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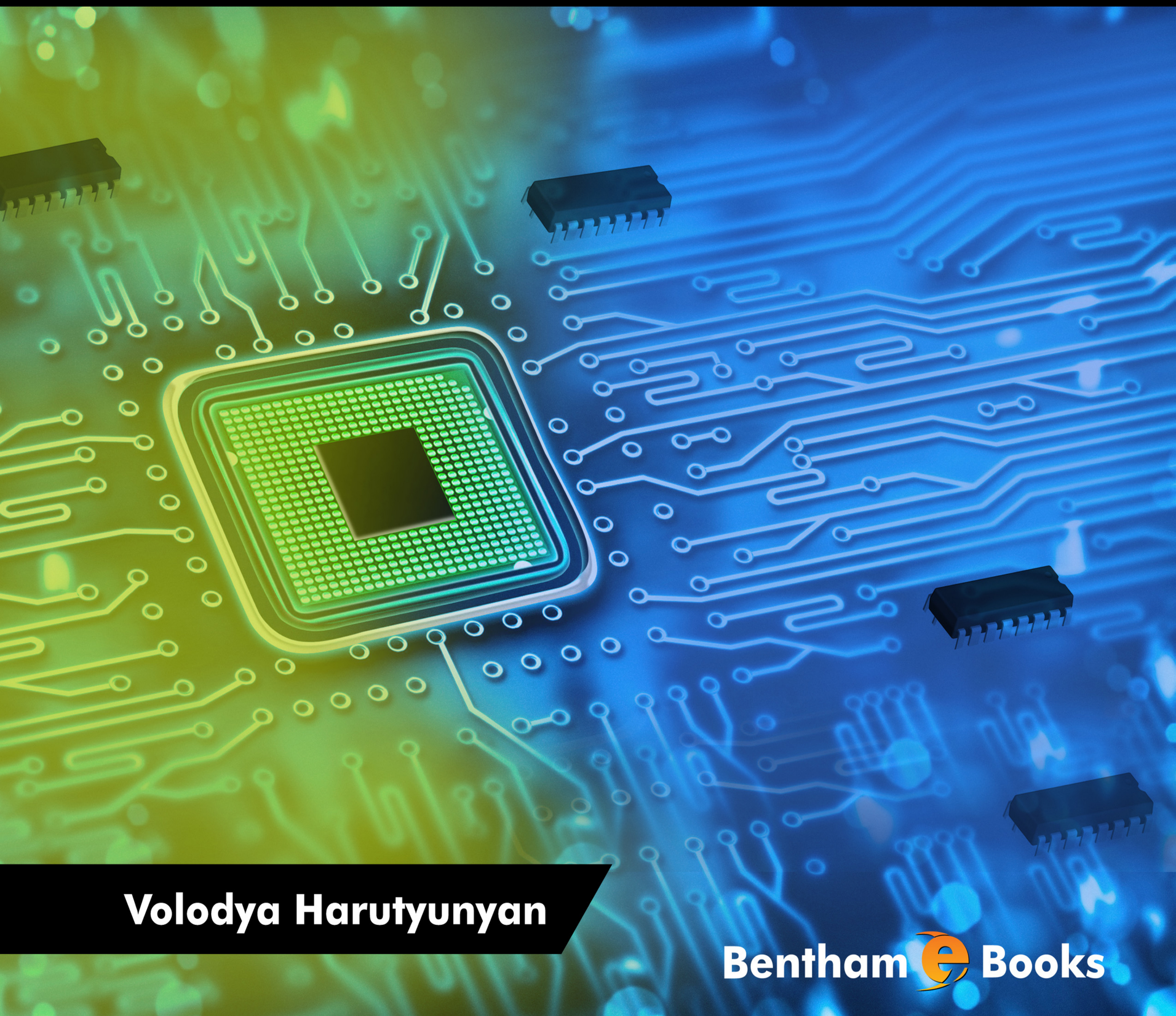
Effect of Static Electric Fields on The Electronic and Optical Properties of Layered Semiconductor Nanostructures

PART I: Effect of Static Electric Fields on The Electronic Properties of Layered Semiconductor Nanostructures



Volodya Harutyunyan

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Effect of Static Electric Fields on The Electronic and Optical Properties of Layered Semiconductor Nanostructures

Part I: Effect of Static Electric Fields on The Electronic Properties of Layered Semiconductor Nanostructures

