Optical Absorption in GaAs/AlGaAs Quantum Well due to Intersubband Transitions

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Intersubband transition in quantum wells have strong potential for device application and are challenging field of fundamental studies. In this paper, intersubband optical absorption in GaAs/AlGaAs quantum well is investigated. Using a simple numerical approach and mathematical modeling applied to the first two conduction subbands, simplified expression for the optical absorption is obtained. The results obtained shows that the dephasing and other scattering mechanism have impact on absorption peaks and can only be tolerated to certain limits.

1 Introduction

Since the early years of quantum well studies, intersubband transitions in quantum well (QW) structures have attracted much attention. Both theoretical and experimental investigation were carried out by different researchers [1].

Rybalko et al. [2] proposed new approach to study light absorption in tunnel-coupled GaAs/AlGaAs quantum wells for electro-optic. In addition, Refs. [3] report the investigation of the effect of intersubband optical transitions of the magnetic field and tilt angle. Many physical effects of a semiconductor in quantum well structures have been exploited, such as infrared photodetectors [4, 5]. Furthermore, intersubband transitions in a multiple quantum well (MQW) structures were reported in Refs. [6–8]. Numerical investigation for absorption spectra induced by an ultrafast infrared pulse on the double quantum well structure were studied by Wu [9].

In this paper, we will derive the equation of optical absorption in GaAs/AlGaAs quantum well, by the modified version of Lorentzian approximation that is well proven itself in describing of electronics properties of these semiconductors. The equation obtained will be numerically solved and discussed.

2 Model Equation

We consider an intersubband transition in a P-conduction band $n_{12} = 1, 2$, interacting with photon energy governed by

$$E_n = \frac{n\hbar^2}{2m_e^*}\left(\frac{\pi}{L}\right)^2, \qquad (1)$$

where m_e^* is the electron effective mass in the conduction band, L is the length of the quantum well, $\hbar$ is the reduced Planks constant and the transition energy ΔE between the two subbands is obtained from $E_{12} = E_2 - E_1$.

After projection of the photon energy along the dipole moment, the optical absorption coefficient as in Ref. [10] can be written as

$$\alpha(\hbar\omega) = \frac{2\pi\omega}{n_r V c \epsilon_0} \sum_{\vec{k}_t} \mathrm{g}\left(E_b - E_a - \hbar\omega\right)\left|\hat{e}\,\vec{\mu}_{ba}\right|^2 (f_b - f_a), \quad (2)$$

where ω is the frequency of the photon energy, n_r is the refractive index, c is the velocity of light, $\mathrm{g}\left(E_b - E_a - \hbar\omega\right)$ is the line shape function, e the electronic charge, μ_{ba} is the intersubband dipole moment, V is the volume of the entire material, ϵ_0 is the permittivity of the material, f_b and f_a are the carrier densities populating subbands a and b, respectively. We consider numerically calculated transition adjusted to a simple Lorentzian approximation given by

$$\mathrm{g}\left(\Delta E\right) = \frac{1}{\pi}\frac{(\Gamma/2)}{\Delta E^2 + (\Gamma/2)^2}, \qquad (3)$$

where Γ is the linewidth. Therefore the modified Lorentzian approximation in terms of photon energy can be written as

$$\mathrm{g}(\Delta E - \hbar\omega) = \frac{1}{\pi}\sum_{1\neq 2}\frac{(\Gamma/2)}{(\Delta E - \hbar\omega)^2 + (\Gamma/2)^2}, \qquad (4)$$

where ΔE and $\hbar\omega$ are the transition photons energy between subband $(1, 2)$ and the adjusted frequency, respectively. However, transition $(2, 1)$ occurs at the top conduction subband corresponds to the highest subband, after photon emission with electrons being annihilated from subband $a = 1$ to $b = 2$. Therefore, setting $(\Delta E - \hbar\omega) = 0$, in (4) one gets

$$\mathrm{g} = \frac{1}{\pi}\frac{1}{(\Gamma/2)}, \qquad (5)$$

where Γ is the resulting Lorentzian broadening term, which we refer as dephasing energy in the subbands. Furthermore, the dipole moment is obtained by normalization of the enveloped wavefunction along the quantum well growth direction z, which is due to the electron excitation by the light

beam this can be expressed in the form

$$\mu_{21} = e \int_0^{L_z} \psi_2(z)\, z\, \psi_1(z)\, dz, \qquad (6)$$

where

$$\psi_1(z) = \sqrt{\frac{2}{L_z}} \sin\left(\frac{\pi}{L_z} z\right) \qquad (7)$$

and

$$\psi_2(z) = \sqrt{\frac{2}{L_z}} \sin\left(\frac{2\pi}{L_z} z\right). \qquad (8)$$

