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A Modeling of Eigen-States in $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ Multi-Quantum Wells Structure Using Photocurrent Spectroscopy

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Abstract– Determination of parameters is important for application to opto-electronic devices. We determined some band parameters in $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ multi-quantum wells before. And experimental transition energies were obtained using photocurrent spectroscopy. Effective mass is estimated from the transition energies. $E-k$ curve was drawn using a wave equation for our modeling studied by our experimental parameters.

1. Introduction

Designing optoelectronic devices such as photodetectors and lasers require an eigen-energy description as well as an absorption coefficient model. Because $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ multi-quantum wells (MQWs) are useful to 1.5 micron-band optoelectronic devices, eigen-energy and the effective mass can be known by optical transition energy in a quantum-well (QW). Relation between energy, E, and wave number, k, of electron in conduction band of the bulk is roughly parabolic. As the E is linear for k^2, the $E-k$ dispersion does not occur. Electron effective mass is related constant of these two parameters. The electronic effective mass can be seen as an important basic parameter that influences measurable properties of a solid [1]. But it is conceivable that the linearity may collapse in the MQWs compare to the bulk [2]. Nonlinearity that the effective mass depends on energy is considered. In the InGaAs/InP MQW system with a small conduction band offset 0.22 eV, it was reported that the observed anomalous heavy electron mass was due to penetration of wave functions in InP barriers [3]. As an energy-dependent effective mass normal to the QW plane was not clarified quantitatively, so far, the $E-k$ curve was not drawn in wide energy range from conduction bandedge to 0.5 eV above. This effective mass can be regarded as a function of energy in nonparabolic conduction band [4, 5].

The two-dimensional exciton resonance of the MQWs have been observed in the photocurrent spectra. Photocurrent flowed normally to the QW plane and carriers went over the MQWs barriers after dissociation of excitons. In this paper, we report that $E-k$ curve was drawn using a wave function for our modeling studied by our experimental parameters.

2. Experimental

A specimen including a lattice matched $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ MQWs structure grown by MBE on a (100) surface of an n-type InP substrate was a p-i-n junction structure. Four kinds of specimens were prepared, which had different QW width, 5 nm, 9.4 nm, 10 nm and 20 nm. Barrier width of these specimens was about 10 nm. Number of the MQWs were 33, 25, 10 and 17, respectively. These were named as V720, V706, U10 and V748. A metal probing needle was used as an electrode contacting the heavily-doped p^+-$In_{0.53}Ga_{0.47}As$ layer on top of the specimens. And a metal base under the n-type InP wafer was used as a counter electrode.

Photocurrent signals were measured between the p-i-n junctions, which were measured as a function of wavelength at room temperature. A halogen lamp filtered by a 600-grid/mm-grating monochrometer was employed as a light source at a wavelength range of 800-1800 nm [6]. There are several eigen-states in conduction MQWs and valence MQWs. The interband transition between these eigen-states includes various combinations, and allowed transition and forbidden transition are assessed from overlap of the electron's and hole's wave functions.

The light energy from a halogen lamp was absorbed for each transition. These optical interband transitions, which were assigned from photocurrent spectral structures, are labeled by using the notation nxHl, where n and l are quantum numbers of the electron and hole eigen-states and x=H or x=L indicates heavy hole (HH) or light hole (LH) eigen-state. Major peaks was observed the photocurrent spectra, which correspond to allowed transitions having same quantum numbers ($n = l$).

3. Results

Experimental transition energies about only HH at room temperature are plotted against the quantum number, as shown in Fig. 1. Allowed transitions about LH are not plotted because this figure is complicated and is hard to see plotted points. These plotted points are connected together in a segment of a line to make it easy to distinguish marks. Number of allowed transitions is 2, 3, 3 and 7. If the QW width is narrow, there are few numbers of transitions. Triangles correspond to the transition energy of the V720. Inverse triangles, squares and circles

correspond to the transition energy of the V706, U10, V748, respectively. The inverse triangles and the squares are close to each other, because these QW widths are approximately equal. Two triangles correspond to quantum number 1, 2 of the V720. These transition energies are 0.871 eV and 1.198 eV. Three inverse triangles correspond to quantum number 1, 2 and 3 of the V706. These transition energies are 0.787 eV, 0.952 eV and 1.179 eV. Three squares correspond to quantum number between 1 and 3 of the U10. These transition energies are 0.787 eV, 0.938 eV and 1.152 eV. Circles correspond to quantum number between 1 and 7 of the V748. Transition energies of the V748 are 0.750 eV, 0.800 eV, 0.877 eV, 0.974 eV, 1.084 eV, 1.205 eV and 1.331 eV. Size of error bars is dependent on width of peak appearing on the photocurrent spectra. These are correspond to experimental transition energy of the *n*HH*l* which is explained above. These plotted points gradually bend to lower side with square of the quantum numbers.