Authored By

Volodya A. Harutyunyan
Department of General Physics and Quantum Nanostructures,
Russian-Armenian (Slavonic) University,
Yerevan, Republic of Armenia

Bentham Science Publishers Ltd.
Executive Suite Y - 2
PO Box 7917, Saif Zone
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Email: subscriptions@benthamscience.org

CONTENTS

FOREWORD

The book presents the results of theoretical studies of the effects of uniform and radial electrostatic fields on the single-particle states of charge carriers in low-dimensional semiconductor structures: quantum films and cylindrical and spherical quantized layers. The investigations are conducted within the framework of the effective mass approximation. Depending on the geometrical parameters of the sample and the intensity of the external field, various quantum mechanical approximate approaches are used in the computations: the adiabatic approximation, perturbation theory, variation method, and semiclassical approximation. For all the problems considered, the final solutions are obtained in an explicit analytic form. The book is intended for specialists in the field of low-dimensional semiconductor physics.

"Effect of Static Electric Fields on The Electronic And Optical Properties of Layered Semiconductor Nanostructures"

Dr. Valeri G. Grigoryan
Wiss. Angestellter/Staff Scientist
Physikalische und Theoretische Chemie
Universität des Saarlandes
Postfach 15 11 50
D-66041 Saarbrücken
Germany

PREFACE

Usually, when writing such books, authors necessarily note that the purpose is "…to make academic research more available to a wider audience".

By "wider audience" for which this book can be of real interest, the author assumes senior students, undergraduates, graduate students and other young researchers in the field of physics of low-dimensional semiconductors.

In accordance with it the selection, systematics and presentation of the material are made.

The book presents a theoretical approach to the problems associated with the influence of static electric fields on the state of charge carriers in the quantum wells of semiconductor layered structures with different symmetry. The quantized film, cylindrical nanotube and quantum dot-quantum well structure with spherical symmetry are considered in the capacity of test samples. The homogeneous and radially symmetric electrostatic fields are considered as an external influence on the sample.

The relevance of considering such problems is undeniable, since along with the size quantization, the external static electric field is one of the powerful modulating factors affecting the states of quasi-particles in the sample.

Presentation of the material assumes the reader is familiar with the basics of quantum mechanics and the modern theory of semiconductors.

Given today's opportunities in searching and finding the right information, we decided not to encumber the manuscript with multiple links but confine only to the extremely important ones.

In addition, since the basis of the material presented are the scientific publications of the author, the reader can also find the corresponding necessary references in these articles.

The purpose of our theoretical studies, from the methodical viewpoint, will be finding for the problems considered solutions in an explicit analytic form.

The author will be grateful for comments and suggestions by the readers.

CONFLICT OF INTEREST

The author confirms that this book contents have no conflict of interest.

ACKNOWLEDGEMENTS

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V.A. Harutyunyan
Department of General Physics and Quantum Nanostructures,
Russian-Armenian (Slavonic) University,
Yerevan, Republic of Armenia.
volharut@gmail.com

CHAPTER 1

Single-Electron States in Quantum Well (Quantum Film) in the Presence of External Uniform Electrostatic Field

Abstract: External static electric fields are one of the powerful modulating factors that may significantly affect the quasi-particle states in low-dimensional semiconductors. In this chapter we will consider the influence only of the external uniform electrostatic field on the sample. The change of charge carriers' states under the influence of a uniform electric field which is directed along the quantization axis of the system in low dimensional semiconductors was first examined in semiconductor quantized films. From a purely physical point of view, the essence of this phenomenon is the following: a uniform external field applied along the quantization axis alters the profile of the bottom of the quantum well and in a certain way modifies both the energy spectrum of the charge carriers and their wave functions. Under the influence of the field the coordinate of the center of gravity of the electron cloud in quantum well is shifted, thereby the area of overlap of wave functions is also changed. Under the influence of the field also the shift in the energy levels of the charge carriers in the well takes place (quantum-confined Stark - effect). In this chapter we present analytical calculations for the energy spectrum and the envelope wave functions of single-electron states in a quantum well in the presence of a uniform electrostatic field transversal to the plane of the well. Calculations are performed for three different intervals of the external field in which we conventionally define the field as "weak", "moderate" and "strong".

Keywords: Analytical solution, Boundary conditions, Charge carriers, Effective mass, Energy spectrum, Moderate field, Numerical calculation, Perturbation theory, Probability distribution, Quantum film, Quantum well, Space separation, Stark-effect, Strong field, Strong quantization, Uniform field, Variation method, Wave function, Weak field, WKB-method.

