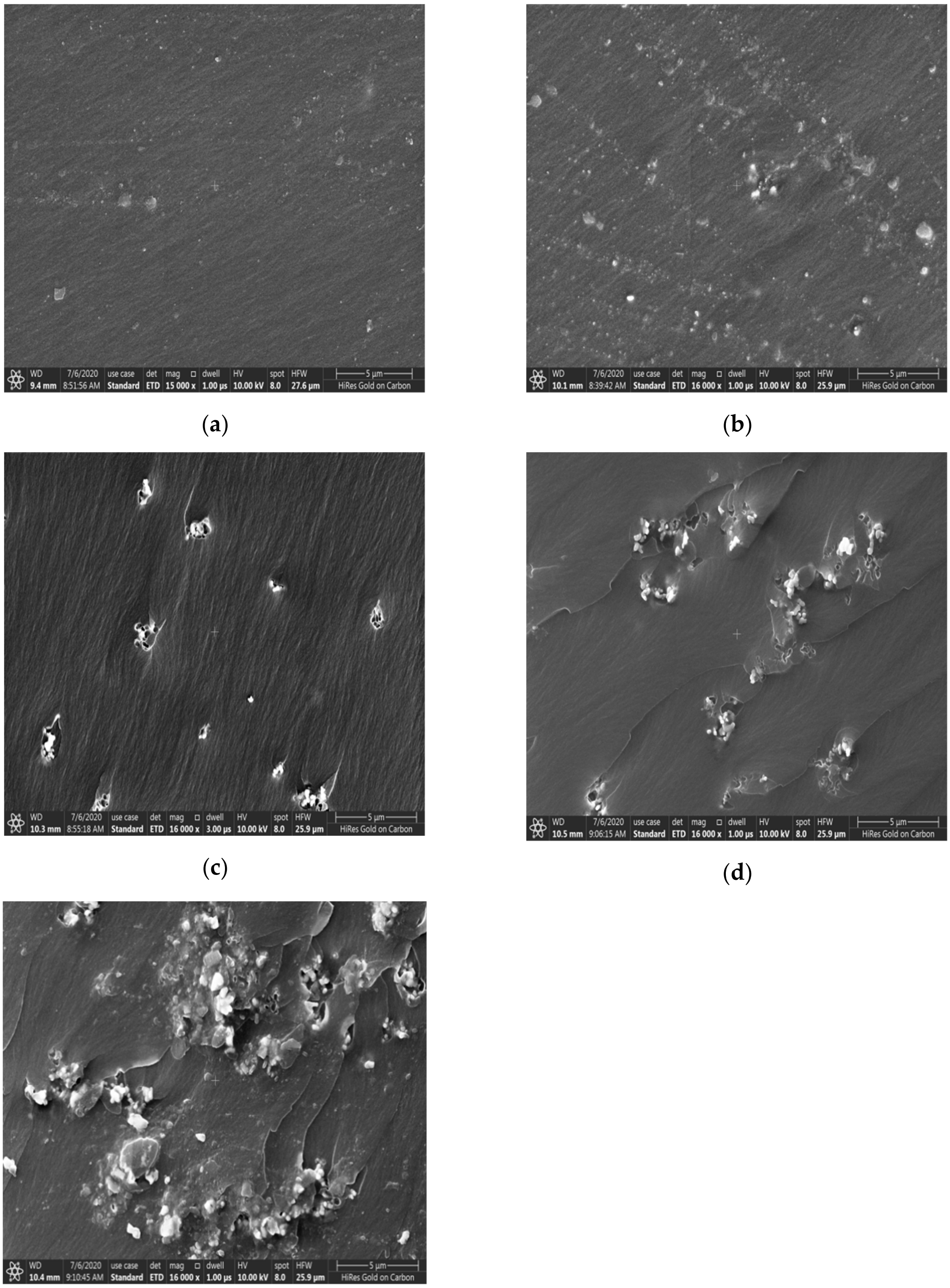
2.3.5. Breakdown Strength

A voltage breakdown test equipment (Huabo Technology Industry Co., Ltd., HJC-100KV, Changchun, China) was used to determine the breakdown strength of the composites with different mass fractions at different temperatures. A test ball electrode with a diameter of 25 mm was used, and the speed was uniformly increased by 1 V/s by pressing until the sample broke down. The ratio of the breakdown voltage of the test sample to the average thickness of the sample is the breakdown strength, expressed in kV/mm. Each sample was measured 10 times.

