Anisotropic Electroabsorption and Optical Modulation in InGaAs/InAlAs Multiple Quantum Well Structures

KOICHI WAKITA, YUICHI KAWAMURA, YUZO YOSHIKUNI, HAJIME ASAHI, AND SHINGO UEHARA

Abstract—**The first measurements to be made of large anistropic electroabsorption and modulation of long-wavelength light propagating along the plane of InGaAs/InAlAs multiple quantum well (MQW) structures grown by molecular beam epitaxy (MBE) are reported. Photocurrent response of waveguide p-i-n diodes is studied for incident light polarization parallel and perpendicular to the MQW layers. Photocurrent increase with reverse bias throughout the entire photoresponse spectrum is observed for both polarizations. The MQW p-i-n optical modulator shows a capacitance-limited pulse response of 250 ps and the modulation depth is 14 percent.**

I. Introduction

RECENTLY, MQW structures have been extensively studied from both physical and device application aspects. To date, many reports have been published in high-speed optical modulators using GaAs/AlGaAs MQW structure [1]–[4]. However, application of such material is limited to short-wavelength regions. From the applicational standpoint, much interest has been generated with regard to external modulators for long-wavelength injection lasers in high-bit-rate and long-haul optical communication systems. This is because these devices offer chirping-free high-speed modulation. Wavelength chirping associated with high-speed (exceeding 1 Gbit/s) direct modulation of laser diodes results in a dispersion penalty [5]. The InGaAs/InAlAs system discussed here is very suitable material for MQW structures operating in the long-wavelength region. The conduction band discontinuity ΔE_c (0.5 eV) [6] of the InGaAs/InAlAs is larger than that (0.2 eV) of the InGaAs/InP, which is another candidate for long-wavelength MQW; thus, quantum size effects are more pronounced in the former system.

Quantum size effects such as photoluminescence (PL) peak wavelength shortening [7]–[9], PL half-width narrowing [9], and exciton-resonance-induced step-like structures with dips in optical transmission spectrum [9] have been observed in InGaAs/InAlAs MQW structures. Electric-field-induced absorption changes (electroabsorption) have also been reported [10] in this system. Recently, the existence of room temperature exciton resonance peaks has been clearly confirmed in the optical transmission spectrum [11], [12], and a high-speed optical modulator operating at 1.5 μm has been demonstrated [13]. However, all of the reports are for normal incidence configuration, i.e., incident light propagates perpendicular to the MQW layers. This results in a short interaction length between the light and the MQW's that is limited to the epitaxial thickness, which is usually less than 1 μm. In parallel incidence or waveguide configurations, on the other hand, the interaction length is large. Recently, high on/off ratio modulation has been reported for GaAs/AlGaAs MQW's using the waveguide structure [3], [4]. This configuration also enables us to observe the difference in electroabsorption between the light polarized parallel and perpendicular to the MQW layers. Such observation must offer much information on MQW nature. This paper reports first observations [14] of a large anisotropic electroabsorption effect and optical modulation in a waveguide-type InGaAs/InAlAs MQW p-i-n structure operating at long wavelengths.

II. InGaAs/InAlAs MQW Structures

The MQW structures were fabricated by the ANELVA 830S-II MBE system [12]. In (6N), Ga (7N), Al (6N) were used as group III beam sources. Arsenic (7N) was used as a Group V beam source. Si and Be were used as n-type and p-type dopants, respectively.

InGaAs/InAlAs MQW structures were grown on Fe-doped semi-insulating (100) InP substrates or Sn-doped (100) InP substrates (n = 1–2 $\times$ 10^{18} cm^{-3}). The substrate temperature during growth was 500°C, and the growth rate was 150 Å/min.

The undoped InGaAs layer is an n-type with room temperature carrier concentration of 4 $\times$ 10^{15} cm^{-3} and electron mobility of 9700 cm^2/V $\cdot$ s, while the undoped InAlAs layer has rather high resistivity (40 Ω $\cdot$ cm) at room temperature.