INTRODUCTION

The study of low-dimensional semiconductor structures has both fundamentally scientific and purely practical meaning, and that is dictated by the needs of rapidly

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progressing modern nanotechnology [1 - 9]. Various representatives of this low-dimensional quantum "family" are (and will be) the basis for the design of solid-state semiconductor electronic devices [10 - 16]. From this point of view, the quasi-two semiconductor quantum structures with one-dimensional quantum well (QW), in particular, the quantized semiconductor films (QFs) can be considered pioneers in this field. In quantum wells based on thin semiconductor films, the size quantization along one direction leads particularly to the appearance of new properties of a two-dimensional sub-system of charge carriers, completely differing from the case of a bulk sample, that may be explained by their wide application in various quantum equipments as an active element [17 - 28].

Simultaneously, as is well known the static external electric field, along with the geometric characteristics of the system, is one of the most powerful modulating factors enabling purposeful control of the energy spectrum of the charge carriers and other characteristics of the band structure of the size-quantized semiconductor structures [22 - 24, 29, 30]. In this sense, quantum wells – quantum films again are kind of pioneers. It is on these structures that the effect of a uniform electric field on the states of charge carriers in the conditions of quantum size effect was first considered [22 - 24, 29 - 41].

The specific behavior of charge carriers in these physical conditions (size quantization plus the electric field along the axis of quantization) pretty quickly gained wide use of device application: infrared photodetectors, optical filters, high-speed optical modulators, optical switches, and a number of other devices for receiving and processing of signals [42 - 48]. The investigation of these physical systems intensively continues also at present [49 - 57]. And it definitely means that the investigation of the effects of a uniform electric field on the state of charge carriers in the quantum well is of particular interest today both in purely scientific and application aspects. Let us also try to join in the process.

GENERAL APPROACH TO THE PROBLEM

This paragraph is actually an introduction to the subsequent presentation, therefore we will consider the problem here in more detail. It is well known, that one of the most common physically adequate models for the semiconductor quantized film (QF) is the approximation of an infinitely deep potential well [22 - 24]:

$$U^{(0)}(z)=\begin{cases}\infty; & z\le 0, z\ge L\\ 0; & 0<z<L\end{cases} \tag{1}$$

Here z is the coordinate along the direction of size quantization, and L is the width of the well (the film's thickness) (Fig. **1**). We will hold further discussions within the framework of this model. In the future, we will always assume that the film thickness L is much smaller than the bulk exciton Bohr radius (a_{ex}) in the film material:

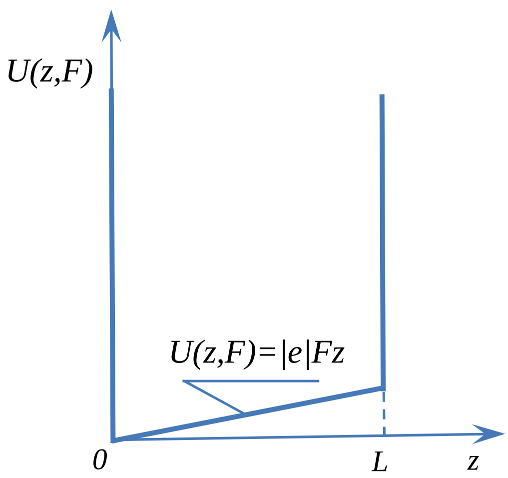

Fig. (1). Profile of the potential well in QF in the presence of a uniform electrostatic field $\vec{F}=\vec{F}(0,0,F)$ for a negative charged particle ($q=-|e|$).

$$L \ll a_{ex} \tag{2}$$

i.e. the problem is solved in an environment when a "strong quantization regime" is implemented in the film. From the energy point of view, this means that the energy of Coulomb interaction between the electron and the hole in this sample (by order $\hbar^2/2\mu a^2_{ex}$) is much smaller compared with the energy of size quantization (by order $\hbar^2/2\mu L^2$) of charge carriers in QW: by order $L^2/a_{ex}^2<1$. In the framework of this approximation for the unperturbedenergy levels $E_n^{(0)}$ and envelope wave

CHAPTER 2

Single-Electron States in Cylindrical Nanolayers in the Presence of External Uniform Electrostatic Field

