Eigen-States and Wave functions in Asymmetric Double Multi-Quantum Wells Lattice-Matched to InP Substrate

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***Abstract*—We have been studied experimentally $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ multi-quantum wells (MQWs) and have derived some physical parameters. Using these parameters, eigen-energies of eigen-states and wave functions were studied numerically for asymmetric $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ double MQWs. These were examined with optical interband transitions experimentally obtained by photocurrent spectroscopy (PC). The results of numerical calculation agreed well with Experimental data.**

Keywords—asymmetric MQWs, eigen-energy, wave function

I. Introduction

Recently, semiconductor photonic devices composed of the MQWs are applied as some high-speed devices [1]. Energy structure of the MQWs that is distorted by an external electric field causes the quantum-confined Stark effect (QCSE), which has been recognized as a potential for establishing light modulation mechanisms [2]. If such wells and barriers are applied with different widths and materials, the energy structure becomes aperiodic and asymmetric, electrical and optical properties become complicated and are necessary to be investigated. We studied about asymmetric double quantum wells, using experimentally derived parameters based on the MQWs having single quantum-well repetition. Experimental eigen-energies of the asymmetric $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ double MQWs were deduced from interband transitions measured by the PC and agree with the calculated. Since wave functions were decided for each carrier, probability of the interband transition can be estimated. Energy shift due to the QCSE under an electric field was also well consistent with experimental. In this paper, we report comparison of calculated and experimental eigen-energies and calculated wave functions.

II. Experimental

As the asymmetric double MQWs structures three specimens were prepared, which were consisting of $In_{0.53}Ga_{0.47}As$ well layers and $In_{0.52}Al_{0.48}As$ barrier layers on the surface of n-type InP substrates (100). One of the three specimens has simply repeated 5 nm quantum wells. Other two specimens have repetition of main quantum wells, 5 nm, and other narrow quantum wells. These narrow quantum wells have different width for the two, which were 0.5 nm and 1.0 nm.

Our experimentally obtained parameters of the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ MQWs were as follows [3]. Effective masses were 0.38 m_0 for heavy hole and 0.051 m_0 for light hole in the quantum well. This m_0 was the electron rest mass, 9.1×10^{-31} kg. This electron effective mass was 0.041 m_0, which depended on energy in the quantum well. In the barrier, the effective mass was 0.41 m_0 for heavy hole, 0.1 m_0 for light hole and 0.075 m_0 for electron, which referred bulk values.

Simple and accurate algorithm based on the transfer matrix method had been introduced for solving time independent Schrodinger equation in asymmetric MQWs structures [4]. Eigen-energies of eigen-states were deduced based on this method in confined MQWs having the asymmetric double quantum wells. The boundary condition was used that wave functions connected smoothly between inside-and-outside of the wells. Bandgap energy of $In_{0.53}Ga_{0.47}As$ was taken into account in identifying peaks.

The PC was measured in normal direction for the MQWs structure at room temperature, while irradiating with the light emission of a halogen lamp as an excitation source. In the Fig.

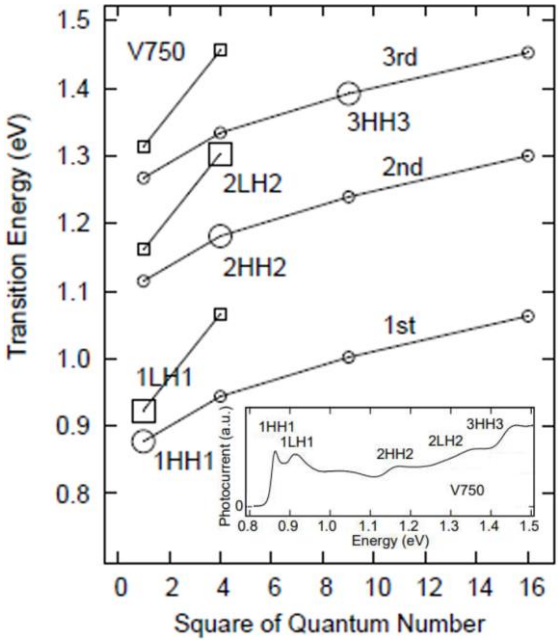


Fig. 1. Experimental transition energies.

1 experimental transition energies are plotted against square of quantum number. Because interband transitions occur between eigen-states of heavy or light holes, and an electron eigen-state, the transition energies are plotted by circles or squares, respectively. These plotted transition energies originating same electron eigen-state are connected by line

segments. Number of the eigen-states are four for the heavy hole and two for the light hole. In an inner figure, photocurrent corresponding to energy of the irradiating light is shown as a spectrum. Peaks are correspond to the interband transitions that identified from above calculation.

III. Calculation and Discussion

As experimental parameters agree well to eigen-energies, wave functions were calculated using our parameters.