Optical transmission and PL measurements were carried out on an MQW wafer comprised of 60 undoped InGaAs wells (well thickness L_Z = 75 Å) and 59 undoped InAlAs barriers (barrier thickness L_b = 75 Å) sandwiched by InAlAs layers. The optical absorption spectrum at room temperature is shown in Fig. 1 where incident light is perpendicular to the MQW layers. The absorption edge is 1.5 μm and the clear step-like structure and two peaks at the absorption edge are observed, corresponding to the two-dimensional density of states and exciton level formation. These two peaks arise from the

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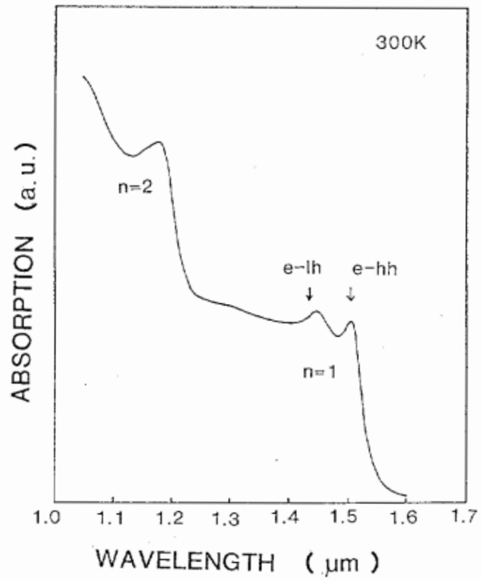

Fig. 1. Optical absorption spectrum for undoped MQW wafer at room temperature. The *hh* and *lh* indicate the heavy hole and light hole exciton resonance peaks, respectively.

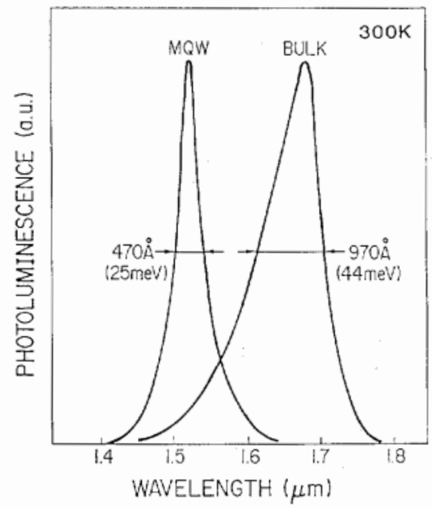

Fig. 2. Photoluminescence spectra for the undoped MQW wafer and the undoped InGaAs layer. Each intensity is normalized to an equal value.

heavy-hole (*hh*) and light-hole (*lh*) excitons. The arrows in Fig. 1 indicate the calculated value for $n = 1\ e - hh$ and $n = 1\ e - lh$ exciton peaks which were obtained using the conduction band and valence band discontinuity ΔE_c of 0.5 eV and ΔE_v of 0.2 eV, respectively, and the Kronig–Penney model taking into account band nonparabolicity [8]. The discrepancy between the calculation and experimental result indicates that the value of ΔE_c is slightly large [11].

Various optical absorption spectra corresponding to different L_z values (from L_z = 50–125 Å, step 25 Å) were investigated and the *hh* exciton binding energies were estimated by using a semi-empirical line shape model [15], and were 12 and 16 meV for L_z = 125 Å L_z = 50 Å with L_b = 75 Å, respectively. The binding energy is strongly increased by the confinement, but these binding energies are much larger than the theoretical ones. This is not clear as yet. The difference may be due to hole nonparabolicity owing to valence subband mixing [16]. These relatively large binding energies well explain the observation of well-resolved *hh* and *lh* excitonic resonances in the absorption spectrum as high as 460 K [17].

The room temperature PL spectrum for the undoped MQW wafer and that for the undoped InGaAs layer grown by MBE are shown in Fig. 2 [12]. The PL peak wavelength of the MQW wafer (1.52 μm) is shorter than that of the InGaAs bulk layer (1.66 μm). The PL half width of the MQW wafer (470 Å, 25 meV) is about 57 percent of that of the InGaAs bulk layer (970 Å, 44 meV).

The PL spectrum agrees with calculations based on the relationship with the absorption spectrum using the empirical line shape model. The PL peak wavelength is slightly longer than that of *hh* exciton resonance because of thermal broadening in the MQW quasi-two-dimensional density of states. The PL half width corresponds to the exciton resonance half width. The room temperature exciton resonance half width consists of thermal broadening due to LO phonon absorption [18] and inhomogeneous broadening originated from the fluctuations of the confinement energy caused by variations of the layer thickness [19]. The low-temperature exciton linewidth has been ascribed to fluctuations of layer thickness and alloy disorder. In this sample, the lateral dimensions of monolayer fluctuation at the interface were about 100 Å [17].

