Intersubband optical transitions in semiconductor cylindrical nanolayer in the presence of radial electrical field

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I. Introduction

Recent breakthroughs in the growth of semiconductor low-dimensional structures have opened up great opportunities for nanoscale device applications, increasing the interest in different quasy-one-dimensional nanostructures. In particularly, along with many low-dimensional systems different axial-symmetrical semiconductor nanocrystalline layers have been studied intensively both experimentally and theoretically during the last two decades [1]. These heterophase structures "synthesize" inside itself a number of physical characteristics of both quantized films and quantum wires [2] and therefore they are very perspective in terms of creation of up-to-date optoelectronic devices. Thereupon, it is interesting to investigate the modulating influence of different static fields on the physical characteristics of such quasi-one-dimensional semiconductor quantized layers. In this report the influence of lateral (radial) electrostatic field on the electronic and optical properties of direct-band semiconductor cylindrical heterolayer in the regime of "strong quantization" is investigated theoretically. The following problems are considered:

a) definition of energy spectrum and single-electron wave functions in the layer at the absence of external field,

b) the spectrum of intersubband optical transitions in the layer without external field

c) modification of single-particle energy spectrum of charge carriers in the layer under lateral to the symmetry axis radial electrical field

d) the influence of this static field on the optical spectrum of inband-intersubband transitions in the quantum well of the layer.

II. Approach and Physical Model

The nanoheterostructure under consideration is a composition core/layer/shell in which the homogeneously charged core plays the specific role of the "source" of static radial electrical field. We assume that the system is infinite in the direction of symmetry axis *(Z)*, and that the Coulomb binding energy of *3D* exciton in the layer is much smaller than the confinement energy of charge carriers in radial direction. From the technical point of view, the most realistic (and correspondingly physically more interesting) is the case when the thickness *(L)* of the layer is comparatively smaller than the inner (R_1) and outer (R_2) radii of the layer. In our paper we consider the most realistic cases of "large" $\left(L^2 \times R_{1,2}^{-2} << 1\right)$ and of "moderate" $\left(L^3 \times R_{1,2}^{-3}\right)$ radii of heterostructure. Relative to the contacting materials of heterostructure we assume that the band gap of the layer's material is narrow compared to that of the material of the core (shell). Besides we assume that the band offsets at the interface (for overlapping band gaps) are much greater than the charge-carrier confinement energy. In this case, for not very large quantum numbers, as an adequate physical model of the layer will be the model of "potential well folded into a tube" [2]. In this respect the CdS/HgS/CdS-type compositions are typical [2-3]. Taking into account the above-mentioned conditions we can "separate" the radial and orbital motions of charge carriers in the layer and obtain the explicit expressions of the energy spectrum and envelope wave functions for single-particle states in effective-mass (μ) approximation

$$E_{n,m} \cong \varepsilon_1 n^2 + \frac{\hbar^2\left(4m^2-1\right)}{8\mu R_1 R_2} \tag{1}$$

$$\Phi_{n,m}\left(r\right) \cong \sqrt{\frac{2}{L}}\left(1-\alpha_{n,m} r\right)\frac{\sin\left(\pi n r / L\right)}{\sqrt{r}} \tag{2}$$

Here *n* and *m* are the radial and orbital numbers, respectively, ε_1 is the lowest radial confinement energy, and parameter $\alpha_{n,m} L \sim L^3 / R_1^3$.

III. Results and Discussion

Taking into account the approximations above we obtain the following spectrum of intersubband dipole optical transitions $|n_i, m_i\rangle \to |n_f, m_f\rangle$, where *i f* characterize the initial and final band states,respectively. .

