Carbon quantum dots: synthesis, properties and applications

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Carbon quantum dots (CQDs, C-dots or CDs), which are generally small carbon nanoparticles (less than 10 nm in size) with various unique properties, have found wide use in more and more fields during the last few years. In this feature article, we describe the recent progress in the field of CQDs, focusing on their synthetic methods, size control, modification strategies, photoelectric properties, luminescent mechanism, and applications in biomedicine, optronics, catalysis and sensor issues.

1. Introduction

Carbon-based quantum dots consisting of graphene quantum dots (QGDs) and carbon quantum dots (CQDs, C-dots or CDs) are a new class of carbon nanomaterials with sizes below 10 nm. They were first obtained during the purification of single-walled carbon nanotubes through preparative electrophoresis in 2004,1 and then via laser ablation of graphite powder and cement in 2006.2 Carbon-based quantum dots with fascinating properties have gradually become a rising star as a new nanocarbon member due to their benign, abundant and inexpensive nature.3 Carbon is commonly a black material, and was generally considered to have low solubility in water and weak fluorescence. Wide attention has been focused on carbon-based quantum dots because of their good solubility and strong luminescence, for which they are referred to as carbon nanolights.4 During the past few years, much progress has been achieved in the synthesis, properties and applications of carbon-based quantum dots, as reviewed by Baker et al.,1 Lee et al.,4 and Zhu et al.5 Compared to traditional semiconductor quantum dots and organic dyes, photoluminescent carbon-based quantum dots are superior in terms of high (aqueous) solubility, robust chemical inertness, facile modification and high resistance to photobleaching. The superior biological properties of carbon-based quantum dots, such as low toxicity and good biocompatibility, entrust them with potential applications in bioimaging, biosensor and biomolecule/drug delivery. The outstanding electronic properties of carbon-based quantum dots as electron donors and acceptors, causing chemiluminescence and electrochemical luminescence, endow them with wide potentials in optronics, catalysis and sensors.

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As the properties and applications of GQDs have been systematically summarized elsewhere, we will focus our horizons on CQDs due to their unique properties and great potential in various applications (Fig. 1). In this feature article, we describe the recent progress in the field of CQDs, focusing on their synthetic methods, size control, modification strategies, optical properties, luminescent mechanism, and applications in biomedicine, optronics, catalysis and sensor issues.

2. Synthesis, size control and modification

Many methods have been proposed to prepare CQDs during the last decade, which can be roughly classified into “Top-down” and “Bottom-up” approaches, and they can be modified during preparation or post-treatment (Fig. 2). Three problems facing CQDs preparation need to be noticed: (i) carbonaceous aggregation during carbonization, which can be avoided by using electrochemical synthesis, confined pyrolysis or solution chemistry methods, (ii) size control and uniformity, which is important for uniform properties and mechanistic study, and can be optimized via post-treatment, such as gel electrophoresis, centrifugation, and dialysis and (iii) surface properties that are critical for solubility and selected applications, which can be tuned during preparation or post-treatment. We will discuss the main methods for CQDs synthesis, the size control via confined pyrolysis and the modification of CQDs, including functionalization, doping and nanohybrids. The features of different synthetic methods for the preparation of CQDs are summarized in Table 1.

2.1. Synthetic methods

2.1.1. Chemical ablation. Strong oxidizing acids carbonize small organic molecules to carbonaceous materials, which can be further cut into small sheets by controlled oxidation. This method may suffer from harsh conditions and drastic processes. Peng and Travas-Sejdic reported a simple route to prepare luminescent CQDs in an aqueous solution by dehydrating carbohydrates with concentrated H2SO4, followed by breaking the carbonaceous materials into individual CQDs with HNO3, and finally passivating with amine-terminated compounds (4,7,10-trioxa-1,13-tridecanediamine). The surface passivation was essential for the photoluminescence (PL) of these CQDs. The emission wavelength of these CQDs can be tuned by differing the starting material and the duration of the nitric acid treatment. The multicolor emission capabilities and nontoxic nature of these CQDs enable them to be applied in life science research.

Photoluminescent CQDs were synthesized in one-pot using polyethylenimine (PEI), a cationic branched polyelectrolyte, as both a carbon source and passivating agent via HNO3 oxidation. In contrast to the commonly reported pH-insensitive CQDs, the PL of these CQDs was highly pH-sensitive, i.e., the PL intensity decreased with increasing pH from pH 2 to 12. In addition, the pH response of the PL behaviour was reversible. This property endows them the potential to serve as proton sensors in monitoring cell metabolism processes with proton release. When incubated with HeLa cells, the CQDs could readily penetrate the cell membrane and exhibit low cytotoxicity and favorable biocompatibility, which is essential for HeLa cell imaging.

2.1.2. Electrochemical carbonization. Electrochemical soaking is a powerful method to prepare CQDs using various bulk carbon materials as precursors. However, there are only a few reports about electrochemically carbonizing small molecules to CQDs. Preparation of CQDs via the electrochemical carbonization of low-molecular-weight alcohols is proposed by Zhang and co-workers. Two Pt sheets were used as the working and auxiliary electrode, and a calomel electrode mounted on a freely adjustable Luggin capillary was used as the reference electrode. The alcohols were transformed into CQDs after electrochemical carbonization under basic conditions. The sizes and graphitization degrees of these CQDs increase with the increasing applied potential. The resultant CQDs with amorphous core exhibited excellent excitation- and size-dependent PL properties without complicated purification and passivation procedures. Note that the quantum yields (QYs) of these CQDs can reach 15.9%. CQDs can be prepared from different small molecular alcohols showing low toxicity to human cancer cells.
2.1.3. **Laser ablation.** Sun and co-workers produced CQDs via laser ablation of a carbon target in the presence of water vapour with argon as a carrier gas at 900 °C and 75 kPa. After refluxing in HNO₃ for 12 h and passivating the surface by attaching simple organic species such as PEG₁₅₀₀N (amine-terminated polyethylene glycol) and poly(propionylethyleneimine-co-ethyleneimine) (PPEI-EI), the acid-treated CQDs gave bright luminescence emission. Du et al. reported the synthesis of fluorescent CQDs by laser irradiation of a suspension of carbon materials in an organic solvent (Fig. 3). By selecting organic solvents, the surface states of the CQDs could be modified to achieve tunable light emission. Based on control experiments, the origin of the luminescence was attributed to the surface states related to the ligands on the surface of the CQDs. Li et al. reported a simple laser ablation approach to prepare CQDs using nano-carbon materials as the starting material and a simple solvent as the liquid media. In a typical procedure, 0.02 g of nano-carbon material was dispersed in 50 mL of solvent (such as ethanol, acetone, or water). After ultrasonication, 4 mL of the suspension was dropped into a glass cell for laser irradiation. A Nd:YAG pulsed laser with a second harmonic wavelength of 532 nm was used to irradiate the suspension. After laser irradiation, the solution was centrifuged to obtain the supernatant containing the CQDs.

