Characterization of InP/InGaAs/InP Single Quantum Wells Grown by OMVPE

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Abstract– The optical transition energies in InP/InGaAs/InP single quantum wells (SQWs) grown by organometallic vapor phase epitaxy (OMVPE) with well thicknesses from 1 to 5 monolayers(ML) were investigated by room-temperature photoreflectance (PR) measurements. PR features due to subband transitions were clearly observed even in the SQWs with extremely thin well thicknesses. PR spectra showed e(1)-hh(l) and e(1)-lh(1) transitions in the lnGaAs wells together with the band-to-band transition in the lnP layers. Clear PR spectra indicate excellent optical quality of these OMVPE-grown structures. The transition energies were determined by fitting the PR spectra to the theoretical line-shape expression. The resultant e(1)-hh(l) transition energies were close to energy positions of emission peaks observed in photoluminescence measurements at room temperature. The e(1)-hh(1) and e(1)-lh(1) transition energies decreased with increasing well thicknesses. This behavior agreed qualitatively with the theoretical prediction, although there is a significant discrepancy in transition energies.

บทคัดย่อ–การถ่ายทอดพลังงานในบ่อควอนตัมของสารกึ่งตัวนำ InP/InGaAs/InP โครงสร้างบ่อควอนตัมเดี่ยวปลูกผลึกโดยวิธี Organometallic Vapor Phase Epitaxy (OMVPE) ถูกตรวจสอบโดยวิธีวัดโฟโตรีแฟลกแตนซ์ (Photoreflectance,PR) ที่อุณหภูมิห้อง ลักษณะสเปคตรัมของ PR ที่แสดงถึงการถ่ายทอดพลังงานในบ่อที่บางอย่างยิ่งยวดถูกสังเกตุเห็นอย่างชัดเจนซึ่งเป็นการถ่ายทอดพลังงานระหว่าง e(1)-hh(1) และ e(1)-lh(1) กับการถ่ายทอดพลังงานระหว่างแถบพลังงานต้องห้ามของ InP สเปคตรัม PR ที่สังเกตุเห็นอย่างชัดเจนบ่งชี้ถึงคุณภาพของการปลูกผลึกโดยวิธีนี้ ค่าการถ่ายทอดพลังงานได้จากการ Fitting ข้อมูลที่ได้จากการทดลองเข้ากับทฤษฎี ค่าที่ได้รับนี้ใกล้เคียงกับการวัดโดยวิธีโฟโตลูมิเนสเซนต์ (Photoluminessence,PL) การถ่ายทอดพลังงานระหว่าง e(1)-hh(1) และ e(1)-lh(1) ลดลงเมื่อบ่อศักย์กว้างขึ้น พฤติกรรมนี้เหมือนกันกับการยืนยันทางทฤษฎี แม้มีค่าที่แตกต่างกัน

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1. Introduction

$In_{0.53}Ga_{0.47}As$ lattice-matched to InP has emerged as a very important semiconductor material. This material is promising for ultrahigh speed devices utilizing the high electron mobility and high peak velocity which is approximately 50 percent higher than that of GaAs at comparable impurity concentrations at 300 K[1-4]. The band gap of 0.75 eV (1.65 μm) is ideal for photodetectors in optical communications systems with the optimum wavelength range between 1.3-1.6 μm. Furthermore, semiconductor injection lasers

utilizing InGaAs/InP quantum well structures allow emission wavelength to be shifted from the 1.65 μm to the 1.3-1.55 μm region by having different well thickness[5,6].

Modulation spectroscopy is an important technique for study and characterization of energy-band structures of semiconductors. Modulation techniques such as electroreflectance (ER) and photoreflectance (PR) are particularly useful since they yield spectra with sharp features at critical-point energies. The features in these spectra appear at energies corresponding to the band gap characteristic points or other peculiarities in the dielectric function. PR is of considerable interest because it is contactless, requires no special mounting of the sample, can be performed in a variety of transparent ambients, and is sensitive to surface and interface electric fields.

Reddy *et al.*[7] have reported PR results on GaAs/(Al,Ga)As multiple quantum wells of different well thicknesses. Their results concern with transitions involving the so-called "unconfined" states. They also performed PR studies on a series of InGaAs/GaAs single quantum well (SQW) already defined with different well thicknesses in a range between 8 to 12 nm.[8] Their study indicated that the conduction-band discontinuity is 0.420 eV. Yaguchi *et al.*[9] studied the band offsets at the heterointerface of GaAs/$GaAs_{1-x}P_x$ SQWs structures of different well thicknesses in a range between 5 nm to 20 nm using PR. The band offsets were found to be almost linearly dependent on the phosphorus composition in the range of x 0.23

In this report, we conducted room-temperature PR measurements to investigate optical transition energies in InP/InGaAs/InP SQWs with extremely thin well thicknesses of 1 to 5ML, i.e., 0.3~1.5 nm, grown by a low-pressure organometallic vapor phase epitaxy (OMVPE). The subband transitions were clearly observed even in the SQWs with ultra thin well thickness, and their energies will be discussed with theoretical calculation.

