FREE CARRIERS LIGHT ABSORPTION IN SEMICONDUCTIVE QUANTUM WIRES AT THE ELECTRON SCATTERING ON THE ALLOYED DISORDER

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The theory of free-carriers light absorption is developed in quasi-one dimensional triple semiconductive structures at the carriers scattering on the alloyed disorder and the direction of the photons polarization along the wire length. Obtained expressions for the absorption coefficient show the oscillatory dependence on the photons frequency and on the area of the wire cross-section. The absorption coefficient grows with the reduction of semiconductive wires cross sizes. Obtained results are compared with those of the quasi-two-dimensional case. The examined absorption is compatible with that, caused by the electron-photon interaction.

Last years semiconductive heterostructures are successfully used in optic and microelectronics. The modern technology allows to create semiconductive heterostructures with quantum wells and quantum points. The quantum wires research is of great interest, so far as it's possible to observe in these systems optical and kinetic properties, untypical for massive crystals.

In ultrathin semiconductive wires, called usually wires with the quantum well, carriers are quantized in two cross directions, move only along the wire length and behave as quasi-one- dimensional electron gas. Optical electron transitions are widely investigated for a long time in various quantum nanostructures. Particularly, free carriers light absorption (FCA) in quantum wells is investigated in details in papers [1-11].

FCA in the quantum wires is mainly examined at the scattering on photons [12-13]. However, if the material of the quantum well is the solid solution, then it's necessary to take into account the electron scattering on the alloyed disorder side by side with the simple scattering mechanism. This additional scattering process comes because of the disordering atoms locations in the alloy lattice nodes. The electron scattering in triple structures [14-17] and quantum wells on the base of triple semiconductors are investigated in many papers [18-24].

The purpose of the present paper is to examine the light absorption by the quasi-one-dimensional (Q1D) electron gas at the electrons scattering on the alloyed disorder.

We consider the quantum wire from the alloy, marked by a symbol $A_{1-x}B_xC$. We put down the well-known expression for the energy spectrum and wave function of the electron in the rectangular wire

$$\mathrm{E}_{knl} = \mathrm{E}_k + \mathrm{E}_n + \mathrm{E}_l = \frac{\hbar^2 k^2}{2m^*} + n^2 \mathrm{E}_a^0 + l^2 \mathrm{E}_b^0,$$

$$\boldsymbol{E}_a^0 = \frac{\boldsymbol{p}^2 \hbar^2}{2m^* a^2} \quad , \quad \boldsymbol{E}_b^0 = \frac{\boldsymbol{p}^2 \hbar^2}{2m^* b^2} \qquad n, l = 1,2,3,\ldots , \qquad (1)$$

$$\boldsymbol{Y}_{knl} = \left[2/\left(abL\right)^{1/2}\right] \sin\left(\boldsymbol{p}nx/a\right) \sin\left(\boldsymbol{p}ly/b\right) \exp\left(ikz\right),$$

Where a and b are cross sizes, L is the wire length. In quasi -one –dimensional systems the second order of the perturbation theory is used at the FCA coefficient calculation. The matrix transition element from the state knl into the state $k'n'l'$ is determined by the following formula:

$$< k'n'l'|M|knl >= \sum_{k''n''l''} \left[\frac{< k'n'l'|H_R|k''n''l'' >< k''n''l''|H_{dis}|knl >}{E_{knl} - E_{k''n''l''}} + \frac{< k'n'l'|H_R|k''n''l'' >< k''n''l''|H_{dis}|knl >}{E_{knl} - E_{k''n''l''} + \hbar\Omega} \right] \qquad (2)$$

Where indices $nlk, n''l''k''$ and $n'T'k'$ denote the initial, intermediate and final electron states, Ω is the photon frequency, H_R is the electron-photon interaction operator, H_{dis} is the scattering potential on the alloyed disorder. The matrix element of electrons interaction with photons is equal to

$$\left\langle k'n'l' \left| H_R \right| knl \right\rangle = -\frac{\mathring{a}\hbar}{m^*} \left(\frac{2\boldsymbol{p}\hbar n_0}{V\Omega\in} \right)^{1/2} (e\hat{e}) \boldsymbol{d}_{\hat{e}\hat{e}'} \boldsymbol{d}_{nn'} \boldsymbol{d}_{ll'}, \qquad (3)$$

