Phase Modulator with InGaAs/InAlAs FACQW Grown by MOVPE

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Abstract - The optical properties of InGaAs/InAlAs five-layer asymmetric coupled quantum well (FACQW) grown by MOVPE are investigated. The FACQW phase modulator is fabricated and its large phase shift is successfully observed.

1. Introduction

A prerequisite for ultrafast modulators at 40 Gb/s and beyond for TDM optical fiber communications will be that modulating voltages are as low as possible. A wideband wavelength range of operation of an ultrafast modulator is also very important for its extension to DWDM systems. A Mach-Zehnder (MZ) modu-lator with a multiple quantum well (MQW) waveguide is a promising candidate because of its low chirp and adjustable chirp modulation characteristics. For such phase modulation devices, a group that included one of the present authors previously proposed a GaAs/AlGaAs five-layer asymmetric coupled quantum well (FACQW) and theoretically and experimentally studied[1,2]. InGaAs/InAlAs FACQWs for 1.55 μm wavelength region was also proposed and their electrorefractive characteristics were theoretically studied [3]. We have been investigating growth of the FACQW structure by molecular beam epitaxy (MBE) because the FACQW consists of ultra-thin layers.

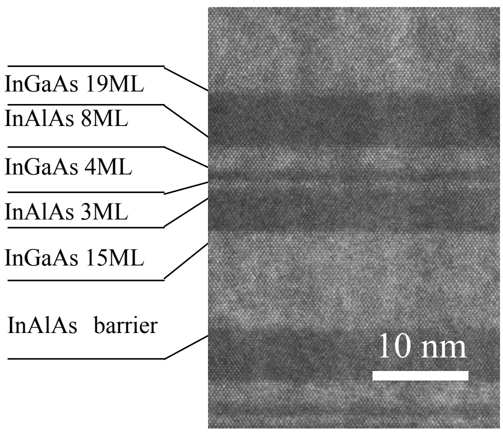


Fig.1. shows a transmission electron microscope (TEM) image of the cross-section of the FACQW wafer grown by MOVPE.

In this paper, we report the optical properties of the InGaAs/InAlAs FACQWs grown by metal-organic vapor phase epitaxy (MOVPE) and its application to a phase modulator. The experimental results showed the FACQW with good quality can be obtained by MOVPE.

2. InGaAs FACQW Structure

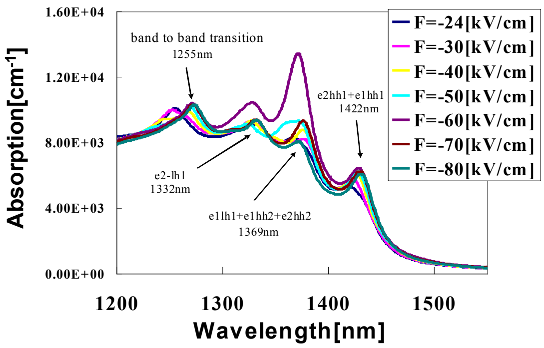
The proposed lattice-matched InGaAs/InAlAs FACQW is composed of 19-monolayer (ML) $In_{0.53}Ga_{0.47}As$ (lattice-matched to InP)QW(QW1) and 19-ML(4+15) $In_{0.53}Ga_{0.47}As$ QW(QW2) with $In_{0.52}Al_{0.48}As$ 3-ML barrier layer inserted for potential modification[4]. The InGaAs/InAlAs FACQW is expected to exhibit giant electrorefractive (ER) sensitivity $|dn/dF|$ (4.4 x 10^{-4} cm/kV) over 100 nm wavelength range can be expected at around electric field F =−30~ −60 kV/. The detailed operation mechanism is described in Ref. 4.

Figure 1 shows a transmission electron microscope (TEM) image of the cross-section of the FACQW wafer grown by MOVPE. Fig.2 shows the dependence of Δn of the FACQW at 1.55 μm (approximately 130 nm from the absorption edge) on applied electric field. As can be seen, fine qunatum well structure including a 3-ML InAlAs layer is successfully fabricated.

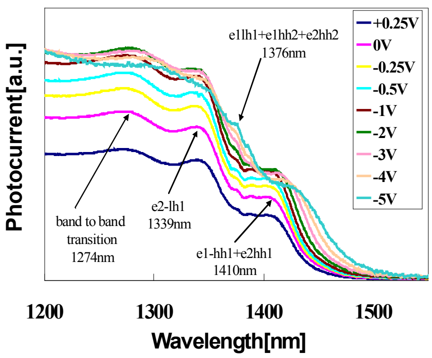
3. Photocurrent Measurements of InGaAs FACQW

The *p-i-n* structure with the InGaAs/InAlAs multiple (6 sets) FACQW in the core layer was grown by MOVPE on an n-InP(100) substrate. Total thickness of the FACQWs is 156 nm. The FACQWs is sandwiched with i-InGaAlAs separate confinement heterostructure (SCH) layers. The upper and lower cladding layers are InP.

