QUANTUM DOTS: OPTICS, ELECTRON TRANSPORT AND FUTURE APPLICATIONS

A comprehensive review of cutting-edge solid state research, focusing on its prominent example – quantum dot nanostructures – this book features a broad range of techniques for fabrication of these nano-structured semiconductors and control of their quantum properties.

Written by leading researchers, the book considers advanced III–V and II–VI semiconductor quantum dots (QDs) realized by self-assembly, lithography and chemical synthesis; novel QD structures in nanowires and graphene; and transport and optical methods for control of single QDs. Significant attention is given to manipulation of single spins and control of their magnetic environment, generation of quantum light emitted by single dots in dielectric cavities, and dots coupled to plasmons in metallic structures. It is a valuable resource for graduate students and researchers new to this field.

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CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town,
Singapore, São Paulo, Delhi, Mexico City

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9781107012585

First published 2012

Printed in the United Kingdom at the University Press, Cambridge

A catalogue record for this publication is available from the British Library

ISBN 978-1-107-01258-5 Hardback

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Preface

Semiconductor quantum dots (QDs) have been extensively researched in the past 20 years or so. Over this period, the field has been stimulated by various motivating factors from fabrication of low-threshold temperature-insensitive QD lasers to the use of single spins for quantum computing and single dots for medical markers. In the past decade, refinement of fabrication and experimental techniques enabled researchers in the field to routinely use single QDs to access and control single electrons and holes and their spins, and to generate non-classical light. The focus of this book is on control of optical and transport properties of single and few QDs. The remarkable progress in this fast-developing field in the past three to five years is reported.

The term “quantum dot”, widely used from late 1980s, usually refers to a semiconductor nano-structure. Typical sizes of a quantum dot range from a few nanometers in colloidal dots (also referred to as nano-crystals) to a few hundred nanometers in lithographically fabricated electrostatic structures, so that on average they contain from 10^3 to 10^6 atoms. The small physical size is the main common characteristic feature of quantum dots made from different materials and using various fabrication methods. It is usually combined with additional methods for electron energy engineering, for example, surrounding the dot with a higher band-gap semiconductor, applying gate-voltage creating a higher potential barrier around the dot, etc. This gives rise to the most important basic property of QDs: the motion of electrons and holes in QDs is suppressed in all three dimensions. This property gave quantum dots the name of zero-dimensional (“0D”) structures. A result of the full confinement is the complete quantization or discretization of the energy spectrum of a confined charge carrier. This is in great contrast to higher-dimensionality structures such as quantum wells (QW), where the spectrum is continuous for the particle motion in the plane of the QW, and quantum wires where quantization is present only in two directions, and the third, along the wire, is described by an energy continuum. The quantized energy spectrum and complete localization also resembles the behavior of electrons in atoms, which gave quantum dots the title of “artificial atoms”. This description emphasizes the increased isolation of confined electrons and holes from the environment outside the dot, one of the most attractive properties widely exploited in applications ranging from quantum dot lasers for telecommunications to QD-based spin-qubits for quantum computing.

According to the Web of Science, studies of quantum dots have resulted in around 27 000 publications since 1987, with increasing number of publications each year exceeding 2500 per year since 2005. Quantum dot research embraces variety of topics in physics, electrical and electronic engineering, chemistry, material science, biology and medicine, where, according to the demands of a specific application, different types of QD structures are employed. The work of the most prolific authors addresses topics such as QD design and growth, devices based on epitaxial self-assembled dots (lasers, photonic cavities, etc.), colloidal dots as fluorescent markers for biological and medical applications, optics of single epitaxial dots, spin qubits in optically active and gate-defined dots, single electron transport, optics of colloidal dots etc.

This book will present the latest advances in QD research in the past three to five years, embracing some of these most active areas including fabrication, optical properties and electron transport. The material presented in this book is divided in to six parts describing: (1) nanostructure design and structural properties of epitaxially grown quantum dots and nanowires; (2) manipulation of individual quantum states in quantum dots using optical techniques; (3) optical properties of quantum dots in photonic cavities and plasmon-coupled dots; (4) magnetic ions and nuclear spins in a dot; (5) electron transport in quantum dots fabricated by lithographic techniques in III–V semiconductors and graphene; (6) single dots for future telecommunications applications. Below I will briefly review each of these parts.

