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P-8-5

Electroabsorptive Properties of InGaAs/InAlAs Five-Layer Asymmetric Coupled Quantum Well (FACQW)

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1. Introduction

For semiconductor optical modulators and switches such as Mach-Zehnder modulators, large electrorefractive (ER) index change Δn with a small absorption loss is necessary in quantum wells (QWs). A group that included one of the present authors previously proposed a five-layer asymmetric coupled quantum well (FACQW)[1] for giant electrorefractive index change. A giant ER sensitivity $|dn/dF|$ of transverse electric (TE)-mode light was observed in GaAs/AlGaAs FACQWs[2]. InGaAs/InAlAs FACQWs for 1.55 μm wavelength region were also proposed and their electrorefractive characteristics were theoretically studied [3, 4].

In this work, the electroabsorptive (EA) and ER properties of the InGaAs/InAlAs FACQW were theoretically studied. Molecular beam epitaxy (MBE) growth and photocurrent measurements of multiple FACQW were also discussed.

2. Electroabsorptive and Electrorefractive Effect of InGaAs/InAlAs FACQW

The proposed lattice-matched FACQW is composed of 20-monolayer (ML) $In_{0.53}Ga_{0.47}As$ (lattice-matched to InP) QW (QW1) and 26-ML (=6+20) $In_{0.53}Ga_{0.47}As$ QW (QW2) with $In_{0.52}Al_{0.48}As$ 2-ML barrier layer inserted for potential modification as shown in Fig.1. The positive direction of an applied electric field is defined as shown in the figure.

The wavefunction of hh1 (the ground state of a heavy hole) is distributed dominantly in QW1, and that of hh2 (the first excited state of a heavy hole) is distributed dominantly in QW2 under no electric field. As a result, when the electric field $|F|$ is slightly increased, the exciton absorption strengths and binding energies of e1 (the ground state of an electron)-hh1 and e2 (the first excited state of an electron)-hh2 transitions remarkably decrease while those of e1-hh2 and e2-hh1 transitions increase. This large change contributes to the very large absorption coefficient change $\Delta\alpha$ in the FACQW for TE mode light[1].

The ER effect in the proposed FACQW structure was analyzed with the same method referred in Ref.[1]. Through the Kramers-Kronig relation, the large $\Delta\alpha$ of the FACQW brings about a large Δn in the transparent wavelength region. Figure 2 shows the dependence of Δn of the FACQW at F=–30 kV/cm on wavelength. The Δn of a 6.5 nm-thick $In_{0.53}Ga_{0.47}As$/ $In_{0.52}Al_{0.48}As$ rectangular quantum well (RQW) is shown for comparison. As shown in the figure, we can expect that the FACQW produces a giant ER sensitivity $|dn/dF|$ (approximately 1 x 10^{-4} cm/kV) over 100 nm wavelength.

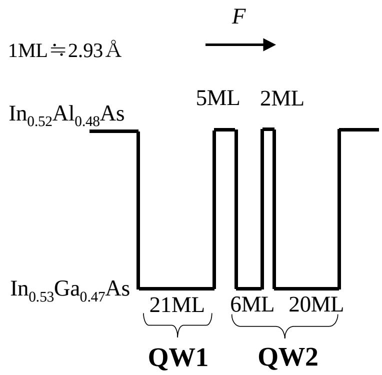

Fig.1 Schematic diagram of InGaAs/InAlAs FACQW for 1.55 μm wavelength.

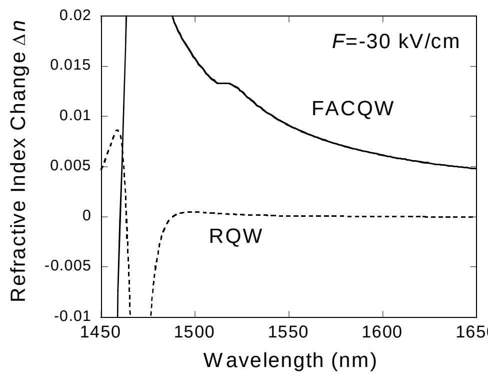

Fig.2 Electrorefractive index change Δn (for TE mode) of the InGaAs/InAlAs FACQW and RQW (6.5nm).