3. Results and Discussion

3.1. SEM Imaging

Figure 1 shows the SEM images of the cross-section of the samples with different contents of MgO nanoparticles. Figure 1a–e represent the SEM images of composites with an MgO content of 0.5%, 1%, 3%, 5%, and 7%, respectively. The MgO nanoparticles can be observed as more brightly colored in the sample. As the doping concentration increased, the distribution density of the MgO nanoparticles gradually increased, maintaining a uniform distribution with no obvious reunion phenomenon in the early stage. The epoxy resin composite has good interfacial properties. With the increase in the doping amount of the filler, the distance between nanometer magnesium oxide particles decreases, and the surface of the composite has large protrusion, which indicates that there is agglomeration in the material. When the packing mass fraction reaches 5%, the composites begin to agglomerate, but the degree of agglomeration is relatively light. With the increase in the packing mass fraction, the agglomeration became more and more obvious when the packing mass fraction reached 7%. The presence of aggregates is conducive to the formation of the thermal conductivity network chain, which increases the thermal conductivity of epoxy resin. Compared with pure epoxy resin, the volume resistivity of the composite material with a mass fraction of 7% was lower than that of pure epoxy resin, and the dielectric loss and breakdown performance of the composite material were significantly increased.



(**a**) (**b**)

(**c**) (**d**)

(**e**)

Figure 1. SEM images of cross-sections of MgO/epoxy composites. (**a**) 0.5 wt%; (**b**) 1 wt%; (**c**) 3 wt%; (**d**) 5 wt%; (**e**) 7 wt%.

3.2. Thermal Properties

As shown in Figure 2, the thermal conductivity of the composites increased with an increasing MgO nanofiller content [31]. This was attributed to the high thermal conductivity of the nano-MgO. When the content of MgO nanoparticles was 7%, the thermal conductivity of the composites increased by 75% compared with the pure epoxy resin. The thermal conductivity of the composites increased slowly at low nano-MgO doping ratios, which may be due to the fact that the nanoparticles were independent of each other, and a thermal conductive chain was not yet formed. The internal thermal conductivity of the epoxy composites consisted of a tandem structure, which increased with the increase in MgO nanoparticle content. The nanoparticles and polymer matrix interacted with each other at higher MgO nanoparticle contents in the matrix to form a single thermal conductive chain which reduced the thermal resistance of the channel and formed parallel structures, leading to the emergence of a thermal conductive network.

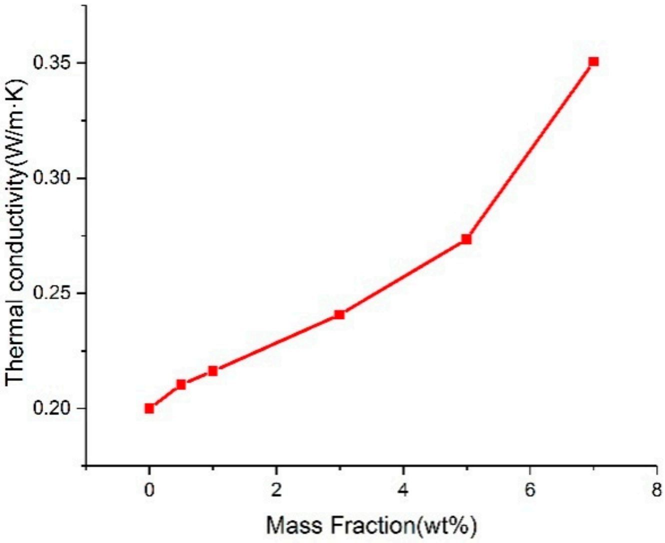


Figure 2. Thermal Conductivity of MgO/epoxy composites.

