The dependence of the exciton binding energies on quantum well widths of the donor doped GaAs/AlGaAs QW influencing on the intersubband transition

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Abstract. In this research, we theoretically investigated the exciton binding energies as a function of QW widths with the variation of the percent alloy contents. For any certain percent of alloy contents, the exciton binding energies increase proportionally with the increasing of QW widths. We also simulated the exciton binding energies as a function of the percent alloy contents of Al\textsubscript{x}Ga\textsubscript{1-x}As barrier with the variation of QW widths. For the narrower QW widths, with any certain percent of alloy contents, the exciton binding energies show higher discrete energy characteristic compared with the wider well widths. These results can explain the intersubband transition with MIR and Far-IR emission between donor doped levels in conduction band.

1. Introduction

Since Terahertz (THz) range laser radiation (0.1\text{THz}-10\text{THz}) shows potential for use in many important applications, such as medical imaging, telecommunications and security scanning system [1-4], there are many researches about the improvement of the properties and the performance of THz range laser have been published, such as: the designs of Quantum Cascade Lasers (QCL) [5-7], donor and acceptor doped structure in QW. In addition, the role of exciton energy levels on intersubband transition in donor doped QW of GaAs/AlGaAs also has been researched [8]. From that research, the intersubband transition from exciton energy level to electron subband energy level in QW with Far-IR emission has been presented. Therefore, in the search for improvements in the design of QW for the THz laser radiation, the study of the exciton binding energies for THz or Far-IR range emission in QW as a function of QW width and the percent of alloy contents of Al\textsubscript{x}Ga\textsubscript{1-x}As barrier in order to improve the intersubband transition is our interest. In this research, we used the time-independent Schrödinger equation and a quantum model of electron effective mass, together with k·p perturbation theory to simulate the dependence of exciton binding energy levels on QW widths and the percent of alloy contents of GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As QW.
2. Researched structure and theoretical model

The studied structure consisted of a GaAs/Al_{0.3}Ga_{0.7}As quantum well (QW) with a well width of 7.6 nm of GaAs. This structure was donor doped (Si doped) in the central region of QW with the concentration of $5 \times 10^{10}$ cm$^{-3}$. Figure 1 presents the schematic band diagrams and the conduction band profiles of the structure, which were calculated by the one dimensional time-independent Schrodinger equation and quantum model of electron effective mass, together with $k$-$p$ perturbation theory [9].

![Figure 1](image_url)

**Figure 1.** The conduction band profiles of the donor doped GaAs/Al_{0.3}Ga_{0.7}As QW structure and the envelope wavefunctions of the first ($e_1$) and second ($e_2$) electron subbands.

We simulated exciton energy by using the time-independent Schrodinger equation [10]. The equation can be written as:

$$\frac{-\hbar^2}{2m_{eh}} \left[ \left( \frac{\partial^2 \psi}{\partial \rho^2} + \frac{1}{\rho} \frac{\partial \psi}{\partial \rho} \right) \right] - \frac{e^2}{\chi \sqrt{(z_e - z_h)^2 + \rho^2}} \psi = \varepsilon_{ex} \psi$$

(1)

Where $\rho = (x_e - x_h, y_e - y_h)$ is the coordinate of the electron-hole relative motion in the QW plane, $\chi$ is dielectric constant, $z_e, z_h$ are the electron and hole coordinate in the growth direction, $m_{eh}$ is electron and hole effective mass, and $\varepsilon_{ex} = -\frac{m_{eh} e^4}{2 \chi^2 \hbar^2 \left( i - \frac{1}{2} \right)}$, $i = 1, 2, 3, ...$ is the exciton binding energy. The QW widths were varied from 0.1 nm to 7.6 nm and were conducted at the lattice temperature of 4.6 K.

3. Results and discussion

The dependence of the exciton binding energies on QW widths with the variation of the percent of alloy contents is presented in Figure 2. As a result, the exciton binding energies increase with the increasing of QW widths that is because of the range of well width (0.1 nm to 7.6 nm) is greater than the Bohr radius of exciton. Therefore, the quantum confinement for the electron subband energy levels
give the discrete property of QW with the eigenvalue of energy of exciton binding energy from (1). The Decreasing of the percent alloy contents gives higher exciton binding energy which is effected from the changing in lattice constant of barrier structure.

We also simulated the dependence of the exciton binding energies on the percent of alloy content with the variation of QW widths as shown in Figure 3. Obviously, for narrower well width, the exciton binding energies show the higher different value of energies than the wider well width. This characteristic explains the property of discrete energy levels of electron subbands in QW. Moreover, the dependence of the percent alloy contents on the exciton binding energy agrees with the results of Figure 3, which explains the characteristic of lattice constants.

![Figure 2](image2.png)

**Figure 2.** The exciton binding energies, with the variation of percent alloy content (x), as a function of QW widths.

![Figure 3](image3.png)

**Figure 3.** The exciton binding energies, with the variation of QW widths, as a function of percent of alloy content (x), also the expansion of scales for greater well width is presented.
4. Conclusion

This research is a theoretical research which studied the exciton binding energies as a function of QW widths with the variation of the percent alloy contents of the Al\textsubscript{x}Ga\textsubscript{1-x}As barrier. The exciton binding energies are proportional with the QW widths at any certain value of the percent alloy contents and they increase proportionally with the decreasing of the percent alloy contents. That is because of the percent of alloy contents effects on the changing in lattice constant of barrier structure, which can be explained by Vegard’s law. Moreover the exciton binding energies as a function of the percent alloy contents with the variation of QW widths also has been researched. The characteristic of discrete energy levels of electron subbands in QW shown in the narrower QW with at any certain value of the percent alloy contents. These obtained results from this research can contribute the indication of MIR and Far-IR emission from intersubband transition in QW.

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