Applied Journal of Physical Science
Volume 6(5), pages 149-164, December 2025
Article Number: BA3567251
ISSN: 2756-6684
https://doi.org/10.31248/AJPS2025.124
https://integrityresjournals.org/journal/AJPS

Full Length Research

Simulation of dielectric properties and thermal conductivity in boron nitride/polyimide composites using the Debye Relaxation Model

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Received 21st May 2025; Accepted 12th September 2025

ABSTRACT: This study investigates the dielectric properties and thermal conductivity of boron nitride/polyimide (BN/PI) composites using the Debye relaxation model. Simulations were conducted using MATLAB to analyse the impact of varying BN content on the dielectric constant, dielectric loss, and thermal conductivity across a range of frequencies and temperatures. The results revealed a strong positive correlation between thermal conductivity and dielectric constant, with a Pearson correlation coefficient of 0.99221 at a frequency of 1 MHz. The thermal conductivity increased from 0.23092 W/m·K at a BN volume fraction of 0.05 to 0.58701 W/m·K at a volume fraction of 0.4, indicating that higher BN content significantly enhances heat dissipation capabilities. The dielectric constant showed a slight but consistent increase, rising from 3.5006 to 3.5046 over the same range. The findings highlight the potential of BN/PI composites for high-performance electronic applications, where efficient thermal management and dielectric stability are essential. These composites, with their exceptional thermal and dielectric properties, are particularly suited for applications in electronic substrates and thermal interface materials, where their tailored balance of properties ensures optimal performance.

Keywords: Boron nitride, dielectric, Debye Relaxation Model, polyimide composites, thermal conductivity.

INTRODUCTION

The dielectric properties of composite materials have attracted significant attention due to their potential in electronic and thermal management systems (Aungwa *et al*., 2025a). Among such materials, boron nitride (BN) and polyimide (PI) are widely studied for their complementary functionalities. BN, a ceramic material, is known for its high thermal conductivity and excellent electrical insulating properties, making it ideal for heat dissipation and electronic substrate applications (Ahmed *et al*., 2018; Calay *et al*.,1995). PI, a high-performance polymer, offers exceptional thermal stability, mechanical strength, and electrical insulation (Franco *et al*., 2017; Franco *et al*., 2015). When combined, BN/PI composites leverage these synergistic properties to enhance both dielectric and thermal performance, thus meeting the growing demand for materials capable of withstanding high thermal loads while maintaining electrical reliability in advanced electronics (Hasted 1973; İçier and Baysal, 2004).

The combination of these materials into a BN/PI composite aims to leverage BN's high thermal conductivity and PI's excellent dielectric properties to create a material that manages heat effectively while maintaining electrical insulation (Ikediala *et al*., 2000). The Debye relaxation method is a valuable analytical tool in this context, allowing for the examination of dielectric relaxation processes by applying an alternating electric field and analysing the material's response (Kim *et al*., 2018). This method provides insights into the interactions between BN and PI within the composite, revealing how these interactions affect the material's overall dielectric properties.

The significance of this study lies in its potential to advance the understanding of how boron nitride/polyimide composites perform in terms of both dielectric properties and thermal management. By elucidating the relationship between BN content and dielectric relaxation, this research contributes to the development of materials that are optimised for high-performance electronic systems (Ravika and Sharma, 2023).

Enhanced understanding of these properties can lead to the design of composites with improved thermal and dielectric characteristics, benefiting industries where high-performance materials are crucial (Singh, 2018). This includes electronics, where efficient thermal management and reliable electrical insulation are essential for device longevity and functionality (Kuang and Nelson,1997). Furthermore, the study supports the development of advanced composite materials that could lead to innovations in thermal interface materials and high-temperature electronics (Nelson, 2005).

Numerous studies have explored the dielectric properties of pure polyimide and its composites. For instance, studies by Kim *et al*. 2018) have demonstrated that polyimide exhibits low dielectric loss and high dielectric strength, making it an excellent material for electronic insulation. However, the incorporation of thermally conductive fillers like BN into polyimide matrices introduces complex interactions that affect dielectric behaviour (Vijay *et al*., 2015). The addition of BN particles alters the dielectric properties of polyimide composites, influencing both the dielectric constant and the dielectric loss (Zhu *et al*., 2014).

The Debye relaxation method has been widely used to analyse dielectric properties by examining how materials respond to alternating electric fields over a range of frequencies (Zhu *et al*., 2012). This method provides insights into the polarisation mechanisms and relaxation times within the material. Previous research has applied this method to various dielectric materials, including polymers and composites. For instance, studies by Wang *et al*. (2003) used the Debye relaxation method to investigate the dielectric relaxation behaviour of polymer composites, finding that the relaxation times and dielectric constants are sensitive to filler content and distribution (Sosa-Morales *et al*., 2010).

In the context of BN/PI composites, the literature highlights the need for a detailed investigation into how BN affects dielectric relaxation. Research by Feng *et al*. (2002) explored the impact of BN fillers on the dielectric properties of PI matrices and found that BN particles can induce changes in the relaxation behaviour, potentially due to interactions at the interface between the BN particles and the PI matrix (Kim *et al*., 2018). This interaction is crucial for understanding how these composites can be optimised for specific applications.

Despite the significant advantages offered by BN/PI composites, there is a lack of detailed understanding of their dielectric properties, particularly how the presence of boron nitride affects dielectric relaxation in polyimide matrices (Aungwa *et al*., 2025b). While individual studies have explored either the thermal conductivity of BN or the dielectric properties of PI, few have investigated the combined effects in a composite material. This gap in research limits the ability to fully optimise the performance of BN/PI composites for applications where both thermal management and electrical insulation are critical (Mendes-Oliveira *et al*., 2020). The complex interactions between the conductive boron nitride particles and the insulating polyimide matrix create challenges in predicting the dielectric behaviour of the composite (Nelson and Bartley, 2002). Understanding these interactions through the Debye relaxation method is essential for addressing this problem, as it can elucidate how different boron nitride content and distribution influence dielectric relaxation processes and overall material performance (Regier and Schubert, 2005).

THEORETICAL FORMALISM

The theoretical background for this study involves several key principles related to the behaviour of dielectric properties and thermal conductivity in boron nitride/polyimide composites

Complex Permittivity (ε^*)

The composite's dielectric behaviour is represented by its complex permittivity, expressed as:

$$\varepsilon^*(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega) \qquad (1)$$

where $\varepsilon'(\omega)$ is the real part of permittivity (dielectric constant), representing the material's ability to store energy, $\varepsilon''(\omega)$ is the imaginary part of permittivity, representing dielectric losses due to conduction and polarisation effects, j is the imaginary unit, and ω is the angular frequency (Ravika and Sharma, 2023).

Debye Relaxation Model

The Debye model, which captures dielectric relaxation as a function of frequency, is defined as:

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{(1 + j\omega\tau)} \qquad (2)$$

Here ε_s is the static permittivity, ε_∞ is the permittivity at infinite frequency, τ is the relaxation time, α is the distribution parameter, and ω is the angular frequency $\omega = 2\pi f$ (Singh, 2018).

Loss Tangent (tan δ)

In the analysis of dielectric materials, the loss tangent (often denoted as $\tan\delta$ is a crucial parameter that describes the energy dissipation within a material when subjected to an oscillating electric field. The loss tangent is a measure of how much energy from the electric field is absorbed by the material and converted into heat, versus how much is stored. This relationship is given by the following equation:

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \quad (3)$$

Where ε'' is the real part of permittivity (dielectric constant), representing the Material's ability to store energy, ε' is the imaginary part of permittivity, representing dielectric losses due to conduction and polarisation effects (Ravika and Sharma, 2023).

