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Intersubband optical absorption in GaAs parabolic quantum well due to scattering by ionized impurity centers, acoustical and optical phonons

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ABSTRACT

The intersubband absorption linewidth dependence on well width in GaAs quantum well is calculated. Three mechanisms of scattering have been discussed there: carriers scattering by optical (LO), acoustic (LA) phonons and ionized impurity centers (ION). The method which used for calculations is similar to a well-known method of calculating transport mobility. The estimation for absorption coefficient is proposed, based on two-dimensional dynamical conductivity expression. The LO phonon emission process is activated starting from some quantum well (QW) width so it has its impact on absorption linewidth.

1. Introduction

Intersubband transitions (ISBT) in QW have a huge interest currently due to their unique characteristics: great ability to customize the wavelength of transitions, ultrafast relaxation, many-body effects, etc. [1–5].

The importance of this can be found not only in terms of fundamental physics but also the development of new technological applications. Many devices are developed based on ISBT in semiconductor quantum wells, such as infrared photodetectors [6–8], intersubband laser [9], optical switches [10], ultrafast optical modulators [11], etc. These transitions play even bigger and key role in improving the performance of quantum cascade lasers [12].

It is important to a have detailed understanding of processes behind ISBT in this context. The performance of devices based on IBST depends on its properties, such as the transition line shape broadening. The mechanisms of the broadening depend on various scattering processes. The lack of correlation between transport broadening and intersubband linewidth brings to the need of detailed consideration of different scattering mechanisms input into intersubband absorption linewidth.

The intersubband linewidths have been measured for various well widths [13], temperatures [14], alloy compositions [13], and doping positions [15] in different QWs. According to those results, the absorption linewidth has a weak dependence on temperature and alloy composition. Also, it has little correlation with mobility. However, its strong well-width dependence suggests that the main contribution is from interface roughness scattering.

In a paper [16], authors discussed the effect of interface roughness scattering on linewidth by comparing calculations based on a theory by Ando [17] and experimental data for modulation-doped GaAs/AlAs QWs with a well width of 80°A. The results show that linewidth is much more sensitive to interface roughness scattering than transport mobility is, because the contribution from the intrasubband scattering in the first excited subband is much larger than that in the ground subband [16]. Even in wide GaAs QWs, where interface roughness scattering should be less effective, recent reports [18,19] showed that interface roughness scattering has a larger effect on linewidth than either electron-electron scattering or bulk impurity scattering.

However, due to further development of heterostructures growing techniques it is quite natural to expect, that the contribution of interface roughness scattering mechanism should decrease. Thus, the detailed discussion of other scattering mechanisms, mainly phonon and ionized impurity scattering mechanism, are still actual and need more detailed investigation. Furthermore, quantitative estimation of intersubband absorption coefficient in QWs is still actual.

To calculate broadening due to scattering by LO, LA phonons and ION in order to compare their respective contributions to intersubband absorption linewidth, we apply the method described in Ref. [20], based on Ando's theory [17]. Moreover, we offered a way to estimate absorption coefficient based on a formula for the two-dimensional (2D) dynamical conductivity.

From the other side, there is a need to consider a more realistic model of the confining potential, which takes into consideration both the physical and chemical properties of the structure and its geometry. Different models were applied for confinement potentials in low-dimensional systems for these purposes (see e.g. Refs. [21,22]). In the

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first approximation, the confinement potential can be approximated by a parabolic one [24]. It should be mentioned, that the ideal parabolic approximation works better for comparably low levels. So, we may suppose, that QW confinement potential may appear as:

$$V_{conf}(z) = \frac{m^*\omega_0^2 z^2}{2}, \tag{1}$$

where m^* is the effective mass of electron, ω_0 is the frequency of QW confinement potential, defined with the help of virial theorem and equals [24,25]

$$\omega_0 = \frac{\gamma\hbar}{m^* L^2}, \tag{2}$$

where γ is some fitting parameter.

