

# ON THE MAIN APPLICATION PROPERTIES OF THE QUANTUM CONFINED STARK EFFECT

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**Abstract:** The present work is motivated by the tremendous interest in the semiconductor nanostructures. The study of the quantum confined Stark effect (QCSE) in semiconductor superlattices and semiconductor quantum wells has attracted a lot of attention, as it is important both for fundamental physics and in devices for optoelectronic applications. The present paper is a brief review of the main electronic properties, which are the basis for the QCSE device applications of semiconductor superlattices and semiconductor quantum wells.

**Keywords:** QUANTUM CONFINED STARK EFFECT (QCSE), ELECTRONIC STATES, SEMICONDUCTOR QUANTUM WELLS, SEMICONDUCTOR SUPERLATTICES, DEVICE APPLICATIONS OF QCSE, SEMICONDUCTOR NANOSTRUCTURES, ELECTRIC FIELD EFFECT, OPTICAL PROPERTIES

## 1. Introduction

Semiconductor nanostructures and particularly, double heterostructures, including superlattices, quantum wells, quantum wires, and quantum dots, are today the subject of research of two-thirds of the semiconductor physics community [1]. In modern age, the low-dimensional semiconductor nanostructures find practical applications in all important fields of industry and in our daily life. Some of the references include [1-16]. Modern electronic and optoelectronic devices are approaching nanometric dimensions and employ semiconductor nanostructures. As example, electronic devices based on quantum wells (QWs), such as the high electron mobility transistor, have shown outstanding performances, pushing the cut-off frequencies up to several hundred of GHz. Long-wavelength lasers for modern telecommunications have active regions with a sequence of QWs obtained from the heterojunction of two or more semiconductors.

Today, investigation of the electric field dependence of electronic and optical properties in semiconductor nanostructures, namely, semiconductor superlattices (SLs) and semiconductor quantum wells (QWs), is of great interest. This is mainly due to their actual and potential applications in various electro-optical devices, and thus the possibility to optimize nanostructure-based devices. Atomistic approaches become necessary for modeling structural, electronic and optical properties of such nanostructures and nanostructured devices [2].

In this paper we will make a brief survey of the most distinguished electronic and excitonic properties, which are the basis for the QCSE device applications of the quantum well (QW) structures (SLs and QWs).

## 2. The Stark effect – definition and description

The effect of an external constant electric field  $F$  on the energy electron states of quasi two dimensional electron gases or QW structures is one of the most common definitions of the QCSE (or Stark effect) [3,4].

Under application of a static electric field perpendicular to the QW layers, the energy levels are shifted (Stark shifts) from their zero-field positions (see Fig. 1) which is the QCSE (see Fig. 2).

There are two kinds of QCSE in QWs, depending on direction of applied electric field  $F$ :

- longitudinal QCSE.  $F$  is parallel to the growth axis / perpendicular to QW layers;
- transverse QCSE.  $F$  is perpendicular to the growth axis.

The transverse field problem is similar to the bulk problem and excitonic transition disappears at low field ( $< 10$  kV/cm). The

absorption edge shifts to lower energy as in the bulk problem. Therefore here we will pay attention only to the longitudinal QCSE.

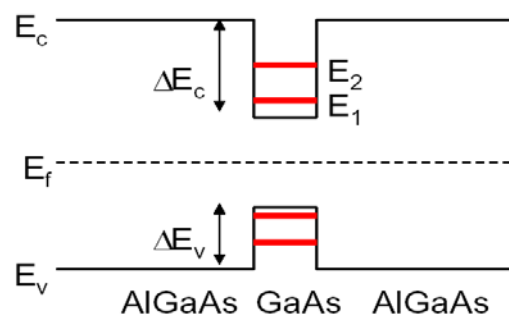


Fig. 1 Energy levels in  $Al_xGa_{1-x}As/GaAs/Al_xGa_{1-x}As$  QW without application of  $F$ .