2.1.4. **Microwave irradiation.** Microwave irradiation of organic compounds is a rapid and low-cost method to synthesize CQDs. Using sucrose as the carbon source and diethylene glycol (DEG) as the reaction media, green luminescent CQDs were obtained within one minute under microwave irradiation. These DEG-stabilized CQDs (DEG-CQDs) could be well-dispersed in water with a transparent appearance. With an increase in the excitation wavelength, the intensity of the PL first increased to a maximum (360 nm excitation) and then decreased. However, no perceptible shift of the PL peak over an excitation range from 320 to 380 nm could be observed. Moreover, these DEG-CQDs could be efficiently ingested by C6 glioma cells and exhibited a low cytotoxicity, suggesting their potential in bioimaging. Liu et al. promoted microwave-mediated pyrolysis of citric acid with various amine molecules to synthesize highly luminescent CQDs. The amine molecules, especially primary amine molecules, play dual function as N-doping precursors and surface passivating agents for the CQDs, which enhanced the PL performance. The QY values greatly increased with an increase in N content for the CQDs fabricated from citric acid and 1,2-ethylenediamine, showing a QY up to 30.2%. The resultant CQDs are highly biocompatible and have great potential for biomedical applications.

2.1.5. **Hydrothermal/solvothermal treatment.** Hydrothermal carbonization (HTC) or solvothermal carbonization is a low cost, environmentally friendly, and nontoxic route to produce novel carbon-based materials from various precursors. Typically, a solution of organic precursor is sealed and reacted in a hydrothermal reactor at high temperature. CQDs were prepared via HTC from many precursors such as glucose, citric acid, chitosan, banana juice, and protein. Mohapatra et al. prepared highly photoluminescent CQDs with a QY of 26% in one step by hydrothermal treatment of orange juice followed by centrifugation. These CQDs with sizes of 1.5–4.5 nm were applied in bioimaging due to their high photostability and low toxicity. Liu et al. reported a one-step synthesis of amino-functionalized fluorescent CQDs by hydrothermal carbonization of chitosan at 180 °C for 12 hours. Note that the amino-functionalized fluorescent CQDs can be used directly as novel bioimaging agents.

Solvothermal carbonization followed by extraction with an organic solvent is a popular approach to prepare CQDs. Typically, carbon-yielding compounds were subjected to heat treatment in high boiling point organic solvents, followed by extraction and concentration. Bhunia et al. synthesized two kinds of the CQDs, hydrophobic and hydrophilic with diameters less than 10 nm from the carbonization of carbohydrates. The hydrophobic ones were produced by mixing different amounts of carbohydrate with octadecylamine and octadecene before being heated up to 70–300 °C for 10–30 minutes. The hydrophilic ones can be synthesized by heating an aqueous solution of carbohydrate within wide pH ranges.
hydrophilic CQDs with yellow and red emissions can also be synthesized by mixing an aqueous solution of carbohydrate with concentrated phosphoric acid followed with heating at 80–90 °C for 60 min (Fig. 4).

2.2. Size control-confined pyrolysis

For particular applications and mechanistic study, it is important to control the sizes of CQDs to get uniform properties. Many approaches have been proposed to obtain uniform CQDs during preparation or post-treatment. In most of the reports, the as-synthesized CQDs fragments were purified via post-treatments like filtration, dialysis, centrifugation, column chromatography and gel-electrophoresis. It is of great importance to control the size during the preparation process. Discrete CQDs with tunable and uniform sizes can be prepared via confined pyrolysis of an organic precursor in nanoreactors (Fig. 5). Three steps were used as follows: (i) absorbing the organic precursor into porous nanoreactors via capillary force, (ii) pyrolysis of the organic precursor confined in the nanoreactors into carbonaceous matter, (iii) release of the as-synthesized CQDs by removing the nanoreactors. The size and size-distribution of the CQDs produced from this method are dictated by the texture parameters of the nanoreactors.

Porous silicas are the most widely used nanoreactors for their various, tunable and easily obtained textures, thermal stability and easy removal.43–45 Zhu et al. synthesized hydrophilic CQDs with mesoporous silica nanospheres as nanoreactors by impregnation of a citric acid precursor (Fig. 5).43 After pyrolysis at 300 °C for 2 hours in air, followed by silica removal and dialysis, CQDs with a uniform size of 1.5–2.5 nm were prepared and showed good photostability, low toxicity, excellent luminescence, and up-conversion properties.

Polymeric core–shell nanoparticles are also effective nanoreactors with thermally cross-linkable core and thermally removable shell.46–47 Recently, we prepared CQDs via pyrolysis of PAN@PMMA core–shell nanoparticles prepared using a one-pot micro-emulsion polymerization process (Fig. 6).48 The core PAN domain was crosslinked and chipped at 270 °C under air with protection from the shell PMMA domain. Furthermore, elevating the temperature caused the carbonization of the PAN fragments and decomposition of the PMMA domains to release the N-doped CQDs. The prepared CQDs showed dual emission at about 410 nm and 450 nm and stable PL in moderate pH solutions, which is essential for bioimaging.

Thermally unstable polymers are also used as block matter to avoid carbonaceous aggregation during thermal treatment, especially when the carbon-yielding domain is a cross-linkable polymer.49–51 We prepared well-defined CQDs with tunable and uniform sizes from single-chain polymeric nanoparticles, which were formed using a Bergman cyclization-intermediated chain collapse52–55 of linear polymers containing enediyne units (Fig. 7). The polynaphthylene-containing polymeric nanoparticles formed were transformed to CQDs via a bijective way (one-to-one correspondence). The sizes of the final CQDs can be easily tuned by changing the length of the polymeric chains or the grafting degrees of the enediyne in each chain. The prepared CQDs showed size-dependant luminescent properties and the PL peak blue-shifted with an increase of size. The PL mechanism of CQDs was also investigated based on experimental results and theoretical simulation, and it will be discussed in detail in Section 3.2.

2.3. Surface functionalization

Surface modification is a powerful method to tune the surface properties of materials for selected applications. There are
many approaches for functionalizing the surface of CQDs through the surface chemistry or interactions, such as covalent bonding, coordination, π–π interactions, and sol–gel technology.

The majority of CQDs are rich in oxygen-containing groups, which endows them with feasibility in covalent bonding. Surface passivation via covalent bonding of amine-containing agents is a common method to improve the PL of CQDs, which showed an important influence on the properties of CQDs. Fluorescent CQDs with diameters of about 3 nm emitting blue-green light were synthesized using a hydrothermal carbonization of 2Na-EDTA. Then, the CQDs were functionalized with spiropyrans to obtain surface-functionalized CQDs. The emission of the functionalized CQDs centered at 510 nm could be switched off, while being turned on at 650 nm via energy transfer between the CQDs and spiropyrans after irradiation with ultraviolet (UV) light (Fig. 8). The process could be reversed using irradiation with visible light. The functionalized CQDs show excellent photo-reversibility and high stability.

