



Article

Effects of Four Different Types of Nitride and Oxide Particles on the Thermal Performance of an Epoxy Resin Used in Microelectronic Devices

Esin Akca ^{1,2} and Cevdet Kaynak ^{2,*} 

¹ ASELSAN Inc., Ankara 06750, Turkey; esakca@aselsan.com.tr

² Materials and Metallurgical Engineering Department, Middle East Technical University, Ankara 06800, Turkey

* Correspondence: ckaynak@metu.edu.tr

Abstract

The main purpose of this study was to investigate the effects of 10, 20, and 40 wt% micron-sized particles (aluminum nitride, aluminum oxide, silicon nitride, and silicon oxide) on the thermal performance of an epoxy resin used in microelectronic devices. Specimens were produced via a solution mixing technique followed by molding and curing. Although there were slight differences between the particle types used, various thermal analyses revealed that increasing the amount of all particle types significantly improved the thermal performance of the epoxy resin. The property that influences the thermal performance of microelectronic devices the most is thermal conductivity (λ). Heat produced during operation should be released via heat diffusion, which requires a certain level of λ . In this study, the use of a 40 wt% particle content increased the thermal conductivity (λ) by more than 3 times compared to neat epoxy (0.15 W/m·K). Another significant problem during the operation of these devices is the formation of “thermal strain mismatch” due to the different thermal expansion coefficients (α) of the materials used in the device that might lead to a loss of dimensional stability and malfunctioning. In this study, a particle content of 40 wt% decreased the thermal expansion coefficient of epoxy ($49 \times 10^{-6}/\text{K}$) down to $28 \times 10^{-6}/\text{K}$, a decrease of -43% . Thermal performance also depends on the Glass Transition Temperature (T_g) values. In this study, a particle content of 40 wt% increased the T_g from 51 °C (neat epoxy) to 68 °C, an increase of 17 °C, and increased the Thermal Degradation Temperature (T_d) from 324 °C (neat epoxy) to 356 °C, an increase of 32 °C. Moreover, it was also revealed that there was no decrease in the lap shear adhesion strength of the epoxy resin after incorporation of any of the particle types. Additionally, the particles also increased the mechanical rigidity of the epoxy in terms of Storage Modulus at 25 °C and 50 °C.



Academic Editor: Haifeng Zhao

Received: 5 February 2026

Revised: 25 February 2026

Accepted: 28 February 2026

Published: 7 March 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: epoxy resin; aluminum nitride; aluminum oxide; silicon nitride; silicon oxide; thermal behavior; microelectronic devices

1. Introduction

Epoxy resins are one of the most significant subclasses of thermosetting polymers with epoxide rings as the key functional group. In industry, the most common type of epoxy resin is based on the crosslinking reaction of the diglycidyl ether of bisphenol A (DGEBA) using an amine-type curing agent. This type of epoxy resin has a wide range

of applications including paints, coatings, adhesives, and as the matrix material of fiber-reinforced structural composites.

In the electronics industry, these epoxy resins are used in many microelectronic devices as the following:

- Die Bonding Adhesives: Epoxy resins are used to bond semiconductor chips to substrates, lead frames, or package bases.
- Underfills: Epoxy resins are used in flip chip and ball grid array (BGA) packaging to mechanically reinforce solder joints.
- Glob Top Encapsulation: Epoxy resins are directly used over wire-bonded semiconductor devices, forming a protective encapsulant.
- Conformal Coating: Epoxy resins are applied as thin, uniform layers onto printed circuit boards and electronic assemblies to protect them from moisture, chemicals, and ionic contaminants.
- Potting and Sealing: Epoxy resins are used to encapsulate entire electronic device to protect it from the environmental conditions.

In all these microelectronic applications of epoxy resins, the two most important aspects are their (i) curing behavior and (ii) thermal properties. Isothermal curing behavior is especially important in determining the optimal time and temperature for efficient curing of the components during their production. The thermal properties of epoxy systems such as the thermal conductivity, thermal expansion coefficient, Glass Transition Temperature, and Thermal Degradation Temperature are also critical for the performance of microelectronic parts that are subjected to severe heating and cooling cycles during operation.

In some ordinary applications, the use of neat epoxy resins might be sufficient for these requirements. For advanced microelectronic applications, the performance of epoxy resins can be improved by adding certain particles. Researchers have tested many different types, forms, and sizes of inorganic particles, particularly nitrides and oxides.

Thus, in order to improve the curing behavior and thermal properties of epoxy resins, four different types of particles were investigated in this study: aluminum nitride (AlN), aluminum oxide (Al₂O₃), silicon nitride (Si₃N₄), and silicon oxide (SiO₂). Previous studies on the effects of these particles on the isothermal curing behavior of epoxy are summarized below and in Table 1. However, the number of studies is very limited, and they focused on aluminum nitride [1], aluminum oxide [2,3], and silicon oxide [4].

A high degree of thermal conductivity (λ) is required to release the heat produced during the operation of the electronic parts. A literature survey revealed that aluminum nitride [5–13], aluminum oxide [8,10,12–21] silicon nitride [9,22–24], and silicon oxide [11,13,21] can be used at very high volume filler fractions (50–70 vol%) to improve the intrinsically low thermal conductivity (λ) of neat epoxies.

Studies have shown that the thermal expansion coefficient (α) can be lowered by adding aluminum nitride [7,11], aluminum oxide [12,21,25–27], silicon nitride [23,24], or silicon oxide [11,13,21,24,27,28] particles. α is a key parameter in epoxy electronic packaging as it determines the magnitude of thermal stresses when bonded to other substrates. Neat epoxy typically exhibits high α values in the range of $50\text{--}90 \times 10^{-6}/\text{K}$, which is far greater than that of semiconductor materials such as silicon, resulting in significant mismatch stresses during thermal cycling.

The Glass Transition Temperature (T_g) of an epoxy can be modified by incorporating aluminum nitride [11], aluminum oxide [3,20,25,26,29–31], silicon nitride [9], or silicon oxide [11,20,32–35] particles.

It has also been reported that addition of aluminum nitride [11,36], aluminum oxide [10,20,26,37,38], silicon nitride [23], and silicon oxide [11,13,20,28,33,35,37,39–41] could influence the Thermal Degradation Temperature (T_d) of neat epoxies.

In terms of adhesion strength of epoxies, only one study reported [42] the effect of adding silicon oxide.

As shown in Table 1, only one type of particle has been tested for effects on isothermal curing behavior and/or one or two thermal properties.

Table 1. Previous studies that tested the addition of AlN, Al₂O₃, Si₃N₄, or SiO₂ particles on the isothermal curing behavior and/or thermal properties of epoxy resins.

	AlN	Al ₂ O ₃	Si ₃ N ₄	SiO ₂
Isothermal Curing Behavior	[1]	[2,3]	None	[4]
Thermal Conductivity	[1,5–13]	[8,10,12–21]	[9,22–24]	[11,13,21]
Thermal Expansion Coefficient	[7,11]	[12,21,25–27]	[23,24]	[11,13,21,24,27,28]
Glass Transition Temperature	[11]	[3,20,25,26,29–31]	[9]	[11,20,28,32,34,35]
Thermal Degradation Temperature	[11,36]	[10,20,26,37,38]	[23]	[11,13,20,28,33,35,37,39–41]
Adhesion Strength	None	None	None	[42]

Therefore, in order to contribute to the literature on this topic, this study tested four different types of particles at three different loadings and measured their effects on the isothermal curing behavior and all thermal properties (thermal conductivity, thermal expansion coefficient, Glass Transition Temperature, and Thermal Degradation Temperature) of an epoxy resin. Additionally, since proper adhesion of epoxy-based parts in microelectronic devices is crucial, the effects of these particles on the adhesion strength were also analyzed, which was often neglected in previous studies.

2. Materials and Methods

In this study, the experimental work was conducted in five main stages: (i) size-range determination of the fillers, (ii) production of the particle-filled epoxy samples, (iii) calorimetry analysis of the samples to study isothermal curing behavior, (iv) analyses of the thermal properties of the specimens, and (v) adhesion strength measurements, which are necessary to determine the suitability of the epoxy for use in microelectronic devices. The experimental techniques used in each step are summarized below.

2.1. Epoxy Resin System and Oxide/Nitride Particles

The preferred epoxy resin and curing agent system for microelectronic devices were used: a diglycidyl ether of bisphenol A (DGEBA)-type epoxy and trimethyl-1, 6-hexadamine-type curing agent (EPO-TEK 301, Epoxy Technology Inc., Billerica, MA, USA). Four different fillers were used: aluminum nitride (AlN; purity: 99.95%), aluminum oxide (Al₂O₃; purity: 99.5%), silicon nitride (Si₃N₄; purity: 99.5%), and silicon oxide (SiO₂; purity: 97.3) particles (Nanografi Nanotechnology Inc., Ankara, Turkey).

In this study, the neat epoxy system (designated as EP) was filled with 10, 20, and 40 wt% of each particle type. The filled epoxy specimens are named based on the particle type and content (wt%): EP/AlN x%, EP/Al₂O₃ x%, EP/Si₃N₄ x%, and EP/SiO₂ x%.

2.2. Dynamic Light Scattering (DLS) Analysis

In order to determine the size distribution of the oxide and nitride particles, DLS (Malvern, Zetasizer Nano ZS, London, UK) measurements were carried out in triplicate at room temperature using a 633 nm red laser. Samples were prepared by sonicating them in isopropanol for 3 min prior to the measurements. In the size distribution calculations,

the refractive index values used for AlN, Al₂O₃, Si₃N₄, and SiO₂ were 1.76, 2.15, 2.04, and 1.46, respectively.

2.3. Scanning Electron Microscopy (SEM) Analysis

Scanning electron microscopy (SEM, FEI Quanta 3D 600 Dual Beam, Hillsboro, OR, USA) was performed at an accelerating voltage of 20 kV as an additional technique to determine the morphology and size range of the filler particles. The particles were adhered to double-sided carbon tape and sputter coated with gold to minimize electrostatic charging.

It should be noted that SEM analysis was also used to examine the fracture surfaces of broken specimens to observe the degree of filler dispersion in the epoxy matrix. Since filled epoxy specimens are not electrically conductive, they were also sputter coated with gold.

