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Optical Generation and Control of Quantum Coherence in Semiconductor Nanostructures

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With 137 Figures

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To Marta and Metodi Slavchev

Preface

The fundamental concept of quantum coherence plays a central role in quantum physics, cutting across disciplines of quantum optics, atomic and condensed matter physics. Quantum coherence represents a universal property of the quantum systems that applies both to light and matter thereby tying together materials and phenomena. Moreover, the optical coherence can be transferred to the medium through the light-matter interactions. Since the early days of quantum mechanics there has been a desire to control dynamics of quantum systems. The generation and control of quantum coherence in matter by optical means, in particular, represents a viable way to achieve this longstanding goal and semiconductor nanostructures are the most promising candidates for controllable quantum systems. Optical generation and control of coherent light-matter states in semiconductor quantum nanostructures is precisely the scope of the present book.

Recently, there has been a great deal of interest in the subject of quantum coherence. We are currently witnessing parallel growth of activities in different physical systems that are all built around the central concept of manipulation of quantum coherence. The burgeoning activities in solid-state systems, and semiconductors in particular, have been strongly driven by the unprecedented control of coherence that previously has been demonstrated in quantum optics of atoms and molecules, and is now taking advantage of the remarkable advances in semiconductor fabrication technologies.

A recent impetus to exploit the coherent quantum phenomena comes from the emergence of the quantum information paradigm. The scientific effort in this field is focussed on how to exploit the properties of the quantum systems to perform computations. The issues in computation theory are fascinating and recent progress has generated a great deal of excitement. Furthermore, in recent years, a new paradigm focussed on the exploitation of the previously largely ignored spin degree of freedom, has emerged. Spin offers the opportunity to store and manipulate phase coherence over much larger length and time scales than is typically possible in charged-based devices. In this respect, the idea of encoding the quantum information in the spin degree of freedom has been particularly promising and extensively investigated. Furthermore, spin can be accessed through the orbital properties of the electron in solid state, which in turn can be efficiently manipulated by light according to angular momentum conservation laws, through the optical orientation mechanism. An all-optical implementation of quantum coherent spin control in semiconductor nanostructures, is of particular interest since it takes full advantage of the cutting edge ultrafast laser technologies and enables the implementation of ultrafast schemes for quantum computation.

Although quantum information is undoubtedly a worthy and useful goal in its own right, many more conventional and near-term problems ranging from novel lasers to spintronics are all bound up with issues in coherence. Historically, the quest for the demonstration of fundamental coherent quantum-optical effects in semiconductor systems that have been initially observed in atomic systems has proved to be very successful and has enormous potential for applications. For instance, the idea of achieving Bose-Einstein condensation in solid state at elevated temperatures originates from the cold atom field and was proposed more than 40 years ago. The recent experimental discovery of the room-temperature polariton lasing and the superfluid properties of exciton-polaritons in semiconductor microcavities have opened up new and exciting opportunities for tangible applications of the quantum coherent phenomena of the Bose-Einstein condensation and superfluidity. On the other hand, the exploitation of coherent optical effects, such as electromagnetically-induced transparency and coherent population trapping in semiconductor systems opens up pathways to freeze light in future devices and to build an inversionless laser. This is yet another demonstration of a fruitful transfer of ideas built around the concept of coherence from cold atoms field to the solid state. Although the atomic and semiconductor physical systems are very different, from conceptual and theoretical point of view there are many cognate issues between atomic coherence and the coherence of relatively simple many-body systems such as excitons or exciton-polaritons in semiconductors. The study of these more controllable systems is extremely helpful to interpret and guide work on complex materials with their innumerable confounding issues.

The main focus of this book is the study of the optical manipulation of the coherence in excitonic, polaritonic, and spin systems as model systems for complex coherent semiconductor dynamics, towards the goal of achieving quantum coherence control in the solid-state. The book is intended for graduate students, postdocs and active researchers in the fields of semiconductor quantum optics, nonlinear and coherent ultrafast optical spectroscopies, quantum information processing and quantum computation, semiconductor spintronics, and for physicists and engineers, who want to become familiar with recent experimental and theoretical advances in this frontier research field.

The book provides a selection of review articles written by leading scientists, focusing on various aspects of optically-induced quantum coherence in semiconductor nanostructures. The latest research findings, interpretation and ideas in this rapidly developing field are discussed in four parts: (i) Carrier dynamics in quantum dots; (ii) Optically-induced spin coherence in quantum dots; (iii) Novel systems for coherent spin manipulation, and (iv) Coherent light-matter states in semiconductor microcavities.

Finally, we would like to thank the authors for their enthusiastic response, dedication and full support of the book project until its successful completion. We wish to express our gratitude to R. Murray, E. Clarke, P. Spencer, M. Taylor and E. Harbord for fruitful discussions, providing assistance and valuable feedback on the manuscript. In addition, we are very much indebted to Angela Lahee of Springer-Verlag whose continuous guidance and help during the course of the project were invaluable. Special thanks are due to our families for their encouragement, appreciation and continuous support.

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Contents

Part II Optically-induced spin coherence in quantum dots