3.3. *Volume Resistivity*

Figure 3 shows the change of the volume resistivity of the nano-MgO/EP composite dielectric with the MgO nanoparticle content at room temperature. As the content of MgO nanoparticles increased, the volume resistivity of the composite dielectric first increased and then decreased. When the content of MgO nanoparticles was 1%, the volume resistivity of the composite dielectric reached the maximum, which was 26.8% higher than that of the pure epoxy resin, and then the volume resistivity began to decrease. When the content of MgO nanoparticles was 7%, the volume resistivity reached the minimum, which was 6% lower compared to the pure epoxy resin. This indicates that the doping of an appropriate amount of MgO nanoparticles can increase the volume resistivity of the epoxy resin, and excessive doping will decrease the volume resistivity. It was hypothesized that the concentration and mobility of carriers can affect the dielectric resistivity. The doping of trace nano-MgO increased the volume resistivity of the epoxy matrix because the size of the nanoparticles is small and there was a Coulomb blocking effect, in which the migration process of carriers in composites increases the resistivity. At the same time, the addition of nanoparticles introduced a large number of interfaces and deep traps into the matrix. The traps affect carrier mobility by trapping carriers, making the resistivity of the composites increase. As the content of MgO nanoparticles increased, the volume resistivity decreased significantly. The large specific surface area and high surface energy of the MgO nanoparticles have a strong influence on adsorbing impurities, so doping with nanoparticles will increase the carrier concentration in the composite system. Therefore, the concentration of carriers in the medium led to a decrease in the resistivity of the composites [32].