2.4. Production of Particle-Filled Epoxy Samples

As schematically illustrated in Figure 1, the epoxy-based liquid samples and solid specimens were produced using two main stages.

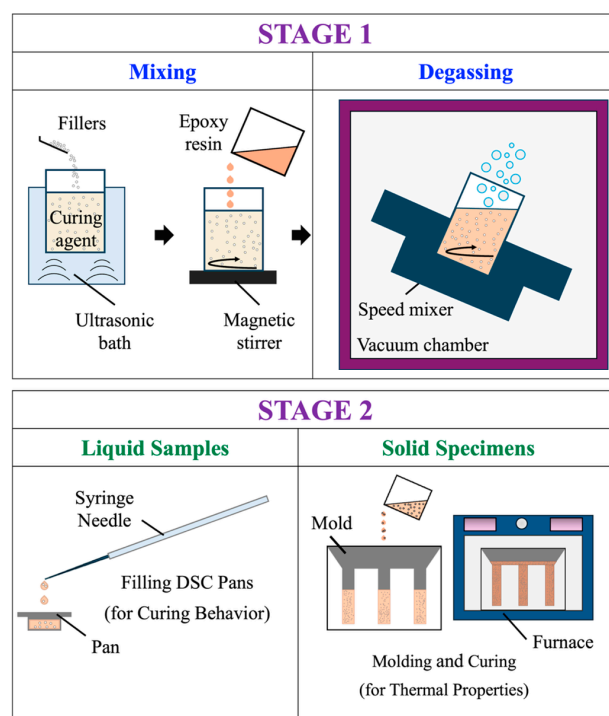


Figure 1. Two main stages for the production of liquid samples and solid specimens.

(i) Mixing and Degassing:

The viscosity of resin systems starts to increase as soon as the curing agent is added, leading to difficulty in homogeneously dispersing fillers. Therefore, the particles were added to the curing agent. In order to prevent agglomeration, this mixture was stirred in an ultrasonic bath (Elmasonic, P180H, Singen, Germany) for around 20 min at a power of 250 W. Then, epoxy resin (in a 4:1 ratio) was added to the curing agent/particle mixture and stirred using a magnetic stirrer (IKA, RCT Basic, Staufen, Germany) at 100 rpm for 10 min.

In order to remove any bubbles formed during mixing, degassing was applied along with further stirring using a speed mixer (FlackTek, DAC 1200-300 VAC, Louisville, CO, USA) at 2000 rpm for 5–10 min in a vacuum chamber.

(ii) Liquid Sample and Solid Specimen Production

After mixing and degassing, two different paths were followed depending on the required liquid sample or solid specimen geometry for the different analyses. In the first path, used for isothermal curing behavior analysis, was very straightforward: filling the DSC pans right after the degassing step.

In the second path used for the production of solid specimens for the thermal property analyses, specimen molding and then curing were performed. First, flexible molds with the specific cavity for each testing method were produced using a polydimethylsiloxane elastomer. After filling these molds with the prepared liquid resin systems, they were cured at 80 °C for 6 h in a furnace to obtain solid rigid specimens.

2.5. Differential Scanning Calorimetry (DSC) Analysis

DSC analysis (TA Instruments, DSC Q2000, San Diego, CA, USA) of 2–10 mg samples in sealed aluminum pans were conducted by recording the heat flow as a function of time. All procedures were performed under a nitrogen flow of 50 mL/min. Analyses were conducted to investigate the effects of filler particles on the isothermal curing behavior of the epoxy system. For this purpose, all samples were isothermally kept at 80 °C for around one hour.

2.6. Thermal Conductivity Analysis

In order to determine the effects of filler particles on the thermal properties of the epoxy system, thermal conductivity measurements were conducted. Neat and filled epoxy samples were molded and cured into disk-shaped specimens with a diameter of 50 mm and thickness of 2 mm according to the ASTM E1530 standard [43]. Prior to the measurements, the specimens were conditioned at room temperature and 50% relative humidity for 24 h. After applying a known heat pulse, the temperature rise at the surface was recorded and analyzed using the software of the instrument (TA Instruments, DTC-300, San Diego, CA, USA) to determine their thermal conductivity values. All measurements were carried out at ambient temperature.

2.7. Dilatometry Analysis

Next, dilatometry (Netzsch, DIL 402 Expedit Supreme, Selb, Germany) thermal analysis was performed on all specimen types in order to determine their thermal expansion coefficient values. Cylindrical specimens with a length of 30 mm and diameter of 10 mm were molded and cured in accordance with the ASTM E228 standard [44]. The specimens were cooled down to −180 °C and then heated to 70 °C at a cooling and heating rate of 10 °C/min.

2.8. Dynamic Mechanical Analysis (DMA)

In order to observe the effects of the particles on the Glass Transition Temperature of the epoxy system, DMA (TA Instruments, DMA Q800, San Diego, CA, USA) was conducted on bar-shaped (30 × 5 × 2 mm) molded specimens under the single cantilever mode from room temperature to 100 °C, using a heating rate of 5 °C/min. The results were used to determine the *Tan Delta* curves and the changes in the mechanical stiffness of the specimens were evaluated using the Storage Modulus (E') values at 25 °C and 50 °C.

2.9. Thermogravimetric Analysis (TGA)

To reveal effects of the particles on the Thermal Degradation Temperature of the epoxy system, TGA (TA Instruments, TGA Q500, San Diego, CA, USA) was conducted: 5–10 mg specimen pieces in platinum pans were heated to 800 °C at a heating rate of 10 °C/min under a nitrogen flow. The percent weight losses in each specimen were evaluated to determine their Thermal Degradation Temperature.

2.10. Lap Shear Adhesion Tests

Since epoxy systems are used for “adhesive or coating purposes” in many electronic devices, the effects of the particle fillers on the epoxy system were investigated by conducting lap shear adhesion tests in accordance with the ASTM D1002 standard [45].

Aluminum alloy plates ($100 \times 25 \times 1$ mm) were used as the adherent; they were carefully cleaned with acetone and isopropanol in an ultrasonic cleaner (Elma, Elmasonic Select 80, Singen, Germany) and then neat and filled liquid epoxy resin samples were uniformly applied and carefully pressed in between two aluminum plate adherents. The proper alignment fixture was used so that the same bonding area (12.5×25 mm) could be used for each specimen (Figure 2).

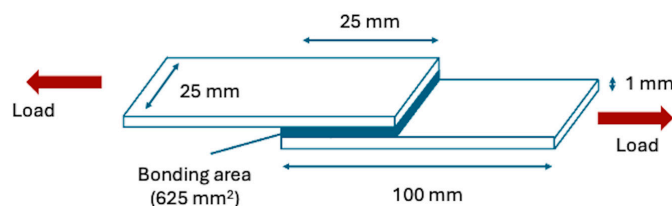


Figure 2. Schematic of the lap shear adhesion test specimens.

After curing the specimen system at $80\text{ }^{\circ}\text{C}$ for 6 h in an oven, tensile loads were uniformly applied (at a rate of 0.5 mm/min) using a Universal Test System (Instron 5960, Norwood, MA, USA). The load versus displacement curves obtained from each test were evaluated to determine the lap shear strength (MPa) of each specimen system by dividing the maximum in load (N) to the bonding area (mm^2). The tests were repeated three times for each specimen. Failure modes (adhesive, cohesive, or mixed) were also examined after each test.

3. Results and Discussions

First, the size ranges and dispersion of the oxide and nitride particles in the matrix will be discussed, followed by the effects of each type of particle on the isothermal curing behavior and thermal properties of the epoxy resin system and their adhesion strength.

3.1. Size Range and Dispersion of Oxide and Nitride Particles in Epoxy Matrix

SEM analysis was conducted to determine the size range and morphology of the particles and found that their diameter range was $1\text{--}5\text{ }\mu\text{m}$, which could be classified as “microparticles” (Figure 3). The aluminum nitride particles had a rather “polyhedral” morphology, while the other three had more “round” morphology.

The DLS analysis results showed a normal (Gaussian-type) size distribution (Figure 4) with average particle sizes of 2341, 1892, 1211, and 661 nm for AlN, Al_2O_3 , Si_3N_4 , and SiO_2 , respectively, which are consistent with the size range obtained from the SEM analysis (Figure 3).

To determine the degree of filler dispersion in the epoxy matrix, SEM analysis was conducted on the fractured surfaces of the specimens containing 10, 20, and 40 wt% particle contents. Since high filler contents were required to improve the thermal properties, the particles (all types) were found to be generally dispersed in the matrix with a certain degree of “agglomeration”. Figure 5 shows examples of the dispersion of a 20 wt% particle content in the epoxy matrix.

Bekeshev et al. [46] revealed that chemically modifying the surface of fillers increases their chemical compatibility with epoxies, thus inducing better dispersion and mechanical characteristics. Similar observations were also observed in other studies [39,47–51].

However, because of the “outgassing” problem in many microelectronic devices, no surface treatment was applied to the particles in this study. Microelectronic components in which “outgassing” is a key reliability concern include MEMS, sensors, optoelectronics, and power modules.

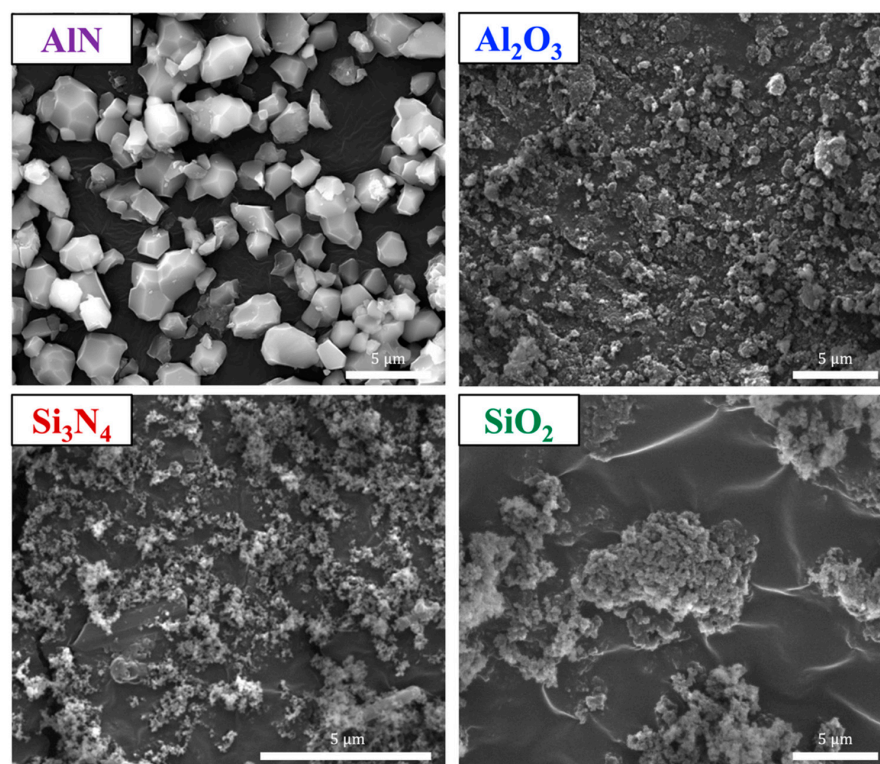


Figure 3. SEM images showing size range and morphology of the particles.