Abstract: In this chapter, we "curl up" the quantized semiconductor film into a tube. As a result, we obtain the quantized semiconductor nano-cylindrical layer or, as it is also called, a semiconductor nanotube (SNT). Thereafter, we investigate theoretically the influence of lateral uniform electrostatic field on the energy spectrum of charge carriers in this SNT. We first consider the single-particle states in SNT in the absence of an external field. Investigation was conducted at different ratios between the thickness of the layer and its inner radius. Explicit expressions are obtained for the energy spectrum and envelope wave functions of single-particle states in the layer in the absence of an external field. After that the states of charge carriers in SNT in the presence of weak (perturbing), moderate and strong electrostatic fields are considered in each case separately. For each of these cases the corresponding theoretical approach is presented and explicit analytical expressions are obtained for the energy and particle envelope wave functions of charge carriers in the nanotube in the presence of a perpendicular to the axis of symmetry of the system uniform electrostatic field. If necessary, the analytical results are also compared with the results of numerical calculations. An explicit dependence of the Stark splitting on the geometric dimensions of the sample and the intensity of the external field are obtained. On the example of InSb cylindrical nanolayer the behavior of the charge carriers in the narrow-gap SNT in the presence of strong lateral electric field is also considered.

Keywords: Adiabatic approximation, Boundary conditions, Cylindrical nanolayer, Effective mass, Energy spectrum, Moderate field, Nanotube, Perturbation theory, Probability distribution, Quantized layer, Quantum well, Space separation, Stark-effect, Strong field, Strong quantization, Uniform field, Variation method, Wave function, Weak field.

INTRODUCTION

Now imagine that the discussed in the previous chapter quantum film, without

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changing its thickness, is rolled up into a cylinder. If the radius of this cylinder is much less than its length, and the thickness of the layer is of the order of a nanometer, then such a structure is called a quantum tube, or nanotube, nano-cylindrical layer *etc*. We will stick to the term nanotube. Such nanostructures of different materials (carbon, polymers, inorganic materials) are currently intensively investigated both theoretically and experimentally.

Around a decade after the discovery of carbon nanotubs [1, 2], first nanotubes made of inorganic semiconducting materials were designed [3 - 13]. The subject of our discussion here will be exactly semiconductor nanotubes (SNTs).

During the last decade along with various low-dimensional structures SNTs are one of the urgent objects of investigation and had been studied extensively both experimentally and theoretically [14 - 25]. SNTs represent a new class of nanotechnology building blocks and the interest in these systems is caused by a number of reasons. SNT is an emerging field and possesses potential to provide a wide range of functionalities. These heterophase structures exhibit novel electronic and optical properties owing to their unique structural one-dimensionality and possible quantum confinement effects in two dimensions. The precise controllability of structural and spatial positioning and versatile functionality make SNTs promising candidates for practical application in next generation nano-electronic and nanophotonic devices. Thus, with a broad selection of compositions and band structures, SNTs are considered to be the critical components in a wide range of potential nanoscale device applications [5, 7, 14 - 18, 20, 21, 26 - 31]. Large surface-to-volume ratios and the possibility of various functionalizations on both the internal and external surfaces make the latter systems also of interest for application in their specific range (for example, in addition to above mentioned optoelectronic devices, in biology and biochemical areas).

Indeed, recently, semiconductor nanotubes have been applied also in improving existing biological and medical devices and in developing novel devices for gene and drug delivery [13, 32 - 36].

With the progress in synthesis and fabrication of different nanomaterials various kinds of tubular structures, such as CdX, HgX (X=S, Se and Te), InGaAs/GaAs, SiGe/Si [37 - 43], ZnO, GaN, AlN, AlGaN, InP/InAs/InP, BN, ZnS, SiGe/SiO [44 - 49], SiGe/Si/SiN/Cr [50] and others, are obtained and attract much attention. It is necessary to note also that one of the distinctive features of SNTs is the compositional dependence of their electronic, structural, optical and have drawn properties [51]. Note that in addition to SNTs with a solid semiconductor core, in the present time hollow SNTs are grown also, where charge carriers are confined in a thin semiconductor shell [16, 44, 51 - 54].

Various effects, which have no equivalent ones not only in the bulk sample but in the planar geometry, have been discovered in SNT. On the other hand SNTs synthesize and combine a number of physical characteristics of quantum wires (QWs), quantum films (QFs) and quantum rings (QRs).

At the same time, let us recall again that the electronic, kinetic, optical and a number of other physical properties of low-dimensional structures (as well as those of bulk samples) are strongly affected by external electrostatic fields. In this chapter, we consider the influence of an external uniform electrostatic field on the states of charge carriers in SNT.

