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Effect of electron–phonon scattering mechanisms on free-carrier absorption in quasi-one-dimensional structures

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Abstract

The free-carrier absorption in ultrathin wires fabricated from III–V semiconductors such as n-type InSb has been investigated for the case where the electrons are scattered either by polar optical phonons or acoustic phonons. We study the interaction of longitudinal polar optical phonons with electrons and have neglected the interaction between electrons and transverse optical phonons in solids. The energy band of electrons in semiconductors is assumed to be nonparabolic. The scattering mechanisms of the interaction between electrons and phonons we consider here come from (a) electron-polar–optical-phonon scattering, (b) electron–acoustic–phonon scattering, and (c) piezoelectric scattering in semiconductors. Results are shown that the free-carrier absorption coefficient for the deformation-potential coupling is much larger than that for the piezoelectric coupling. It is also shown that the free-carrier absorption coefficient for the electron-polar–optical-phonon scattering is smaller than that for the electron–acoustic–phonon scattering. However, the free-carrier absorption coefficient increases quite slowly with the photon frequency for the electron–acoustic–phonon scattering. This is not the same result as that for the quasi-two-dimensional semiconducting structures. © 2002 Published by Elsevier Science B.V.

Keywords: Semiconducting wires; Polar optical phonons; Acoustic phonons

1. Introduction

One-dimensional structures such as quantum wires have received a considerable attention in recent years because of their physical properties and their potential device applications [1,2]. The motion of electrons in such semiconducting structures is confined and leads to size quantization effects which play an important role in determining their optical and electronic properties. In this work, we investigate the intraband optical absorption in quantum-well wire structures due to the absorption of the photons by free electrons in the system and study the size quantization effect in quasi-one-dimensional structures. We consider a nondegenerate electron gas with a Maxwell–Boltzmann distribution for nondegenerate semiconductors. Here, it is assumed that the interaction between electrons and phonons originates from

(a) electron-polar–optical-phonon scattering,
(b) electron–acoustic–phonon scattering, and
(c) piezoelectric scattering in semiconductors.

2. Theory

For a rectangular thin wire of dimensions a and d, the eigenfunctions and eigenvalues for electrons

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in a semiconductor with nonparabolic band structure are given by [3]

$$\Psi_{k_x\ell n}(\mathbf{r}) = \frac{2}{V^{1/2}} b_{k_x\ell n}\, \mathrm{e}^{\mathrm{i}k_x x} \sin\left(\frac{\pi \ell y}{a}\right) \sin\left(\frac{\pi n z}{d}\right), \quad (1)$$

$$E_{k_x\ell n} = -\frac{1}{2}E_{\mathrm{g}}\left\{1 - \left[1 + \frac{4}{E_{\mathrm{g}}}\left\langle \frac{\hbar^2 k_x^2}{2m^*} + \frac{\pi^2\hbar^2}{2m^*} \times \left(\frac{\ell^2}{a^2} + \frac{n^2}{d^2}\right)\right\rangle\right]^{1/2}\right\}, \quad \ell, n = 1, 2, 3, \ldots, \quad (2)$$

where V is the volume of the thin wire, m^* is the effective mass of electrons in semiconductors, E_{g} is the energy gap between the conduction and valence bands, and $b_{k_x\ell n}$ is the annihilation operator of electrons, satisfying commutative relations of the Fermi type. The absorption coefficient for the absorption of photons can be expressed as [4]

$$\alpha = \frac{\varepsilon^{1/2}}{n_0 c}\sum_i W_i f_i, \quad (3)$$

where ε is the dielectric constant of the material, n_0 is the number of photons in the radiation field, f_i is the free-carrier distribution function, and W_i is the transition probability. The transition probability is given with the Born approximation

$$W_i = \frac{2\pi}{\hbar}\sum_f [|\langle f|M_+|i\rangle|^2 \delta(E_f - E_i - \hbar\Omega - \hbar\omega) + |\langle f|M_-|i\rangle|^2 \delta(E_f - E_i - \hbar\Omega + \hbar\omega)], \quad (4)$$

where E_i and E_f are the initial and final electron energies, $\hbar\Omega$ is the photon energy, and $\hbar\omega$ is the phonon energy. For the interaction between electrons, photons, and phonons, the transition matrix elements $\langle f|M_\pm|i\rangle$ can be calculated from the electron–phonon interaction Hamiltonian and different electron–phonon scattering mechanisms. The transition probabilities for different mechanisms are given as follows.

