ISSN 2959-6157

Applications of Graphene Materials in Optoelectronic Devices

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Abstract:

Graphene is a groundbreaking material at the forefront of material science and nanotechnology area. Graphene exhibit special qualities, including great mechanical strength, strong electrical conductivity and thermal conductivity. Consequently, the optical property of graphene is focused in this work. The excellent optical properties of graphene make it a good candidate material for optoelectronic devices. In recent years, a great deal of research has been conducted on the use of graphene for optoelectronic devices. Therefore, conducting research in this field is of great significance. In this work, researches are analyzed and studied to gain new insights into this area. In addition, a summary of the prevalent synthesis methods utilized for the production of graphene is provided, accompanied by a detailed examination of the merits and demerits associated with each technique. Finally, the applications of graphene materials in optoelectronic devices are discussed in depth to further understand the development status of graphene materials. This work seeks to generate new ideas and directions for the future development of optoelectronic technology.

Keywords: Graphene; optical properties; synthesis methods; optoelectronic devices.

1. Introduction

Graphene, the new nanomaterial with many excellent properties, has emerged as a research focus in recent years. Since the single layer of graphene was first prepared by Geim, this unique two-dimensional film has developed quickly [1]. Researchers in the field of innovation, set off a wave of graphene research. Graphene has extraordinary mechanical, optical, and electrical performances, due to its unique two-dimensional honeycomb lattice structure. As a result, graphene materials have a vast potential for development and use in the optoelectronics sector.

Graphene has been reported to improve the performance of optoelectronics devices. It was found that semiconductor epitaxial graphene was prepared on single crystal SIC substrate (SEG) [2]. It has a band gap of 0.6 eV. It also display high room temperature mobility which is 10 times that of silicon and 20 times that of other two-dimensional semiconductors. The chemical, mechanical and thermal stability of SEG makes it suitable for nanoelectronics. Meanwhile, the good performances of SEG also lay the root for future development of electronic appliance. At present, the available synthesis processes of graphene could be categorized into two types which include top-down method and bottom-up method [3]. However, due to technical, environmental, cost and other reasons, these methods are difficult to achieve large-scale production.

Therefore, this paper focuses on the various outstanding properties and common synthesis methods of graphene. It also outlines the latest research progress of graphene in optoelectronic devices.

2. Optical Properties

2.1 Linear Optical Properties

Graphene is a two-dimensional substance. It is made up of a single layer of carbon atoms. Optical properties are an important branch in the optical fields, which mainly studies the behavior of light and matter under linear interaction. Its unique electronic structure of graphene allows it to exhibit a variety of excellent optical properties. The absorption rate, including low-intensity light waves of any wavelength, is about 2.3% and increases linearly with the number of graphene layers.

The linear optical absorption of graphene is independent of optical frequency [4]. Therefore, single-layer graphene have obvious absorption properties in the visible light range, while absorption rate of multilayer graphene grows. Due to this property, graphene possesses potential applications in the optical field, for example, in promoting the performances of transparent electrodes, photovoltaic cells, and light-emitting devices.

In addition, the ultrafast carrier relaxation kinetic process of graphene is also an important aspect of its linear optical properties. Under ultra-short pulse excitation, the in-band thermal equilibrium relaxation time of graphene is about 100 femtoseconds. The transition relaxation time of it is about several picoseconds. This rapid relaxation process makes graphene a promising candidate in ultrafast photonics.

2.2 Non-linear Optical Properties

Graphene has superb nonlinear optical properties. These properties make it one of the most potential non-linear optical materials in the future. Graphene has excellent photoelectric properties such as ultra-high carrier mobility, ultra-high thermal conductivity and ultra-wide response band. Graphene has broad application prospects in microelectronics devices, photoelectric sensing and integrated photonics. In recent years, the non-linear optical properties of graphene have become the forefront and hot spot of scientific research. Second harmonic (frequency doubling effect) is a kind of second-order nonlinear optical effect, which can be generated only when the detected material meets the symmetry breaking requirement of center inversion. The nonlinear optical properties of graphene, especially the contradiction between theoretical and experimental results in the four-wave mixing phenomenon, brings new opportunities for the research and application of graphene [5].

Through the development of theoretical models, researchers explain the bizarre light transmission spectrum of graphene. In addition, they also explore the possibility of using graphene to make transparent electrodes. The strong terahertz nonlinear optical effect of graphene is reported and explored by researchers. Meanwhile, a model of graphene man-made composite material is constructed theoretically. A relativistic Townes type stable spatial optical soliton in the terahertz region is predicted and realized, which starts a new guidance to the research and utilization of graphene [5]. These studies deepen the comprehending of the non-linear optical properties of graphene. Besides, it also provide theoretical basis and technical support for the development of low-cost and high-efficiency photonic devices.