SINGLE-PARTICLE STATES IN CYLINDRICAL NANOLAYER IN THE ABSENCE OF EXTERNAL FIELD

General Approach and Approximations

We note at once that all calculations will be made in the framework of a simple two-band model in the effective mass approximation.

In the direction of axis of symmetry (z) the system will be treated as unlimited. It is known that in these quasi-one-dimensional systems the energy and envelope wave functions of charge carriers along the symmetry axis are defined by the following expressions [55 - 59]:

$$E\left(p_z\right)=\frac{p_z^2}{2\mu}; \quad \psi\left(z\right)\sim\exp\left(\frac{i}{\hbar}p_z\right) \tag{95}$$

Here p_z is the particle quasi-momentum along the z- axis, and μ is the isotropic

CHAPTER 3

Single-Particle States in a Cylindrical Nanolayer in the Presence of External Nonuniform Electrostatic Fields

Abstract: The single-particle states in a semiconductor cylindrical nanolayer (nanotube) in the presence of lateral-radial electrical field are considered. It is assumed, that the regime of strong quantization for radial motion of charge carriers in the nanotube takes place. The explicit analytic forms of the energy spectrum and envelope wave functions of the single-electron states are obtained in the cases of weak and strong radial electric fields, respectively. The comparison of results of analytical and numerical calculations is carried out. The degree of agreement of these results shows the adequacy of the choice of such theoretical approach for the solution of the considered problems. The single-particle states in a wide-gap semiconductor cylindrical nanotube placed in the field of a uniformely charged ring are considered theoretically in the effective-mass approximation. It is shown, that the electrostatic field of the charged ring creates in the tube an additional quantum well along the symmetry axes of the system. It is shown also, that this quantum well can be described as one-dimensional modified Coulomb-like potential. By using a variation-method the wave functions and energy levels of the first two states of charge carriers in this well were obtained. The electronic states are considered for the narrow gap InSb nanotube in the field of homogeneously charged ring. The problem is also solved in the framework of the variational approach. Energy spectrum and wave functions for heavy and light charge carriers in the presence of charged ring's field are obtained in the explicit analytical form.

Keywords: Adiabatic approximation, Boundary conditions, Charged ring, Coulomb potential, Cylindrical nanolayer, Effective mass, Energy spectrum, Nanotube, Non-uniform field, Perturbation theory, Probability distribution, Quantized layer, Quantum well, Space separation, Strong field, Strong quantization, Variation method, Wave function, Weak field, WKB-method.

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INTRODUCTION

In the previous **CHAPTER**, we noted that the semiconductor nano-layered cylindrical structures are currently objects of quite intensive research (see References [1 - 4] in **CHAPTER 2**) and examined the influence of an external uniform electrostatic field on the states of charge carriers in SNT. It is clear that of certain interest is the study of the modulating effect on such layers not only of uniform but also inhomogeneous electrostatic fields. In this chapter, we will continue consideration of the modulating effect of external electrostatic fields on the semiconductor nanotube. We will discuss the effect of two types of non-uniform electric fields on the single-particle states of charge carriers in the semiconductor nano-cylindrical heterolayer: radial electrostatic field, when the source of the field is located along the axis of symmetry of the system and the field of a uniformly charged ring whose axis coincides with the axis of symmetry of the system.

The action of the radial electric field on the state of the semiconductor was considered in connection with the piezoelectric phenomena [1, 2], in optoelectronic emitters [3] and in the study of distribution of charge and of carrier density in streamer channel [4]. The radial electric field effect in a coaxial cylindrical capacitor configuration was used to study the modification of transport and thermoelectric properties of semiconductor microwires [5, 6]. In Refs. [7, 8] the states of impurity center in a semiconductor quantum ring in the presence of a radial electric field are studied theoretically. In a number of works by the author and coauthors the effect of the radial electric field on the electronic and optical properties of semiconducting nanotubes are examined [9 - 15]. We could not find any literature on the action of the electrostatic field of a charged ring on the states of the charge carriers in the semiconductor nanotube. So, leaving aside modesty, apparently it can be assumed that the work of the author and coauthors [16 - 18] so far are the only publications on the subject.

We proceed now to the consideration of the problems.