3. MBE Growth and Photocurrent Measurements of Multiple FACQW

Lattice-matched InGaAs/InAlAs multiple FACQW structures were grown on InP (100) substrates with solid-source MBE. For obtaining the expected excellent performance, thickness fluctuations of each layer in the FACQW should be as small as possible [3]. Therefore, the MBE method is the most suitable technique for growing FACQW structures. The structure was grown at 520 °C with a growth rate of 350 nm/h. Figure 3 shows a transmission electron microscopy image of the FACQW. A p-i-n structure with 10 sets of the FACQW in the *i*-layer was also grown on an n-InP (100) for photocurrent measurements. Total thickness of the *i*-layer was about 380 nm. From the results of X-ray diffraction and photoluminescence measurements, it was found that the grown FACQW was composed of 23-ML $In_{0.55}Ga_{0.45}A$ QW (QW1) and 30-ML (=8+22) $In_{0.55}Ga_{0.45}As$ QW (QW2) with $In_{0.52}Al_{0.48}As$ 3-ML barrier layer. Therefore the absorption spectra of this structure were recalculated for this structure (Fig. 4).

The photoabsorption currents were measured at normal incidence of monochromated light to cleaved side facet. Figure 5 shows the measured absorption current spectra under various bias voltages. The peak at absorption edge did not shift to the longer wavelength. The peak intensity of the absorption edge increased with increasing the bias voltage, and decreased again. This tendency is in good agreement with the calculated results in Fig. 4. For comparison, the measured photocurrent absorption spectra of a sample with $In_{0.53}Ga_{0.47}As$(10nm)/$In_{0.52}Al_{0.48}As$ multiple RQW (12 sets) were also measured. The results showed the typical quantum-confined Stark effect (QCSE). Absorption peak at the absorption edge shifted to the long wavelength side with the increase of the bias voltage, and quenching of the peak was observed.

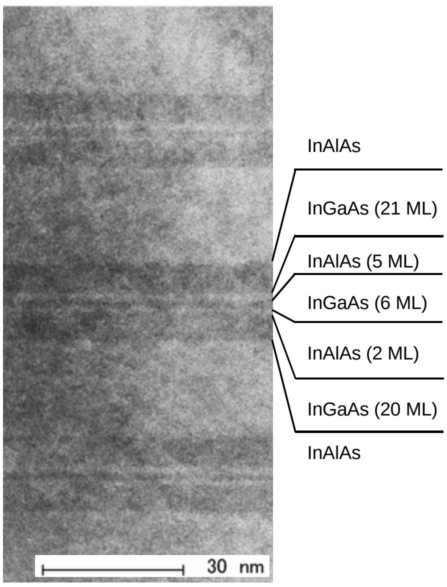

Fig.3 Transmission electron microscopy (TEM) image of the cross-section of a multiple InGaAs/InAlAs FACQW sample.

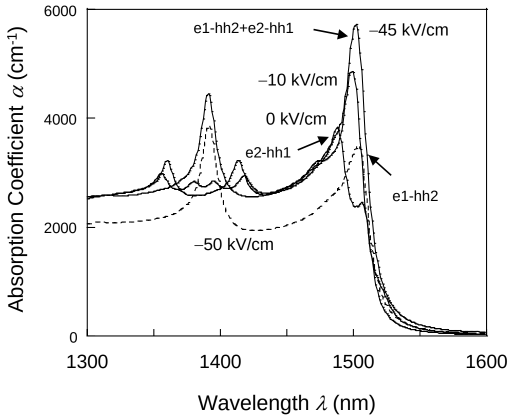

Fig.4 Calculated absorption coefficient spectra of InGaAs/InAlAs FACQW.

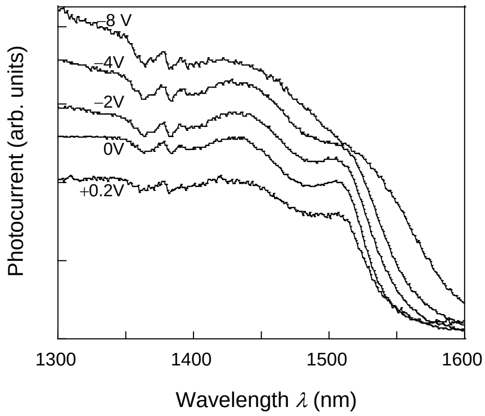

Fig.5 Measured photoabsorption current spectra of the grown multiple InGaAs/InAlAs FACQW.

4. Conclusion

Electroabsorptive and electrorefractive properties of the InGaAs/InAlAs FACQW were theoretically and experimentally studied. The results of photocurrent measurements of MBE-grown multiple FACQW were very consistent with the calculated absorption spectra. These results show that the giant electrorefractive index change will be obtained in the FACQW as theoretically predicted, and it is very promising for ultrahigh speed and low-voltage optical modulators/switches.

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