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THEORY OF FREE-CARRIER ABSORPTION IN CYLINDRICAL QUANTUM WIRES

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Abstract* : *A theory of free - carrier absorption is given for cylindrical quantum wires when carriers are scattered by longitudinal – optical (LO) and acoustic phonons and the radiation field is polarized along the length of the wire. The free – carrier absorption coefficient is found to be function of the photon frequency and of the wire radius.

Keywords: quantum wire, free-carrier absorption, size quantization effect

1. INTRODUCTION

Recently there has been considerable interest in systems in which electron motion is confined to one or two dimensions. The most interesting situation occurs when the confinement is on the order of the de Broglie wavelength for confined electrons. In a quantum wire, when it's the width becomes much less than the mean free path, the motion of the electrons within becomes quasi-one-dimensional. In one dimensional system, the motion of electrons is restricted in two dimensions, so they can flow freely in one dimension. The motion of electrons in such semiconducting structures thus leads to size quantization effect [1-14].

Optical and transport properties of low –dimensional semiconductor structures are important part of the modern physics of semiconductors. The mobility of electrons in rectangular [1-3] and cylindrical [4-7] quantum wire has been investigated theoretically for many different scattering mechanisms. The free carrier absorption is well-known as a good tool for investigating the scattering mechanisms of carriers and hence, can be used to probe electron-phonon scattering processes. The free carrier absorption of electromagnetic wave was considered in quantum wells [8-10] and in rectangular quantum wires [11-13]. However, in cylindrical quantum wires, the free carrier absorption of electromagnetic waves is still open for studying. A cylindrical quantum wires is formed by a cylindrical wire of material one (such as GaAs) whose length is very much larger than radius, embedded in material two where the band-gap is much larger that it is in material one (such as AlGaAs).

In this paper, we present the theory of free carrier absorption for quasi one dimensional electron gas in cylindrical quantum wires when carriers are scattered by optical and acoustic phonons. We consider the free carrier absorption for cases where the radiation field is polarized along the length of the wire.

2. FORMALISM

We assume that the electrons are confined to move in a cylindrical wire of radius R and are free to move along the axis of the wire, which is of length L. Within the framework of effective-mass approximation the electron wave function in quantum wire is given by [7,14]

$$\Psi_{nlK}(r)=\frac{\exp(iKz)\exp(il\vartheta)}{(\pi R^2 L)^{1/2}}\varphi_{nl}(\rho) \qquad (1)$$

where

l=0,1,2,3,…, n=1,2,3,…,

$$\varphi_{nl}(\rho)=\frac{J_l(k_{nl}\rho)}{J_{l+1}(k_{nl}R)} \qquad (2)$$

here r is (ρ,ϑ,z), ϑ is the azimuthal angle about the wires, K is the wave vector of the electron along the z axis, which is chosen along the axis of the cylindrical wire, $J_l(x)$ is the Bessel function of the first kind with order l. In order to satisfy the boundary condition that $\Psi(\rho=R)=0$, k_{nl} is the nth zero of $J_l(k_{nl}R)$.

The eigenvalues corresponding to Eq.(1) are

$$E_{nlk}=E_k+\frac{\hbar^2 k_{nl}^2}{2m^*} \qquad (3)$$

where E_k is the electron kinetic energy along the z direction, and m^* is the electron effective mass. When the de Brogile wavelength of electrons becomes comparable to the transverse dimensions of the wire, the electrons are confined to their lowest quantum state as far as their transverse motion is concerned ($n=1$, $l=0$ for a cylindrical wire) while their motion along the axis of the wire is unaffected [15]. For such a ground state wave function k_{10} =2.403/R.

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The FCA coefficient α, which is related to the quantum-mechanical transition probabilities in which the carriers absorb or emit a photon with the simultaneous scattering of the carriers from phonons, is given by [12]

$$\alpha = \frac{\in^{1/2}}{n_0 c}\sum_i W_i f_i$$

here $\in$ is the dielectric constant of material, n_0 is the number of photons in the radiation field and f_i is the free-carrier distribution function. The sum is over all the possible initial states *'i'* of the system. The transition probabilities W_i can be calculated using the standard second-order Born golden rule approximation:

$$W_i = \frac{2\pi}{\hbar}\sum_{fq}\left[\left|\langle f|M_+|i\rangle\right|^2\delta\left(E_f - E_i - \hbar\Omega - \hbar\omega_q\right) + \left|\langle f|M_-|i\rangle\right|^2\delta\left(E_f - E_i - \hbar\Omega + \hbar\omega_q\right)\right] \quad (4)$$

here E_i and E_f are the initial and final state energies, respectively, of electrons, $\hbar\Omega$ is the photon energy, $\hbar\omega_q$ is the phonon energy, and $\langle f|M_\pm|i\rangle$ are the transition matrix elements from the initial state to the final state for the interaction between electrons, photons and phonons. This transition matrix elements can be represented by