GENERAL APPROACH AND PHYSICAL MODEL

We want to investigate the influence of lateral radial electrostatic field on the electronic properties of a direct-band and wide-gap SNT in the regime of "strong quantization"; that is, the following problem will be considered: the modification of single-particle energy spectrum of charge carriers in SNT under radial electrical field perpendicular to the symmetry axis of the system.

We assume that the considered system core/layer/clad (medium) is infinite along the symmetry axis (z), just as in the case of a "usual" quantum wire, and the relations between the physical characteristics of composition's components allow us to approximate a layer in the radial direction (r) by an infinitely deep potential well "rolled up into a tube" (see **CHAPTER 2**, Exps. (96) - (100)). The role of "source" of the radial field in this system is played by the homogeneously charged core of the composition.

The electrostatic potential in this case, as is known, has a logarithmic dependency on the radial variable [19].

Correspondingly, for the potential energy of charge-carriers in the layer we can write now:

$$U(r)=\begin{cases}\infty; & r<R_1;\ r>R_2;\\ \gamma\ln\dfrac{r}{R_1}; & R_1\le r\le R_2;\end{cases} \tag{214}$$

where R_1 and R_2 are the inner and outer radii of the layer respectively, and γ is the "interaction constant" between the "source" of the field and charge carrier. At the same time, we assume that within the limits of the layer the regime of "strong quantization" takes place for charge carriers, which are expressed by the condition

$$L \ll R_1;\ L \ll a_L, \tag{215}$$

Here $L= R_2-R_1$ is the layer thickness and a_L is the Bohr radius of a bulk exciton in the layer's material. As it is noted,from the point of view of fulfillment of the regime of strong quantization in the layer one can consider as typical, in

CHAPTER 4

Quasy-Two- and Quasy-One-Dimensional Excitons in Uniform Electric Field

Abstract: The states of interacting electron-hole pair in semiconductor nanotube in the presence of strong lateral homogeneous electric field are considered theoretically. It is shown in single-particle approximation that along with the size-quantization of charge carriers' motion by the radial direction the external strong electric field leads to the additional (field) localization of particles also by the angular variable. At the same time the strong external field polarizes the electron–hole pair and traps them on the opposite ends of tube's diameter. Consequently, the excitonic complex with transversal dimensions of the order of the system's diameter is formed in a nanotube. By using the variation approach the binding energies and wave functions of the first two states of such field exciton-like complex (FELC) in the tube are calculated. The specificities of interacting electron-hole pair states in semiconductor quantum ring in the presence of strong lateral homogeneous electrostatic field are also considered. The influence of the longitudinal uniform electrostatic field on two- dimensional and one-dimensional excitonic states in the quantum film and quantum wire are considered, respectively. In the quasiclassical approximation the probabilities of ionization of two-dimensional and one-dimensional excitons under the influence of a longitudinal external electric field are calculated. The dependence of the ionization probability on the external field strength is obtained in the explicit analytical form. The results show that when the dimensionality of the system is reduced, the dependence of the exciton ionization probability on the value external field as compared to the three-dimensional case is weakened.

Keywords: Adiabatic approximation, Boundary conditions, Coulomb interaction, Cylindrical nanolayer, Effective mass, Energy spectrum, E-h pair, 1D-exciton, 2D-exciton, Ionization, Longitudinal field, Quantum well, Quantum wire, Quasiclassical approximation, Strong field, Strong quantization, Transversal field, Uniform field, Variation method, Wave function.

INTRODUCTION

In semiconductors, as it is known, due to the Coulomb interaction the electron and

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hole can be linked to a hydrogen-quasiparticle complex - exciton [1 - 5]. In the future we mean only large-radius excitons, *i.e.* Wannier-Mott excitons [1 - 5].

When electron-hole interactions are considered, a large number of bound electron-hole states are found within the gap [1 - 5]. These states, called excitons, play a large role in determining the optical and other properties of semiconductors. Namely by taking into account the excitonic effects and considering the interaction of excitons with other quasiparticles in the crystal, the most complete description of some properties of the system can be reached.

In this regard, the electronic structure of excitons, their interactions with phonons and photons, and their further role of transporting excitation energy have been intensively investigated and discussed for several decades [1 - 18]. Furthermore, by considering the statistical ensemble of excitons it is possible to describe a number of collective properties of the electron-hole subsystem at high excitation levels and quantum-degenerate states of the semiconductor [19 - 23].

