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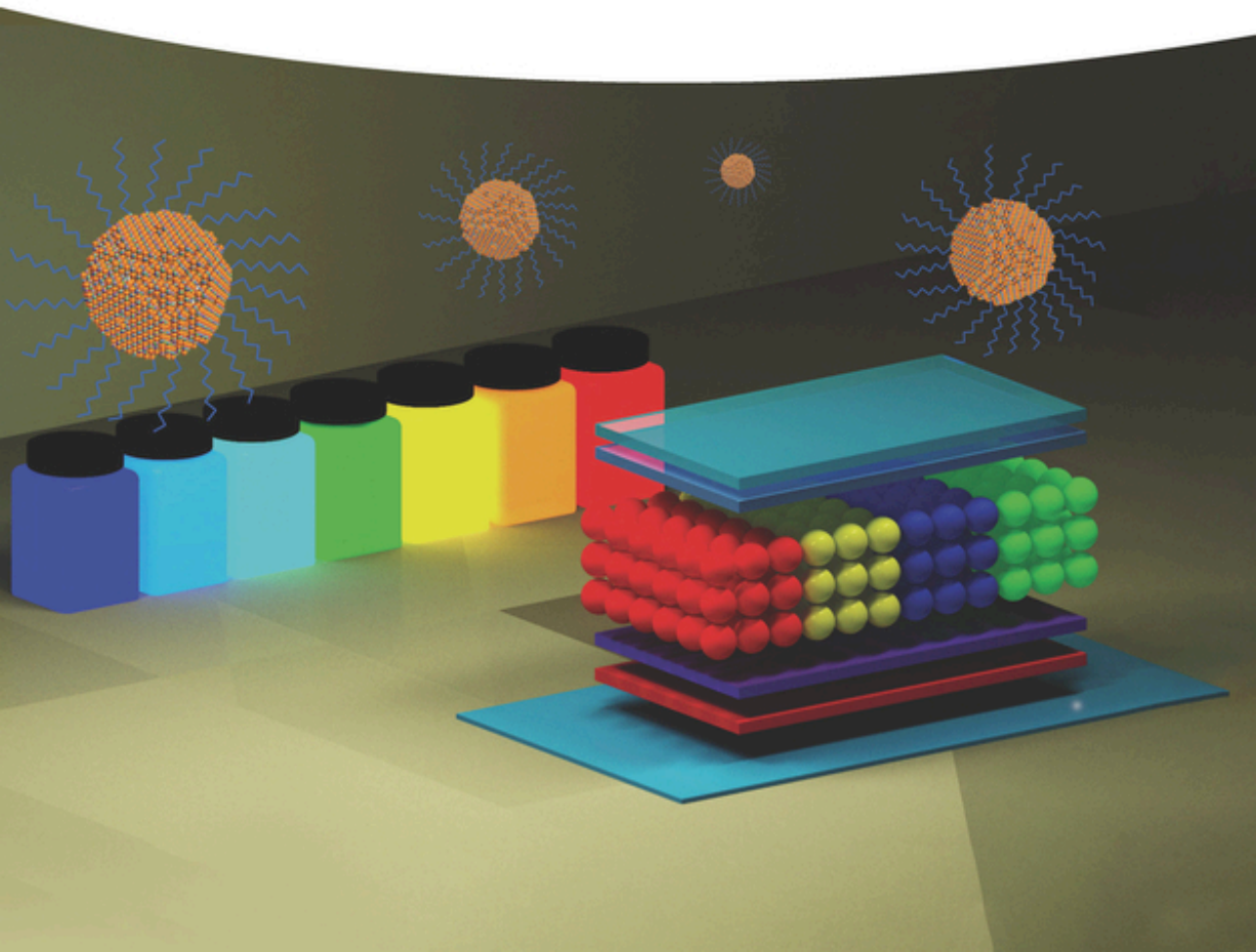
Materials and Devices



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Contents

Preface

Light has played a significant role in human life since the beginning of civilization, from the discovery of fire to the invention of electric light. As technology has advanced, so has the need for more efficient, cost-effective, and environmentally friendly lighting solutions. The advent of quantum dot light-emitting diodes (QDLEDs) is a significant step forward in the development of new-generation display and lighting technologies. QDLEDs have shown tremendous potential in various fields, including flat-panel displays and solid-state lighting.

This book aims to provide an in-depth understanding of the recent developments in colloidal quantum dot light-emitting materials and devices. It comprises 14 chapters that discuss key materials and optimization schemes for QDLEDs, exploring the relationship between material synthesis and device performance. The first chapter provides a brief overview of the history and development of quantum dots and QDLEDs, while the second chapter introduces the structure and operating principles of QDLEDs. Chapters 3–9 review the latest research results in red, green, blue, near-infrared, white, and cadmium-free quantum dot light-emitting materials and devices. Chapter 10 discusses the luminescence principles of AC-driven QDLEDs, and Chapter 11 delves into the stability study and decay mechanism of QDLEDs. Chapter 12 covers electron/hole injection and transport materials in QDLEDs, and Chapter 13 summarizes the industrialization development and patent layout of quantum dots, while Chapter 14 illustrates the patterning and printing technology in QDLED development.

