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Effect of nonparabolicity on free-carrier absorption in n-type InSb films for polar optical phonon scattering

Chhi-Chong Wu[a,]*, Chau-Jy Lin[b]

[a] *Institute of Electronics, National Chiao Tung University, Hsinchu, Taiwan*
[b] *Department of Applied Mathematics, National Chiao Tung University, Hsinchu, Taiwan*

Abstract

The free-carrier absorption in n-type InSb films has been studied for quantum well structures fabricated from III–V semiconducting materials where the polar optical phonon scattering is predominant. We consider here two special cases: the electromagnetic radiation is polarized parallel to the layer plane and perpendicular to the layer plane separately. The energy band of electrons in semiconductors is assumed to be nonparabolic. Results show that when the electromagnetic radiation is polarized parallel to the layer plane, the free-carrier absorption coefficient is independent of temperature in a small quantum well region such as $d < 30$ Å, but the absorption coefficient oscillates with the quantum well and depends upon the temperature in the region of larger quantum wells. When the electromagnetic radiation is polarized perpendicular to the layer plane, the dependence of the free-carrier absorption coefficient on the quantum well and temperature becomes quite complicated. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Free-carrier absorption; Optical phonon scattering; Electromagnetic radiation

1. Introduction

Due to the confinement of carriers in quasi-two-dimensional structures, the size quantization will play an important role to determine the transport properties of carriers in semiconductors. In addition to the direct interband and intersubband optical transitions, the optical absorption can take place via indirect intrasubband optical transitions in which the carriers absorb a photon with simultaneous scattering of carriers from phonons, ionized impurities and other imperfections in semiconductors [1]. Such free-carriers absorption accounts for the absorption of the electromagnetic radiation with frequencies Ω lower than those which give rise to interband transitions in semiconductors, i.e., $\hbar\Omega < E_g$, where E_g is the energy gap between the conduction and valence bands. It has been found that the free-carrier absorption coefficient depends upon the polarization of the electromagnetic radiation relative to the direction normal to the quasi-two-dimensional structure, the width of quantum wells, the photon frequency, and temperature when the free carriers are scattered by acoustic phonons [2]. In this work, we investigate the free-carrier absorption in quasi-two-dimensional semiconducting structures when the polar optical phonon

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*Corresponding author. Fax: + 886-3-5724361; e-mail: chhiwu@cc.nctu.edu.tw.

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scattering of free carriers is dominant and the processes involve both emission and absorption of polar optical phonons in solids. We neglect the effect of screening on the interaction between carriers and the polar optical phonons by using an unscreened potential for the polar optical phonon scattering potential.

2. Theory and numerical results

For carriers confined to move in a quasi-two-dimensional system, the free-carrier absorption coefficient can be expressed as [1,3]

$$\alpha = \frac{\varepsilon^{1/2}}{n_0 c}\sum_i (W_i^{\mathrm{abs}} - W_i^{\mathrm{em}}) f_i, \tag{1}$$

where ε is the dielectric constant of the material, n_0 is the number of photons in the radiation field, and f_i is the carrier distribution function. The transition probabilities are given by

$$W_i^{\mathrm{abs,em}} = \frac{2\pi}{\hbar}\sum_{f,j}\left(\frac{\langle f|H_{\mathrm{rad}}|j\rangle\langle j|V_{\mathrm{s}}|i\rangle}{E_j - E_i \mp \hbar\omega} + \frac{\langle f|V_{\mathrm{s}}|j\rangle\langle j|H_{\mathrm{rad}}|i\rangle}{E_j - E_i - \hbar\Omega}\right)^2 \times \delta(E_f - E_i - \hbar\Omega \mp \hbar\omega). \tag{2}$$

Here, E_i and E_f are the initial and final energies, respectively, of electrons, and $\hbar\omega$ is the optical phonon energy. The electron–photon interaction Hamiltonian is given by

$$H_{\mathrm{rad}} = -\left(\frac{e}{m^*}\right)\left(\frac{2\pi\hbar n_0}{\varepsilon\Omega V}\right)^{1/2}\hat{\varepsilon}\cdot\boldsymbol{p}, \tag{3}$$

where $\hat{\varepsilon}$ is the polarization vector of radiation, V the volume of the material, and $\boldsymbol{p}$ is the electron momentum. The scattering potential is given by [4,5]

$$V_{\mathrm{s}} = \mathrm{i}e\omega\left(\frac{4\pi}{\varepsilon' V}\right)^{1/2}\sum_q \frac{\boldsymbol{q}\cdot\hat{\varepsilon}_q}{|\mathrm{q}|^2} \times [\exp(-\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r})Q_q^* - \exp(\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r})Q_q], \tag{4}$$

where $\boldsymbol{q}$ is the wave vector of polar optical phonons, Q_q^* and Q_q are creation and annihilation operators for optical phonons, $\hat{\varepsilon}_q$ is the polarization vector of optical phonons and $\varepsilon' = (1/\varepsilon_\infty - 1/\varepsilon_0)$, where ε_∞ is the optical dielectric constant and ε_0 is the static dielectric constant.

