Chapter

Recent Advancement on the Excitonic and Biexcitonic Properties of Low-Dimensional Semiconductors

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Abstract

Knowing excitonic and biexcitonic properties of low-dimensional semiconductors systems is extremely important for the discovery of new physical effects and for the development of novel optoelectronics applications. This review work furnishes an interdisciplinary analysis of the fundamental features of excitons and biexcitons in two-dimensional semiconductor structures, one-dimensional semiconductor structures, and zero-dimensional (0D) semiconductor structures. There is a focus on spectral and dynamical properties of excitons and biexcitons in quantum dots (QDs). A study of the recent advances in the field is given, emphasizing the latest theoretical results and latest experimental methods for probing exciton and biexciton dynamics. This review presents an outlook on future applications of engineered multiexcitonic states including the photovoltaics, lasing, and the utilization of QDs in quantum technologies.

Keywords: excitonic states, biexcitonic states, multiexcitonic states, reduced dimensionality semiconductors, quantum wells, quantum wires, quantum dots, applications

1. Introduction

The scientific significance in the field of the physics of excitons comprises both basic research and applied research, this area of physics being one of the most actively studied subjects. The interest in the physics of excitons has raised actively over the past two decades, this interest being provoked by the unique properties of excitons that provide the development's context of optoelectronic and photovoltaic of various device applications such as electrically driven light emitters [1–3], photovoltaic solar cells [4–6], photodetectors [7, 8], and lasers [9–12].

An important concern for the researchers of this field is to obtain a decrease of the dimension of the macroscopic semiconductor systems to nanoscale, this thing leading not only to manufacturing and observing low-dimensional semiconductor structures (LDSs) but also to the emergence and development of new electronic and optical properties that are significantly different from bulk semiconductors properties. Because the essential distinction between low-dimensional semiconductor structures and bulk semiconductor structures can be explained using the terminology of improved excitonic effects that are determined by exciton localization result, it is crucial that, in these quantum-confined materials, the excitonic properties to be better understood and mastered to be able to use them in the development of the innovative and proficient optoelectronic devices utilizing these types of the materials.

Numerous researches have already shown that exploring the excitons' behavior in low-dimensional semiconductor systems can find new ways of controlling the fundamental exciton properties for light generation and light harvesting and finding novel materials for the next-generation high-efficiency excitonic light-harvesting tools at low cost [13–15].

Excitons in low-dimensional semiconductor structures have been widely investigated latterly. A low-dimensional semiconductor structure is a system which presents quantum confinement effects, the movement of electrons or other particles (holes, excitons, etc.) being limited in one or more dimensions.

The promising area of excitonics represents the science and manufacturing of the excitons in disordered and low dimensionality semiconductors (organic semiconductors, hybrid perovskites, colloidal semiconductor nanoparticles) [16–23] and guarantees much quicker efficiency of harmonizing with fiber optics, realizing some novel stages to perform exciton-based computation at room temperatures [24].

It is known that the absorption by a semiconductor of a photon with energy equal to or greater than its bandgap stimulates an electron from the valence band into the conduction band, the vacancy left behind in the valence band being characterized as a hole which is a quasiparticle carrying positive charge. The Coulomb attraction type between these particles with electrical charges of opposite sign provides a quantum structure of electron–hole pair type which is electrical neutral, called exciton. Excitons have numerous characteristics similar to those of atomic hydrogen [25, 26]. Using this type of hydrogen atom model, in crystalline materials, two types of excitons can be discussed in the two limiting cases of a small dielectric constant when the exciton is tightly bound Frenkel-like (the electron and the hole are tightly bound; the Coulomb interaction is poorly screened) in contrast with large dielectric constant when the exciton is weakly bound Wannier-like (the Coulomb interaction is strongly screened by the valence electrons, the electron, and the hole being weakly bound) [27–32]. For a semiconductor exciton named Wannier exciton which has a radius greater than lattice spacing, the effective-mass approximation can be used [33–40].

The entire gamut of low-dimensional semiconductor systems comprises quantum dots (QDs) or zero-dimensional (0D) systems if the excitons are dimensionally confined in all directions, quantum wires (QWRs) or one-dimensional systems (1D) if they are semiconductor nanocrystals in which the excitons are confined only in the diameter direction and quantum wells (QWs), or two-dimensional systems (2D) if the quantum confinement occurs in the thickness direction, while the particle motion is free in the other two directions [41–43].

It has been shown that in the quantum confinement conditions, the size and shape of semiconductor nanocrystals show an influence on the exciton fine structure, this being presented like the mode in which the energetic states of the exciton are divided by crystal field asymmetry consequences and low-dimensional semiconductor structures shape anisotropy [41–50].

