Physica B 507 (2017) 61–66

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

Fine structure of the exciton electroabsorption in semiconductor superlattices

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ARTICLE INFO

Keywords:
Excitons
Superlattices
External fields
Optical absorption Coefficients

ABSTRACT

Wannier-Mott excitons in a semiconductor layered superlattice (SL) are investigated analytically for the case that the period of the superlattice is much smaller than the 2D exciton Bohr radius. Additionally we assume the presence of a longitudinal external static electric field directed parallel to the SL axis. The exciton states and the optical absorption coefficient are derived in the tight-binding and adiabatic approximations. Strong and weak electric fields providing spatially localized and extended electron and hole states, respectively, are studied. The dependencies of the exciton states and the exciton absorption spectrum on the SL parameters and the electric field strength are presented in an explicit form. We focus on the fine structure of the ground quasi-2D exciton level formed by the series of closely spaced energy levels adjacent from the high frequencies. These levels are related to the adiabatically slow relative exciton longitudinal motion governed by the potential formed by the in-plane exciton state. It is shown that the external electric fields compress the fine structure energy levels, decrease the intensities of the corresponding optical peaks and increase the exciton binding energy. A possible experimental study of the fine structure of the exciton electroabsorption is discussed.

1. Introduction

Since semiconductor superlattices (SLs) were originally proposed by Esaki and Tsu [1] one of the most fascinating phenomena in the physics of SLs, namely Wannier-Stark (WS) localization [2] of the electrons and holes, has been comprehensively studied both experimentally [3–7] and theoretically [8–13]. Carriers subject to a time-independent (dc) electric field $\overrightarrow{F}$ directed parallel to the axis of the SL with period d exhibit Bloch oscillations [14] within the spatial region $\frac{\Delta_j}{2eF}$, $j = e, h$ where Δ_j is the electron (e) or hole (h) miniband width. The energies of these spatially localized particles are the WS levels separated in energy by eFd and have been observed in corresponding optical experiments [15,4–6] (see also the monograph [16] and references therein). Linder [17] followed the transition from the low electric field Franz-Keldysh (FK) regime to the strong field WS regime, covering extended Bloch and localized WS states, respectively. Illustrative sketches of the conduction- and valence-band profiles for the SL subject to weak and strong electric fields providing the extended FK and localized WS states have been given in Refs. [15] and [18]. FK effect [19] induced penetration of the interband optical absorption inside the bulk semiconductor energy gap and frequency oscillations above the edge were observed for SLs in the beginning of the nineties [20].

At the same time Dignam and Sipe [10] pointed out that all experiments in which the WS levels have been identified were performed on undoped SLs and consequently photoinjected electrons and holes should be united into excitons considerably modifying the electrooptical properties of the SLs. In Ref. [10] the 1 s exciton state in the SL exposed to electric fields has been calculated numerically using localized exciton wave functions as a basis set for the expansion of the exciton eigenstates. It was shown that several important features become more prominent for very-short-period SLs for which their period is much shorter than the exciton Bohr radius. Several works were dedicated to bring the theory of exciton absorption close to experimental observation with realistic biased SLs. This includes the determination of the complex valence-band structure [11], anticrossing of the WS levels related to the different SL subbands [17,21], band nonparabolicity [21], mismatch of the effective masses of the carriers and dielectric constants in the well and barrier regions [22] and Fano resonances, caused by the coupling between the discrete and continuous exciton states [17,23,24]. Note that the majority of the mentioned papers referred to employ numerical approaches to the problem under

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http://dx.doi.org/10.1016/j.physb.2016.11.017
Received 5 November 2016; Accepted 15 November 2016
Available online 19 November 2016
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consideration. We remark that the state of the art of the physics of excitons in SLs has been summarized in a number of reviews and monographs [25–27].

Recently qualitatively novel results related to excitons in SLs have been reported. In the work of Suris [28] the effect of the centre of mass motion of the Wannier-Mott exciton on its binding energy in a layered semiconductor superlattices (SL) has been studied analytically. The SL period was assumed to be much smaller than the 2D excitonic Bohr radius. As a result the electron and hole motions decompose into two parts: the fast longitudinal motion parallel to the SL z-axis and the adiabatically slow transverse in-plane motion governed by the SL potential and the 2D quasi-Coulomb exciton field, respectively. The fine structure of each 2D exciton energy level adjacent from the high energies was found to occur and the energy of the fine structure ground state has been calculated. This energy group consists of closely spaced satellite energy levels which in turn relate to the adiabatically slow longitudinal relative exciton motion in the triangular quantum well $\sim F_0|z|$. This well is formed by the quasi-uniform effective electric field F_0 caused by the corresponding in-plane exciton state. A similar structure was studied originally in the pioneering work of Kohn and Luttinger [29] when considering the donor states in the Ge and Si bulk crystals with extremely anisotropic isoenergetic surfaces. Clearly, the effect of a longitudinal uniform external dc electric fields F on the exciton states and the exciton optical absorption spectrum in the semiconductor SL associated with the transitions to these satellite states are in this context certainly of relevance.