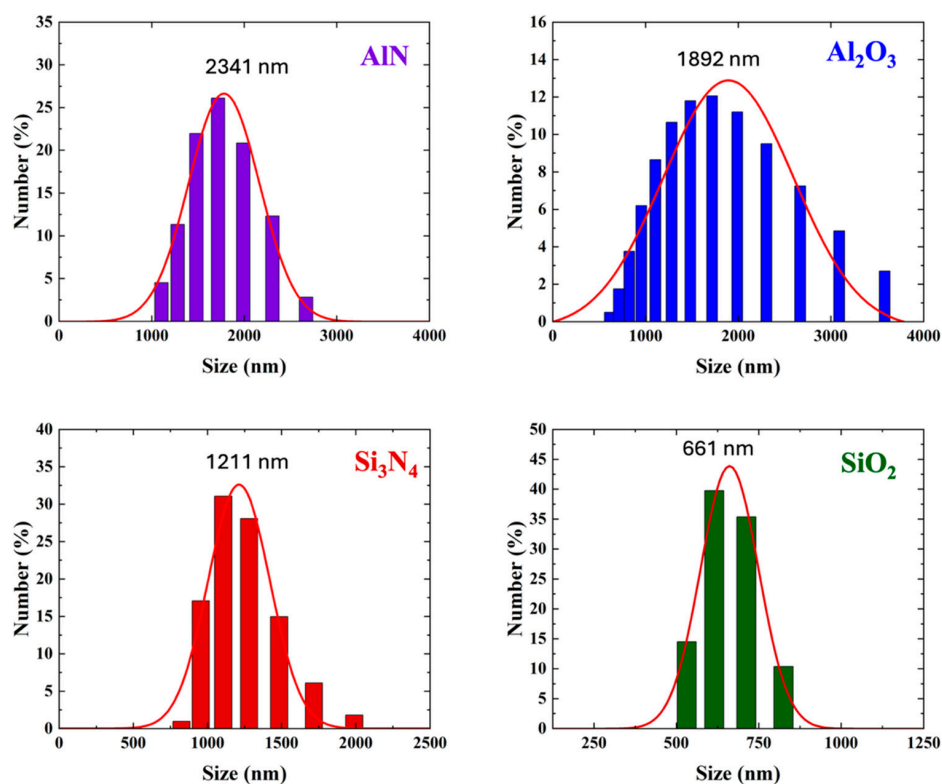


Figure 4. Size distribution of the particles determined by DLS analyses.

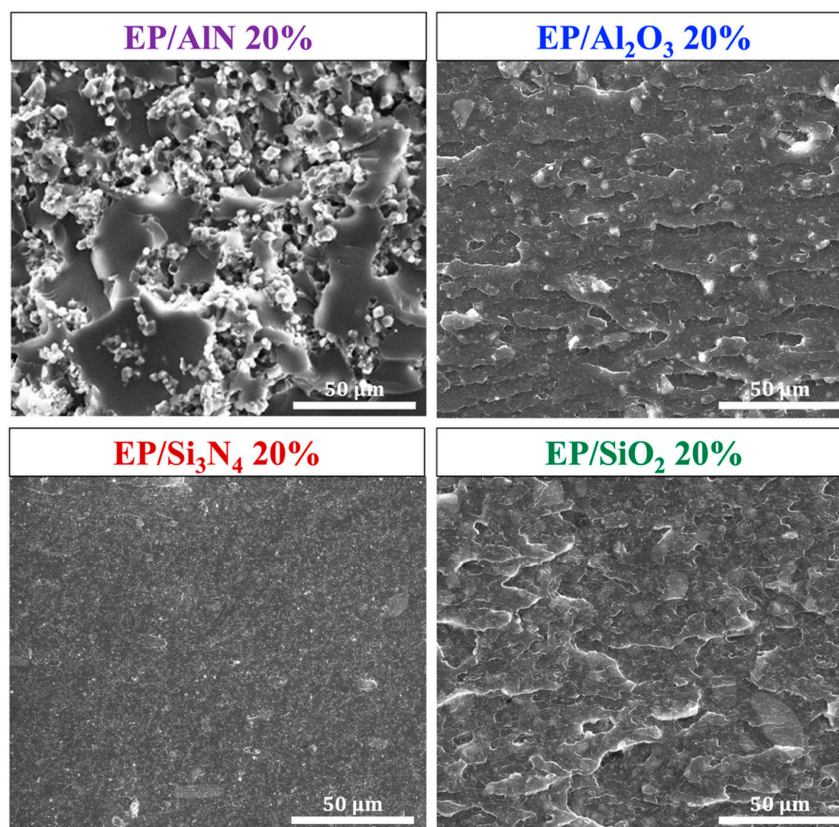


Figure 5. SEM images showing dispersion of the particles in the epoxy matrix.

3.2. Effects of Particles on Isothermal Curing Behavior

In industrial applications including microelectronic devices, epoxy resin systems are generally cured isothermally at the temperature recommended by the resin suppliers or according to the user's experience. The temperature used for the resin system in this study was 80 °C. Therefore, in order to reveal effects of the oxide and nitride particles on the isothermal curing behavior of the epoxy system, isothermal DSC analyses were conducted on the liquid samples at 80 °C.

Figure 6 shows a comparison of the heat flow versus time curves of all filled samples and the neat epoxy (EP) sample. The exothermic peaks of the curing reaction decreased as the amount of oxide and nitride particles used increased.

In practice, curing “conversion” versus “time” curves are more informative than isothermal “heat flow” versus “time” curves in demonstrating the effects of particles on isothermal curing behavior. Therefore, the data in Figure 6 were transformed into curing conversion versus time curves (Figure 7).

The percent conversion at each time point was determined by calculating the cumulative area between the curve of the thermogram and the x -axis, with respect to the overall heat produced by the reaction.

In addition, all the curves in Figure 7 were evaluated in terms of time required for 50%, 75%, and 100% curing conversion (Table 2).

Figure 7 and Table 2 show that the incorporation of the nitride and oxide particles into the epoxy resin significantly increased the time required for isothermal curing conversion. Delays in the isothermal curing conversion were more pronounced at higher particle loadings. For example, when particles were added at a dose of 40 wt%, the time required for 50% curing conversion increased from 2 min (neat epoxy) to up to 5 min; for 75% curing conversion, the time increased from 4 min up to 10 min, and for 100% curing conversion, the time increased from 16 min up to 27 min.

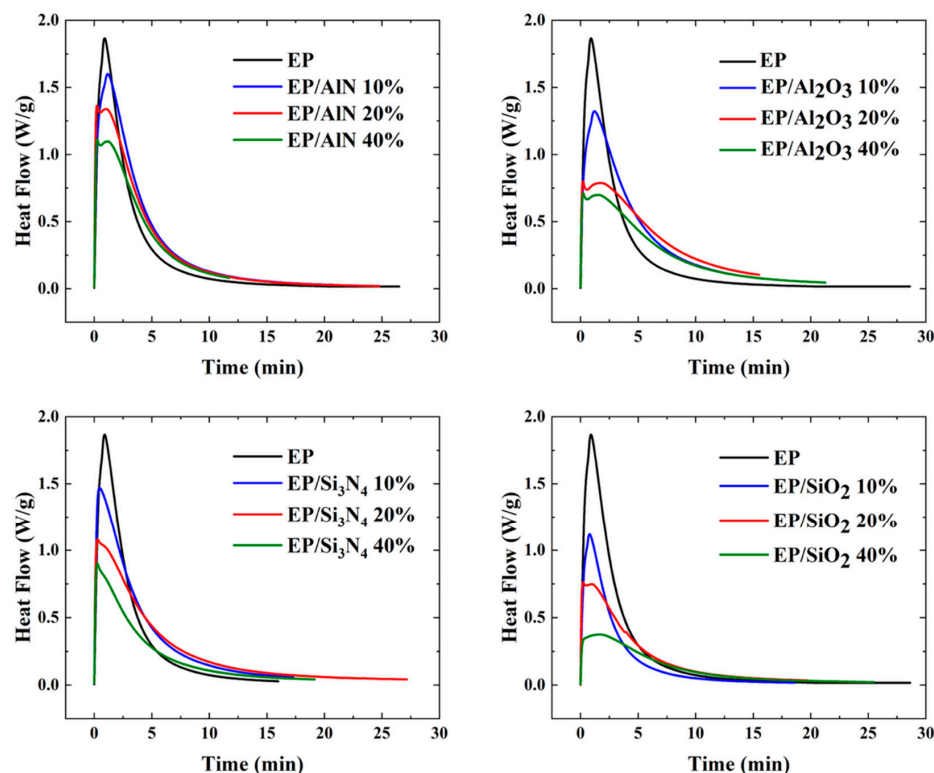


Figure 6. Effects of the particles on the isothermal heat flow versus time curves of the epoxy.