2. Scattering rates

The absorption linewidth theory for ISBT in 2D systems was formulated by Ando [10,17] for elastic scatterers in case of single-particle excitation. Absorption lineshape for transitions between the lowest subbands is described as real part of 2D dynamical conductivity:

$$\mathrm{Re}\,\sigma_{zz}(\omega) = \frac{e^2 f_{10}}{2m^*}\int \frac{m^*}{\pi\hbar^2} dE f(E) \frac{\hbar\Gamma_{\mathrm{op}}(E)}{(\hbar\omega - E_{10})^2 + \Gamma_{\mathrm{op}}(E)^2}, \tag{3}$$

where

$$\Gamma_{\mathrm{op}}(E) = \frac{1}{2}[\Gamma_{\mathrm{intra}}(E) + \Gamma_{\mathrm{inter}}(E)], \tag{4}$$

where $\Gamma_{\mathrm{intra}}(E)$ and $\Gamma_{\mathrm{inter}}(E)$ are intrasubband and intersubband scattering terms [17], respectively, e is the electron charge, $\hbar$ − reduced Planck constant, m^* − the electron effective mass, f_{10} − the oscillator strength, $E_{10} = (E_1 - E_0)$ − intersubband energy difference between lowest subbands, $f(E)$ − Fermi distribution function at temperature T. It is suggested, that all electrons are initially in the ground subband. As in Ref. [20], the full width at half maximum of the spectrum given by Equation (4) as $2\Gamma_{\mathrm{op}}$.

The total scattering rate (broadening) can be obtained as the sum of rates for different scattering mechanisms, such as scattering by interface roughness (IFR), LO phonons, LA phonons, alloy disorder (AD), and ionized impurities (ION):

$$\Gamma_{\mathrm{op}}(E) = \Gamma_{\mathrm{op}}^{(IFR)}(E) + \Gamma_{\mathrm{op}}^{(LO)}(E) + \Gamma_{\mathrm{op}}^{(LA)}(E) + \Gamma_{\mathrm{op}}^{(AD)}(E) + \Gamma_{\mathrm{op}}^{(ION)}(E) + \ldots \tag{5}$$

As mentioned above, in this paper we discuss the following scattering mechanisms: LO, LA phonons and ION. We perform numerical calculations for a single QW with a parabolic confinement potential, and the origin of the z axis is set at the center. Material constants are taken for a GaAs QW.

Thus, an electron wave function is given by

$$\varphi_{n,\vec{k}_{/\!/}}(\vec{\rho}, z) = \sqrt{\frac{1}{S}}\, e^{i\vec{k}_{/\!/}\vec{\rho}}\zeta_n(z), \tag{6}$$

where

$$\zeta_n(z) = \frac{1}{\sqrt{2^n n!}}\left(\frac{\gamma}{\pi L^2}\right)^{1/4} e^{-\frac{\gamma z^2}{2L^2}} H_n\left(\frac{\sqrt{\gamma}z}{L}\right), \tag{7}$$

2.1. Scattering on LO phonon

In this section three-dimensional (3D) polar optical (LO) phonons scattering is considered, as they are hardly confined to QWs. For phonon emission processes the scattering matrix element is given by Ref. [23]:

$$\langle|M_{3D}|^2\rangle = \frac{2\pi e^2\hbar\omega_{\mathrm{LO}}(N_{\mathrm{LO}}+1)}{Q^2}\left(\frac{1}{\kappa_\infty} - \frac{1}{\kappa_0}\right) \tag{8}$$