III. Electroabsorption in InGaAs/InAlAs MQW

When an electric field is applied perpendicular to MQW layers, a change in the optical absorption occurs. This electroabsorption effect is associated with an enhanced shift to lower energies in band-edge features relative to that seen in bulk material. This shift is explained by changes in particle confinement energy in the wells and a change in exciton binding energy [20].

Previous reports [1], [2] on electroabsorption effects in MQW's were for the incident light perpendicular to the plane of the MQW layers. The authors were the first to report observation of room temperature field-induced absorption changes in InGaAs/InGaAlAs MQW's where the incident light propagates parallel to the MQW layers [10]. This configuration has the potential to realize high modulation efficiency in low applied voltage. However, clearly defined changes were not observed because of poor crystal quality. Recently, waveguide-type modulation in GaAs/GaAlAs MQW's [3], [4] and anisotropic absorption of light in GaAs/GaAlAs single quantum well waveguides have been reported [21]. In this section, anisotropic electroabsorption in the high-quality InGaAs/InAlAs MQW's, where sharp *hh* and *lh* excitons are separately observed at temperatures up to 460 K, is described.

A schematic view of an InGaAs/InAlAs MQW p-i-n diode used in the experiment is shown in Fig. 3. It consists of 0.5 μm thick undoped MQW layers (40 periods of 75 Å InGaAs well and 50 Å InAlAs barrier) surrounded by an Si-doped (1×10^{18} cm^{-3}) 0.1 μm InAlAs

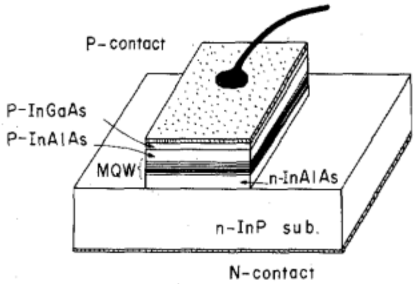

Fig. 3. Schematic view of the MQW p-i-n diode.

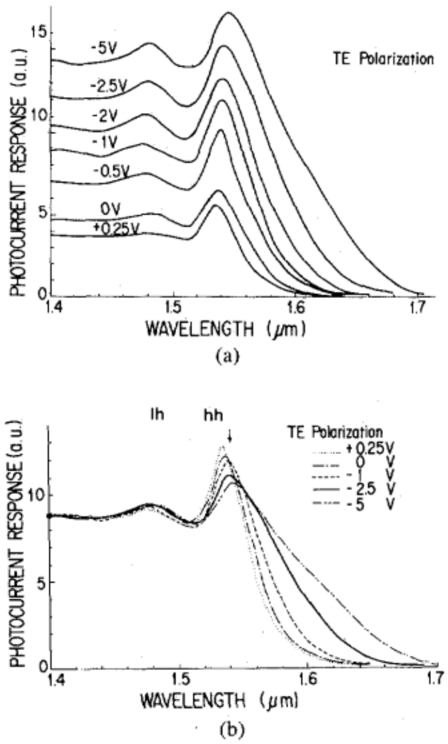

Fig. 4. (a) Room temperature absorbed current spectra of a 120 μm long MQW waveguide as a function of reverse applied bias. Incident light is polarized parallel to the plane of the layers. (b) Normalized spectra of this sample to equal photocurrent magnitude at 1.4 μm.

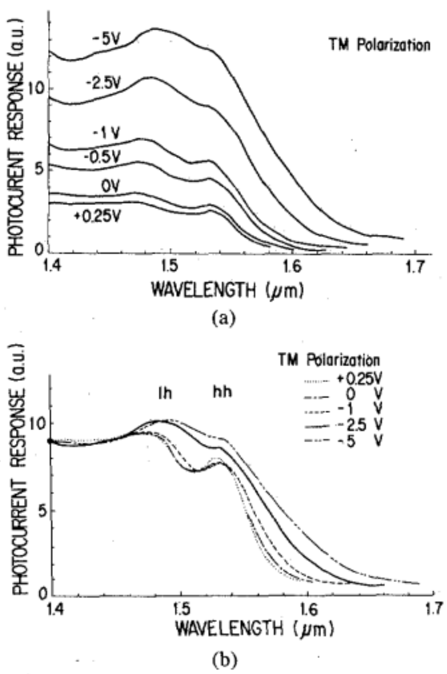

Fig. 5. (a) Room temperature absorbed current spectra for incident light polarization perpendicular to the plane of the layers. (b) Normalized data to equal photocurrent magnitude at 1.4 μm.

layer and Be-doped 1.5 μm InAlAs and 0.2 μm InGaAs layers grown on an Sn-doped InP substrate. The device has an 80 μm wide, 120 μm long, and 2.3 μm high mesa etched to the n-InP substrate. The capacitance of this device was 3.2 pF, implying an *RC* time constant of 150 ps when shunted by a 50 Ω load. No antireflection coating was applied on the surface.

