SES 2013
Ninth Scientific Conference with International Participation
SPACE, ECOLOGY, SAFETY
20 – 22 November 2013, Sofia, Bulgaria

QUANTUM-CONFINED STARK EFFECT IN SEMICONDUCTOR NANOSTRUCTURES AND ITS DEVICE APPLICATIONS

Adelina Miteva[1], **Valeria Stoyanova**[2]

[1]Space Research and Technology Institute – Bulgarian Academy of Sciences
[2]Institute of Physical Chemistry – Bulgarian Academy of Sciences
e-mail: ad.miteva@gmail.com; valeria@ipc.bas.bg

Keywords: *Quantum confined Stark effect (QCSE), device applications, semiconductor nanostructures, semiconductor quantum-wells*

Abstract: *This work is motivated by the tremendous interest in the semiconductor nanomaterials and heterostructures and their applications in constructing of various electro-optical devices. Changes in the electro-optical properties of such materials have been induced under the influence of an external constant electric field, the so called quantum confined Stark effect (QCSE). The QCSE has found practical application in ultrafast optoelectronics, electro- absorption modulators and in telecommunications, as well as in such devices as solar cells, advanced tuneable semiconductor lasers, etc. In this paper we will make a survey of several such devices based on QCSE in semiconductor quantum-well materials.*

КВАНТОВО-РАЗМЕРЕН ЩАРК ЕФЕКТ В ПОЛУПРОВОДНИКОВИ НАНОСТРУКТУРИ – ПРИБОРНИ ПРИЛОЖЕНИЯ

Аделина Митева[1], **Валерия Стоянова**[2]

[1]Институт за космически изследвания и технологии – Българска академия на науките
[2] Институт по физикохимия – Българска академия на науките
e-mail: ad.miteva@gmail.com; valeria@ipc.bas.bg

Ключови думи: *Квантово-размерен Щарк ефект, приборни приложения, полупроводникови наноструктури, полупроводникови квантови ями*

Резюме: *Тази работа е мотивирана от огромния интерес към полупроводниковите наноматериали и хетероструктури, и техните приложения в конструирането на различни електрооптични устройства. Промени в електрооптичните свойства на тези материали се предизвикват под въздействието на външно постоянно електрическо поле, т. нар. квантово размерен Щарк ефект (QCSE). QCSE е намерил практическо приложение в ултрабързата оптоелектроника, електро-абсорбционни модулатори и в областта на телекомуникациите, както и в такива устройства, като соларни клетки, регулируеми полупроводникови лазери и т.н. В този кратък обзор ние ще направим преглед на няколко такива устройства, базирани на QCSE в полупроводниковите материали с квантови ями.*

Introduction

Nowadays, nanostructures are of great fundamental interest and are important for their actual and potential applications. The evidence is the Nobel prizes in physics for 2000 [1] (“developing semiconductor heterostructures used in high-speed and opto-electronics”) and for 2010 [2] (“grapheme nanotechnology”) years. Semiconductor nanostructures (superlattices and quantum wells) are already employed in electronic and optoelectronic devices [3-18]. Many semiconductor devices with built-in quantum wells work under application of an electric field. In semiconductor quantum wells (QWs), 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. This is the well-known quantum confined Stark effect (QCSE). The QCSE in QW structures is the basis and is now utilized for realizing many fast electro-optical devices. For achieving high device performances, such as high on/off ratio and low operation voltage, it is desirable that the decrease in the exciton peak height be small and that this peak move at a faster rate by using an applied electric field.

Here we will make a brief survey of several device applications based on the QCSE in semiconductor quantum-well materials. In the next part of this paper we present several examples of device applications of QCSE.

"Stark ladder" Laser

"Stark ladder" [6] laser of a semiconductor superlattice with a coherent electronic subsystem is described in [7] and the schematic diagram is shown in Fig.1.