In addition to covalent bonding to CQDs, coordination is another useful strategy. A simple method for phosphate (Pi) detection (Fig. 9) was established by developing an off-on fluorescence probe using europium-adjusted CQDs, which was successfully applied to the detection of Pi in complicated matrices such as an artificial wetlands system. When the surface carboxyl groups on the CQDs were coordinated with Eu³⁺, the fluorescence of the CQDs was turned off. The fluorescence can, however, be switched on when Eu³⁺ was specifically coordinated with Pi.

The Sol–gel technique is also a promising approach for decorating the surface of CQDs with functional molecules. Liu et al. reported a method to synthesize highly luminescent (QY = 47%) amorphous CQDs in one minute using organo-silane as a coordinating solvent. The CQDs, benefited from the surface methoxysilyl groups, have a diameter of ~0.9 nm and can easily be fabricated into pure CQDs fluorescent films or monoliths by simply heating at 80 °C for 24 h. Moreover, the water-insoluble CQDs can be further transformed into water-soluble CQDs/silica particles with good biocompatibility and low toxicity. CQDs@MIP (molecularly imprinted polymer) was synthesized by a one-pot, room-temperature, sol–gel polymerization and was applied as a fluorescence sensor for the detection of dopamine in an aqueous solution.

2.4. CQDs doping

Doping is a widely used approach to tune the PL properties of photoluminescent materials. Various doping methods with dozens of elements such as N, S, P and Pd have been reported to tune the properties of CQDs.

N-doping is the most studied way to enhance the emission of the CQDs by inducing an upward shift in the Fermi level and electrons in the conduction band. It was demonstrated that only the nitrogen bonding to carbon can really enhance the PL emission of CQDs. The N-CQDs show nitrogen content-dependent PL intensities with multicolor and two-photon up-conversion properties. A Mg/N co-doping strategy to fabricate highly luminescent CQDs with QY of 83% was studied by Liu et al. (Fig. 10). After hydrothermal treatment of a homogeneous solution containing citric acid and Mg(OH)₂ at 200 °C for 3 h, the raw products were treated by filtration, dialysis and lyophilization to obtain CQDs denoted as Mg-CQDs. The Mg-citric acid chelate in the carbon source was utilized to introduce Mg and preserve the majority of the carboxyl groups, which
together with the N-passivation contributed to a dramatic increase in the PL enhancement of the final CQDs.

P- and N-co-doped CQDs were synthesized via microwave irradiation of DMF in the presence of phosphoric acid.62 These CQDs exhibited excellent photoluminescent characteristics with high electrocatalytic activity and good tolerance to the methanol crossover effects in the oxygen reduction reaction (ORR) in an alkaline medium due to heteroatom functionalization. Sulfur- and nitrogen-co-doped CQDs (S–N-CQDs) were synthesized on a large-scale using sulfuric acid to carbonize and etch hair fiber.63 It was found that S and N can form different binding configurations in the S–N-CQDs framework, such as a −C−S− covalent bond of the thiophene-S and −C−SO− (x = 2, 3, 4, sulfate or sulfonate) for S-doped, pyridinic N and pyrrolic N for N-doped, respectively. Moreover, a higher reaction temperature leads to the formation of S–N-CQDs with smaller size, higher S content, and longer wavelength of photoluminescent emissions. The resultant S–N-CQDs also exhibited good luminescence stability, low toxicity, excellent biocompatibility, and high solubility.

2.5. CQDs nanohybrids

More recently, many efforts have been focused on the preparation of novel hybrids comprised of CQDs and inorganic nanoparticle cores (e.g., iron oxide,64 zinc oxide, silica,65 and titania66). The resultant hybrids integrate the fluorescence properties of the CQDs with the magnetic, optical or mechanical properties of the oxide cores. Such hybrids hold great promise as magneto-optical biolabeling agents or efficient photocatalysts.

TiO2/CQDs composites were synthesized in situ from bidentate TiO2-vitamin-C (VC) complexes via a hydrothermal method.67 The effects of the amounts of VC, hydrothermal temperatures and reaction times were explored for the H2 generation from photocatalytic water splitting catalyzed by the TiO2/CQDs nanohybrids. The TiO2-NPs/CQDs nanohybrids obtained at 200 °C for 2 h with a VC amount of 0.001 g showed a 9.7-fold higher H2 production rate than bare TiO2 NPs and showed good cycling performance (Fig. 11). The TiO2-NWs/CQDs nanohybrids prepared at 90 °C for 4 h also produced hydrogen at a rate of 1189.7 μmol g−1 h−1, which is 4.2 times higher than that of bare TiO2 NWs. The superior photocatalytic performance of these nanohybrids may be attributed to the synergetic effects of the hydrothermal treatment along with the favourable electron transfer ability and up conversion of the CQDs.

Au NPs were used to enhance the fluorescence of CQDs by forming Au-PAMAM-CQD conjugates using an amidation reaction.68 In this process, PAMAM serves as a spacer of a suitable size to keep the Au NPs and CQDs at an appropriate distance from one another for PL enhancement. Both the amount of Au NPs and CQDs can influence the fluorescence enhancement. An appropriate amount of Au NPs and CQDs linked to PAMAM leads to an optimum fluorescence enhancement. The PL intensity of CQDs can be enhanced as much as 62-fold by conjugating Au NPs and CQDs with an optimized molar ratio to PAMAM, which is desirable for many applications.

3. Properties and luminescent mechanism

3.1. Optical properties

3.1.1. Adsorption. CQDs typically show optical absorption in the UV region with a tail extending to the visible range (see Fig. 12A (ref. 2) for representative spectra). There may be some absorption shoulders (Fig. 10a for an example) attributed to the π−π* transition of the C−C bonds, the n−π* transition of C=O bonds and/or others.

3.1.2. Fluorescence. One of the most fascinating features of CQDs, both from fundamental and application-oriented perspectives, is their PL (see Fig. 12 for representative spectra). In most cases of early study, one unique feature of the PL of CQDs was the clear λex dependence of the emission wavelength and intensity. Whether this occurs because of optical selection of differently sized nanoparticles (quantum effect) and/or
were oxidants, such as potassium permanganate (KMnO₄) and cerium(IV), such as KMnO₄ and cerium(IV), and cerium(IV), can oxidize the CQDs, resulting in energy release in the form of CL.

Fig. 12 (A) Absorbance and PL spectra with increasingly longer excitation wavelengths (in 20 nm increments starting from 400 nm) of 5 nm PPE-EI CQDs in an aqueous solution formed using laser ablation methods (inset shows the normalized PL spectra). Adapted with permission.© Copyright 2006, American Chemical Society. (B) PL of 1.9 nm CQDs at different excitation wavelengths of 290–380 nm. Adapted with permission.© Copyright 2008, Royal Society of Chemistry.