An absorbed photocurrent spectrum for the MQW p-i-n diode near the band edge with a parameter of applied reverse bias where the incident light electric field is parallel to the MQW layers (TE polarization) is shown in Fig. 4. Chopped monochromatic light from a tungsten iodine lamp passing a grating monochrometer was polarized by a Glan-Thompson prism and was used to irradiate the cleaved facet of the diode. Corrections have been applied to the spectra for monochrometer grating wavelength and lamp emission characteristics. The spot size on the sample facet was about 50 μm in diameter and much thicker than the MQW active layer (0.5 μm) so a large part of the light beam was not guided in the active layer.

In this configuration, both *hh* and *lh* excitons are observed, and these results are similar to those obtained using MQW's with light propagating perpendicular to the layers. As the bias is increased from +0.25 to −5 V, a red shift of the absorption edge is observed, along with an increase in the photocurrent amplitude of several factors.

In order to clarify the spectrum shape change in photoresponse with applied voltage, the data in Fig. 4 (a) are replotted by normalizing each photocurrent magnitude to that of − 2 V at 1.4 μm as shown in Fig. 4 (b). The half widths of the *hh* exciton resonances increase with applied voltage. In a wavelength range longer than the arrow position, the optical absorption increase rate was found to be large. As for *lh* exciton resonance peaks, the shift is not as large as *hh* exciton resonances.

Photocurrent response for the incident light polarized perpendicular to the layers (TM polarization) is shown in Fig. 5. The absolute magnitude of photocurrent is on the same order as that obtained in TE polarization. The photocurrent response differences between TE and TM polarization are remarkable. In TE polarization, both *hh* and *lh* excitons are present, whereas in TM polarization, the *lh* exciton peak is mainly observed and the *hh* exciton peak is small. The red shift of *lh* exciton resonance associated with a reverse applied voltage increase is also observed in the TM configuration. The shift in exciton absorption is primarily explained in terms of a change in the confinement energies of the electron and hole in the quantum well plus some small change in the exciton binding energy. The energy shift was calculated, based on the theory

[20], [22], neglecting any change in the exciton binding energy [23] because of its small contribution (less than 1 meV for an electric field of 1.5×10^5 V/cm) for the structures under investigation ($L_z = 75$ A). The calculated results of the energy shift were larger than experimental results both for *hh* and *lh* excitons. Similar results were obtained for various samples fabricated from different wafers, although there was an ambiguity in estimating the low electrical field absolute magnitude in the quantum wells due to built-in potential. This discrepancy is considered to be due to the field inhomogeneity problems associated with multiple quantum wells. Reference [20] shows that when the field is parallel to the MQW layers, the excitons broaden with field, disappearing at fields of 10^4 V/cm, whereas when the field is perpendicular to the MQW layers, the exciton peaks shift to lower energies by up to 2.5 times the zero field binding energy with the excitons remaining resolved at up to 10^5 V/cm.

A bump corresponding to *hh* exciton resonance is observed in addition to the *lh* exciton resonance, as shown in Fig. 5. From the selection rules for absorption [24], the *hh* absorption should disappear or at least be significantly reduced for light polarization perpendicular to the layers. At present, it is not clear whether a spurious effect, which may be caused by the scattered light, or valence band mixing in the exciton wave function, as pointed out in [21], is responsible for the observed bump.

A photocurrent increase with applied bias throughout the entire photoresponse spectrum results from two effects [25]. The absorption mechanism for wavelengths longer than band edge or exciton absorption resonances involves the Franz–Keldysh effect in quantum well structures (quantum confined Stark effect):QCSE on the absorption edge. The absorption which results in the shoulders probably involves the QCSE effect and some shallow impurity level or defect center. The increase in quantum efficiency with increased bias at the shorter wavelengths is due to the increased depletion width and the QCSE shift of the absorption edge. Similar phenomena have recently been reported for AlInAs/GaInAs MQW APD grown by MBE [26] and GaInAs/InP MQW detectors grown by a gas source MBE [27], both operated at normal light incidence. However, the photocurrent increase caused by reverse bias application is only about three factors for present results, while the increase was over one to three orders of magnitude for the others. This may be because the low-bias quantum efficiency, which is considered to be limited due to carrier trapping at heterointerfaces, is rather low for the other devices.

