ON SOME EXPERIMENTAL STUDIES OF THE QUANTUM CONFINED STARK EFFECT IN SEMICONDUCTOR NANOSTRUCTURES

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Abstract: *Quantum confined Stark effect is a strong, electric field dependent change in optical absorption that has been seen in nanostructure materials. Its study 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 overview of the experimental methods and techniques for investigation of QCSE in quantum well materials, based on measurements of their photoluminescence, absorption spectra, exciton transitions, cathodoluminescence spectroscopy, electrorefraction, etc.*

НЯКОИ ЕКСПЕРИМЕНТАЛНИ ИЗСЛЕДВАНИЯ НА КВАНТОВО-РАЗМЕРНИЯ ЩАРК ЕФЕКТ В ПОЛУПРОВОДНИКОВИ НАНОСТРУКТУРИ

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Ключови думи: *Квантово-размерен Щарк ефект, експериментални изследвания, квантови ями, полупроводникови наноструктури*

Резюме: *Квантово-размерният Щарк ефект (QCSE) е силна промяна в оптичното поглъщане, което е наблюдавано в наноструктурни материали, при прилагане на електрическо поле. Неговото проучване е привлякло много внимание, тъй като това е важно както за фундаменталната физика, така и в устройствата за оптоелектронни приложения. Настоящата статия е един кратък преглед на експерименталните методи и техники за изследване на QCSE в материалите с квантови ями, на базата на измервания на тяхната фотолуминисценция, абсорбционни спектри, екситонни преходи, катодолуминесцентна спектроскопия, елестроотражение и т.н.*

Introduction

The present work is motivated by the tremendous interest in the semiconductor nanostructures. This interest is due to their actual and potential applications in various electro-optical devices. Semiconductor heterostructures and particularly, double heterostructures, including semiconductor superlattices (SLs), quantum wells, quantum wires, and quantum dots, are today the subject of research of two-thirds of the semiconductor physics community [1].

The definition of quantum confined Stark effect (QCSE) in semiconductor QWs is: effect of an external constant electric field on the energy levels of quasi 2D electron gases or quantum well (QW) structures [2] (see Fig.1.).

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

(a) - longitudinal QCSE. *F* parallel to the growth axis / perpendicular to QW layers;
(b) - transverse QCSE. *F* 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 pay attention only to the longitudinal QCSE.

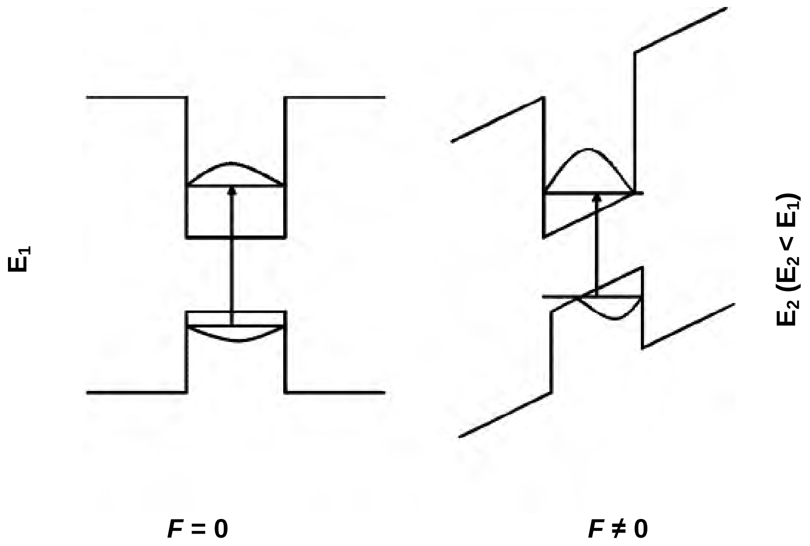

Fig.1. - QCSE in QWs. The distortion of the QW potential with applied electric field *F*. Under application of a static electric field perpendicular to the QW layers, the energy levels are shifted from their zero-field positions

The study of the QCSE when a longitudinal electric field *F* is applied to the QWs has attracted much attention both experimentally and theoretically [1-12], 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 principle. The present paper is a brief overview of the experimental methods and techniques for investigation of the QCSE in quantum well materials. 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 [7-12]. The experimental methods and techniques for investigation of QCSE in quantum well materials are presented in this paper in the form of a sequence of examples.

Experimental studies

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 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).

Usually, there are two ways of applying the electric field to the QW microstructures designed for Stark effect experiments. The electric field *F* is applied either via a Shottky barrier or barrier semiconductor / electrolyte interface; or by inserting the structure into the intrinsic part of a p.i.n. junction / diode.