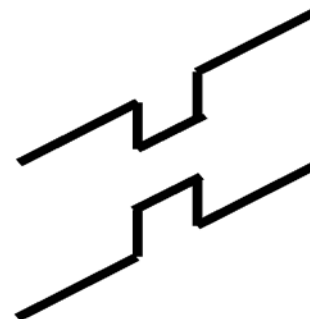


Fig. 2 QCSE in a QW. The distortion of the QW potential with applied electric field  $F$ .

The study of the QCSE when a constant longitudinal electric field  $F$  is applied to the QWs has attracted much attention both experimentally and theoretically [1-16], as it is important both for fundamental physics and in devices for optoelectronic applications. The detailed knowledge of the electronic and consequently optical spectra in QWs is quite essential to understand their device applications, for understanding the operating principles of the devices, based on the QCSE application. The theoretical and experimental methods and techniques for investigation of QCSE in QW materials are presented in many papers in the contemporary literature on the subject.

Some of the experimental techniques employed in measurements of QCSE and energy level Stark shifts in QWs are: picosecond luminescence, absorption current spectroscopy, electroabsorption, photoluminescence spectroscopy, electroreflectance and time-resolved photoluminescence [5-11].

The QCSE is an entirely quantum mechanical effect and it can not be explained classically.

The QCSE can be understood on the basis of the same formalism as the one discussed for the exciton and band to band transitions in absence of the electric field as long as one can assume that the QW subband levels are reasonably confined states. In principle, the QW states are quasi-bound states in the presence of the field with the wavefunction primarily peaked in the QW region. In the addressing exciton problem one assumes that the subband states are localized in the well and the exciton can be made up of only the confined states. There are several effects that occur in the presence of the longitudinal electric field:

1. The intersubband separations change. The field pushes the electron and hole functions to opposite sides (towards each band edge) making the ground state intersubband separation smaller. This effect is the dominant term in changing the exciton resonance energy.

2. Due to the separation of the electron and hole wavefunction, the binding energy of the exciton decreases (ground-state exciton peak energy decreases without severe line broadening of the exciton resonance).

When near bandgap light is shone on the QW structure, excitons are formed between the QW valence and conduction subbands. We shall be above all concerned with the lowest lying heavy hole ( $E1-HH1$ ) and light hole ( $E1-LH1$ ) excitons. The electric field polarizes  $E1$  and  $HH1$  ( $LH1$ ) along opposite directions and thus weakens the excitonic binding. However, the exciton association is considerably hindered by the conduction and valence potential barriers. In other words, the optical absorption near the bandgap energy can be shifted to lower photon energies (red shift) without destroying the strong excitonic features.

The electric fields as large as 500 kV/cm can be applied to QW structures without destroying the excitonic binding. In semiconductor QWs and SLs, sharp excitonic absorption peaks are clearly observed even at room temperature. When an electric field is applied perpendicular to the QW layers, the energy of the fundamental absorption edge shifts by a large amount without severe broadening of the exciton resonance. These properties enable one to utilize QWs for high-performance room temperature optoelectronic devices. This improved excitonic stability, which leads to peaked structures in the absorption coefficient, is accompanied by a tunability of the excitonic resonance energy.

It is interesting to note that some peculiarities occur when one applies electric field on the absorption spectra of the QW structures [12]. In that case not only the  $HH1$  and  $LH1$  exciton shift to lower energy, but some of the forbidden transitions become observable. At the same time, electric field makes some of the allowed transitions stronger or weaker.

The attempts to increase the exciton energy shift for a given applied field have involved more complex structures, particularly graded gap QWs, double QWs, delta-doped QWs, etc.

Moreover, to improve the performance of these optical devices, band structure modifications in QWs have also been investigated. The electric field effects on the graded-gap QW structures, where the band gap of the well is inclined along the growth direction, are one of the most promising among the modifications for applications of making various fast optoelectronic devices [1,12-15]. The modification of the well potential shape can create different optical properties and thus optimize nanostructure-based devices.