2.1. Electron-polar–optical-phonon scattering

$$W_i^{\mathrm{POP}} = \frac{2\pi^3 e^4 \hbar n_0 n_{\mathbf{q}} \omega(\Omega-\omega)^2}{\varepsilon\varepsilon'(m^*)^2\Omega V^2} \times \sum_{\ell_f, n_f}\Big[(\Omega+2\omega)^{-2}(2\Omega+\omega)^{-2}\Lambda^2_{\ell_i\ell_f}(q_y)\Lambda^2_{n_i n_f}(q_z) \times \delta(E_f - E_i - \hbar\Omega - \hbar\omega) + \Omega^{-2}(2\Omega-\omega)^{-2} \times \Lambda^2_{\ell_i\ell_f}(-q_y)\Lambda^2_{n_i n_f}(-q_z)\delta(E_f - E_i - \hbar\Omega + \hbar\omega)\Big] \times \left[2K^{1/2}(\ell_i,\ell_f;n_i,n_f) - L^{1/2}(\ell_i,\ell_f;n_i,n_f) \times \tan^{-1}\frac{2L^{1/2}(\ell_i,\ell_f;n_i,n_f)K^{1/2}(\ell_i,\ell_f;n_i,n_f)}{2L(\ell_i,\ell_f;n_i,n_f) - (\Omega/v_s)^2}\right], \quad (5)$$

where $\varepsilon' = (\varepsilon_\infty^{-1} - \varepsilon^{-1})^{-1}$, ε_∞ and ε are the high-frequency and static dielectric constants, respectively, and $n_{\mathbf{q}}$ is the number of phonons in the mode of a wave vector $\mathbf{q}$ in the thermal equilibrium. Moreover,

$$\Lambda_{nn'}(q) = \delta_{q,\pi(n'-n)/a} + \delta_{q,-\pi(n'-n)/a} - \delta_{q,\pi(n'+n)/a} - \delta_{q,-\pi(n'+n)/a} = \Lambda_{nn'}(-q), \quad (6)$$

$$K(\ell_i,\ell_f;n_i,n_f) = \left(\frac{\Omega}{v_s}\right)^2 - \left(\frac{\pi}{a}\right)^2(\ell_f-\ell_i)^2 - \left(\frac{\pi}{d}\right)^2(n_f-n_i)^2, \quad (7)$$

$$L(\ell_i,\ell_f;n_i,n_f) = \left(\frac{\pi}{a}\right)^2(\ell_f-\ell_i)^2 + \left(\frac{\pi}{d}\right)^2(n_f-n_i)^2. \quad (8)$$

2.2. Electron-acoustic phonon scattering

$$W_i^{\mathrm{ACP}} = \frac{\pi^2 e^2 n_0 E_{\mathrm{d}}^2 k_{\mathrm{B}} T(\Omega-\omega)^2}{3(m^*)^2\rho v_s^2 \varepsilon V^2\Omega} \times \sum_{\ell_f,n_f} K^{3/2}(\ell_i,\ell_f;n_i,n_f) \times [(\Omega+2\omega)^{-2}(2\Omega+\omega)^{-2} \times \Lambda^2_{\ell_i\ell_f}(q_y)\Lambda^2_{n_i n_f}(q_z)\delta(E_f - E_i - \hbar\Omega - \hbar\omega) + \Omega^{-2}(2\Omega-\omega)^{-2}\Lambda^2_{\ell_i\ell_f}(-q_y)\Lambda^2_{n_i n_f}(-q_z) \times \delta(E_f - E_i - \hbar\Omega + \lambda\omega)], \quad (9)$$