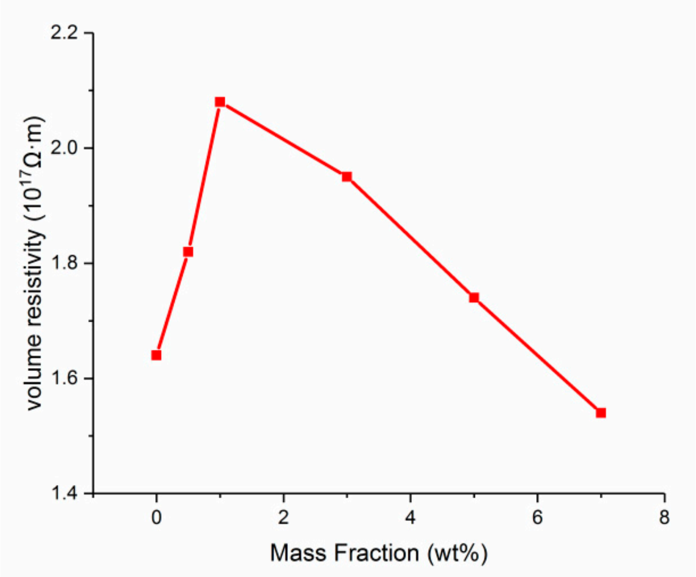
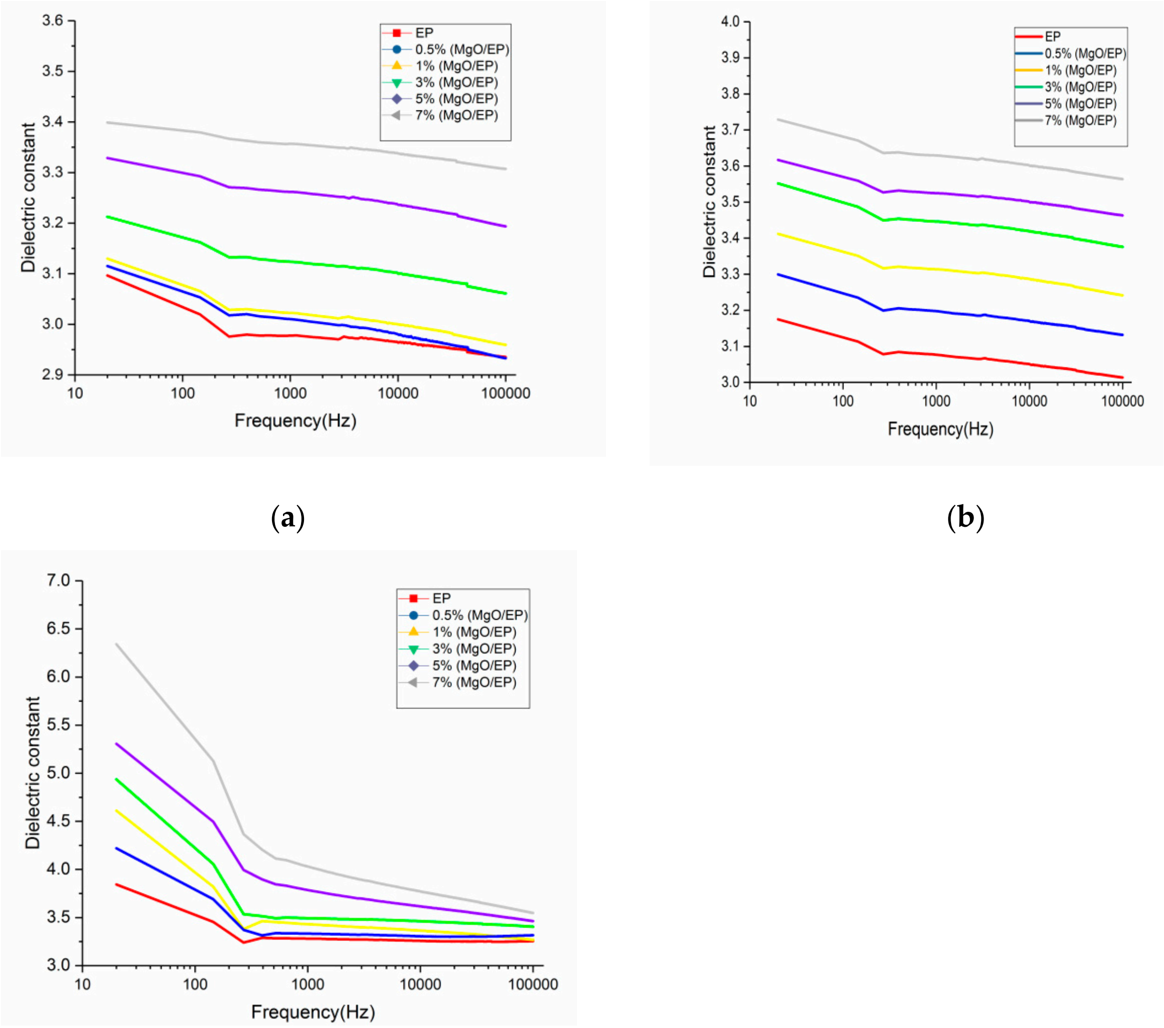


Figure 3. Volume resistivity of MgO/epoxy composites.

3.4. Dielectric Performance

The dielectric constant and dielectric loss of the pure epoxy resin and the MgO/epoxy composites with different mass fractions at environmental temperatures of 20, 80, and 150 °C were measured.

As shown in Figure 4, the dielectric constant of the epoxy composites gradually increased with the increase in MgO nanofillers. It was hypothesized that as the content of MgO nanofillers increased, the distribution of the MgO nanofillers in the epoxy-matrix became denser, and the degree of cross-linking in the matrix system increased, which enhanced the polarity effect of the interface, thereby increasing the dielectric constant of the composites. Comparing the dielectric constants at different temperatures, it was found that the dielectric constant of the epoxy composites increased with temperature because the positive and negative ions inside the material migrate in opposite directions under the action of an electric field, resulting in a non-zero average dipole moment. As the temperature increased, the decrease in the binding force between the positive and negative ions led to an increase in its polarization, and the dielectric constant increased. In addition, as the frequency increased, the dielectric constant of the epoxy composites decreased. This may be due to the action of the electric field, where the dipoles were deflected by the electrostatic force and arranged regularly along the direction of the electric field, showing polarity to the outside. As the frequency increased, the steering of dipoles may not keep up with the change in the direction of the electric field [17].