3.1.4. Chemiluminescence (CL). CL properties of CQDs were firstly discovered when the CQDs coexisted with some oxidants, such as potassium permanganate (KMnO₄) and cerium(IV). The electron paramagnetic resonance (EPR) reveals that oxidants, such as KMnO₄ and cerium(IV), can inject holes into the CQDs. This process increases the population of the holes in the CQDs and accelerates the electron-hole annihilation, resulting in energy release in the form of CL emission. Moreover, the CL intensity was dependent on the concentration of the CQDs in a certain range. It was also found that increasing the temperature had a positive effect on the CL due to the thermal equilibrium of electron distribution in the CQDs as shown in Fig. 14. It is interesting for this system that the CL properties can be designed by changing their surface groups.

A novel CL phenomenon was also observed for the as-prepared CQDs in a strong alkaline solution (NaOH or KOH). The CQDs exhibited excellent electron donor ability towards dissolved oxygen to form the superoxide anion radical (O₂⁻) in a solution of NaOH. These results directly provided evidence for the excellent electron-donating ability of CQDs. Radiative recombination of the injected electrons by “chemical reduction” of the CQDs and thermally excited generated holes was suggested to account for the CL behaviour in strong alkaline solutions.

The CL of CQDs opens up new opportunities for their potential in the determination of reductive substances. The dual role of CQDs as an electron donor and acceptor offers great potential in optoelectronics and catalysis as described in Section 4.2 and 4.3.
3.1.5. Electrochemical luminescence (ECL). To understand how the composition, morphology, and surface structure of CQDs affects the PL and ECL in selected applications, CQDs with low and high oxidation levels, denoted as r-CQDs and o-CQDs, were synthesized via a carbonization–extraction strategy and carbonization–oxidation process, respectively. The results showed that the electrochemical response was controlled by the diffusion of o-CQDs onto the electrode surface (Fig. 15B). The ECL wave started at 1.10 V and reached its peak value at 1.30 V (Fig. 15C), which is consistent with the oxidation peak in the cyclic voltammograms (CVs); thus, the ECL emission was related to the direct oxidation of o-CQDs. Fig. 15D shows the ECL under continuous cyclic scans with high reproducibility.

The reduction of \( \text{S}_2\text{O}_8^{2-} \) releases a strong oxidizing agent, the \( \text{SO}_4^{2-} \) radical, which accepts an electron from the anionic o-CQD\(^{-} \) to form the emitters for ECL emission. The low ECL activity of r-CQDs also showed that the ECL is related to the oxidation state of the surface.

3.1.6. Up-conversion photoluminescence (UCPL). The UCPL properties of CQDs can be attributed to the multi-photon activation process, in which the simultaneous absorption of two or more photons leads to the emission of light at a shorter wavelength than the excitation wavelength (anti-Stokes type emission). The UCPL of CQDs opens up new opportunities for cell imaging with two-photon luminescence microscopy, as well as highly efficient catalyst design, for applications in bioscience and energy technology. Upon excitation in the NIR region, the PL spectra showed a fixed emission peak at 540 nm that did not shift with a variation of the excitation wavelength (anti-Stokes type emission). The UCPL opens up new possibilities for cell imaging with two-photon luminescence microscopy, as well as highly efficient catalyst design, for applications in bioscience and energy technology. Upon excitation in the NIR region, the PL spectra showed a fixed emission peak at 540 nm that did not shift with a variation of the excitation wavelength (anti-Stokes type emission). The UCPL opens up new opportunities for cell imaging with two-photon luminescence microscopy, as well as highly efficient catalyst design, for applications in bioscience and energy technology. Upon excitation in the NIR region, the PL spectra showed a fixed emission peak at 540 nm that did not shift with a variation of the excitation wavelength (anti-Stokes type emission). The UCPL opens up new opportunities for cell imaging with two-photon luminescence microscopy, as well as highly efficient catalyst design, for applications in bioscience and energy technology. Upon excitation in the NIR region, the PL spectra showed a fixed emission peak at 540 nm that did not shift with a variation of the excitation wavelength (anti-Stokes type emission).

The UCPL of CQDs is a fascinating feature, however, very recently, a UCPL study on five differently synthesized CQDs and GQDs demonstrated that the CQDs and GQDs did not exhibit observable UCPL. Under the experimental conditions reported earlier, so-called UCPL in five differently synthesized CQDs and GQDs in a commercial fluorescence spectrophotometer was observed. However, the UCPL actually originates from the normal fluorescence excited by the leaking component from the second diffraction in the monochromator of the fluorescence spectrophotometer (Fig. 16C). The leaking component and thus UCPL can be eliminated by adding a suitable long-pass filter in the excitation pathway of a fluorescence spectrophotometer. Intensity dependent experiments clearly confirmed that the so-called UCPL is actually the normal fluorescence with linear response rather than a multiple phonon process (Fig. 16D). These experiments suggested that most of the CQDs and GQDs may not have detectable UCPL. Note that it is necessary to eliminate the normal fluorescence and measure the excitation intensity dependence of the fluorescence when observing UCPL of CQDs.

3.1.7. Photoinduced electron transfer (PET) property. For the utilization of PL compounds in light-energy conversion and related areas, there have been extensive investigations on their photoresponse, photoinduced charge separation and electron transfer processes.

Sun et al. found that the PL from a CQDs solution could be efficiently quenched in the presence of either electron acceptors such as 4-nitrotoluene and 2,4-dinitrotoluene or electron donors such as \( N,N \)-diethylaniline. Namely, the photoexcited...
CQDs are excellent as both electron donors and electron acceptors. They also found efficient PL quenching in CQDs by surface-doped metals through disrupting the excited state redox processes.\(^3\) Electron transfer in nanocomposites of CQDs–GO, CQDs–MWCNTs and CQDs–TiO\(_2\) NPs without linker molecules was also studied.\(^4\) Significant PL quenching was observed in the CQD–GO system, which was attributed to the ultrafast electron transfer from CQDs to GO with a time constant of 400 fs. In comparison, addition of carbon nanotubes resulted in static quenching of fluorescence in CQDs. No charge transfer was observed in either CQD–MWCNT or CQD–TiO\(_2\) nano-composites. These interesting PET properties of CQDs as an electron donor/acceptor may offer new opportunities for light-energy conversion, catalysis and related applications, as well as mechanistic elucidation.

3.2. PL mechanism

Although there have been many efforts focused on the physicochemical properties of CQDs, the origin of the observed optoelectronic behaviour is a topic of discussion to date. The origin of the PL of CQDs has been assigned to several reasons in the literature: optical selection of differently sized nanoparticles (quantum effect),\(^5\),\(^6\) defects and surface states,\(^2\) surface groups,\(^7\) surface passivation,\(^8\) fluorophores with different degrees of \(\pi\)-conjugation,\(^9\),\(^10\) and the recombination of electron–hole pairs localized within small sp\(^2\) carbon clusters embedded within a sp\(^3\) matrix.\(^11\)

A systematic investigation on the formation mechanism of the CQDs prepared from pyrolysis of citric acid (CA)–ethanolamine (EA) precursor at different temperatures was presented recently.\(^12\) Pyrolysis at 180 °C leads to a CQD precursor with an intense PL and high QY formed by the dehydration of CA–EA. At higher temperatures (230 °C) a carbonaceous core starts to form. The PL at this stage is contributed from the presence of both molecular fluorophores and the carbonaceous core (Fig. 17). CQDs that exhibit mostly or exclusively PL arising from carbonaceous cores were obtained at even higher temperatures (300 and 400 °C, respectively). Since the molecular fluorophores predominate at low pyrolysis temperatures while the carbonaceous core starts forming at higher temperatures, the PL behaviour of CQDs strongly depends on the conditions used in their synthesis.

