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Journal of Crystal Growth 284 (2005) 335–340
JOURNAL OF CRYSTAL GROWTH
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Optical properties of digital-alloy $In_{0.49}(Ga_{1-z}Al_z)_{0.51}P/GaAs$ and $InGaP/In_{0.49}(Ga_{1-z}Al_z)_{0.51}P$ multi-quantum wells grown by molecular-beam epitaxy

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Received 26 April 2005; received in revised form 13 July 2005; accepted 13 July 2005
Available online 29 August 2005
Communicated by M. Schieber

Abstract

Optical properties of digital-alloy InGaAlP and InGaP/InGaAlP multiple-quantum wells (MQWs) grown by molecular beam epitaxy were characterized by 300 and 10 K-photoluminescence (PL). For digital-alloy $In_{0.49}(Ga_{1-z}Al_z)_{0.51}P$ grown at 425 °C with $z = 0.2$, 0.4, and 0.5, the energies of PL peak were in the range 2.0–2.167 eV. As the growth temperature increased from 425 to 470 °C for the digital-alloy $In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$, the intensity of PL peak increased 2.5 times. However, the energy and line width of PL spectrum did not change significantly. The L peak at 2.148 eV and the H peak at 2.189 eV from 8 K-PL were also observed and the intensity ratios of L peak to H peak (I_L/I_H) were 0.046, 0.048, and 0.043 for 425, 450, and 475 °C, respectively. For the digital-alloy InGaP/InGaAlP MQW structure grown at 450 °C, PL peak energy of 1.911 eV and PL line width of 38 meV were obtained successfully. The band gap and compositions of InGaAlP were easily controlled by digital-alloy technique without degrading the crystal quality.

Keywords: A3. Molecular beam epitaxy; A3. Superlattices; B1. InGaAlP

1. Introduction

High-power semiconductor lasers operating at 630–650 nm wavelength range have been investigated intensively and they have been improved for applications, such as the digital versatile disk (DVD) player, bar-code readers and laser pointers [1–4]. In most cases, InGaAlP lasers are grown by metalorganic chemical vapor deposition (MOCVD) [5–7] and a few results for high-quality InGaAlP material grown by molecular beam

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doi:10.1016/j.jcrysgro.2005.07.020

epitaxy (MBE) have been reported. It is well known that materials grown by MBE have high quality and abrupt interface between different materials. However, MBE has disadvantages when complex structures having many layers of different compositions are to be grown. Even though the cell temperature can be changed during the growth interruption for layers of different composition, it is required to get long flux stabilization time [8]. Therefore, a number of group III source cells in MBE system are essential for various composition layers. To overcome this disadvantage in MBE system, digital-alloy or short-period superlattice, consisting of binary or ternary layers of a few monolayers has been suggested [9,10]. Although optical properties of digital-alloy AlGaAs [11] and InGaAlAs [10] have been investigated, optical properties of digital-alloy InGaAlP have not been reported thoroughly.

In this paper, optical properties of digital-alloy $In_{0.49}(Ga_{1-z}Al_z)_{0.51}P$ on GaAs substrate have been characterized using room- and low-temperature photoluminescences (PLs). To change the Al composition (z) of $In_{0.49}(Ga_{1-z}Al_z)_{0.51}P$, the thickness ratio of $In_{0.49}Ga_{0.51}P$ and $In_{0.51}Al_{0.49}P$ layers were adjusted. The effects on the optical properties of digital-alloy $In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ for various growth temperature were investigated. For device applications, such as laser diode, optical properties of InGaP (well)/digital-alloy InGaAlP (barrier) multi-quantum well (MQW) were also characterized.

2. Experimental procedure

InGaAlP layer was grown on GaAs (1 0 0) substrate by VG 80H-10 K solid source MBE system equipped with Veeco-EPI arsenic cracker cell and GaP decomposition source cell for the group V elements. The growth temperature was measured by spot thermometer. Gallium oxide on GaAs substrate was removed at 600 °C. After thermal deoxidation, the growth temperature was ramped down to 570 °C. A 500 nm-thick GaAs buffer layer was grown for smooth surface and sharp (2 × 4) patterns of reflection high energy electron diffraction (RHEED) appeared after the GaAs buffer growth.

To ensure no parasitic contamination in the interfaces between the phosphide and arsenide, the cell temperature of GaP was ramped from idling temperature to 1030 °C for InGaAlP layers during the growth interruption as shown in Fig. 1. The idling temperature of GaP decomposition cell was set to 800 °C, because the background pressure of phosphorus at idling temperature is three orders less than that at the operating temperature. As the temperature and flux of GaP decomposition were stabilized, arsenic cell and phosphorus cell were closed and opened, respectively, at the same time.

For the growth of $In_{0.49}(Ga_{1-z}Al_z)_{0.51}P$ layer, the growth temperature was ramped down to the range of 425–470 °C and at this temperature range all samples were grown. The thickness of digital-alloy InGaAlP layer was fixed at 400 nm for all samples. The compositions of the latticed-matched InGaAlP were controlled by the ratio of thicknesses of $In_{0.49}Ga_{0.51}P$ and $In_{0.51}Al_{0.49}P$ layers. The Al composition (z) of digital-alloy $In_{0.49}(Ga_{1-z}Al_z)_{0.51}P$ was determined from the thickness ratio of $In_{0.49}Ga_{0.51}P$ and $In_{0.51}Al_{0.49}P$ using:

$$z = \frac{\text{Thickness of } In_{0.51}Al_{0.49}P}{\text{Thickness of } In_{0.49}Ga_{0.51}P + \text{Thickness of } In_{0.51}Al_{0.49}P}. \tag{1}$$