Where $\in$ is the high-frequency dielectric constant, n_0 is the photons number in the radiation field, ε is the polarization vector, V is the crystal volume. Here electromagnetic waves are polarized along the wire length (in the x direction)

When the quantum well consists of triple semiconductors (like $Ga_{1-x}In_xAs$). Then in the approximation of the virtual crystal the electron scattering potential on the alloyed disorder has the form [18,25-26]:

$$H_{dis} = dV\left\{(1-x)\sum_{r_{In}} Y_{\Omega_0}(r-r_{In}) - x\sum_{r_{Ga}} Y_{\Omega_0}(r-r_{Ga})\right\}, \quad (4)$$

Where $Y_{\Omega_0}(r_a - r_b) = 1/\ \Omega_0$, when r_a *and* r_b are inside of the same unity cell and vanish elsewhere, and summations run over all unit cell, Ω_0 is the volume of the unit cell. At such potential form, the matrix transition element from the state *knl* into the state $k'n'l'$ has the form;

$$\langle k'n'l'|\mathrm{H}_{dis}|knl\rangle = dV\left[\frac{\Omega_0}{V}x(1-x)\left(1+\frac{1}{2}d_{nn'}\right)\left(1+\frac{1}{2}d_{ll'}\right)\right]^{1/2} \quad (5)$$

We receive for the transition rate at the transition from the initial state into the final state

$$W_{knl,k'n'l'} = \frac{4p^2 å^2 n_0 (dV)^2 \Omega_0 x(1-x)}{m*^2\ \Omega^3 \in V^2}\sum_{n'l'}\left(1+\frac{1}{2}d_{n\,n'}\right)\left(1+\frac{1}{2}d_{ll'}\right)|k'-k|^2 \cdot d\left(E_{k'n'l'} - E_{knl} - \hbar\Omega\right) \quad (6)$$

The absorption coefficient is calculated by summation of all occupied initial and unoccupied final states. We receive for the FCA coefficient at the electron scattering on the alloy disorder:

$$a = \frac{2p å^2 (dV)^2 W_0 x(1-x)}{\hbar^4 W^3 \in^{1/2}\ (ab)^2 c} \times$$
$$\times \sum_{nl}\sum_{n'l'}\left(1+\frac{1}{2}d_{nn'}\right)\left(1+\frac{1}{2}d_{ll'}\right)\iint \frac{(E_{k'}+E_k)}{\sqrt{E_{k'}}\sqrt{E_k}}(f_{knl} - f_{knl})d(E_{k'n'l'} - E_{knl} - \hbar W)dE_{k'}dE_k \quad (7)$$

where f_{knl} is the electron distribution function. In the case of the nondegenerate electron gas:

$$f_{knl} = \frac{(2p)^{1/2}\hbar n_e ab}{gd\left(m^* K_B T\right)^{1/2}} exp\left[\frac{n^2 E_n^0 + l^2 E_n^0}{K_B T}\right] exp\left(-\frac{\hbar^2 k^2}{2m^* K_B T}\right) \quad (8)$$

where: $g = \sum_n \exp\left(-\frac{n^2 E_n^0}{K_B T}\right)$, $d = \sum_l \exp\left(-\frac{l^2 E_l^0}{K_B T}\right)$

here n_e is the electron concentration.