The author of this book has extensively researched the latest progress and results in academia and industry, citing relevant contents, diagrams, and data in the references. This book is a collaborative effort, with contributions from researchers at various levels, including PhD and MS students, who have made significant contributions to the formation and drafting of the book content in Chinese. The publication of this book would not have been possible without the support and help of the relevant staff of the publisher and the assistance of ChatGPT during the editing and finalization of the book in English.

The author of this book would like to express his sincere gratitude to everyone who has contributed to the creation and publication of this book. The team of authors is thankful to their students, postdocs, research assistants, and staff for their hard work and dedication in researching and writing this first-edition book in Chinese.

They also appreciate the editors, translators, proofreaders, and designers who helped to bring the book to life in multiple languages and formats. Lastly, the authors extend their heartfelt thanks to their families, colleagues, and friends for their unwavering support and encouragement throughout this project.

This book is a culmination of the authors' efforts to share their knowledge and expertise on colloidal quantum dot light-emitting materials and devices with readers. It is hoped that this book will serve as a useful reference for researchers, scientists, engineers, students, and anyone interested in the development and application of QDLEDs. The authors believe that the contents of this book will help promote the research and development of QDLEDs and contribute to the progress of the lighting and display industries.

May 2023

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History and Introduction of QDs and QDLEDs

Semiconductor nanocrystals (NCs) are the most widely studied of the nanoscale semiconductors. In early 1981, Alexei Ekimov and Alexander Efros, working at the S.I. Vavilov State Optical Institute and A.F. Ioffe Institute, Russia, discovered nanocrystalline, semiconducting quantum dots (QDs) in a glass matrix and conducted pioneering studies of their electronic and optical properties. Simultaneously, in 1985, Louis Brus at Bell Laboratories in Murray Hill, NJ, discovered colloidal semiconductor NCs (QDs), for which he shared the 2008 Kavli Prize in Nanotechnology. Over the years, QDs have been established as a new type of semiconductor nanocrystalline material whose size is smaller than or close to the excitonic Bohr radius of its bulk material. Common semiconductor materials include Si, Ge, compounds of group II–VI (e.g. CdSe), and compounds of group III–V (e.g. indium phosphide [InP]). When the size of these bulk semiconductor materials is larger than their exciton Bohr radii, electrons and holes are able to move freely and independently in the bulk materials. However, when the size of QDs is smaller than their own exciton Bohr radius, after being excited by light, an electron in the valence band will leap to the conduction band, leaving a hole in the valence band, and the electron and hole form an exciton due to Coulomb effect, which is confined in a space smaller than the exciton Bohr radius, and the electron and hole will be quantized, which is called the "quantum size effect" of nanomaterials. This quantum size effect allows QDs to have discrete energy levels, thus giving them unique physicochemical properties [1]. Colloidal semiconductor NCs have size-dependent particle properties, while their surface ligands make them solution-processable, which gives them a "particle-solution" duality.

Figure 1.1a shows the energy level diagrams of molecular, QD, and bulk semiconductor materials. The molecular orbital energy level diagram is composed of the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO), while the energy level diagram of QDs consists of some discrete energy levels, and the bulk semiconductor material consists of conduction and valence bands. Figure 1.1b illustrates the spatial extent of the confined domains of electrons and holes and the respective energy as a function of the density of electronic states for bulk semiconductor materials, two-dimensional

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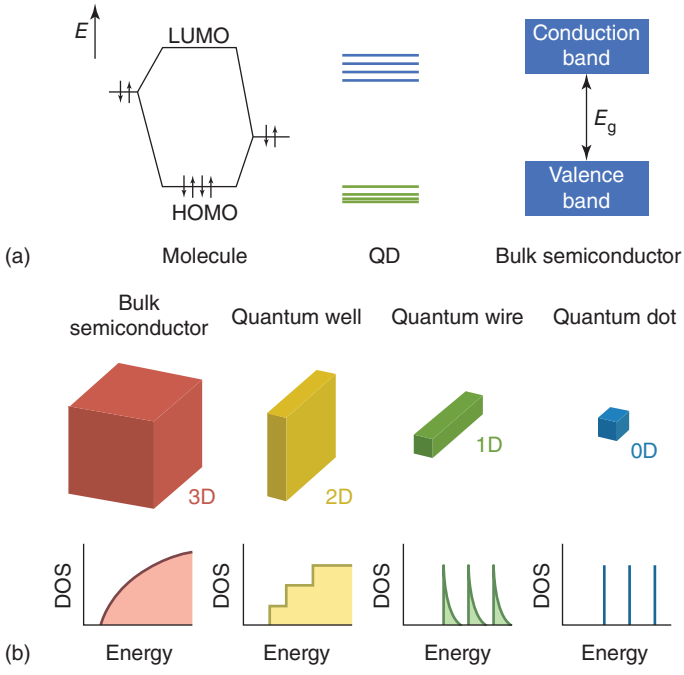

Figure 1.1 (a) Schematic diagram of energy levels of molecular, quantum dot, and bulk semiconductor materials; (b) spatial extent of the confined domain of electrons and holes and the respective energy as a function of the density of electronic states for bulk semiconductor materials, two-dimensional quantum sheets, one-dimensional quantum wires, and zero-dimensional quantum dots depending on the material size.