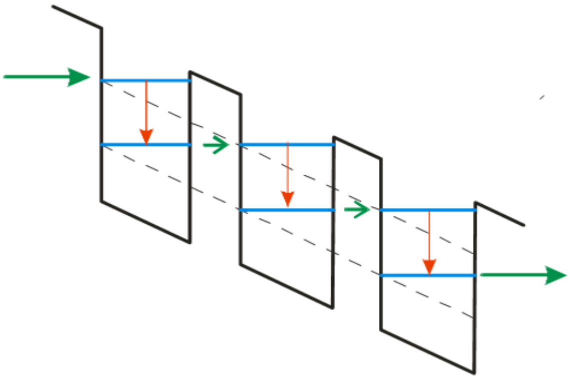

Fig. 1. Wannier Stark ladder [6,7]

QCSE Modulators

In [8] are described the principles of the QCSE modulators. Reduction in energy of bound states in a quantum well under an applied electric field leads to the modulation of ‘effective band gap’. The input optical signal gives as the output a modulated optical signal. Change in energy levels gives change in electron – hole overlap (see Fig. 2).

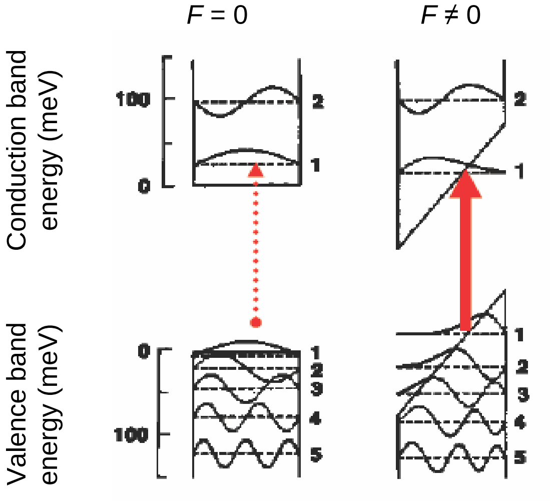

Fig. 2. Stark shift in QW [8]

Electro-absorption modulator (EAM)

Electro-absorption modulator (EAM) [9] is a semiconductor device which can be used for modulating the intensity of a laser beam via an electric voltage. A change in the absorption spectrum caused by an applied electric field, which changes the bandgap energy (thus the photon energy of an absorption edge) but usually does not involve the excitation of carriers by the electric field. For modulators in telecommunications small size and modulation voltages are desired. The EAM is candidate for use in external modulation links in telecommunications. Compared with Electro-optic modulator (EOM), EAM can operate with much lower voltages (a few volts instead of ten volts or more). They can be operated at very high speed; a modulation bandwidth of tens of gigahertz can be achieved, which makes these devices useful for optical fiber communication. A convenient feature is that an EAM can be integrated with distributed feedback laser diode on a single chip to form a data transmitter in the form of a photonic integrated circuit. Compared with direct modulation of the laser diode, a higher bandwidth and reduced chirp can be obtained.

Semiconductor quantum well EAM is widely used to modulate near-infrared (NIR) radiation at frequencies below 0.1THz. Here [10], the NIR absorption of undoped quantum well was modulated by strong electric field with frequencies between 1.5 and 3.9 THz. The THz field coupled two excited states (excitons) of the quantum wells, as manifested by a new THz frequency-and power- dependent NIR absorption line. The THz field generated a coherent quantum superposition of an absorbing and a nonabsorbing exciton. This quantum coherence may yield new applications for quantum well modulators in optical communications.

Electroabsorption modulators have been widely used in fiber optic communication systems, because of their small size, low driving voltage, low chirp, high extinction ratio, high modulation efficiency, and wide modulation bandwidth. Advantages of EA modulators are the possibilities for integration with DFB (distributed feedback laser) laser (see Fig.3. [10] – utilized by Alcatel).

