

Fabrication and characterization of hexagonal boron nitride/polypropylene composites using maleic anhydride compatibilizer for microelectronic applications

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ABSTRACT

This work investigated composites prepared using a polypropylene (PP) matrix and hexagonal boron nitride (hBN) filler for microelectronic applications. The influence of filler loading (10–40 wt%) and compatibilization using maleic anhydride-grafted polypropylene (MAPP) was studied. MAPP-modified composites showed improved hBN dispersion and interfacial compatibility with the PP matrix, as verified by SEM images. Experimental results showed that hBN addition increased density, void content, and water absorption; however, MAPP reduced the increases in void content and water uptake. Tensile and flexural strengths reached maxima at approximately 25 wt% hBN, whereas compressive strength and hardness continued to increase with filler loading. Thermal conductivity increased markedly with hBN content, while the coefficient of thermal expansion decreased. At 40 wt% hBN with MAPP, thermal conductivity reached approximately $1.85 \text{ Wm}^{-1}\text{K}^{-1}$, corresponding to approximately 6.2 times the thermal conductivity of neat PP. Dielectric properties showed marginal increases with filler loading but remained within ranges considered suitable for potential microelectronic applications. Overall, the developed PP/hBN/MAPP composites

demonstrate strong potential for thermal management in microelectronics.

Highlights:

1. Novel PP-based thermoplastic composites were developed using raw and MAPP-compatibilized hBN.
2. Maleic anhydride compatibilization improved interfacial bonding and dispersion.
3. Thermal conductivity increased by up to 6.2-fold with 40 wt% MAPP-modified hBN.
4. A favorable balance of mechanical and dielectric properties was achieved at approximately 25 wt% filler loading.
5. The composites show potential for microelectronic packaging, thermal interface materials, and heat-dissipation applications.

Table 1: Abbreviations used in the manuscript

Abbreviation	Full form
PP	Polypropylene
hBN	Hexagonal boron nitride
MAPP	Maleic anhydride grafted polypropylene
SEM	Scanning electron microscopy

KEYWORDS

Composite materials, Dielectric properties, Mechanical Properties, Microstructure, Thermal properties, Microelectronics applications

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CTE	Coefficient of thermal expansion
TIM	Thermal interface material
ASTM	American Society for Testing and Materials
T _m	Melting temperature
MWS	Maxwell–Wagner–Sillars
wt%	Weight percent

INTRODUCTION

In the era of rapid technological advancement, electronic devices are becoming increasingly compact, powerful, and intelligent (Zhang et al. 2020). From smartphones and laptops to electric vehicles, 5G/6G infrastructure, and high-performance computing systems, the demand for miniaturization has led to a significant rise in power density within increasingly confined device volumes. This trend has created critical challenges in thermal management, signal integrity, and long-term reliability of electronic components (He et al. 2021; Evans et al. 2021). Effective heat dissipation has emerged as a major design challenge, as excessive heat accumulation can cause thermal runaway, reduce device lifespan, and degrade overall performance. According to recent analyses, more than 50% of electronic failures are thermally related (Li et al. 2021). Therefore, the development of advanced materials that offer high thermal conductivity, low dielectric constant, low CTE, adequate mechanical strength, and good processability has become a priority in microelectronics (Nayak et al. 2020).

Traditional materials used in electronic packaging, such as silica-filled epoxy resins, have been widely used for decades. However, with the increasing demand for higher thermal conductivity requirements, often exceeding $0.5\text{--}1.0\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, these materials are reaching their performance limits (Hu et al. 2021). Epoxy-based composites typically achieve thermal conductivity values below $0.5\text{ W}/\text{m}\cdot\text{K}$ even at high filler loadings, which is insufficient for next-generation applications (Chen et al. 2018). Moreover, thermosetting matrices like polyester and epoxy suffer from drawbacks such as difficult recyclability, brittleness after curing, and complex processing routes that limit large-scale manufacturing flexibility (Sumdani et al. 2022).

Thermoplastic polymers, particularly polypropylene (PP), have gained considerable attention as alternative matrix materials for electronic applications (Muratov et al. 2021; Chen et al. 2017). Polypropylene is one of the most widely used commodity thermoplastics due to its low cost, low density (approximately $0.90\text{--}0.91\text{ g}\cdot\text{cm}^{-3}$), excellent chemical resistance, good fatigue resistance, and superior processability through melt-based techniques such as extrusion and injection molding (Agrawal et al. 2020). Unlike thermosets, PP can be easily recycled and reprocessed, aligning with the growing emphasis on sustainable manufacturing in the electronics industry (Kushwaha et al. 2023). Furthermore, PP exhibits inherently low dielectric constant (typically $2.2\text{--}2.8$ at 1 MHz) and low dielectric loss, making it suitable for high-frequency signal transmission where minimal signal delay and low energy dissipation are required (Pan et al. 2017). However, like most polymers, neat PP suffers from very low intrinsic thermal conductivity (around $0.2\text{--}0.3\text{ W}/\text{m}\cdot\text{K}$), which limits its direct use in thermal management applications (Hou et al. 2014; Jang et al. 2017).

To overcome the thermal conductivity limitation of polymers, the incorporation of thermally conductive fillers has been widely explored (Jiang et al. 2018). Among various fillers, hexagonal boron nitride (hBN) is a promising candidate for microelectronic composites (Muratov et al. 2021 & Zhou et al. 2014). hBN, often called “white graphene,” possesses a unique combination of properties: high in-plane thermal conductivity (up to $300\text{--}600\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), excellent electrical insulation (bandgap $\sim 5.9\text{ eV}$), low dielectric constant ($\sim 4.0\text{--}4.8$), low coefficient of thermal expansion ($\sim 4 \times 10^{-6}\text{ }^{\circ}\text{C}^{-1}$), and high chemical and thermal stability (Feng et

al. 2023; Kim et al. 2022). These attributes make hBN particularly attractive for applications requiring both efficient heat dissipation and electrical insulation, such as thermal interface materials (TIMs), heat spreaders, printed circuit board substrates, and encapsulants (Li et al. 2021; Nayak et al. 2020).