The graded gap QWs were proposed in order to improve the Stark effect characteristics of the conventional rectangular QWs. The goal was to obtain a wider electric field region where the oscillator strengths are significantly large without any significant decrease of the Stark shifts. In the other words: from device point of view, it is desirable to have QW structures with a high absorption coefficient and a large Stark shift under low driving bias. The most

investigated with varying composition graded gap QWs are of the systems  $Al_xGa_{1-x}As/GaAs$ . When we consider compositional graded gap QWs of the system  $Al_xGa_{1-x}As$ , the employed Al-concentration profiles are linear or parabolic. Besides Al - concentration profiles, i.e. composition, the other structural parameters of the QWs also play a significant role on the QCSE in the QW. For example: the widths of the QWs and the type of the barriers.

The theoretical description of semiconductor nanostructures is of crucial importance since it allows us both to investigate fundamental physics and to optimize nanostructure-based devices. The capability of theoretical techniques to investigate and to predict physical phenomena concerning nanostructures is essentially related to the possibility of applying these techniques to treat the nanostructures which are usually composed by a large number of atoms. Theoretical calculations of the QW electronic structure in the presence of an electric field may include or may not include excitonic and temperature effects. The reason for these simplifications is that the main source of the red-shift of the exciton resonance is the field dependence of  $E1(F) + HH1(F)$ . These results play an essential role in searching and developing of new ideas for QW device applications.

Traditionally, nanostructures are studied via  $k,p$  approaches in the context of the envelope function approximation (EFA) [2]. In this case, only the envelope of the nanostructure wave function is described, regardless of atomic details. Modern applications, however, push nanostructures to dimensions and geometries where EFA may not be as accurate as required. Nowadays, advanced ab initio density functional approaches can be applied to describe systems with thousands of atoms. Such high-level description, however, requires large parallel supercomputer facilities which may not be suitable for routine structure and device simulations. Thus, the use of an intermediate level approach which improves the description of the system, i.e. leading to ab initio results (a complete quantum mechanical description based on a full band approach), but with a complexity similar to the  $k,p$  EFA, is highly required. Moreover, the charge rearrangement induced by the presence of electric fields should be considered for a realistic description of nanostructures and nanostructured devices.

Two basic methods have been proposed for atomistic nanostructured description, namely the tight-binding (TB) approach and the empirical pseudopotential method (EPM).

Of particular interest for device applications are the magnitude of the electric field induced changes in the energy levels (Stark shifts energy levels) and localization of the wave function inside the QWs.

In the paper [15] we present a realistic tight-binding (TB) numerical calculation of the energy values for the main bound electronic and hole states as well as their spatial distributions of single  $Al_xGa_{1-x}As$  rectangular and graded gap parabolic concentration profile quantum wells QWs under and without application of a constant electric field applied perpendicular to the interfaces. We have used for numerical calculations the algorithm described and applied in [13,14] for detailed calculations of different graded composition QWs. This algorithm makes possible the application of the SGFM method for matching a final nonhomogeneous region with semi-infinite homogeneous regions. This allows realistic tight TB calculations for electronic states in rectangular and graded composition QWs in the presence of a constant electric field. We describe the presence of an external constant electric field  $F$  perpendicular to the interfaces with shifting of the diagonal terms of the empirical TB Hamiltonian matrix by the corresponding potential drop (in meV) across one monolayer. The width of both QWs is 12,43 nm or  $N=44$  ML. The growth direction is [100]. The Al concentration  $x$  in the barriers is  $x=0.36$ . In the rectangular QW (RQW)  $x$  is  $x=0$ . In the parabolic QW (PQW)  $x$  varies parabolically from 0.02 at the barriers to 0.12 in the middle of the well. The calculated energies include excitonic and temperature effects in comparison with the experimental data.