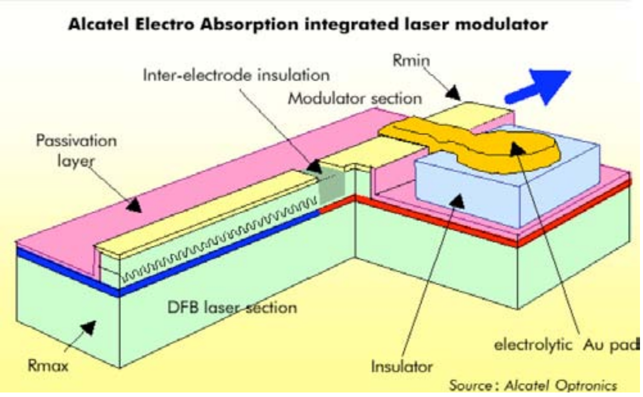

Fig. 3. Advantages of EA modulator (Alkatel [10]) - Integration with DFB laser

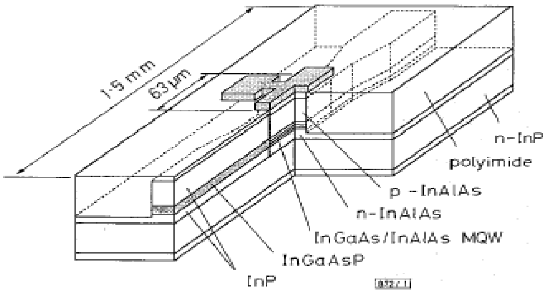

Fig. 4. 40GHz Modulator [11]

In Fig. 4. [11] is shown one 40GHz modulator, which is characterized by long device length for easy packaging; short modulator section to reduce capacitance; low driving voltage of 2.8V and low insertion loss of 8dB.

QW structures for deep-UV emitters

Utilization of AlGaN-based QW structures is one of most important key issues for the application of solid-state deep-UV light-emitting devices such as light-emitting diodes (LEDs) and laser diodes (LDs) operated in the wavelength range between 200 and 350 nm. In [12] have been reported barrier-height and well-width dependence of room-temperature PL from AlGaN-based QW structures for deep-UV light emitting device applications. A QW sample consisting of 1.5 nm-$Al_{0.15}Ga_{0.85}N$ wells/7 nm-$Al_{0.40}Ga_{0.60}N$ barriers showed the largest emission intensity in their samples. QCSE on the emission energy and intensity in wide-well conditions, carrier penetration into the barrier regions in narrow well conditions and heterointerface defect formation were comprehensively considered in the discussion. In [12] the conclusion was: if the heterointerface defect formation is ideally suppressed by optimal growth conditions, QW structures with narrow wells and high barriers will be a better design for highly efficient deep-UV light emitting devices.

Double quantum wells violet InGaN laser diodes

In [13] the effects of QCSE and QW thickness on the optical properties of violet InGaN LDs have numerically been investigated. The simulation results indicated that the QCSE greatly affects the optical properties of LDs, where QCSE relates to the QW thickness and it increases when the QW thickness is wider which leads to deteriorating of the optical proprieties of the violet InGaN LD. The polarization in the active region of the InGaN LD has been estimated by the blue shift of the wavelength and it is found that the blue shift of the wavelength depends on the QW thickness. The major simulation result has shown that the best properties of violet InGaN LD can be obtained with smaller QW thickness, where more carriers can be restricted, stayed and overlapped inside the QW which leads to a larger stimulated recombination rate and optical material gain which in turn increase the output power of the LD; while decreasing the threshold current of the LD.

QW Photodetector

GaAs/AlGaAs quantum well infrared photodetectors (QWIPs) have attracted much attention and been demonstrated with a detection cutoff of 19 mm. QWIP detectors with longer wavelengths would be of interest for space applications such as infrared astronomy and satellite mapping where high detectivity, low dark current, high uniformity, radiation hardness and low power consumption are important. For these uses, arrays of QWIPs would provide a useful alternative to the Si and Ge detectors currently available in this wavelength range with detectivities ranging from 10^9 to 10^{14} cm√Hz/W. In the letter [14] were presented the first far-infrared results based on a bound-to-bound intersubband transition in a GaAs/AlGaAs QWIP with peak response at 27.2 μm (see Fig. 5.).

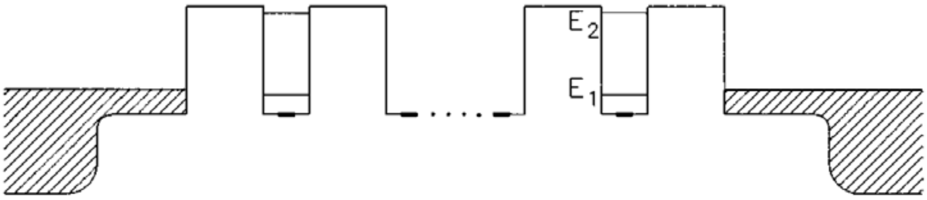

Fig. 5. The detector design [14]. Structure designed for the bound-to-bound GaAs/AlGaAs QWIP with a predicted peak response of 28.8 μm. The energy bands were at E_1=10.5 meV and E_2=53.5 meV

Single quantum well optical modulator

QCSE in a single quantum well [15] is not only of scientific but also of practical interest, since it is possible to provide an optical modulator laser radiation on the structure of one quantum well (QW or a small number of QWs) in multiple passage of radiation through it.