Besides the hydrogen characteristics of the exciton, it is known that in QWs, QWRs, and QDs, there are hydrogen atom-like exciton pair-state populations or larger bound systems called biexcitons [25–27, 51–56].

Various researchers have shown that with the rise of the exciton binding energy value in low-dimensional semiconductor systems, the biexciton binding energy value with growth confinement is also raised [25, 57–67]. All of the papers in this field have shown that by improving the biexciton creation in reduced dimensional semiconductor structures, the quantum yield (QY) of photovoltaic cells has been enhanced [57, 68–71]. Also, biexcitons are important for quantum-information and computation areas due to their stunning benefit for the creation of coherent combination of quantum states, in this sense being used to find new platforms for the obtaining of future and scalable quantum-information applications such as some greater efficiency non-blinking single-photon sources of biexciton, entangled light sources, and laser based on biexciton states [72–75].

Multiple exciton generation (MEG) in low-dimensional semiconductors is the procedure by which multiple electron–hole pairs, or excitons, are created after the absorption of a single high-energy photon (larger than two times the bandgap energy) and is an encouraging research direction to maximize the solar energy conversion efficiencies in semiconductor solar cells at a possibly much diminished price [76–78]. Numerous studies have shown that the photo-physical properties of MEG are due to the character of inherent multiexciton interaction [79, 80].

This present chapter reviews the recent advancement in the understanding of the excitons' and biexcitons' behavior in LDSs, this fact being important for new experiments and optoelectronic devices.

The second section of this paper comprises three important parts that analyze the way in which the properties of excitons and biexcitons in two-dimensional structures, one-dimensional semiconductor structures, and zero-dimensional semiconductor structures are influenced by the nanometric dimensions case.

The final section recapitulates the fundamental and special issues that have been debated.

2. Excitonic and biexcitonic properties in low-dimensional semiconductors

This part of the chapter contains some crucial and novel concepts of excitonic and biexcitonic properties of semiconductor structures of low dimensionality (e.g., QWs, QWRs, QDs) which are relevant for the characterization of the active constituents in advanced tools.

2.1 Excitons and biexcitons in two-dimensional semiconductor structures

This section presents a subject of an enormous significance for the excitons and biexcitons effects in two-dimensional semiconductor structures. In 2005, Klingshirn [25] reported some essence results which emphasize the optical properties of excitons in QWs, in coupled quantum wells (CQWs), and superlattices.

In the last years, in the area of excitons in LDSs, there has been much study which integrates experimental, theoretical, and technical features about the effective-mass theory of excitons and explains numerical procedures to compute the optical absorption comprising Coulomb interaction cases [81–84].

Xiao and coworkers [85, 86] emphasized the case of the excitons functioning in some layered two-dimensional (2D) semiconductors, presenting new different methods of the obtaining of some propitious materials structure (like molybdenum disulfide MoS_2) with perfect properties for the evolving of the operable optoelectronics and photonics such as light-emitting diodes (LEDs), lasers, optical modulators, and solar cells based on 2D materials. In Ref. [87] the study of the enhanced Coulomb interactions in WSe_2-$MoSe_2$-WSe_2 trilayer van der Waals (vdW) heterostructures via neutral and charged interlayer excitons dynamics is mentioned.

In the situation of cryogenic temperatures, an increasing photoluminescence quantum yield in the conditions of the inclusion of a WSe_2 layer in the trilayer composition in contrast with the example of the bilayer heterostructures has been reported.

Owing to the fact that the class of 2D materials presents some distinctive features, which are highly dissimilar in comparison with those of their three-dimensional (3D) correspondents, it is used for the next-generation ultra-thin electronics [88]. In this context some researchers explained the role of the expansion of indirect excitons (an indirect exciton—IX—is a bound pair of an electron and hole in separated QW layers [89]), which is observed in vdW transition metal dichalcogenide (TMD) heterostructures at room temperature, this study helping for the progress of excitonic devices with energy-productive computation and ideal connection quality for optical communication cases [90, 91]. Various theoretical and experimental analyses have been developed for the improvement of the excitonic devices that use IXs propagation in different types of single QWs and coupled QWs [92, 93]. Fedichkin and his colleagues [94] studied a novel exciton transport model in a polar (Al, Ga)N/GaN QWs calculating the propagation lengths up to 12 μm at room temperature and up to 20 μm at 10 K.

In Ref. [95] a theoretical portrayal of the ground and excited states of the excitons for GaAs/AlGaAs and InGaAs/GaAs finite square QWs of different widths is presented which eases the elucidation of the experimental reflectance and photoluminescence spectra of excitons in QWs.