Substituting (8) in (7), we receive the formula for the FCA coefficient

$$a = \frac{2^{5/2} p^{3/2} å^2 (dV)^2 W_0 x(1-x) n_å (K_B T)^{1/2}}{c\hbar^3 W^3 \in^{1/2}\ abm^{*3/2} gd}\left(1 - exp\left(-\frac{\hbar W}{K_B T}\right)\right)\sum_{nl}\sum_{n'l'}\left(1+\frac{1}{2}d_{nn'}\right)\left(1+\frac{1}{2}d_{ll'}\right)\times$$
$$\times exp\left[-\frac{n^2 E_n^0 + l^2 E_l^0}{K_B T}\right] Z\, exp(Z) K_1(Z) \quad (9)$$

where:

$$Z = \frac{\hbar\Omega - E^0{}_n\left(n'^2 - n^2\right) - E^0{}_l\left(l'^2 - l^2\right)}{2K_B T}$$

Here $K_1(Z)$ is the modificated Bessel function. As it follows from (9), the FCA coefficient is the oscillatory function of the photons frequency and the cross size of the quantum wire.

Let's further analyse the simplest case of low temperatures, when electron occupies just the first subzone bottom. This situation is realized, when. $E_a/K_B T >> 1$, $E_l/K_B T >> 1$. If the quantum energy isn't enough for the electron transference in second and high subzones, then summands give the main contribution to (9) at $n = n¢ = l = l¢ = 1$. In this case we receive for the FCA coefficient:

$$\alpha = \frac{9\pi^{3/2}\hat{a}^2(d\grave{I}\ )^2\Omega x(1-x)}{\sqrt{2}\in^{1/2} ab(m^* K_B T)^{1/2} c\hbar^2\Omega^2}\exp\left(\frac{\hbar\Omega}{2K_B T}\right)\left(1-\exp\left(-\frac{\hbar\Omega}{2K_B T}\right)\right)K_1\left(\frac{\hbar\Omega}{2K_B T}\right) \quad (10)$$

It's known, that the absorption coefficient reduces as ω^2 in long waves limits and has the semiclassic form [27]. This expression, which will be received below; is considered as semiclassical, because the electron movement is quantum – mechanical, and the classic Drude theory takes into account the light interaction with electrons.

The semiclassical expression is obtained in approximation $K_BT>>\hbar\Omega$ for the nondegenerat electron gas. At the asymptotic application of the modified Bessel function for small argument values ($\frac{\hbar\omega}{2K_BT}$ <<1) the FCA coefficient has the form:

$$\alpha^{sc} = \frac{9\pi^{3/2}e^2(dV)^2\omega_0 x(1-x)n_e}{\sqrt{2\in ab(m^* K_B T)^{1/2} c\hbar^2\omega^2}} \quad (11)$$

Using the formula [24], for the electron gas at the scattering on the alloy

$$m = \frac{4\sqrt{2}eab\hbar^2}{9\sqrt{\pi}m^{*3/2}(dV)^2\omega_0 x(1-x)} \quad (12)$$

We receive

$$\alpha^{sc} = \frac{4\pi e^3 n_e}{\in^{1/2} m^{*2} c\omega^2 m} \quad (13)$$

For the comparison we present the absorption coefficient of the Q1D electron gas at the scattering on the acoustic phonon [13]:

$$\alpha_{a\tilde{n}} = \frac{2^{7/2}\sqrt{\pi}n_e e^2 E^2{}_d (K_b T)^{3/2}}{\in^{1/2} c\rho u^2{}_s m^{*1/2} abgd}\frac{\left[1-exp\left(-\frac{\hbar\omega}{K_B T}\right)\right]}{(\hbar\omega)^3}\times$$
$$\times\sum_{nl}\sum_{n'l'}\left(1+\frac{1}{2}\delta_{nn'}\right)\left(1+\frac{1}{2}\delta_{ll'}\right)exp\left[-\frac{n^2E_n^0+l^2E_l^0}{K_B T}\right]Z\exp(Z)K_1(Z) \quad (14)$$

From (10) and (14) we determine for $\alpha_{alloy}/\alpha_{ac}$

$$\frac{\alpha_{alloy}}{\alpha_{ac}} = \frac{\pi(dV)^2\omega_0 x(1-x)\rho u_s^2}{2E_d^2 K_B T} \quad (15)$$

Where ρ is the crystal density, υ_s is the sound velocity, E_d is the deformational potential. This ratio value estimation for $Ga_{0.47}In_{0.53}As$ –516/T, i.e. the scattering on the alloyed disorder gives the greater contribution to the common FCA coefficient, than on acoustic photons.

