Colloidal Quantum Dot Optoelectronics and Photovoltaics

Capturing the most up-to-date research in colloidal quantum dot (CQD) devices, this book is written in an accessible style by the world's leading experts. The application of CQDs in solar cells, photodetectors, and light-emitting diodes (LEDs) has developed rapidly over recent years, promising to transform the future of clean energy, communications, and displays. This complete guide to the field provides researchers, students, and practitioners alike with everything they need to understand these developments and begin contributing to future applications.

Introductory chapters summarize the fundamental physics and chemistry, whilst later chapters review the developments that have propelled the field forwards, systematically working through key device advances. The science of CQD films is explained through the latest physical models of semiconductor transport, trapping, and recombination, whilst the engineering of organic and inorganic multilayered materials is shown to have enabled major advances in the brightness and efficiency of CQD LEDs.

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Preface

2013 is a landmark year for the field of colloidal quantum dot (CQD) optoelectronics. Nearly three decades have passed since the pioneering syntheses of CQDs; since then countless innovations in synthesis and processing of quantum dots have led to multifunctional colloidal nanoparticles and nanomaterials, achieved via advanced control over particle size, shape, and composition. A deeper understanding has been gained of the physical chemistry of these materials, with electronic and optical properties increasingly elaborated and traced to detailed atomic-scale composition. Excitingly, the first products based on this new class of materials have been announced and will revolutionalize optoelectronics. No longer will high-efficiency and high-performance devices be limited to the realm of single-crystal epitaxy. Companies large and small will deploy CQDs in their next-generation displays to improve the efficiency and quality of the displays. Quantum dots will feature in high-efficiency light-emitting diodes, enabling vastly improved color rendering in displays and lighting alike. The first quantum-dot-based cameras will soon be shipped to customers, offering high-fidelity imaging and professional camera features in a mobile platform. Impacting the economically vast and societally important field of solar energy harvesting is within sight as photovoltaic devices leverage CQDs' spectral tunability for more spectrally efficient harvesting via multijunction architectures or multiexciton processes now demonstrated in devices.

This book aims to provide an updated snapshot of this fast-moving field. It is intended for both new researchers in the CQD dot field, and also experts seeking to gain an up-to-date view of CQD domains adjacent their own.

The book has three main sections: chemistry and synthesis of CQDs and their assembly; the physics and optoelectronic properties of these materials; and optoelectronic devices including lasers, light-emitting diodes, photodetectors, and solar cells.

In Chapters 1 and 2 we present advances in the synthesis and self-assembly of CQDs into solids. Chapter 1 focuses on the organometallic synthesis of CQDs and nanocrystals, and presents the innovative synthetic schemes that have enabled enhanced control over size, shape, and composition. It devotes considerable attention to the organic and the new inorganic ligands that are used to control the properties of the quantum dots and reviews the self-assembly of quantum dots into supra-nanocrystalline solids. Chapter 2 presents aqueous-based synthesis of CQDs and their self-assembly into functional thin films. Aqueous-based CQDs have enabled biological applications and may offer a less materials- and energy-consuming route to CQD optoelectronics.

The second section of the book examines the physical properties of CQDs and quantum dot nanocomposites. Chapter 3 presents the fundamental physical processes that describe how photons and charge carriers interact inside quantum dots. It lays out the theoretical framework within which to understand the quantum size effect, a distinguishing feature of quantum dots that sets them apart from bulk materials and has earned them the name artificial atoms. Chapter 4 explores the optoelectronic properties of hybrid nanocomposites of quantum dots and polymers that have been exploited in light emission, detection, and solar harvesting. It offers a fundamental picture of charge transfer dynamics and energy transfer in quantum dot polymer composites and their applications to devices. Chapter 5 focuses on multiple exciton generation, a phenomenon at play in colloidal quantum dots that enhances their potential in third-generation photovoltaics. The chapter reviews how the Shockley–Quiesser limit can be overcome, looking at both basic physics and applications.

The third section shines a light on optoelectronic devices made using CQDs. Chapter 6 presents the development of light-emitting diodes based on CQDs for display and lighting applications. After consideration of the fundamental mechanisms at play in CQD electroluminescent devices, the chapter presents different architectures and reviews metrology and characterization techniques of CQD light-emitting diodes. Chapter 7 lays out the ideas that have enabled sensitive, rapid, and convenient photodetection using CQD solids, beginning with the first observations of photoconduction and proceeding to advanced photodetector architectures including photoconductors, photodiodes, and phototransistors. The last chapter of this section reviews lasing from quantum dots with emphasis on optically pumped laser cavities and the physics of optical gain and lasing in CQD materials.

The last three chapters of the book are dedicated to the timely and fast-growing field of CQD solar cells: Chapter 9 introduces and elaborates on polymer–nanocrystal hybrid solar cells and the key achievements in the synthesis of quantum dots, rods, and tetrapods that brought about a significant boost in performance in these solar cell architectures. Chapter 10 discusses the solar cells that have led to the highest certified CQD photovoltaic performance reported, architectures that employ a dense and crosslinked quantum dot solid from which electrons and holes are extracted using selective solid-state contacts. Chapter 11 deals with the evolution of dye-sensitized solar cells via the employment of inorganic sensitizers comprising CQDs. It considers the physics involved and the deployment of CQDs on the surface of mesoporous nanostructured electrodes.