In the present paper this effect is investigated for the case that the period of the SL is much smaller than the 2D exciton Bohr radius. One of the reasons for the consideration of these SLs is that a short period SL causes the quasi-2D exciton to be stronger bound [10]. In units of the effective exciton Rydberg constant Ry, the binding energy $E_{2D}^{(b)}$ of the 2D exciton is 4, while for the 3D exciton realized in the long-period SL it is $E_{3D}^{(b)} = 1$. For the simple band model in the effective mass approximation the overlapping exciton wave function is expanded in SL Wannier functions that in turn allow us to use the tight-binding and the adiabatic approximations to calculate analytically the exciton states in the SL subject to a longitudinal external electric field. The dependencies of the exciton states and the exciton absorption coefficient on the SL parameters (period and minibands widths) and on the external electric field strength are presented explicitly. Since the exciton fine structure is induced by the weak quasi-uniform electric field F_0 [28] we are mostly focusing on the FK regime of the comparable weak electric field F. These fields compensate the field F_0, destroy the exciton fine structure, generate the extended longitudinal electron and hole states and increase the 2D exciton binding energies. In addition, in order to emphasize the common character of our approach we calculate the exciton electroabsorption for the WS regime of strong electric fields. In conclusion we discuss the applicability conditions of the obtained results and estimate the expected experimental values. Undoubtedly, realistic SLs involve further complications such as band structure complexity, nonparabolicity of the energy bands, different effective masses and dielectric constants in the well and barrier regions etc., and require numerical calculations and can modify our obtained analytical results. Here we do not intend to compete with the corresponding numerical studies. Instead at the first stage of our investigation it is reasonable to leave aside the listed details in order to highlight the specific effect of the external electric fields on the SL exciton absorption fine structure. The mentioned band properties can be subject of further considerations.

The paper is organized as follows. In Section 2 in the tight-binding and adiabatic approximations the general equation describing the exciton in the SL in the presence of the longitudinal external dc electric fields is derived. The exciton energies and wave functions are presented in an explicit form in Section 3. In Section 4 we calculate the exciton absorption coefficient and trace its dependencies on the SL parameters and on the external electric field strengths as well as discuss the applicability of the obtained results. We also estimate the expected experimental values. Section 5 contains the conclusions.

2. General approach

We consider a Wannier-Mott exciton in a semiconductor SL subject to an uniform external electric field $\vec{F}$ directed parallel to the SL z-axis. The semiconductor energy bands are taken to be parabolic, nondegenerate, spherically symmetric and separated by a wide energy gap E_g. In the effective mass approximation the envelope wave function Ψ of the exciton consisting of the interacting electron (e) and hole (h) with the effective mass m_j, charges $e_j (e_e = -e_h = -e)$ and positions $\vec{r_j} (\vec{\rho_j}, z_j) j = e, h$ obeys the equation

$$\left\{ \sum_{j=e,h} \left[-\frac{\hbar^2}{2m_j} \vec{\nabla}_j^2 + V_j(z_j) + e_j F z_j \right] + U(\vec{r_e} - \vec{r_h}) \right\} \Psi(\vec{r_e}, \vec{r_h}) = E \Psi(\vec{r_e}, \vec{r_h}). \tag{1}$$

In Eq. (1)

$$U(\vec{\rho_e} - \vec{\rho_h}, z_e - z_h) = -\frac{e^2}{4\pi\varepsilon_0 \epsilon \sqrt{(\vec{\rho_e} - \vec{\rho_h})^2 + (z_e - z_h)^2}} \tag{2}$$

is the Coulomb potential of the electron-hole attraction in the semiconductors with the dielectric constant ϵ, E is the total exciton energy, $V_j(z_j) = V_j(z_j + nd)$, $n = 0, 1, \ldots N$ are the periodic model potentials of the SL formed by a large number $N \gg 1$ of quantum wells of width d, separated by δ-function type potential barriers (see Ref. [30]). The chosen model correlates well with the nearest neighbor tight-binding approximation for the interwell tunneling and enables us to perform calculations in an explicit form. Since we follow the original approach to the problem presented in detail in Ref. [28], only a brief outline of the calculations will be provided.

First we assume that the energies of the size-quantization b_j considerably exceed the miniband widths Δ_j, the distance eFd between the Wannier-Stark (WS) energy levels, and the exciton Rydberg constant Ry, determined by the exciton Bohr radius $a_0 \gg d$, i.e.

$$\Delta_j, \quad Ry, \quad eFd \ll b_j, \tag{3}$$

where

$$b_j = \frac{\hbar^2 \pi^2}{2m_j d^2}; \quad Ry = \frac{\hbar^2}{2\mu a_0^2}; \quad a_0 = \frac{4\pi\varepsilon_0 \epsilon \hbar^2}{\mu e^2}; \quad \mu^{-1} = m_e^{-1} + m_h^{-1}; \, j = e, h$$

.

The imposed conditions (3) decompose the particle motion into two components: the fast longitudinal parallel to the SL z-axis and the slow transverse in-plane $\vec{\rho}$-motions governed by the SL potentials $V_j(z_j)$ and the electric fields F, and the exciton attraction (2), respectively. This allows us to employ the approximation of isolated, namely, ground minibands and expand the exciton function Ψ over the orthonormalized basis set of the SL Wannier functions $w(z_j - n_j d)$

$$\Psi(\vec{r_e}, \vec{r_h}) = \sum_{n_e, n_h} w(z_e - dn_e) w(z_h - dn_h) \Phi(n_e, \vec{\rho_e}; n_h, \vec{\rho_h}), \tag{4}$$

where $n_{e,h}$ in the Φ-function are the coordinates $z_{e,h}$ scaled with the SL period d. Clearly, the total exciton momentum with the transverse $\vec{P}$ and longitudinal Q components is kept constant. The wave function Φ can be written in the form

$$\Phi(n_e, \vec{\rho_e}; n_h, \vec{\rho_h}) = \exp\left\{ i \left[\vec{P} \vec{R_\perp} + \frac{1}{2} Q d (n_e + n_h) - \gamma d n \right] \right\} \chi(n, \vec{\rho}), \tag{5}$$

where

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