However, to solve for the intersubband dipole moment we substituted (7) and (8) into (6), we get

$$\mu_{21} = \frac{2e}{L_z} \int_0^{L_z} \sin\left(\frac{2\pi}{L_z} z\right) z \sin\left(\frac{\pi}{L_z} z\right) dz. \qquad (9)$$

Integrating eq. (9) simplifies to

$$\mu_{21} = -\frac{16}{9\pi^2} e L_z. \qquad (10)$$

Equation (10) is the resulting dipole moment of the quantum well. We will now analyze the absorption coefficient due to intersubband transition in quantum well of GaAs/AlGaAs. Equation (10) lead to the absorption related to absorption coefficient of the intersubband governed by

$$\alpha(\hbar\omega) = \frac{\pi\omega}{n_r\, c\, \epsilon_0}\, g\,(\Delta E - \hbar\omega)\, |\mu_{21}|^2\, (N_2 - N_1), \qquad (11)$$

where N_1 and N_2 are the population densities of the 1st and 2nd subbands, respectively.

However, when $N_2 = 0$, in which $E_1 < E_F < E_2$ in subband 1, then one finds

$$\alpha(\hbar\omega) = \frac{\pi\omega}{n_r\, c\, \epsilon_0}\, g\,(\Delta E - \hbar\omega)\, |\mu_{21}|^2\, N_1, \qquad (12)$$

which is proportional to doping concentration. Furthermore, with $E_2 < E_F$ in subband 2, then

$$N_1 = \frac{m_e^* k_B T}{\pi \hbar^2 L_z} \ln\left[1 + e^{\left(\frac{E_F - E_1}{k_B T}\right)}\right], \qquad (13)$$

where k_B is Boltzmann's constant, T is the temperature and E_F is the Fermi energy. Equation (13), can be simplified to

$$N_1 \approx \frac{m_e^*}{\pi \hbar^2 L_z} (E_F - E_1), \qquad (14)$$

and subsequently,

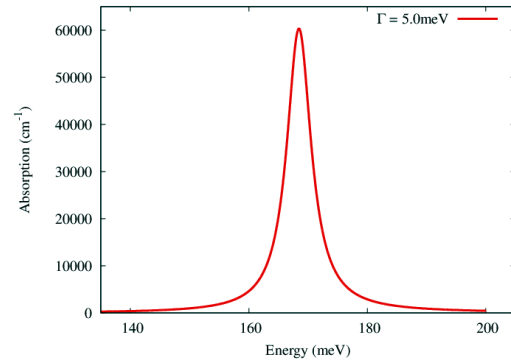$$N_2 \approx \frac{m_e^*}{\pi \hbar^2 L_z} (E_F - E_2). \qquad (15)$$

Fig. 1: Absorption spectra as a function of the incident photon energy in GaAs/AlGaAs dephasing energy $\Gamma = 5.0\, meV$.
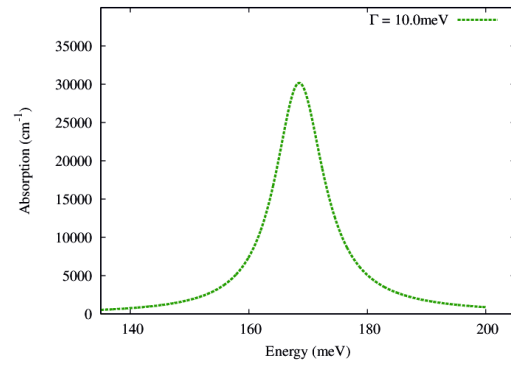

Fig. 2: Absorption coefficient against photon energy with dephasing energy $\Gamma = 10.0\,$meV.