3. Synthetic Methods

3.1 Redox Method

The redox method for preparing graphene is a preparation method with low cost and high production efficiency. The redox method generally has three steps of oxidation, stripping and reduction. The first step needs to use a strong oxidizer to oxidize the graphite structure. In this process, the intermolecular force decreases. Afterwards, graphene oxide is obtaianed by using the stripping method. Finally, graphene oxide undergoes a reduction reaction to form a layer of graphene. The Hummers method is mainly used to prepare graphene, while this method can obtain more graphene samples. However, there are some defects of the redox method. Therefore, an improved Hummers method has emerged [6]. For the improved Hummers method, graphite is peeled by chemical oxidation. Afterwards, graphite oxide is obatined. Finally, graphene is obtained by high temperature reduction.

3.2 Epitaxial Growth Method

The epitaxial growth method uses silicon carbide as raw material. It is heated at ultra-high temperature under vacuum condition. When silicon evaporates, the carbon atom structure is rearranged to form a graphite layer to achieve the preparation of graphene. Large area and good quality are typical properties of graphene generated using this method. Nevertheless, the cost of generating graphene using this method is very high because of the high processing temperature and high raw material costs.

3.3 Chemical Vapor Deposition

Chemical vapor deposition (CVD) has high production efficiency, and it can prepare large surface area graphene. It is currently recognized as one of the most potential preparation methods, and it is also considered suitable for large-scale industrial production. This process also requires a high temperature and a high heat resistance of the material. A research team has found a new CVD method, which reduces the temperature required for the preparation of graphene to $50^{o}C$ by introducing the catalyst gallium [7, 8]. Therefore, it greatly reduces the cost and difficulty of CVD method.

4. Applications in Optoelectronic Devices

One of the important applications of graphene in optoelectronic devices is to prepare and modify Light emitting diode (LED). LED originated in 1907. Round found that the microcrystalline structure of SiC has the ability to emit light, which is the history of mankind to produce the first LED. This LED is not a p-n junction structure, while it display Schottky structure. Subsequently, scientists produced a variety of light-emitting wavelengths of the LED. The LED light-emitting principle is further understood until 1970. With the development of technology, a variety of colors of LED was produced. It can be seen that light-emitting diodes are important members of semiconductor devices, and they play an important role in lighting, display, communication and other fields. Among them, graphene, a material that can be simply peeled off from a layered structure, and it provides a great convenience for solving this problem.

Researchers at Seoul National University in South Korea have grown high-quality GaN epitaxial films on multilayer graphene with dense rows of ZnO nanorods as the transition layer [9]. By this eay, they prepared and obtained light-emitting diodes, and further realized the transfer of these functional devices to different substrates, such as glass, metal, and plastic. This device demonstrates the luminescent properties of GaN semiconductors. It also makes use of graphene's mechanical and electrical characteristics, providing a flexible idea for the integrated design of electronics and optoelectronics devices. Gallium nitride-based light-emitting diodes are developing rapidly. It display great qualities including low energy consumption and good brightness [10]. These advantages are all considered to be the key components in the development of solid-state lighting technology. The use of graphene for modifying such devices will also become a promising research direction.

Based on the transparent and conductive properties of graphene, researchers from Peking University applied it to organic electroluminescent devices [11]. They prepared light-emitting diodes with a multilayer structure, which obtains a high luminescence effect. In addition, utilizing similar properties to those studied by Peking University, Stanford University and Nankai University, graphene is fabricated into electrodes for organic light-emitting devices (OLED) using a solution method [12].

Ren et al. has produced new light-emitting materials from two different forms of graphene. It is demonstrated for the first time in a light-emitting system based on the graphene material that it is possible to tune different colors of light with just one LED. It covers almost all colors of the visible light spectrum, except for dark blue and violet [13].

In 2019, Gyu-Chul Yi et al. used micropatterned graphene as an interlayer between GaN and tungsten to selectively grow GaN microstructures on tungsten metal electrodes [14]. Uniform electroluminescence was observed on a microscopic scale. A novel method for producing high-performance and high-resolution LEDs quickly was discovered.

In a collaborative effort, a novel method for producing nanopatterned graphene is presented. A selective graphene is prepared on the c-plane of a nanopatterned sapphire substrate (NPSS) [15]. It demonstrates its application to epitaxial growth of aluminium nitride thin films. By taking advantage of the chemical and physical characteristics of NPSS, patterned graphene has been successfully grown directly, and their vital uses in the epitaxy of AlN films with LED construction have been shown. In order to fulfill the cutting-edge applications of graphene, this work could encourage and provide additional advancements. Controlling the growth of various patterned graphene on dielectric substrates is a highly promising development direction.

5. Conclusion

Graphene materials have made remarkable progress and will have more extensive applications in the future. The preparation techniques for graphene materials are compiled in this article. A summary of the use in optoelectronic devices was also provided. In summary, graphene can achieve improved performance in both LED and OLED applications. However, the manufacturing of graphene still faces technical challenges. In addition, there are still problems of high cost and low yield which need to be resolved. Therefore, the integrated application of graphene in optoelectronic devices still needs further exploration. Especially, achieving patterned preparation of graphene is of great significance for the future development of this field. In the future, with the continuous optimization and progress of preparation technology, it is expected to realize the large-scale and low-cost preparation of graphene. In addition, based on the excellent flexibility of graphene, exploring flexible LEDs will also be a promising research direction in the future.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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