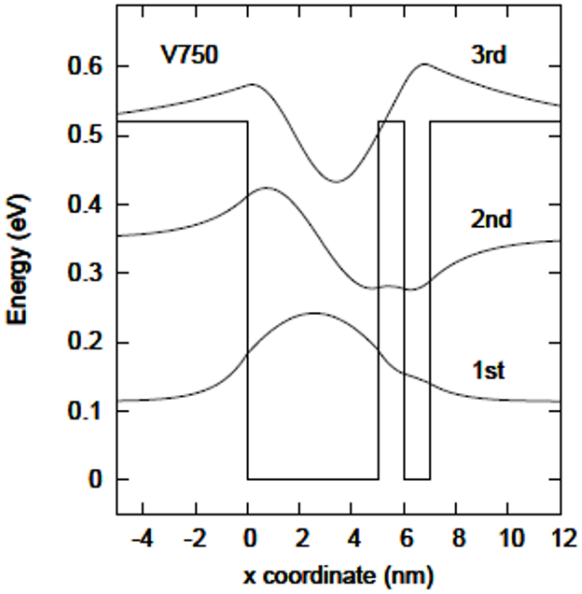
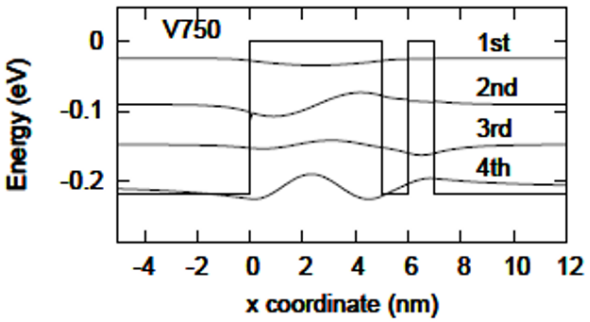


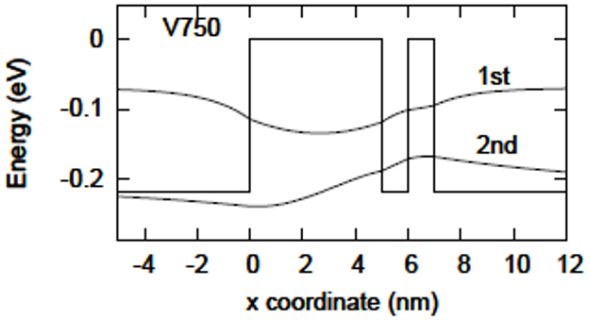
Fig. 2. Wave functions of conduction quantum well

Wavefunctions for specimen named V750 are shown in Fig. 2. In the conduction band main quantum well lies from 0 to 5 nm and a narrow quantum well attaches between 6.0 and 7.0 nm, and both depths are 0.52 eV. The wave functions increase in amplitude within the quantum well and taper off in the barrier layers. Number of eigen-states depends on the well depth, here three. Three wave functions are drawn in order of quantum number from the bottom. They correspond to 1st, 2nd and 3rd states, respectively. These drawing positions are shifted according to eigen-energy of its corresponding quantum number. These wave functions are like sine waves, which undulate depending on the quantum number in the narrow quantum well and ooze to the well outside. These correspond to 0.5, 1.0 and 1.5 wavelengths in the quantum well, respectively. When the quantum number is 1, which is an odd number, amplitude of this wavefunction increases in the center of the quantum well. For quantum number 2 (even), the amplitude increases close to the barrier. For quantum number 3 (odd), the wave function has three antinodes. Due to the narrow quantum well, the right side of the wave function becomes large and asymmetric.

Wave functions in valence band are drawn in inverse quantum wells, 0.22 eV depth in Fig. 3. About heavy hole, number of eigen-states depending on the effective mass is four. Four wave functions are drawn in order of quantum number from the top in the inverse quantum wells, as shown in Fig 3 (a). These are drawn to shift according to the eigen-energy of its corresponding quantum number, respectively. These wave functions undulate depending on the quantum number in the narrow quantum well and ooze to the well outside. In particular, the undulation of the wave function at the high quantum number is intense.



(a) Wave functions for heavy holes



(b) Wave functions for light holes.

Fig. 3. Wave functions of valence quantum well

About light hole, number of eigen-states depending on the effective mass is two, as shown in Fig 3 (b). The reason why the number of eigen-states is small is that the light hole has a lighter effective mass than the heavy hole, so the eigen-energy becomes higher and exceeds the quantum well. Two wave functions are drawn in order of quantum number from the top, because wave functions are drawn in inverse quantum wells. The wave functions of the asymmetric quantum well were drawn for each carrier and the influence of the attached narrow quantum well was clarified.

IV. Summary

Eigen-energies and wave functions of the asymmetric $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ double MQWs were deduced from by calculation based on the transfer matrix method. Interband transitions were experimentally obtained by the photocurrent spectroscopy. There is no contradiction between calculation and experimental. The wave function of the asymmetric quantum well was obtained for each carrier and the influence of the attached narrow well was clarified.

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