2. Sample preparation

The samples were prepared using a low-pressure OMVPE. Trimethylgallium (TMGa), trimethylindium (TMIn), AsH_3, and PH_3 were used as the source gases. A 100 nm thick InP buffer layer was grown on all semi-insulating InP substrates, followed by InGaAs well layers with varied thicknesses (L_w) from 1 ML to 5 ML, and a 2 nm thick InP cap layer. The growth temperature was 600 ^{0}C. Flow sequence of source gases and the sample structure are shown in Fig. 1.

3. Photoreflectance measurement system

In our PR measurements, a modulation light was provided by a 2 mW He-Ne (λ=632.8 nm) laser. The chopped laser light was irradiated onto the sample with a spot radius of about mm. A 100 W tungsten lamp was dispersed by a 20 cm monochromator and used as a probe light. The reflected probe light from the sample was detected by a nitrogen-cooled Ge detector. The detected signal contains two parts, ac part and dc part. The ac part measured by the lock-in

amplifier synchronized to the modulating frequency is related to the change in reflectivity, dR. The dc part of the detected signal is related to the reflected light, R, itself. Using a computer for data acquisition and processing, a spectrum of dR/R versus photon energy can be obtained.

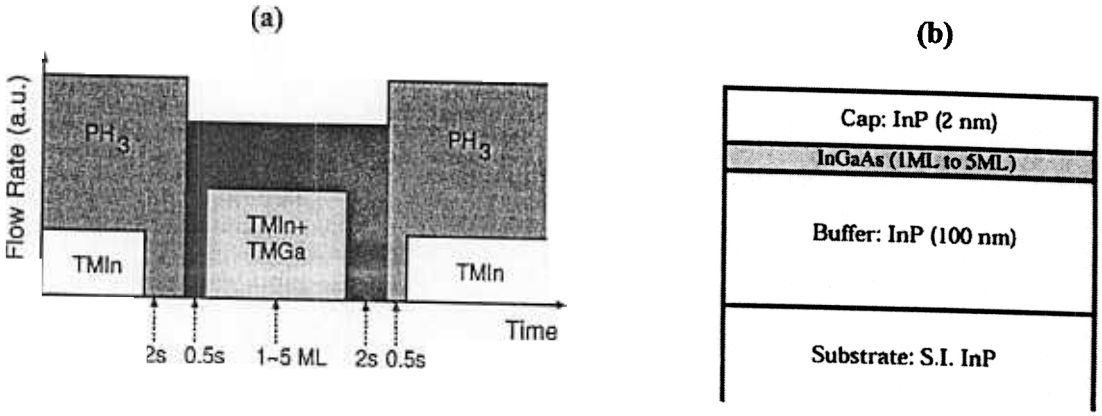

Fig. 1. (a) Flow sequence of source gases **(b)** InP/InGaAs/InP SQW structures.

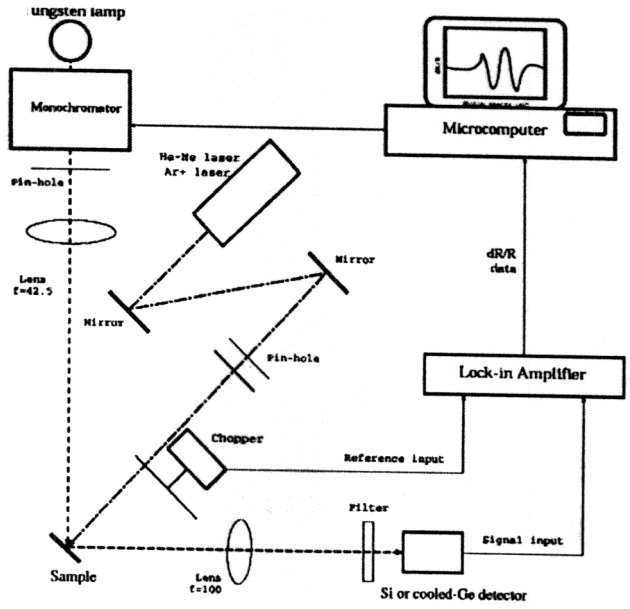

Fig. 2. Schematic diagram of the room-temperature PR measurement system.