Despite its advantages, the successful utilization of hBN in polymer matrices faces several challenges. The primary issues include poor interfacial compatibility between the non-polar PP matrix and the relatively polar hBN surface, leading to weak interfacial bonding, high thermal contact resistance, filler agglomeration at high loadings, and increased void formation (Agrawal et al. 2022). These factors can limit the effective thermal conductivity enhancement and degrade mechanical properties. To address these interfacial issues, various surface modification and compatibilization strategies have been developed (Pen et al. 2018; Ma et al. 2011). Traditional silane coupling agents, while effective in some thermoset systems, show limited compatibility with non-polar thermoplastics like PP (Gu et al. 2012).

“Maleic anhydride grafted polypropylene” (MAPP) has emerged as a highly effective compatibilizer specifically for PP-based composites (Zhou et al. 2012; Ramdani et al. 2015). MAPP contains reactive maleic anhydride groups that can form chemical or strong physical interactions (hydrogen bonding or esterification) with the hydroxyl groups present on the hBN surface. Simultaneously, the long PP chains of MAPP entangle with the bulk PP matrix, thereby improving interfacial compatibility (Qiao et al. 2015). This dual functionality significantly improves filler dispersion, reduces interfacial thermal resistance, minimizes void content, and enhances stress transfer between the matrix and filler. Several researchers have reported that the use of MAPP in PP composites filled with inorganic particles leads to improvements in mechanical, thermal, and morphological properties (Lule et al. 2019; Fang et al. 2017).

Previous studies on hBN-reinforced polymer composites have primarily focused on thermosetting matrices such as epoxy and polyester (Huang et al. 2011; Zhou et al. 2023). For instance, many works have demonstrated 4–6-fold increases in thermal conductivity in epoxy/hBN systems with surface treatments (Wang et al. 2023). However, limited attention has been paid to thermoplastic PP/hBN systems, particularly with MAPP compatibilization (Wu et al. 2022). Some researchers have explored PP/hBN composites without compatibilizers and reported moderate thermal conductivity enhancement (up to 3–4 times at 40–50 wt% loading), but with compromised mechanical properties due to poor interfacial adhesion (Bisht et al. 2021; Semerci et al. 2021). The incorporation of MAPP may address this limitation by providing better dispersion and stronger interfaces, potentially achieving higher thermal conductivity while preserving processability and mechanical integrity (Sasikala et al. 2016; Thomas et al. 2009).

Recent literature has shown promising results with PP/hBN systems. Pan et al. achieved a thermal conductivity of $0.721\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ (4-fold increase) using exfoliated hBN in PP at 29 wt% loading (Pan et al. 2016). Wu et al. demonstrated significant enhancement using polydopamine-modified BN in PP composites (Wu et al. 2023). Other studies using MAPP or similar compatibilizers have reported improved interfacial bonding and thermal performance in PP-based systems (Chen et al. 2020; Yang et al. 2022).

The present study investigated the effect of hBN filler loading (10–40 wt%) and MAPP compatibilization on the physical, mechanical, thermal, and dielectric properties of PP/hBN composites. The composites were prepared using industrially viable “twin-screw melt extrusion” followed by injection molding, ensuring scalability. Detailed characterization, including density and void content measurement, water absorption behavior, tensile, flexural, and compressive properties, Shore hardness, thermal conductivity,

coefficient of thermal expansion, melting behavior, and frequency-dependent dielectric properties, was carried out. Scanning electron microscopy (SEM) was employed to understand the morphological changes induced by MAPP.

This study is significant for several reasons. First, it addresses the growing need for recyclable, easily processable thermally conductive composites for sustainable electronics (Kashfipour et al. 2022). Second, it demonstrates the effectiveness of MAPP as a compatibilizer in enhancing the performance of PP/hBN systems, which have received comparatively limited attention. Third, by achieving a balanced set of properties—high thermal conductivity, acceptable mechanical strength, and suitable dielectric behavior—the developed composites may serve as candidate materials for advanced applications such as LED heat sinks, power electronics packaging, and flexible electronic components (Roy et al. 2022).

The remainder of this paper is organized as follows: Section 2 describes the materials and experimental methods in detail. Section 3 presents the results and discussion of the influence of filler loading and MAPP compatibilization. Finally, Section 4 summarizes the key findings and provides recommendations for future research.

These studies indicate that the performance of PP/hBN composites is strongly dependent on filler morphology, filler loading, surface modification, and interfacial compatibility. However, direct comparisons of mechanical strength, thermal conductivity, dimensional stability, and dielectric response within the same MAPP-compatibilized PP/hBN system remain limited. Therefore, the present study provides a broader structure–property assessment by evaluating these properties under a common processing and formulation framework.

Although previous studies have demonstrated the potential of hBN as a thermally conductive and electrically insulating filler, relatively limited attention has been given to polypropylene/hBN systems incorporating maleic anhydride grafted polypropylene (MAPP), particularly with respect to their combined physical, mechanical, thermal, and dielectric performance. Most reported studies have primarily focused on thermal conductivity enhancement, while the relationships among filler loading, MAPP-mediated interfacial compatibility, mechanical performance, dimensional stability, and dielectric behavior remain insufficiently explored. Therefore, the present study systematically investigates PP/hBN composites containing 10–40 wt% hBN, with and without MAPP compatibilization, and evaluates their physical, mechanical, thermal, dimensional, and dielectric properties within a common processing and formulation framework. The novelty of this work lies in the comprehensive structure–property assessment of a single PP/hBN/MAPP system and in identifying the filler loading that provides a suitable balance among these properties for potential microelectronic applications.

MATERIALS AND METHODS

Raw Materials Used

Isotactic polypropylene (PP) pellets with a melt flow index of 12 g/10 min and density of 0.90 g.cm⁻³ were supplied by Reliance Industries Limited, India. Polypropylene is a low-cost thermoplastic with excellent processability, good chemical resistance, and low dielectric constant, making it suitable as a matrix for microelectronic composites. It has moderate thermal conductivity (approximately 0.30 W.m⁻¹K⁻¹), a melting temperature of around 165 °C, and a coefficient of thermal expansion of approximately 110 × 10⁻⁶ °C⁻¹.