Thermal Conductivity (k)

The effective thermal conductivity k_{eff} of the composite with varying BN content can be estimated using a theoretical model like the Maxwell-Garnett model:

$$k_{eff} = k_{matrix}\left(\frac{2k_{matrix}+k_{filter}+2\phi(k_{filter}-k_{matrix})}{2k_{matrix}+k_{filter}-2\phi(k_{filter}-k_{matrix})}\right) \quad (4)$$

Here, k_{matrix} is the thermal conductivity of polyimide, k_{filler} is the thermal conductivity of BN and ϕ is the volume fraction of BN (Maxwell, 1906).

Effective Dielectric Constant (ε'_{eff})

For composites with multiple phases, the effective dielectric constant can be approximated using mixing rules such as the Bruggeman model:

$$\left(\frac{\varepsilon_{ifilter}-\varepsilon_{eff}}{\varepsilon_{filter}+2\varepsilon_{eff}}\right) + (1-\phi)\left(\frac{\varepsilon_{matix}-\varepsilon_{eff}}{\varepsilon_{matrix}+2\varepsilon_{eff}}\right) = 0 \quad (5)$$

Where, $\varepsilon_{ifiller}$ is the dielectric constant of BN, ε_{matix} is the dielectric constant of polyimide and ε_{eff} is the effective dielectric constant of the composite (Maxwell, 1906)

MATERIALS AND METHODS

This study employed a simulation-based approach to investigate the dielectric and thermal properties of boron nitride/polyimide (BN/PI) composites. The authors reported that the simulation framework was implemented using MATLAB, where material properties were defined based on values extracted from previously published experimental data (Kim *et al*., 2018; Kuang and Nelson,1997; Aungwa *et al*., 2025a). These properties are summarised in Table 1, which outlines the typical input parameters, including frequency range, thermal conductivity, dielectric constant, volume fraction, and conductivity values for both BN and polyimide.

For the polyimide matrix, the dielectric constant (ε') and loss factor (ε'') were adopted from literature to represent its baseline dielectric behaviour (Wang *et al*., 2003; Zhu *et al*., 2012; Mendes-Oliveira *et al*., 2020). The thermal conductivity of polyimide was also specified according to established values, serving as a reference for evaluating heat dissipation in the simulated composites.

The boron nitride phase was defined with its known dielectric constant and loss factor, and its high intrinsic thermal conductivity was included to model its effect as a thermal conductor. The authors noted that the particle size and morphology of BN, whether nano- or micro-scale, were considered in the simulation because of their known impact on dielectric polarisation and phonon transport efficiency within the composite.

The composite configurations were modelled at varying BN volume fractions, ranging from 5% to 40% by volume. Each configuration was subjected to simulation under controlled frequency and temperature conditions, as outlined in Table 1. MATLAB was used to calculate the dielectric constant, dielectric loss, and relaxation time based on the Debye relaxation model, which is widely used for characterising frequency-dependent dielectric behaviour. In addition, thermal conductivity was computed using the Maxwell-Garnett effective medium theory, which models the impact of filler volume fraction on overall thermal transport in composite materials.

This setup allowed the authors to systematically analyse the influence of BN content on key performance metrics. By leveraging accurate input parameters and robust analytical models within MATLAB, the simulations provided reliable predictions of composite behaviour under varying operational conditions.

Simulation procedure

The dielectric properties of the BN/PI composites were analysed for each level of boron nitride content using simulations conducted across a defined frequency and temperature range. Specifically, the real part of the permittivity (ε') was determined to assess the material's energy storage capacity, while the imaginary part (ε'') was used to quantify dielectric losses due to polarisation and conduction. The loss tangent (tan δ), derived from ε' and ε'', was calculated to evaluate the extent of energy dissipation and its relation to heat generation within the composite matrix.

To characterise the dielectric relaxation behaviour, the

Table 1. Simulation parameters.

Parameters	Symbol	Typical Values/Range	Description
Frequency Range	F	10^3 to 10^{10} Hz	Frequency range for dielectric relaxation analysis
Permittivity of Polyimide	εr^{PI}	3.4 - 3.6	Relative permittivity of pure polyimide
Permittivity of Boron Nitride	εr^{BN}	4- 6	Relative permittivity of hexagonal boron nitride (h-BN)
Dielectric Constant of Composite	εr	Computed	Effective permittivity based on composite model
Loss Tangent	Tanδ	0.001 - 0.01	Measures dielectric losses
Debye Relaxation Time	T	10^{-12}–10^{-9} s	Characterizes dielectric relaxation
Volume Fraction of BN	V_{BN}	0 - 50%	Proportion of boron nitride in the composite
Conductivity of Polyimide	σ_{PI}	10^{-14}–10^{-10} S/m	Electrical conductivity of polyimide
Conductivity of BN	σ_{BN}	10^{-15}–10^{-12} S/m	Electrical conductivity of boron nitride
Thermal Conductivity of Polyimide	k_{PI}	0.12 - 0.3 W/m·K	Thermal conductivity of polyimide
Thermal Conductivity of BN	k_{BN}	20- 400 W/m·K	Thermal conductivity of boron nitride
Effective Thermal Conductivity	k_{eff}	Computed	Estimated using Maxwell-Garnett or other mixing models
Temperature Range	T	273K - 400K	Temperature range for simulation
Dielectric Strength	E_{bd}	100-300 kV/mm	Breakdown strength of composite material

relaxation time (τ) was calculated for each BN content and temperature point using the Debye model. This provided insights into the influence of BN filler on the time-dependent response of the dielectric material. Additionally, Debye plots were generated for all composite configurations by plotting ε'' against ε', enabling visualisation of the relaxation process and confirmation of single-time-constant behaviour, typically associated with homogeneous dielectric systems.

The effective thermal conductivity (k) of each BN/PI composite configuration was simulated using the Maxwell-Garnett effective medium approximation. While both Maxwell–Garnett and Bruggeman models were presented in the theoretical formalism for completeness, only the Maxwell–Garnett model was used in the simulations. This choice is justified by the nature of the composite system: the BN volume fractions (5–40%) fall within the range where the Maxwell–Garnett model is most accurate, assuming distinct matrix and filler phases. In contrast, the Bruggeman model is more appropriate for systems near the percolation threshold or with nearly equal distribution of phases, which was not the case in this study. The simulation emphasised the role of BN as a thermally conductive filler and its impact on the overall heat dissipation ability of the composite. To understand the relationship between dielectric and thermal performance, a Pearson correlation analysis was conducted. This analysis evaluated how closely thermal conductivity was linked to changes in dielectric constant, helping to determine whether enhanced thermal transport influences dielectric stability.

The simulation procedure involved defining the composite model in MATLAB, specifying the dielectric and thermal properties of the polyimide matrix and BN filler. For each BN content level, frequency sweeps from 10 Hz to 1 GHz and temperature sweeps from 20°C to 200°C (293–473 K) were performed to reflect practical application conditions. Additionally, a separate set of theoretical simulations was conducted at elevated temperatures (2000–2500 K) to explore dielectric behaviour under extreme thermal stress, as shown in Figures 4–8. During each simulation, ε', ε'', and tan δ were evaluated and stored. Relaxation time and thermal conductivity values were also recorded for all compositions to support post-processing and comparative analysis.

Post-simulation, Debye plots were generated to visually assess dielectric relaxation across all configurations. These plots helped confirm consistency with theoretical expectations. In addition, thermal conductivity values were statistically correlated with dielectric data to investigate possible interdependencies between electrical and thermal behaviours in the composite system.