1) When there is no external field we have the following selection rules for these transitions:

$$\Delta|m| = \pm 1;\ \Delta n = 0; \tag{3}$$

$$\Delta|m| = \pm 1;\ \Delta n = 2k+1, (k = 0,1,2,...) \tag{4}$$

The corresponding matrix elements and threshold frequencies are as follows:

1.a) transitions $\Delta|m| = \pm 1,\ \Delta n = 0$

$$M_{n,n}^{(\pm)} \sim \left(2|m_i| \pm 1\right) \ln \frac{R_2}{R_1} \tag{5}$$

$$\omega_{n,n}^{(\pm)} = \frac{\hbar\left(2|m_i| \pm 1\right)}{2\mu R_1 R_2} \tag{6}$$

Here the upper signs correspond to absorption and down signs correspond to emission of photon. These diagonal by radial quantum number transitions take place between the discrete sublevels in the same "one-dimensional" subband and are connected only and only to the orbital motion of charge carriers.

1.b) transitions $\Delta|m| = \pm 1,\ \Delta n = 2k+1$

$$M_{f,i} \sim \frac{n_f n_i}{n_f^2 - n_i^2}\left[1 \mp \left(2|m_i| \pm 1\right)\frac{L^2}{R_1 R_2}\frac{1}{\left(n_f^2 - n_i^2\right)}\right] \tag{7}$$

$$\omega_{f,i} = \frac{\pi^2\hbar\left(n_f^2 - n_i^2\right)}{2\mu L^2} \pm \frac{\hbar\left(2|m_i| \pm 1\right)}{2\mu R_1 R_2} \tag{8}$$

These transitions take place between the different "one-dimensional" subbands in the same band. For these transitions the "film" factor is dominant, but the orbital motion modulate the intensity (7) and leads to splitting of "film" threshold frequency to two frequencies (8). In the sense of electronic states modification, the application of radial field does not influence "directly" on the orbital motion of charge carriers but as the perturbation theory shows, it leads to a "Stark-like" shift of its radial confinement energy levels. The value of this shift depends on the intensity of field (γ) and on the geometrical sizes L, R_1 of the sample:

$$\Delta E_n \cong \frac{\gamma L}{2R_1} + \frac{\left(\gamma L\right)^2}{48 R_1^2 \varepsilon_1 n^2}\left(1 - \frac{15}{\pi^2 n^2}\right) \tag{9}$$

Here γ is the effective "interaction constant" between the field's source and particle. At the same time the field leads to spatial modulation of both the amplitude and the phase of radial envelope functions. Thus $\alpha_{n,m} r \to \alpha_{n,m} r + \beta_n r$ - in the amplitude, and $1 \to 1 + \beta_n r$ - in the phase of radial envelope wave function (2). Here $\beta_n L \sim \alpha_{n,m} L$, and $\beta_n = \beta_n(\gamma, L, n)$. As a result we'll observe narrowing of localization area of the particle in the layer under the presence of the field. Correspondingly the field effectively increases (decreases) the rotation radius of particle when the repulsion (attraction) between the particle and charged core takes place.

The comparative analysis of optical spectrum of intersubband transitions under the radial field with the case without the field demonstrates the following:

1) when the diagonal ($\Delta n = 0$) transitions take place, the new modulating field factor in Exp. (5) emerges:

$$M_{n,n}^{(\pm)} \to M_{n,n}^{(\pm)}\left(1 + \frac{\beta_n L}{4n^2 - \beta_n L}\right) \tag{10}$$

At the same time the field doesn't change the threshold frequency (6).

2) The matrix element from Exp.(7) is modulated by corresponding field factor as well. These field factors increase when the intensity of field increases and decrease with increasing of the quantum numbers.

3) The threshold frequencies from Exp.(8) sift under the influence of field to short-wave region. The deviation of frequency is defined by Stark-like shift from Exp.(9).

4) the new "satellite" intersubband transitions are possible in the presence of radial field when Δn is even and their intensities increase with the increasing of field. The threshold frequencies of these transitions has the same form as in the case of odd Δn.

It is evident here that one can contr5ol the optical energy parameters of the structure changing the geometrical sizes of the sample and the field intensity.

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