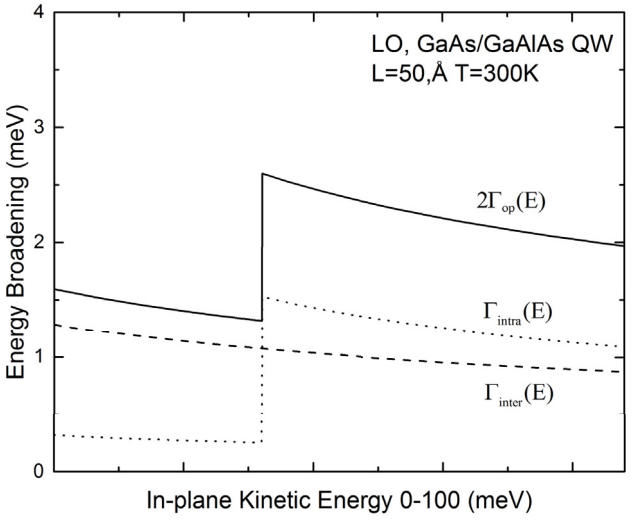

Fig. 1. The dependence of $\Gamma_{\mathrm{inter}}^{(\mathrm{LO})}(E)$, $\Gamma_{\mathrm{intra}}^{(\mathrm{LO})}(E)$ and $2\Gamma_{\mathrm{op}}(E)$ due to LO phonon scattering on in-plane kinetic energy. LO phonon energy is 36.5 meV and QW width is $L = 50$ Å.

Accordingly, for absorption processes:

$$\langle|M_{3D}|^2\rangle = \frac{2\pi e^2\hbar\omega_{\mathrm{LO}}N_{\mathrm{LO}}}{Q^2}\left(\frac{1}{\kappa_\infty} - \frac{1}{\kappa_0}\right), \tag{9}$$

where Q is the absolute value of the scattering vector, κ_∞ is the optical dielectric constant, ω_{LO} is the LO phonon frequency, and N_{LO} is the LO phonon occupation.

Expressions for scattering rates are described in Ref. [20], and here we present the numerical results.

Fig. 1 shows $\Gamma_{\mathrm{inter}}^{(\mathrm{LO})}(E)$, $\Gamma_{\mathrm{intra}}^{(\mathrm{LO})}(E)$ and $2\Gamma_{\mathrm{op}}(E)$ dependence on carriers in-plane kinetic energy due to LO phonon scattering for temperature $T = 300$K and for QW width of $L = 50$ Å. As it can be seen from the figure, intrasubband scattering rate is greater than intersubband rate for energies $E > \hbar\omega_{\mathrm{LO}}$ and $E_{10} > \hbar\omega_{\mathrm{LO}}$. The first condition assures phonons emission for intrasubband scattering, which brings to abrupt increase of intrasubband scattering rate. The second one provides continuous behavior for intersubband scattering rate (see wider QW case below). If $E < \hbar\omega_{\mathrm{LO}}$ only phonon absorption occurs for intrasubband scattering. But for rather narrow QWs, when $E_{10} > \hbar\omega_{\mathrm{LO}}$ (for opposite condition – see below), intersubband scattering rate is greater than intrasubband rate.

2.2. Scattering on LA phonon

LA phonon scattering, which is acoustic phonon scattering via deformation potential coupling, is treated as elastic. The scattering matrix element for both LA phonon emission and absorption processes is [26]:

$$\langle|M_{3D}|^2\rangle = \frac{k_B T D^2}{2c_l}, \tag{10}$$

where D − the deformation potential constant, c_l − longitudinal elastic constant. Note that Equation (10) does not depend on the scattering vector. The reason is the linear dispersion relation of LA phonons. Thus, for intersubband scattering rate we have:

$$\Gamma_{\mathrm{inter}}^{(LA)}(E) = \frac{m^* k_B T D^2}{2c_l}\int_0^\pi d\theta \int_0^\infty dz\,[\xi_0(z)\xi_1(z)]^2 = \frac{1}{2}\sqrt{\frac{\gamma}{2\pi}}\frac{m^* k_B T D^2}{L\hbar^2 c_l}, \tag{11}$$

and for intrasubband scattering rate: