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Synthesis, properties and applications of carbon quantum dots

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Abstract:

This article explains the preparation, properties, applications, and outlook of nano-material Carbon Quantum Dots. Considered by the application, the material can be prepared by top-down approach or bottom-up approach. In terms of the top-down approach, arc discharge, laser ablation, electrochemical method and chemical oxidation are included. The advantage of the approach is easy-operated and water-soluble. However, the high equipment requirement, hard controllability of particle size and morphology are the barriers of this approach. In comparison, the template, microwave, and hydrothermal methods from bottom-up approach overcomes the top-down approach's flaws perfectly, but it faces reproducibility and purification problems. As one of the highly attracted nano-materials, Carbon Quantum Dots have excellent physicochemical and optical properties, which drives them to get big blaze in sensing and drug delivery applications. To become more proficient with this material, there is a prediction that enhancing precise control and customized optoelectronic properties would be the keys in following development.

Keywords: Carbon Quantum Dots; Nano-material; Optical Property.

1. Introduction

Nano-technology is growing rapidly and replacing bulk materials because of nano materials' high performance, unique structures, and their larger surface area. They also facing tasks that bulk materials cannot accomplish due to their smaller size. Among all nanomaterials, Carbon Quantum Dots (CQDs) have been attracted as one of the most promising carbon-based nanostructures because of their low toxicity, great hydrophilicity, high chemical stability, and tunable fluorescence. Since Xu and his colleagues discovered CQDs during the arc discharge process of preparing single-walled carbon nanotubes in 2004, CQDs have been widely developed and applied in fields such as sensing and drug delivery [1].

CQDs production is a major determining factor for their physical and optical properties. The synthesis approaches can be mainly divided into two groups: top to bottom and bottom to top. The top-down approach stands for breaking the larger carbon materials down into nano-CQDs. This is accomplished using either the physical or chemical method. The methods are found to be simple and efficient and render water-soluble CQDs. However, this approach is hard to control the formation of nanoparticles and the morphology of particle structure and always needs a sophisticated setup for their realization. In contrast, the bottom-up approach refers to the construction of CQDs starting from smaller molecules containing atoms from the carbon sources. This strategy permits better size control and the production of CQDs with more diverse surface functionalization considering the cost.

The raw materials for CQDs can be classified into several types. Such as bulk carbon materials, organic molecules, and biomass. Each one is applicable due to their merits (cost, convenience, practicability, ecological stability, and effectiveness).

2. Preparation of CQDs

Preparation methods of CQDs can be mostly classified into two categories: top-down approach and bottom-up approach. The method of a top-down style is the one that subdivides the large-sized carbon materials into nanoscale CQDs. This is done through various methods. The methods are easy to apply and yield CQDs of water solubility. However, this method may not lead to the desired completion of the particle size, and their morphology is unknown, which requires high-tech equipment. Unlike the top-down methods, the bottom-up means of synthesis would involve the use of the small molecules as the precursors of the CQDs. That approach can help obtain CQDs of better quality as far as size distribution and surface adjustments are concerned, and in the same way, it is cheaper.

The component for CQDs can be divided into several groups. Those are the bulk carbon materials, organic small molecules, and biomasses. With carbon nanofibers and carbon nanotubes, activated carbon is one of them. Commonly, citric acid, carboxylate group, urea, amino acids are small organic molecules. With respect to biomass, reed fencing, animal hairs, banana skins, and banana trees can be the considerations [2].

2.1 Top-down Approach

2.1.1 Arc Discharge

In 2014, according to Arora and Sharma, it is possible for the rearrangement of the atoms of the carbon to be done through the arc discharge effect [3]. The action of the electric current inside a sealed reactor can create a temperature of 4000 K, which can therefore produce high-energy plasma. At the cathode, carbon vapor accumulates for the creation of CQDs.

The process of producing CQDs by the arc discharge was originally described in 2004 by Xu et al. [1]. While producing the Single-Walled Carbon Nanotubes in arc discharge, the researchers unexpectedly got three types of carbon nanoparticles with fluctuating molecular masses and also with the fluorescent properties. Subsequently, the CQDs that are formed give blue and green light, which also display orange light when exposed to 365 nm light. Their experiments indicated that the surface of CQDs is covered by hydrophilic groups of carboxyl. Regarding the method used to obtain this CQDs, it provides excellent water solubility with the carbon particles. Notably, the diverse size of the graphite and tangle particles together with the big particle size distribution is the drawback of this method. This diminishes the area of the active surfaces of the CQDs, possibly affecting the electrocatalytic efficiency of the process [4].

2.1.2 Laser Ablation

Laser ablation is a technology that has emerged mainly because of the effectiveness of bright photon beams in manufacturing processes like pulsed laser deposition technique. The ultimate result of a laser irradiation will be extreme temperatures and pressures. Additionally, the material will be evaporated instantly, and an enormous plasma to come forth. Finally, the condensation of the vapor takes place with the condensation of vapor and formation of nanoparticles. Li et al. (2011) reported laser technique for CQDs creation with a simple strategy. This method employs the irradiation of carbon precursor molecules which are dispersed in conventional organic solvents [5]. Through this method, CQDs fluorescently emit radiation at different wavelengths in the visible range. In addition, by the selecting appropriate organic solvents upon irradiation, the surface CQDs transformed to new state, and the PL characteristics can also be controlled by using the suitable organic solvent. Laser ablation can provide CQDs with a small size cousin. With this method, CQDs possess mainly water solubility and show high wavelength-independent lumines and light properties. Nevertheless, this method has the disadvantages such as complex operation and high costs.

