Physica E 64 (2014) 7–14

Contents lists available at ScienceDirect

Physica E

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

Electroabsorption in a narrow gap semiconductor nanotube in the field of uniformly charged ring

V.A. Harutyunyan [a,*], E.M. Kazaryan [a], H.A. Sarkisyan [a,b]

[a] *Russian-Armenian (Slavonic) University, Yerevan, Armenia*
[b] *Yerevan State University, Yerevan Armenia*

HIGHLIGHTS

- Interband and intraband electrooptical transitions in nanotube are considered.
- In the field of homogeneously charged ring.
- The field of the charged ring is brought to the field of the modified one dimensional Coulomb-like potential.

ARTICLE INFO

Article history:
Received 11 April 2014
Received in revised form
21 June 2014
Accepted 25 June 2014
Available online 4 July 2014

Keywords:
Electroabsorption
Nanotube
Charged ring

ABSTRACT

The electronic states as well as interband and intraband electrooptical transitions are considered for the narrow gap InSb nanotube in the field of homogeneously charged ring. The problem is solved in the framework of the variational approach. The field of the charged ring is brought to the field of the modified one dimensional Coulomb-like potential. Physically appropriate wave functions are suggested for this potential and the intensities of the threshold frequencies of the electrooptical transitions are calculated.

1. Introduction

Semiconductor nanowires and nanotubes exhibit novel electronic and optical properties due to their unique structural one-dimensionality and possible quantum confinement effects in two dimensions. With a broad selection of compositions and band structures, these one-dimensional semiconductor nanostructures are considered as a good candidate for element base of nanoscale semiconductor devices of new generation [1].

Group III–V semiconductors i.e., InAs, InP, GaAs, GaP, and InSb, have attracted substantial scientific and technological interests in nanoelectronic devices due to their high electronic transfer characteristic with low leakage currents [2]. Among the elements of III–V group, indium antimony (InSb) is a promising direct-bandgap semiconductor material with zinc blende structure. Due to its narrow band gap (for bulk sample: $E_g = 0.17$ eV, at 300 K [3]), InSb is extensively used in the fabrication of infrared optical detectors, infrared homing missile guidance systems, and infrared astronomy [4–6]. A significant advantage of InSb is that it has extremely high electron mobility (electron mobility of 77,000 cm^2 V^{-1} s^{-1}) which is the result of the natural small effective mass and the ballistic length (up to 0.7 μm at 300 K) higher than those of any known semiconductor [7,8]. However, there are some limitations of the detectors using bulk InSb, such as high dark current and the requirement of cryogenic temperatures. These problems may overcome by using InSb nanowires, because quantum confinement in one-dimensional (1D) nanowires leads to their unique optoelectronic properties. Dark current of nanowire-based photodetectors will be reduced significantly due to the size shrinkage and phonon scattering suppression in nanostructures, resulting in a higher operating temperature.

Hence, there is significant interest in the investigation of the properties of InSb for potential application in nano-optoelectronic devices [9]. It is known [10] that the valence band in this compound disintegrates into non-interacting bands of light holes, heavy holes and the band of spin–orbit interaction. While the dispersion law for heavy holes (hh) is parabolic, it is no longer parabolic for light holes (lh) and electrons (e) and it coincides by the form with the relativistic dispersion law. It is apparent that non-parabolicity of the dispersion law will necessarily be

* Corresponding author.
E-mail address: volharut@gmail.com (V.A. Harutyunyan).

http://dx.doi.org/10.1016/j.physe.2014.06.023
1386-9477/

displayed in the character of physical properties of layered nanostructures. Therefore it is important to study the physical properties of the InSb nanotubes taking into account the complicated dispersion law for electrons and holes. Note that in earlier work [11] the optical properties of InSb cylindrical layered quantum dot has been studied in the presence of axial magnetic and weak electric fields. On the other hand on the example of InSb, the authors of [12] have considered the influence of a strong homogeneous electric field on the quantum states of carriers in a narrow gap cylindrical layer in the case of Kaine dispersion law. From the experimental point of view it is important to mention Ref. [13], where the authors inform about realization of InSb quantum dots and dashes.

In this paper on the example of InSb we theoretically investigate the influence of electrostatic field of charged ring on the energy spectrum of charge carriers in narrow gap semiconductor nanotube (NBSNT). The special features of electroabsorption in the tube in the presence of this field are considered as well.

The paper is organized as follows: in Section2 we describe the general modeling approaches of the problem. In Section3 we obtain the analytical expressions for the wave functions and energy spectrum of heavy and light charge carriers in nanotube in the presence of external field. In Section4 we discuss the electro-optical interband and intraband transitions in the mentioned system. The Conclusions are presented in Section 5.

2. General approach and approximations

The system we consider is an infinite tube (along the z-axis) with cylindrical symmetry.

Let us assume that we are considering a cylindrical nanotube that is placed in the external field of a uniformly charged thin ring. The both axis of the tube and the charged ring are directed along the z coordinate.

