

Application of Graphene in the Fabrication of Thermal Management Materials

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Abstract: Graphene, as a novel two-dimensional material, possesses a thermal conductivity far exceeding that of traditional thermal management materials, effectively addressing the heat dissipation challenges of various devices. This project focuses on the thermal dissipation properties of graphene. It comprehensively reviews various graphene-based thermal management materials, summarizing their performance characteristics, primary preparation methods along with their respective advantages and disadvantages. It also compares novel graphene heat sinks with traditional ones, thereby summarizing their practical applications across various fields and future trends.

Keywords: Graphene; Thermal Conductivity; Heat Dissipation; Thermal Interface Material (TIM)

1. Introduction

With the rapid advancement of electronic technology, the integration density of electronic components continues to increase while their size shrinks. The power density of electronic devices has already exceeded 300 W/cm². This has led to increasingly severe heat generation issues in various devices, significantly impacting their lifespan and performance. Effectively dissipating heat has thus become a subject of significant research importance. Traditional heat dissipation methods are often limited by environmental factors, structural design and the poor thermal conductivity of materials. Therefore, finding thermal management materials with excellent thermal conductivity has become crucial for the development of the electronics field. Graphene, as a novel two-dimensional material, has garnered significant attention for heat dissipation applications due to its extremely high thermal conductivity. Traditional heat dissipation methods, such as natural convection and heat

conduction via metal heat sinks, are constrained by multiple factors. In contrast, graphene's thermal conductivity is among the highest known for any material, offering outstanding thermal performance with minimal environmental influence. Its thermal conductivity is significantly higher than traditional materials like copper (Cu) and aluminum (Al). Studies show that the thermal conductivity of single-layer graphene ranges from 3000 to 5000 W/(m·K) [1]. Applying graphene to thermal management materials enables highly conductive thermal interface materials (TIMs) to eliminate air gaps between electronic components and heat sinks, establishing efficient heat transfer pathways [2]. This minimizes contact thermal resistance, ensuring the operational efficiency and longevity of electronic devices.

2. Preparation Principles of Graphene Thermal Management Materials

Graphene is a two-dimensional crystalline lattice structure material composed of carbon atoms, exhibiting outstanding thermal conductivity. Based on the current research status of graphene's thermal properties, the primary preparation methods for graphene thermal management materials are as follows.

2.1 Mechanical Exfoliation

This method involves using mechanical forces, such as shear or friction, to peel graphene layers from graphite crystals, producing high-quality graphene with excellent crystallinity, where the single-layer proportion exceeds 90%. The process follows fracture mechanics principles, with a critical peeling energy $E_c = 1.5 \text{ J/m}^2$ [3]. However, this method has low efficiency, typically yielding only 0.5 mg of graphene per cm² of substrate, and suffers from poor uniformity, with an edge defect density reaching 10^8 cm^{-2} as measured by AFM. It is only suitable for small-scale laboratory preparation.

2.2 Chemical Vapor Deposition (CVD)

This method involves depositing carbon atoms from carbon-containing gases onto a metal substrate under high temperatures to form large-area, continuous, high-performance graphene films. Methane is typically used as the carbon source, undergoing catalytic decomposition on Ni (111) substrates. The growth rate can be adjusted between 0.5-2 $\mu\text{m}/\text{min}$ by controlling H_2 partial pressure [4]. This method is suitable for industrial production of high-precision device heat dissipation components. Optimized processes, such as adding Pd nanoparticles, can increase the growth rate by 40% [4], and using PMMA-assisted transfer can reduce interface contamination to 0.3 nm [5].

2.3 Chemical Oxidation-Reduction

Graphite powder is reacted with strong oxidizing agents to produce graphene oxide (GO), which is then reduced back to graphene using reducing agents. Microwave-assisted oxidation can shorten the reaction time from 48 hours to 2 hours. Reduction processes typically include thermal reduction (e.g., 200°C vacuum treatment reducing C=O content from 38% to 8%) and laser reduction (e.g., nanosecond laser pulses enabling localized reduction with micron-level precision). This method offers lower preparation costs and higher yields. The cost per monolayer for industrial production is only 1/50th of CVD [6]. However, the quality of the resulting graphene thermal materials is often suboptimal, and the process carries environmental pollution risks [6].

2.4 Coating Method

The main process involves dispersing graphene or its derivatives (like graphene oxide) in a solvent to form a graphene coating solution, which is then applied to a substrate material. After drying and curing, a graphene thermal dissipation coating is obtained. For coating, solvents like NMP can achieve dispersion concentrations of 5 mg/mL with viscosity <1000 cP; stabilizers like polyvinylpyrrolidone (PVP) can significantly reduce sedimentation rates [7]. Various film-forming techniques are available, including spin coating, spray pyrolysis, and plasma-assisted spraying. This method features a simple preparation process, yields materials with excellent performance, is suitable for industrial production of thermal management materials

with relatively less stringent precision requirements, and allows for adjustment of coating thickness and thermal conductivity as needed.