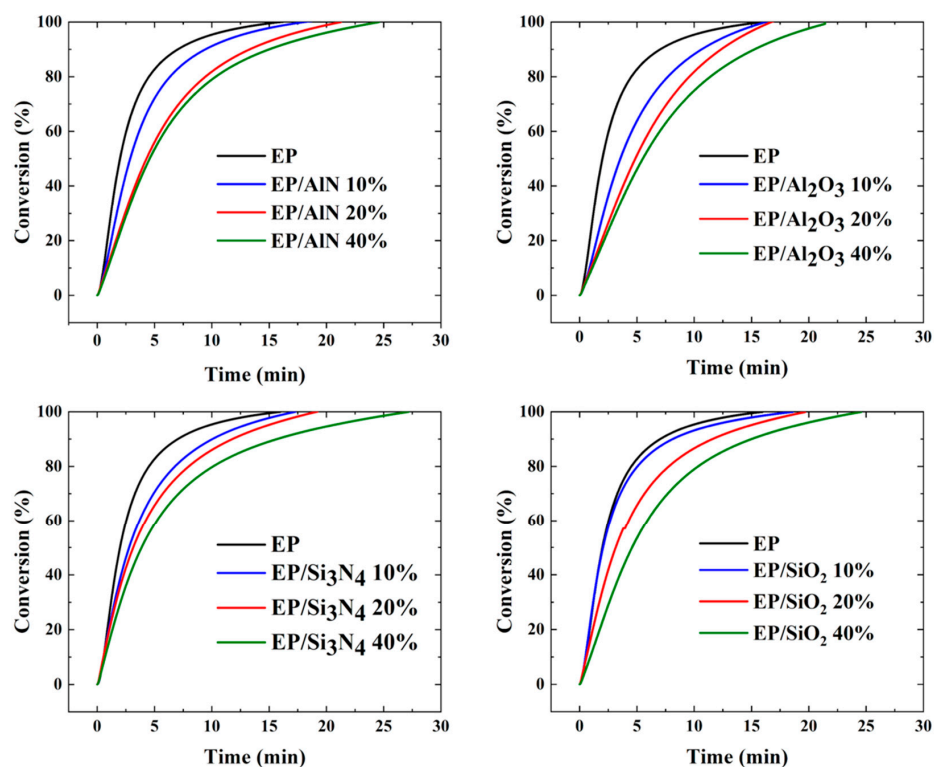


Figure 7. Effects of the particles on the curing conversion versus time curves of the epoxy.

These increases in conversion time for isothermal curing might be due to the physical constraint action of the particles, leading to decreases in the segmental mobility of the epoxide and amine oligomers required for efficient cross-linking reactions during curing. Therefore, increasing the amount of the particles in the epoxy resin system increases the particle-induced steric hindrance, leading to more delays during isothermal curing.

The AlN, Al₂O₃, Si₃N₄, and SiO₂ particles all lead to reductions in the curing rate relative to neat epoxy, reflecting increased viscosity, reduced free volume, and diffusion-controlled limitations imposed by the particulate phases. At higher filler loadings, these effects were more pronounced for all systems, with extended reaction tails reflecting delayed network formation and vitrification.

However, the degree of this retardation also depends on filler chemistry and interfacial characteristics. Among the investigated fillers, AlN and Si₃N₄ exhibited lower degrees of suppression of the initial curing rate, particularly at moderate filler loadings, suggesting comparatively weaker restriction of epoxy–hardener mobility during the early stages of curing. This behavior could be attributed to their lower surface polarity and more thermally conductive nature, which can promote more homogeneous heat distribution and reduce localized vitrification effects.

Table 2. Effects of the particles on the values of $t_{50\%}$, $t_{75\%}$, and $t_{100\%}$ (time required for 50%, 75% and 100% curing conversion).

	$t_{50\%}$ (min)	$t_{75\%}$ (min)	$t_{100\%}$ (min)
EP	2.1	3.9	16.1
EP/AlN 10%	2.9	5.4	18.1
EP/AlN 20%	4.4	8.4	21.3
EP/AlN 40%	4.6	9.1	24.6
EP/Al ₂ O ₃ 10%	3.6	6.7	16.2
EP/Al ₂ O ₃ 20%	4.9	8.6	16.7
EP/Al ₂ O ₃ 40%	5.6	10.2	21.4
EP/Si ₃ N ₄ 10%	2.9	5.7	17.3
EP/Si ₃ N ₄ 20%	3.2	6.9	19.1
EP/Si ₃ N ₄ 40%	3.9	8.4	27.2
EP/SiO ₂ 10%	2.2	4.3	18.6
EP/SiO ₂ 20%	3.2	6.6	19.8
EP/SiO ₂ 40%	4.6	8.9	24.6

In contrast, Al₂O₃ and especially SiO₂ induced a more significant reduction in peak reaction rate and broader curing profiles, indicating a dominant influence of physical hindrance and stronger interfacial confinement. The higher polarity on the surfaces of Al₂O₃ and SiO₂ likely enhance filler–matrix interactions, leading to constrained interphase regions that limit reactive group accessibility and accelerate the transition to diffusion-controlled kinetics.

Yang et al. [4] reported similar observations where SiO₂ incorporation reduced the curing rate due to steric hindrance from the inorganic network.

3.3. Effects of Particles on Thermal Conductivity

The most important property influencing the thermal performance of epoxy resins in microelectronic devices is thermal conductivity (λ). Heat produced during the operation of these devices should be released to the environment via heat diffusion, which requires a certain λ value. Unfortunately, all polymers, including epoxy, have extremely low levels of thermal conductivity. For the neat epoxy resin used in this study, its λ is 0.15 W/m·K, which is mainly due to the cross-linked network structure of its thermosetting polymers, leading to significant phonon scattering and limited heat transport.

Since ceramic materials, including the nitride and oxide particles used in this study, have intrinsic thermal conductivity values much higher than 10 W/m·K, one of the best

ways to improve the thermal performance of epoxy resins is incorporating these types of particles.

The thermal conductivity analyses (Figure 8 and Table 3) revealed that, although there were slight differences between the types of particles, increasing the amount of particles increased the thermal conductivity values. For example, particle contents of 10, 20, and 40 wt% increased λ values by 180%, more than 200%, and more than 300%, respectively.

Although a more than three-fold increase in λ (from 0.15 to 0.56 W/m·K) seems to be insignificant compared to the extremely high conductivities of metallic materials, it would significantly contribute to the thermal performance of microelectronic parts made from these particle-filled epoxies since the heat produced during the operation of devices using these epoxies would be released more than three-fold more easily compared to parts made from neat epoxy. In the literature on particle-filled epoxy systems [1,11,17,19,52–54], very similar λ increases of around 0.40–0.50 W/m·K were also reported.

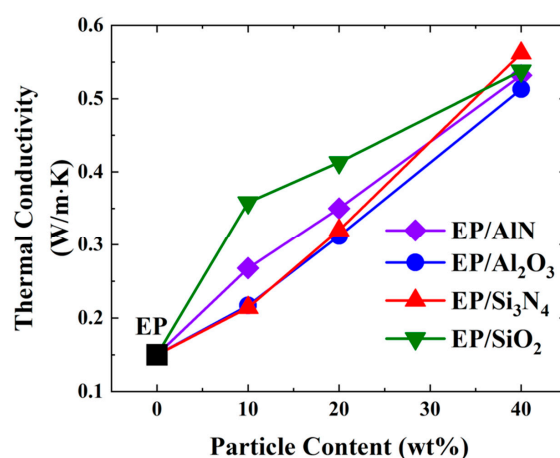


Figure 8. Effects of the particles on the thermal conductivity of the epoxy.

Table 3. Effects of the particles on the thermal conductivity (λ), thermal expansion coefficient (α), Glass Transition Temperature (T_g), and Thermal Degradation Temperature (T_d) of the epoxy.

	λ (W/m·K)	α ($10^{-6}/K$)	T_g ($^{\circ}C$)	T_d ($^{\circ}C$)
EP	0.15	49	51	324
EP/AlN 10%	0.27	45	54	334
EP/AlN 20%	0.35	44	63	342
EP/AlN 40%	0.53	28	68	349
EP/Al ₂ O ₃ 10%	0.22	42	58	329
EP/Al ₂ O ₃ 20%	0.31	38	62	337
EP/Al ₂ O ₃ 40%	0.51	34	65	340
EP/Si ₃ N ₄ 10%	0.21	44	54	332
EP/Si ₃ N ₄ 20%	0.32	40	62	338
EP/Si ₃ N ₄ 40%	0.56	35	65	345
EP/SiO ₂ 10%	0.36	44	55	335
EP/SiO ₂ 20%	0.41	42	61	339
EP/SiO ₂ 40%	0.54	40	65	356

These improvements in the λ values with increasing particle content can be attributed to the progressive formation of thermally conductive pathways within the epoxy matrix. As the nitride and oxide particle content increases, particle–particle interactions become more significant, facilitating the formation of certain conductive pathways that reduce phonon scattering at the polymer–filler interfaces and improve overall heat transport.

3.4. Effects of Particles on Thermal Expansion Coefficient

Another significant problem in terms of the thermal performance of microelectronic devices arises when there are different parts made from different materials. The heat produced during operation of these devices would lead to “thermal strain mismatch” due to the different thermal expansion coefficients (α) of each material used in the device. If the degree of “thermal strain mismatch” is above the acceptable design limits, the microelectronic device loses its dimensional stability, leading to malfunctioning.

Thus, the thermal expansion coefficient (α) of epoxy resins intended for use in microelectronic devices should be measured. All polymers, including epoxy, have extremely high α values. The neat epoxy resin used in this study has an α of $49 \times 10^{-6}/\text{K}$. Since the nitride and oxide ceramic particles used in this study have thermal expansion coefficient (α) values much lower than $10 \times 10^{-6}/\text{K}$, incorporating these particles can improve the thermal performance of the epoxy resin by decreasing its α value.

The thermal expansion coefficient analyses (Figure 9 and Table 3) found that, although there were slight differences between the different types of particles, increasing the amount of particles decreased the thermal expansion coefficient value. Particle contents of 10, 20, and 40 wt% decreased α to 42, 38, and $28 \times 10^{-6}/\text{K}$, decreases of -15% , -33% , and -43% , respectively. In the literature, significant decreases in the α value ($23\text{--}30 \times 10^{-6}/\text{K}$) after the incorporation of Si_3N_4 particles was reported [24].

