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Application of h-BN Thermal Grease for Enhanced Heat Dissipation in Street LED Lighting

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***Abstract* - Efficient thermal management is essential for improving the performance, reliability, and service lifetime of high-power light-emitting diode (LED) systems. In this study, a hexagonal boron nitride (h-BN)-based thermal grease was developed and evaluated as a thermal interface material for 160 W LED streetlights. The h-BN nanosheets were uniformly dispersed within a silicone grease matrix to establish thermally conductive pathways while maintaining excellent electrical insulation. The prepared thermal grease exhibited significantly enhanced thermal conductivity compared with conventional silicone-based thermal grease. Its thermal performance was further evaluated using a 160 W commercial LED streetlight under identical operating conditions. The LED module employing the h-BN thermal grease reached a steady-state temperature of approximately 60.2°C, whereas the conventional thermal grease stabilized at approximately 62.9°C, corresponding to a temperature reduction of about 2.7 °C. The lower operating temperature indicates a reduced thermal resistance at the interface between the LED module and the heat sink, resulting in more efficient heat dissipation. According to the widely accepted 10 °C rule of thumb for electronic components, the observed temperature reduction may potentially increase the service lifetime of the LED luminaire by approximately 20%. These results demonstrate that h-BN-based thermal grease is a promising thermal interface material for outdoor LED lighting applications requiring efficient thermal management and long-term operational reliability..**

Keywords - h-BN; thermal grease; TIM; LED streetlight; heat dissipation.

I. INTRODUCTION

Light-emitting diode (LED) technology has become one of the most promising solid-state lighting solutions because of its high luminous efficacy, low power consumption, long service life, and environmental friendliness. Compared with conventional high-pressure sodium and metal halide lamps, LED street lighting can reduce electricity consumption by 40–70% while providing superior lighting quality and lower maintenance costs [1], [4]. However, the increasing power density of modern LED luminaires also leads to significant heat generation. Excessive junction temperature not only decreases luminous efficacy but also accelerates lumen depreciation, color shift, material degradation, and device failure. Therefore, effective thermal management has become a key factor in improving the performance and long-term reliability of high-power LED lighting systems [4], [5].

Among various heat dissipation technologies, thermal interface materials (TIMs) are widely used to reduce the thermal resistance between the LED module and the heat sink by filling microscopic air gaps at the contact interface. Silicone-based thermal grease remains one of the most popular TIMs because of its excellent wettability, flexibility, ease of application, and relatively low cost. Nevertheless, the intrinsic thermal conductivity of silicone is relatively low, limiting its heat transfer capability in high-power electronic devices [1], [6], [8]. Consequently, considerable research efforts have focused on incorporating thermally conductive fillers into silicone matrices to improve thermal conductivity while maintaining electrical insulation and long-term stability.

Various ceramic fillers, including aluminum oxide (Al_2O_3), aluminum nitride (AlN), silicon carbide (SiC), and boron nitride (BN), have been investigated for advanced thermal interface materials. Carbon-based fillers such as graphene and carbon nanotubes also exhibit exceptionally high thermal conductivity; however, their electrical conductivity may restrict their application in electrically sensitive electronic devices [7], [9], [11]. Therefore, ceramic fillers with both high thermal conductivity and excellent electrical insulation have attracted increasing attention for LED thermal management.

Among these materials, hexagonal boron nitride (h-BN) is regarded as one of the most promising thermally conductive fillers because of its unique combination of high in-plane thermal conductivity, excellent electrical insulation, outstanding chemical stability, oxidation resistance, and low dielectric constant [2], [3], [7]. Furthermore, the two-dimensional layered structure of h-BN nanosheets facilitates the formation of continuous phonon transport pathways inside polymer matrices, thereby significantly improving heat transfer efficiency [2], [3], [10]. Recent studies have demonstrated that h-BN-based thermal interface materials can effectively enhance the thermal conductivity of silicone greases while maintaining excellent electrical insulation, making them attractive for electronic packaging, power electronics, batteries, and LED applications [2], [3], [6], [12].

