NONLINEAR TRANSITIONS IN SINGLE, DOUBLE, AND TRIPLE $\delta$-DOPED GaAs STRUCTURES

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Abstract. In this study, the intersubband optical absorption coefficient and the refractive index change in single, double, and triple delta-doped GaAs structure will investigate for the uniform doping distribution model. The electronic properties of the structure such as potential profile, subband energies and wave functions will be calculated by solving the Schrödinger and the Poisson equations self-consistently. Dependence on different doping wells of the intersubbands nonlinear transitions is more important for potential variations in photodetectors and optical modulators. These structures will play a key role in researches of quantum electronics and photonic devices in future.

Key words: Nonlinear optics, self consistently, delta-doped, absorption coefficient, refractive index change.

1. INTRODUCTION

The studies on quantum heterostructures open a new range in fundamental physics, and also offer a wide field of potential applications for optoelectronic devices [1–2]. In addition, modern material growth techniques, such as the Molecular-Beam Epitaxy (MBE) and Metal Organic Chemical Vapor Deposition (MOCVD), conduce to the accelerated development of research in this area. By changing the profile of a semiconductor quantum well (QW), both the subband state energy levels and their wave functions vary, and so do various physical properties depending on them. Due to a large diversity of technological applications, the semiconductor quantum well structures have been commonly investigated in different situations including external perturbations, such as magnetic, electric and intense laser fields and distinct doping processes.

A typical $\delta$-doped semiconductor contains a sheet of impurity atoms located within a few atomic layers of crystal and thus the doping profile along the growth direction $z$ can be described by Silicon is widely used as the $n$-type dopant in GaAs growth using MBE. When Si donors are localized into an atomic plane during epitaxial growth, a sheet of ionized donors produces a V-shaped potential well which confines the electron along the direction perpendicular to a $\delta$-doped plane and leads to formation of a quasi-two-dimensional electron gas (2DEG).

The eigenstates of such 2DEG depend on the shape of the space-charge potential. The electronic structure of the system has been calculated by solving the Schrödinger and Poisson equations self-consistently [3–4].

In order to fabricate high-mobility δ-doped semiconductor devices, some authors are focused in improving doping and material growth techniques [5]. An alternative way to improve the electron mobility in the δ-doped semiconductors, which has been proposed recently, is to make a structure with double or triple δ-layers [6–10]. The enhancement in mobilities and concentrations in these structures are due in part to the fact that more carriers distribute at the centre of the two δ-doped GaAs wells. In these structures the carrier transport is spatially separated from ionized impurity scattering centres and consequently the electron mobility is increased by two to five times over that of a single δ-doped case [6]. Thus, double or triple δ-layer structures open up the possibilities for higher electron mobility than those in single layer systems.

The nonlinear optical properties related to the intersubband transitions within the conduction band have attracted considerable attention due to the strong quantum-confinement effect, large values of dipole transition matrix elements and possibility of achieving resonance conditions. Among the optical properties of low dimensional semiconductor systems, the linear and nonlinear intersubband optical transitions have been drawn more attention at theoretical and experimental investigations [11–19].

In this study, for SW (single δ-doped layer), DW (two coupled δ-doped layers) and TW (three coupled δ-doped layers) I investigate the nonlinear optical absorption coefficients and refractive index changes within n-type δ-doped GaAs layer for the (1–2) transition. The nonlinear optical transitions in single, double and triple Si δ-doped structures is investigated in this work, as different from Ref. [10] (The linear intersubband optical absorption coefficients for single, double and triple Si δ-doped GaAs layers under applied electric field). To my knowledge, there is no calculated the nonlinear intersubband optical absorption coefficients and the refractive index changes within n-type δ-doped GaAs layers with different quantum wells. These intersubband optical transitions are predicted to have a narrow bandwidth and are of practical interest for the modeling of tunable optoelectronic semiconductor devices.