3. Characteristics of Graphene Thermal Management Materials

Graphene is currently the only known free-standing two-dimensional atomic crystal. It is the fundamental structural unit of sp^2 -hybridized carbon, forming the basis for zero-dimensional fullerenes, one-dimensional carbon nanotubes, and three-dimensional graphite [8]. It exhibits superior properties in both thermal and electrical domains compared to conventional materials. The surface of pristine graphene consists of a two-dimensional crystal formed by hexagonal rings without any unstable chemical bonds. Despite graphene's exceptional in-plane thermal conductivity, its molecular structure lacks active functional groups, necessitating reliance on a polymer matrix for interfacial bonding. Studies show that adding just 0.5 wt% graphene increases the tensile strength of epoxy resin from 35 MPa to 60 MPa while maintaining fracture elongation retention above 90% [7]. This low filler loading characteristic effectively resolves the contradiction inherent in traditional inorganic fillers, where high loading leads to increased brittleness and reduced thermal stability.

Notably, the sp^2 -hybridized carbon network of graphene possesses unique π - π interaction sites [8], enabling the formation of heterostructures with metal, oxide, and sulfide nanoparticles via physical adsorption or chemical bonding. Experiments demonstrate that graphene-Au composites exhibit a 2-order-of-magnitude increase in electrical conductivity [4], while graphene- TiO_2 systems show a 47% improvement in photocatalytic activity compared to pure TiO_2 [9], indicating better electrocatalytic activity and specific capacitance. Regarding graphene composites, common examples include graphene-phenolic resin composites with a three-dimensional cross-linked network [7], constructed by in-situ growth of graphene to build multi-scale thermal conduction pathways. These composites exhibit extremely high in-plane thermal conductivity while significantly reducing volume resistivity. Their comprehensive thermal-electrical-chemical stability surpasses traditional PPO (polyphenylene oxide)

engineering plastics and approaches that of aluminum-based composites, making them novel composite materials far exceeding plastics in terms of high thermal dissipation, high electrical conductivity, and strong corrosion resistance. In practical applications, graphene's thermal conductivity may fall short of theoretical values due to defects or increased layer count introduced during preparation, affecting thermal performance. Additionally, graphene's anisotropy-excellent in-plane conductivity but poor out-of-plane conductivity-may limit its application in scenarios requiring three-dimensional heat dissipation.

4. Performance Comparison: Graphene vs. Traditional Thermal Management Materials

Current typical heat dissipation methods include natural convection, forced air cooling (fans), liquid cooling (heat pipes/loops), and heat conduction via metal heat sinks. Natural convection dissipates heat primarily through natural convection and radiation between an object's surface and the surrounding environment. While energy-efficient, simple, and environmentally friendly, its efficiency is low and often insufficient for high-temperature or high-power devices. Forced air cooling uses fans to generate airflow, carrying heat away from the heat sink. However, hot air may be obstructed by internal layouts, leading to internal recirculation and reduced effectiveness. Liquid cooling relies on water or other coolants circulating in a closed system to transfer heat from the heat source to a larger-surface-area radiator, where it is dissipated by other means. It offers high

efficiency and compact size but involves higher costs and risks of liquid leakage damaging equipment. Metal heat sink conduction transfers heat directly from the device to a cooler contacting object. The effectiveness of this method heavily depends on the thermal conductivity of the contact object and the temperature difference; poor conductivity drastically reduces performance.

In contrast, graphene composite materials demonstrate significant advantages over traditional methods in thermal conductivity, physical properties, and application adaptability.

4.1 Ultra-High Thermal Conductivity and Dissipation Efficiency

Graphene's intrinsic thermal conductivity far exceeds that of traditional metals like copper and aluminum. Its unique two-dimensional honeycomb structure facilitates rapid formation of continuous heat conduction paths. Applying graphene thermal coatings to LED lamps reduces temperature rise by over 10°C. Experiments show that graphene-based composite thermal materials used in SSD cooling result in temperatures 5°C lower than commercial copper heat sinks, with heat dissipation speeds 200 times faster [10]. Furthermore, graphene's high in-plane conductivity and breakthroughs in through-thickness conductivity address the challenge of dissipating localized hot spots in high-frequency devices.

Table 1 are the thermal physical parameters of various materials measured at room temperature of 25 degrees Celsius.

Table 1. Thermophysical Parameters of Various Materials

Material	Thermal Conductivity (W/m·K)	Coefficient of Thermal Expansion (10 ⁻⁶ /K)	Density (g/cm ³)
Cu	398	16.5	8.96
Al	237	23.1	2.7
Graphene (Single layer)	1500-2500	2.7	2.1
Cu-Graphene Composite	850	18.3	8.3

and lightweight electronics.