The calculation of the electrostatic potential ϕ which is generated by the charged ring [14,15] inside the tube leads to the following expression:

$$\phi(r,R,z)=\frac{4\gamma R}{\sqrt{(R+r)^2+z^2}}\int_0^{\pi/2}\frac{d\vartheta}{\sqrt{1-k^2\sin^2\vartheta}};\left(k^2=\frac{4rR}{(R+r)^2+z^2}\right). \quad (1)$$

Here γ – is the linear density of electric charge on the ring, r – is the radial variable in the layer ($r\in[R_1,R_2]$, R_1,R_2- are the inner and outer radii of the tube), R- is the ring radius and the angle ϑassociated with the polar angle φ by following relation: $2\vartheta=\pi-\varphi/2$ (Fig. 1).

It has been assumed that the confining potential of quantized heterolayer of the tube can be approximated, in radial direction, by the quantum well "rolled-up into a tube" [15]:

$$U_{conf}(r)=\begin{cases}0, & when \quad R_1<r<R_2\\ \infty, & when \quad r\le R_1, r\ge R_2\end{cases}. \quad (2)$$

For example, in the case of InSb/InP heterostructure, the widths of the band gaps differ approximately 8 times and the model of infinitely high barriers is reasonable for low energy levels.

It is also assumed, that the layer is "thin enough" and lies fairly far from the symmetry axis (z):

$$L\ll R_1,\ R_2;(L=R_2-R_1) \quad (3)$$

and, that the following condition takes place as well:

$$R_1,R_2\ll R. \quad (4)$$

At the same time we will also restrict the analysis with the strong confinement in the tube when the Coulomb interaction between the electron and hole in the layer can be neglected in comparison with the confinement energies of transversal motion of charge carriers. This means that the thickness of the layer L is sufficiently smaller than the Bohr radius a_L of the bulk exciton in the layer material:

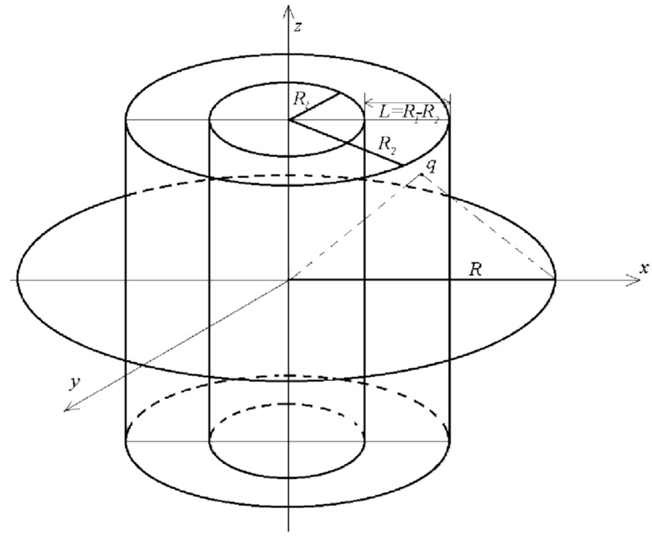

Fig. 1. Geometry of the problem.

$$L\ll a_L \quad (5)$$

As it is mentioned above the InSb valence band splits into heavy hole (μ_{hh}) and light (μ_{lh}) hole subbands. Neglecting the band of spin–orbit interaction, in the Kane's two-band model, the dispersion law for heavy holes is quadratic:

$$E^{hh}(\vec{p})=\frac{\vec{p}^{\,2}}{2\mu_{hh}}, \quad (6)$$

and the dispersion law for light holes (lh)and electrons of the conduction band is given by the following expression [16]:

$$E^c(\vec{p},s)=E^{lh}(\vec{p},s)=\sqrt{\vec{p}^{\,2}s^2+\mu_c^2s^4};(s\sim10^8\ \text{cm/s}) \quad (7)$$

In the literature the values of effective mass of the heavy holes (μ_{hh}) are varied from $\mu_{hh}=0,4m_0$to$\mu_{hh}=0,5m_0$ (m_0- free electron mass) and for light holes (μ_{lh}) and conduction band electrons ($\mu_c,\mu_c=\mu_{lh}$) these values are varied from $\mu_c=0.013m_0$ to $\mu_c=0.018m_0$ [3,16]. Correspondently, values from $a_L\sim60$ nm to $a_L\sim100$nm are given for Bohr radius of the bulk exciton. In this paper we investigate the behavior of the charge carriers in "strong quantization regime", when condition (6) takes place. Further, for numerical estimations we will use the following values of the relevant parameters:

$$\mu_c=\mu_{lh}=0.014m_0,\ \mu_{hh}=0.42m_0,\ R_1=15\div60\ \text{nm}, L=5\div20\ \text{nm},$$
$$E_g=0.17\ \text{eV},\ \ a_L=60\ \text{nm}.$$

In the previous works of some authors it has been shown that if the conditions (4) and (6) take place one can use the adiabatic approximation in the case of the absence of external field ($\phi=0$) [17]. For wave functions and energy spectrum of transversal motion of heavy and light carriers in the tube at $\phi=0$ we have, respectively [17]:

$$\psi_{hh}(r,\varphi)=\phi_n(r)f_m(\varphi)=\sqrt{\frac{2}{L}}\frac{\sin\ \pi n/L(r-R_1)}{\sqrt{r}}\frac{e^{im\varphi}}{\sqrt{2\pi}}, \quad (8)$$

$$E_{trs}^{hh}=\frac{\pi^2\hbar^2n^2}{2\mu_{hh}L^2}+\frac{\hbar^2(m^2-1/4)}{2\mu_{hh}R_n^2}\equiv E_{rad}^{hh}+E_{rot}^{hh};$$