quantum sheets, one-dimensional quantum wires, and zero-dimensional QDs, depending on the size of the material. For a bulk semiconductor material, the dimensions in all three dimensions are larger than its own Bohr exciton radius, and electrons and holes are free to move independently in all three dimensions; while for a two-dimensional quantum sheet, the dimensions in two dimensions are larger than its own Bohr exciton radius, and electrons and holes are free to move independently in two dimensions; and for a one-dimensional quantum wire, the dimensions in one dimension are larger than its own Bohr exciton radius, while for a one-dimensional quantum wire, the dimensions in one dimension are larger than its own Bohr exciton radius, and electrons and holes are free to move independently in two dimensions. For a one-dimensional quantum wire, whose dimension in one dimension is larger than its own exciton radius, electrons and holes are free to move independently in one dimension; and for a zero-dimensional QD, whose dimension in all three dimensions is smaller than its own exciton radius, electrons and holes are restricted from moving freely and independently in all dimensions. In general, QD is a collective term for a two-dimensional quantum sheet, a one-dimensional quantum wire, and a zero-dimensional QD.

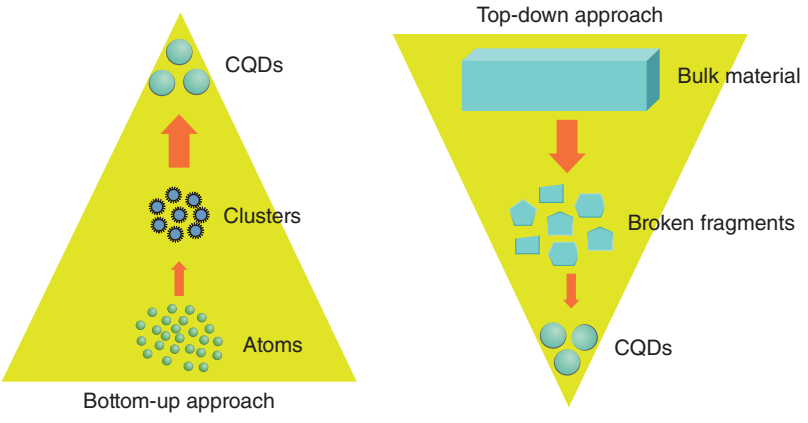

Figure 1.2 Preparation pathways for quantum dots: the "top-down" method and the "bottom-up" method.

1.1 Preparation Route of Quantum Dots

There are two completely different ways to prepare QDs, namely the "top-down method" and the "bottom-up method", as shown in Figure 1.2. The top-down method is to prepare QDs by reducing the dimensionality and size of the bulk semiconductor material; the bottom-up method is to combine atoms or molecules into QDs by chemical synthesis. The former approach is limited by the ultra-fine processing technology, which cannot produce QDs below 10 nm at present, and the morphological regulation of QDs is also limited to some extent. The latter is mainly achieved through colloidal chemical synthesis, which can produce colloidal QDs of different sizes and shapes.

1.2 Light-Emitting Characteristics of Quantum Dots

1.2.1 Particle Size and Emission Color

QDs are semiconductor particles having a few nanometers in size, their optical and electronic properties are quite different from those of larger particles as a result of quantum mechanics. When the QDs are illuminated by UV light, an electron in the QD can be excited from the transition of an electron valence band to the conductance band. The excited electron can drop back into the valence band releasing its energy as light. The color of that light depends on the energy difference between the conductance band and the valence band. The QD absorption and emission features correspond to transitions between discrete quantum mechanically allowed energy levels in the box, which are reminiscent of atomic spectra.

1.2.2 Quantum Dot Optical Property

The QDs are defined as the semiconductor NCs with the quantum confinement. Thus, the semiconductor nanoparticles with dimensions QDs have the following features:

1.2.2.1 Quantum Surface Effect

The surface effect refers to the fact that as the particle size of QDs decreases, most of the atoms are located on the surface of QDs, and the specific surface area of quantum dots increases with decreasing particle size. Due to the large specific surface area of QDs (nanoparticles), the increase in the number of atoms in the surface phase leads to the lack of coordination, unsaturated bonds, and suspension bonds of surface atoms. This makes these surface atoms highly reactive, extremely unstable, and easily bonded with other atoms. This surface effect will cause the large surface energy and high activity of nanoparticles. The activity of surface atoms not only causes changes in the surface atomic transport and structural type of nanoparticles but also causes changes in the surface electron spin conformation and electronic energy spectrum. This feature offers a route to manipulate QD interactions with their environment. QDs can be tethered to proteins, antibodies, or other biologic species and used as optically addressable bio-labels. On the other hand, passivation of QD surface can improve the QD stability and increase the photoluminescent quantum efficiency. Surface defects lead to trapped electrons or holes, which in turn affect the luminescent properties of QDs and cause nonlinear optical effects. Metallic materials show various characteristic colors through light reflection. Due to the surface effect and size effect, the light reflection coefficient of nanoparticles decreases significantly, usually less than 1%, so nanoparticles are generally black in color, and the smaller the particle size, the darker the color, i.e. the stronger the light absorption ability of nanoparticles, showing a broadband strong absorption spectrum. Surface effect or ligand modification offers an additional tool for manipulating energy levels and electronic and optical properties.