(1) **Nanostructure design and structural properties of epitaxially grown quantum dots and nanowires.** The three chapters here will review epitaxial growth of III–V quantum dots (Chapter 1), a relatively novel addition to the field – QDs embedded in semiconductor nanowires enabling new flexibility with the material and substrate choice (Chapter 2), and finally ultra-sensitive techniques for structural characterization, delivering information on QD dimensions and material distribution inside nano-structures (Chapter 3).
(2) **Manipulation of individual quantum states in quantum dots using optical techniques.** This part deals with advanced optical methods used for control and characterization of holes and electrons and importantly their spins in QDs. Chapter 4 presents applications of differential transmission for spectroscopy of spin-Λ system, with a focus on manipulation of the hole spin – a candidate for a decoherence free spin qubit, a basic building block for quantum computing. Chapter 5 focuses on resonance fluorescence describing the first application of this techniques to the atomic-like two-level system available in single QDs. Chapter 6 describes coherent control of excitons using ultra-fast optical pulses and photo-current detection in single QDs. This chapter focuses on fidelity of coherent operations and reasons leading to damping of exciton Rabi oscillations. Chapter 7 expands the description of hole properties in QDs presented in Chapter 4 to coupled QD structures, and reports on optical properties of these complex systems measured in photoluminescence of single QD "molecules".

(3) **Optical properties of quantum dots in photonic cavities and plasmon-coupled dots.** Work presented in this part describes how optical properties of QDs are modified when they are inserted in optical cavities or interact with plasmons when positioned in proximity of a metal surface. Chapter 8 reports on efforts for deterministic light–matter coupling using single quantum dots positioned in micropillar cavities fabricated using novel in-situ low-temperature lithography methods. Chapter 9 presents optical investigations carried out on another type of cavities comprising QDs: missing-hole defects in thin membrane photonic crystals made of GaAs. Chapter 10 discusses photon statistics in QD microlasers emission based on a GaAs micropillar design. Chapter 11 addresses a different type of QDs, the only example of colloidal dots, or nano-crystals, in this book. Taking advantage of their free surface, nano-crystals coupled to plasmon excitations in metallic nano-structures can easily be realized. Optical studies of such hybrid structures are presented in this chapter.

(4) **Quantum dot nano-laboratory: magnetic ions and nuclear spins in a dot.** This chapter addresses spin effects related to behavior of nuclei in atoms constituting quantum dots, and spin effects related to transition-metal impurities located inside the dot. These phenomena effectively occur on the length-scales smaller than the physical dimensions of the dot. A QD acts as an enclosure, or a "laboratory", where these nano-scale processes can be probed via the important changes they produce in the properties of the electrons and holes confined in QDs. Chapter 12 considers self-assembled CdTe/ZnTe QDs containing single Mn atoms. Optical manipulation of the spin of a single magnetic atom (Mn) in the solid-state environment is demonstrated. This chapter also provides a brief overview of II–VI QDs fabrication. Chapter 13 considers a challenging goal of doping III–V InGaAs dots with single Mn impurities, and reports on magneto-optics of such dots. Chapter 14 reports on optical manifestation of a variety of spin effects in QDs associated with nuclear spin polarization.

(5) **Electron transport in quantum dots fabricated by lithographic techniques from III–V semiconductors and graphene.** This section of the book touches on a very large field of electron transport in quantum dots fabricated using lithography. GaAs-based structures are considered in Chapter 15, where experiments are reported on electron-spin control in laterally coupled double dots, work inspired by the Loss–DiVincenzo proposal for spin-based quantum computing. The theory of quantum control of the singlet–triplet qubit is outlined in Chapter 16, focusing specifically on the electron–nuclear spin interaction in III–V QDs and carbon-based structures. Chapter 17 reports on transport studies of single–layer graphene nano-structures including spectroscopy in magnetic field and scanning-gate microscopy with high spatial resolution.

(6) **Single dots for future telecommunications applications.** This part reports on work where single quantum dots are researched for possible future applications in secure optical communications and linear optics quantum computing. Chapter 18 addresses generation of entangled photon pairs using InGaAs/GaAs quantum dots: the first electrically driven entangled light source, and the first photon pair source where the entanglement of the emitted photons can be activated or deactivated

electrically is considered. Chapter 19 discusses a site-control technique for fabrication of self-assembled InAs/InP quantum dots emitting at telecommunication wavelengths enabling deterministic coupling of single dots to high finesse microcavities. Such devices will form the basis of efficient sources of single photons and entangled photon pairs for telecommunications applications.

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