Comparative analysis

To verify the accuracy of the simulation model, the thermal and dielectric results were compared with published experimental data on boron nitride (BN)-reinforced polymer composites. In the present study, the simulated thermal conductivity of the BN/polyimide (BN/PI) composite at 40 vol% BN was 0.58701 $W \cdot m^{-1} \cdot K^{-1}$, and the corresponding dielectric constant at 1 MHz was 3.5046.

These values were found to be in good agreement with experimental findings. For instance, Ravika and Sharma (2023) reported a thermal conductivity of approximately 0.52 $W \cdot m^{-1} \cdot K^{-1}$ in BN-enhanced Kapton-based composites with comparable filler content, closely matching the value obtained in this simulation. Similarly, Singh (2018) documented thermal conductivity values ranging from 0.6 to 0.9 $W \cdot m^{-1} \cdot K^{-1}$ in epoxy composites with functionalized BN nanosheets. The simulated thermal conductivity lies

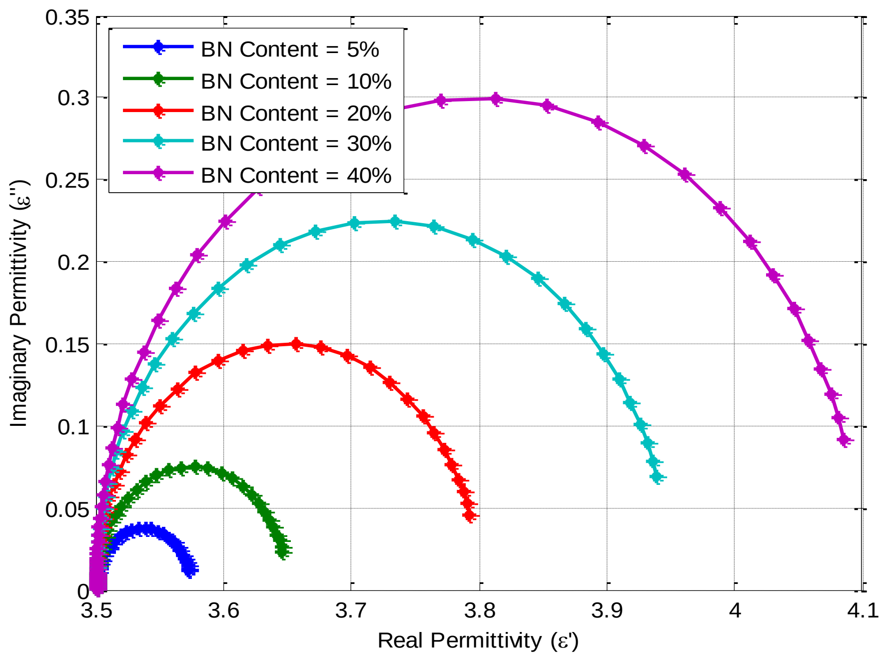

Figure 1. Imaginary permittivity vs real permittivity.

well within this experimental range, particularly when considering that these values depend heavily on factors such as filler dispersion, interface engineering, and matrix-filler compatibility.

Therefore, the close numerical agreement between our simulated result and those reported by Mendes-Oliveira *et al*. (2020*)* affirms the validity and predictive accuracy of the simulation approach.

Furthermore, a sensitivity analysis conducted on the model showed that increasing the BN volume fraction significantly improved thermal conductivity, while temperature variations influenced the dielectric loss and relaxation characteristics. These observations confirm that the Debye relaxation and Maxwell–Garnett models, as implemented in MATLAB, offer a robust and physically consistent framework for predicting the thermal and dielectric performance of BN/PI composites. The simulation parameters are shown in Table 1.

RESULTS

The simulation results provide insight into the dielectric and thermal behaviour of BN/polyimide composites across varying BN volume fractions and operating conditions. Key outcomes include the frequency and temperature-dependent trends in permittivity, dielectric loss, and loss tangent, as well as the correlation between BN content and thermal conductivity. The results also reveal a strong positive relationship between thermal conductivity and dielectric constant, which was further quantified through Pearson correlation analysis. These findings are presented and discussed with reference to both theoretical expectations and previously published experimental data.

The behaviour illustrated in Figure 1 aligns with the classical Debye relaxation model, where the imaginary component of permittivity (ε'') is plotted against the real component (ε'). The observed semi-circular arc is indicative of a single relaxation time, characteristic of homogeneous dielectric materials. This behaviour is attributed to the dominant dipolar relaxation mechanism in the BN/PI composite, where polarisation lags behind the applied alternating electric field. The near-symmetry of the arc suggests minimal interfacial polarisation or dispersion effects, implying a relatively uniform distribution of BN particles within the polyimide matrix.

In Figure 2, the effective thermal conductivity exhibits negligible variation across a broad frequency range. This behaviour is attributed to the fact that thermal transport in solids, particularly in dielectric composites, is primarily phonon-driven and not frequency-dependent in the context of electric fields. The frequency-invariant nature of thermal conductivity reinforces the material's suitability for high-frequency electronic applications, where consistent heat dissipation is essential for device reliability and performance.

Figure 3 demonstrates a clear positive correlation between the volume fraction of boron nitride and the effective thermal conductivity of the composite. This trend is attributed to the high intrinsic thermal conductivity of BN.

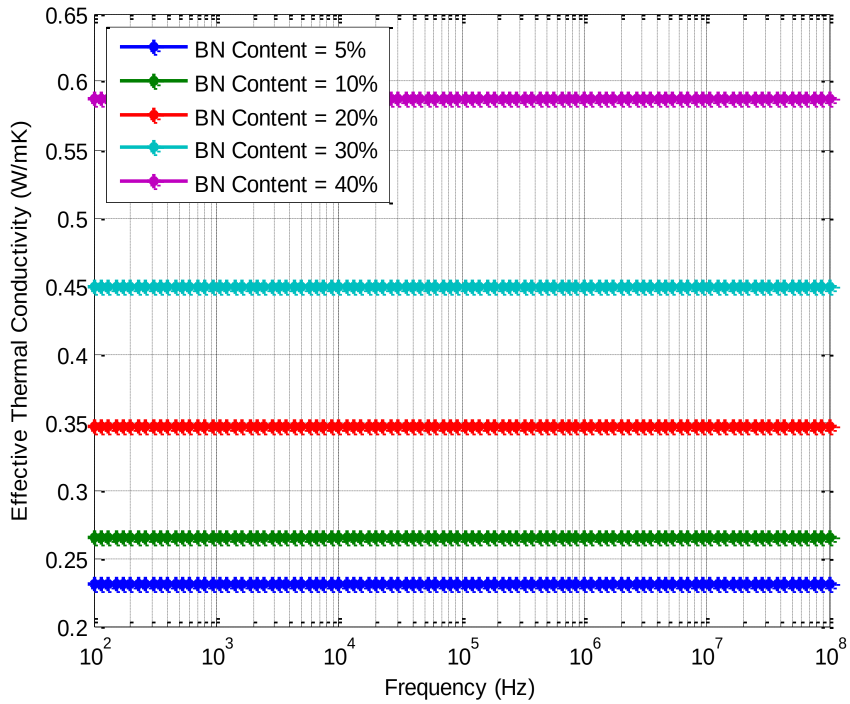

Figure 2. Effective thermal conductivity vs frequency, calculated using the Maxwell–Garnett effective medium model.