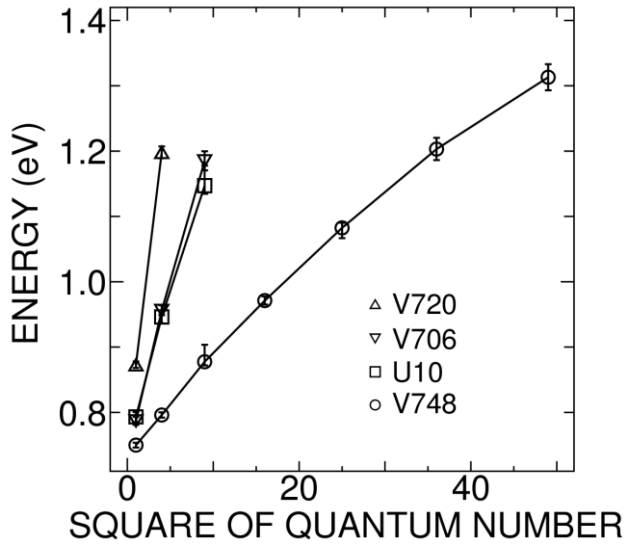

Fig. 1 Experimental transition energies. Energy of HH allowed transitions are not linear to the square of quantum number.

Bandgap energy of the $In_{0.53}Ga_{0.47}As$ is 0.74 eV (300 K) [7], which correspond to the bottom of conduction and valence QW. As depth of the conduction QW is 0.52 eV and one of the valence QW is 0.22 eV [6], transition energy exist from 0.74 eV to 1.48 eV. The transition energy has quantum number dependence, which is linear against square of quantum number in infinite QW. But in case of finite QW the transition energy is nonlinear to the square of quantum number. And, as well as a reason that the wave function seeps out from the finite QW, it is a reason that electron effective mass increases with energy of the electron eigen-state.

Based on the envelope function, electron effective masses were calculated on electron eigen-states that were induced from transition energy [9]. If the bandgap energy and the binding energy of an electron-hole pair are equal at each transition, this subtraction canceled out uncertainty of the energies by each other. Therefore, the experimental values for calculation are given from this subtraction.

The electron effective masses of our four specimens are plotted against each eigen-state energy in the conduction QW in Fig. 2, which are expressed in effective mass ratio for electron rest mass, $m_0 = 9.1 \times 10^{-31}$ kg, as a unit. The eigen-state energies are based on the bottom of the conduction QW. The mark at energy 0 corresponds to effective mass ratio of the bulk $In_{0.53}Ga_{0.47}As$. Energy of plotted points is electron eigen-energy in the conduction QW which corresponds to transition energy of the Fig. 1. Marks of this figure used same ones of the Fig. 1. The effective mass ratio of the V720 is 0.051 derived with 1HH1 at eigen-state energy, 0.117 eV. Eigen-state energies are derived from corresponding transition energies. Effective mass ratio is 0.073 derived with 2HH2 at 0.376 eV. About V706, effective mass ratio is 0.044 at 0.053 eV, 0.051 at 0.192 eV and 0.060 at 0.379 eV, which are derived from 1HH1, 2HH2 and 3HH3. About U10, effective mass ratio is 0.047 at 0.047 eV, 0.058 at 0.163 eV and 0.062 at 0.340 eV against corresponding transition energy. About V748, effective mass ratio is 0.042 at 0.016 eV, 0.046 at 0.061 eV, 0.051 at 0.126 eV, 0.056 at 0.208 eV, 0.061 at 0.299 eV, 0.067 at 0.398 eV and 0.071 at 0.497 eV against corresponding transition energy.

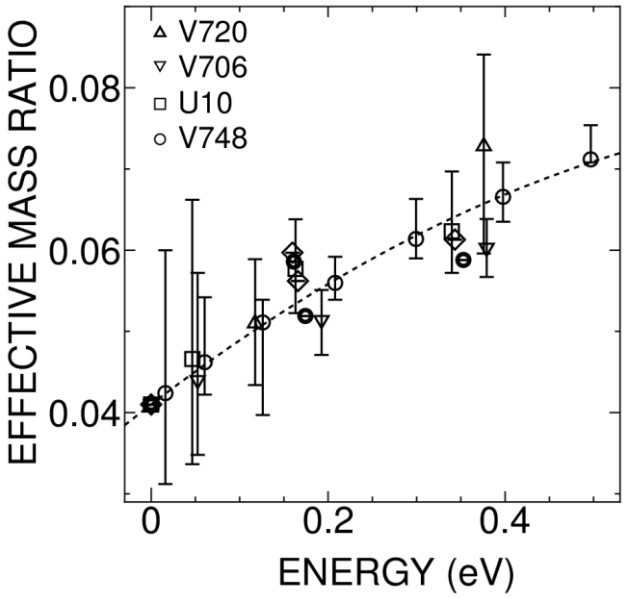

Fig. 2 Electron effective masses. Effective mass increases with the energy and is nonlinear to energy. Approximate curves are good agreement about all specimens.