For comparison we present the FCA coefficient of the Q1D electron gas at the scattering on the alloyed disorder [11]

$$\alpha_{alloy}^{2d} = \frac{9\pi^2 e^2\Omega_0(dV)^2 n_e x(1-x)K_B T}{8\in^{1/2}\hbar^4 cd\omega^3}\left[1-\exp\left(-\frac{\hbar\Omega}{K_B T}\right)\right]\left(1+\frac{\hbar\Omega}{2K_B T}\right) \quad (16)$$

Where *d* is the quantum well thickness. As it follows from (15) and (10), $\frac{\alpha_{alloy}^{1d}}{\alpha_{alloy}^{2d}}$ has the form:

$$\frac{\alpha_{alloy}^{1d}}{\alpha_{alloy}^{2d}} = \frac{4\sqrt{2}e^{\frac{\hbar\Omega}{K_B T}}\left(1-e^{-\frac{\hbar\Omega}{2K_b T}}\right)K\left(\frac{\hbar\Omega}{2K_B T}\right)\hbar^2\Omega d}{\sqrt{\pi}abm^{*1/2}(K_B T)^{3/2}\left(1-e^{\frac{\hbar\Omega}{K_B T}}\right)\left(1+\frac{\hbar\Omega}{2K_B T}\right)} \quad (17)$$

Using asymptote of the modified Bessel function $K_1(Z)$ for greater argument values, we receive from (16)

$$\frac{\alpha_{alloy}^{1d}}{\alpha_{alloy}^{2d}} = \frac{2\sqrt{2}\hbar^{3/2}\pi^{1/2}d}{abm^{*1/2}\left(1+\frac{\hbar\Omega}{2K_BT}\right)K_BT} \qquad (18)$$

Graphs constructed by means of (9), are shown on fig.1-2. Schemes types correspond to the mentioned above analytical results on the FCA coefficient behaviour. Calculations were conducted for the absorption coefficient $Ga_{0.47}In_{0.53}As$. Peaks, which correspond to intersubzone transitions, are observed in frequency Ω (fig.1).

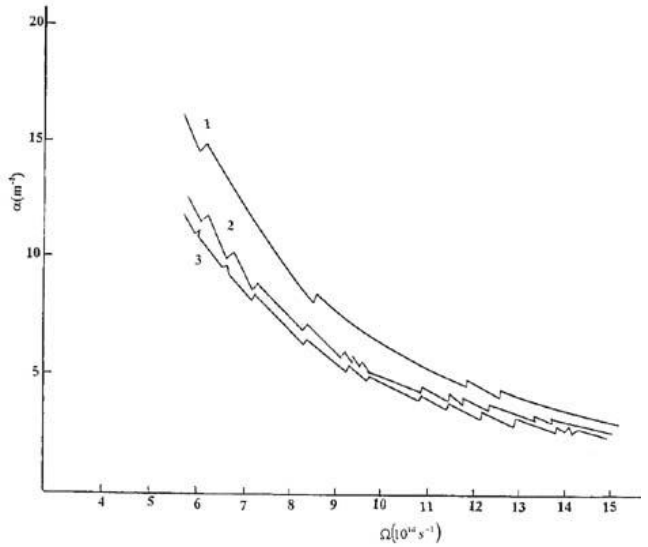

Fig 1. The free –carrier light absorption in a quantum wire is shown as a function of the photon frequency for the case of alloy-disorder scattering for various transverse sizes of the wire. We have chosen1.$a=b=10^{-6}$ñì; 2.$a=2\times10^{-6}$ñì; $b=10^{-6}$ñì; 3. $a=b=2\times10^{-6}$ñì.