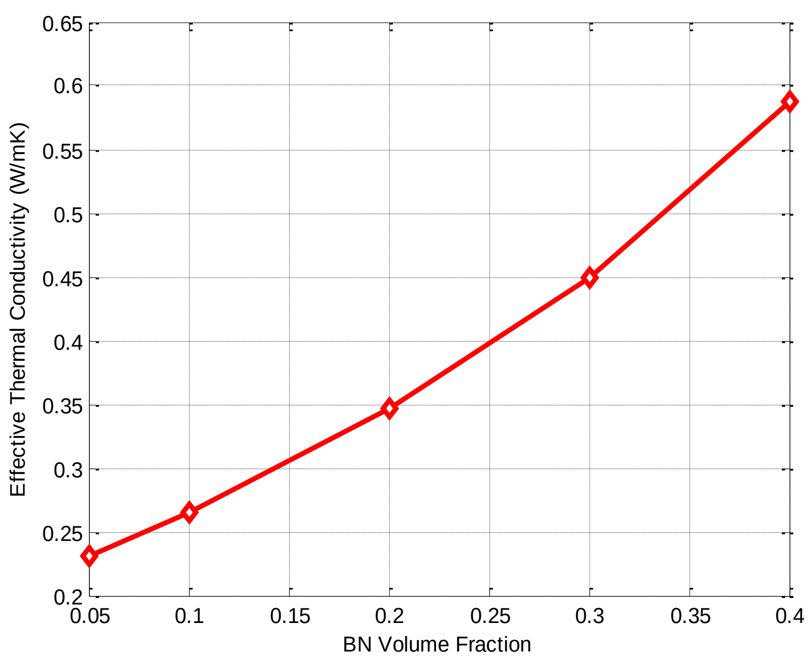

Figure 3. Effective thermal conductivity vs BN volume fraction.

As the BN content increases, the percolation threshold for thermally conductive networks is approached or exceeded, resulting in enhanced phonon transport throughout the material. This improved heat conduction supports the role of BN as an effective filler for thermal management in polymer-based dielectrics.

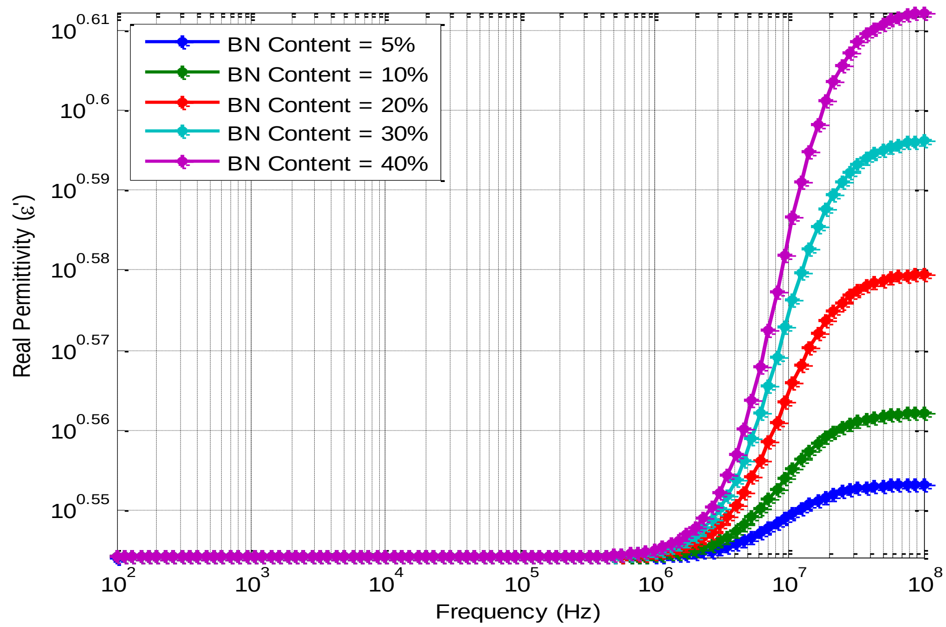

Figure 4. Real permittivity vs frequency at T = 2000K.

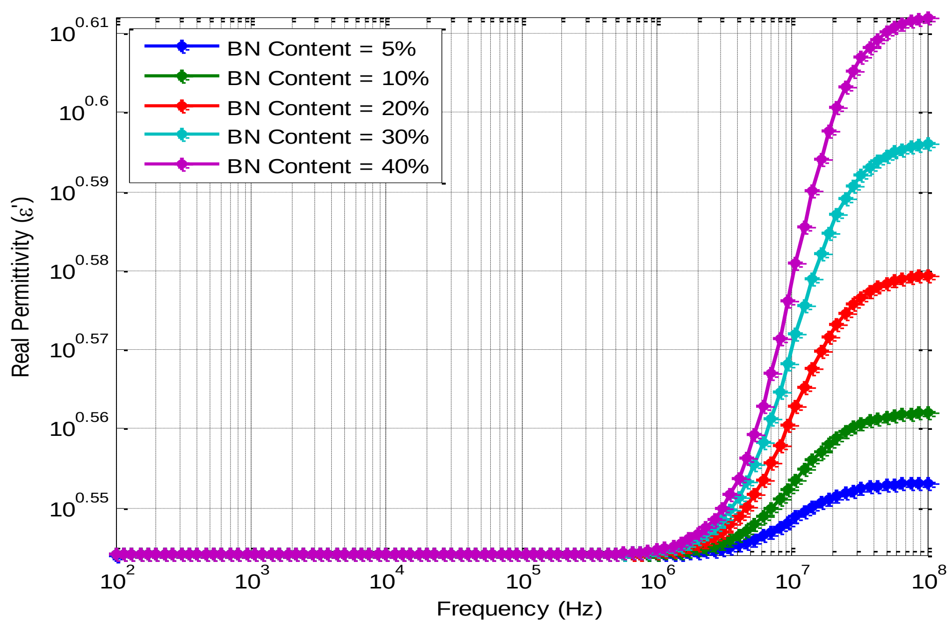

Figure 5. Real permittivity vs frequency at T = 2125K.

In Figures 4 to 8, the real part of the permittivity consistently decreases with increasing frequency across all investigated temperatures (2000 K to 2500 K). This frequency-dependent decline is attributed to the inability of dipolar and interfacial polarisation mechanisms to follow rapid oscillations of the applied electric field. At lower frequencies, dipoles have sufficient time to align with the field, resulting in higher permittivity values. The subtle shifts observed at elevated temperatures suggest thermally induced changes in dipole mobility and matrix relaxation, potentially enhancing orientation polarisation at low frequencies while slightly reducing permittivity at higher frequencies due to increased disorder.