IV. Optical Modulation

The optical modulation in MQW operating at long wavelength has been reported [13] with incident light perpendicular to the layers. The response speed of the modulator is reported to be less than 190 ps and is only attributed to the *RC* time constant and instrumental limitation. However, the modulation depth was minimal (1 percent) because of low optical interaction length. In this section, waveguide-type MQW optical modulators operating in a long-wavelength region using the electroabsorption effect in MQW structures described in the former section are presented.

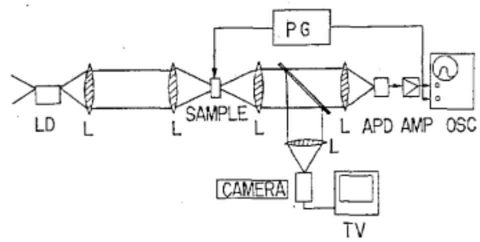

Fig. 6. Experimental block diagram for optical modulation.

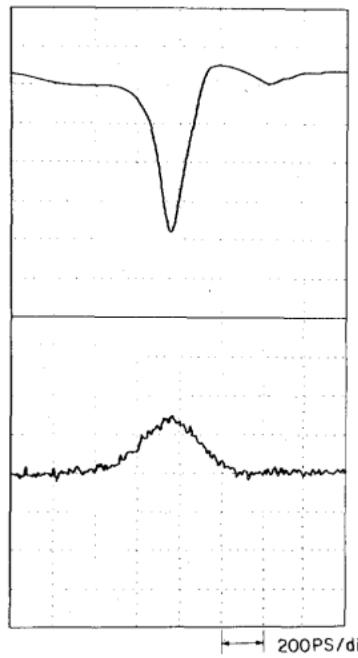

Fig. 7. Detected response of optical modulator under CW illumination of DFB laser diodes. The upper trace indicates electrical drive pulse and the lower trace indicates optical response.

The experimental block diagram is shown in Fig. 6. In order to observe the guided light near field, a TV camera with a PbS detector was used. To measure the dynamic optical response, the diode was bridged with a 50 Ω resistor shunt and driven by a pulse generator with a 150 ps rise time. The modulator was illuminated with focused light from a 1.56 μm CW InGaAsP/InP BH DFB laser diode. The optical output was detected with a reach-through Ge APD with a rise time of about 150 ps. The detected signal from the APD was preamplified with a B&H DC3002 amplifier (rise time 130 ps).

The observed signal recorded on an averaging sampling oscilloscope is shown in Fig. 7 when the diode is driven at 6 V. The configuration of TM polarization was used because the bandgap energy of MQW is so small that TE polarized light is almost absorbed by the MQW active layer. The sample used in this optical modulation is the same as that used in the previous section. The observed rise time is about 250 ps and is attributed only to the *RC* time constant and instrumental limitations. As for modulation efficiency, the modulation depth is observed at 14 percent. This value is quite improved from that of the modulator with incident light perpendicular to the MQW's [13]; however, it is not said to be sufficient. One reason is that unguided light passing through the transparent InP substrate without absorption in the active layer is detected directly at Ge–APD. Another reason is that the optical absorption in the waveguide is too large for modulated and guided light to diminish during the transmission. This is in part due to abnormally large absorption of the *hh* exciton resonance unexpected from the absorption selections rules. However, further improvement is expected by optimizing the MQW modulator structure to waveguide the light efficiently, in addition to adjusting the MQW absorption wavelength to use TE polarization and applying the antireflection coating to the facets to lower the insertion loss.

Summary

Quantum size effects such as PL peak wavelength shortening, PL spectrum narrowing, and well-resolved heavy hole and light hole exciton resonances at room temperature in optical absorption spectra were observed in InGaAs/InAlAs MQW structures grown by MBE. Large anisotropic electroabsorption for light propagating along the plane of the MQW layer has been discussed. An external quantum efficiency increase with the reverse applied bias has also been observed. A waveguide-type optical modulator operating at long wavelengths has been demonstrated in InGaAs/InAlAs MQW p-i-n diodes. This configuration enables fabrication of a new type of high-speed optical modulator or detector monolithically integrated with lasers. The observed anisotropic electroabsorption effect has the potential for application to polarization-sensitive devices. Work is presently in progress on the monolithic integration of MQW modulator and DFB laser diodes.

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