For electrons confined to move in the x–y plane in a semiconductor with the nonparabolic energy band [6], the eigenvalues E_{kn} are given by the relation

$$E_{kn}\left(1 + \frac{E_{kn}}{E_{\mathrm{g}}}\right) = \frac{\hbar^2 \boldsymbol{k}^2}{2m^*} + \frac{(\pi\hbar n)^2}{2m^* d^2}, \quad n = 1, 2, 3, \ldots, \tag{5}$$

while the corresponding eigenfunctions Ψ_{kn} are given by

$$\Psi_{kn} = \left(\frac{2}{V}\right)^{1/2} b_{kn}\exp(\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x})\sin\left(\frac{n\pi z}{d}\right), \tag{6}$$

where m^* is the effective mass of electrons, d the width of quantum wells, $\boldsymbol{k} = (k_x, k_y)$ the electron wave vector in the x–y plane, and b_{kn} is the annihilation operator of electrons satisfying commutative relations of the Fermi type. From Eqs. (1)–(6), the

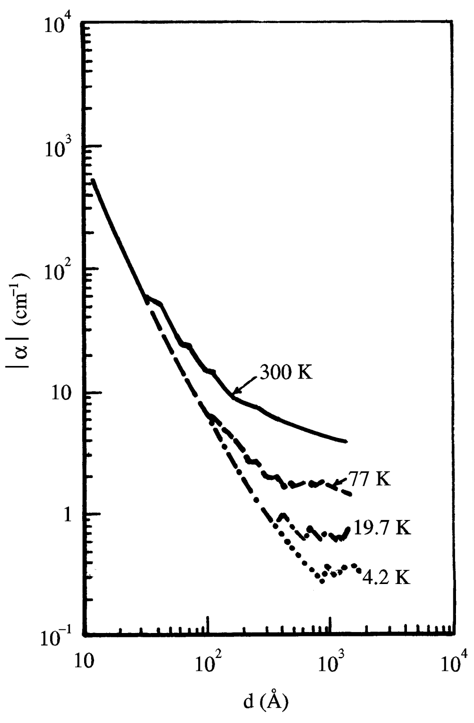

Fig. 1. Free-carrier absorption coefficient as a function of the quantum well width with $\Omega = 28$ THz for the radiation field polarized parallel to the layer plane.

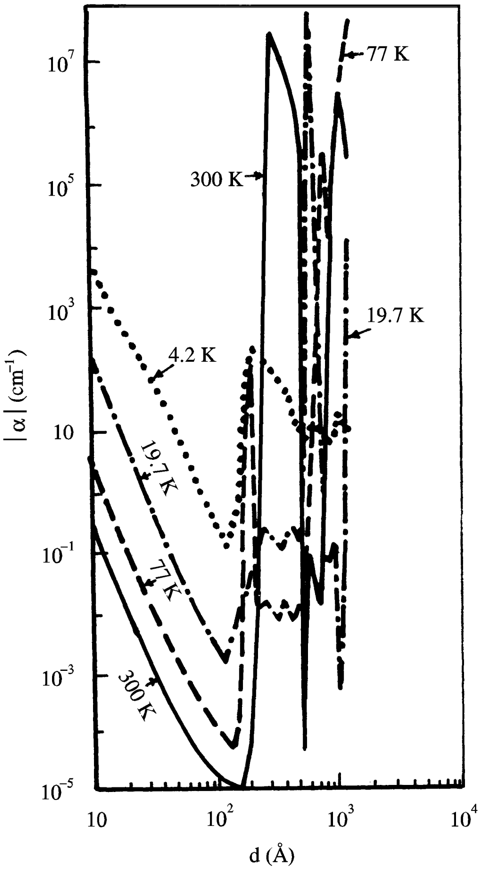

Fig. 2. Free-carrier absorption coefficient as a function of the width of quantum wells with $\Omega = 28$ THz for the radiation field polarized perpendicular to the layer plane.

free-carrier absorption coefficient for a quasi-two-dimensional electron gas can be obtained.

The relevant values of physical parameters for an n-type InSb thin film are taken to be [2,6] n_e (the electron concentration in semiconductors) $= 1.75 \times 10^{14}\,\mathrm{cm}^{-3}$, $m^* = 0.013\, m_0$ (m_0 is the free electron mass), $\varepsilon = \varepsilon_0 = 18$, $\varepsilon_\infty = 16$, $E_g = 0.2$ eV, $v_s = 4 \times 10^5$ cm/s, and the optical phonon angular frequency $\omega = 5.5 \times 10^{13}$ rad/s.

In Fig. 1, the free-carrier absorption coefficient decreases with increasing width of quantum wells, and increases with increasing temperature at the photon frequency $\Omega = 28$ THz for the radiation field being polarized parallel to the layer plane. It is also shown that the free-carrier absorption coefficient oscillates with the width of quantum wells at large quantum wells. However, as the width of quantum wells decreases, the dependence of temperature on the free-carrier absorption coefficient disappears in lower temperatures.

In Fig. 2, the free-carrier absorption coefficient is plotted as a function of the width of quantum wells for the radiation field being polarized perpendicular to the layer plane. It shows that the free-carrier absorption coefficient changes discontinuously with the width of quantum wells. Thus the dependence of the free-carrier absorption coefficient on the quantum well and temperature becomes quite complicated when the electromagnetic radiation is polarized perpendicular to the layer plane.

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