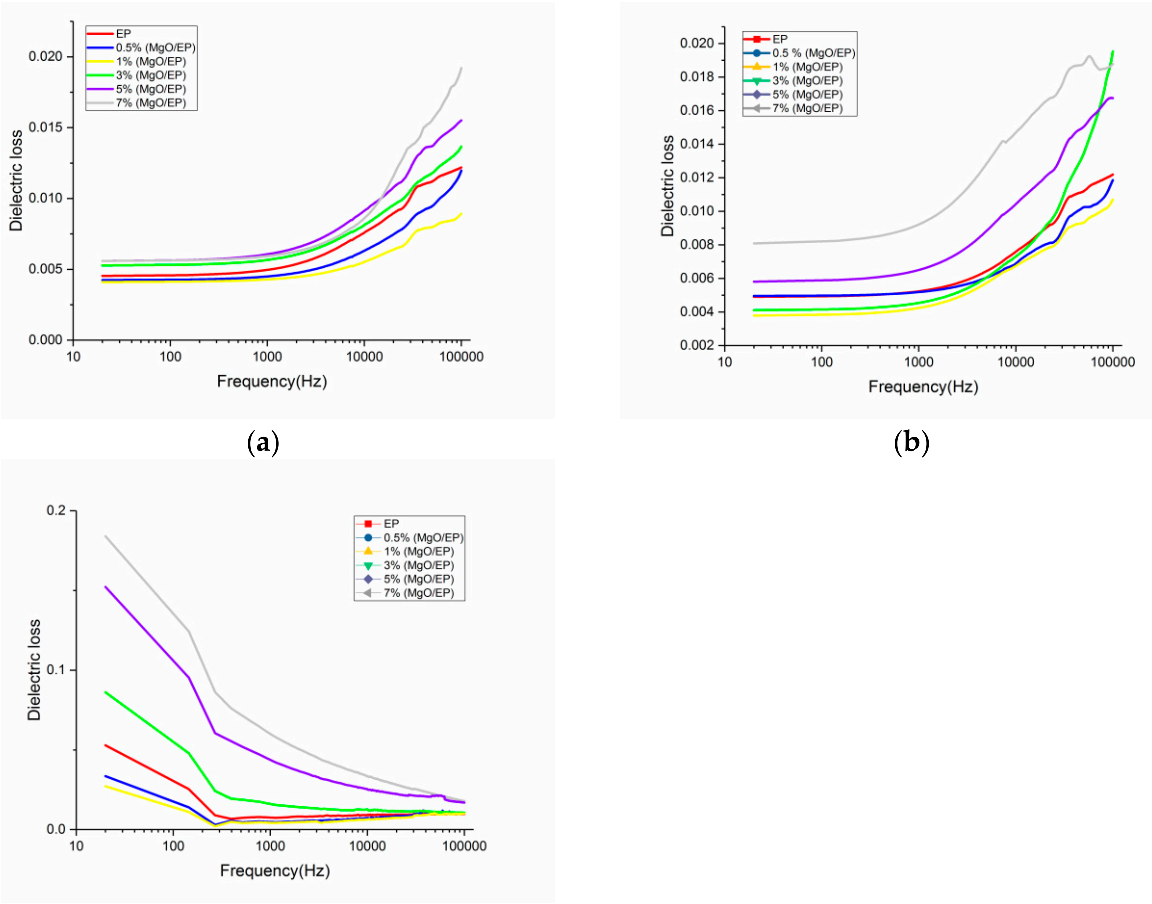


(a) (b) (c)

Figure 4. Dielectric constant of nano-MgO/epoxy composites as a function of frequency at (**a**) 20 °C; (**b**) 80 °C; (**c**) 150 °C.