Finally, the optical absorption coefficient can be written as

$$\alpha(\hbar\omega) = \frac{\pi\omega}{n_r c \epsilon_0}\, g\,(\Delta E - \hbar\omega)\left(\frac{16}{9\pi^2} e L_z\right)^2 \qquad (16)$$

which is independent of doping concentration. The peak absorption is obtain where $\Delta E = \hbar\omega$ and can be expressed as

$$\alpha_{max}(\hbar\omega) = \frac{\omega}{n_r c \epsilon_0}\, \frac{1}{(\Gamma/2)}\left(\frac{16}{9\pi^2} e L_z\right)^2 N. \qquad (17)$$

3 Results and Discussion

The result obtained for the absorption coefficient in the quantum well structure is computed and plotted using Equation (16) for 10 Å quantum well width and different dephasing energy. In figure 1, we plotted the optical absorption spectra as a function of photons energy with dephasing energy $\Gamma = 5.0\,$meV. Figure 2 - 4 show absorption spectra with dephasing energies $\Gamma = 10.0, 15.0$ and $20.0\,$meV, respectively. In our result, one could clearly see that the absorption peaks decreases as the different dephasing energies are increase as shown in figure 5.
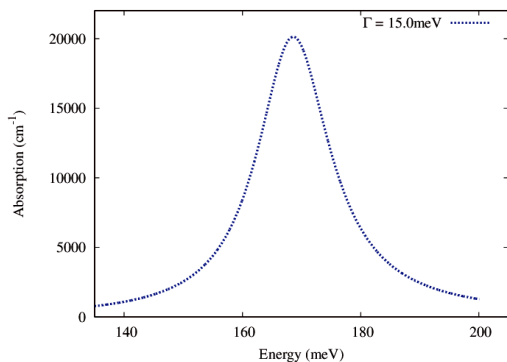
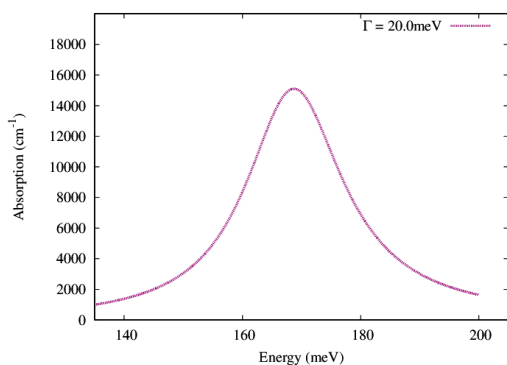Fig. 3: Absorption coefficient against photon energy with dephasing energy $\Gamma = 15.0$ meV.

Fig. 4: Absorption coefficient as a function of the photon energy with dephasing energy $\Gamma = 20.0$ meV.
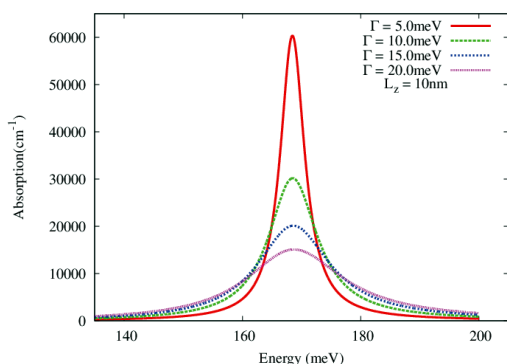

Fig. 5: Absorption coefficient as a function of the photon energy with various dephasing energy $\Gamma = 5.0, 10.0, 15.0$ and 20.0 meV and $L_z = 10$ nm.

4 Conclusion

On conclusion, we have showed the impacts of dephasing mechanism in the study of intersubbands optical absorption in GaAs/AlGaAs quantum well. Simulation results for transitions between the first two conductions subbands clearly re-

vealed that, the optical absorption decreases with increasing the dephasing as indicated in figure 5. This effects can be controlled by adjusting the carries densities populating the lower subband or controlling the quantum well width, which will be presented in our next publications.

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