The experimental methods and techniques for investigation of QCSE in quantum well materials are presented in this paper in the form of a sequence of examples.

Photoluminescence (PL) spectroscopy

In the paper [7] was investigated the dependence on the well thickness of the Stark effect in $GaAs/Ga_{1-x}Al_xAs$ QWs, by means of the low-temperature photoluminescence spectroscopy (see Fig.2.). Provided the quality of the samples was good enough to provide sharp lines in the PL, the effects of the electric fields could be studied not only on free excitons but also on impurity-bound excitons. The results for the three different samples with the well thicknesses of 130 Å, 160 Å and 230 Å, were presented. An electric field perpendicular to the interfaces was applied via a semi-transparent Schottky contact. The QW luminescence was excited either, indirectly, with the 5145 Å line of the Ar^+ laser, above the $Ga_{0.65}Al_{0.35}As$ band-gap edge, or, selectively, with the 6471 Å , line of the Kr^+ laser. The PL signal was dispersed by a ¾ Spex double monochromator and detected with a cooled-GaAs-cathode photomultiplier. These small voltages indicate the nearly perfect confinement of the photo-excited carriers in the QW, when they are excited below the $Ga_{0.65}Al_{0.35}As$ band gap.

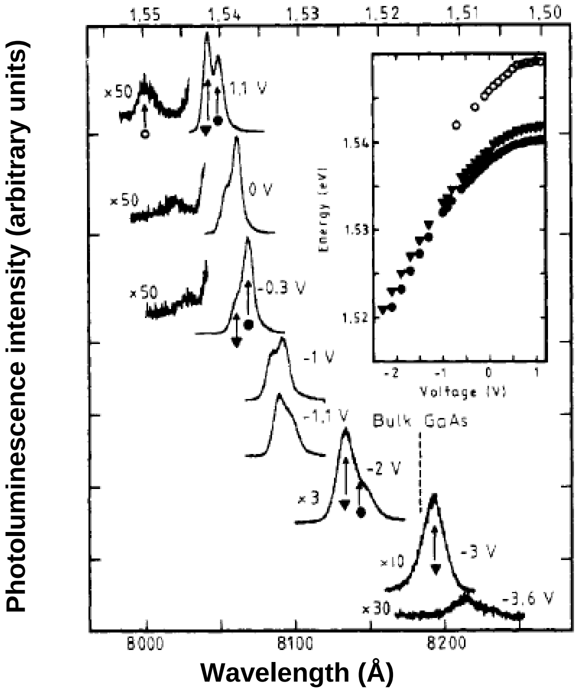

Fig. 2. - Photoluminescence spectra of the sample (130 Å QW) [7], at different bias voltages. The highest-energy peak corresponds to the (1 E - 1 LH) exciton (E means electron and LH - light hole), the high energy line of the doublet to the (1 E - 1 HH) exciton (HH means heavy hole), and the lowest-energy peak to a donor-bound exciton

Time-resolved photoluminesce measurements

Time-resolved photoluminescence measurements of excitons in $GaAs/Ga_{1-x}Al_xAs$ quantum wells subjected to an electric field perpendicular to the well plane have been made in [8]. With increasing the field, both integrated luminescence and luminescence lifetime decrease. Thus the electric field increases the exciton nonradiative decay rate. Estimates of several possible mechanisms suggested that Fowler-Nordheim tunneling is responsible for the quenching. With increasing pump laser intensities, larger electric fields are required to quench the lifetime because of exciton screening of the field.

In Fig.3. [8] is shown the photoluminescence decay of the intrinsic n = 1 exciton at several values of the externally applied voltage V_{ext} for a sample with a well thickness of about 30 Å and a barrier thickness of 100 Å. The average laser power here was 100 µW, corresponding to a peak carrier density of about 5 x 10^{17} cm^{-3}. The monochromator energy was 1.637 eV (0.001 eV resolution).

Picosecond luminescence studies

Picosecond electroluminescence studies of the QCSE on GaAs/ AlGaAs QWs were performed in [9]. A drastic increase of the recombination lifetime was accompanied by a Stark shift of the photoluminescence of the lowest free exciton for electric fields perpendicular to the quantum-well layers. The experimental results for the shifts of the QW PL were summarized in Fig.4. (see Fig.2. in [9]), where the positions of the PL peaks for the different QWs were plotted as a function of V_{ext}.