These significant decreases in the α values with increasing particle content can be attributed to the intrinsically lower α values of ceramic particles, leading to mechanical constraints on the macromolecular structures of the epoxy polymers and limiting their ability to undergo the thermally induced segmental mobility required for volume expansion. This restriction against volume expansion becomes increasingly effective at higher particle contents where particle–particle interactions and the formation of the mechanically constraining network become more pronounced.

Although all the filler-incorporated systems exhibited a decreasing trend in the thermal expansion coefficient with increasing particle content, the nitride-based fillers, particularly 40 wt% AlN , resulted in a more pronounced suppression effect compared to the oxide-based fillers. This behavior can be attributed to the inherently lower intrinsic α and higher elastic modulus of these fillers, which impose a stronger mechanical constraint on the polymer matrix and more effectively restrict thermally induced chain mobility. A similar behavior was also observed in other studies [11,26].

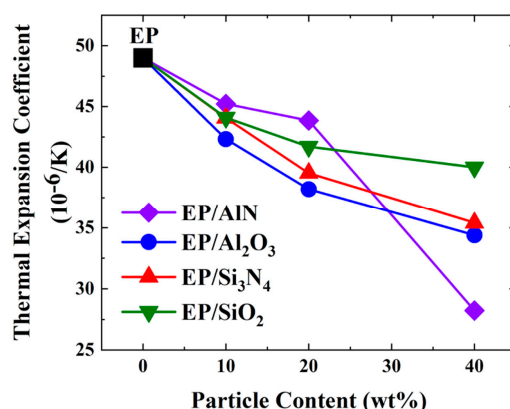


Figure 9. Effects of the particles on the thermal expansion coefficient of the epoxy.

3.5. Effects of Particles on Glass Transition Temperature

To determine if incorporating the nitride and oxide particles affects the Glass Transition Temperature (T_g) of the epoxy system, DMA was conducted from room temperature to

100 °C to determine the *Tan Delta* ($\tan \delta$) curves of the specimens (Figure 10), which is the ratio of the Loss Modulus to Storage Modulus. The “peaks” of the $\tan \delta$ curves are the Glass Transition Temperatures (Figure 11 and Table 3). The incorporation of the nitride and oxide particles into the epoxy resin all resulted in increases in the Glass Transition Temperature compared to neat epoxy (51 °C). Although there were slight differences between the different types of particles, the increases in the T_g values were more pronounced with higher particle loadings. Particle contents of 10, 20, and 40 wt% increased the T_g values by up to 7 °C, 12 °C, and 17 °C, respectively. In the literature [32,35], similar increases in T_g from 49 °C to 51–58 °C were observed after incorporating SiO₂ particles.

The $\tan \delta$ peaks obtained from dynamic mechanical analysis are commonly associated with the α -relaxation process of the thermosetting epoxy network structure and provide a reliable indication of T_g .

When the temperature rises to the T_g of the epoxy system, its mechanical rigidity and Storage Modulus drop significantly via the α -relaxation process and mainly depends on the segmental mobility of the cross-linked epoxy network structure.

Therefore, the addition of nitride and oxide particles resulted in a shift of the $\tan \delta$ peaks towards higher temperatures due to their restrictive actions on the segmental mobility of the neat epoxy structure. Increasing the particle content leads to more segmental restriction, resulting in larger T_g increases.

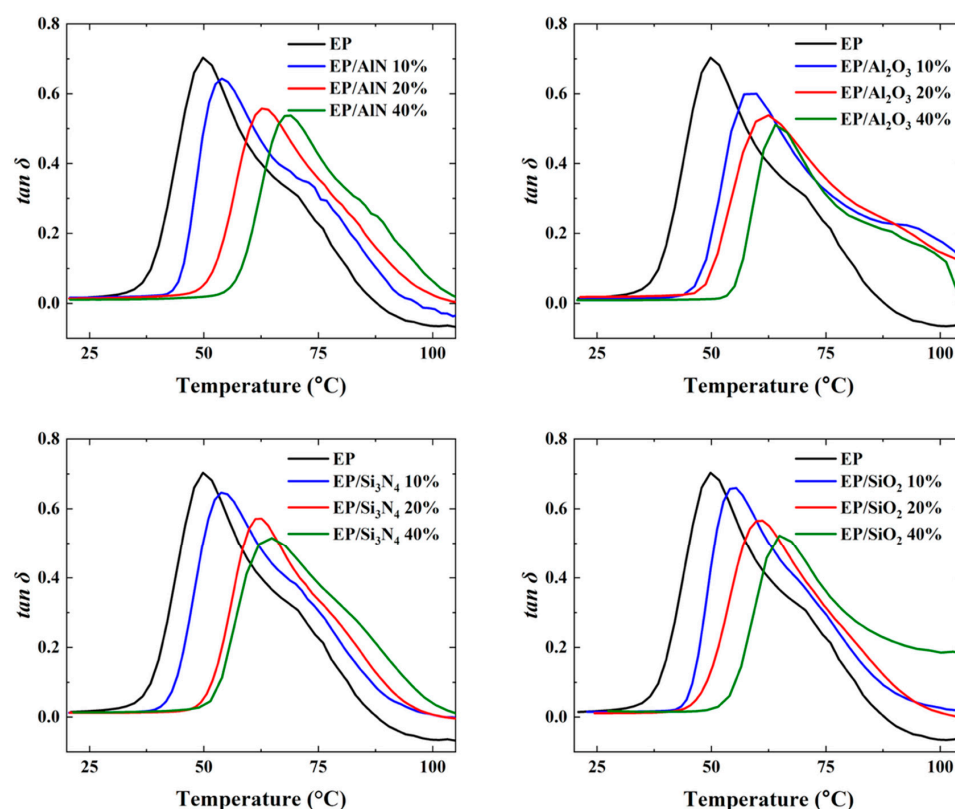


Figure 10. Effects of the particles on the *Tan Delta* curves of the epoxy, as determined by DMA.

In the curves of the filled epoxy specimens in Figure 10, apart from the shift of the $\tan \delta$ peaks, there are also significant decreases in peak intensity and a broadening of the peaks, which indicate a limitation to the effect on segmental mobility and an increase in the heterogeneity of the network structure when fillers are incorporated. Similarly Omrani et al. [3] reported that this significant decrease in peak intensity and peak broadening indicates a wider distribution of relaxation times and increased microstructural heterogeneity.

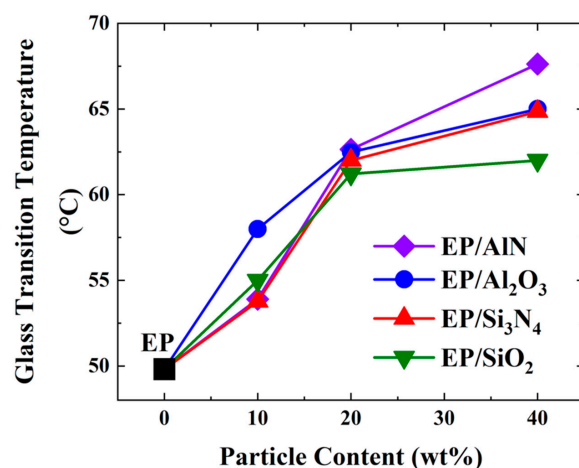


Figure 11. Effects of the particles on the Glass Transition Temperature of the epoxy.

Oxide surfaces (SiO_2 and Al_2O_3) tend to generate a more pronounced interphase (via polar surface groups and stronger secondary interactions), often leading to stronger broadening and high-temperature tailing that indicate a larger fraction of constrained polymers.

Nitride-based filler systems (AlN and Si_3N_4), while still shifting T_g upward, can show comparatively different peak shapes depending on how effectively they disperse and interact with the matrix; in such cases, broadening is influenced more by physical barrier/confinement and microstructural heterogeneity than strong interfacial bonding.

3.6. Effects of Particles on Thermal Degradation Temperature

In order to reveal the effects of nitride and oxide particles on the Thermal Degradation Temperature (T_d) of the epoxy system, TGAs were conducted on neat and filled specimens. The Thermogravimetric (TG) curves are shown in Figure 12 and the Derivative Thermogravimetric (DTG) curves are shown in the insets of each graph. The DTG peaks represent the temperature for maximum weight losses, which were taken as the Thermal Degradation Temperature (T_d) of the specimens. The effects of the particles on the T_d values of the epoxy are shown in Figure 13 and Table 3.

The addition of the nitride and oxide particles into the epoxy resin all resulted in increases in the T_d compared to neat epoxy (324 °C). Although there were slight differences between the different types of particles, the increases in T_d values were more pronounced at higher particle loadings. Particle contents of 10, 20, and 40 wt% increased T_d values by up to 11 °C, 18 °C, and 32 °C, respectively. One study reported a rise in T_d values of around 8–9 °C [35].

It is known that thermal degradation of the epoxy structure occurs due to the chemical deterioration and decomposition of certain covalent bonds in the cross-linked network structure.

Thus, these increases in T_d values could be due to the heat barrier effects of the particles during thermal decomposition of the epoxy. Compared to the epoxy, AlN , Al_2O_3 , Si_3N_4 , and SiO_2 particles are all *high-temperature ceramic materials* and have much higher thermal stability (higher than 1000 °C) and shielding effects that slow the movement of heat and the volatile products formed during thermal decomposition of the epoxy matrix.

Although filler loading is the dominant factor controlling thermal stability, particle chemistry and interfacial characteristics also influence the resistance to degradation. The improved T_d values can be attributed to the barrier effect of inorganic particles, which restrict heat transfer within the matrix, delay volatile product diffusion, and hinder chain scission reactions. Among the investigated systems, the 40 wt% SiO_2 -filled specimen resulted in the highest stabilization, indicating stronger matrix–particle interactions, which

can be linked to the surface silanol groups or more effective thermal shielding compared to the other ceramic fillers.

