Eigen-State Energies in Asymmetric double Quantum Wells Lattice-Matched to InP

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Abstract-**Asymmetric $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ multi-quantum wells (MQWs) were studied theoretically and experimentally. Eigen-energies of eigen-states and wave functions confined in the asymmetric MQWs were deduced from by calculation based on the transfer matrix method and optical interband transitions were obtained by photocurrent spectroscopy. Results of the calculation agree well with experimental data.**

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 [1] such as Multi-Quantum Wells structures (MQWs). These are aperiodic with varying well and barrier widths and asymmetric i.e., having different materials and effective masses for the different regions of the wells and barriers. Adjacent wells are coupled through the barriers. As electrical property, optical property, effect of barrier width on the tunneling properties has also been investigated. We observed experimentally and deduced theoretically interband transitions in $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ MQWs. Experimental data agree well with results of the calculation. In this paper, we report about eigen-energies of eigen-states and wave functions confined in the asymmetric MQWs by calculation and optical interband transitions obtained by photocurrent (PL) spectroscopy.

II. Experimental

Undoped MQWs structures were fabricated by growth in the Molecular Beam Epitaxy device. Specimens were prepared as MQWs structures consisting of In0.53Ga0.47As well layers and In0.52Al0.48As barrier layers, which were in succession to an n-InAlAs buffer layer on each (100) surface of n-type InP substrates. There were three specimens, V720, V749 and V750, varying in shape of the quantum wells. The V720 was a structure having 33 times of simple combination of the quantum wells and barriers. The width of the quantum wells was 5 nm. Other 2 specimens have repetition of double quantum wells varying in well widths. The width of the main quantum well was 5 nm and other narrow quantum well was attached. The V749 had main quantum well 5 nm and narrow quantum well 0.5 nm and barrier width between these two quantum wells was 0.5 nm. The V750 consisted of main well 5 nm, narrow quantum well 1.0 nm and the barrier width 1.0 nm. Because 33 combinations of the main and the narrow quantum wells were put in domain of 495nm, the distance between these combinations was different by the specimens. It was 10 nm for the V720, 9 nm for the V749 and 8 nm for the V720, respectively. A heavily-doped p-InGaAs layer was on top of each MQWs structure, which was as an electrode for PL measurement. The PL were measured about such a p-i-n junction, which were the top p-InGaAs layer, the undoped MQWs and the n-type substrate, while irradiating with He-Cd laser light as excitation source. These PL spectra were measured in 0 bias voltage at room temperature.

III. Calcuration

It was calculated that the eigen-energies and corresponding wave functions for the eigen-states in the asymmetric MQWs structures. As simpler and accurate algorithm based on the transfer matrix method had been introduced for solving time independent Schrodinger equation in the asymmetric MQW structure [2]. Quantum confined eigen-energies were calculated using the boundary condition that a wave function connected smoothly between inside-and-outs. They were calculated using our parameters obtained so far [3]. Effective mass ratio for the electronic rest mass (m_0;9.1×10^{-31} kg) was 0.38 for heavy hole and 0.051 for light hole in the quantum well. This electron effective mass ratio depended on energy E in the quantum well, which was expressed as $m^*_{ew}/m_0(E[\mathrm{eV}]) = 0.041\times(1+2.2E-1.4E^2)$. Other effective mass ratios of the barrier layer were 0.41 for heavy hole, 0.1 for light hole and 0.075 for electron. Depth of the quantum wells was 0.52 eV for the conduction band and 0.22 eV for the valence band.

IV. Results and discussion

Wave functions confined in the conduction quantum well were obtained from the calculation as shown in Fig 1. About

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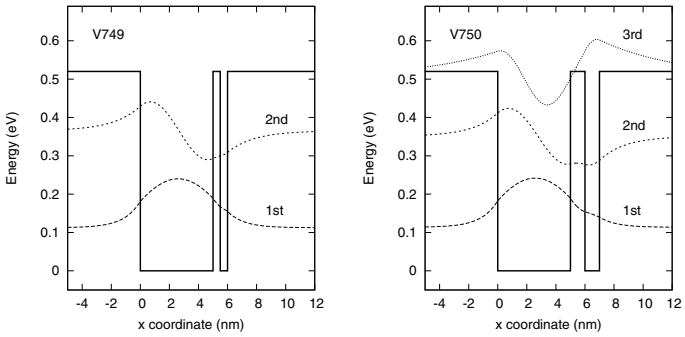

