Minibands of Eigen-State Energies of $In_{0.53}Ga_{0.47}As$ Multi-Quantum Wells Lattice-Matched to InP

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***Abstract*—Nonparabolic subband structure of $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ multi-quantum wells was studied theoretically and experimentally. In periodic potential of the multi-quantum-well structure, if barrier layers are thin, electron eigen-states become minibands having with energy width. In 10 nm width barrier, the energy width becomes wider at higher energy. When the eigen-state is more than 0.5 eV and near top edge of the quantum well, the energy width is calculated as more than 0.012 eV.**

Keywords—MQWs; photocurrent; electron eigen-state; nonparabolicity

I. Introduction

Recently, the studies on very high-speed and large-capacity data communication and the processing systems of data utilizing optical techniques are rapidly advancing. Some high-speed devices consist of semiconductor photonic elements such as quantum well structures [1]. The optical property of such quantum wells has been studied. We observed interband transitions on photocurrent spectra in $In_{0.53}Ga_{0.47}As$ /$In_{0.52}Al_{0.48}As$ multi-quantum wells (MQWs) and its nonpalabolicity were theoretically deduced from application of Kane's bulk band theory. In this paper, we report that eigen-states of conduction subbands confined within the MQWs were experimentally deduced by photocurrent spectroscopy and the eigen-states become minibands having energy width near top edge of the quantum wells by calculation.

II. Experimental

Four specimen including undoped MQWs were grown by the Molecular Beam Epitaxy on each (100) surface of n-type InP substrates. The MQWs consisting of $In_{0.53}Ga_{0.47}As$ well layers and $In_{0.52}Al_{0.48}As$ barrier layers were in succession to an n-InAlAs buffer layer on the n-type InP substrate. Width of the well layers of each specimen was different, which were 5, 9.4, 10 and 20 nm. Numbers of quantum wells were 33, 25, 10 and 16, respectively. Width of the InAlAs barriers was commonly 10 nm. A heavily-doped p-InGaAs layer was on this MQW structure except the 10 nm specimen, which was as an electrode. About the 10nm specimen, an electrode was attached on outside top. Photocurrent were measured about such a p-i-n junction, while irradiating with He-Cd laser light as excitation source. These photocurrent spectra (PL) were measured in 0 bias voltage at room temperature.

III. Results and Discussion

The photocurrent spectra measured by a polychrometor were shown in Fig. 1. As these spectra are normalized by wavelength dependence of sensitivity of detectors, step-like structures reflect the MQWs. The photocurrent spectra are shown in the bottom for the 5 nm specimen, in second from bottom for the 9.4 nm specimen, in third from bottom for the 10 nm specimen and in top for the 20 nm specimen. A big rise exists on all spectra, which comes from band-gap of the n-InP substrate at 1.3 eV. Each step originates from band-gap energy of the two-dimensional $In_{0.53}Ga_{0.47}As$ that are corresponding to ground eigen-states. This energy is between 0.7 eV and 0.9 eV, which is high in narrow well. Exciton peaks that accompanied each edge correspond to interband transitions between conduction and valence eigen-states. When the well layer is narrow, exciton peaks are large and clear. When the well layer is wide, peaks are small. Major peaks correspond to allowed transitions having same quantum numbers (n=l) that are caused by heavy holes (HH). Types of the interband transitions are assigned from these spectral structures, which are labeled by using the notation nHHl, where n and l are quantum numbers against the conduction and valence eigen-states. Because peaks that related with the light hole are tiny, it is removed from this analysis.

By the concept of the envelope function and of the effective mass using a nonparabolic conduction band, energies of electron eigen-states were calculated with our parameters in case of single quantum well and multi-quantum wells [2]. The interband transition energies, $E_{n\mathrm{HH}n}$, is expressed with electron eigen-state energies, $E_e(n)$, the HH eigenstate energies, E_{HH}, the band-gap energy of InGaAs, E_g and the exciton binding energy, E_{ext}. Even if the E_g and the E_{ext} are not known, the E_e(n) can be discussed from energy differences between each $E_{n\mathrm{HH}n}$ and ground state, $E_{1\mathrm{HH}1}$, as

$$E_e(n) = (E_{n\mathrm{HH}n}-E_{1\mathrm{HH}1}) + (E_{\mathrm{HH}}(n)-E_{\mathrm{HH}}(1)) + E_e(1). \qquad (1)$$