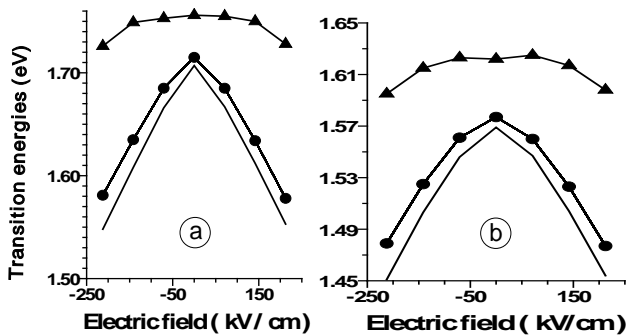


Fig. 1 Transition energies as a function of applied electric field for a) PQW and b) RQW.  $E(C1-HH1)$  - solid line;  $E(C1-LH1)$  - closed circles;  $E(C2-HH2)$  - triangles.

Figure 1 shows the calculated main optical transition energies  $E(C1-HH1)$ ,  $E(C1-LH1)$ ,  $E(C2-HH2)$  without and in the presence of a constant electric field for parabolic(a) and rectangular(b) QWs. For both QWs the transition energies decrease with increasing applied electric field. The transition energies are larger in the parabolic than in the rectangular QWs under application of the same electric field.

Figure 2 and Figure 3 show the total spectral strength spatial distributions for the conduction  $ECl$  and the valence band  $EHHl$  bound states without (a) and in the presence (b) of a constant electric field. The field in Figures 2(b) and 3(b) is  $F = 70.8$  kV/cm. For both QWs there is a complete overlapping of the spatial distributions at  $F=0$ . Both distributions of  $ECl$  and  $EHHl$  have the amplitudes displaced in the same direction in the presence of the electric field, but the displacement for the parabolic QW (PQW) is larger than for the rectangular QW (RQW), which is a result of the concentration profile. At the critical value of the electric field the intensity of the optical transition tends to zero due to the absence of spatial overlap between the states. The critical value of the electric field is a very important characteristic for device application of the QW structure. This is the maximal value of the field, which can be applied to the device. The available experimental data are in a satisfactory agreement with these calculations.

The results obtained here demonstrate that the energy levels in the PQWs are more strongly affected by the electric field than in the RQWs. In this case the PQW has better Stark effect characteristics than the RQW.

The QCSE offers tunable optical response. Modern crystal growth techniques allow the doping of semiconductors down to atomic resolution ( $\delta$ -doping). Impurity atoms give rise to strong confinement (localisation in two-dimensional system) by space charge potential, hence forming a quasi-two dimensional electron gas. The Stark effects in the single and multiple  $\delta$ -doped systems are being intensively investigated in order to study their subband energies mainly because they are substantial for their numerous potential applications in semiconductor devices.

The first TB calculations of the QCSE in Si  $\delta$ -doped GaAs QWs is presented in [15]. We have studied in detail the Stark shifts of the electronic states and their spatial distributions, as well as the subband spectra and intersubband transitions of electrons. The results obtained help to better understand the properties of  $\delta$ -doped QWs with different impurity densities subjected to an electric field with different magnitudes. Such investigations are very promising in looking for  $\delta$ -doped structures that provide good Stark effect characteristics for potential device applications, such as FETs and infrared devices, based on the electron intersubband transitions. The results demonstrate that the TB method can be used to investigate the Stark effect in a double asymmetric QW system, which is interesting for coherent intraband radiation applications.

We conduct realistic numerical TB calculations of the electron bound states, the hole bound states and their spatial distributions without and with applying a various values of the constant

longitudinal electric field  $F$  for four types of RQWs with different depth. We can say that the results from the TB calculations, such in this work, help to study the physics of the nanostructures in the presence of applied electric field intensities. Such investigations that make possible to study in details the Stark shifts of the electronic and hole states and their spatial distributions, the subband spectra and intersubband transitions of electrons, are very promising in looking for quantum well structures that provides good Stark effect characteristics for potential device applications. Such investigation will help us to find a QW potential profile with better Stark effect characteristics. The investigation of the electric field effects on the optical properties of the QW structures with graded gap potential profiles (not conventional RQWs) is essential for the optimization of QW-based devices. The work is in progress in this direction.

