Temperature dependence of photoluminescence from InAsP/InP strained quantum well structures grown by metalorganic chemical vapor deposition

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Abstract

In this article, we report the growth and characterization of InAsP/InP strained single quantum well (SSQW), strained single quantum well (SSQW) stack, and strained multiple quantum well (SMQW) structures on (1 0 0)-oriented InP substrates grown by metalorganic chemical vapor deposition. Double-crystal X-ray diffraction, photoluminescence (PL) and transmission electron microscope (TEM) are used to characterize the strained quantum wells. The high-quality crystalline InAs\textsubscript{y}P\textsubscript{1-y}(72Å)/InP SSQW structure with \( y \approx 0.36 \) exhibits a 9.9 meV full-width at half-maximum (FWHM) of 10 K PL spectra. The peaks in the PL spectra for SSQW stack structure with a well thickness of 8, 14, and 35 Å vanish above 100, 150, and 296 K, respectively, presumably due to the decrease of photons yielded by electron–hole recombination in thinner quantum well regions on increasing the temperature. The PL peak emission energy dependence of well thickness in the InAsP/InP SSQW stack structure is in good agreement with the calculated results. In addition, the variations of the PL peak energy and FWHM in all the InAsP/InP SSQW, SSQW stack, and SMQW structures are described in detail. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: InAsP strained quantum well structures; Photoluminescence; MOCVD

1. Introduction

Strained quantum well structures have attracted considerable attention. The biaxial strain incorporated into the quantum wells by an intentional lattice mismatch causes the reduction of in-plane hall effective mass, and thus reduces the valence-band density of states [1,2]. Therefore, population inversion of the laser diodes occurs at low injection carrier densities that result in a lowering at threshold current [3]. The altered valence band–band structure also suppresses the intervalence band absorption and the Auger recombination [1]. Moreover, the effects of strain on the energy band structure are of importance and they have been
explicitly used in many material systems to design novel optoelectronic devices such as lasers and photodetectors [4,5]. In addition, the heterojunction band offset at strained-layer interfaces has been used to modify the charge confinement and transport in modulation-doped field-effect transistors [6] and heterojunction bipolar transistors [7]. On the other hand, the employment of strained quantum wells in devices extends the choice of compatible materials and greatly increases the ability to control their optical and electronic properties.

The interest in the strained InAsP/InP system has been investigating in recent years since it is suitable for compressively strained quantum well in all range of alloy composition and covers a luminescence band gap in the 1.0–3.0 μm wavelength range. In addition, InAsP has the added benefit of a large conduction band offset, ΔE_c = 0.7 ΔE_g [8,9] as compared to InGaAs/InP or InGaAsP/InP, ΔE_c = 0.4 ΔE_g [10,11]. A larger conduction band offset more tightly confines carriers to the quantum wells especially at higher operating temperatures. Yamamoto et al. [12] reported a compressively strained multiple quantum well (SMQW) InAsP laser operating at 132°C. Moreover, many papers reported the theoretical prediction and basic experimental results for high-speed electronic devices [13,14].

Several groups have investigated the temperature dependence of photoluminescence (PL) for SMQW structures. Studies on bulk-ordered AlGaInP and GaInP alloys showed the existence of localization energy [15,16]. The carrier emission process from quantum wells to barrier layers has been studied in the AlGaAs/GaAs [17], InGaAs/GaAs [18], AlGaInP/GaInP [19], Al(Ga)InP/GaInP [20] and InGaAs/InP [21] quantum wells. A published study of the temperature behavior for the InAsP/InP system indicated that the transition energy E_1h between the n = 1 electron subband and the n = 1 heavy-hole subband changes with temperature, and depends mainly on the evolution of the strained band gap of InAsP layers [22]. However, the report on the temperature dependence of PL in InAsP/InP strained quantum well structures is still lacking. Better understanding of this temperature-dependence behavior would be helpful in the optoelectronic device development.