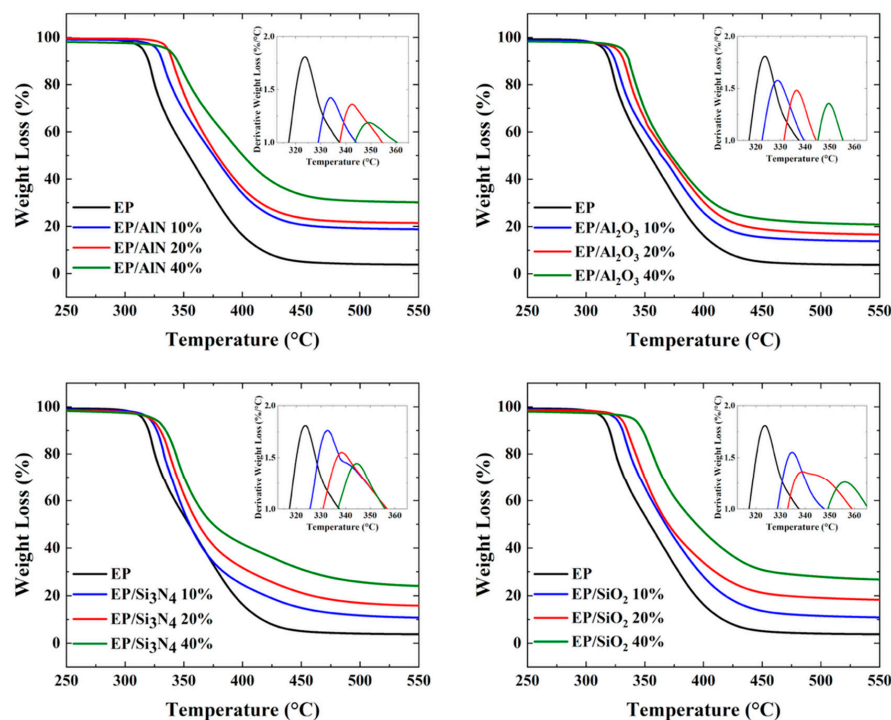


Figure 12. Effects of particles on the Thermogravimetric (TG) and Derivative Thermogravimetric (DTG; in insets) curves of the epoxy.

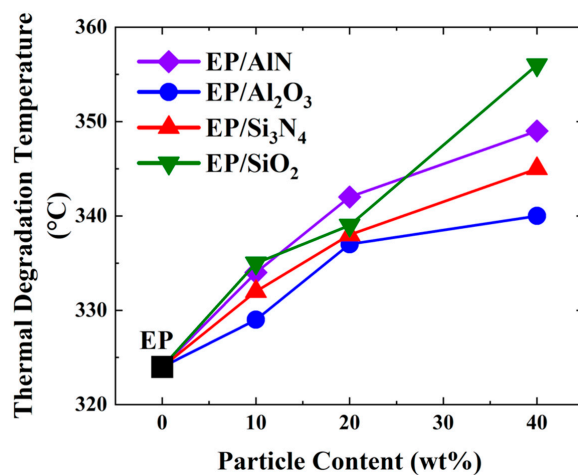


Figure 13. Effects of the particles on the Thermal Degradation Temperature of the epoxy.

3.7. Effects of Particles on Adhesion Strength

Epoxy resins used in microelectronic devices must have a sufficient thermal performance as well as a certain degree of adhesion strength since epoxy resins are often used as “underfill” or “coating” materials. In order to observe effects of the nitride and oxide particles on the degree of adhesion, lap shear adhesion tests were conducted and the results are shown in Figure 14.

The lap shear adhesion strength of the neat epoxy resin was 8 MPa; incorporating all the different particles at all loadings did not cause any detrimental effects, indicating that the adhesion strength of the neat epoxy resin could be maintained.

In fact, incorporating the particles increased the adhesion strength by up to 12–13 MPa. These enhancements can be attributed to the reinforcing action of the particles that suppresses epoxy matrix deformation under shear loading.

After each test, the failure region of the specimen surfaces was carefully examined in order to determine whether the failure mode was “adhesive”, “cohesive”, or “mixed”. As shown in Figure 15, the majority of the specimens exhibited a “mixed” failure mode.

One study reported that adding SiO₂ particles to an epoxy resulted in an adhesion strength of 9–10 MPa [42]. In other studies [55–57] using other ceramic particles, they also observed a mixed failure mode in lap shear tests.

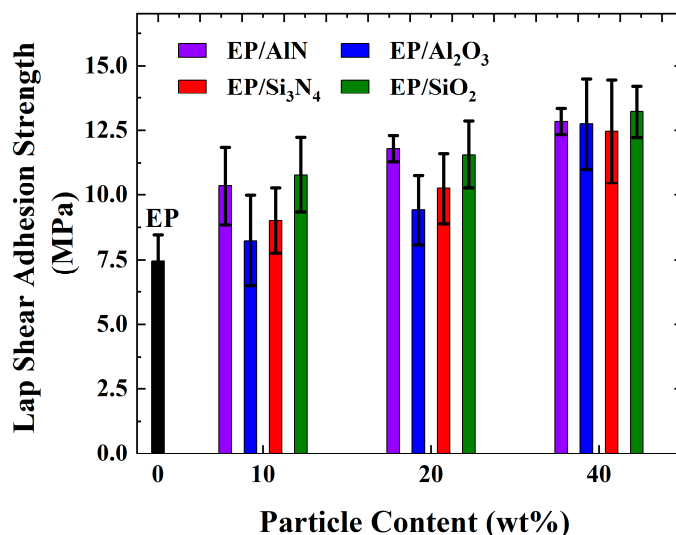


Figure 14. Effect of the particles on the lap shear adhesion strength of the epoxy.



Figure 15. Examples of the “mixed” failure mode during the lap shear adhesion tests.

3.8. Effects of Particles on Storage Modulus

As discussed in Section 3.5, DMA was conducted from room temperature to 100 °C to obtain the *Tan Delta* curves and T_g values. Since temperature could critically influence the mechanical performance of microelectronic parts, changes in the mechanical stiffness of the specimens were evaluated by measuring their Storage Modulus (E') at 25 °C and 50 °C.

The storage Modulus of neat epoxy at 25 °C was only 1.98 GPa. Figure 16 and Table 4 clearly show that for all the different types of particles, the E' values at 25 °C increased with increasing particle content. The improvements were more significant (almost 50% increases) when the particle content was 40 wt%. For instance, for the EP/SiO₂ 40% specimen, the E' value at 25 °C increased to 3.66 GPa.

These enhancements in the Storage Modulus can be attributed to the two typical *stiffening mechanisms* observed in polymer matrix composite materials: a “decrease in the mobility of matrix” and “efficient load transfer from the matrix”, which result in intrinsically stronger and stiffer ceramic particles.

As expected, when the temperature was raised to 50 °C, the E' value of neat epoxy was almost zero (only 0.2 GPa). However, incorporating any of the particles resulted in increasing E' values at 50 °C with increasing particle content. For all the nitride and oxide particles at a content of 40 wt%, the E' values at 50 °C were all above 2 GPa.

Thus, it can be stated that incorporation of nitride and oxide particles into epoxies can not only increase the thermal performance of microelectronic parts, but they can also maintain the mechanical rigidity of the devices at temperatures up to at least 50 °C.

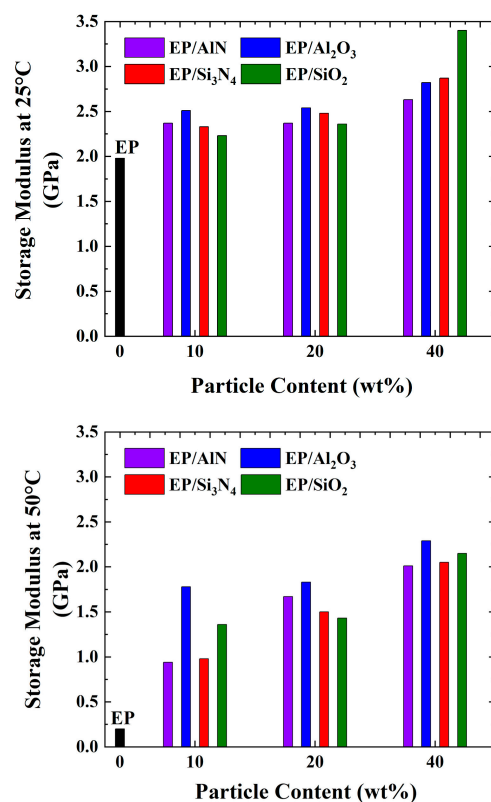


Figure 16. Effect of the particles on the Storage Modulus of the epoxy.

Table 4. Effect of the particles on the Storage Modulus (E') of the epoxy at 25 °C and 50 °C.

	E' at 25 °C (GPa)	E' at 50 °C (GPa)
EP	1.98	0.20
EP/AlN 10%	2.35	0.94
EP/AlN 20%	2.37	1.67
EP/AlN 40%	2.63	2.01
EP/Al ₂ O ₃ 10%	2.51	1.78
EP/Al ₂ O ₃ 20%	2.54	1.83
EP/Al ₂ O ₃ 40%	2.82	2.29
EP/Si ₃ N ₄ 10%	2.33	0.98
EP/Si ₃ N ₄ 20%	2.48	1.50
EP/Si ₃ N ₄ 40%	2.87	2.05
EP/SiO ₂ 10%	2.23	1.36
EP/SiO ₂ 20%	2.36	1.43
EP/SiO ₂ 40%	3.66	2.13

4. Conclusions

The main conclusions on the effects of incorporating 10, 20, and 40 wt% micron-sized particles (aluminum nitride, aluminum oxide, silicon nitride, and silicon oxide) into an epoxy resin used in microelectronic devices, especially its thermal performance, are summarized below.