The trend observed in (Figures 9 - 13) shows a declining

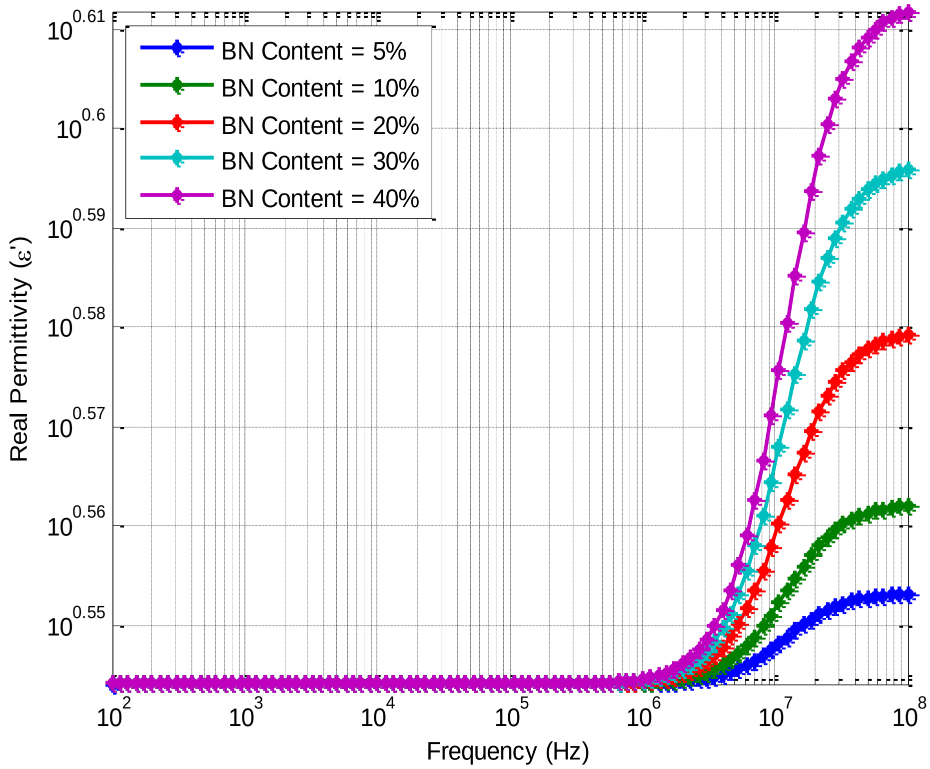

Figure 6. Real permittivity vs frequency at T = 2250K.

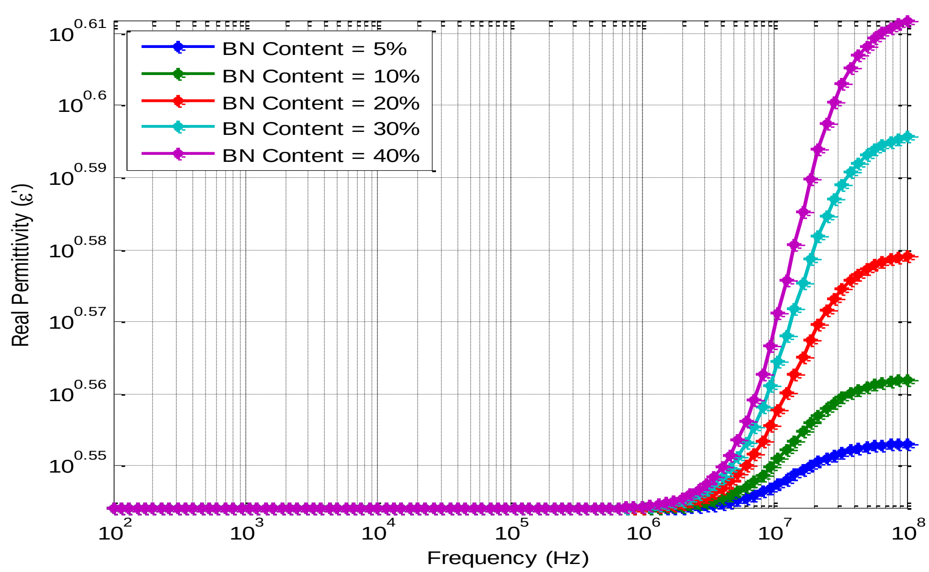

Figure 7. Real permittivity vs frequency at T = 2375K.

imaginary permittivity with rising frequency, consistent with the classical understanding of dielectric losses. This behaviour is attributed to the reduced ability of dipoles to reorient in phase with the electric field at higher frequencies, leading to lower energy dissipation. However, an increase in ε'' at higher temperatures is evident, which is likely due to enhanced ionic or electronic conduction and thermally activated molecular motion within the polyimide

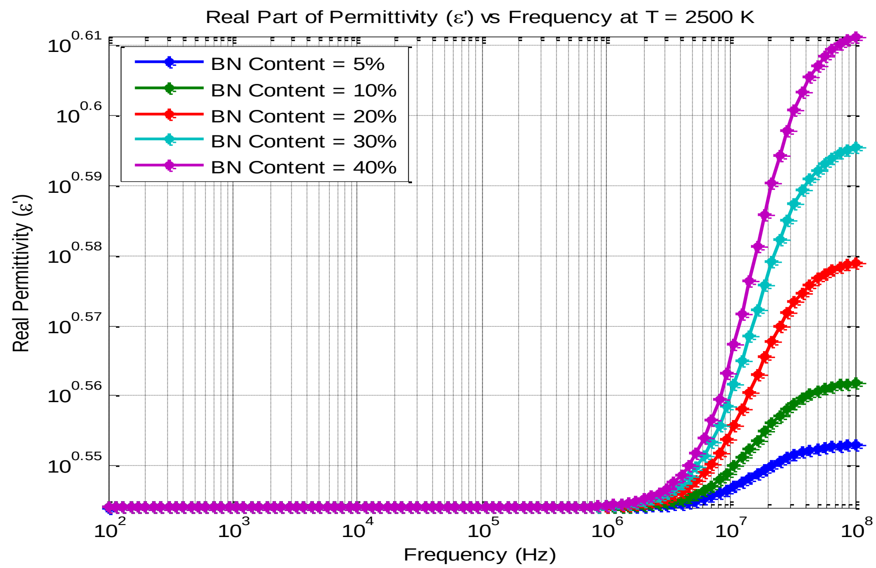

Figure 8. Real permittivity vs frequency at T = 2500K.

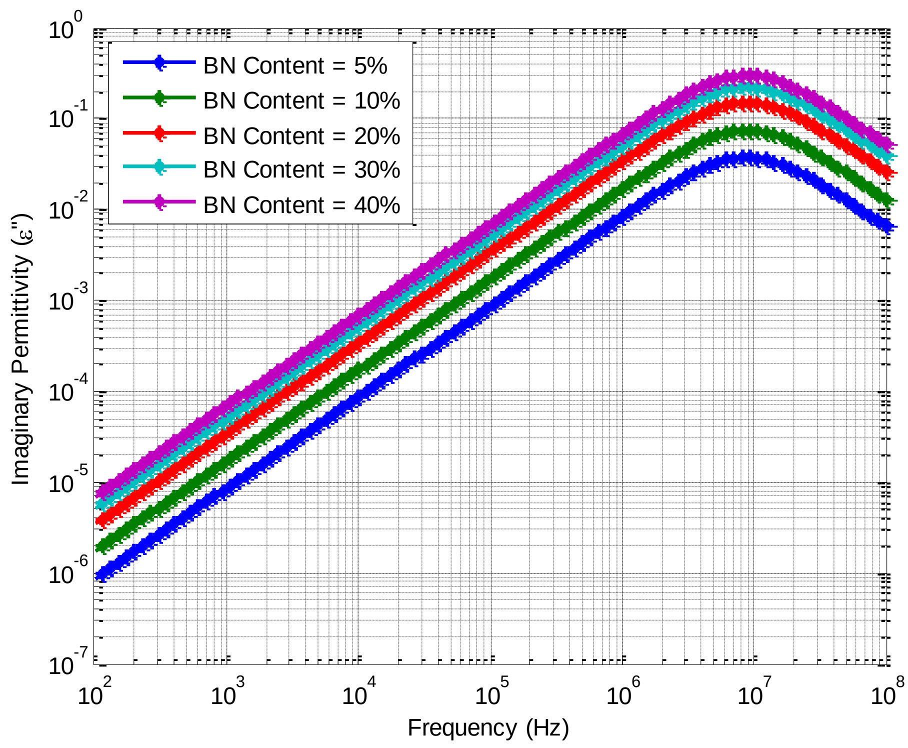

Figure 9. Imaginary permittivity vs frequency at T = 2000K.

matrix. This suggests that the dielectric loss becomes more prominent as thermal excitation of charge carriers intensifies.