In this article, we present the PL spectra of the strained single quantum well (SSQW), strained single quantum well (SSQW) stack, and SMQW structures in the temperature range of 10–296 K. The temperature dependence of the PL peak energy can be adequately expressed by Varshni equation. The relation between well width and PL peak energy of InAsP/InP SSQW stack is also reported in the different temperatures.

2. Experimental procedure

The InAsP/InP strained quantum well structures were grown on (1 0 0)-oriented Fe-doped InP substrates at 580°C in a horizontal cold-wall quartz reactor by low-pressure metalorganic chemical vapor deposition (MOCVD) at a pressure of 100 Torr and a growth rate of approximately 6 Å/s. Trimethylindium (TMIn) was used as the group III source, and phosphine and arsine were used as the group V reactants. The V/III ratio for InAsP growth is varied from 205 to 207 and the flow rate of PH₃ and TMIn was 200 and 376 sccm, respectively. A high hydrogen flow of 12 l/min allows an efficient purge of the reactor, which is necessary to obtain sharp interfaces. The grown quantum well structures in this study, as shown in Fig. 1, consist of SSQW, SSQW stack, and SMQW. Prior to the growth of strained quantum wells, an 1800 Å InP buffer layer was initially grown. The chosen wells in the SSQW structure are InAs₀.₃₆P₀.₆₄ and InAs₀.₃₉P₀.₆₁. The SSQW stack had the InAs₀.₃₃P₀.₆₇ wells, while the SMQW structure had the InAs₀.₅₀P₀.₅₀ wells. All the epitaxial layers were undoped.

The composition was determined from the measurement of the double-crystal X-ray diffraction (DC-XRD) and the layer thickness was measured from the cross-sectional view, using a JEOL JEM 2000 EX transmission electron microscope (TEM). The PL measurements were made using argon laser excitation (488 nm line) with an average power density of ~5 W/cm² and a spot size of ~1 mm in diameter. The luminescence spectra were analyzed by a ½ m spectrometer and detected with a Ge photodetector. Standard lock-in amplifier synchronous detection technique was used. The
samples were mounted on a holder inside a cryostat and the temperature was varied and controlled by a thermal foil heater wound near the holder and detected by a Pt temperature sensor.

3. Results and discussion

Fig. 2 shows the PL spectra of the InAs$_y$P$_{1-y}$/InP SSQW structures with $y = (a) 0.36$ and $(b) 0.39$ at various temperatures between 10 and 296 K. The spectra are normalized to the same peak intensity. The peaks of the PL spectra in Figs. 2a and b are in light of the $E_{1b}$ transition between the $n = 1$ electron subband and the $n = 1$ heavy-hole subband. In the temperature range of 70–300 K, the variations of the electron subband energy and the exciton binding energy are much less than those of the strained band gap, while the variation of the heavy-hole subband energy can be neglected [22]. For both samples, when the temperature is lowered, the peak energy first increases up to around 70 K, slightly shifts to the lower-energy side at low temperatures, and then is kept almost constant in the 10–70 K range. This trend is similar to the reported case of GaInAsSb/AlGaAsSb SSQW [23]. The above temperature-dependent behavior of the luminescence peak energy has been ascribed to free exciton recombination above 70 K, while recombination via excitons trapped to material defects, such as disorder defects and misfit dislocations in our SSQW structures, dominates the low-temperature PL spectra. Meanwhile, the full-width at half-maximum (FWHM) broadens with increasing temperature. On the other hand, the broader FWHM of PL spectra for the InAs$_{0.39}$P$_{0.61}$/InP SSQW structure indicates that the interface is less abrupt and somewhat rough due to steps or compositional grading in the region near the interface. The low crystalline quality in the InAs$_{0.39}$P$_{0.61}$/InP SSQW sample can also be observed from the emergence of the shoulder denoted as X in the 12 K PL spectrum of Fig. 2b, which is attributed to the fluctuation of larger lattice mismatch.