As shown in Figure 5 the dielectric loss first decreased and then increased with the MgO nanoparticle content. When the content of MgO nanoparticles was 1%, the dielectric loss reached the minimum value, indicating that a small amount of nano-doping can reduce the epoxy resin. The dielectric loss of the composite dielectric then decreased, which may be because the nano-MgO and epoxy resin were tightly bonded in the interaction zone, making it difficult to turn the molecular chains in the composite dielectric, which inhibited the turning polarization process and reduced the steering polarization loss. When the content of MgO nanoparticles was greater than 1%, the dielectric loss increased with the increase in MgO nanoparticle content. This may be due to the overlap in the interaction zone, which formed a local conduction channel inside the material and increased the conductive. On the other hand, as the doping concentration increased, the agglomeration effect of MgO nanoparticles led to an increase in dielectric loss.

At low temperatures, the dielectric loss of the epoxy composites increased with the increase in frequency. At high temperatures, the dielectric loss decreased sharply with an increasing frequency. This may be because composites mainly exhibit a relaxation polarization and conductive loss in the electric field. At lower temperatures, composite dielectric loss consists mainly of relaxation polarization loss, and conductive loss is inversely proportional to frequency, which has a smaller effect at low temperatures. The dielectric loss thus increased with frequency. At high temperatures, the kinetic energy of the carriers inside the composite material increased, thereby improving carrier mobility, and the main body consisted of a conductive loss. With an increase in frequency, the change time of the electric field direction and the composite dipoles turn. When such a time is similar, the relaxation polarization loss gradually increases, causing the dielectric loss of composites to increase rapidly. With the increase in environmental temperature, the conductive loss is inversely proportional to the frequency at lower frequencies, and the dielectric loss of the composites decreased rapidly. As the frequency increased, the conductive loss decreased, and the relaxation polarization loss has a smaller effect at high temperatures, resulting in a decrease in the dielectric loss [20].



(**a**) (**b**)

(**c**)

Figure 5. Dielectric loss of MgO/epoxy composites as a function of frequency at (**a**) 20 °C; (**b**) 80 °C; (**c**) 150 °C.

3.5. Breakdown Performance

The process of breakdown is complex, and the measurement of breakdown data is affected by many factors. After years of experimental research, Swedish physicists finally discovered the law of the Weibull distribution [33]. This law is widely used to study the breakdown distribution and product service life prediction. The Weibull distribution expression of two parameters is:

$$P_e = 1 - e^{-(E/E_0)^{\beta}} \tag{2}$$

where P_e is the breakdown probability of the sample, E is the field strength when the sample is broken down, β is the shape parameter, and E_0 is the breakdown strength when the probability of occurrence is 63.2%. The logarithmic change of Equation (2) is:

$$In(-In(1-P_e)) = \beta(InE - InE_0) \tag{3}$$

If E is certain, then it can be calculated by:

$$P_e = \frac{i-0.5}{n+0.25}\oplus \tag{4}$$

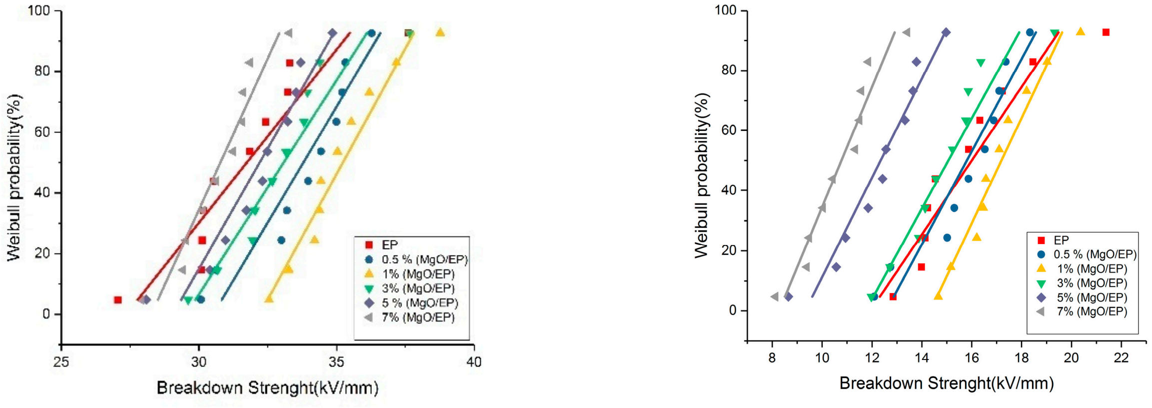
where i is the number of times the sample breakdown field strength is arranged in ascending order, and n represents the total number of tests for each sample.