1.2.2.2 Quantum Size Effect

Quantum size effect refers to the phenomenon that the electron energy levels near the Fermi energy level change from quasi-continuous to discrete energy levels, that is, when the particle size drops to a certain value, the energy level splits or energy gap widens, in other words, the energy spectrum becomes discrete, and as a result, the bandgap becomes size-dependent. When the change in energy level is greater than the change in thermal, optical, and electromagnetic energy, it leads to the magnetic, optical, acoustic, thermal, electrical and superconducting properties of nanoparticles being significantly different from those of conventional materials. This feature of QDs is that the energy gap changes with the increase in the grain size, the larger the grain size, the smaller the energy gap, and *vice versa*, the larger the energy gap. That is, the smaller the QD, the shorter the wavelength of light (blueshift), and the larger the QD, the longer the wavelength of light (redshift). According to the size effect of QDs, we can use the method of changing the size of the grain to regulate

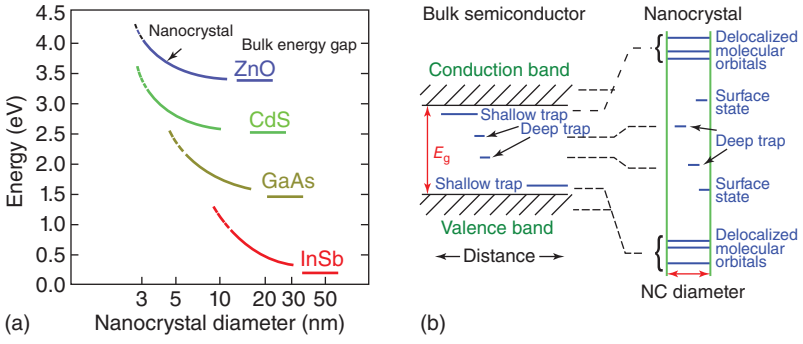

Figure 1.3 Theoretical ideas from the early 1980s. (a) Calculated size-dependent shift of the lowest exciton levels in strong confinement (b) Spatial electronic state correlation diagram for bulk semiconductors and NCs. The bulk valence and conduction bands, together with shallow trap states, evolve into the NC molecular orbitals. Deeply localized defect states in the bulk have essentially the same energy as those in the NC. New localized surface states exist in the NC. Source: Efros and Brus [2]/American Chemical society.

the tuning of the light spectrum of the material and no longer need to change the chemical composition of QDs.

1.2.2.3 Quantum Confinement Effect

Quantum confinement can be observed once the diameter of a material is of the same magnitude as the de Broglie wavelength of the electron wave function. When the QD size of the particle reaches the nanometer scale, the electronic energy level near the Fermi energy level splits from the continuum to the discrete energy level, and their electronic and optical properties deviate substantially from those of bulk materials (Figure 1.3). For semiconductor materials, the size of the bandgap can be adjusted by changing the scale of the particles, thus changing the reliance on certain very costly semiconductor materials (Figure 1.4). Quantum confinement effects in QDs can also result in fluorescence intermittency, called “blinking” [4].

1.2.2.4 Quantum Tunnelling Effect

Quantum tunning effect is one of the fundamental quantum phenomena, i.e. when the total energy of a microscopic particle is less than the height of the potential barrier, considering the motion of a particle encountering a potential barrier above the energy of the particle, the particle is still able to cross this barrier, which indicates that on the other side of the barrier, the particle has a certain probability that the particle penetrates the potential barrier. For QDs, electron movement in the nanoscale space, the carrier transport process will have obvious electronic fluctuations, the emergence of quantum tunneling effect, and the energy level of the electron is discrete [5]. To achieve the quantum effect, it requires the formation of nano-conducting domain in a few μm to tens of μm tiny area. When the voltage is low, the electrons are confined to the nanoscale range of motion, and increasing the voltage can make the electrons cross the nanopotential barrier to form a sea of Fermi electrons, making the system conductive. The

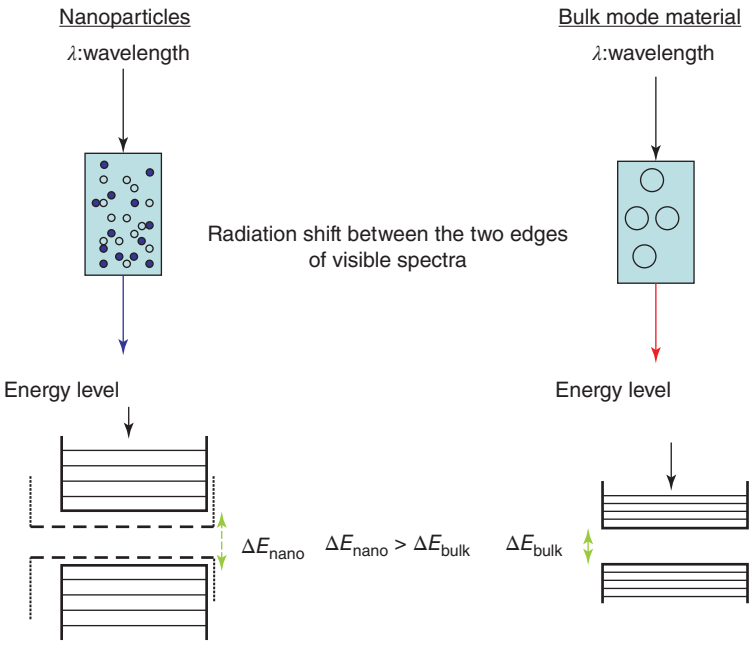

Figure 1.4 QDs Confinement effect: As the size of the particles decreases, the electrons and electron holes come closer, and the energy required to activate them increases, which ultimately results in a blueshift in light emission. Source: Adapted from Kang and Min [3].

quantum tunneling effect occurs when electrons cross the quantum barrier from one quantum well into another quantum well, and this insulating to conducting critical effect is a characteristic of the QDs in a nano-ordered array system. Most QD solids exhibit complex charge-carrier interactions between carrier confinement, interfacial properties, and quantum tunneling effects in the nature of electronic coupling [6].