The schematic diagram of the PR measurement system is shown in Fig. 2. All PR measurements were conducted at room temperature.

4. Results and Discussion

Fig. 3 shows PR spectrum of the sample with 2 ML (0.6 nm) thick InGaAs well. The e(1)-hh(1) and e(1)-lh(1) transitions from the InGaAs well are clearly observed with the band-to-band transition in the InP layer. For comparison, the photoluminescence (PL) spectrum measured at room temperature is also shown in Fig. 3. The resultant e(1)-hh(1)

transition energy is close to the energy position of emission peak observed in the PL spectrum. PR spectra of all the samples are shown by solid lines in Fig. 4. The PR spectra reveal e(1)-hh(1) and e(1)-lh(l) transitions in InGaAs wells together with the band-to-band transition in the InP layers. The clear PR spectra indicate excellent optical quality of these OMVPE-grown structures.

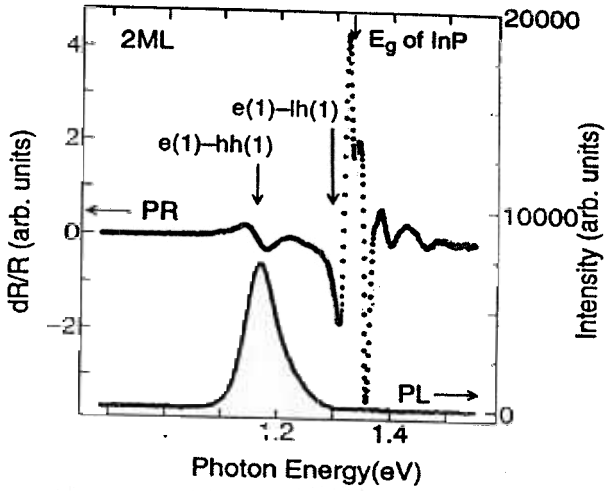

Fig. 3. Room-temperature PR and PL spectra of the InP/InGaAs/InP SQW with 2 ML (0.6 nm) thick InGaAs well.

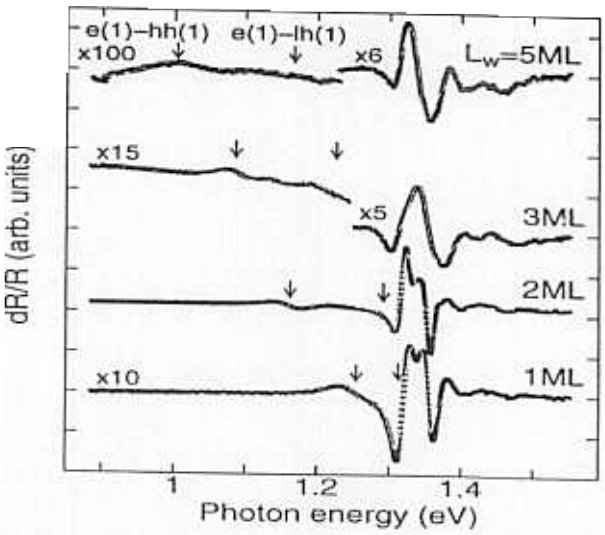

Fig. 4. Room-temperature PR spectra as a function of the well thickness. The fittings of Eq. (1) to the PR spectra are shown by bright lines. The e(1)-hh(1) and e(1)-lh(1) transition energies determined by the fittings are indicated by arrows.

The PR spectra as a function of photon energy can be analyzed using the familiar Aspnes third-derivative function in the low electric field limit'[10], i.e.,

$$\frac{\Delta R}{R}=\mathrm{Re}\sum_{j=1}^{p}C_j e^{i\theta_j}(E-E_{gi}+i\Gamma_j)^{-n} \qquad (1)$$

Here, R is the reflectance, ΔR is the induced change in the reflectance by modulation light, E is the photon energy, p is the total number of spectral structures to be fitted, E_{gi}, Γ_j, C_j and θ_j are transition energy, broadening parameter, amplitude and phase, respectively, of the feature corresponding to the j^{th} critical point. The parameter n is a factor used to specify the critical point dimension.