2. THEORY

Within effective-mass approximation, in order to obtain the subband structure (the confining potential, the subband energies, the electron concentrations and Fermi energy) I have solved self-consistently the Schrödinger and Poisson equations for the uniform distribution. A flow chart of the self-consistent calculation is shown in Figure 1. Further details about the self-consistent calculation can be found in Ref. [10].
After the confined $\delta$-potential profile, the subband energies and their corresponding wave functions and Fermi energy are obtained, the linear absorption
coefficient $\beta^{(1)}(\omega)$ and the third-order nonlinear absorption coefficient $\beta^{(3)}(\omega, I)$ for the (1–2) intersubband transition between the subbands can be clearly calculated as [14, 20],

$$\beta^{(1)}(\omega) = \frac{\omega \mu c}{n_r} |M_{21}|^2 \frac{\sigma_v}{(E_2 - E_1 - \hbar \omega)^2 + (\hbar / \tau_{in})^2}, \quad (1)$$

$$\beta^{(3)}(\omega, I) = -\frac{\omega \mu I}{n_r \left( \frac{\hbar}{2e} \right)} |M_{21}|^2 \frac{\sigma_v}{(E_2 - E_1 - \hbar \omega)^2 + (\hbar / \tau_{in})^2} \times \left[ 4|M_{22} - M_{11}|^2 \left( (E_2 - E_1 - \hbar \omega)^2 - (\hbar / \tau_{in})^2 \right) \right] \quad (2)$$

and the linear and the third-order nonlinear refractive index changes can be expressed as [14, 20], respectively.

$$\left( \frac{\Delta n^{(1)}(\omega)}{n_r} \right) = \frac{\sigma_v |M_{21}|^2}{2n_r^2 \epsilon_0} \frac{(E_2 - E_1 - \hbar \omega)}{(E_2 - E_1 - \hbar \omega)^2 + (\hbar / \tau_{in})^2} \quad (3)$$

$$\left( \frac{\Delta n^{(3)}(\omega, I)}{n_r} \right) = -\frac{\mu c}{4n_r^2 \epsilon_0} |M_{21}|^2 \frac{\sigma_v}{(E_2 - E_1 - \hbar \omega)^2 + (\hbar / \tau_{in})^2} \times \left[ 4(E_2 - E_1 - \hbar \omega)|M_{21}|^2 - \frac{(M_{22} - M_{11})^2}{(E_2 - E_1)^2} \times \left( \frac{(E_2 - E_1 - \hbar \omega)[(E_2 - E_1)(E_2 - E_1 - \hbar \omega) - (\hbar / \tau_{in})^2]}{2(E_2 - E_1 - \hbar \omega)} \right) \right] \quad (4)$$

$$\sigma_v = \frac{k_B T}{L_{eff} \pi \hbar^2} \ln \left( \frac{1 + \exp \left( (E_F - E_1)/k_B T \right)}{1 + \exp \left( (E_F - E_2)/k_B T \right)} \right). \quad (5)$$

Here $I$ is the optical intensity of incident electromagnetic wave that excites the structure and leads to the intersubband optical transition, $\mu$ is the permeability, $\omega$ is the angular frequency of the incident photon, $c$ is the speed of light in free space, $n_r$ is the refractive index, $\tau_{in}$ is the intersubband relaxation time, $L_{eff}$ is the effective spatial extent of electrons, $E_F$ is the Fermi energy, $E_1$ and $E_2$ are the quantized energy levels for the ground and second subband states, respectively.
The dipole matrix element is defined by

\[ M_{fi} = \int \psi_i^*(z) |e| z \psi_f(z) dz \quad (i, f = 1, 2). \]  

(6)

The total absorption coefficient is given by:

\[ \beta(\omega, I) = \beta^{(1)}(\omega) + \beta^{(3)}(\omega, I) \]  

(7)

and the total refraction index change can be written as

\[ \Delta n(\omega, I) = \Delta n^{(1)}(\omega) + \frac{\Delta n^{(3)}(\omega, I)}{n_r}. \]  

(8)

3. RESULTS AND DISCUSSION

For numerical calculations, we have taken \( m^* = 0.0665 \, m_0 \) (\( m_0 \) is the free electron mass), the separation between the adjacent two doping layers is 8 nm (for DW and TW), thickness of the donor distribution is 4 nm, \( T = 4.2 \, K \), \( L_{\text{eff}} = 40 \, nm \), \( \tau_m = 0.14 \, ps \), \( n_r = 3.2 \) and \( I = 0.2 \, MW/\text{cm}^2 \). Total \( N_d^{2D} \) is taken as \( 12 \times 10^{11} \, \text{cm}^2 \) (i.e. for SW \( N_d^{2D} = 12 \times 10^{11} \, \text{cm}^2 \), for DW \( N_d^{2D} = 2 \times 6 \times 10^{11} \, \text{cm}^2 \) and for TW \( N_d^{2D} = 3 \times 4 \times 10^{11} \, \text{cm}^2 \)).