Effective mass increases with the energy, which is good agreement about all specimens. Size of error bars is considered with the errors of the transition energies as

shown in the Fig. 1. Furthermore, when energy is low, calculated error of these effective mass increases. The effective mass increases from 0.041 m_0 to 0.071 m_0 with increasing energy. This electron effective mass, m^*_{we}, is expressed as a following equation:

$$m^*_{we}(E\,[\mathrm{eV}]) = \left(1 + 2.2E - 1.4E^2\right) m_{e0} \qquad (1)$$

where E is energy in the conduction QW [9]. The effective mass has a nonlinearity for energy. A dashed curve shows this effective mass expression. The term, m_{e0}, is effective mass 0.041 m_0 at bottom of the conduction QW [10], which correspond to one at bandedge of the bulk $In_{0.53}Ga_{0.47}As$.

Nonparabolic tendency is recognized by the increasing effective mass as the Eq. (1) [11, 12]. Electron, HHs and LH that is confined in each QW have eigen-energy, E, and wave number, k. Relation between the E and the k is calculated using following equation:

$$E = \frac{(\hbar k)^2}{2m^* m_0}. \qquad (2)$$

Parameters, $\hbar$ and m^*, shown in above equation are Plank constant, 1.05×10^{-34} Js, and effective mass ratio. If this effective mass is constant, electron's or hole's eigen-energy is linear for k^2. But if m^* has energy dependence, this relation is nonlinear. The electron effective mass had energy dependence from our experiment, and, such energy dependence did not exist for the HH and the LH. The effective mass ratio is 0.38 for HH and 0.051 for LH. The eq. (2) was used for calculation of the k.

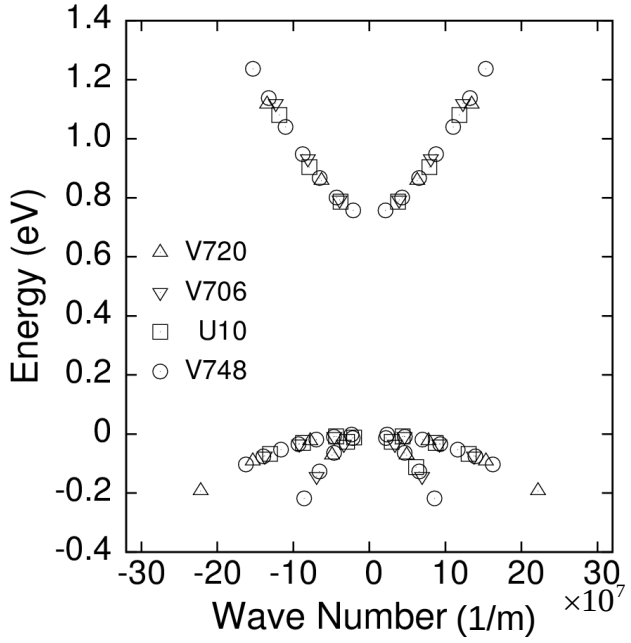

Fig. 3 E–k plots of MQWs all Experimental transition energies. Energy dispersions of this E–k curves are larger with the higher conduction quantum number.

Calculated E and k is plotted in Fig. 3. Vertical axis is energy, which is based on the bottom of the valence QW. Upswing curve is for the electron and two downward curves are for the two holes. The curve that the curvature is small in the two downward is for the heavy HH. The other becomes the LH. The energy of electron are padded in consideration of the bandgap energy of the $In_{0.53}Ga_{0.47}As$. And there is the E–k dispersion towards outside because the electron effective mass increases with energy. The drawn range is within the energy of each depth of the QW. The wave number depends on the number of antinodes of the standing wave formed in QW. As width of the QW is from 5 nm to 20 nm, the wave number becomes from 10^7 to around 10^8 in consideration of exudation of the wave function. Marks of this figure are same with the Fig. 1. The E–k plots of all specimens are drawn on one curve when electron is confined in only the one-dimensional region. Energy dispersions of this E–k curves are larger with the higher conduction quantum number. The reason is that the effective mass becomes heavier with energy. The reason why there is not a point to $k = 0$ of this figure is that there is not an eigen-state there. The E–k dispersion of the MQW can be compared with the bulk $In_{0.53}Ga_{0.47}As$.

4. Conclusion

We estimated the effective mass in the $In_{0.53}Ga_{0.47}As$ /$In_{0.52}Al_{0.48}As$ MQWs from transition energies, using the photocurrent spectroscopy and draw E–k curve in the energy region of the MQWs. This might be useful model for determination of band parameters of the $In_{0.53}Ga_{0.47}As$ QW such as eigen-states.

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