4.2 Balance of Lightweight and High Strength

Graphene has a density of only 2.26 g/cm³, significantly lower than aluminum and copper. Composite heat sinks can be 30%-50% lighter. Simultaneously, graphene's strength is 200 times that of steel, enabling thin designs while ensuring structural stability. An oxidized graphene film merely 0.8 μm thick can achieve a thermal conductivity of 3200 W/m·K [11], making it indispensable for wearable devices

4.3 Excellent Corrosion Resistance and Stability

Graphene exhibits outstanding chemical stability, maintaining performance even in acidic or alkaline environments. Compared to traditional copper/aluminum heat sinks prone to oxidation and corrosion, graphene-based materials pose no rust risk in long-term use within water heating systems. This makes graphene heat sinks

extremely robust and durable, significantly reducing maintenance costs. A graphene coating on aluminum sheets can increase their thermal emissivity from 7% to 88% while protecting the metal substrate from direct exposure to corrosive environments.

4.4 Multi-Dimensional Thermal Management Optimization

Graphene composites can dissipate heat synergistically through radiation, conduction, and convection, significantly improving efficiency in natural convection scenarios. Additionally, graphene's flexibility allows it to conform to irregular surfaces. In CPU cooling, for instance, graphene composite thermal grease can stabilize temperatures at 47°C [12], demonstrating significantly better cooling than traditional grease.

4.5 Energy Efficiency, Environmental Friendliness, and Cost Advantage

Graphene's heat conversion efficiency exceeds 99%, minimizing energy waste. In heating systems, graphene radiators heat up 30% faster than copper/aluminum radiators and consume 20% less energy in the insulation state. Moreover, biomass-derived graphene feedstocks are abundant, and the resulting products exhibit good dispersibility and easy storage. Biomass graphene production avoids strong oxidants and chemical reduction processes. The heat sink casting process is streamlined, not only preventing environmental pollution and enabling green manufacturing but also ensuring the absence of chemical residues in the final product, greatly enhancing biosafety. In terms of cost, after scaling up production, the manufacturing cost of graphene composites is 20%-50% lower than aluminum, and complex post-processing is unnecessary.

5. Practical Applications of Graphene Thermal Management Materials

Since 2010, when scientists Andre Geim and Konstantin Novoselov were awarded the Nobel Prize for isolating graphene from graphite using micromechanical cleavage, graphene has been extensively researched, developed, and applied. Based on the distinct advantages and application scenarios of various graphene thermal materials, they can be utilized in multiple fields, as illustrated by the following examples. Graphene thermal pads are now widely used in

consumer electronics to rapidly conduct internal heat away, ensuring devices maintain suitable temperatures during prolonged use while improving performance. For instance, Huawei's Mate 60 Pro utilizes graphene combined with a vapor chamber (VC) for temperature averaging, reducing average gaming temperatures by 5.3°C. Intel integrates graphene GaN heat sinks on silicon photonic chips, boosting photoelectric conversion efficiency by 18%.

In the new energy vehicle (NEV) industry, graphene composite thermal materials can be applied to components like radiators and water tanks, improving cooling efficiency and lowering engine temperatures. They also significantly enhance the heat dissipation capability of hub motor stators [13]. Tesla's 4680 battery pack employs a graphene-phase change material (PCM) composite cooling layer. Testing shows this extends thermal runaway warning time from 5 minutes to 12 minutes and increases cycle life from approximately 1500 cycles to 2200 cycles, substantially improving NEV performance and safety.

Furthermore, graphene thermal materials find applications in aerospace and satellite thermal control systems. NASA's X-57 electric aircraft uses graphene skin for heat dissipation, slightly reducing structural weight and decreasing efficiency loss under high-temperature conditions [14]. In satellite thermal control systems, graphene-aluminum composite radiator panels optimize performance; ESA test data indicates improved emissivity and reduced on-orbit temperature fluctuations.

6. Summary

This paper focuses on the heat dissipation challenges of electronic devices, systematically exploring the preparation principles, performance advantages, and practical applications of graphene thermal management materials. Research demonstrates that graphene, prepared via diverse methods like mechanical exfoliation and CVD, exhibits thermal conductivity far surpassing copper and aluminum. Its composites overcome bottlenecks of traditional materials-such as brittleness from high filler loading and single-mode thermal management-through innovative designs like constructing 3D thermal pathways and leveraging synergistic effects in heterostructures. Its outstanding thermal conductivity and lightweight characteristics have made it a crucial

material for solving heat dissipation problems. However, challenges remain, including insufficient out-of-plane thermal conductivity and pollution risks associated with some preparation methods. Future efforts should focus on constructing 3D thermal networks, developing green biomass-based preparation processes, and integrating cross-scale thermal management systems to drive breakthroughs in industrial applications for extreme environment heat dissipation scenarios. With technological advancements and the maturation of graphene preparation techniques, the application prospects of graphene in the thermal management field will continue to expand.

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