The energy spectrum of the exciton has a hydrogen-type character [1 - 5]. However, unlike a “conventional” hydrogen atom, an exciton is one of the possible excited states of the crystal and naturally has a finite lifetime. Besides, in nature, as is known, *2D* and *1D* atoms do not exist. However, in semiconductors with decreasing of the dimension of the system the dimension of the exciton is also reduced [24 - 35]. In *2D* and *1D* semiconductors, for example, in the case of strong quantization electron and hole are bounded to *2D* [36 - 46] and *1D* [47 - 57] excitons, respectively.

Low-dimensional semiconductors have become a vital part of today's semiconductor physics, and corresponding low-dimensional excitons in these systems are ideal objects that bring textbook quantum mechanics to life. Furthermore, their theoretical understanding is important for relevant experiments and using these structures in optoelectronic devices.

From this perspective, apparently the consideration of the action of an external electric field on the exciton states in low-dimensional semiconductors is an important and necessary step in the study of the properties of semiconductor quantum structures. Indeed, in a number of studies in various aspects the action of an external electric field on the *2D* [10, 26, 29, 44, 58 - 64] and *1D* [32, 65 - 75] exciton states in low-dimensional semiconductors is considered.

In this Chapter, we examine the effects of a strong transversal uniform electric field on the exciton states in a semiconducting nanotube [76] and nanoring [77] as well as the influence of the longitudinal uniform electric field on the exciton states in quantum film [78, 79] and quantum wire [80].

SEMICONDUCTOR NANOTUBE IN STRONG UNIFORM ELECTROSTATIC FIELD TAKING INTO ACCOUNT THE ELECTRON-HOLE INTERACTION

In all the previous problems, we did not consider the interaction between the electron and the hole. In the case of SNT for the motion in the plane(x,y)(or (r,φ)) it is a direct result of the geometrical configuration of the considered system:

$$L << a_L; \quad L << R_1 \tag{298}$$

i.e. under the conditions (298) a strong quantization regime holds laterally, and the Coulomb interaction between electrons and holes here really can be neglected.

However, for a more accurate overall solution of the problem we must take into account the electron-hole interaction in the SNT along the z-axis. Indeed, because in this direction nothing prevents the electrons and holes interaction with each other. As a result of this interaction a quasi-one-dimensional excitonic state is formed in the SNT [34, 35, 76]. In this section we investigate the influence of a lateral strong electrostatic field on the quasi-one-dimensional excitonic states in SNT [76].

Interacting Electron-hole Pair in the Tube: Modeling Approach and Schrodinger Equation

As before, the system we consider is an infinite tube (along the z-axis) with cylindrical symmetry. We will take into account the actual thickness of the heterolayer and will not neglect the actual radial confinement of charge carriers . It has been assumed that the confinement potential of quantized heterolayer of the

CHAPTER 5

Spherical Nanolayers in Uniform and Radial Electrostatic Fields

Abstract: In the strong quantization regime the single-particle states in quantum heterostructures core/layer/clad in conditions when the localization of charge carriers in the layer-component of composition takes place, are considered. Investigation was conducted both in the absence of an external field and in the presence of weak and strong homogeneous electrostatic fields as well as when the radially symmetric electric field is present. In the case of weak fields the confinement Stark effect in the layer is considered. Correspondingly, the energy shifts of the radial and orbital motions of charge carriers in the layer and corresponding perturbated envelope single-electron wave functions are calculated under the external homogeneous electrical field. The calculations are carried out separately for both cases of perturbation of the radial and orbital motions of charge carriers in the layer. The influence of a strong homogeneous electric field on the states of charge carriers in the structure of quantum dot-quantum well (QDQW) is studied theoretically. It is shown that a strong external field changes radically the character of carrier motion in the structure and leads to an additional field-localization of the particle along the polarangle variable. An explicit form of the wave functions and energy spectrum of single-particle states in the structure in the presence of an external field is obtained. The possibilities of experimental and operational applications of the theoretical results obtained for the study of core/layer/shell structures as well as of hollow spheres are also shown. Explicit analytical expressions for the energy spectrum and the envelope wave functions in the presence of a source of the radial electrostatic field in the center of the heterostructure are obtained. The quantitative estimations for concrete CdS/HgS/CdS structure are given as well.

Keywords: Adiabatic approximation, Boundary conditions, Effective mass, Electric field, Energy spectrum, Moderate field, Perturbation theory, Probability distribution, Quantized layer, Quantum dot, Quantum well, Radial field, Space separation, Stark-effect, Strong field, Strong quantization, Uniform field, Variation method, Wave function, Weak field, WKB-approximation.