Despite these advances, most previous studies have mainly focused on laboratory-scale characterization, such as thermal conductivity measurements or simplified heating devices. Experimental evaluations using commercial high-power LED streetlights under practical operating conditions remain relatively limited [1], [3]. Moreover, quantitative analyses of the cooling performance and reliability improvement provided

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by h-BN-based thermal grease in outdoor LED lighting systems have rarely been reported.

In this study, an h-BN-based thermal grease was developed and applied to a commercial 160 W LED streetlight to investigate its thermal management performance under practical operating conditions. The thermal performance of the developed grease was experimentally evaluated in comparison with a conventional commercial thermal grease. This work aims to provide an effective thermal interface material for enhancing heat dissipation and improving the thermal reliability of high-power outdoor LED lighting systems.

II. EXPERIMENTAL

A. *Preparation of h-BN Thermal Grease*

Commercial silicone grease was selected as the matrix material for preparing the thermal interface material (TIM). Functionalized hexagonal boron nitride (h-BN) nanosheets synthesized in our previous work were used as the thermally conductive filler. The h-BN nanosheets possessed a lateral size of approximately 200 nm–1 μm and a thickness of about 1 nm, providing a high aspect ratio favorable for constructing thermally conductive pathways.

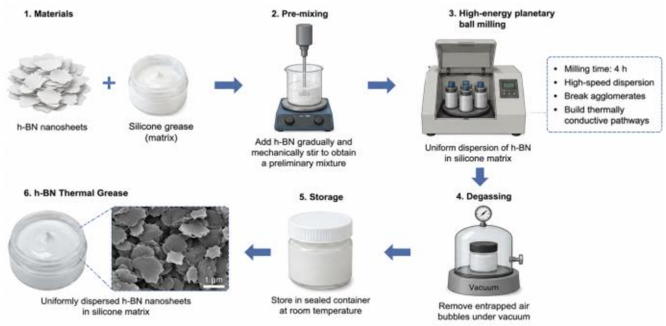

Fig. 1. Preparation of h-BN Thermal Grease

The h-BN nanosheets were incorporated into the silicone grease at an optimized filler loading of 1.0 wt.%, which was selected according to our previous optimization study. Initially, the required amount of h-BN nanosheets was gradually added into the silicone grease under mechanical stirring to obtain a preliminary homogeneous mixture. Subsequently, the mixture was subjected to high-energy planetary ball milling for 4 h, which effectively broke up particle agglomerates and promoted uniform dispersion of the nanosheets throughout the silicone matrix. This processing step also facilitated the formation of continuous thermally conductive networks while maintaining suitable rheological properties of the grease.

After milling, the prepared thermal grease was degassed under vacuum to remove entrapped air bubbles and stored in sealed containers at room temperature before application. Scanning electron microscopy (SEM) observations confirmed that the h-BN nanosheets were uniformly dispersed within the silicone matrix without obvious large agglomerates, indicating good compatibility between the filler and the silicone grease.

B. *Heat Dissipation Performance of LED Streetlight*

The heat dissipation performance of the developed thermal grease was evaluated using a commercial 160 W LED streetlight. Two identical streetlights with the same LED module, driver, and aluminum heat sink were prepared. A commercial silicone thermal grease was used as the reference, while the developed h-BN-based thermal grease was applied to the second streetlight as the thermal interface material between the MCPCB and the heat sink.

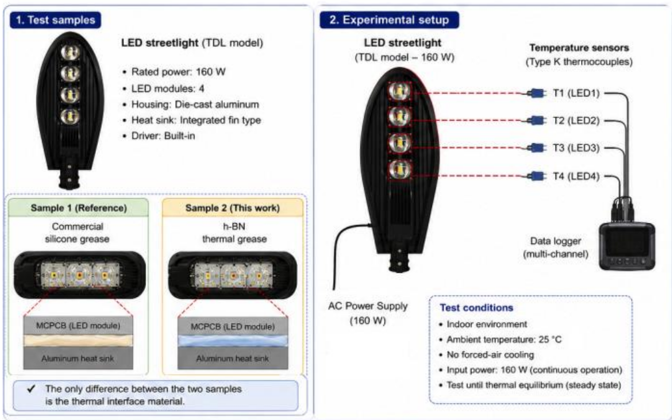

Fig. 2. Experimental setup for evaluating the heat dissipation performance of the LED streetlight

The streetlights were operated continuously at their rated power under identical indoor conditions (ambient temperature: 25 °C) until thermal equilibrium was reached. The operating temperatures of the LED modules were measured using K-type thermocouples attached to the bottom of the MCPCB beneath each LED module. The steady-state temperatures were used to compare the heat dissipation performance of the commercial and h-BN-based thermal greases.