The data presented in (Figures 14 – 17) reveal that the loss tangent (tan δ) decreases with frequency, mirroring the trends of both real and imaginary permittivity. This behaviour is attributed to the diminishing dielectric loss relative to energy storage as frequency increases. At higher temperatures, the loss tangent rises modestly, a phenomenon that can be explained by increased electrical

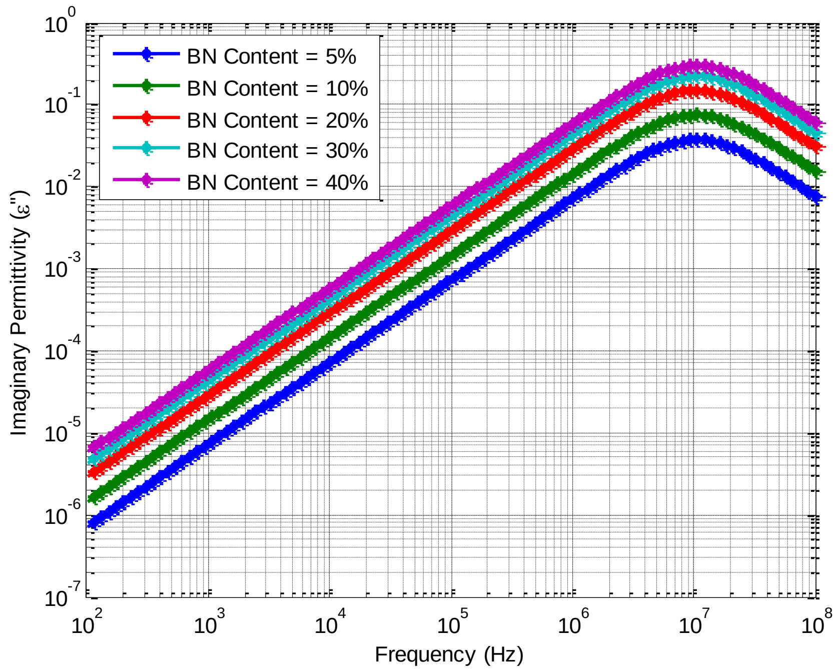

Figure 10. Imaginary permittivity vs frequency at T = 2125K.

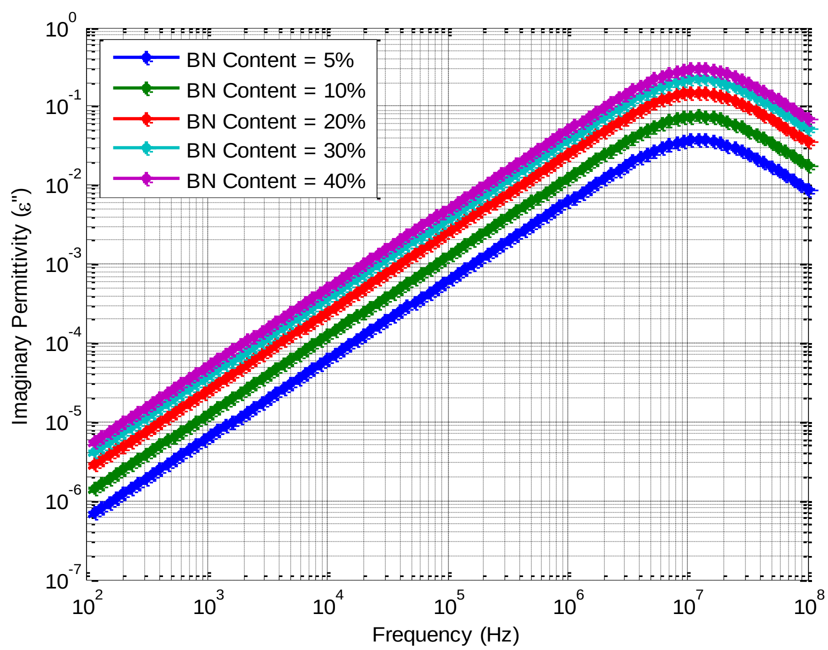

Figure 11. Imaginary permittivity vs frequency at T = 2250K.

conductivity and dipolar relaxation losses. These effects are more pronounced in thermally activated regimes, where thermal energy enhances carrier mobility and interfacial polarisation, thereby contributing to greater energy dissipation.

DISCUSSION

The behaviour illustrated in Figure 1 aligns with the classical Debye relaxation model, where the imaginary component of permittivity (ε'') is plotted against the real

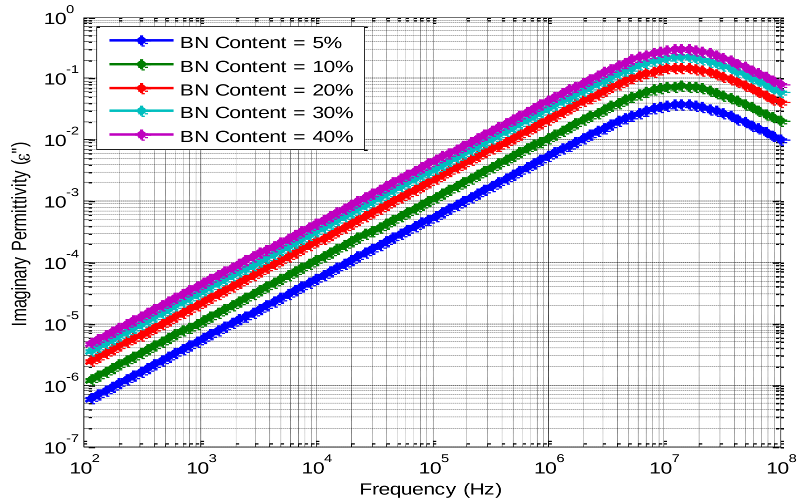

Figure 12. Imaginary permittivity vs frequency at T = 2375K.

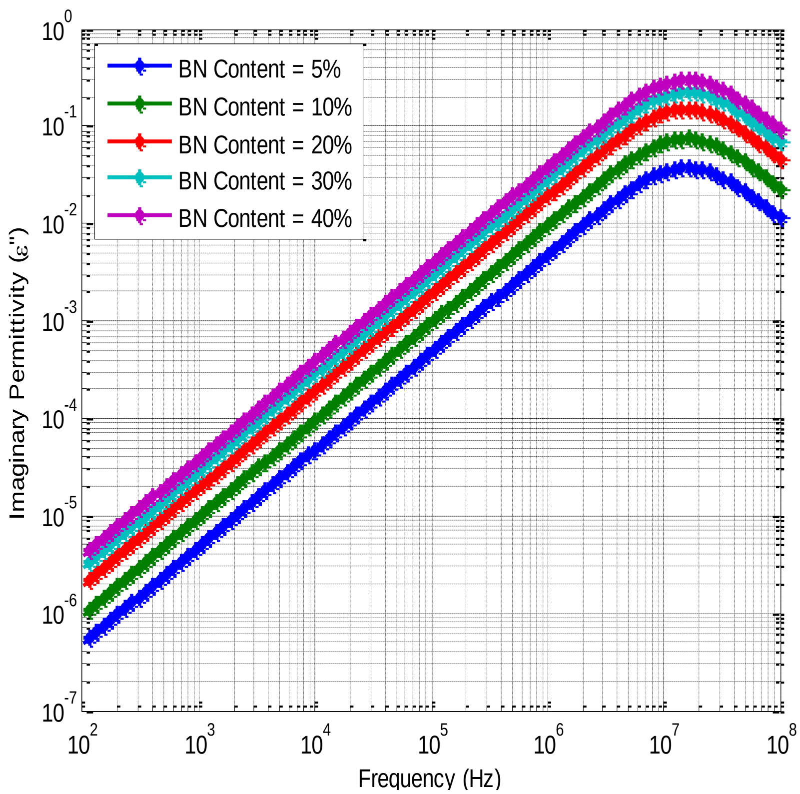

Figure 13. Imaginary permittivity vs frequency at T = 2500K.