The energy levels associated with e(1)-hh(1) and e(l)-lh(1) transitions were determined by least-square fitting of Eq. (1) to PR spectra obtained experimentally. In this calculation, the n value for the e(1)-hh(l) and e(1)-lh(1) features is 3, while the value is 5/2 for the band gap transition[11,12]. The resultant least-square fittings are also shown by bright lines in Fig. 4. The e(1)-hh(l) and e(1)-lh(1) transition energies obtained from these fittings are shown by arrows in the figure. In Fig. 5. The e(l)-hh(l) transition energies determined from PR measurements are plotted by closed lozenges as a function of the well thickness, while open circles denote energy positions of emission peaks observed in PL measurements. The transition energy decreases with increasing well thickness. The e(l)-hh(1) transition energies obtained from PR measurements agree quite well with PL results for all samples. Figure 6 shows the well thickness dependence of the e(l)-lh(l) transition energies plotted by closed lozenges. The transition energy also decreases with increasing well thickness, which is similar to the behavior of the e( )-hh(l) transition.

We have made a simple calculation for quantum levels in finite quantum wells. The one-dimensional Schrodinger equation for a finite square well was solved to obtain a stationary wave function. The e(1)-hh(1) and e(1)-lh(1) energies were calculated without considering any other effects such as excitons and the Stark effect. In the calculation, 0.73 eV and 1.35 eV were used as room temperature band gaps for InGaAs and InP, respectively. The conduction-band discontinuity ΔE_c of 0.217 eV and valence-band discontinuity ΔE_v of 0.403 eV were applied[13]. The calculated transition energies are also plotted as a function of the well thickness by closed circles for the e (1)-hh(1) transition in Fig. 5 and for the e(1)-lh (1) transition in Fig. 6. The behavior of measured transition energies agrees qualitatively with the theoretical prediction, which decreases with the increasing well thickness. However, we observed a significant discrepancy between the measured and the calculated values. The measured energies are, in general, 50 meV below the calculated energies.

Now we should discuss the origin of the discrepancy in the transition energies determined experimentally and calculated theoretically. The first possible candidate for the origin is the limi of our simple theory for the prediction of the transition energies. Yamada *et al.*, theoretically studied subband structure of the InP/InGaAs/InP SQWs using the envelope function approximation method taking into account band nonparabolicity.[14] According to their calculation, nonparabolicity plays an important role in the

InP/InGaAs/InP SQWs and experimental PL energies for wide quantum wells are reasonably explained by this theory. For the well thickness less than 5 nm, the PL energies are significantly lower than the theoretical results. Gradually increasing discrepancies with decreasing well width is contradictory to the participation of impurities in the recombination process. The possibility of the participation of free excitons is, however, not excluded, since the half-widths of PL spectra are relatively broad. But the discrepancies seem to be somewhat larger than the binding energies of the exciton confined in the InGaAs wells.

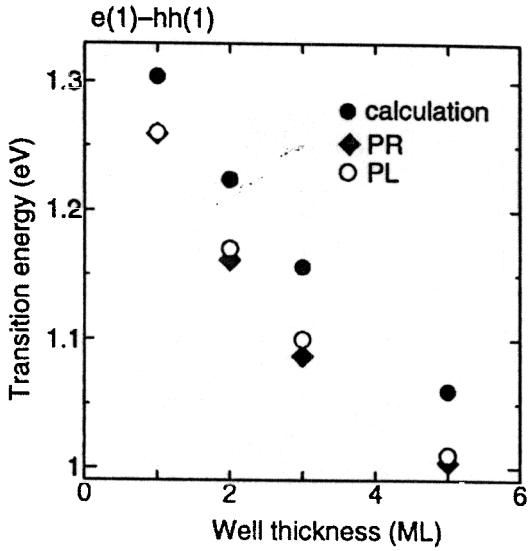

Fig. 5. Dependence of transition energy e(1)-hh(1) on well thicknesses. Closed lozenges and open circles show the PR and PL results, respectively. Closed circles show the calculated values.

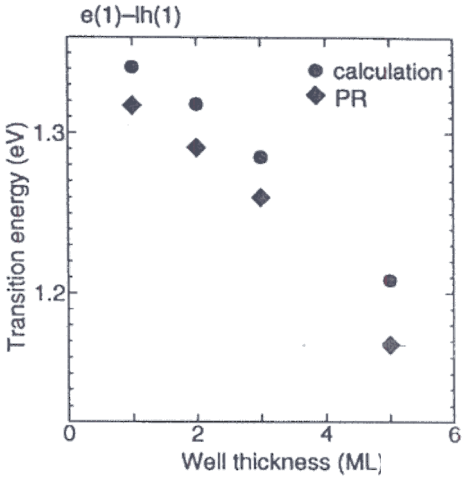

Fig. 6. Dependence of transition energy e(1)-lh(1) on well thicknesses. Closed lozenges show the PR results. Closed circles show the calculated values.