It is a structure (see Fig.6.) on a substrate n-GaAs, a plate with bevelled at an angle of 45 degrees by the lateral edges. Through one of these faces of the laser beam is introduced, which after multiple reflections from the plane-parallel top and bottom faces and passing through the QW is discharged through another face. On the upper bound with epitaxial heterostructure QW applied rectifying contact (for example Al) Schottky diode on the bottom side - ohmic contact. Both contacts are both deaf reflecting mirrors. With a length of 1 cm and a plate thickness of 0.5 mm can be obtained about 20 beam passing through the QW. To bring the number up to 50 passages, as in multiwell modulators, respectively, or you can increase the length of the modulator, or use a structure with two or three closely spaced QW.

The Quantum Well Self-Electrooptic Effect Devices

Electro-optical effects, such as the quantum confined Stark effect in quantum well structures, lead to strong optoelectronic nonlinearities which form the basis for optical modulators and optically bistable devices. They result from a modification of the optical absorption properties by an applied electric eld and are particularly pronounced in the case of low dimensional semiconductors. In [16] was done a review of theoretical modelling and computer simulations of such optoelectronic devices in particular for ZnSe based quantum well structures, where excitonic features dominate even at room temperature. The field dependent absorption spectra were calculated by a many-body theory including the full electron-electron interaction. The transition from the quantum confined Stark effect, which is found for well widths smaller than the exciton Bohr diameter, to the Franz-Keldysh effect, which corresponds to the limit of wide wells, was studied. Optical bistability and switching was found in R-SEED and D-SEED congurations, and the optimization of the device performance was discussed.

Extended experimental and theoretical results were reported in [17] for the quantum well self-electrooptic effect devices. Four modes of operation are demonstrated: optical bistability; electrical bistability; simultaneous optical and electronic self-oscillation; and self-linearized modulation and optical level shifting. All of these can be observed at room-temperature with a CW laser diode as the light source. The nature of the optoelectronic feedback underlying the operation of the devices was discussed, and the physical mechanisms which give rise to the very low optical switching energy (approximately 4 fJ/μm^2) were discussed.

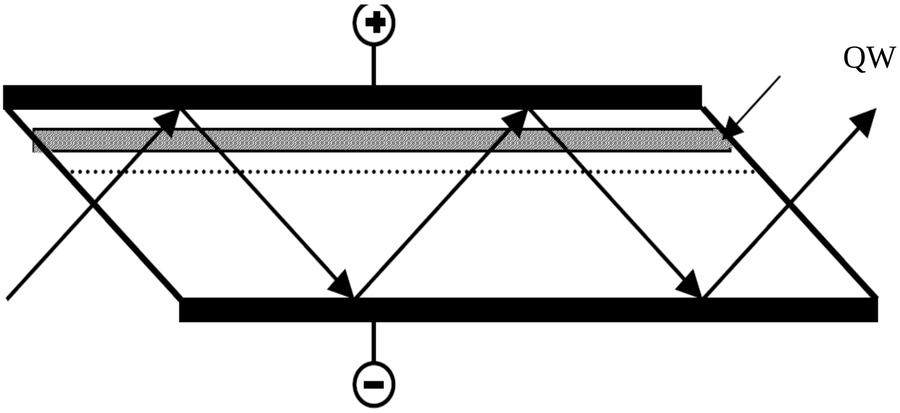

Fig. 6. Optical modulator on a single quantum well [15]

Blue quantum electroabsorption modulators

The authors [18] present the design, growth, fabrication, experimental characterization, and theoretical analysi of blue quantum electroabsorption modulators that incorporate ~5 nm thick $In_{0.35}Ga_{0.65}N/GaN$ quantum structures for operation between 420 and 430 nm. Growing it on polar c-plane of sapphire, they obtain quantum structures with zigzag potential profile due to alternating polarization fields and demonstrate that their optical absorption blueshifts with applied electric field, unlike the redshift of conventional quantum confined Stark effect.