Hexagonal boron nitride (hBN) microparticles with an average particle size of 5 µm were procured from Souvenir Chemicals,

Mumbai, India. hBN was selected as the filler due to its high intrinsic thermal conductivity (up to 300 W.m⁻¹K⁻¹ in the basal plane), excellent electrical insulation, low dielectric constant (≈ 4.0–4.8), and low coefficient of thermal expansion (≈ 4 × 10⁻⁶ °C⁻¹).

MAPP containing 1–2% maleic anhydride content was used as the compatibilizer. MAPP was supplied by Pluss Polymers Pvt. Ltd., India. It serves as an effective interfacial agent that improves the compatibility between the non-polar PP matrix and the hBN filler through potential interactions between the maleic anhydride groups and the hydroxyl groups present on the hBN surface.

Surface Modification and Compatibilization of hBN

To improve the interfacial bonding between hBN and the PP matrix, a compatibilization approach using maleic anhydride grafted polypropylene (MAPP) was adopted. The modification process was carried out as follows:

First, 4 wt% MAPP (relative to the weight of hBN) was dissolved in hot xylene at 120 °C under continuous stirring for 30 minutes to obtain a homogeneous solution. Pre-dried hBN powder was then slowly added to this solution, and the mixture was stirred vigorously for 1 hour at 130 °C. This step allowed the maleic anhydride groups to react with the hydroxyl groups on the hBN surface to promote interfacial interactions. The treated hBN slurry was then precipitated in cold ethanol, filtered, and washed multiple times with ethanol to remove unreacted MAPP. Finally, the modified hBN was dried in a vacuum oven at 80 °C for 12 hours to remove residual solvent. The resulting MAPP-modified hBN powder was stored in a desiccator for further use. This compatibilization method enhances the dispersibility of hBN particles within the non-polar PP matrix and was intended to reduce the interfacial thermal resistance, which is critical for achieving high thermal conductivity.

Composite Fabrication

Two series of polypropylene-based composites were prepared: one with raw (untreated) hBN and the other with MAPP-modified hBN. The filler loadings were varied from 10 wt% to 40 wt% in both series.

The composites were fabricated using a twin-screw extruder (Thermo Scientific, L/D ratio 40:1) with a temperature profile ranging from 160 °C to 200 °C and a screw speed of 60 rpm. Polypropylene pellets were pre-dried at 80°C for 4 hours. The required amount of raw or MAPP-modified hBN was fed into the extruder along with the PP matrix through a side feeder for better dispersion. The extruded strands were cooled in a water bath, pelletized, and dried. The pellets were then injection molded (using an Arburg injection-molding machine) into standard test specimens for mechanical, thermal, and dielectric characterization. The mold temperature was maintained at 60°C, and injection pressure was optimized for proper filling. The composition of the prepared samples is presented in Table 2. Based on the trend observed in this initial screening, additional composites with 25 wt% raw and MAPP-modified hBN were subsequently prepared using the identical extrusion and injection-molding procedure to more precisely identify the composition corresponding to maximum tensile and flexural strength; their composition and properties are presented in Table 4 in the Results section.

Table 2: Samples prepared for experimentation.

Set	Composition	Set	Composition
Set A1	Polypropylene + 10 wt% of untreated hBN	Set B1	Polypropylene + 10 wt% of MAPP-modified hBN
Set A2	Polypropylene + 20 wt% of untreated hBN	Set B2	Polypropylene + 20 wt% of MAPP-modified hBN
Set A3	Polypropylene + 30 wt% of untreated hBN	Set B3	Polypropylene + 30 wt% of MAPP-modified hBN
Set A4	Polypropylene + 40 wt% of untreated hBN	Set B4	Polypropylene + 40 wt% of MAPP-modified hBN

Characterization

The density of the prepared samples was experimentally determined using the water immersion technique according to ASTM D792. Theoretical density was calculated using the rule of mixtures, and void content was estimated from the difference between theoretical and measured density. Water absorption behavior was studied according to ASTM D570 by immersing the samples in distilled water at room temperature and measuring weight gain periodically up to 168 hours. Mechanical properties were evaluated using a universal testing machine (UTM). Tensile tests were performed according to ASTM D638, flexural tests according to ASTM D790, and compressive tests according to ASTM D695. Shore D hardness was measured using a PosiTector SHD durometer according to ASTM D2240. Thermal conductivity was measured using a guarded heat flow meter (Unitherm Model 2022) according to ASTM E1530. The coefficient of thermal expansion (CTE) was determined using a Perkin-Elmer TMA-7 thermomechanical analyzer according to ASTM E831, and melting temperature was determined by differential scanning calorimetry (DSC) using a Perkin-Elmer DSC instrument according to ASTM D3418. Dielectric constant and dielectric loss were measured over the frequency range of 1 kHz to 1 MHz using a Hioki 3532-50 LCR HiTester, and from 1 MHz to 1 GHz using a Keysight E4991B RF Impedance/Material Analyzer. The surface morphology of the fractured specimens was examined using a Carl Zeiss scanning electron microscope (SEM) after gold sputtering to study the dispersion and interfacial adhesion of hBN particles. All tests were

performed in at least triplicate, and average values with standard deviations are reported.

RESULTS AND DISCUSSION

Surface Morphology

Figure 1 shows the scanning electron microscopy (SEM) images of polypropylene composites filled with raw hBN and MAPP-modified hBN. Figure 1(A) presents the PP composite with 20 wt% raw hBN. The hBN microparticles are distributed within the PP matrix, but clear interfacial gaps and debonding are visible between the filler and matrix (indicated by arrows). This poor adhesion is consistent with the incompatibility between the non-polar PP and the polar surface of hBN.