In the dependence $\alpha(\Omega)$ peaks shift to the part of the high photons frequency at the reduction of cross sizes. It's connected with the fact, that the distance between subzones increase with the reduction of wire cross sizes. It was determined in [24], that the electron scattering on the alloyed disorder in Q1D structures grows with the reduction of wire cross sizes. Such rise is explained by the FCA coefficient growth with the reduction of semiconductive wire cross sizes. When the photon energy is higher, than the distance between various subzones, then the electron, simultaneously absorbing a photon, scatters and makes transitions in the same or other subzones. With the wire cross sizes reduction, the distance between neighbour subzones increases and then transitions occur by means of the alloyed scattering only in the same subzone. In this case, the absorption process depends on the rate of the electron on the alloyed disorder.

The dependence of the absorption coefficient α on the cross section is given on fig.2 for various values of waves lengths. It's seen from figure, that the absorption coefficient dependence on the area of the quantum wire cross section has the oscillatory form. Schemes, constructed by means of (18), are shown on fig.3.

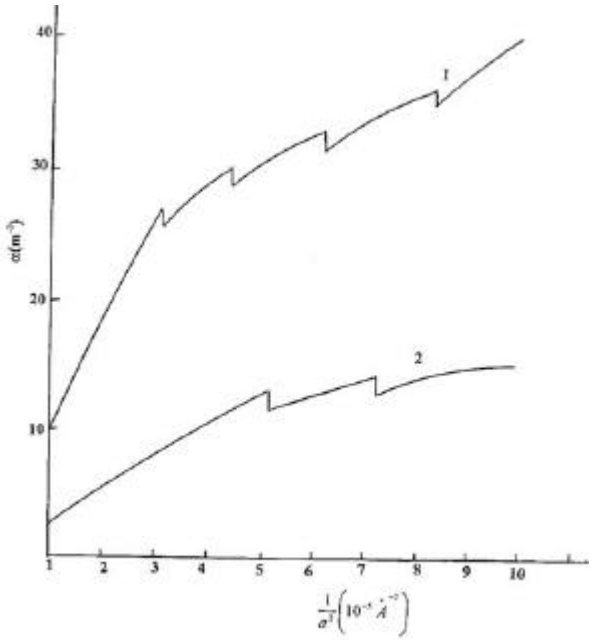

Fig. 2. The free-carrier absorption coefficient is shown as a function of the reciprocal of the cross section of the quantum well wire, $1/a^2$, at 300K. Curve 1is for the wavelength λ=5 μm and curve2 is for l=3μm

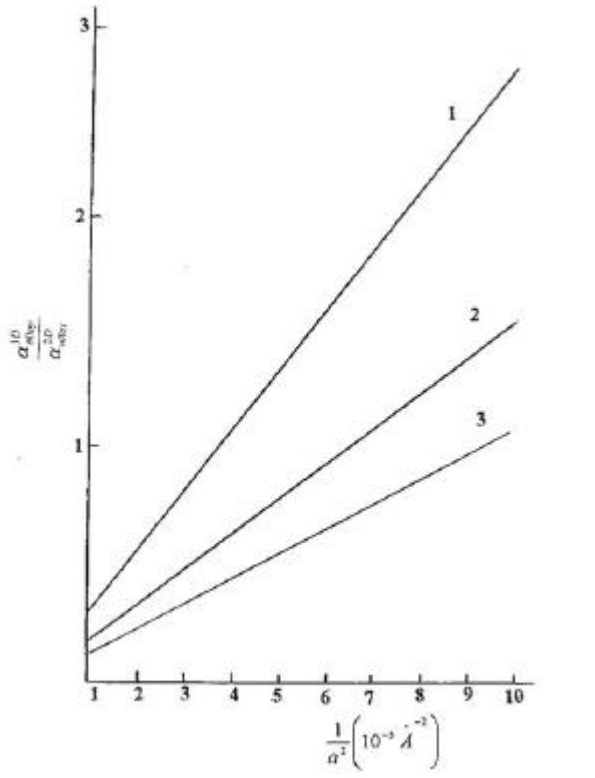

Fig. 3. The ratio of the free-carrier absorption in a quantum wire to its value in the quantum well is shown as a function of the reciprocal cross section of the quantum well wire $1/a^2$. Curve 1 is for the wavelength l=10μm, curve 2 is for the wavelength l=5μm, curve 3 for the wavelength l=3μm.

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