Conclusions

This brief survey of some QCSE based devices and their main characteristics could enhance the common understanding of some modern and contemporary knowledge and techniques.

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 for new potential QCSE device applications.

References:

1. Alferov, Z. I., Nobel Lecture: The double heterostructure concept and its applications in physics, electronics, and technology, Rev. Mod. Phys., Vol. 73, No. 3, 2001, 767-782.
2. Geim, A. K., Nobel Lecture: Random walk to graphene, Rev. Mod. Phys., Vol. 83, No. 3, 2011, 851-862.
3. Di Carlo, A., Microscopic theory of nanostructured semiconductor devices: beyond the envelope-function approximation, Semicond. Sci. Technol. 18, 2003, R1-R31.
4. Bastard, G., Wave mechanics applied to semiconductor heterostructures, Les Edition de Physique, Les Ulis Cedex , 1988.
5. Singh, J., Physics of Semiconductors and Heterostructures. Singapore, McGraw-Hill Booc Co., 1993.
6. Wannier, G. H., Dynamics of Band Electrons in Electric and Magnetic Fields, Rev. Mod. Phys., Vol. 34, No. 4, 1962, 645-655.
7. Елесин, В. Ф., Ю. В. Копаев, Лазер на „Штарковской лестнице” с когерентной электронной подсистемой, ЖЭТФ, Vol. 123, No. 6, 2003, 1308-1322.

8. Ramp, R. J., Lecture 12: Introduction to Modulators, Electrical Engineering, Massachusetts Institute of Technology, http://rleweb.mit.edu/sclaser/6.973%20lecture%20notes/Lecture%2012e.pdf.
9. Morrison, G. B., J. W. Raring, C. S. Wang, E. J. Skogen, Y-C. Chang, M. Sysak, L. A. Coldren, Electroabsorption modulator performance predicted from band-edge absorption spectra of bulk, quantum-well, and quantum-well-intermixed InGaAsP structures, Solid-State Electronics, Vol. 51, No. 1, 2007, 1-186.
10. Sankaralingam, R., EE 698, Electroabsorption Modulators, https://www3.nd.edu/~gsnider/EE698A/Rajkumar_opt_mod.pdf.
11. Ku, P-Ch., Electro-absorption Modulators, April 24 & 26, 2001.
12. Kajitani, R., K. Kawasaki, M. Takeuchi, Barrier-height and well-width dependence of photoluminescence from AlGaN-based quantum well structures for deep-UV emitters, Mat. Sci. & Eng. B, Vol. 139, 2007, 186–191.
13. Abdu llah, R. A., K. Ibrahim, Effects of quantum confined stark effect and well thickness on optical properties of double quantum wells violet InGaN laser diodes, Optik - International Journal for Light and Electron Optics, Vol. 124, No. 4, 2013, 283-376.
14. Perera, A. G. U., W. Z. Shen, S. G. Matsik, H. C. Liu, M. Buchanan, W. J. Schaff, GaAs/AlGaAs quantum well photodetectors with a cutoff wavelength at 28 μm, Appl. Phys. Lett., Vol. 72, No. 13, 1998, 1596-1598.
15. Горшков, А. П., И. А. Карпович, Исследование квантово-размерного эффекта Штарка в гетеронаноструктурах с квантовыми ямами InGaAs/GaAs методом фотоэлектрической спектроскопии, Нижегородский университет им. Н.И. Лобачевского, 2006.
16. Schöll, E., Modelling of devices for optoelectronic applications: The quantum confined Stark effect and self-electrooptic effect devices, Tr. J. of Physics, Vol. 23, 1999, 635 - 648.
17. Miller, D. A. B., D. S. Chemla, T. C. Damen, T. H. Wood, C. A. Burrus, A. C. Gossard, W. Wiegmann, The Quantum Well Self-Electrooptic Effect Device: Optoelectronic Bistability and Oscillation, and Self Linearized Modulation, IEEE J. Quantum Electron, Vol. QE-21, 1985, 1462-1476.
18. Sari, E., S. Nizamoglu, T. Ozel, H. V. Demira, Blue quantum electroabsorption modulators based on reversed quantum confined Stark effect with blueshift, Appl. Phys. Lett., Vol. 90, 2007, 011101-011103.