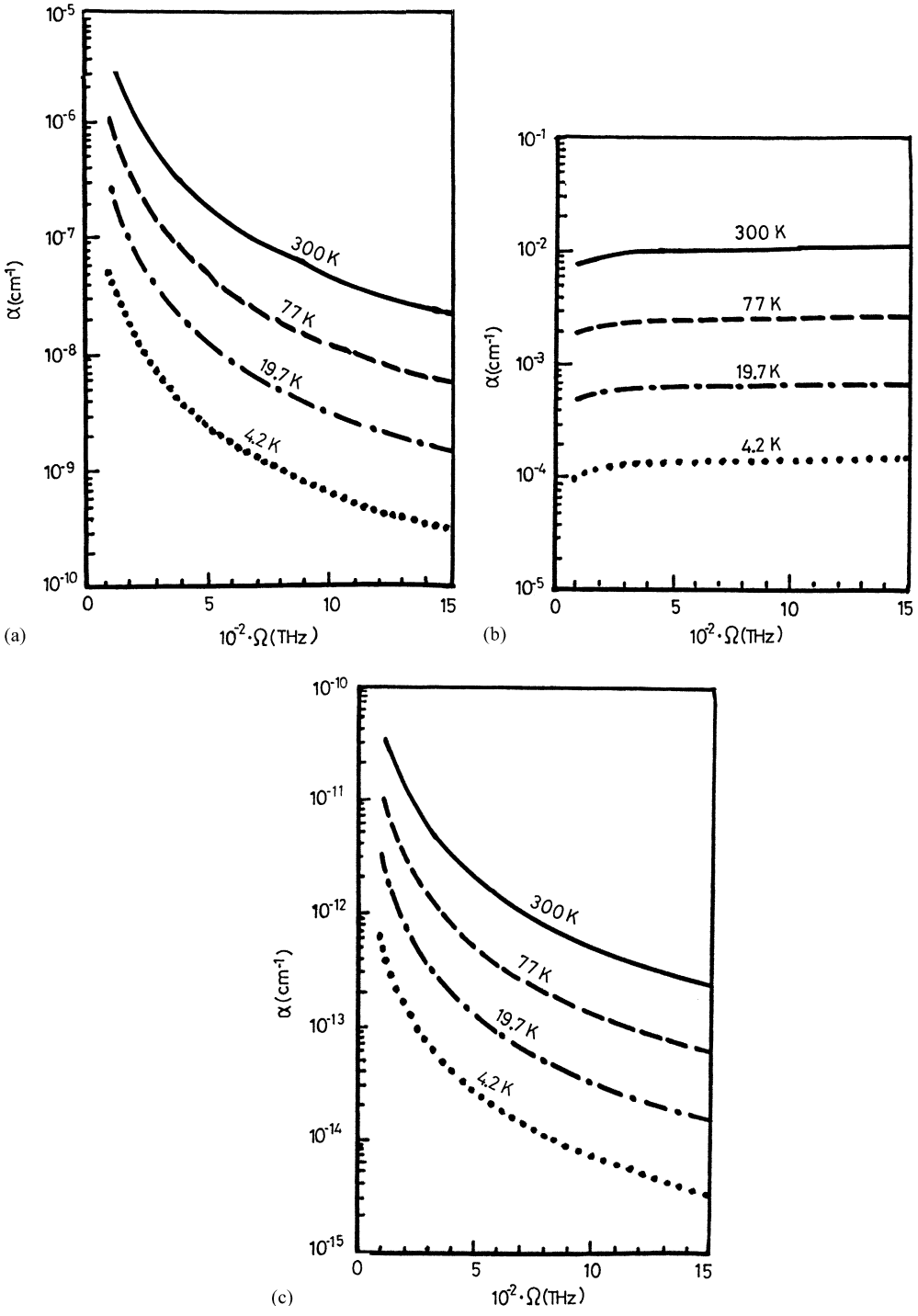

Fig. 1. (a) Free-carrier absorption coefficient in n-type InSb wires as a function of photon frequency with $a = 100$ Å and $d = 200$ Å for electron-polar–optical-phonon scattering. (b) Free-carrier absorption coefficient in n-type InSb wires as a function of photon frequency with $a = 100$ Å and $d = 200$ Å for electron–acoustic–phonon scattering. (c) Free-carrier absorption coefficient in n-type InSb wires as a function of photon frequency with $a = 100$ Å and $d = 200$ Å for piezoelectric scattering.