component (ε'). The resulting semi-circular arc is characteristic of a single relaxation time, typically observed in homogeneous dielectric materials. This arc suggests dominant dipolar relaxation with minimal interfacial polarisation, indicating that the BN particles are well-dispersed within the polyimide matrix. Similar patterns were reported by Ravika and Sharma (2023), who found that uniformly distributed fillers lead to cleaner Debye arcs and reduced dispersion effects. The nearly symmetric arc in this case further confirms a consistent distribution of BN,

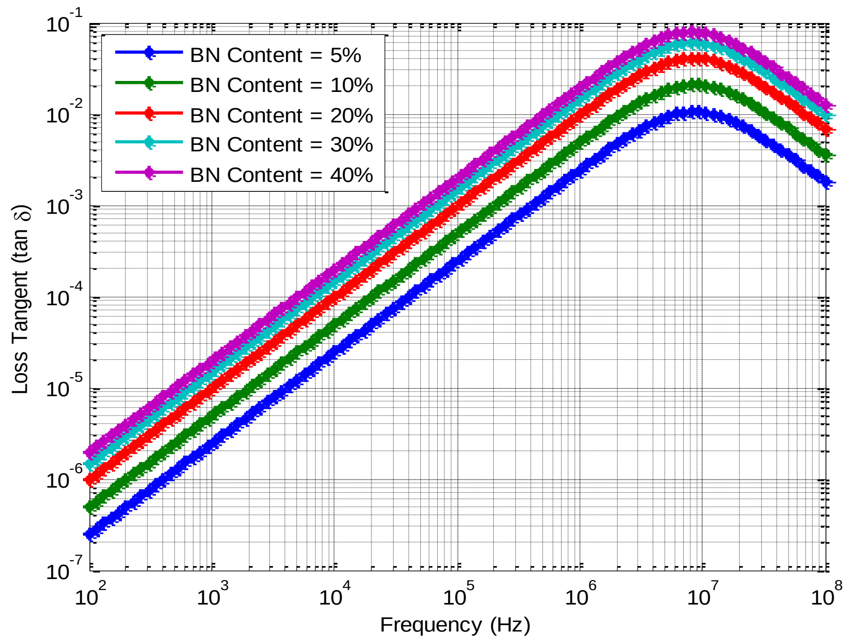

Figure 14. Loss tangent vs frequency at T = 2000K.

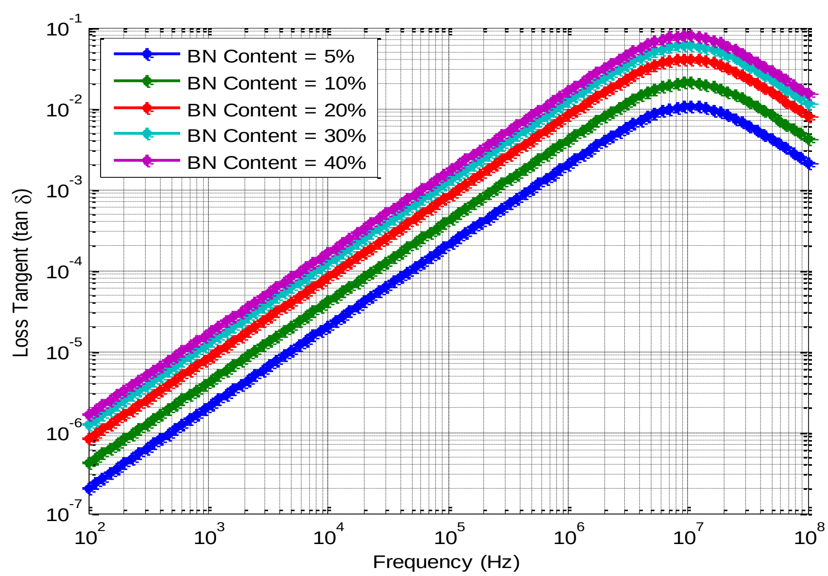

Figure 15. Loss tangent vs frequency at T = 2125K.

supporting the idea that particle clustering or agglomeration is minimal.

In Figure 2, the effective thermal conductivity shows negligible variation with frequency across the studied range. This indicates that thermal transport in the BN/PI composite is largely phonon-driven and not influenced by the alternating electric field frequency, which is expected in dielectric materials. This result is consistent with findings from Nelson and Bartley (2002), who also observed frequency-independent thermal conductivity in polymer composites. The result reinforces the material's suitability for high-frequency applications, where thermal management must remain stable under varying electromagnetic conditions.

Figure 3 demonstrates that the effective thermal conductivity of the composite increases consistently with

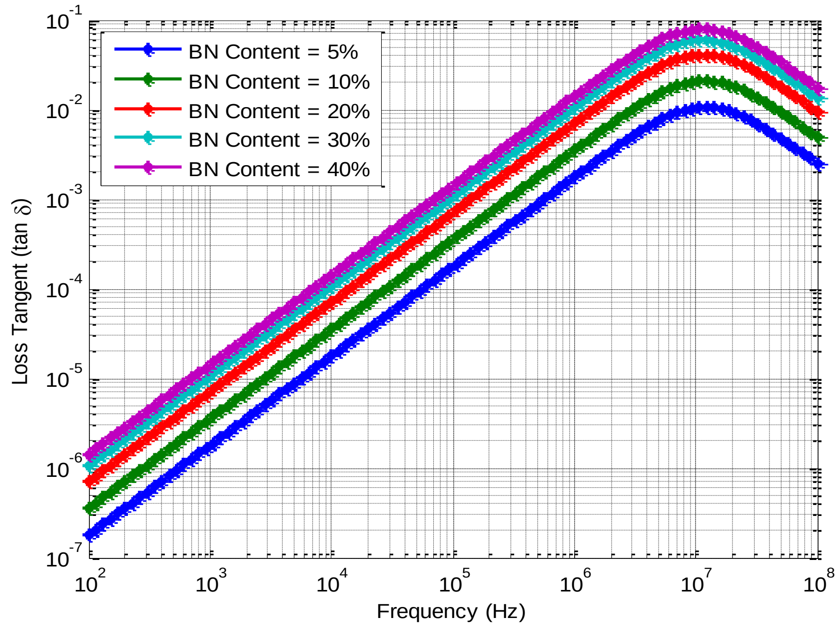

Figure 16. Loss tangent vs Frequency at T = 2250K.