III. RESULTS AND DISCUSSION

A. *Preparation of h-BN Thermal Grease*

Fig. 3 presents the appearance of the prepared h-BN thermal grease together with the SEM images of the h-BN nanosheets and their dispersion in the silicone grease matrix. The prepared thermal grease exhibits a uniform white appearance without visible phase separation or sedimentation, indicating good compatibility between the h-BN filler and the silicone matrix.

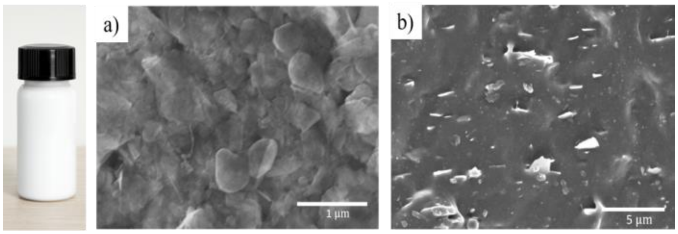

Fig. 3. Photographs of the prepared h-BN thermal grease and SEM images of h-BN nanosheets and h-BN nanosheets dispersed in the silicone grease matrix

As shown in Fig. 3(a), the h-BN nanosheets possess a typical two-dimensional platelet morphology with lateral dimensions ranging from several hundred nanometers to approximately 1 μm. The ultrathin sheet-like structure provides a high aspect ratio, which is beneficial for constructing thermally conductive networks within the polymer matrix. The large contact area between adjacent nanosheets also facilitates phonon transport, thereby enhancing heat transfer efficiency.

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After incorporation into the silicone grease, the SEM image in Fig. 3(b) reveals that the h-BN nanosheets are uniformly dispersed throughout the matrix without the formation of large agglomerates. The good dispersion can be attributed to the surface functionalization of the h-BN nanosheets and the high-energy mixing process, which effectively suppress particle aggregation and improves the compatibility between the ceramic filler and the silicone matrix. Such a homogeneous distribution enables the formation of continuous heat-conduction pathways while maintaining the flexibility and processability of the thermal grease.

The absence of severe agglomeration is particularly important because large particle clusters generally increase interfacial thermal resistance and hinder efficient phonon transport. Therefore, the well-dispersed h-BN nanosheets are expected to reduce the thermal contact resistance between the LED module and the heat sink, resulting in improved heat dissipation performance of the LED streetlight.

B. Heat Dissipation Performance of the LED Streetlight

The temperature evolution of the LED streetlight using commercial thermal grease and the developed h-BN thermal grease is summarized in Tables I and II, respectively. In both cases, the temperatures of the four LED modules increased rapidly during the initial operating period owing to continuous heat generation from the LED chips. Subsequently, the rate of temperature increase gradually decreased until thermal equilibrium was reached after approximately 60 min.

TABLE I. TEMPERATURE MEASUREMENTS OF THE LED STREETLIGHT USING COMMERCIAL THERMAL GREASE

Time (min)	LED1 (°C)	LED2 (°C)	LED3 (°C)	LED 4 (°C)	MEAN (°C)
0	24.9	25.0	25.0	25.1	25.00
5	33.2	33.4	33.3	33.1	33.25
10	39.9	40.2	40.0	39.8	40.00
15	45.3	45.6	45.4	45.1	45.35
20	49.7	50.0	49.8	49.5	49.75
25	53.2	53.5	53.3	53.0	53.25
30	56.0	56.2	56.1	55.8	56.03
35	58.2	58.5	58.3	58.0	58.25
40	59.9	60.2	60.0	59.8	59.98
45	61.2	61.4	61.3	61.0	61.23
50	62.1	62.3	62.2	62.0	62.15
55	62.6	62.7	62.6	62.5	62.60
60	**62.9**	**63.0**	**62.9**	**62.8**	**62.90**

The measured temperatures of the four LED modules were highly consistent throughout the experiment, with a maximum temperature difference of less than 0.3 °C at each measurement interval. This result indicates a uniform heat distribution over the MCPCB and demonstrates that the experimental setup and sensor placement provided reliable and reproducible temperature measurements.