Figure 2 shows the calculated absorption spectra (Fig. 2.(a)) and the measured photo-absorption current spectra at room temperature (Fig. 2.(b)) of the InGaAs /InAlAs FACQW. Four absorption peaks were observed and these peak positions are almost consistent with calculated ones. The calculated results predict that the large refractive index change will be produced by the large change in absorption at 1380 nm. The measured results in Fig. 2(b) showed similar behavior. That is, the increase of absorption peak at 1376 was observed with the increase of reverse bias voltage. The results indicates



(a)



(b)

Fig.2. (a) . Calculated absorption spectra of the FACQW. (b) Measured photo-absorption current spectra at room temperature.

the large refractive index change is expected in the transparent wavelength region as predicted by the theory.

In Fig. 2(b), a total photo-absorption current increased with the change of reverse bias voltage from V =0 to −1V. This means that the multi-FACQW core layer is not fully depleted at the voltage range and some FACQWs are outside of the depletion layer. The depletion layer thickness under a reverse bias voltage was measured by a capacitance-voltage (*C-V*) method. The results show that the depletion layer expanded with the increase of reverse bias voltage and at V= −2V the the *i*-core layer was fully depleted. The carrier density in the *i*-core layer was about 1 x 10^{17} cm^{-3} due to the impurity unintentionally doped during MOVPE growth. The high carrier density causes a non-uniform intensity of the applied electric field in the core layer. The behavior of the FACQW is quite sensitive to an applied electric field, therefore, this non-uniformity of an electric field deteriorates the total electrorefractive index change in a multi-FACQW.

4. InGaAs FACQW Phase Modulator

We fabricated a ridge waveguide phase modulator using wet etching process. We investigated phase modulation characteristics at the wavelengths of 1510 ~ 1570 nm (100~160 nm longer that the wavelength of the absorption edge) by the Fabry-Perot resonance method. Figure 3 shows the measured phase modulation characteristics of the InGaAs/InAlAs FACQW grown by

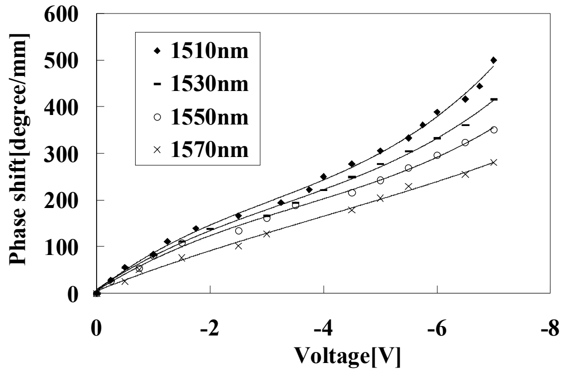


Fig.3. Phase modulation characteristics of the FACQW phase modulator.

MOVPE. These phase modulations are caused by the combination of some physical effects such including the quantum confined Stark effect (QCSE), the carrier depletion effect [3], and the Pockels effect. The phase shift at V = 0V ~ -2V is mainly due to the carrier depletion effect when the thickness of the depletion layer in the core layer expands. The phase shift at V = -2V~ -7V is probably due to the QCSE in the FACQW. Similar tendency was observe in InGaAsP QW phase modulator [3]. However, in the InGaAsP QW phase modulator, the intensity modulation due to the absorption occured at higher reverse bias voltage (>3.5 V). This is caused by the large red-shift of absorption edge due to the QCSE in the conventional QWs. On the other hand, in the FACQW, the intensity modulation was not observed up to V= −7. This is because the red-shift of the absorption edge is small in the FACQW. This large refractive index change without absorption in the FACQW is promising for realization of high-performance modulators and switches based on phase modulation.

5. Conclusion

The optical properties of InGaAs/InAlAs five-layer asymmetric coupled quantum well (FACQW) grown by MOVPE are investigated. The FACQW phase modulator is fabricated and its large phase shift is successfully observed. The experimental results show the InGaAs/InAlAs FACQW is a promising material for high-speed and low-driving voltage optical modulators and switches based on phase modulation.

Acknowledgment

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