The experimental results reveal that the breakdown strength of the composites at 20 and 80 °C was very small. When the temperature reached 150 °C, the breakdown strength of the composites decreased significantly. Compared with the strength at 20 °C, the maximum breakdown strength decreased by 51.3%. As shown in Table 1, the parameters of the Weibull distribution of the composites decreased with an increasing temperature. For example, the dispersion of breakdown strength increased and the stability of the composites at high temperatures decreased. This may be due to the fact that, at low temperatures, the composites are in a glassy state. At this time, the internal molecular structure of the composites is stable, the movement of the molecular structure is very low and the breakdown performance of the material does not change significantly, thus resulting in a low breakdown strength. When the temperature was higher than the glass transition temperature of the composites, the molecular chains inside the material began to move violently, showing the characteristics of a rubbery state, and as the temperature further increased, the binding of the molecular structure inside the material weakened. Consequently, the material exhibited viscous flow characteristics, and the molecular movement was violent. Under the action of an external electric field, the molecular structure changed greatly, and the performance was affected by the temperature. The dielectric loss greatly increased, and the breakdown strength of the material rapidly decreased. On the other hand, the interaction zone formed between the added MgO nanoparticles and the epoxy-matrix makes the structure of the composites closer. When the mass fraction of MgO nanoparticles increased, the interaction zone in the epoxy-matrix formed a pathway, which was conducive to the formation of a breakdown pathway, and the breakdown strength of the composites decreased. The increase in temperature led to intensified molecular motion and the inhibition of the interaction zone. This weakened as the temperature increased, decreasing the breakdown strength of the composites [34].

Table 1. Weibull distribution size and shape parameters of pure epoxy resin and MgO/epoxy composites with different mass fractions.

Percentage	E_0 (20/150 °C)		β (20/150 °C)	
EP	32.426	16.324	16.523	12.482
0.5 wt%	34.994	16.884	19.799	13.576
1 wt%	35.534	17.456	26.049	16.137
3 wt%	33.814	15.762	22.573	13.426
5 wt%	33.226	13.324	17.822	12.213
7 wt%	31.579	11.498	20.135	13.902

As shown in Figure 6, the breakdown strength first increased and then decreased with the increase in MgO nanoparticle content. At a concentration of 1%, the breakdown strength of the composite dielectric reached the maximum value of 35.15 kV/mm, which was 11.1% higher than the breakdown strength of the pure epoxy resin (31.63 kV/mm). When the content of MgO nanoparticles was 7%, the electrical strength of the composite dielectric was close to that of the pure epoxy resin. It was hypothesized that the introduction of a large number of heterogeneous crystal nuclei into the composites increased their crystallinity. The area of the interface formed between the crystalline and amorphous phase per unit volume increased, increasing the trap density of the composites and the trap energy level. Therefore, the carriers were easily captured during the movement of the electrodes, which hindered the directional movement of electrons to a certain extent. Moreover, the shape parameter of the nano-MgO/epoxy composites was relatively large, which indicates that the dispersion in the polymer was relatively uniform, and the unit cells were closely arranged. As a result, the electron pathway was tortuous and the breakdown field strength was effectively improved. With the increase in the MgO nanoparticle content, the electrical strength of the epoxy resin decreased, because when the composite was doped with a small amount of nanoparticles, the interaction zone formed by the particles and the epoxy-matrix presented no overlap. At this time, the interaction zone can be changed. As an isolated unit, it was difficult for carriers to overcome the barrier to participate in conduction, so the electrical strength increased. When the content of nanoparticles was greater than 1%, the distance between adjacent particles decreased, exceeding the seepage threshold, and the interaction zone overlapped. Consequently, local conductive channels were formed inside the sample. Under the action of the electric field, carriers migrated along these conductive channels, which accumulated a higher energy and collided with the defects in the interaction zone, resulting in the power frequency of the sample. Therefore, the electrical strength was reduced. On the other hand, when no fillers were added to the epoxy resin, defects appeared due to incomplete curing, resulting in a decrease in the breakdown strength. When MgO nanoparticles were added to the epoxy resin, a tight connection was formed between molecules and chains. This connection prevented the movement of initial electrons and brought MgO nanoparticles into close contact with the epoxy resin, eliminating the defects of the epoxy resin itself due to the large specific area of the nanoparticles. Moreover, MgO nanoparticles did not introduce defects, therefore the composites exhibited a higher breakdown strength.