1.2.2.5 Quantum Optical Properties

Owing to the above-mentioned effects of QDs, the QD absorption and emission features correspond to transitions between discrete quantum mechanically allowed energy levels in the box, which are reminiscent of atomic spectra. QDs have intermediate properties between bulk semiconductors and discrete atoms or molecules. Their optoelectronic properties change as a function of both size and shape. Larger QDs of 5–6 nm diameter emit longer wavelengths, with colors such as orange, or red. Smaller QDs (2–3 nm) emit shorter wavelengths, yielding colors like blue and green. Whereas, the specific colors vary depending on the exact composition of the QD. It turns out that QDs have broad absorption spectra, meaning that they can be excited across a pretty expansive range of light wavelengths. Figure 1.5 shows the emission color of QDs dependent on their respective sizes.

Recent studies have also shown that the shape of the QD may play a role in the band-level energy of the QD, thus affecting the frequency of fluorescence emission

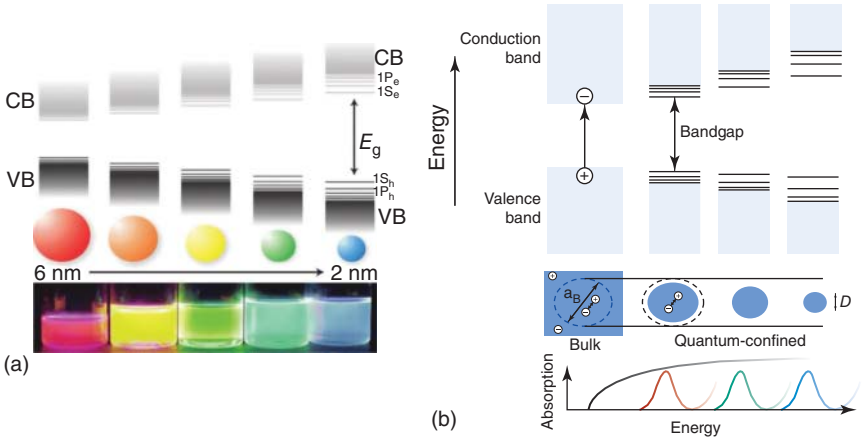

Figure 1.5 (a) Schematic representation of the quantum confinement effect on the energy level structure of a semiconductor material. The lower panel shows colloidal suspensions of CdSe NCs of different sizes under UV excitation. Source: Donegá [7]/Royal Society of Chemistry.; (b) Quantum confinement, leading to size-dependent optical and electrical properties that are distinct from those of parental bulk solids, occurs when the spatial extent of electronic wave functions is smaller than the Bohr exciton diameter. Source: García de Arquer et al. [8]/American Association for the Advancement of Science.

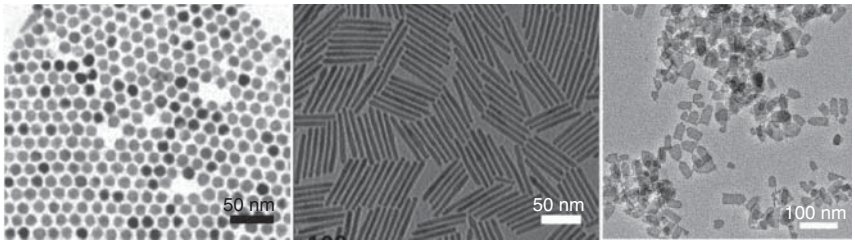

Figure 1.6 Pictures of quantum dots with various sizes and morphologies taken with transmission electron microscopy (a) quantum dots, (b) quantum rods, and (c) quantum sheets.

or absorption. The luminescence characteristics of QDs are closely related to their size and shape, the presence or absence of core–shell structure, and their surface chemistry. QDs of various sizes, morphologies, and core–shell structures can be synthesized by colloidal chemistry, as shown in the transmission electron microscope image in Figure 1.6.

The ligand type and ligand concentration on the surface of colloidal QDs also have an effect on their luminescence properties. For example, Peng et al. observed a shift of several nanometers in the peak position of the fluorescence emission peak of CdSe/CdS core–shell structured QDs ligated by fatty acid cadmium salt surface after ligand exchange treatment by aliphatic amines (Figure 1.7). The QDLED luminescence performance indexes such as external quantum yield and lifetime of CdSe/CdS core–shell QDs with different surface ligands are even more different when prepared