Multiple fluorescence intensity levels of individual CQDs were observed recently.\(^13\) Imaging of single CQDs at different excitation energies revealed significant heterogeneity in the lower energy trap sites between particles. It is also found that individual CQDs exhibit single-step photobleaching and transient blinking to the background level suggesting single-molecular behaviour. These observations suggest the possibility that single CQDs can possess multiple chromophoric units associated with the CQDs core and oxygenated defect-related emissive traps. Interestingly, the majority of the reduced CQDs showed multiple levels, while the oxidized CQDs predominantly showed a single level. A possible reason for this is that after the initial excitation the energy is transferred from the higher energy absorbing site to a lower energy emissive site in the oxidized CQDs. In contrast, the low-energy emissive traps were entirely or partially removed when CQDs are reduced, blocking the energy-transfer pathways. Consequently, the emission for reduced CQDs is likely to be from the originally excited chromophores. The presence of the emissive traps or quenching states would likely be dependent on the synthetic methods and the post-treatment of CQDs.

Fig. 17 Schematic representation of the emission characteristics of three photoactive species produced from the thermal treatment of a mixture of CA and EA. During pyrolysis, the organic fluorophores (blue groups) are consumed for the build-up of the carbonaceous core (black sphere) so that the PL component, which corresponds to the carbonaceous core (black bars), increases at the expense of the component that arises from the organic fluorophores (blue bars). Adapted with permission.\(^14\) Copyright 2011, American Chemical Society.

Fig. 18 shows the optical images of CQDs of four typical sizes, illuminated by white and UV light, and the corresponding emission spectra from left to right.\(^15\) The PL properties vary sensitively with the size of the CQDs (Fig. 18c), and with increasing size, the emissions were red-shifted. The theoretical calculations (Fig. 18d) showed the dependence of the HOMO–LUMO gap on the size of the graphene fragments. As the size of the fragment increases, the gap decreases gradually, and the gap energy in the visible spectral range was obtained from graphene fragments with a diameter of 14–22 Å, which agrees well with the visible emission of CQDs with diameters of <3 nm. Thus, it is deduced that the strong emission of CQDs comes from the quantum-sized graphite structure instead of the carbon–oxygen surface.

We recently prepared soluble CQDs with tunable sizes from single-chain polymeric nanoparticles (Fig. 7).\(^6\) PL study shows that the optimal emission wavelength of CQDs is red-shifted when the size of CQDs decreases, which is different from the trends typically found in semiconductor quantum dots and CQDs prepared from graphitized materials.\(^16\) To clarify the PL mechanism of CQDs prepared from different sources, a theoretical study based on density functional theory was performed. Two series of model compounds, fused aromatic rings and
CQDs synthesized by electrochemical ablation and small molecule carbonization, as well as CQDs fabricated by solvothermally cutting graphene oxide, are three typical green fluorescence carbon-based quantum dots. Ultrafast spectroscopy was used to investigate the PL origin in these fluorescent carbon-based quantum dots. According to the change of surface functional groups during chemical reduction and the obvious emission-type transformation, these green luminescence emissions are unambiguously assigned to special edge states consisting of several carbon atoms on the edge of carbon backbone and functional groups with C=O functionality (carbonyl and carboxyl groups). These findings suggest that the competition among various emission centers (bright edge states) and traps dominate the optical properties of fluorescent carbon-based quantum dots.

### 3.3. Biological properties

Impressive progress has been made in engineering bright CQDs bioprobes with good stability. However, biocompatibility of the functionalized CQDs is still a critical issue for further applications in live cells, tissues, and animals. Systematic cytotoxicity evaluations were carried out on both raw CQDs and passivated CQDs during the last few years. Sun’s group employed CQDs produced by the arc-discharge of graphite rods, and then refluxed in HNO$_3$ for 12 h for cytotoxicity assay. The bare CQDs were apparently nontoxic to cells up to a relatively high concentration of 0.4 mg mL$^{-1}$. Luminescent CQDs synthesized by the electrochemical treatment of graphite were also evaluated in terms of cytotoxicity assay using a human kidney cell line, in which the cell viability was not affected by the dots. Furthermore, Ray et al. improved a soot-based approach for CQDs synthesis with diameters of 26 nm. The experimental results of cell viability also confirmed that the CQDs showed negligible cytotoxicity at concentrations required for fluorescence bioimaging.

The cytotoxicity of the CQDs passivated with functional groups, such as PEG, PPEI-EI, PEI$_9$, BPEI (branched poly(ethyleneimine)), and PAA (poly(acrylic acid)), were also evaluated in cytotoxicity assays. The PEGylated CQDs in all available configurations were non-cytotoxic up to concentrations much higher than that is necessary for cell imaging and related applications. In addition, CQDs functionalized with PEG$_{1500N}$ were injected into mice for toxicity evaluation up to 28 days, and the results suggested no significant toxic effects in vivo. Moreover, experimental results indicated that the PPEI-EI-passivated CQDs were mostly nontoxic to the cells below a relatively high threshold of carbon core-equivalent PPEI-EI concentration. According to the MTT assay, a PEI free sample was apparently nontoxic to HT-29 cells even at relatively high concentrations. However, the PEI-functionalized CQDs were more cytotoxic than PPEI-EI-functionalized CQDs. The more ethylenimine (EI) units within the PEI may be associated with the lower concentration thresholds for the CQDs to become cytotoxic, as PEI is the homopolymer corresponding to PPEI-EI with an extreme EI fraction of 100%. Free PAA in a nonaqueous solution was found to be harmful to cells even at relatively low
concentrations (50 μg mL⁻¹). The PAA-functionalized CQDs were generally comparable to free PAA at the same CQD core-equivalent concentrations, both were toxic to the cells with an exposure time of 24 h, but less so when the exposure time was shortened to 4 h. Overall, molecules with low cytotoxicity even at high concentrations such as PEG and PPEI-EI are suitable for CQDs functionalization for in vivo imaging and biosensing. Molecules with higher cytotoxicity including BPEI and PAA, can still be used to functionalize CQDs used in vivo if their concentrations are maintained low enough and the incubation time short enough.92

4. Applications

4.1. Biomedicine

4.1.1. Bioimaging. As fluorescent nanomaterials with biocompatibility and low biotoxicity, CQDs show great potential for fluorescent bioimaging,25,26,40,96 and multimodal bioimaging of cells and tissues,97 which have been reviewed elsewhere.98–100 The pioneering work on CQDs for bioimaging in vitro and in vivo was reported by Sun’s group. Confocal microscopy images of E. coli ATCC 25922 labeled with the PEGylated CQDs were obtained at different excitation wavelengths. Yang et al. were the first to explore the feasibility of CQDs as a fluorescence contrast agent in mice.27 In the experiments, PEGylated CQDs in an aqueous solution were injected subcutaneously into mice, and the fluorescence images at different excitation wavelengths collected. There was sufficient contrast for the imaging in both green and red emissions.28 Tao et al. applied the same protocol to nude mice and obtained similar results.101 More specifically, an aqueous solution of CQDs was injected subcutaneously into mice, followed by fluorescence imaging with excitations at seven different wavelengths from 455 nm to 704 nm. The best fluorescence contrast was obtained at an excitation of 595 nm (Fig. 20).