2.1.3 Electrochemical Method

Electrochemistry is simple, and the instrument can be installed under normal temperature and pressure conditions. The unified particle size and variations in the luminescence properties of the CQDs that are synthesized can be achieved through changes in the synthesis parameters [4].

2.1.4 Chemical Oxidation

Chemical oxidation, as it involves applying oxidizing agents, is used for the synthesis of CQDs from raw mate-

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rials, which mainly consist of organic components. Nitric acid is the principal oxidizer in the lab. The oxidation process mediated by this compound does not require any precise instrument, since, in most cases, the carbon sources are simple and easily attainable, and thus this method is referred as an effective synthesis method for mass production CQDs. At the same time, specific strong oxidants can be fairly expensive sources of pollution for the environment [6].

2.2 Bottom-up Approach

2.2.1 Template Method

The template method uses the adsorption or coating of the carbon source on the surface of the carrier material. This arc process is usually followed by removal of the carrier material by high-temperature pyrolysis, solvent removal, acid-base corrosion, or some other chemical reactions to obtain nanoscale CQDs. The beauty of template method is that the size, shape, morphology, and structure of the CQDs can be strictly controlled, consequently enhancing the CQDs' photoluminescence quantum efficiency and stability. In contrast, though, its process is complicated and too expensive, template agents do not distill freely from water and separate and purify itself, and the yield to the CQDs is low [6].

2.2.2 Microwave Method

Microwave method is a promising and peaceful tool, which is favored among the practitioners because of its rapid synthesis and convenience under the atmospheric condition. The method is quick, effective, and non-hazardous method of producing oxygen-rich carbon quantum dots [4].

2.2.3 Hydrothermal Method

Hydrothermal method is one of the most environmentally friendly methods for preparing CQDs. These techniques require straightforward tools and give a result with the particles of high uniformity. In addition, this method is characterized by high quantum yield of the catalyzate. Tansforming small organic molecules or polymers into a solution usually takes place in water or some organic solvent. The solution is then sealed in a Teflon-lined stainless steel autoclave and is put under high-temperature treatment. Then, organic precursors polymerize, changing into carbon seed nuclei, and after some time, these nuclei will develop into CQDs typically with less than 10 nm diameter [7].

3. Typical Properties of CQDs

CQDs have distinctive characteristics because the structures have non-uniform surfaces with functional groups such as amino groups, hydrozeronide groups, and polymer chains. Surface functionalities closely govern the photoluminescent activity of CQDs, as these functional groups induce bend gap increase. Besides, they are in excellent ability to capture light, non-toxicity, ease of preparation, and low production cost, and for these reasons, CQDs have become preferred materials for advanced optoelectronic devices [8].

3.1 Optical Property

CQDs enter the excited state when they absorb electromagnetic radiation and return to the ground state with the emission of fluorescence. Varying the synthesis parameters such as particle size of CQDs, surface functional groups, and method of preparation causes fluorescence properties like spectrum and intensity to change. In addition, CQDs' layer integrity of themselves and life of CQDs as the thickness, the increase is quite strong. CQDs have excellent fluorescence emission control and strong durability, even extreme conditions cannot hinder fluorescence intensity and quantum yield [6].

3.2 Chemically Inertness

CQDs show extremely inert chemical characteristics due to the stability of the surface and the resistance of the material to a chemical reaction with neighboring compositions. They maintain high fluorescence intensity and quantum yield even under extreme conditions such as high concentrations, high temperatures, and exposure to strong acids and bases.

4. Application of CQDs

4.1 Chemical Sensing

Heavy metals including Hg^{2+} being one of the most toxic elements out there are known to be detrimental to both the environment and human physiology, so it is vital to develop their detection methods. CQDs are a visible fluorescence material with little toxicity and water solubility that have good stability and reactivity with heart metals, which makes it to be the nice detector [9].

4.2 Drug Delivery

The medical domain is where the scientists are investigating the possibilities of CQDs use. This mechanism is the transfer of drugs into the human body that leads to the manifestation of a therapeutic action. CQDs are compatible surface chemistry and tiny size, and their EM exhibition and light dependence. Their wide range of luminescence excitation spectra and big stokes energy absorb help to instantaneously measure drug loading and release at the macro and sub-molecular levels [6].

5. Outlook

Although CQDs demonstrate outstanding performance in fields such as sensing, catalysis, bioimaging, and drug delivery, it still facing large scale production, uniform particle size distribution, stable luminescent performance, and environmentally sustainable processing challenge. Top-down approach is effective, but it is limited by high costs and difficulty in controlling particle uniformity. While bottom-up approach is more flexible, but may face limitations in reproducibility and purification. In the future, enhancing precise control over CQDs structure, surface state, and functional groups will be critical. Additionally, customizing controllable optoelectronic properties according to specific application requirements will be essential.

6. Conclusion

Overall, CQDs have excellent physicochemical properties, tunable optical characteristics, and stability. In the future development of nanomaterials, they will be more attracted due to their great performances. With constant growth in synthesis, characterization, and application strategies, CQDs material will be more mature and emerge as a key material in nanotechnology.

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