For the eigen-energies fairly far from the conduction band edge of bulk, correction due to the nonparabolicity in the conduction band can be important. The electron effective mass of the well and the barrier is 0.041 m_0 and 0.051 m_0 at band edge of the bulk, respectively. The m_0 is the electron mass in vacuum. The effective mass gets heavy with increasing energy. This $E_e(1)$ was deduced using nonparabolic tendency of the electron

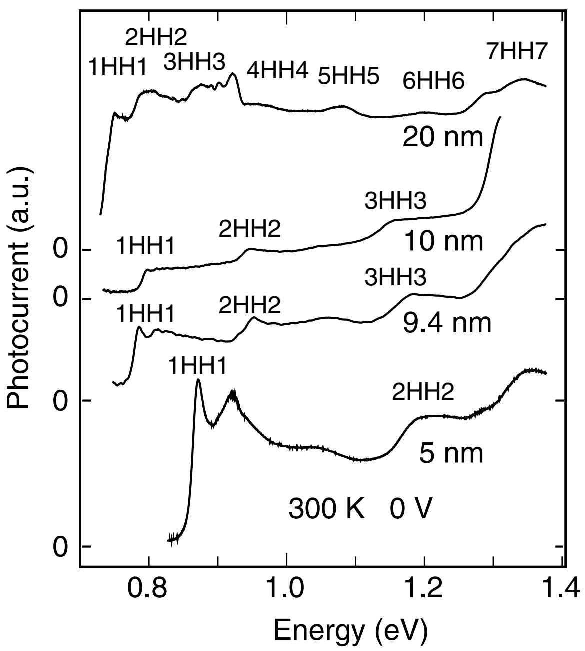

Fig. 1 Photocurrent spectra.

effective mass [3]. Conduction band offset is 0.52 eV. Calculated energies of the eigen-states are shown in TABLE 1. If the quantum well becomes wide, the number of the eigen-states increases.

TABLE I. ENERGY OF ELECTRON EIGEN-STATES

Quantum Number	**Energy of Eigen-State (eV)**			
	5 nm	***9.4 nm***	***10 nm***	***20 nm***
1	0.118	0.052	0.047	0.016
2	0.390	0.184	0.169	0.061
3		0.359	0.333	0.126
4			0.507	0.205
5				0.295
6				0.394
7				0.496

Exciton peaks in the Fig. 1 are clear at lower interband transitions but those are not clear at higher transitions. In periodic potential of the MQWs, if barrier layers are thin the electron eigen-states become minibands having with energy width. In other words, energy of each eigen state has width. The width of such miniband was calculated using the parameter mentioned above. The calculated energy widths of corresponding eigen-states are plotted for each specimens, as shown in Fig. 2. The width of the miniband is less than 0.0001 eV in lower energy of eigen-states less than 0.3 eV. This width becomes wider at higher energy. Fourth eigen-state of 10 nm is more than 0.5 eV and near top edge of the quantum well and this width is 0.012 eV. The reason why the exciton peaks of higher quantum numbers do not appear clearly on the photocurrent spectra might be that energy width of the electron eigen-state as the minibands is wide.

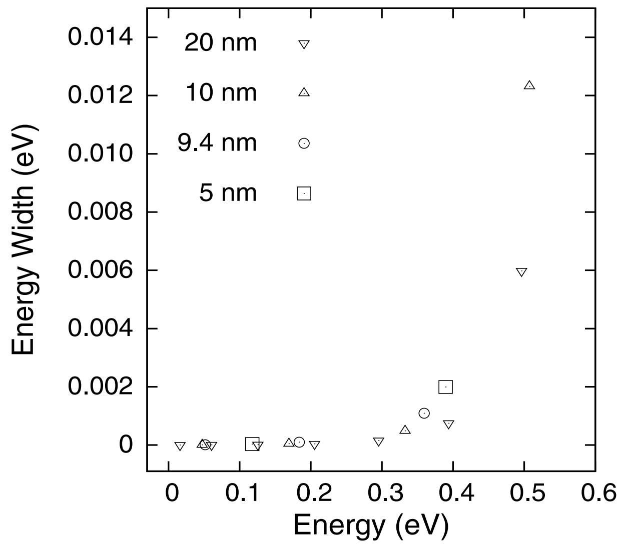

Fig. 2 Energy width of each eigen-state.

IV. CONCLUSION

After Photocurrent spectra were measured about the four undoped $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ MQWs specimens. Nonparabolic structure of the energies of eigen-states agreed theoretically and experimentally. In the periodic potential of the MQWs the electron eigen-states became minibands having energy width near the top edge of the quantum wells. The reason why the exciton peaks of higher quantum numbers do not appear clearly on the photocurrent spectra might be that wide minband is formed for the electron eigen-state.

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