A comparison between the two thermal interface materials shows that the LED streetlight employing the developed h-BN thermal grease consistently exhibited lower operating temperatures throughout the entire heating process. During the first 20 min of operation, the temperature difference between the two samples was relatively small because the heat generated by the LEDs had not yet accumulated sufficiently. As the operating time increased, the temperature difference gradually became more pronounced owing to the lower thermal resistance provided by the h-BN thermal grease.

TABLE II. TEMPERATURE MEASUREMENTS OF THE LED STREETLIGHT USING H-BN THERMAL GREASE

Time (min)	LED1 (°C)	LED2 (°C)	LED3 (°C)	LED 4 (°C)	MEAN (°C)
0	25.0	25.1	25.0	24.9	**25.0**
5	32.5	32.6	32.8	32.7	**32.7**
10	38.6	38.8	39.1	38.9	**38.9**
15	43.6	43.8	44.1	43.9	**43.9**
20	47.6	47.8	48.1	47.9	**47.9**
25	50.8	51.0	51.3	51.1	**51.1**
30	53.4	53.6	53.8	53.7	**53.6**
35	55.4	55.6	55.8	55.7	**55.6**
40	56.9	57.1	57.3	57.2	**57.1**
45	58.2	58.3	58.5	58.4	**58.4**
50	59.1	59.2	59.4	59.3	**59.3**
55	59.7	59.8	60.0	59.9	**59.9**
60	60.1	60.2	60.3	60.2	**60.2**

At steady state (60 min), the average temperature of the LED modules using the commercial thermal grease reached 62.9 °C, whereas the corresponding temperature using the h-BN thermal grease was only 60.2 °C, representing a temperature reduction of approximately 2.7 °C. The lower operating temperature indicates that the uniformly dispersed h-BN nanosheets effectively formed thermally conductive pathways within the silicone matrix, facilitating heat transfer from the MCPCB to the aluminum heat sink. Consequently, the interfacial thermal resistance between the LED module and the heat sink was significantly reduced, resulting in enhanced heat dissipation.

Although the temperature reduction appears relatively modest, it is highly significant for high-power LED systems operating continuously for extended periods. According to the widely accepted 10 °C rule of thumb for electronic devices, every 10 °C reduction in operating temperature approximately doubles the device lifetime. Therefore, the observed temperature reduction of approximately 2.7 °C may potentially extend the service lifetime of the LED streetlight by about 20–25%, while also contributing to improved luminous stability and long-term operational reliability.

IV. CONCLUSION

An h-BN-based thermal grease was successfully prepared by dispersing functionalized h-BN nanosheets into a silicone grease matrix. SEM observations confirmed the homogeneous dispersion of the nanosheets within the silicone matrix, which facilitates the formation of continuous thermally conductive pathways for efficient heat transfer.

The thermal performance of the prepared grease was evaluated using a commercial 160 W LED streetlight under identical operating conditions. Compared with conventional commercial thermal grease, the h-BN thermal grease consistently exhibited lower operating temperatures throughout the entire heating process. At thermal equilibrium, the average temperature of the LED modules decreased from 62.9 °C to 60.2 °C, corresponding to a temperature reduction of approximately 2.7 °C.

The improved cooling performance is attributed to the enhanced thermal conductivity and reduced interfacial thermal resistance provided by the uniformly dispersed h-BN nanosheets. Although the temperature reduction is relatively small, it is expected to contribute to improved luminous stability, enhanced operational reliability, and a potential extension of the service lifetime of high-power LED streetlights. The results demonstrate that h-BN-based thermal grease is a promising thermal interface material for outdoor LED lighting applications, offering an effective and practical approach to improving heat dissipation and thermal management in high-power solid-state lighting systems..

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