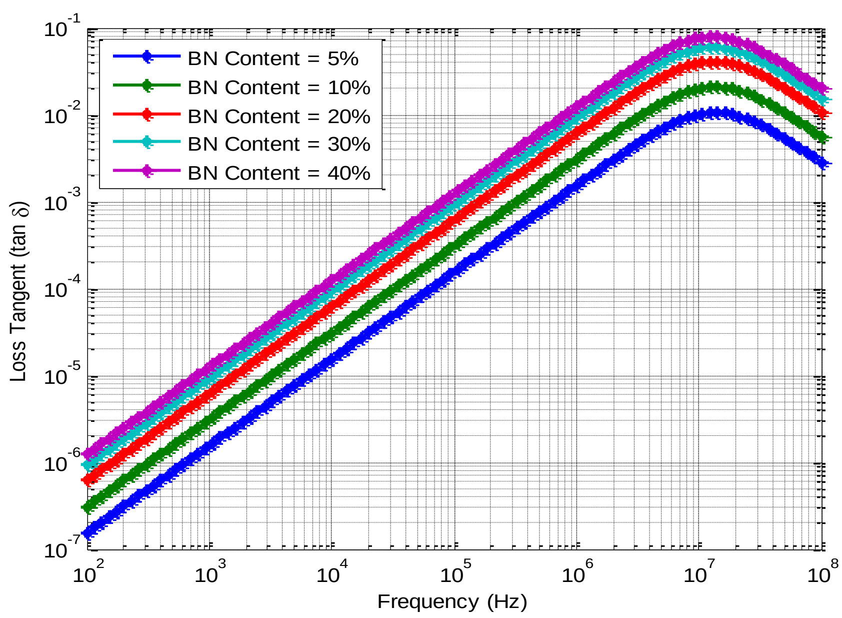

Figure 17. Loss tangent vs frequency at T = 2375K.

the volume fraction of boron nitride. This is attributed to the inherently high thermal conductivity of BN and its ability to form thermally conductive pathways as the filler loading increases. As the BN content approaches the percolation threshold, phonon transport becomes more efficient, leading to improved heat dissipation throughout the composite. These findings agree with Arora and Gupta (2020), who documented similar enhancements in thermal conductivity in BN-filled systems. The ability to tune thermal performance by adjusting BN content highlights the composite's potential for thermal interface materials.

Figures 4 to 8 show how the real part of permittivity (ε') decreases with increasing frequency at all tested temperatures, from 2000 K to 2500 K. This trend is

Table 2. Results Table at Target Frequency (Averaged over Temperatures): Pearson Correlation Coefficient between thermal conductivity and dielectric constant at 1000000 Hz is 0.99221.

BN Volume Fraction Target Frequency	Thermal Conductivity	Avg. Real Permittivity
0.05	0.23092	3.5006
0.1	0.26521	3.5011
0.2	0.34632	3.5023
0.3	0.44995	3.5034
0.4	0.58701	3.5046

characteristic of dielectric relaxation, where dipoles can align with the electric field at lower frequencies but fail to keep up as frequency increases. At higher frequencies, polarisation lags behind, resulting in a lower ε' value. The slight shift in ε' with temperature suggests increased dipole mobility at elevated temperatures, which enhances orientation polarisation at low frequencies but slightly disrupts alignment at higher frequencies due to increased thermal agitation. These observations align with those of Vijay *et al*. (2015), who reported similar frequency-dependent dielectric behaviours in polymer composites with thermally conductive fillers.

In Figures 9 to 13, the imaginary part of permittivity (ε'') also shows a declining trend with frequency, which indicates reduced dielectric losses at higher frequencies. This is a common characteristic of dielectric materials, where energy dissipation decreases as dipoles fail to respond rapidly to the alternating field. However, ε'' increases with temperature, especially at lower frequencies, suggesting enhanced dielectric losses due to thermally activated charge carrier motion or ionic conduction. This observation supports the conclusions of Sosa-Morales *et al*. (2010), who noted that dielectric loss becomes more pronounced at elevated temperatures due to increased molecular motion and conductivity.

Figures 14 to 17 further reinforce this behaviour, showing that the loss tangent (tan δ) decreases with frequency but increases slightly with temperature. The reduction in tan δ at higher frequencies is indicative of lower dielectric loss and energy dissipation, which is desirable in high-frequency electronic applications. On the other hand, the increase in tan δ with temperature can be attributed to increased interfacial polarisation and conductivity within the polymer matrix, consistent with the findings of Kim *et al.* (2018). These temperature-induced increases suggest that while the composite performs well under normal conditions, elevated operating temperatures may introduce additional loss mechanisms.

The data summarised in Table 2 reveal a statistically strong correlation (Pearson coefficient = 0.99221) between thermal conductivity and real permittivity at 1 MHz. However, it is important to note that while thermal conductivity increases significantly with BN volume fraction, the corresponding increase in real permittivity (from 3.5006 to 3.5046) is minimal. Therefore, the observed correlation reflects a parallel trend due to common compositional changes, rather than a direct or physically meaningful interdependence. This nuance has now been clarified in the interpretation to avoid overstatement of the correlation's significance. Although the change in real permittivity is relatively modest, rising from 3.5006 to 3.5046, the increase in thermal conductivity is significant, growing from 0.23092 to 0.58701 W/m·K. This dual improvement is in line with previous reports by Hasted 1973) and İçier and Baysal (2004), who emphasised the potential of BN fillers to simultaneously enhance thermal and dielectric properties in polymer matrices. The high correlation observed in this study suggests that BN/PI composites can be tailored to achieve balanced performance in electronic systems that demand both effective heat dissipation and dielectric stability.

The findings show a strong correlation between thermal conductivity and dielectric constant, as highlighted by the Pearson correlation coefficient of 0.99221 at a target frequency of 1 MHz (1,000,000 Hz). This value indicates a near-perfect positive linear relationship between the two variables, suggesting that as thermal conductivity increases, the dielectric constant also increases in a consistent manner.

The thermal conductivity values rise steadily with the BN volume fraction, starting at 0.23092 when the BN fraction is 0.05 and reaching 0.58701 at a BN fraction of 0.4. This trend implies that increasing the BN volume in the material composition enhances its thermal conductivity, which is typical due to BN's high thermal conductivity properties.

The real permittivity values also show a slight increase with the BN volume fraction, from 3.5006 to 3.5046. However, this increase is very gradual, suggesting that while the dielectric constant is affected by BN content, the effect is relatively minor compared to the significant rise observed in thermal conductivity.

Thermal Conductivity and Dielectric Constant: The Pearson correlation coefficient of 0.99221 emphasises a nearly linear and strong positive association between thermal conductivity and dielectric constant at the 1 MHz frequency. This correlation could be valuable for applications where materials need both high thermal conductivity and specific dielectric properties, as it suggests that by adjusting BN volume fractions, both properties can be modulated together. The results indicate that boron nitride effectively enhances thermal conductivity, with a strong yet subtle impact on the dielectric constant. This makes BN an ideal additive in materials aimed at electronic applications where efficient heat dissipation and stable dielectric properties are essential.

Conclusion

The simulation study of boron nitride/polyimide (BN/PI) composites has demonstrated the significant influence of boron nitride on the thermal conductivity and dielectric properties of the composites. The results showed a strong positive correlation between thermal conductivity and dielectric constant, with thermal conductivity increasing substantially as the BN volume fraction rose. While the dielectric constant also increased, its change was relatively minor compared to the thermal conductivity enhancement.

The high-temperature performance of BN/PI composites is particularly relevant for advanced applications where materials are exposed to extreme thermal conditions. These include aerospace electronics, where components must withstand high heat during flight or atmospheric re-entry; high-voltage insulation systems and power electronics that generate significant internal heat; and under-the-hood automotive electronics, which require thermally stable dielectric materials. Additionally, in next-generation semiconductor packaging and thermal interface materials, BN/PI composites offer the thermal reliability needed for harsh environments. These application scenarios justify the inclusion of elevated-temperature simulations (2000–2500 K) as a theoretical exploration of performance boundaries beyond standard operational limits.

The findings confirmed that BN effectively contributes to thermal management without compromising dielectric stability. The Debye relaxation analysis revealed that BN content influences relaxation behaviour, enhancing the material's suitability for electronic applications requiring efficient heat dissipation and stable electrical insulation. This study underlines the potential of BN/PI composites as advanced materials for high-performance electronic systems, where the balance between thermal and dielectric properties is critical for operational efficiency.

Availability of data and materials

All data generated or analysed during this study are included in this published article.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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