Fig. 3 shows the variations of PL peak energy and FWHM as a function of temperature for both InAsP/InP SSQW structures. The temperature dependence of the PL peak energy in both InAs$_y$P$_{1-y}$/InP samples can be expressed as Varshni equation [24]:

$$E_g(T) = E_g(0) - \alpha T^2/(T + \beta),$$

where $E_g(0)$ is the energy gap at 0 K, $\alpha$ and $\beta$ are material constants. The fitted $\alpha$ and $\beta$ are
Fig. 2. Photoluminescence (PL) spectra of the InAs$_{1-y}$P$_y$/InP SSQW structures with $y = (a) 0.36$ and (b) 0.39 at various temperatures between 10 and 296 K. The spectra are normalized to the same peak intensity.

$8.48 \times 10^{-4}$ eV/K and 1000 K, respectively. The $E_g(0)$ is 1.053 and 1.026 eV for the InAs$_{0.36}$P$_{0.64}$/InP and InAs$_{0.39}$P$_{0.61}$/InP SSQW structures, respectively. The FWHM is found to increase with increasing temperature, because of scattering by longitudinal optical phonons [23]. In general, the luminescence line shape is a convolution of an inhomogeneous part and a temperature-dependent homogeneous part. The inhomogeneous linewidth in the strained quantum well structure is mainly due to the interface roughness and random alloy disorder. Nevertheless, the minimum PL line-widths for SSQW structures may be limited by the presence of atomic-scale clustering at the hetero-interface, as observed in MBE grown structures [25]. The nanoscale compositions within the InAsP alloy layers lead to an asymmetry in interface quality. Because of the symmetrical PL line shape and no impurity transition involved in the low-energy side of the low-temperature luminescence spectra, the inhomogeneous broadening is not taken into account. As the temperature increases, scattering by longitudinal optical phonons becomes dominant due to the increasing phonon population,
which gives rise to the homogeneous part of the linewidth broadening. However, the broadening in PL spectra is significantly reduced for \( \text{InAs}_{0.36}\text{P}_{0.64}/\text{InP} \) SSQW structure, due to the suppression of roughness in the interface. The FWHM is 9.9 and 14.8 meV at 10 K, and 28.0 and 32.6 meV at 296 K for the \( \text{InAs}_{0.36}\text{P}_{0.61}/\text{InP} \) and \( \text{InAs}_{0.39}\text{P}_{0.61}/\text{InP} \) SSQW structures, respectively. These results indicate that a high crystalline quality for \( \text{InAs}_{y}\text{P}_{1-y}(72\text{Å})/\text{InP} \) SSQW structures with \( y \leq 0.36 \) can be successfully grown by MOCVD.

Fig. 4 shows the PL spectra of the \( \text{InAs}_{0.33}\text{P}_{0.67}/\text{InP} \) SSQW stack structure with 5 wells at various temperatures between 10 and 296 K to show the gradual evolutions of the peaks. The spectra are also normalized to the same maximum peak intensity. Similar to the case of SSQW structure, all the peak positions shift to longer wavelengths and FWHMs broaden with increasing temperature. However, the peaks of the PL spectra for SSQW stack with the well thickness of 8, 14 and 35 Å vanishes above 100, 150 and 296 K, respectively, presumably due to the decrease of photons yielded by electron–hole recombination in thinner quantum-well regions on increasing the temperature. Because of the lack of electron–hole pairs resulted from inadequate carrier confinement, it will decrease the probability of electron–hole recombination in thinner quantum-well region at higher temperatures.

Fig. 5 shows the experimentally observed PL emission energy as a function of well thickness at different temperatures for the \( \text{InAsP}/\text{InP} \) SSQW stack. Some reported data of \( \text{InAsP}/\text{InP} \) strained quantum well structures measured at 2 K included in Fig. 5 is used as in Ref. [9]. The solid curves are
Fig. 5. The experimentally observed PL emission energy as a function of well thickness at different temperatures for the InAsP/InP SSQW stack. Some reported data of InAsP/InP strained quantum well structures measured at 2 K included in this figure is used as a reference.