Figure 1(B) shows the PP composite with 20 wt% MAPP-modified hBN. Significant improvement in interfacial adhesion is observed. The gaps between hBN particles and the PP matrix are markedly reduced, consistent with improved interfacial adhesion after MAPP treatment. Figure 1(C) shows the composite with 30 wt% MAPP-modified hBN. At higher loading, some agglomeration of hBN platelets is observed; however, the overall dispersion remains better than in raw hBN composites. The improved morphology in MAPP-modified samples is expected to enhance stress transfer and thermal conductivity.

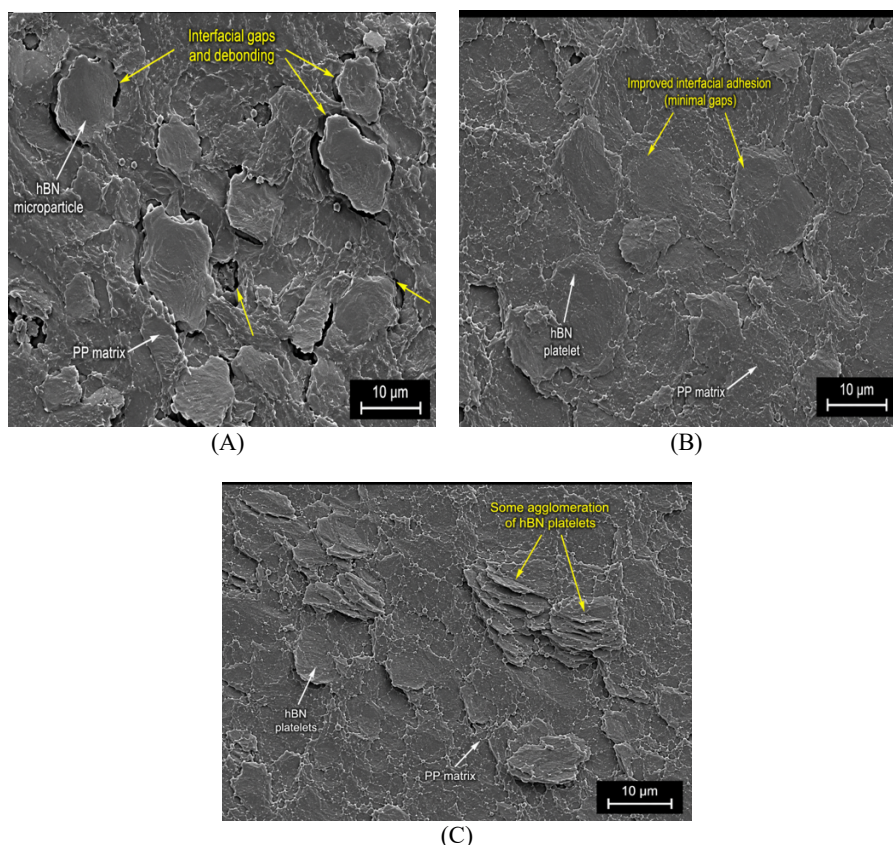


Figure 1: Surface morphology of polypropylene/hBN composites. (A) PP composite with 20 wt% raw hBN; (B) PP composite with 20 wt% MAPP-modified hBN; (C) PP composite with 30 wt% MAPP-modified hBN.

Physical Properties

The densities and void contents of the polypropylene/hBN composites evaluated in the present investigation are presented in Table 3. The density rose with increasing hBN content irrespective of the type of hBN used (raw or MAPP-modified). The same trend was observed for both the measured and theoretical densities. The density of neat PP was measured to be 0.90 g/cm³. The density of

its composites increased and reached 1.33 g/cm³ and 1.37 g/cm³ with 40 wt% of untreated and MAPP-modified hBN, respectively. The difference in density between the two composite series for a given filler loading is due to different void contents in the two composite series. A composite system containing more air voids shows a lower density.

Table 3: Density and void content of polypropylene/hBN composites.

Composition	Theoretical density (g/cm ³)	Measured density (raw hBN)	Void content (%) (raw)	Measured density (MAPP)	Void content (%) (MAPP)
Neat PP	0.90	0.90	-	-	-
PP + 10 wt% hBN	1.04	1.01	2.88	1.02	1.92
PP + 20 wt% hBN	1.17	1.12	4.27	1.14	2.56
PP + 30 wt% hBN	1.30	1.23	5.38	1.26	3.08
PP + 40 wt% hBN	1.43	1.33	6.99	1.37	4.20

Table 3 shows that the content of voids grows with filler loading for both series of composites. The maximum void content for PP/untreated hBN composites was 6.99%, whereas for PP/MAPP-modified hBN composites it was 4.20%. This is consistent with improved wetting and adhesion between the PP matrix and hBN particles resulting from MAPP modification. Because the theoretical density calculation does not account for voids, measured densities were lower than theoretical values. During fabrication of the composites using twin-screw extrusion and injection molding, the generation of voids is unavoidable.

The absorption of moisture by polymer composites has a noticeable effect, as higher water absorption is generally associated with greater degradation of material properties. Hence, the study of water absorption behavior is important. The water absorption behavior of the composites is shown in Figure 2. The filled PP absorbs more water than neat PP, and the absorption increases with hBN content as presented in the figure.