Some works examined new different excitonic properties of the 2D organic–inorganic halide perovskite materials showing that this type of perovskite is very qualified to be used for the construction of the photonics devices [96–98] containing LEDs [99, 100], photodetectors [101], transistors, and lasing applications [102]. Wang et al. [103] provided a valuable research about the special characteristics of the long-lived exciton, trion, and biexciton cases in CdSe/CdTe colloidal QWs, proposing a novel model of light harvester with minimal energy losses.

2.2 Excitons and biexcitons in one-dimensional semiconductor structures

One-dimensional semiconductor structures have obtained a remarkable consideration within the last decade. 1D semiconductor nanostructures including wires, rods, belts, and tubes possess two dimensions smaller than 100 nm [104]. Among these types of 1D nanostructures, semiconductor QWRs have been investigated thoroughly for a broad range of materials. This type of 1D nanostructures is used for an essential study due to their exclusive constitutional and physical properties comparative with their bulk correspondents. Crottini et al. [105] communicated the 1D biexcitons behavior in high-quality disorder-free semiconductor QWRs, evaluating the biexciton binding energy value at 1.2 meV.

Sitt and his coworkers [106] reviewed the excitonic comportment of a diversity of heterostructured nanorods (NRs) which are used for a series of applications comprising solid-state lighting, lasers, multicolor emission, bio-labeling, photon-detecting devices, and solar cells. In the same work [106], some multiexciton effects are shown, and the dynamics of charge carriers is presented in core/shell NRs with potential applications in the optical gain field and in the light-harvesting section.

For the case of the single crystalline silicon nanowires (SiNWs), which is a key structure for nanoscale tools including field-effect transistors, logic circuits, sensors, lasers, Yang [107] described some excitonic effects and the case of the optical absorption spectra using the Bethe-Salpeter equation.

In Ref. [108] the physical properties of elongated inorganic particles are reported in the case of the nanoparticle shape modification from spherical to rod-like with the help of the exciton storage process.

2.3 Excitons and biexcitons in zero-dimensional semiconductor structures

Zero-dimensional semiconductor structures have captivated a notable interest owing to the fact that the motion is confined in all three directions, the size of a QDs being smaller than or comparable to the bulk exciton Bohr radius [109–112]. In this part of the chapter, some recent progresses in the topic which deals with the excitonic and biexcitonic effects for QDs applications case are emphasized, including computing and communication field, light-emitting devices, solar cells area, and biological domain [113, 114].

Pokutnyi [115–120] realized the foremost theoretical analyses that accurately describe different absorption mechanisms in such nanosystems, discussing many issues related to the complicated interrelationship between the morphology of the zero-dimensional semiconductor structures and their electronics and their optical properties and which help to the progress of novel proficient optoelectronic devices.

Plumhof and his colleagues [121] proved that QDs with an adequately small excitonic fine structure splitting (FSS) can be utilized as some valuable deterministic sources of polarization-entangled photon pairs to improve the building blocks' quality for quantum communication technology.

Golasa et al. [122] presented some new statistical properties of neutral excitons, biexcitons, and trions for the case of QDs which are created in the InAs/GaAs wetting layer (WL), confirming that the WLQDs structure is a useful model to be applied in the area of quantum-information processing applications.

Singh and his team of researchers [123] found a new multipulse time-resolved fluorescence experiment for the CdSe/CdS core/shell QDs case, this work being a crucial spectroscopic procedure which can separate and measure the recombination times of multiexcited state for the proposed sample.

In Ref. [124] a comprehensive review is furnished about the appropriately engineered core/graded-shell QDs revealing advantageous optical properties and unique photoluminescence assets of QDs for liquid crystal displays backlighting technologies and organic light-emitting diode tools. In different papers which have to do with the quantum dot-based-light-emitting diodes (QD-LEDs) results [124–127], it is mentioned that for the improvement of the QD-LED performance, two processes must be diminished: trapping of carriers at surface defects and Auger recombination of excitons.

Important studies reveal many novel and interesting experimental and theoretical results on LDSs exhibiting high quantum yield as a result of MEG occurrence with the aim of the improvement of the solar devices field. Considering that Shockley and Queisser determined a basic threshold value for the efficiency of a traditional p-n solar cell of 30%, these essential results prove that there is a possibility to exceed the Shockley-Quiesser threshold employing quantum effects for a recently developed low-cost third-generation solar cell [77, 128–130].

3. Conclusions

In recent decades, low-dimensional semiconductor structures have become one of the most dynamic research areas in nanoscience, the excitons showing some notably novel attributes due to confinement consequence case. In this chapter a review of some modern experimental and theoretical discoveries on excitonic and biexcitonic effects in low-dimensional semiconductors is presented. The paper furnishes an outstandingly multipurpose excitonic aspect of the optoelectronic applications field, including photodetectors and opto-valleytronic tools, computing and communication domain, and light-emitting devices.

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