(**a**) (**b**)

Figure 6. Weibull distribution breakdown strength of h-BN/epoxy composites at (**a**) 20 °C; (**b**) 150 °C.

4. Conclusions

Nano-MgO/epoxy composites with different doping concentrations were prepared. The influence factors of thermal conductivity, volume resistivity, dielectric property and breakdown property of composite materials were analyzed. The conclusions are as follows:

(1) The thermal conductivity of the composites increased slowly in the early stage and more rapidly in the later stage with an increasing MgO nanoparticle content. When the content was 7%, the thermal conductivity of the composites increased by 75% compared with the pure epoxy resin. It is proposed that the increase in thermal conductivity is due to the contact between the particles to form a local thermal conductive chain and network.

(2) As the content of MgO nanoparticles increased, the volume resistivity of the composite dielectric first increased and then decreased. When the content of MgO nanoparticles was 1%, the volume resistivity of the composite dielectric reached the maximum, which was higher than that of the pure epoxy resin. After reaching 26.8%, the volume resistivity began to decrease. When the content of MgO nanoparticles was 7%, the volume resistivity reached the minimum, which was 6% lower than that of the pure epoxy resin. It was hypothesized that the concentration and mobility of carriers affected the dielectric resistivity.

(3) The dielectric constant under different temperatures increased with the increase in temperature. This is because as the temperature increased which led to an increase in the degree of polarization, thereby increasing the dielectric constant. Moreover, the dielectric constant of the epoxy composites decreased with frequency. The reason may be that the dipoles are turned by the electrostatic force. The dielectric loss first decreased and then increased with the content of MgO nanoparticles. When the content was 1%, the dielectric loss reached the minimum. The reason may be that nano-MgO and the epoxy resin were tightly bound in the interaction zone, which inhibited the steering polarization process, thereby reducing steering polarization loss. The dielectric loss of the epoxy composites at low temperatures increased with frequency. This may be because the dielectric loss was mainly attributed to relaxation polarization loss at low temperatures and conductive loss at high temperatures.

(4) With an increasing MgO nanoparticle content, the electrical strength first increased and then decreased. When the content of MgO nanoparticles was 1%, the electrical strength of the nano-MgO/EP composite dielectric was higher than that of the pure epoxy resin. The reason may be that the added MgO nanoparticles introduced a large number of heterogeneous crystal nuclei. At low temperatures, the composites were in a glassy state, with a stable internal molecular structure. When the temperature was higher than the glass transition temperature of the composites, the maximum breakdown strength was reduced by 51.3% compared with the maximum breakdown strength at 20 °C. It is proposed that as the temperature increased, the binding of the molecular structure inside the material weakened and the material exhibited viscous flow characteristics.

Author Contributions: L.H., Y.L. conceived the presented idea; G.G. and Y.T. prepared the material samples; G.G., Y.T. measured the experimental data; L.H. and G.G. processed and analyzed the data; L.H. and G.G wrote the paper. All authors have read and agreed to the published version of the manuscript.

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