It is attractive to integrate multi-imaging technology for one agent for comprehensive understanding of the state of the illness. Most popular nanostructured multimodal imaging probes are combinations of magnetic resonance imaging (MRI) and optical imaging modalities. MRI can offer high spatial resolution and the capacity to simultaneously obtain physiological and anatomical information, whereas optical imaging allows for rapid screening.102 Zboril et al. reported the synthesis of ultrafine Gd(III)-doped CQDs with a dual fluorescence/MRI character through the thermal decomposition of a precursor composed of an organic salt and a gadolinium(III) complex (Fig. 21).37 The dots were water-dispersible, displaying bright fluorescence in the visible range upon light excitation, showing strong T1-weighted MRI contrast comparable to commercial Gadovist and possessing low cytotoxicity. In our opinion, it is possible to combine a common T1 MRI agent with CQDs via robust covalent bonding, which can increase the rotational correlation time (τR) of the T1-imaging probes.103,104 Srivastava et al. fabricated iron oxide-doped CQDs (IO-CQDs) for multi-modality (MR/fluorescence) bioimaging.105 The IO-CQDs were prepared using the thermal decomposition of organic precursors in the presence of small Fe₃O₄ nanoparticles (with an average size of 6 nm). The IO-CQDs could be taken by RAW 264.7 cells, and the fluorescence was mainly detected in the cell cytoplasm. For in vivo imaging, the IO-CQDs were introduced into rats through intravenous injection. Fluorescence signals due to the IO-CQDs were observed in the spleen slide samples. The MRI results suggested enhanced signals in the brain blood vessel under both T1 and T2 models. It is also possible to combine other imaging technologies with the fluorescent imaging of CQDs for multi-modal bioimaging due to the biocompatibility of CQDs.
4.1.2. Biosensor. CQDs have been used as biosensor carriers for their high solubility in water, flexibility in surface modification, nontoxicity, excitation-dependent multicolor emission, excellent biocompatibility, good cell permeability, and high photostability. The CQDs-based biosensors can be used for visual monitoring of glucose,\textsuperscript{106} cellular copper,\textsuperscript{107} phosphate,\textsuperscript{55} iron,\textsuperscript{55} potassium,\textsuperscript{108} pH,\textsuperscript{109} and nucleic acid.\textsuperscript{36}

CQDs can be used as an effective fluorescent sensing platform for nucleic acid detection with selectivity single-base mismatch. The general concept was based on the adsorption of the fluorescently labeled single-stranded DNA (ssDNA) probe by CQD via π–π interactions, which is accompanied by substantial fluorescence quenching, followed by specific hybridization with its target to form double-stranded DNA (dsDNA).\textsuperscript{56} This results in desorption of the hybridized dsDNA from the CQD surface accompanied with subsequent recovery of fluorescence, probing the target DNA (Fig. 22).

A robust and multifunctional CQD-based fluorescence resonance energy transfer (FRET) probe for detecting and imaging mitochondrial H$_2$O$_2$ was demonstrated. The CQDs serve as the donor of energy transfer and the carrier for the sensing system. A boronate-based H$_2$O$_2$ recognition element, boronate-protected fluorescein (Fig. 23), was covalently linked onto the CQDs.\textsuperscript{110} It can be used for tracking the exogenous H$_2$O$_2$ levels in L929 cells, and can also be used to visualize the endogenously produced H$_2$O$_2$ in RAW 264.7 macrophage cells.

4.1.3. Biomedicine delivery system. It is an attractive prospect to combine medical therapy and bioimaging diagnostics for visual drug distribution and monitoring of their effects.\textsuperscript{111} A multifunctional theranostic agent (CD-Oxa) was prepared by the conjugation of an anticancer agent (oxidized oxaliplatin, oxa(IV)–COOH) onto the surface of CDs containing amine groups.\textsuperscript{53} CD-Oxa successfully integrates the optical properties of the CDs and the therapeutic performance of Oxa. The \textit{in vitro} results indicated that CD-Oxa possesses good biocompatibility, bioimaging function, and anticancer effects. The \textit{in vivo} results demonstrate that it is possible to follow the track or distribution of the drug by monitoring the fluorescence signal of CD-Oxa, which helps customize the injection time and dosage of the medicine (Fig. 24A).

Kim \textit{et al.} coupled CQDs with gold nanoparticles for an assembly, which was then conjugated with PEI–pDNA for delivering DNA to cells.\textsuperscript{112} Note that fluorescence emissions from the assembly of CQD-gold nanoparticles could be quenched by pDNA; thus, the release of pDNA could be probed by the recovery of the fluorescence signals. The experimental results suggested that the assembly entered the cells with the CQDs located in the cell cytoplasm and the released pDNA entered the cell nuclei, achieving significant transfection efficiency (Fig. 24B). Pandey \textit{et al.} used CQDs functionalized gold nanorods for the delivery of doxorubicin in a multi-modality fashion, including drug delivery, photothermal therapy, and bioimaging using the same platform.\textsuperscript{113} The widely used anti-
psychotic drug haloperidol (HaLO)-grafted CQDs with cysteamine hydrochloride (CysHCl) as a linker can offer controlled release under physiological conditions for more than 40 h following the Hixson–Crowell model under standardized conditions. A broad spectrum antibiotic, ciprofloxacin attached to CQDs with bright green fluorescence can not only pave a way for bioimaging but also provide an efficient new nanocarrier for controlled drug release with high antimicrobial activity under physiological conditions.

4.2. Optronics

4.2.1. Dye-sensitized solar cells (DSCs). DSCs have aroused intense attention due to their diversity, low cost and easy processing. Though DSCs benefit from the diversity of organic dyes and get respectable efficiency, the photobleaching of organic dyes or the high cost and toxicity of ruthenium containing dyes, even the volatile electrolyte may hamper its widely application. CQDs with stable light absorption made from broad and cheap sources show its potential in DSCs.