- Thermal conductivity (λ) was identified as the most critical parameter governing the heat dissipation capability of epoxy components in microelectronic assemblies. The incorporation of filler particles enhanced λ , increasing it from 0.15 W/m·K (neat epoxy) to more than three times this value at a 40 wt% loading. This improvement can be attributed to the formation of certain conductive pathways within the polymer matrix and reduced phonon scattering due to the presence of high-conductivity ceramic phases. Although minor differences were observed between particle types, filler loading was the dominant factor controlling thermal transport behavior.
- A significant reduction in the thermal expansion coefficient (α) was achieved with higher filler contents, decreasing from $49 \times 10^{-6}/\text{K}$ (neat epoxy) to approximately $28 \times 10^{-6}/\text{K}$ (40 wt%), corresponding to a 43% reduction. This decrease is primarily associated with the inherently low α values of the fillers and the restriction of polymer chain mobility at the particle–matrix interface. The reduced thermal expansion mismatch is particularly beneficial for minimizing thermomechanical stresses and improving dimensional stability in microelectronic structures where “thermal strain mismatch” between dissimilar materials is a critical issue.
- All the investigated nitride and oxide fillers increased the T_g from 51 °C (neat epoxy) to up to 68 °C at higher loadings. The elevation in T_g suggests enhanced interfacial interactions, reduced segmental mobility of the polymer macromolecules, and improved thermal reliability under service conditions with elevated operating temperatures.
- The addition of the nitride and oxide particles also resulted in increased thermal degradation resistance, raising the T_d from 324 °C to approximately 356 °C with a 40 wt% filler loading. This enhancement can be attributed to the barrier effect of dispersed particles, which delay volatile product diffusion and limit thermal decomposition. The improved thermal stability further supports the suitability of these composites for high-temperature microelectronic applications.
- The lap shear adhesion tests revealed that the incorporation of all particle types at all loadings did not affect the adhesion strength of the epoxy, with only slight increases from 8 MPa to 12–13 MPa. Thus, incorporation of these fillers resulted in substantial improvements in thermal properties while having no detrimental effects on adhesive performance. The preservation of adhesion strength indicates that the incorporation of micron-sized fillers does not compromise the interfacial bonding capability, which is essential for maintaining structural integrity in bonded microelectronic assemblies.
- The incorporation of all the particle types only increased the Storage Modulus at 25 °C from 1.98 GPa to 3.66 GPa, while at 50 °C, the E' value of neat epoxy (0.2 GPa) was maintained above 2 GPa. Therefore, these findings suggest that nitride- and oxide-filled epoxies could not only improve the thermal performance of microelectronic parts but also maintain the mechanical rigidity of the devices at temperatures up to at least 50 °C.

Overall, the findings of this study demonstrate that optimizing filler loading enables simultaneous enhancement of thermal conductivity, dimensional stability, and thermal resistance while maintaining adequate adhesion performance and mechanical rigidity. Such balanced property improvement is critical for the long-term reliability of epoxy-based components in advanced microelectronic devices.

Author Contributions: Conceptualization, E.A. and C.K.; methodology, E.A. and C.K.; formal analysis, E.A. and C.K.; investigation, E.A. and C.K.; resources, E.A.; data curation, E.A. and C.K.; writing—original draft preparation, E.A. and C.K.; writing—review and editing, E.A. and C.K.; visualization, E.A. and C.K.; supervision, C.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors acknowledge the significant support given by the administrative and technical authorities of ASELSAN Inc. by supplying all of the materials used in this study and the various laboratory facilities required for the experimental work.

Conflicts of Interest: Author Esin Akca was affiliated with the company ASELSAN Inc. The remaining authors declare that they have no conflict of interest.

References

1. Ma, A.; Chen, W.; Hou, Y.; Zhang, G. The Preparation and Cure Kinetics Researches of Thermal Conductivity Epoxy/AlN Composites. *Polym. Plast. Technol. Eng.* **2010**, *49*, 354–358. [\[CrossRef\]](#)
2. Sanctuary, R.; Baller, J.; Zielinski, B.; Becker, N.; Krüger, J.K.; Philipp, M.; Müller, U.; Ziehmer, M. Influence of Al₂O₃ Nanoparticles on the Isothermal Cure of an Epoxy Resin. *J. Phys. Condens. Matter* **2009**, *21*, 035118. [\[CrossRef\]](#)
3. Omrani, A.; Simon, L.C.; Rostami, A.A. The Effects of Alumina Nanoparticle on the Properties of an Epoxy Resin System. *Mater. Chem. Phys.* **2009**, *114*, 145–150. [\[CrossRef\]](#)
4. Yang, C.-F.; Wang, L.-F.; Wu, S.-M.; Su, C.-C. Characterization and Curing Kinetics of Epoxy/Silica Nano-Hybrids. *Materials* **2015**, *8*, 7032–7040. [\[CrossRef\]](#)
5. Hutchinson, J.M.; Roman, F.; Cortes, P.; Calventus, Y. Epoxy Composites Filled with Boron Nitride and Aluminum Nitride for Improved Thermal Conductivity. *Polimery* **2017**, *62*, 560–566. [\[CrossRef\]](#)
6. Chen, X.; Dai, C.; Jiang, T.; Paramane, A. Enhanced Thermal and Dielectric Performance of Epoxy Resin/Aluminum Nitride Nanocomposites at High Temperatures. *Polym. Compos.* **2020**, *41*, 5375–5386. [\[CrossRef\]](#)
7. Kim, W.; Bae, J.; Choi, I.; Kim, Y. Thermally Conductive EMC (Epoxy Molding Compound) for Microelectronic Encapsulation. *Polym. Eng. Sci.* **1999**, *39*, 756–766. [\[CrossRef\]](#)
8. Nagai, Y.; Lai, G.-C. Thermal Conductivity of Epoxy Resin Filled with Particulate Aluminum Nitride Powder. *J. Ceram. Soc. Jpn.* **1997**, *105*, 197–200. [\[CrossRef\]](#)
9. Khan, A.; Puttegowda, M.; Jagadeesh, P.; Marwani, H.M.; Asiri, A.M.; Manikandan, A.; Parwaz Khan, A.A.; Ashraf, G.M.; Rangappa, S.M.; Siengchin, S. Review on Nitride Compounds and Its Polymer Composites: A Multifunctional Material. *J. Mater. Res. Technol.* **2022**, *18*, 2175–2193. [\[CrossRef\]](#)
10. Lee Sanchez, W.A.; Huang, C.-Y.; Chen, J.-X.; Soong, Y.-C.; Chan, Y.-N.; Chiou, K.-C.; Lee, T.-M.; Cheng, C.-C.; Chiu, C.-W. Enhanced Thermal Conductivity of Epoxy Composites Filled with Al₂O₃/Boron Nitride Hybrids for Underfill Encapsulation Materials. *Polymers* **2021**, *13*, 147. [\[CrossRef\]](#)
11. Duwe, S.; Arlt, C.; Aranda, S.; Riedel, U.; Ziegmann, G. A Detailed Thermal Analysis of Nanocomposites Filled with SiO₂, AlN or Boehmite at Varied Contents and a Review of Selected Rules of Mixture. *Compos. Sci. Technol.* **2012**, *72*, 1324–1330. [\[CrossRef\]](#)
12. Agrawal, A.; Satapathy, A. Thermal and Dielectric Behavior of Epoxy Composites Filled with Ceramic Micro Particulates. *J. Compos. Mater.* **2014**, *48*, 3755–3769. [\[CrossRef\]](#)
13. An, H.; Liu, Z.; Tian, Q.; Li, J.; Zhou, C.; Liu, X.; Zhu, W. Thermal Behaviors of Nanoparticle Reinforced Epoxy Resins for Microelectronics Packaging. *Microelectron. Reliab.* **2019**, *93*, 39–44. [\[CrossRef\]](#)
14. Zhao, Y.; Zhai, Z.; Drummer, D. Thermal Conductivity of Aluminosilicate- and Aluminum Oxide-Filled Thermosets for Injection Molding: Effect of Filler Content, Filler Size and Filler Geometry. *Polymers* **2018**, *10*, 457. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Fu, Y.-X.; He, Z.-X.; Mo, D.-C.; Lu, S.-S. Thermal Conductivity Enhancement with Different Fillers for Epoxy Resin Adhesives. *Appl. Therm. Eng.* **2014**, *66*, 493–498. [\[CrossRef\]](#)
16. Hu, Y.; Du, G.; Chen, N. A Novel Approach for Al₂O₃/Epoxy Composites with High Strength and Thermal Conductivity. *Compos. Sci. Technol.* **2016**, *124*, 36–43. [\[CrossRef\]](#)
17. Li, H.; Zheng, W. Enhanced Thermal Conductivity of Epoxy/Alumina Composite through Multiscale-Disperse Packing. *J. Compos. Mater.* **2021**, *55*, 17–25. [\[CrossRef\]](#)