Fig. 6. The typical cross sectional TEM microphotograph of the InAs$_{0.33}$P$_{0.67}$/InP SSQW stack grown by MOCVD.

the results calculated by using the framework of envelope function formalism based on the Kane model developed by Bastard [26] and adapted by Marzin et al. [27] for strained systems. The physical constants of strained InAs$_y$P$_{1-y}$ on InP, such as elastic stiffness constants or deformation potentials, are deduced from a linear interpolation between the values for binaries InP and InAs [28,29], except for the light hole and electron effective masses at $k = 0$ for which the strain-induced modification along the growth direction of the quantum well is considered [30]. The ratio of the conduction band discontinuity to the total energy band discontinuity, $\Delta E_c/\Delta E_g$, is assumed to be 0.7. As shown in Fig. 5, the experimental results for all the InAs$_{0.33}$P$_{0.67}$/InP SSQW layers agree very well with the calculated curves at low temperatures. The slightly smaller energy than the calculated value in thinner well thickness seems to be due to the uncertainty of well thickness. When the temperature increases, the peak energy of all the PL spectra with different well thicknesses shifts to lower energies caused by the temperature dependence of the strained band gap for the InAsP layers. Ikeda et al. [31] also reported a similar trend in the relationship of well width and PL peak energy of GaInP/AlGaInP quantum well structure. A typical cross sectional TEM microphotograph of the InAs$_{0.33}$P$_{0.67}$/InP SSQW stack structure is shown in Fig. 6. Each well in this SSQW stack structure is clearly resolved. The typical thickness for these InAsP well layers is 74, 50, 35, 14 and 8 Å separated by 500 Å InP barrier layers to ensure sufficient decoupling of the SSQW stack structure.

The PL spectra of the five-period InAs$_{0.50}$P$_{0.50}$ (36Å)/InP(144 Å) SMQW structure at various temperatures between 10 and 296 K are shown in Fig. 7. It always shows only one peak in all the PL spectra. Similar to the SSQW and SSQW stack structures, the peak position shifts to longer wavelengths and FWHM broadens with increasing temperature. In contrast to SSQW structure, the
SMQW structure has a broader PL FWHM. Interface roughness of the well wall, misfit dislocations and material defects, conceivably introduced by lateral thickness undulation from the larger lattice mismatch, are all possible explanations for these additional transitions. Fig. 8 shows the variations of the PL peak energy as a function of temperature for the InAs$_0.50$P$_{0.50}$/InP SMQW structure. For the temperature dependence of the PL peak energy for SMQW structure, the experimental results fit very well with the Varshni equation (solid curve) with $E_0(0) = 1.021$ eV. The FWHM at 10 and 296 K of the SMQW structure is 24.6 and 50.5 meV, respectively. Since the InAs$_0.50$P$_{0.50}$ quantum well layers grown on InP are under compression, especially in thicker InAsP well-layer case, the broader FWHM for InAsP/InP SMQW structure is attributed to the dislocations resulted from a large net strain. The period number of SMQW is limited by the onset of strain relaxation, which will degrade the crystalline quality and the interface. Ga$_0.1$In$_{0.9}$P, which has been employed as a substitute for InP as the barrier material previously [32,33], is under tension when grown on InP substrate and thus may compensate the compressive strain in the InAsP.

4. Conclusions

We have demonstrated the temperature dependence of PL spectra in the temperature range 10–296 K for the high crystalline quality of InAs$_0.50$P$_{0.50}$/InP SSQW, SSQW stack, and SMQW structures grown by MOCVD. The 10 K PL spectra of InAs$_0.50$P$_{0.50}$(72Å)/InP SSQW structure
with $y \leq 0.36$ have a narrow FWHM of 9.9 meV. The experimental results for PL emission energy dependence of well thickness in SSQW stack are in good agreement with the calculated values reported in InAsP/InP strained quantum well structures by Monier et al. The peaks of PL spectra for SSQW stack with a well thickness of 8, 14, and 35 Å vanish above 100, 150, and 296 K, respectively, presumably due to the decrease of photons yielded by electron-hole recombination in the thinner quantum-well regions on increasing the temperature. The variations of the PL peak energy and FWHM in all the InAsP/InP structures (i.e., SSQW, SSQW stack, and SMQW) are described in detail.

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