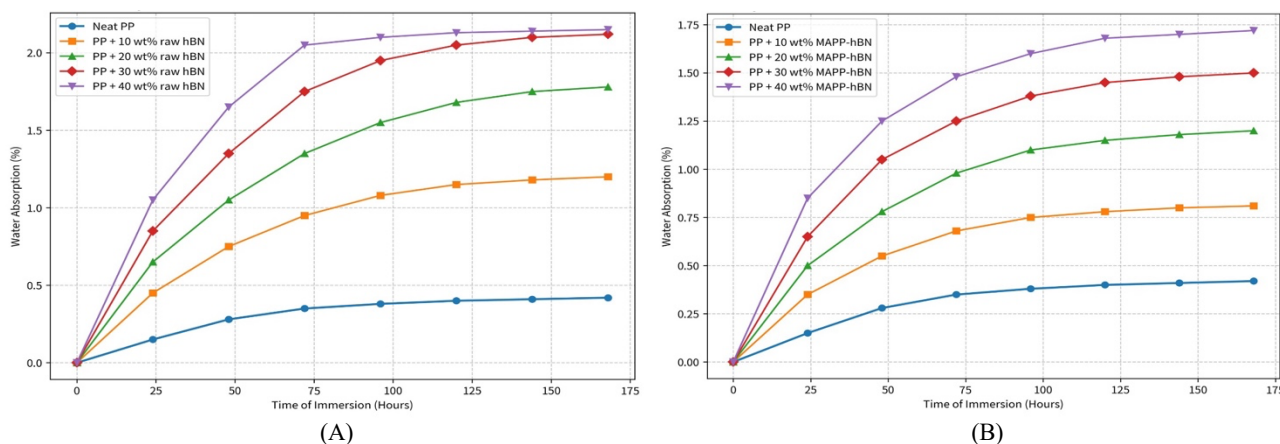


Figure 2: Water uptake as a function of immersion time. (A) polypropylene/raw hBN composite; (B) polypropylene/MAPP-modified hBN composite.

The increase in water uptake with filler content is mainly because of the increase in void content with hBN loading. As shown in Table 3, composites prepared with MAPP-modified hBN have fewer voids; therefore, their water uptake is also lower. In addition, better compatibility and enhanced interfacial bonding between the PP matrix and hBN particles result in a lower water absorption rate of the composites. Maximum water uptakes of 2.15% and 1.72% were recorded for the composites with 40 wt% raw hBN and MAPP-modified hBN, respectively.

Mechanical Properties

The mechanical properties of the polypropylene/hBN composites under investigation for both sets of samples are presented in Figure 3. Figure 3(A) shows the strength of the PP/hBN composites under tensile loading. Figure 3A shows that the composite prepared with MAPP-modified hBN delivers superior tensile strength for a given filler loading. The tensile strength depends on the compatibility between the filler and the matrix material. MAPP modification

improves the compatibility between the two phases by promoting interfacial interactions between hBN and PP, thereby improving stress transfer and tensile strength.

Figure 3A also shows that the increase in tensile strength with filler loading occurs only up to a certain filler content and decreases thereafter. Tensile strength increased approximately linearly with hBN content at lower loadings, whereas it decreased for composites with higher hBN content. This trend was similar in both sets of composites. These results indicate that the maximum tensile strength occurs for a filler content between 20 and 30 wt%. To determine this value, composites with intermediate filler contents between 20 and 30 wt% were also prepared and tested, and the maximum tensile strength occurred at 25 wt% hBN. This value is 42.8 MPa for the composite prepared with MAPP-modified hBN and is 35.9% higher than the tensile strength of neat PP (31.5 MPa). The composition and mechanical properties of these additional 25 wt% samples are presented in Table 4.

Table 4: Composition and mechanical properties of the additional 25 wt% hBN composites prepared to refine the optimum filler content.

Set	Composition	Tensile Strength (MPa)	Flexural Strength (MPa)
A5	Polypropylene + 25 wt% of untreated hBN	~39.5	~62
B5	Polypropylene + 25 wt% of MAPP-modified hBN	42.8	68

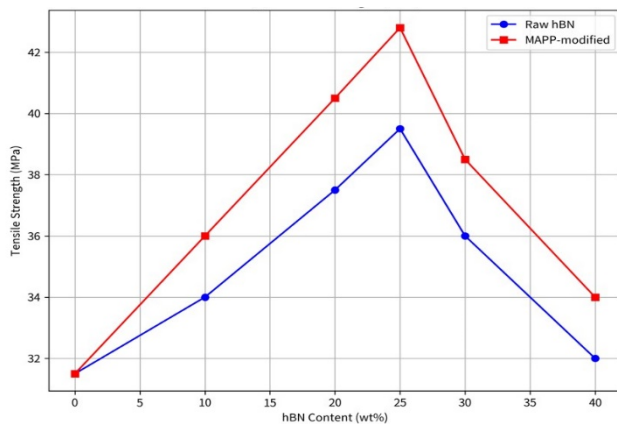


Figure 3A: Mechanical properties of polypropylene/hBN composites as a function of filler loading and MAPP modification. (A) Tensile strength

For the composite prepared with 40 wt% MAPP-modified hBN, the tensile strength decreases due to agglomeration and stress concentration points. At lower filler contents, well-dispersed hBN can enhance load transfer and hinder crack propagation. On the other hand, at high filler loading, factors such as filler agglomeration, stress concentration points, interfacial defects, and improper wetting arise, which drastically reduce the tensile strength. The agglomeration at high filler loading can be seen in SEM images (Figure 1). Similar behavior is reported by several researchers while studying PP/inorganic filler composites.

The elongation at break of the samples is given in Figure 3(B). The figure shows that the elongation at break of the specimens decreased with increasing filler loading. This is because the incorporation of rigid hBN filler develops the interconnected framework of hBN microparticles within the PP matrix which can efficiently resist deformation. Apart from that, with filler incorporation, stress concentrations develop, leading to a decrease in elongation at break. It is observed from the figure that neat PP exhibited an elongation at break of 85%, which decreased to 12% with the addition of 40 wt% MAPP-modified hBN. It is also observed that for the same filler loading, the MAPP-modified hBN-filled PP displays relatively greater ductility than raw hBN-filled composites due to improved interfacial interaction.

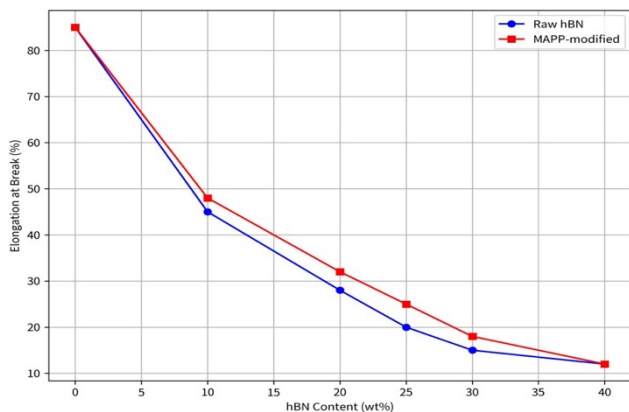


Figure 3B: Mechanical properties of polypropylene/hBN composites as a function of filler loading and MAPP modification. (B) Elongation at break

A similar trend was observed for flexural strength (Figure 3C). Here also, flexural strength increased with filler loading up to a

certain hBN content. In addition, the composite prepared with MAPP-modified hBN delivers superior strength for a given filler content because of improved interfacial adhesion. The maximum flexural strength of 68 MPa was obtained at 25 wt% hBN loading, representing an improvement of approximately 41.7% compared with neat PP (48 MPa).

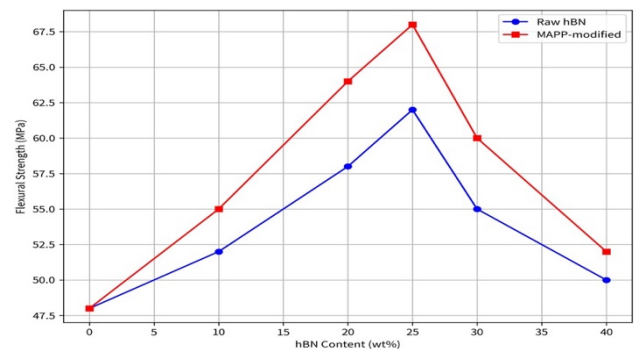


Figure 3C: Mechanical properties of polypropylene/hBN composites as a function of filler loading and MAPP modification. (C) Flexural strength

Figure 3D shows the increase in compressive strength of the PP/hBN composites for the complete range of filler content used in the present investigation. The primary reason for this increase is the rigidity of hBN and improved load transfer associated with better interfacial bonding in MAPP-modified composites. The compressive strength reached 92 MPa at 40 wt% MAPP-modified hBN, corresponding to an improvement of approximately 58.6% compared with neat PP (58 MPa). The treatment of hBN with MAPP had a positive impact on the compressive strength of the material due to improved adhesion and compatibility between the two phases, which helps transfer the load effectively.

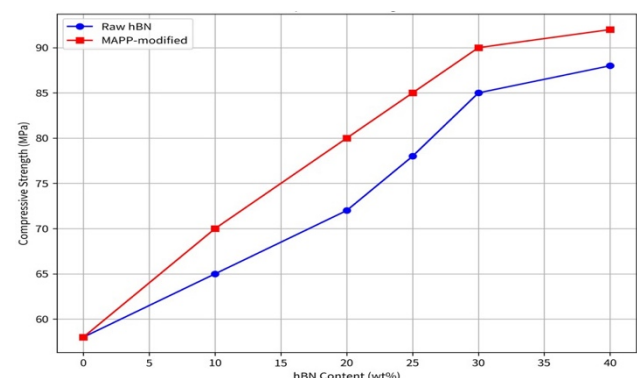


Figure 3D: Mechanical properties of polypropylene/hBN composites as a function of filler loading and MAPP modification. (D) Compressive strength

The variation in the value of the Shore D hardness of the PP/hBN composites is presented in Figure 3(E). hBN has higher hardness than the PP matrix; therefore, its inclusion in PP improves the hardness of the composites. Neat PP has a Shore D hardness of 68, which increases to 82 (an increase of approximately 20.6%) for PP/MAPP-modified hBN composites at 40 wt% loading. The enhancement in hardness is due to the resistance provided by the hBN particles to the plastic deformation of the PP matrix. This resistance restricts localized plastic deformation and polymer-chain mobility, thereby increasing hardness. It is also observed that the composite prepared with MAPP-modified hBN shows a higher Shore D hardness for a given filler loading than the corresponding

raw-hBN composite. This is due to the improved compatibility between the two phases and relatively low void content in the MAPP-modified composites.

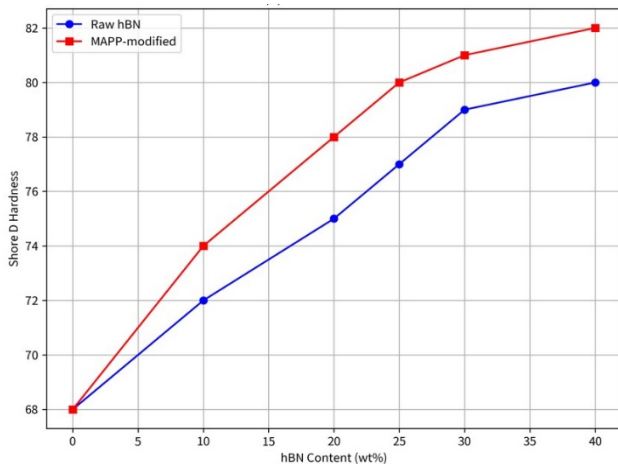


Figure 3E: Mechanical properties of polypropylene/hBN composites as a function of filler loading and MAPP modification. (E) Hardness.

Thermal Properties

The thermal properties of the polypropylene/hBN composites under investigation are presented in Figure 4. Polymers generally have low thermal conductivity, and this is also true for neat PP in the present study ($0.30 \text{ W/m}\cdot\text{K}$). Thermal conductivity can be improved by forming a thermally conductive network or by decreasing interfacial thermal contact resistance. In the present work, a thermally conductive network is developed by increasing the hBN content beyond a certain filler loading, whereas the interfacial thermal resistance between the PP matrix and hBN is reduced by using MAPP-modified hBN.

The variation in the thermal conductivity of PP/hBN composites is shown in Figure 4(A). Figure 4A shows that at low filler loadings, thermal conductivity increased gradually. For a raw hBN content of 10–20 wt%, the enhancement is modest. A similar trend is observed when MAPP-modified hBN is used. The conductivity increases sharply once the filler content reaches a critical value due to the formation of thermally conductive networks. For PP/raw hBN composites, a significant improvement is observed beyond 30 wt%, whereas for MAPP-modified hBN composites, an apparent threshold-like increase appears earlier. At 40 wt% loading:

- Raw hBN: $1.42 \text{ W/m}\cdot\text{K}$ (a 4.73-fold increase relative to neat PP)
- MAPP-modified hBN: $1.85 \text{ W/m}\cdot\text{K}$ (a 6.17-fold increase relative to neat PP)

The maximum improvement for the PP/MAPP-modified hBN composite is markedly higher than that of the raw-hBN counterpart. From the experimentation, it is seen that when the hBN loading increases beyond a certain wt%, the particles start to touch each other and form a conductive path resulting in a marked increase in thermal conductivity. Apart from that, MAPP modification results in improved heat conduction of composites for a given filler loading. This is mainly because of the improvement in dispersion, adhesion of fillers within the matrix, and the establishment of strong interfacial bonding which may reduce interfacial phonon scattering.

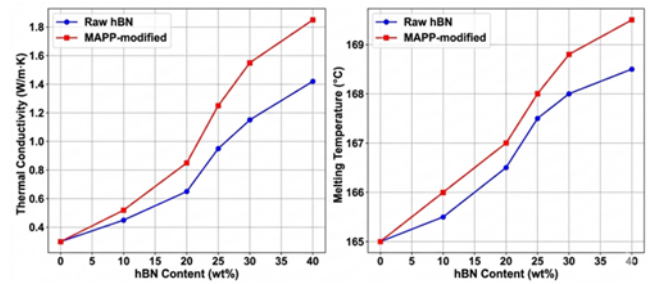


Figure 4: Thermal properties of polypropylene/hBN composites as a function of filler loading and MAPP modification. (A) Thermal conductivity, (B) Melting temperature.

The melting temperature (T_m) of the PP/hBN composites is presented in Figure 4(B). The T_m of filled PP is slightly higher than neat PP (165°C) and increases with hBN loading. The maximum melting temperature for PP/MAPP-modified hBN composites is 169.5°C at 40 wt% hBN loading. This increase may be related to restricted polymer-chain mobility resulting from strong filler-matrix interactions facilitated by MAPP, which may contribute to the modest increase in T_m .

The coefficient of thermal expansion (CTE) of PP/hBN composites prepared with both raw hBN and MAPP-modified hBN is presented in Figure 4(C). The CTE of neat PP is $110 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ and that of hBN is approximately $4 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$. The figure shows that the CTE decreased markedly with increasing hBN content for both series of composites. The CTE decreased from $110 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ for neat PP to $58 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ for the 40 wt% MAPP-modified hBN composite, representing a reduction of approximately 47.3%. This trend is expected because of the relatively lower CTE of hBN than PP. In addition, the inclusion of hBN constrains the expansion of the polymer at fluctuating temperatures. As the hBN content increases, the number of particles increases, which increasingly constrains the polymer chains. It is also noticed that the composites having a strong interface (MAPP-modified) display an additional reduction in CTE for a given filler loading. The improved filler-matrix interfacial network resulting from MAPP compatibilization restricts the thermal expansion of the polymer chains.

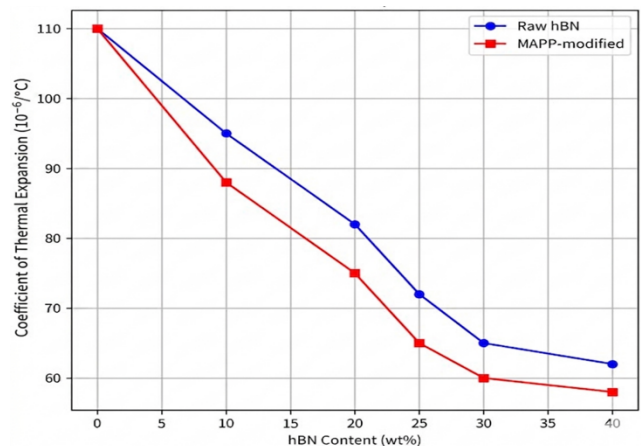


Figure 4C: Thermal properties of polypropylene/hBN composites as a function of filler loading and MAPP modification. (C) Coefficient of thermal expansion.

In addition to favorable physical, mechanical, and thermal properties, low dielectric constant and dielectric loss are important for different microelectronic applications. A low dielectric constant helps in reducing signal propagation delay, whereas low dielectric loss reduces energy dissipation as heat, which can degrade the performance, reliability, and lifespan of the electronic components.

The dielectric constant at different hBN contents and frequencies is shown in Figure 5. Figure 5A presents the values of PP/raw hBN composites, whereas Figure 5B presents the corresponding values

for PP/MAPP-modified hBN composites. First, hBN incorporation increased the dielectric constant of the composite. The enhancement is primarily because of the higher intrinsic permittivity of hBN (≈ 4.0 – 4.8) than the PP matrix. The dielectric constant of neat PP is 2.65 at 1 MHz. With the inclusion of 40 wt% MAPP-modified hBN, it increases to 4.75 at 1 MHz, which remained relatively low.

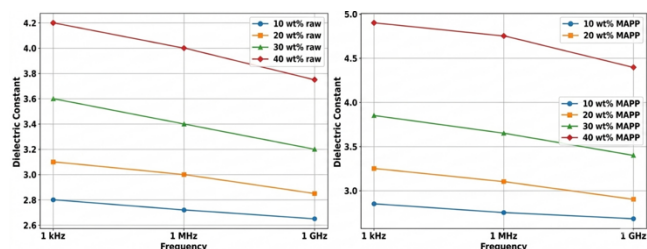


Figure 5: Dielectric constant of polypropylene/hBN composites as a function of filler loading, working frequency, and surface modification. (A) Polypropylene/raw-hBN composites, (B) Polypropylene/MAPP-modified hBN composites.

Another important observation is that the dielectric constant of the composites decreases with increasing frequency, showing typical dielectric dispersion behavior. This reduction is more pronounced at higher filler loadings due to the heterogeneous nature of the composite system. The MAPP-modified composites exhibit slightly higher dielectric constants than raw hBN composites for the same filler loading and frequency. This is attributed to the more uniform distribution of hBN particles and reduced air voids in MAPP-modified systems, which leads to better interfacial polarization.

Figure 6 shows the dielectric loss of the PP/hBN composites as a function of filler loading, working frequency, and surface modification. The addition of hBN to PP increased dielectric loss only marginally; the maximum loss factor remained below 0.085 across all compositions and frequencies (1 kHz–1 GHz). Importantly, the MAPP-modified composites show slightly lower dielectric loss than raw hBN composites. This reduction is mainly due to improved interfacial bonding, reduced void content, and minimized interfacial polarization provided by the MAPP compatibilizer. Surface modification may restrict the movement of charge carriers and reduce leakage current in the composites.

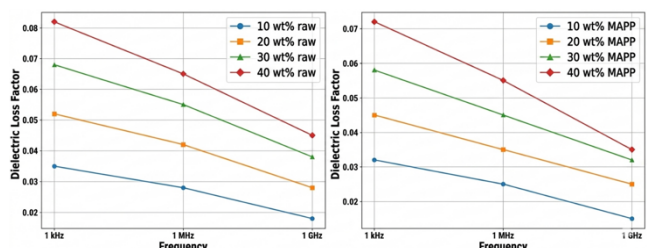


Figure 6: Dielectric loss of polypropylene/hBN composites as a function of filler loading, working frequency, and surface modification. (A) Polypropylene/raw-hBN composites, (B) Polypropylene/MAPP-modified hBN composites.

It is also observed from Figures 5 and 6 that the dielectric properties depend on the working frequency as well. The dielectric constant of neat PP varied little with frequency, indicating good frequency stability. By contrast, frequency stability decreased with increasing filler loading. The improvement in frequency stability with MAPP modification is mainly attributed to the suppression of interfacial polarization effects.

CONCLUSIONS

A series of polypropylene (PP) composites reinforced with micron-sized hexagonal boron nitride (hBN) were successfully fabricated through twin-screw melt extrusion followed by injection molding.

The effect of hBN filler loading (10–40 wt%) and compatibilization using maleic anhydride grafted polypropylene (MAPP) on the physical, mechanical, thermal, and dielectric properties of the composites was systematically investigated for potential microelectronic applications.

The incorporation of MAPP as a compatibilizer significantly improved the interfacial compatibility and dispersion of hBN particles within the non-polar PP matrix. Scanning electron microscopy (SEM) showed reduced interfacial gaps and morphology consistent with improved adhesion in MAPP-modified composites compared to those prepared with raw hBN. This improved interfacial bonding resulted in lower void content and moderated water absorption across all filler loadings.

The addition of hBN increased the density and void content of the composites; however, these increments were noticeably restricted in the presence of MAPP. Tensile and flexural strength showed a positive trend with filler loading up to an optimal range of 20–25 wt%, whereas compressive strength and hardness continued to increase up to 40 wt%. The maximum tensile strength of 42.8 MPa (35.9% improvement over neat PP) and flexural strength of 68 MPa were achieved in MAPP-compatible composites at 25 wt% hBN loading. Compressive strength and Shore D hardness increased continuously with hBN content, reaching 92 MPa and 82, respectively, at 40 wt% MAPP-modified hBN. Although elongation at break decreased with increasing filler content, MAPP helped retain relatively better ductility than raw hBN composites.

One of the most significant achievements of this work is the substantial increase in thermal conductivity. The thermal conductivity of neat PP (0.30 W/m·K) increased to 1.42 W/m·K (a 4.73-fold increase) with 40 wt% raw hBN and reached 1.85 W/m·K (a 6.17-fold increase) with 40 wt% MAPP-modified hBN. An apparent percolation-like threshold was observed at a lower filler loading for MAPP-modified composites compared to raw hBN composites. Additionally, the coefficient of thermal expansion (CTE) was substantially reduced from $110 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ for neat PP to $58 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ at 40 wt% MAPP-modified hBN. The melting temperature also showed a slight increase, which may indicate restricted polymer-chain mobility due to strong filler-matrix interactions.

Dielectric properties were marginally affected by hBN incorporation. The dielectric constant increased from 2.65 (neat PP) to 4.75 at 40 wt% MAPP-modified hBN (measured at 1 MHz), while remaining relatively low. The dielectric loss factor stayed below 0.085 across the tested frequency range (1 kHz–1 GHz), with MAPP-modified composites exhibiting better frequency stability due to reduced interfacial polarization and fewer voids.

In conclusion, the developed PP/hBN/MAPP composites offer a favorable combination of high thermal conductivity, acceptable mechanical strength, low CTE, and suitable dielectric properties. The use of MAPP as a compatibilizer was effective in overcoming the inherent incompatibility between PP and hBN, leading to superior overall performance compared to raw hBN-filled composites. PP offers potential advantages over conventional thermoset polyester or epoxy-based systems in terms of processability (via melt extrusion and injection molding), recyclability, chemical resistance, and cost-effectiveness.

These composites show potential for various microelectronic applications, including thermal interface materials (TIMs), heat spreaders, substrates for printed circuit boards, electronic packaging, LED housings, and insulating components in high-power density devices, subject to application-specific validation. The present study demonstrates that through proper interfacial engineering using MAPP, polypropylene-based hBN composites can serve as potentially more recyclable, high-performance

thermoplastic materials for addressing the growing thermal management challenges in modern electronics.

Future research may focus on hybrid filler systems, optimization of MAPP content, further surface functionalization of hBN, and evaluation of long-term thermal aging, electrical breakdown strength, and flame retardancy to further enhance the applicability of these composites in advanced microelectronic devices. Direct quantification of MAPP grafting and interfacial chemistry, thermal cycling reliability studies, device-level validation, and statistical optimization of hBN/MAPP concentrations are also recommended.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

Akash Deep Kushwaha: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing—original draft, Writing—review & editing, Visualization, and Project administration.

Shailendra Kumar Bohidar and Abhishek Kumar Jain: Methodology, Investigation, Data curation, and Formal analysis.

Vijay Patle and Deepak Funde: Investigation, Formal analysis, and Writing—review & editing.

Jadhav Vijay Baban, Sheetal Gajjalwar, Rakshit Kumar Sisodiya, and Payal: Supervision, Resources, and Writing—review & editing.

All authors reviewed and approved the final manuscript.

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