Extended Abstracts of the 17th Conference on Solid State Devices and Materials, Tokyo, 1985, pp. 91-94

Electric Field Induced Absorption Changes in InGaAsP/InP Multi-Quantum Well

A. Ajisawa, K. Nishi, T. Yanase, M. Fujiwara, and R. Lang

Opto-Electronics Research Laboratories, NEC Corporagtion

4-1-1 Miyazaki, Miyamae-ku, Kawasaki 213, Japan

InGaAsP/InP multi-quantum well (MQW) structure has been fabricated by hydride vapor phase epitaxy (VPE), and the quantum size effect in this quaternary-binary quantum well has been confirmed through the step-like structure in the transmission spectra. Furthermore, electric field induced absorption changes have been observed. Changes near the absorption edge have been found to be more conspicuous than those observed with double hetero structure.

1 Introduction

Electric field effects in multi-quantum well(MQW) structure are very attractive for their potential applicability to novel optical devices, such as very high speed optical modulators and bistable devices. Electric field effects on MQW have been examined in GaAs/AlGaAs[1)] binary-ternary and InGaAs/InAlAs[2)] ternary-ternary material systems, and optical modulators have been fabricated making use of the electro-absorption effect in MQW[1)]. However, few reports have so far been made on InGaAsP/InP quaternary-binary MQW[3)], which would be very useful in 1 μm band optical communication systems.

The following reports direct confirmation of the quantum size effect in InGaAsP/InP MQW through optical transmission spectra measurement. Also, electric field induced changes in the absorption in MQW are reported and they are compared with those in double hetero-structure(DH). To the authors' knowledge, this is the first report on observation of electric field effects in the optical absorption spectra of InGaAsP/InP MQW.

2 Crystal growth

In fabricating InGaAsP/InP MQW structures, hydride transport vapor-phase epitaxy with a double growth chamber reactor[4),5)] is adopted. This epitaxial technique utilizes metallic In and Ga as group III element source, and hydride AsH_3 and PH_3 as the group V element source. One chamber of the double growth chamber reactor is used to grow the InGaAsP layer, and the other chamber is used for InP growth. The substrate is transferred mechanically from one chamber to the other, and this transfer completes within 1 second in order to obtain abrupt hetero-interface and to protect the substrates from thermal damage.

Using this method, MQW samples that contain 30 periods of alternate InGaAsP and InP thin layers have been fabricated. Some DH samples were also fabricated as reference. Substrate and metal source temperature during growth were 691 °C and 874 °C respectively. For InGaAsP growth, flow rates were 2.5 cc/min each for total group III source gas (InCl, GaCl) and for total group V source gas (AsH_3, PH_3). Growth rates calculated from usual DH growth in the same condition yield 18 Å/s for InGaAsP and 11 Å/s for InP growth. Dimethylzinc (DMZ) and H_2S were employed as zinc and sulfur source for p and n type doping. The substrates used for this experiment are sulfur doped InP(100).

The InGaAsP well and InP barrier layer thicknesses are determined by the scanning electron microscope (SEM) observation of angle beveled sample (Fig.1) and the interval of satellite peaks in the x-ray diffraction curve

(Fig.2). The InGaAsP well and InP barrier thicknesses from those measurements agreed almost exactly with those calculated from experimentally confirmed growth rate for thicker layers.

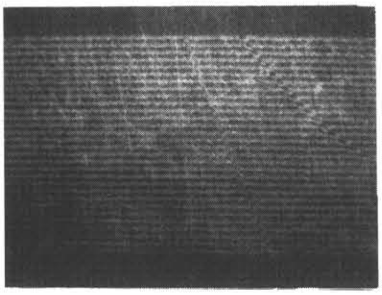

Fig. 1 Scanning electron microscope (SEM) photograph of angle beveled InGaAsP/InP MQW sample. 1500 magnification. White shows InGaAsP well Black shows InP barrier.

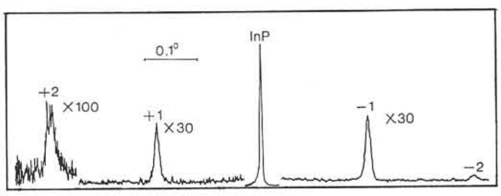

Fig. 2 X-ray diffraction curve.