The second possible candidate for the discrepancy is imperfection of the interfaces between InGaAs and InP. The dependence of optical properties of thin InP/InGaAs/InP SQWs on the gas switching procedure during the OMVPE growth was reported by Bohrer *et al*[15]. In their study, they observed $InAs_{1-x}P_x$, islands at InGaAs/InP interfaces, which were formed as a consequence of the As-P exchange reaction. It is important to note that the islands exist at the interfaces even in the sample prepared with careful control of the gas switching procedure, although the phosphorous composition x of the $InAs_{1-x}P_x$ islands is influenced by the interruption time and the exchange efficiency of group-V elements depending on growth temperature. Based on their observation, existence of the imperfect InGaAs/InP interfaces is reasonably assumed in our samples, resulting in deviation from the ideal square shape of the potential well. The deviation induces changes in well thickness, effective ΔE_c and ΔE_v and effective bulk band gap of the well material. The resultant transition energies are obviously determined by complicated combination of these factors. Furthermore, the influence of the deviation works more significantly in the samples with the thinner well, because the fraction of the interface region is larger in total volume of the well. X-ray crystal truncation rod (CTR) scattering measurements are now in progress on the samples to reveal the atomic-level InGaAs/InP heterointerface structures. Comprehensive discussion on a basis of the atomic-level structures will be described elsewhere.

5. Conclusions

PR measurements were used to investigate optical transition energies in InP/InGaAs/InP SQWs with well thicknesses from 1 to 5 ML (from 0.3 to 1.5 nm) grown by a low-pressure OMVPE. The PR spectra clearly showed the e(l)-hh(1) and e(1)-lh(1) transitions in the SQWs together with the band-to-band transition in the InP layers. Clear PR spectra indicate excellent optical quality of these structures. The transition energies were determined by fitting the PR spectra to the theoretical line-shape expression. The resultant e(l)-hh(1) transition energies were close to energy positions of emission peaks observed in PL measurements at room temperature. The e(1)-hh(1) and e(1)-lh(l) transition energies decreased with the increasing well thickness. This behavior agreed qualitatively with the theoretical prediction, although there is a significant discrepancy in transition energies.

Acknowledgments

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References

[1] Y. Takeda, A. Sasaki, Y. Imamura, and T. Takagi, *J. Appl. Phys.* **47** (1976) 5405

[2] J. D. Oliver, Jr. and L. F. Eastman, *J. Electron. Mater.* **9** (1980) 693

[3] A. Sasaki, Y. Takeda, N. Shikagawa, and T. Takagi, *Jpn. J. Appl. Phys., Supplement*, **16-1** (1977) 239.

[4] H. Ohno, and J. Barnard, "*GaInAsP Alloy Conductors*", edited by T. P. Pearsall (Wiley, New York, 1982), p. 437.

[5] W. T. Tsang, *Appl. Phys. Lett.* **44** (1984) 288.

[6] H. Temkin, K. Alavi, W. R. Wagner, T. P. Pearsall, and A. Y. Cho, *Appl. Phys. Lett.* **42**(1983) 845.

[7] U.K. Reddy, G. Ji, T. Henderson, H. Morkoc, and J. N. Schulman, *J. Appl. Phys.* **62** (1987) 145.

[8] U. K. Reddy, G. Ji, T. Henderson, D. Huang, and R. Houdre, and H. Morkoc, *J. Vac. Sci. Technol.* **BT** (1989) 1106.

[9] H. Yaguchi, X. Zhang, K. Ota, M. Nagahara, K. Onabe, Y. Shiraki, and R. Ito, *Jpn. J. Appl. Phys.* **32** (1993) 544.

[10] D. E. Aspnes, *Surf. Sci.* **37** (1973) 418.

[11] Y. Misiewicz, P. Markiewicz, J. Rebisz, Z. Gumienmy, M. Panek, B. Sciana, and M. Tlaczala, *Phys. Stat. Sol. (b)* **183** (1994) 143.

[12] P. Basmaji, A. M. Ceschin, M. Siu Li, O. Hipolito, A. A. Bernussi, F. Iikawa, and P. Motisuke, *Surf. Sci.* **228** (1990) 356.

[13] M. Nakao, S. Yoshida, and S. Gonda, *Solid State Commun.* **49** (1984) 663.

[14] S. Yamada, A. Taguchi, and A.Sugimura, *Appl.Phys.Lett.***46** (1985) 675.

[15] J. Bohrer, A. Krost, and D. Bimberg, *Appl. Phys. Lett.* **60** (1992) 2258.

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