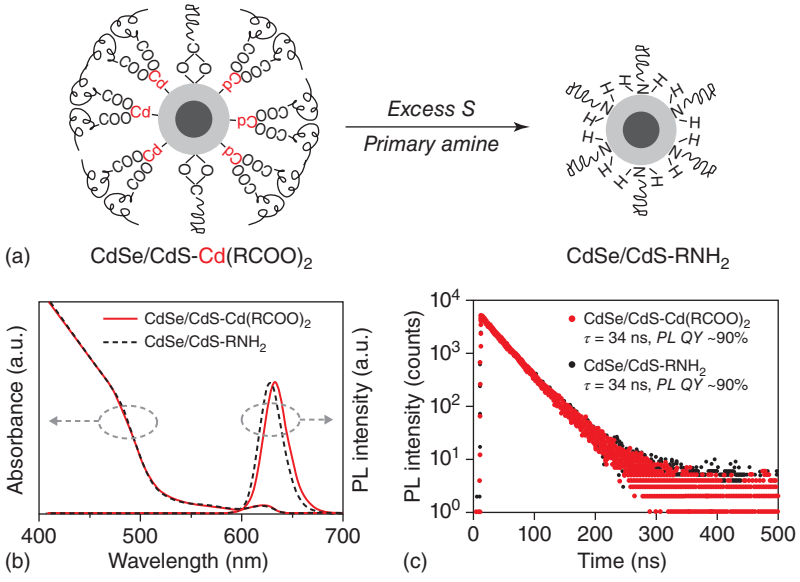

Figure 1.7 Photoluminescence and electroluminescence properties of CdSe/CdS-Cd(RCOO)$_2$ and CdSe/CdS-RNH$_2$ quantum dots. Schematic diagram of CdSe/CdS quantum dots with fatty acid cadmium surface ligands (and also a small amount of negatively charged carboxylates) undergoing ligand exchange to generate CdSe/CdS quantum dots with aliphatic amines. (b) Absorption and steady-state photoluminescence spectra. (c) Time-resolved photoluminescence spectrum with single-exponential decay lifetime (τ) and quantum yield (QY). Source: Pu et al. [9]/CC BY 4.0/Public Domain.

into QDLED devices [9]. Therefore, we should pay special attention to the surface chemical state when studying the luminescence properties of QDs.

The effect of crystal structure can also affect the emission color. Table 1.1 illustrates common bulk semiconductor physical properties. The crystal lattice of a QD semiconductor has an effect on the electronic wave function. As a result, QDs have a specific energy spectrum equal to the bandgap and a specific density of electronic states outside the crystal. Compared to conventional fluorophores, QDs have unique optical and electronic properties. Examples include high quantum yields and molar extinction coefficients, large effective Stokes shifts, broad excitation spectra, narrow emission spectra, a high resistance to reactive oxygen species, protection against material degradation, and nearly impervious to photobleaching.

In highly monodisperse colloidal QD samples, due to the quantum size effect, electrons and holes are subjected to quantum confinement effect, atomic-like structure of electronic states of QDs leads to the formation of discrete energy levels of narrow full-width at half maximum (FWHM) width of 20–80 meV at room temperature and symmetrical fluorescence emission peaks [10] (Figure 1.8).

1.2.3 Core–Shell Structure of QDs

For most core QDs, due to their low PLQYs and poor stabilities, they tend to exhibit a broad red-shifted emission, owing to the surface defects. The issues can be

Table 1.1 Common bulk semiconductor physical parameters.

Material name	Crystal structure type (300 K)	Category	E_{gap} (eV)	Lattice parameters (Å)	Density (g cm^{-3})
ZnS	Sphalerite	II–VI	3.61	5.41	4.09
ZnSe	Sphalerite	II–VI	2.69	5.67	5.27
ZnTe	Sphalerite	II–VI	2.39	6.10	5.64
CdS	Wurtzite	II–VI	2.49	4.14/6.71	4.82
CdSe	Wurtzite	II–VI	1.74	4.3/7.01	5.81
CdTe	Sphalerite	II–VI	1.43	6.48	5.87
InP	Sphalerite	III–V	1.35	5.87	4.79
GaAs	Sphalerite	III–V	1.42	5.65	5.32
PbS	Rock salt	IV–VI	0.41	5.94	7.60
PbSe	Rock salt	IV–VI	0.28	6.12	8.26
PbTe	Rock salt	IV–VI	0.31	6.46	8.22

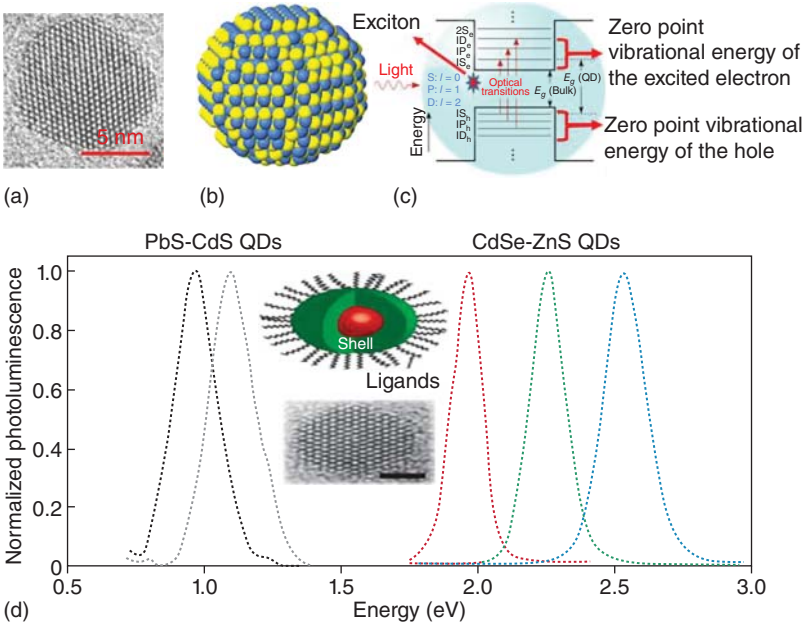

Figure 1.8 (a) TEM image of CdSe nanocrystal; (b) nanocrystal atomic structure; (c) energy level discreteness of the excited electron and the hole in an exciton entity. (d) PL spectra of CdSe–ZnS and PbS–CdS core/shell colloidal QDs. Source: Efros and Brus [2]/American Chemical Society.