This transition matrix elements can be represented by

$$\langle f|M_\pm|i\rangle = \sum_\alpha\left(\frac{\langle f|H_R|\alpha\rangle\langle\alpha|V_s|i\rangle}{E_i - E_\alpha \mp \hbar\omega_q} + \frac{\langle f|V_s|\alpha\rangle\langle\alpha|H_R|i\rangle}{E_i - E_\alpha - \hbar\Omega}\right) \quad (5)$$

where H_R is the interaction Hamiltonian between the electrons and the radiation field, V_s is the scattering potential due to the electron-phonon interaction.

Using the wavefunctions given by expression (1), the matrix elements of the electron-photon interaction Hamiltonians can be written as

$$\langle n'l'K'|H_R|nlK\rangle = -\frac{e\hbar}{m^*}\left(\frac{2\pi\hbar n_0}{V\Omega\in}\right)^{1/2}(\varepsilon K)\delta_{KK'}\delta_{ll'}G_{nl,n'l'}(R) \quad (6)$$

where V is the volume of the crystal. Here the radiation field is polarized along the wire, ε is the polarization vector of the radiation field. In this expression, it is difficult to determine the explicit forms of the matrix element $G_{nl,n'l'}(R)$. So, in the following calculation we will only make use of the radial wave function for the ground state employed recently by [16]. In this case

$$G(R) = \left|G_{nl,n'l'}\right|^2 = \int_0^R \rho\varphi_{10}^4(\rho)d\rho$$ [7].

Since we are interested in the ground state approximation, we may employ the approximate radial wave function proposed in [16]

$$\varphi_{10} \approx \sqrt{3}\left[1 - \frac{\rho^2}{R^2}\right]$$

which gives the corresponding $G(R) = \frac{9R^2}{12}$ [7].

The matrix elements of electron-phonon interaction depend on scattering mechanism:

$$\langle f|V_s|\alpha\rangle = C_{nl}(q_z)I_{n'l',n''l''}(q_{nl})\delta_{K',K''+q_z}$$

where

$$I_{n'l',n''l''}(k_{n'l'}R) = 2\int_0^1 \xi d\xi \frac{1}{J_{l'+1}(k_{n'l'}R)J_{l''+1}(k_{n''l''}R)}J_n(k_{n'l'}R\xi)J_{|n'-n''|}(k_{n''l}R\xi)J_{n''}(k_{n''l''}R\xi)$$

The interaction between electrons and optical phonons confined in a cylindrical nanowire is treated within the dielectric continuum model [17]. In this case

$$\left|C_{n,l,q_z}^{LO}\right|^2 = \frac{e^2\hbar\omega_{LO}}{2\pi\varepsilon_0 LR^2 J_{n+1}^2(k_{nl}R)^2(k_{nl}^2 + q_z^2)}\left(\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_S}\right)$$

ε_0 is the vacuum permittivity; ε_s and ε_∞ are respectively the static and high-frequency relative permittivities.

We consider the deformation potential interaction with acoustic phonons confined laterally in the nanowire. In principle, the boundary condition couple longitudinal acoust beeic (LA) and transverse acoustic (TA) modes. Coupled LA-TA modes interacting with electrons have been considered by [18]. In this case

$$\left|C_{nl,q_z}^{LA}\right|^2 = \frac{D^2\hbar\sqrt{k_{nl}^2R^2 + R^2q_z^2}}{2\pi RL\mu c_s J_{n+1}^2(k_{nl}R)}$$

where c_s the sound celerity, μ is the material density, D is the deformation potential of the band of interest.

CONCLUSIONS

We have investigated theoretically the intraband absorption of electromagnetic radiation for an electron system interacting with phonons in cylindrical quantum wires structures. It is shown that free carrier absorption becomes considerably enhanced as wire radius decreases. It was predicted in [7] that the relaxation rate in cylindrical quantum wires structures increases as the radius of the wire diminish.

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