After the first attempt by Ozin, who introduced CQDs as a sensitizer to capture sunlight in DSCs, much research work has been performed to use this emergent nanolight to improve the performance of DSCs. As the charge recombination of photogenerated electrons in the porous electrode with either the oxidized dye or the electrolyte will reduce the efficiency of DSCs. Inspired by natural photosystems, Lee et al. developed a CQD-bridged dye/semiconductor complex system for the fabrication of highly efficient photoelectric conversion systems. CQDs not only enhanced the UV-vis absorbance of rhodamine B (RhB) solutions due to the synergistic hyperchromic effect between RhB and CQDs (Fig. 25), but also effectively suppressed the recombination of photogenerated electrons, thereby leading to a significantly enhanced photoelectric conversion efficiency. Doping of CQDs into the dye/semiconductor complex significantly improved the photoelectric conversion efficiency of the complex by ~7 times.

4.2.2. Organic solar cells (OSCs). A simple and effective method to prepare CQDs and their polymer based composites was developed and the CQDs with an excitation wavelength independent PL can self-assemble in solution but not agglomerate in the solidified composite. Accordingly, the composite with CQDs luminesce and exhibits a luminescent down-shifting (LDS) property. The P3HT:PCBM based solar cell harvests sunlight from 480 to 650 nm, only covering a part of visible light (380–780 nm) that contains the peak of the Sun’s irradiance output. The remaining portions (380–480 nm and 650–780 nm) are not effectively utilized. Since the CQDs filled polysiloxane composite is able to emit light from 400 to 650 nm under excitation from 320 to 450 nm, its wavelength ranges of both PL and excitation well fit the harvesting spectrum (480–650 nm) and unused light spectrum (380–480 nm) of the bulk heterojunction (BHJ) solar cell. Because the emission wavelength range of the composite coincides with the response curve of the P3HT:PCBM-based BHJ solar cell, power conversion efficiency of the latter is raised by about 12% through coating a layer of the composite on the cover glass as a result of enhanced absorption of the near ultraviolet and blue-violet portions of sunlight (Fig. 26).

4.2.3. Supercapacitor. CQD-based hybrids as excellent electrode materials for supercapacitors were reported recently. The CQDs are fabricated by a facile chemical oxidation method followed by thermal reduction, and further decoration with RuO2 to obtain the composites. The hybrid exhibits a specific capacitance of 460 F g−1 at an ultra-high current density of 50 A g−1 (41.9 wt% Ru loading), and excellent rate capability (88.6, 84.2, and 77.4% of capacity retention rate at 10, 20, and 50 A g−1 compared with 1 A g−1, respectively). Surprisingly, the hybrid shows exceptional cycling stability with 96.9% capacity retention over 5000 cycles at 5 A g−1. Such remarkable electrochemical performance can be primarily ascribed to the significantly enhanced utilization of RuO2 achieved by the efficient dispersion of small reduced CQDs, and the formation of a CQD-based hybrid network structure that can facilitate the fast charge transportation and ionic motion during the charge-discharge process. Moreover, the contact resistance at the interface between active materials and current collectors is determined to be a key factor in determining the performance
of the hybrid (Fig. 27). CQDs-based ionic liquid (CQDIL) as a conductive agent and binder in an activated carbon electrode can improve supercapacitor performance due to the improved wettability of the electrolyte on the CQDIL-functionalized activated carbon electrode or a greater number of active components and a higher conductivity in the CQDIL/AC electrode. In addition, a high power density of 1.64 kW kg$^{-1}$ and an ultra-high energy density of 83.2 W h kg$^{-1}$ were obtained.$^{149}$

4.2.4. Light-emitting devices (LED). CQDs are an emergent material for LEDs due to their stable light emitting, low cost and eco-friendliness.$^{47,120-124}$ Nitrogen-rich CQDs show broad and bright visible light under UV illumination that would be worth utilizing in phosphor applications.$^{125}$ Large-scale (20 × 20 cm) free-standing luminescent films of the CQDs embedded PMMA matrix were fabricated. The polymer matrix can not only provide mechanical support but also disperse the CQDs to prevent solid-state quenching. The obtained films are cost-effective, fully flexible, easily scalable, thermally stable, eco-friendly, and mechanically robust, and they show great potential in large-scale flexible solid-state lighting systems. White LEDs consist of the obtained films as the colour-converting phosphors and InGaN blue LEDs as the illuminators were also demonstrated. CQD-based LEDs with a driving current controlled colour change have been reported.$^{126}$ These devices consist of a CQD emissive layer sandwiched between an organic hole transport layer and an organic or inorganic electron transport layer (Fig. 28A) fabricated by a solution-based process. By tuning the device structure and the injecting current density (by changing the applied voltage), it is possible to obtain multimode emission of blue, cyan, magenta, and white from the same CQDs (Fig. 28B). It is the first observation of switchable EL behaviour with white emission in single emitting layer structured nanomaterial LEDs. This interesting current density-dependent emission was useful for the development of colourful LEDs. The pure blue and white emissions were obtained by tuning the electron transport layer materials and the thickness of the electrode.

4.3. Catalysis

4.3.1. Photocatalysis. Advanced materials for electrocatalytic and photoelectrochemical (PEC) hydrogen evolution reaction (HER) are central to the area of renewable energy. CQDs-modified P25 TiO$_2$ composites (CQDs/P25) were prepared via a facile, one-step hydrothermal reaction.$^{127}$ CQDs/P25 exhibited improved photocatalytic H$_2$ evolution under irradiation with UV-Vis and visible light ($\lambda > 450$ nm) because of the CQDs acting as an electron reservoir to improve the efficient separation of the photoinduced electron–hole pairs of P25 and a photosensitizer to sensitize P25 into a visible light response structure for H$_2$ evolution.

It is expected to utilize the NIR region of sunlight for its large share of sun’s energy. CQDs with the UCPL properties can improve the PEC properties of CQD/CdSe/TiO$_2$ NR photoanodes at the NIR region (over 750 nm) (Fig. 29).$^{128}$ The one-dimensional ordered TiO$_2$/CdSe core/shell heterostructural network (Fig. 29A) not only provides a large surface area for efficient

Fig. 27 (a) Cyclic voltammograms of RCQD/RuO$_2$ at different scan rates. (b) Charge–discharge curves of RCQD/RuO$_2$ at different current densities, and the inset shows a magnification at current densities of 10–50 A g$^{-1}$. (c) Comparison of the specific capacitance change of RuO$_2$ and RCQD/RuO$_2$ as a function of current density. (d) Comparison of the cycling stability of the RuO$_2$ and RCQD/RuO$_2$ at a current density of 5 A g$^{-1}$, and the inset shows the coulombic efficiency of RCQD/RuO$_2$. Adapted with permission.$^{118}$ Copyright 2013, Royal Society of Chemistry.

Fig. 28 (A) Sandwiched structure of LEDs using CQDs as a single emitting layer. (B) Electroluminescence (EL) spectra and true colour photographs of the blue, cyan, magenta, and white emissions. Adapted with permission.$^{121}$ Copyright 2013, American Chemical Society.