Such investigations will help to find a QW potential profile with better Stark effect characteristics. The investigation of the electric field effects on the optical properties of the QW structures with graded-gap potential profiles is essential for the optimization of QW-based devices.

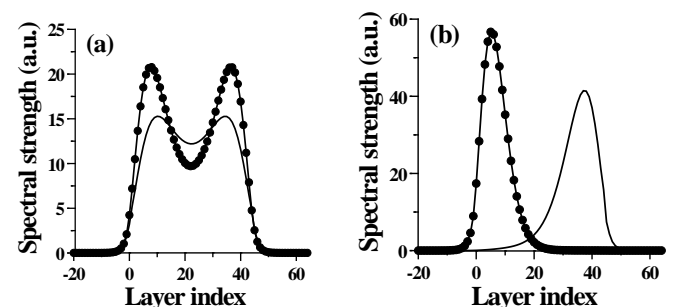


Fig. 2 Spectral strength for PQW, (a) with  $F=0$ , (b) with  $F=70.8$  kV/cm,  $ECl$ (solid line),  $EHHl$  (circles).

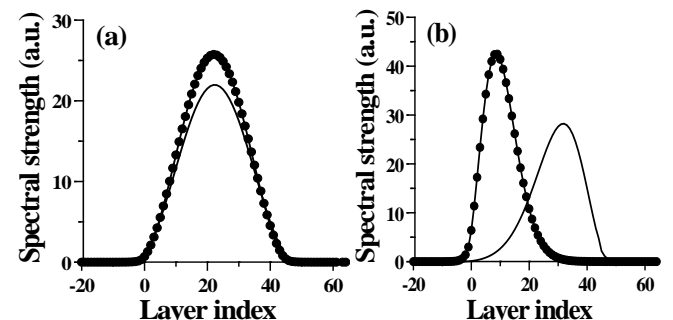


Fig. 3 Spectral strength for RQW, (a) with  $eF=0$ , (b) with  $F = 70.8$  kV/cm,  $ECl$ (solid line),  $EHHl$  (circles).

In the paper [11] were performed electro-absorption experiments on multiple GaAs-Ga<sub>0.68</sub>Al<sub>0.32</sub>As QWs at room temperature. By applying a longitudinal electric field (along the QW growth axes) of approximately 50 kV/cm, the photon energy becomes coincident with the  $E1-HH1$  exciton resonance and the light beam is significantly absorbed. Thus, by switching the field on and off, the beam intensity can be controlled. One advantage of this on-off control is that it can be very fast.

### 3. FINAL REMARKS AND FUTURE WORK

Despite the fact that the QCSE was discovered almost 30 years ago, it still has attracted a lot of attention, due to its diverse actual and potential optoelectronic applications. Nowadays, the QCSE is qualitatively well understood, but there is no complete quantitative solution for the problem so far.

The QCSE operates in the linear absorption regime and uses an applied electric field to modulate the electronic, excitonic and optical properties. It is one of the most promising approaches for optoelectronic intelligent devices. It gives us the opportunity to do the best of optics and electronics.

Both experimental and theoretical studies of the QCSE when a longitudinal electric field is applied to the semiconductor QW structures are quite important for development of device applications. They could facilitate the search for new materials possessing unique electron and optical properties. This review will also help and tremendously facilitate the work of the experimenters and QW crystal growers.

Last but not at least, the Stark shifts of the electronic states and their spatial distributions need to be studied in order to seek unknown and possible QW properties and QW structures for the design of new potential QCSE device applications.

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