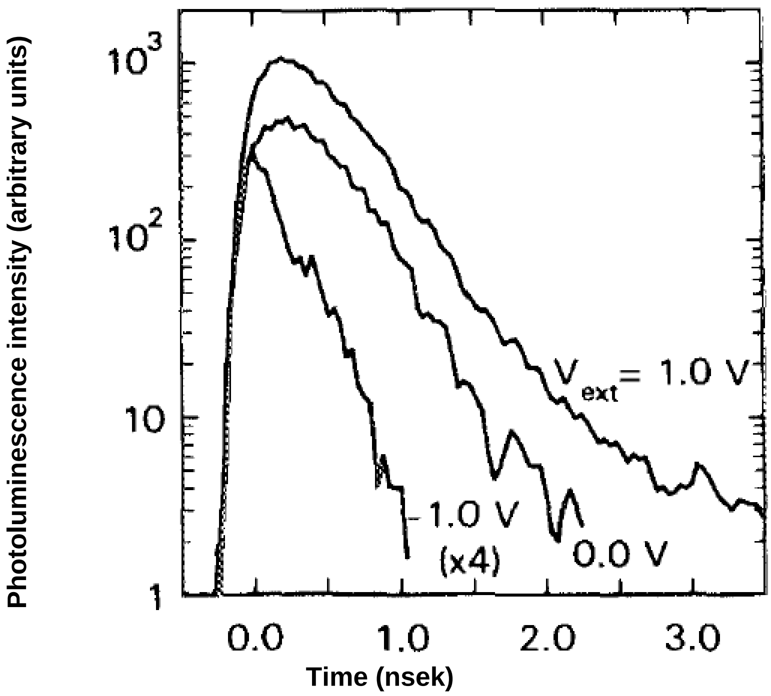

Fig. 3. - [8] Photoluminescence decay of the intrinsic n = I exciton at several values of externally applied voltage V_{ext}. The temperature: T= 8 K

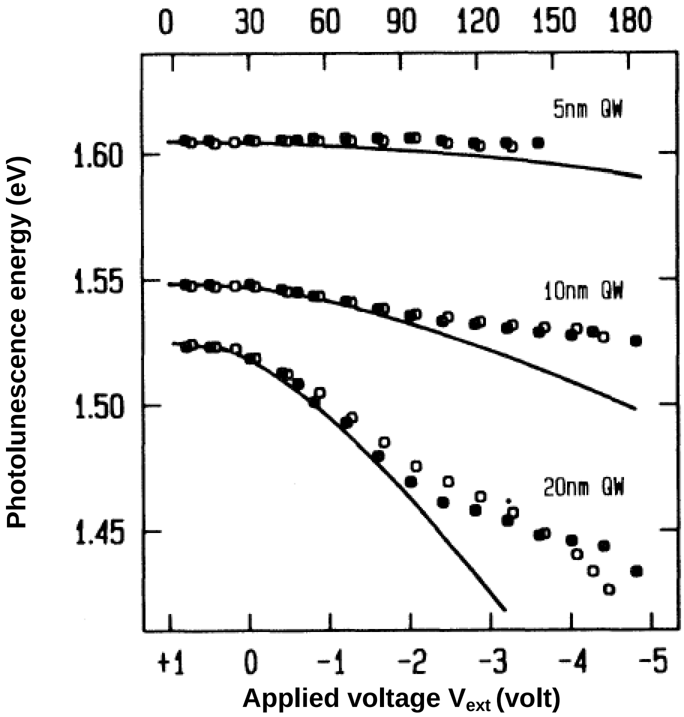

Fig. 4. – [9] PL peak energy position of the QW's as a function of the external voltage (electric field)

Absorption current spectroscopy

In the paper [10], have been fabricated AlGaAs QW structures equivalent to graded-gap QWs and have been observed experimentally their QCSE by the absorption current spectroscopy. Absorption current spectroscopy had revealed larger energy shifts of the fundamental excitonic absorption peak in graded-gap QWs in the low electric field region than those in the conventional square-shaped QWs with the same well widths.

Electroabsorption in QWs

In [11] are presented extended experimental results for the large shift in optical absorption in GaAs/ AlGaAs QW structures with electric field perpendicular to the layers (see Fig.5.). In contrast to the Stark effect on atoms or on excitons in bulk semiconductors, the exciton resonances remain resolved even for shifts much larger than the zero-field binding energy and fields > 50 times the classical ionization field. These results are explained as a consequence of the quantum confinement of the carriers.