addressed to improve efficiency and brightness of semiconductor NCs by growing shells of another higher-bandgap semiconducting material around them, resulting in core–shell QDs. The improvement is due to the reduced access of electrons and holes to non-radiative surface recombination pathways, and in other cases, due to the reduced Auger recombination (AR). Core–shell QDs (core@shell QDs) hold the promise of being emissive components through the precise control of shade and an improved color-rendering index. They exhibit improved optical properties over pure core-only QDs due to the growth of the shell around the QD core, which improves stability and photoluminescence efficiency. A fundamental feature of QDs is the tunability of their emission color through precise control of their size and composition, giving access to UV, visible, and near-infrared wavelengths. Continuing improvements in engineering core–shell QD structures, where a 1–10 nm binary, ternary, or alloyed semiconductor core particle is surrounded by a shell composed of one or more semiconductors of a wider bandgap, have resulted in materials with fluorescence quantum yields that approach unity, narrow symmetric spectral line shapes, and remarkable stabilities, as shown in Figure 1.9, for CdSe/ZnS QDs [11], CdSe/CdS quantum rods [12], CdSe quantum sheets [13]. Interestingly, the fluorescence emission peaks of QDs and quantum rods have a large Stocks shift with the peak position of their first exciton absorption peaks, while the fluorescence emission peaks of quantum sheets have almost no Stocks shift with the peak position of their first exciton absorption peaks. In addition, in terms of fluorescence lifetime, the fluorescence lifetime of rare-earth luminescent materials is at millisecond or microsecond level, while the fluorescence lifetime of QDs is usually in the range of milliseconds [14–16]. While the fluorescence lifetime of QDs is usually below 100 ns [17–19]. It has been found that the fluorescence emission of single QDs has severe blinking behavior, ranging from a few milliseconds to a few minutes, which is mainly due to the non-radiative compounding process caused by the "surface defects" of QDs [20–22].

Although the PL of II–VI QDs can be bright and stable under a reasonable range of excitation light intensities, core–shell QDs universally showed significant "blinking" under the high fluxes used in single QD fluorescence spectroscopy, whereby the PL of single QDs turns "on" and "off" under continuous excitation. This single QD "blinking" not only limits the use of QDs as single photon sources but also

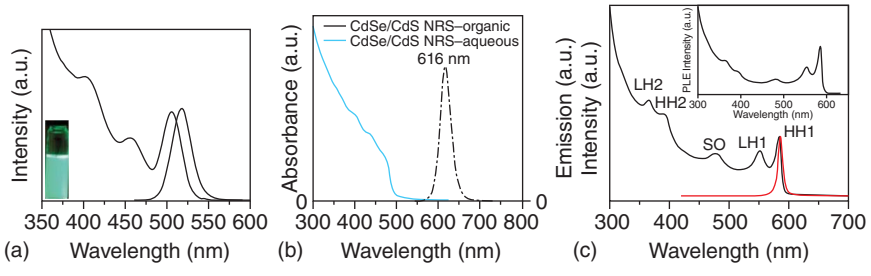

Figure 1.9 Absorption and emission spectra of (a) CdSe/ZnS quantum dots, (b) CdSe/CdS quantum rods, and (b) CdSe quantum sheets.

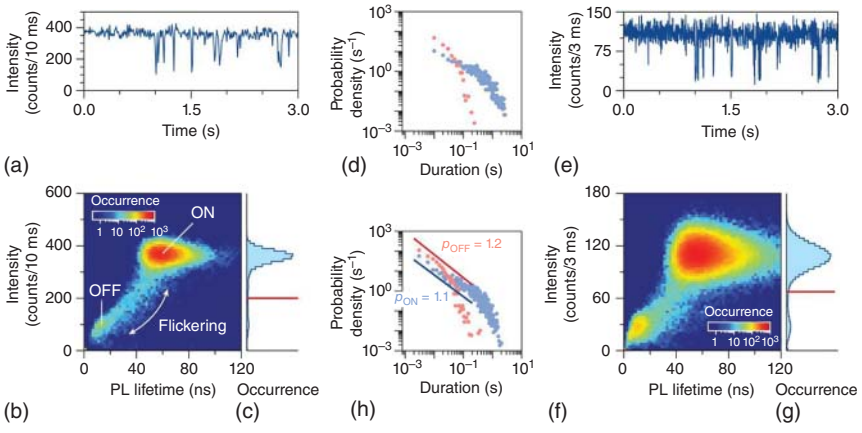

Figure 1.10 (a) Emission intensity from a single CdSe/CdS/ZnS core/shell/shell quantum dot with a temporal resolution of 10 ms under pulsed excitation (405 nm; 10 MHz; 1 μJ cm^{-2}). The diameter of the quantum dot core is 3.2 nm and the shell has 8(2) CdS(ZnS) monolayers. (b) The corresponding "fluorescence lifetime intensity distribution" is a two-dimensional histogram. The plot is based on a 300 seconds experiment, which was divided into 30 000 10 ms time intervals. The effect of scintillation is highlighted. (c) Corresponding 1D intensity histogram with thresholds used for statistical analysis indicated by red lines. (d) Flicker periods (blue) and non-flicker periods (red) extracted from the 10 ms merged and thresholded data in (a) plot. (e–h) Same as (a–d), but using the same single photon data on which there are 3 ms time bins for statistics. Source: Rabouw et al. [22]/American Chemical Society.