18. Moreira, D.C.; Braga, N.R.; Sphaier, L.A.; Nunes, L.C. Size Effect on the Thermal Intensification of Alumina-Filled Nanocomposites. *J. Compos. Mater.* **2016**, *50*, 3699–3707. [\[CrossRef\]](#)
19. Tang, Y.; Ge, G.; Li, Y.; Huang, L. Effect of Al₂O₃ with Different Nanostructures on the Insulating Properties of Epoxy-Based Composites. *Materials* **2020**, *13*, 4235. [\[CrossRef\]](#)
20. Liang, M.; Wong, K.L. Study of Mechanical and Thermal Performances of Epoxy Resin Filled with Micro Particles and Nanoparticles. *Energy Procedia* **2017**, *110*, 156–161. [\[CrossRef\]](#)
21. Vaisakh, S.S.; Hassanzadeh, M.; Metz, R.; Ramakrishnan, S.; Chappelle, D.; Sudha, J.D.; Ananthakumar, S. Effect of Nano/Micro-Mixed Ceramic Fillers on the Dielectric and Thermal Properties of Epoxy Polymer Composites: Dielectric and Thermal Properties of Epoxy-Ceramic Filler Composites. *Polym. Adv. Technol.* **2014**, *25*, 240–248. [\[CrossRef\]](#)
22. Kusunose, T.; Yagi, T.; Firoz, S.H.; Sekino, T. Fabrication of Epoxy/Silicon Nitride Nanowire Composites and Evaluation of Their Thermal Conductivity. *J. Mater. Chem. A* **2013**, *1*, 3440. [\[CrossRef\]](#)
23. Voo, R.; Mariatti, M.; Sim, L.C. Thermal Properties and Moisture Absorption of Nanofillers-filled Epoxy Composite Thin Film for Electronic Application. *Polym. Adv. Technol.* **2012**, *23*, 1620–1627. [\[CrossRef\]](#)
24. Zeng, J.; Fu, R.; Shen, Y.; He, H.; Song, X. High Thermal Conductive Epoxy Molding Compound with Thermal Conductive Pathway. *J. Appl. Polym. Sci.* **2009**, *113*, 2117–2125. [\[CrossRef\]](#)
25. McGrath, L.M.; Parnas, R.S.; King, S.H.; Schroeder, J.L.; Fischer, D.A.; Lenhart, J.L. Investigation of the Thermal, Mechanical, and Fracture Properties of Alumina-Epoxy Composites. *Polymer* **2008**, *49*, 999–1014. [\[CrossRef\]](#)
26. Jiang, W.; Jin, F.-L.; Park, S.-J. Thermo-Mechanical Behaviors of Epoxy Resins Reinforced with Nano-Al₂O₃ Particles. *J. Ind. Eng. Chem.* **2012**, *18*, 594–596. [\[CrossRef\]](#)
27. Hussain, M.; Nakahira, A.; Nishijima, S.; Niihara, K. Effects of Ceramic Particle Addition on the Thermal Contraction of Epoxy Materials at Cryogenic Temperature. *Key Eng. Mater.* **1998**, *161–163*, 363–370. [\[CrossRef\]](#)
28. Ahmad, Z.; Al-Sagheer, F. Novel Epoxy-Silica Nano-Composites Using Epoxy-Modified Silica Hyper-Branched Structure. *Prog. Org. Coat.* **2015**, *80*, 65–70. [\[CrossRef\]](#)
29. Hiremath, V.; Singh, M.; Shukla, D.K. Effect of Post Curing Temperature on Viscoelastic and Flexural Properties of Epoxy/Alumina Polymer Nanocomposites. *Procedia Eng.* **2014**, *97*, 479–487. [\[CrossRef\]](#)
30. Naous, W.; Yu, X.; Zhang, Q.; Naito, K.; Kagawa, Y. Morphology, Tensile Properties, and Fracture Toughness of Epoxy/Al₂O₃ Nanocomposites. *J. Polym. Sci. B Polym. Phys.* **2006**, *44*, 1466–1473. [\[CrossRef\]](#)
31. Simunin, M.M.; Voronin, A.S.; Fadeev, Y.V.; Dobrosmyslov, S.S.; Kuular, A.A.; Shalygina, T.A.; Shabanova, K.A.; Chirkov, D.Y.; Voronina, S.Y.; Khartov, S.V. Influence of the Addition of Alumina Nanofibers on the Strength of Epoxy Resins. *Materials* **2023**, *16*, 1343. [\[CrossRef\]](#)
32. Yao, X.F.; Yeh, H.Y.; Zhou, D.; Zhang, Y.H. The Structural Characterization and Properties of SiO₂-Epoxy Nanocomposites. *J. Compos. Mater.* **2006**, *40*, 371–381. [\[CrossRef\]](#)
33. Aziz, T.; Mehmood, S.; Haq, F.; Ullah, R.; Khan, F.U.; Ullah, B.; Raheel, M.; Iqbal, M.; Ullah, A. Synthesis and Modification of Silica-based Epoxy Nanocomposites with Different Sol-Gel Process Enhanced Thermal and Mechanical Properties. *J. Appl. Polym. Sci.* **2021**, *138*, 51191. [\[CrossRef\]](#)
34. Lim, W.Y.L.; Jaafar, M.; Ishak, K.M.K.; Chinniah, K.; Chan, W.K. Thermo-mechanical Properties of Epoxy Composites Filled with Inorganic Particulate Fillers for Robust Solder Mask Application. *Polym. Int.* **2024**, *73*, 779–788. [\[CrossRef\]](#)
35. Allahverdi, A.; Ehsani, M.; Janpour, H.; Ahmadi, S. The Effect of Nanosilica on Mechanical, Thermal and Morphological Properties of Epoxy Coating. *Prog. Org. Coat.* **2012**, *75*, 543–548. [\[CrossRef\]](#)
36. Dai, C.; Chen, X.; Jiang, T.; Paramane, A.; Tanaka, Y. Improvement of Electrical and Material Properties of Epoxy Resin/Aluminum Nitride Nanocomposites for Packaging Materials. *Polym. Test.* **2020**, *86*, 106502. [\[CrossRef\]](#)
37. Perminov, V.P.; Modyanova, A.G.; Ryabkov, Y.I.; Sevbo, O.A.; Gailyunas, I.A.; Kuchin, A.V. Epoxy Composites Modified with Finely Dispersed Fillers. *Russ. J. Appl. Chem.* **2002**, *75*, 636–640. [\[CrossRef\]](#)
38. De Souza, J.P.B.; Reis, J.M.L.D. A Thermomechanical and Adhesion Analysis of Epoxy/Al₂O₃ Nanocomposites. *Nanomater. Nanotechnol.* **2015**, *5*, 18. [\[CrossRef\]](#)
39. Qiang, D.; Wang, X.; Wang, Y.; Andritsch, T.; Chen, G. Thermal Stability of Epoxy Nanocomposites: Surface Treatment and Morphology Impact Based on Nano SiO₂ and hBN Fillers. *Mater. Res. Express* **2019**, *6*, 105350. [\[CrossRef\]](#)
40. Ou, C.-F.; Shiu, M.-C. Preparation and Characterisation of Epoxy Composites Filled with Silica Nanoparticles. *Polym. Polym. Compos.* **2008**, *16*, 465–469. [\[CrossRef\]](#)
41. Tarrío-Saavedra, J.; López-Beceiro, J.; Naya, S.; Artiaga, R. Effect of Silica Content on Thermal Stability of Fumed Silica/Epoxy Composites. *Polym. Degrad. Stab.* **2008**, *93*, 2133–2137. [\[CrossRef\]](#)
42. Wang, X.; Zhang, X.; Bian, X.; Lu, C.; Li, Q.; Bai, C.; Zhang, L.; Zheng, T. Curing Kinetics and Mechanical Properties of an Underwater SiO₂/Epoxy Adhesive. *J. Adhes.* **2023**, *99*, 1607–1625. [\[CrossRef\]](#)
43. ASTM E1530-19; Standard Test Method for Evaluating the Resistance to Thermal Transmission by the Guarded Heat Flow Meter Technique. ASTM International: West Conshohocken, PA, USA, 2019.

44. ASTM E228-17; Standard Test Method for Linear Thermal Expansion of Solid Materials with a Push-Rod Dilatometer. ASTM International: West Conshohocken, PA, USA, 2017.
45. ASTM D1002-10; Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading. ASTM International: West Conshohocken, PA, USA, 2010.
46. Bekeshev, A.; Mostovoy, A.; Shcherbakov, A.; Tastanova, L.; Akhmetova, M.; Apendina, A.; Orynassar, R.; Lopukhova, M. The Influence of Pristine and Aminoacetic Acid-Treated Aluminum Nitride on the Structure, Curing Processes, and Properties of Epoxy Nanocomposites. *J. Compos. Sci.* **2023**, *7*, 482. [\[CrossRef\]](#)
47. Gao, N.K.; Xu, Z.; Wu, C.; Li, R.H.; Jin, H.Y. Dispersion and Impact Strength of Epoxy Resin/Nano-Al₂O₃ Composites. *Mater. Sci. Forum* **2013**, *761*, 161–164. [\[CrossRef\]](#)
48. Zheng, J.; Zhang, X.; Cao, J.; Chen, R.; Aziz, T.; Fan, H.; Bittencourt, C. Behavior of Epoxy Resin Filled with nano-SiO₂ Treated with a Eugenol Epoxy Silane. *J. Appl. Polym. Sci.* **2021**, *138*, 50138. [\[CrossRef\]](#)
49. Kim, K.-M.; Kim, H.; Kim, H.-J. Enhancing Thermo-Mechanical Properties of Epoxy Composites Using Fumed Silica with Different Surface Treatment. *Polymers* **2021**, *13*, 2691. [\[CrossRef\]](#) [\[PubMed\]](#)
50. Tang, J.; Chen, K.X.; Fu, C.S. Preparation and Properties of β -Si₃N₄/Epoxy Matrix Composite. *Key Eng. Mater.* **2007**, *336–338*, 1350–1352. [\[CrossRef\]](#)
51. Li, G.; He, Y.; Zhu, P.; Zhao, T.; Sun, R.; Lu, D.; Wong, C. Tailored Surface Chemistry of SiO₂ Particles with Improved Rheological, Thermal-Mechanical and Adhesive Properties of Epoxy Based Composites for Underfill Applications. *Polymer* **2018**, *156*, 111–120. [\[CrossRef\]](#)
52. Shimamura, A.; Hotta, Y.; Hyuga, H.; Kondo, N.; Hirao, K. Effect of Amounts and Types of Silicon Nitride on Thermal Conductivity of Si₃N₄/Epoxy Resin Composite. *J. Ceram. Soc. Jpn.* **2015**, *123*, 908–912. [\[CrossRef\]](#)
53. Gao, Z.; Zhao, L. Effect of Nano-Fillers on the Thermal Conductivity of Epoxy Composites with Micro-Al₂O₃ Particles. *Mater. Des.* **2015**, *66*, 176–182. [\[CrossRef\]](#)
54. Pan, D.; Zhang, X.; Yang, G.; Shang, Y.; Su, F.; Hu, Q.; Patil, R.R.; Liu, H.; Liu, C.; Guo, Z. Thermally Conductive Anticorrosive Epoxy Nanocomposites with Tannic Acid-Modified Boron Nitride Nanosheets. *Ind. Eng. Chem. Res.* **2020**, *59*, 20371–20381. [\[CrossRef\]](#)
55. Kumar, R.; Mishra, A.; Sahoo, S.; Panda, B.P.; Mohanty, S.; Nayak, S.K. Epoxy-based Composite Adhesives: Effect of Hybrid Fillers on Thermal Conductivity, Rheology, and Lap Shear Strength. *Polym. Adv. Technol.* **2019**, *30*, 1365–1374. [\[CrossRef\]](#)
56. Han, S.; Meng, Q.; Pan, X.; Liu, T.; Zhang, S.; Wang, Y.; Haridy, S.; Araby, S. Synergistic Effect of Graphene and Carbon Nanotube on Lap Shear Strength and Electrical Conductivity of Epoxy Adhesives. *J. Appl. Polym. Sci.* **2019**, *136*, 48056. [\[CrossRef\]](#)
57. Jojibabu, P.; Jagannatham, M.; Haridoss, P.; Janaki Ram, G.D.; Deshpande, A.P.; Bakshi, S.R. Effect of Different Carbon Nano-Fillers on Rheological Properties and Lap Shear Strength of Epoxy Adhesive Joints. *Compos. Part A Appl. Sci. Manuf.* **2016**, *82*, 53–64. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.