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INTRODUCTION

In the previous chapters we have studied semiconductor nanostructures (layered) like the quantum film and the semiconductor layer nanocylindrical layer (SNT). The rapid progress in the techniques of semiconductor material growth makes it possible to fabricate various quantum nanostructures. Research on semiconductor nanoparticles has become a wide and interdisciplinary field of science over the last two decades. Recently, a class of new and promising heteroquantum dots with spherical configuration, termed quantum-dot quantum - wells (QDQW's), have been successfully synthesized and studied extensively both theoretically and experimentally [1 - 15]. The quantum-dot quantum-well nanostructure is composed of two semiconductor materials one of which, with the smaller band gap (layer, inner shell) is embedded between a core and outer shell (clad) of the material with the larger band gap. In this composition, the material with a narrow band gap (layer) for charge carriers is the quantum well, and the material with a wide band gap (core and outer shell-clad) plays the role of potential barriers. The nano-heterostructure CdS/HgS/CdS is undoubtedly the "old-timer" and the "classic" in the QDQW family. It was prepared two decade ago [16 - 19] and has been intensively studied to this day [20 - 27]. Later, the preparation of many other QDQWs was reported (CdS / CdSe / CdS [28], ZnS / CdS/ ZnS [29], ZnS / CdSe / ZnS [30], GaN / InGaN / GaN [31], CdSe / HgSe / CdSe [32], CdTe / HgTe / CdTe [33], *etc*.) which have also been intensively studied [34 - 42].

The original characteristic of these core/layer/clad composite QDQWs is that their physical properties can be controlled and tuned by changing the core radius, the thickness of the layer (the width of the well) and the size of outermost shell (clad). These QDQW's have internal nanoheterostructures with a quantum-well region contained inside the quantum dot. In particular, these spherical composite multilayered nanoparticles exhibit higher quantum efficiencies in different aspects than single material based nanoparticles, due to the tighter quantum confinement effect of the charge carriers. These complex quantum structures have recently attracted a great deal of attention due to their potential application involving electronic and optical devices [1 - 42] and in the fields of contemporary medicine and biology [43 - 46]. Just as in the case of "classical" nanostructures (planar quantum wells, quantum wires, quantum dots, quantum rings *et al*.), it is of certain interest also to study the modulating influence of external static fields on the properties of electronic subsystem QDQW structures. Indeed, in such heterostructures, along with the geometric dimensions and chemical composition of the sample components, the external electrostatic fields, in particular, will have an important modulatory effect on the system. In this chapter, we examined the effects of uniform and radial electrostatic fields on the single-particle states of charge carriers in spherical QDQWs [47 - 53].

SINGLE-PARTICLE STATES IN THE SPHERICAL NANOLAYER IN THE ABSENCE OF EXTERNAL FIELDS

The General Approach and Approximations

In all subsequent theoretical calculations in this chapter, as spherical QDQW we will mean the composition *CdS/HgS/CdS*. It is clear from the inherent characteristics of the structure (see Table **7** Chapter 2) that the layer of *HgS* in the composition core/shell (layer)/clad can be approximated with high accuracy by an infinitely deep potential well "folded" into a sphere. Later, we were interested in the status of the charge carriers namely in this potential well –in the *HgS*-quantized spherical layer (QSL) of the structure *CdS/HgS/CdS* QDQW (Fig. **35**).

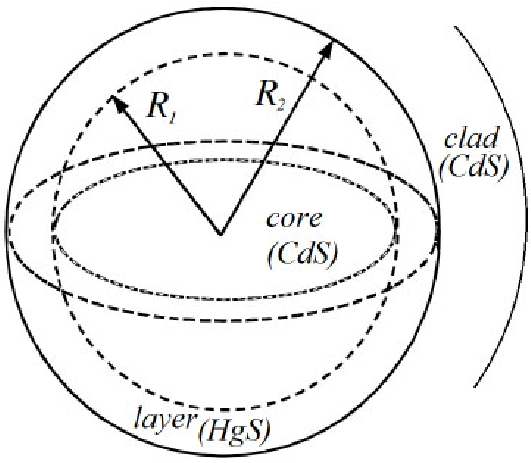

Fig. (35). *CdS/HgS/CdS* core/layer/clad QDQW heterostructure.

Indeed, the photophysical measurements in *CdS/HgS/CdS* [20, 54, 55] and the

SUBJECT INDEX

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