Fig. 29 (A) A schematic diagram showing the CQD/CdSe/TiO$_2$ NR photoanode. (B) A schematic diagram to illustrate how up-conversion of the carbon quantum dots (UCQDs) served as spectral converters for the CdSe/TiO$_2$ NR photoanode. Adapted with permission.$^{126}$ Copyright 2013, Royal Society of Chemistry.
loading of up-conversion CQDs, but also allows an excellent interfacial chemical reaction between the CdSe and electrolyte. Subsequently, CQDs were electrodeposited on the surface of the TiO2/CdSe core/shell NRs to construct a CQD/CdSe/TiO2 composite photoanode. Fig. 29B is the schematic diagram illustrating the whole PEC process under near-IR illumination. The CQDs can absorb near-IR photons and emit visible photons through the up-conversion effect to excite CdSe. Subsequently, the excited electrons in the conduction band of CdSe would rapidly inject into the conduction band of TiO2, and then transfer along the axial direction of the TiO2 NRs to the FTO substrate. The electrons would finally be transferred to the Pt counter electrode under the assistance of a little external bias voltage, and then drive the hydrogen evolution reaction. The holes remaining in the valence band of CdSe would be consumed by the sacrificial agent.

The oxygen reduction reaction (ORR) is another important photocatalytic reaction in many renewable-energy technologies, including fuel cells and water splitting.85 The aggregates of nitrogen-doped CQDs from the hydrothermal treatment of natural willow leaves exhibit excellent electrocatalytic activity for the ORR via a dominant four-electron oxygen reduction pathway in 0.1 M KOH aqueous solution, great stability (even after 20 000 cycles), as well as methanol and CO tolerance superior to a commercial Pt/C catalyst.86 The heteroatom-doped carbon materials not only exhibit good electrochemical activity for the ORR, but also excellent stability and immunity towards methanol and CO in practical applications, which is one of the main challenges that metal-based catalysts are facing.

4.3.2. Other catalysis. A facile and green approach was reported to synthesize bifunctional fluorescent nitrogen-doped CQDs via the one-step hydrothermal treatment of soy milk at 180 °C, which not only showed favorable photoluminescent properties, but also exhibited good electrocatalytic activity towards ORR.129 The number of electrons involved in the overall ORR was calculated to be 3.15 at −1.20 V, indicating that a four-electron pathway and a two-electron transfer pathway occurred simultaneously.

Dey et al. showed the fabrication of CQDs from a bioprecursor and used them for the reduction of PdCl4− salts leading to the formation of Pd@CQD core–shell nanostructures.130 Although bare CQDs were not capable of preventing the agglomeration of the Pd NPs during the Suzuki and Heck reactions, addition of a co-stabilizer in the form of poly-(N-vinyl-2-pyrrolidone) (PVP) led to an efficient composite that showed high catalytic activity towards the formation of C–C bonds. The Pd@CQD-PVP catalysts were reused in subsequent reactions and the results showed efficient catalytic activity after the third cycle even with obvious structural changes.

4.4. Chemical sensors

By monitoring the changes in their fluorescence intensity under external physical or chemical stimuli, CQDs were used to detect substances and quantities such as DNA,38 PO43−,35 thrombin,31 nitrite,132 glucose,106 biothiol,113 Fe3+,114 pH,62 Ag+,115 Hg2+,113,116 and Cu2+.137,138 Qu et al. reported a preparative route toward distinctive fluorescent CQDs from dopamine (DA). Such CQDs exhibit excellent PL properties, and they can be used for multicolour bioimaging. More importantly, these CQDs were used as a new type of sensor for label-free detection of Fe3+ and dopamine (DA) with high sensitivity and selectivity.64 The method relies on the fact that Fe3+ can oxidize the hydroquinone groups on the surfaces of CQDs to the quinone species, which can quench the fluorescence of the CQDs and DA can effectively shelter the fluorescence quenching due to their competition with CQDs to react with Fe3+ (Fig. 30). It offers a convenient “mix-and-detect” protocol for rapid detection of Fe3+ and DA and can be easily accomplished with a rapid one-step (within 10 min) operation. Moreover, this sensing platform exhibits high sensitivity and selectivity toward Fe3+ and DA versus other metal ions and the other DA analogues. Furthermore, no further chemical modification of the CQDs was required, which offers the advantages of simplicity and cost efficiency. More importantly, the new strategy eliminates the need of QDs, organic dyes, and/or organic solvents, showing much more environmentally friendliness.

A FRET ratiometric fluorescent sensor was developed for detecting H2S in aqueous media and serum over a wide pH range of 4.0–9.0, as well as inside live cells. In the sensing system, upon being reduced by H2S, the probe turns into an energy acceptor (naphthalimide–amine), and accordingly exhibits an absorption at around 425 nm and emission at about 526 nm.139 The fluorescence change of the sensor upon addition of H2S was measured and established a working curve by plotting the emission intensity ratio (I425/I526) versus H2S concentration (Fig. 31A). It can be seen that, in the absence of H2S, the excitation of CQDs at 340 nm led to emission of CQDs at 425 nm; moreover, with the addition of H2S, the CQD emission at 425 nm gradually decreased, and a new emission band at 526 nm appeared, corresponding to the fluorescence of naphthalimide–amine. In the presence of H2S, the probe...
(naphthalimide–azide) changed into an energy acceptor (naphthalimide–amine) due to its reduction by H$_2$S. From Fig. 31B, it is clear that the fluorescence ratio ($I_{526}/I_{423}$) increases gradually with an increase in H$_2$S concentration. Furthermore, the fluorescence of the suspension also became bright green upon addition of H$_2$S. By adjusting the amount of the probe moieties coupled onto the CQD, the detection limit can reach 10 nM, which is the lowest among fluorescent sensors for H$_2$S.

5. Summary and outlook

In this feature article, we have described the recent progress in the field of CQDs, focusing on their synthetic methods, size control, modification strategies, PL properties, luminescent mechanism, and applications in biomedicine, energy conversion and storage, catalysis, and sensor issues.

Though several methods have been proposed towards the synthesis of CQDs, well-defined structure and precise sizes are hardly available yet. It is critical to synthesize CQDs in a facile and green manner with designed structure and size for property studies and selected applications.

The explored properties of CQDs and their regulations are fascinating for extensive applications in science, which have been demonstrated. New properties and how to subtly tune these properties, such as fresh phosphorescence and deatable UCPL, are also challengeable for its nibulous luminescent mechanism. The amorphous to nearly crystalline internal structure, nonquantitative surface structure and virtual size polydispersion may block the clarification of the luminescence mechanism. This problem will be solved through the accurate synthesis, careful analysis, and intelligent consideration.

Many studies have demonstrated the CQDs’ versatility in biomedicine: (i) multimodal bioimaging for its flexibility in surface modification to combine other imaging agents for its high biocompatibility, (ii) biosensors for its multi stimulus responses, (iii) delivery carrier for its various combination with biomolecules or drugs via multi reaction and stimulus responses.

It will arouse research interest in using CQDs in optronics, including photovoltaic conversion, photochemical transformation and energy storage, for the optical properties of CQDs such as electroluminescence, down- and up-conversion, as well as its dual role as electron donor and acceptor with good conductivity and distribution.

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Notes and references