Fig. 1 Photocurrent spectra

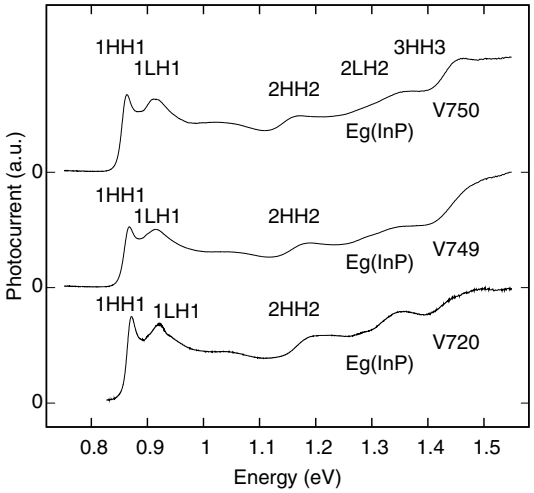

Fig. 2 Energy width of each eigen-state

a coordinate, the direction that is perpendicular to the quantum well plane is assumed as x-axis and the origin is put on one border between the 5 nm well and both side barrier layers. In left figure of the V749, the conduction quantum well lies from 0 to 5 nm and a narrow quantum well is from 5.5 to 6.0 nm, whose depth is 0.52 eV. There are two eigen-states in the quantum well and two wave functions are drawn based on each eigen-energy in Table 1. In right figure of the V750, the quantum well lies from 0 to 5 nm and a narrow quantum well is from 6.0 to 7.0 nm, whose depth is 0.52 eV, too. Three wave functions drawn based on each eigen-energy relatively greatly undulate. Even if width of the narrow quantum well is wider, energy of the ground eigen-state does not much change. However, energies of other eigen-states becomes low depending on this width. These wave functions are like the sine wave, but undulate in the narrow quantum well and ooze to the well outside.

As the interband transitions occur between electron eigen-states and heavy hole or light hole eigen-states, notation is expressed in HH or LH. Major transitions are allowed interband transitions having same quantum number, n, for conduction and valence eigen-states. The transitions are labeled by using the notation nHHn or nLHn. When the Table 1 is into account, 1HH1, 1LH1 and 2HH2 should exist in all specimens, and 2LH2 and 3HH3 probably exist for the V750.

TABLE I ENERGY OF EIGEN-STATES

Carrier	Quantum number	Energy of eigen state (eV)		
		V720	V749	V750
Electron	1	0.118	0.113	0.114
	2	0.389	0.365	0.351
	3			0.503

The PL spectra measured by a monochromator are shown in Fig. 2. Each PL spectrum is place on the bottom for the V720, on middle for the V749 and on top for the V750, which reflects the MQWs structures because these spectra are normalized by wavelength dependence of sensitivity of detectors. Types of the interband transitions are assigned from these spectral structures, Each first step of all is a big rise, which originates from band-gap energy of the two-dimensional $In_{0.53}Ga_{0.47}As$, whose peak are corresponding to interband transition of the ground eigen-states, 1HH1. Next peak is for 1LH1. These are positioned at approximately equal energy, 0.87 eV and 0.92 eV for the all, which are exciton peaks accompanying on an edge of first step. For second HH transition, 2HH2, edges of second step are seen at 1.19, 1.18 eV and 1.17 eV for the V720, V749 and V750, respectively. As the narrow well expands, this energy is lower. When the quantum number is higher, the exciton peaks are smaller. Existence of 2LH2 and 3HH3 is expected for the V750. However there are minimal excitements at 1.29 eV and 1.38 eV. Since these overlaps with a rising of band-gap energy 1.3 eV of the InP substrate, these is hard to see on the spectrum. When the both calculated eigen-energy in the Table 1 and bandgap energy of the $In_{0.53}Ga_{0.47}As$ is in consideration, these calculation results agree well with experimental data.

V. Conclusion

The asymmetric $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ MQWs were studied theoretically and experimentally. Eigen-energies of eigen-states and wave functions confined in the asymmetric MQWs were deduced from by calculation based on the transfer matrix method and optical interband transitions were obtained by PL spectroscopy. Results of the calculation agree well with the experimental data.

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