potentially limits QDs from being a stable photoluminescent output source under relatively high fluxes. A different approach to blinking suppression was explored by growing a thick CdS or CdS/CdZnS/ZnS shell (>5 nm in shell thickness) onto CdSe core QDs with the idea of fully isolating the excited carriers from the QD surface and the surface environment [22]. However, these QDs generally do not have a very good size distribution, exhibit broad PL spectra, and display moderate PL QYs. More recently, synthesis of CdSe/CdS QDs at a high reaction temperature (310 °C) using octanethiol as a sulfur precursor resolved many of these issues (Figure 1.10).

The terms Type I and Type II QDs are used to classify QDs based on their band structure and electron–hole recombination dynamics (Figure 1.11). Type I and Type

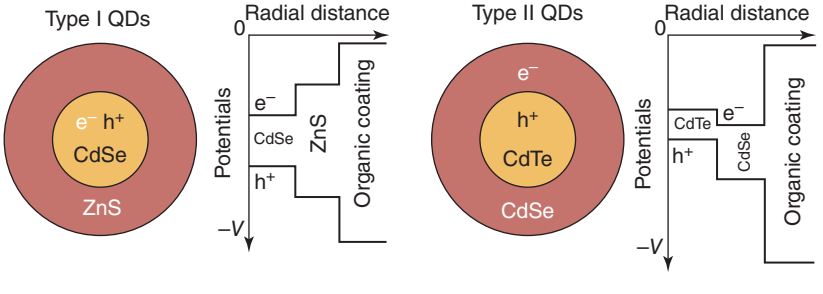

Figure 1.11 Comparison of Type I and Type II CdSe/ZnS core–shell quantum dots. Source: Vaneski [23]/Aleksandar Vaneski.

II QD materials are two different categories of semiconductor nanostructures that exhibit unique electronic and optical properties due to their quantum confinement effects. In a Type I QD, the electrons and holes are confined in the same region of the QD, resulting in a strong overlap of their wave functions. This leads to efficient radiative recombination of the electron–hole pairs, resulting in a high quantum yield and bright fluorescence. Examples of Type I QDs include CdSe, CdTe, and InP QDs. In contrast, in a Type II QD, the electrons and holes are spatially separated between two different regions of the QD due to a band offset at the interface. As a result, radiative recombination of the electron–hole pairs is less efficient than in a Type I QD, leading to lower quantum yields and longer-lived excitons. However, Type II QDs exhibit unique properties such as multiple exciton generation and efficient charge separation, which make them attractive for applications such as solar cells and photocatalysis. Examples of Type II QDs include CdS/CdTe, CdSe/CdTe, and CdSe/ZnTe QDs. Both Type I and Type II QDs have found numerous applications in areas such as optoelectronics, bioimaging, and sensing due to their unique properties and tunability.

Giant QDs are a type of QD structure that is characterized by a larger size and a more complex core–shell structure than traditional QDs. While traditional QDs typically have dimensions on the order of a few nanometers, giant QDs can have dimensions up to tens of nanometers. The larger size of giant QDs offers several advantages over traditional QDs. For example, giant QDs have a higher absorption cross-section, which allows them to absorb more light and generate more charge carriers per photon. They also have a higher quantum yield and longer emission lifetime due to reduced surface recombination and enhanced confinement of excitons. Giant QDs can be synthesized using various methods, including the core–shell approach, which involves the growth of a large core particle, followed by the deposition of multiple layers of shell material. The resulting core–shell structure can have a complex morphology, such as a core–shell–shell or a core–shell–shell–shell structure. Applications of giant QDs include bioimaging, sensing, and photovoltaics. In bioimaging, giant QDs can be used as contrast agents due to their bright and stable emission. In sensing, they can be used as probes for detecting biomolecules due to their high sensitivity and specificity. In photovoltaics, giant QDs can be used as absorbers in thin-film solar cells due to their high absorption efficiency and tunable bandgap.

1.2.4 Continuously Gradated Core–Shell Structure of QDs (cg-QDs)

For most core/shell QDs, such as giant CdSe/CdS core–shell QDs (denoted CdSe/CdS g-QDs, where the small CdSe core is passivated by the large CdS shell) synthesized by the successive ion layer adsorption and reaction (SILAR) method, exhibit reduced surface trapping and AR. Notably, this core/shell QD shows a significant redshift of the emission peak, which indicates that the CdSe core wave function extends into the CdS shell region, i.e. the effective size of the core increases. In addition, the first absorption peaks of CdSe/CdS g-QDs are relatively suppressed, which is due to the fact that the bandgap of CdS is larger than that of CdSe, so the absorption mainly comes from the thick CdS shell. However, due to the large

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