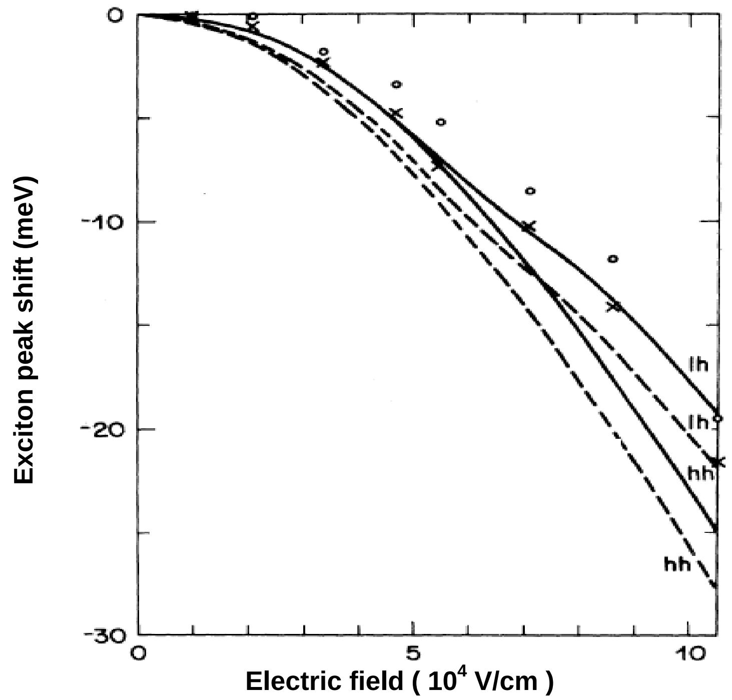

Fig. 5. – [11] Shift of the exciton peak position with applied field. The points are experimental. Where: lh – light hole exciton; hh – heavy hole exciton

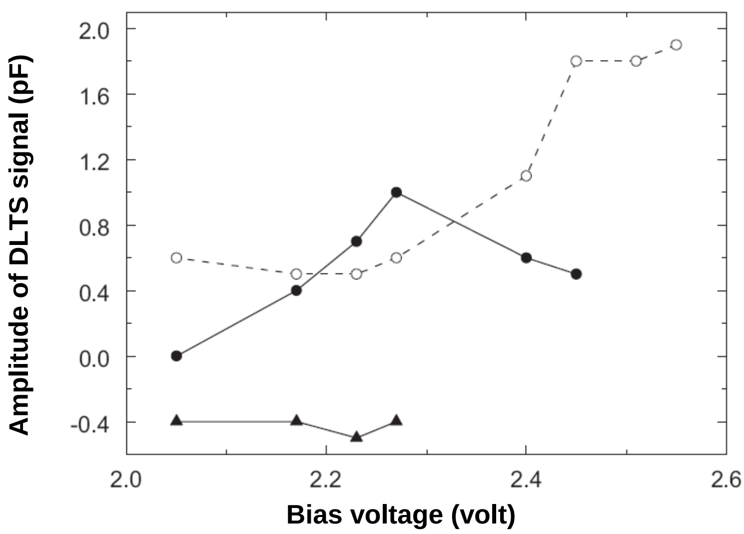

Fig. 6. – [12] Dependence of the amplitudes of the DLTS signals of the E1, E2 and H1 levels on the bias voltage. Where: E1 – empty circles, E2 – full circles, H1 – triangles.

Deep-level transient spectroscopy

In the paper [12] capacitance–voltage(C–V) and deep-level transient (DLTS) spectroscopies has been applied to study the carrier emission from states of the quantum-well superlattice in a p–n InGaN/GaN heterostructure (see Fig.6.). Changes in the DLTS spectra of this structure strongly depend on bias-on–bias-off cooling conditions and the applied bias. It is believed that these changes are determined by: (1) built-in piezoelectric field that leads to spatial separation of the electron and hole ground-state wave functions of the superlattice, defined as a manifestation the quantum-confined Stark effect and (2) localization of the electron wave functions in separate QWs, named the Wannier-Stark localization.

Conclusion

This paper offers a brief overview of some basic experimental methods and techniques for investigation of the QCSE in quantum well materials. The experimental studies of QCSE with longitudinal electric field applied to the semiconductor QW structures are quite important for proper application of the effect in different devices. They could facilitate the search for new materials possessing unique electron and optical properties. Deep knowledge of the physics of QCSE will tremendously facilitate the work of the experimentalists and QW crystal growers. The Stark shifts of the electronic states and their spatial distributions need to be studied both experimentally and theoretically in order to seek a potential QW profile that will provide the best Stark effect characteristics of a given quantum well.

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