where ρ is the density of material and E_d is the deformation potential.

2.3. Piezoelectric scattering

$$W_i^P = \frac{\pi^2 e^4 \beta_P^2 n_0 k_B T(\Omega-\omega)^2}{2\varepsilon^3 (m^*)^2 \rho v_s^2 V^2 \Omega} \sum_{\ell_f, n_f} \left[(\Omega+2\omega)^{-2} \times (2\Omega+\omega)^{-2} \Lambda^2_{\ell_i \ell_f}(q_y) \Lambda_{n_i n_f}(q_z) \delta(E_f - E_i - \hbar\Omega - \hbar\omega) + \Omega^{-2}(2\Omega-\omega) \Lambda^2_{\ell_i \ell_f}(-q_y) \times \Lambda^2_{n_i n_f}(-q_z) \delta(E_f - E_i - \hbar\Omega + \hbar\omega) \right] \times \left[2K^{1/2}(\ell_i, \ell_f; n_i, n_f) - L^{1/2}(\ell_i, \ell_f; n_i, n_f). \times \tan^{-1} \frac{2L^{1/2}(\ell_i, \ell_f; n_i, n_f) K^{1/2}(\ell_i, \ell_f; n_i, n_f)}{2L(\ell_i, \ell_f; n_i, n_f) - (\Omega/v_s)^2} \right], \quad (10)$$

where β_P is the piezoelectric constant.

3. Numerical analysis

From Eqs. (3)–(6), (9) and (10), we can calculate the free-carrier absorption coefficient for different electron–phonon scattering mechanisms. The relevant values of physical parameters for n-type InSb ultrathin wires are taken to be [4,5] n_e (electron concentration) $= 1.75 \times 10^{14}\,\mathrm{cm}^{-3}$, $m^* = 0.013 m_0$ (m_0 is the mass of free electron), $\varepsilon = 18$, $\varepsilon_\infty = 16$, $E_g = 0.2\,\mathrm{eV}$, $E_d = 4.5\,\mathrm{eV}$, $\rho = 5.8\,\mathrm{gm/cm}^3$, $\beta_P = 1.8 \times 10^4\,\mathrm{esu/cm}^2$, $v_s = 4 \times 10^5\,\mathrm{cm/s}$, and $\omega = 5.5 \times 10^{13}\,\mathrm{rad/s}$. In Fig. 1(a), the free-carrier absorption coefficient α in n-type InSb for a quasi-one-dimensional structure is plotted as a function of the photon frequency when the electron-polar–optical-phonon scattering is dominant. It is shown that α decreases monotonically with increasing the photon frequency and increases with increasing temperature. This is similar to what is predicted to occur in quasi-two-dimensional structures when the free carriers are scattered by polar optical phonons [5]. In Fig. 1(b), the free-carrier absorption coefficient is plotted as a function of the photon frequency when the electron–acoustic–phonon scattering is dominant. It can be seen that α increases with increasing the photon frequency initially and then increases quite slowly in the high photon frequency region. This is not the same result as that for quasi-two-dimensional structures when the electrons are scattered by acoustic phonons [6]. In Fig. 1(c), the free-carrier absorption coefficient is plotted as a function of the photon frequency when the piezoelectric scattering is dominant in semiconductors. It shows that α decreases monotonically with increasing the photon frequency and increases with increasing temperature. However, the numerical results of α for the piezoelectric scattering are much smaller than those for other two kinds of phonon scatterings.

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