Carrier concentrations in each structure have been determined by the Schottky barrier type capacitance-voltage measurements between etching electrolytic etchant solution and the etched semiconductor surface using semiconductor profile plotter. The typical results are $n = 3 \times 10^{16}$ cm^{-3} for undoped InP layer, and $n = 2 \times 10^{16}$ cm^{-3} for undoped InGaAsP layer. For the undoped MQW region, $n = 6 \times 10^{15}$ cm^{-3} is obtained as average value between well and barrier layer.

3 Experiments and Results

3-1 Transmission spectra measurements

To confirm the quantum size effect in InGaAsP/InP MQW, transmission spectra have been measured. The schematic view of the MQW sample is shown in Fig.3. Transmission spectra measurements were made with a lock-in detection system, using chopped light from a tungsten lamp passed through a grating monochromator. The transmitted optical power perpendicular to MQW layers was detected with a PbS cell. Measurement resolution was about 10 Å.

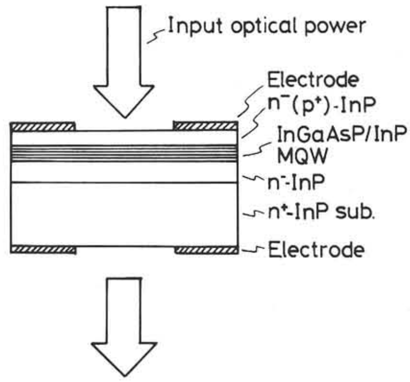

Fig. 3 A view of a MQW sample for transmission measurements.

Measured transmission spectra, at 10 K, for the InGaAsP/InP MQW sample and the reference InGaAsP/InP DH sample are shown in Fig.4. These two samples had the same InGaAsP composition and the same total InGaAsP layer thickness. The MQW sample has the absorption edge at a shorter wavelength than the DH sample and the step-like structures can be observed in its spectrum. Such structures are not recognized in the spectrum for the DH sample. The step-like transmission spectrum in Fig.4 can be ascribed to the change in the state density of carriers, which is brought forth by the decreased dimensionality of the free carrier motion from 3 dimensions to 2 dimensions.

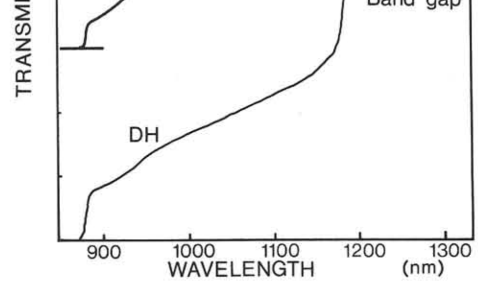

Fig. 4 Measurement transmission spectra, at approximately 10k, for InGaAsP/InP MQW sample and InGaAsP/InP DH sample.

The arrows in the figure indicate theoretical level positions computed with the following basis. 1) Well thickness L_z is taken as 160 Å, which has been determined from SEM observation and X-ray diffraction measurements. 2) Band gap energies of InP and InGaAsP are, respectively, 1.416 eV and 1.045 eV at 10 K, which has been determined from measured transmission spectra for the DH sample. 3) Electron, heavy-hole and light-hole effective masses are assumed, respectively, to be 0.080 m_o, 0.850 m_o and 0.090 m_o in InP, and 0.059 m_o, 0.712 m_o and 0.065 m_o in InGaAsP[6], where m_o is free electron mass. 4) Conduction band discontinuity ΔEc is assumed to be approximately 40% of the total band discontinuity[7].

The calculated transition wavelength between electron subbands and heavy-hole subbands are 1168 nm, 1116 nm and 1043 nm at 10 K. Calculated n=1 and n=2 values are in close agreement with the step positions in the spectrum. Therefore, those results directly confirm the presence of quantum size effect in InGaAsP/InP MQW structures.

However, no step position corresponding to n=3 could be observed in the MQW spectrum. Besides, exciton resonance peaks were not observed. The reasons are not clear at present, but the layer thickness fluctuations and the relatively high background impurity concentration are among the possible causes.

3-2 Electric field induced absorption changes

The electric field effects in the optical absorption spectra were observed with p-i-n structure MQW and DH samples in which the undoped MQW layers or the narrow gap layer is sandwiched between n and p type cladding layers. Carrier concentrations for the InP cladding layers are p = 1 x 10^{18} cm^{-3} for the zinc doped p layer and n = 1 x 10^{18} cm^{-3} for the sulfur doped n buffer layer. The reverse bias voltage was applied perpendicular to the layers. This MQW sample consists of 30 periods of alternate 125 Å InGaAsP well and 95 Å InP barrier, which also exhibited the step-like features in the transmission spectra indicative of the quantum size effect. The absorption edge wavelength for the p-i-n DH sample happened to agree closely with that for the MQW sample, because of the slight shift in the quaternary composition.