![Fig. 2](image-url)
Figure 2 (a–c) displays the effective δ-potential profile, the ground and the second subband energies with their squared envelope wave functions for SW, DW and TW, respectively. Since in a SW the donor impurities are localized in a narrower range with respect to DW and TW, the effective potential is narrow and deeper, the band bending is larger, and the squared wave functions of the confinement subband energies are more confined in the well. Thus, it can be seen that the well width affects the device performance such as the confinement, and the obtained values of the subband energies depend on the different well shapes. These configurations are significant for the linear and nonlinear optical response of the structure. The energy difference between the ground and second subband and Fermi energy value is given in Table 1. Thus, I can say that the shape and height of QW affect the limitation and localization.

The linear, nonlinear and total absorption coefficients as function of incident photon energy for SW, DW and TW are shown in Fig. 3 (a–c). As seen from these figures, the peak heights and positions of absorption coefficients depend on the energy difference between two electronic states and matrix elements of electric dipole moment. The first two electron energy levels and the associated densities of probability yield the important values of the dipole moment matrix elements. Because of the variation of the potential profile, the overlap between the first two state wave functions changes. The absorption coefficients are changed in energy and magnitude as dependent on QW shapes. Such a dependence of the absorption coefficients on the energy differences and the dipole matrix elements can be very
advantageous for diverse optical device applications. The total absorption coefficient are significantly reduced by the negative third-order nonlinear term contribution in the presence incident optical intensity. Therefore, the contribution of both the linear and the nonlinear terms should be allowed in the calculation of the total term near the resonance frequency. For SW, DW and TW, the resonance frequency value and the resonant peak values of linear and nonlinear absorption coefficient are located in Table 1. The resonant peak of total absorption coefficient is significantly split up into two peaks due to the strong bleaching effect. This bleaching effect is more specific in Fig. 3c for TW.

Fig. 3 – (Color figure online). The linear, nonlinear and total absorption coefficients as function of incident photon energy for a) SW, b) DW and c) TW.
In Fig. 4 (a–c) I demonstrate the linear, nonlinear and total refractive index changes versus incident photon energy for SW, DW and TW. These refractive index changes are related to the doped well shape, these changes have been varied in magnitude and position. I can declare that the basic cause for this resonance shift is the variation between energy intervals of two different electronic states which an optical transition arises. Also, by increasing effective well widths, the geometric confinement of the electrons modify. This condition varies the subband dispersion relations and causes an alteration in the overlap function between the ground and second subband. The total refractive index change is reduced by the negative nonlinear refractive index change contribution. Therefore, if it is desired to obtain a
larger change in the total refractive index, then a relatively weaker incident optical intensity should be preferred.

4. CONCLUSIONS

In present study, within the effective mass approximation, I have theoretically calculated the subband structure of single, double, and triple Si δ-doped GaAs by solving the Schrödinger and Poisson equations self-consistently. The linear, nonlinear and total intersubband absorption coefficient and refractive index change as a function of the incident photon energy has been investigated for SW, DW and TW. I showed that the alteration of the potential well shape varies the separation between electron energy states, thus the linear, nonlinear and total refractive index changes and absorption peaks modify in magnitude and position.

Changing values of the structural parameters vary both the peak values and the position of all absorption coefficients and refractive index changes. So, I expect that these conclusions will provide major development in multiple electro-optical semiconductor apparatus applications, for suitable choice of the structural parameters.

The semiconductor devices with δ-doped structures have been recently attracted much attention because of the potential technological applications in electronic and photonic appliances. Thus, such δ-doped semiconductor structures are important for the devices such as high-power FETs, and various infrared optical modulators based on the intersubband transition of electrons.

<table>
<thead>
<tr>
<th>QW</th>
<th>$E_2 - E_1$ (meV)</th>
<th>$E_F$ (meV)</th>
<th>$\omega (\times 10^{13} \text{s}^{-1})$</th>
<th>$\beta^{(0)}(\omega)(\text{cm}^{-1})$</th>
<th>$\beta^{(3)}(\omega, l)(\text{cm}^{-1})$</th>
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<tbody>
<tr>
<td>SW</td>
<td>19.93</td>
<td>18.73</td>
<td>3.028</td>
<td>4730</td>
<td>$-2812$</td>
</tr>
<tr>
<td>DW</td>
<td>17.29</td>
<td>19.91</td>
<td>2.626</td>
<td>4186</td>
<td>$-2927$</td>
</tr>
<tr>
<td>TW</td>
<td>12.71</td>
<td>24.05</td>
<td>1.932</td>
<td>3023</td>
<td>$-2823$</td>
</tr>
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REFERENCES