Figure 5 shows absorption spectra of MQW and DH sample at the applied electric field of E = 0 and 1.6 x 10^5 V/cm, which were obtained from optical transmission normal to the layers. This E = 1.6 x 10^5 V/cm electric field was the maximum field applicable to the MQW sample, calculated from the depletion layer thickness determined by capacitance-voltage maesurement, and applied voltage.

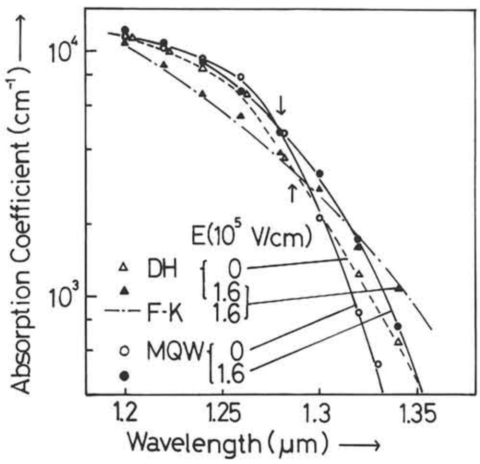

Fig. 5 Absorption spectra for MQW and DH sample at E = 0, 1.6x10^5 V/cm applied electric field.

At zero field it was found that the curve for MQW is steeper than for DH in a wavelength range longer than the arrow position. Consequently, in this range, i.e. passive region the absorption coefficient for MQW is smaller than for DH.

In the wavelength range longer than the the arrow position, optical absorption was found to increase with applied electric field. In this range, the observed relative absorption increase in MQW was greater than that in DH.

On the other hand, in the wavelength range shorter than the arrow position, optical absorption decreases as the electric field is applied.

The theoretical absorption spectra at E = 1.6 x 10^5 V/cm obtained from the Franz-Keldysh (F-K) effect calculation[8] is also shown in Fig.5. The measured absorption coefficients in the DH sample are in good agreement with the theoretical curve for the F-K effect.

4 Discussion

In Fig.5, optical absorption increases in the longer wavelength range near the absorption edge and decreases in the shorter wavelength range as the voltage is applied on both MQW and DH. As to the DH sample, the change is ascribed to the F-K effect in view of the good agreement between experiment and calculation.

In the case of MQW, these changes are presumably due to the field-induced shift of quantized levels and spatial separation of electron and hole wave functions in InGaAsP quantum wells. At zero field the ground state electron and hole wave functions are symmetrical with respect to the center of the well. When a field is applied perpendicular to it, the electron and hole distribution are polarized in opposite directions. Consequently, in the longer wavelength range, optical absorption increases as the absorption edge moves towards the longer wavelength with the shifts in the quantized levels. The relative absorption change in MQW is greater than that in DH. Because, at zero field, MQW has the absorption edge steeper than DH.

In the shorter wavelength range the absorption decreases because of the reduction in the transition probabilities caused by the wave function separation. But the change in MQW is smaller than that in DH. This is presumably due to the carrier confinement into the InGaAsP well which limits the extent of the spatial separation of electron and hole wave functions.[9]

The maximum variation in absorption coefficients in MQW and DH are respectively about $1.3 \times 10^3\ cm^{-1}$, $0.5 \times 10^3\ cm^{-1}$ for 1.6×10^5 V/cm applied field, which is attained at 1.3 μm wavelength. The greater increase of the absorption coefficient and the steeper absorption edge indicate that the InGaAsP/InP MQW is quite suitable for such device application as optical modulators.

5 Conclusions

Direct observation of the quantum size effect in InGaAsP/InP quaternary-binary MQW has been made, for the first time to the authors' knowledge, through the optical transmission spectra which showed steps reflecting the two dimensional density of states of carriers confined in the quantum well. Furthermore, electric field effects in optical absorption have been observed in InGaAsP/InP MQW structures, and enhanced optical absorption change has been observed in the MQW, as compared with the DH, in the longer wavelength range near the fundamental absorption edge. In view of these results, InGaAsP/InP MQW structures are expected to be applicable to optical modulators and other novel high-speed optical devices for optical communication in the 1 μm band.

Acknowledgment

The authors are grateful to K. Onabe, Y.Ide, Y.Kato, Y.Ohta and M.Sugimoto for helpful comments and discussions. They are also grateful to E.Saito for carrier concentraion measurements.

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