The thickness of $In_{0.49}Ga_{0.51}P$ and $In_{0.51}Al_{0.49}P$ layers for digital-alloy $In_{0.49}(Ga_{1-z}Al_z)_{0.51}P$ from $z = 0.2$ to 0.8 have been listed in Table 1. To

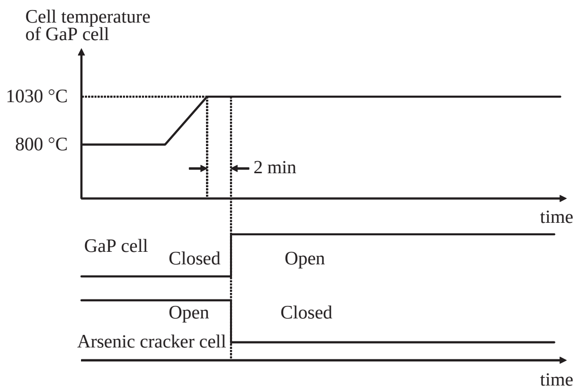


Fig. 1. Sequences of cell temperature and shutter for no parasitic contamination between phosphide and arsenide.

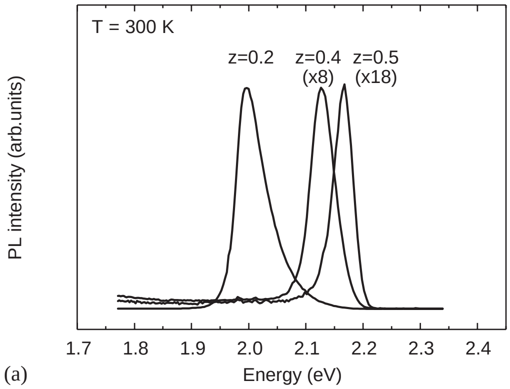
Table 1
The thickness ratio of $In_{0.49}Ga_{0.51}P$ and $In_{0.51}Al_{0.49}P$ for digital-alloy $In_{0.49}(Ga_{1-z}Al_z)_{0.51}P$

Composition (z)	Thickness of InGaP (Å)	Thickness of InA1P (Å)
0.2	14.4	3.6
0.4	9.4	6.2
0.5	6.2	6.2
0.6	6.2	9.4
0.8	3.6	14.4

characterize the optical properties of digital-alloy InGaAlP, PL was measured at 300 and 8 K using an argon ion laser of wavelength 488 nm and an average power of 40 mW.

3. Results and discussion

Fig. 2(a) shows 300 K-PL spectra of digital-alloy $In_{0.49}(Ga_{1-z}Al_z)_{0.51}P$ grown at 425 °C as a function of Al composition (z). To sufficiently reduce the band gap shift due to the ordering effect of InGaAlP, digital-alloy samples were grown at 425 °C. As z increased from 0.2 to 0.6, the energies of PL peak increased from 2.0 to 2.167 eV and PL intensities also began to drop significantly with a dramatic dependence of Al composition. Although PL peak was observed for $z = 0.6$, PL intensity decreased by almost two order of magnitude. Moreover, PL peak was not observed in the case of $z = 0.8$. It is attributed to a transition from the direct band gap to the indirect band gap at $z \sim 0.53$ [12]. Fig. 2(b) shows the PL peak energies and line widths as functions of Al composition (z). As z increases, PL peak energies are shifted to higher energies. However, line width decreases from 58 to 39 meV. This contrasts with earlier reports [12], which showed increasing line width for the higher values of z. The line widths are much narrower than the results (FWHM = 78 meV, $z = 0.48$) which Cao et al. [12] have reported. This means that the crystal quality of digital-alloy $In_{0.49}(Ga_{1-z}Al_z)_{0.51}P$ is comparable to analog-alloy $In_{0.49}(Ga_{1-z}Al_z)_{0.51}P$ [9]. From linear fitting of PL peak energy, energy band gap of digital-alloy



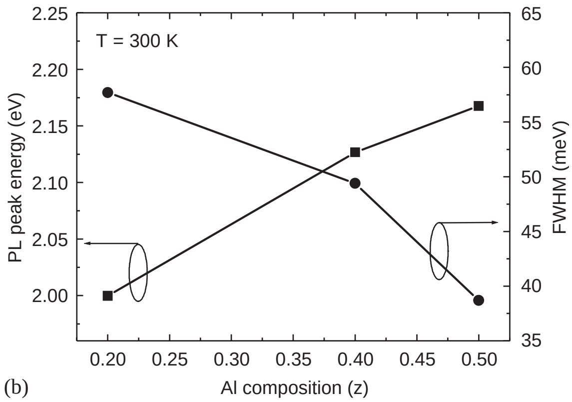


Fig. 2. (a) 300 K-PL spectra of digital-alloy $In_{0.49}(Ga_{1-z}Al_z)_{0.51}P$ grown at 425 °C as a function of Al composition (z). (b) PL peak energy and line width of digital-alloy $In_{0.49}(Ga_{1-z}Al_z)_{0.51}P$ as a function of Al composition (z).

can be expressed by

$$Eg(z) = 1.888 + 0.57z \text{ eV}. \tag{2}$$

Due to the fact that highly disordered InGaP is obtained at this growth temperature [13], the ordering effect in the InGaAlP sample grown at 425 °C could be suppressed efficiently. Therefore, the dependence of Al composition (z) could be considered mainly for the band gap of InGaAlP.

To investigate the dependence of growth temperatures, the samples of digital-alloy $In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ were grown at 425–470 °C. Fig. 3(a) shows 300 K-PL spectra of digital-alloy $In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ as a function of growth temperature. As the growth temperatures increase from 425 to 470 °C, the intensities of PL increase 2.5 times. However, the energy of PL peak and line

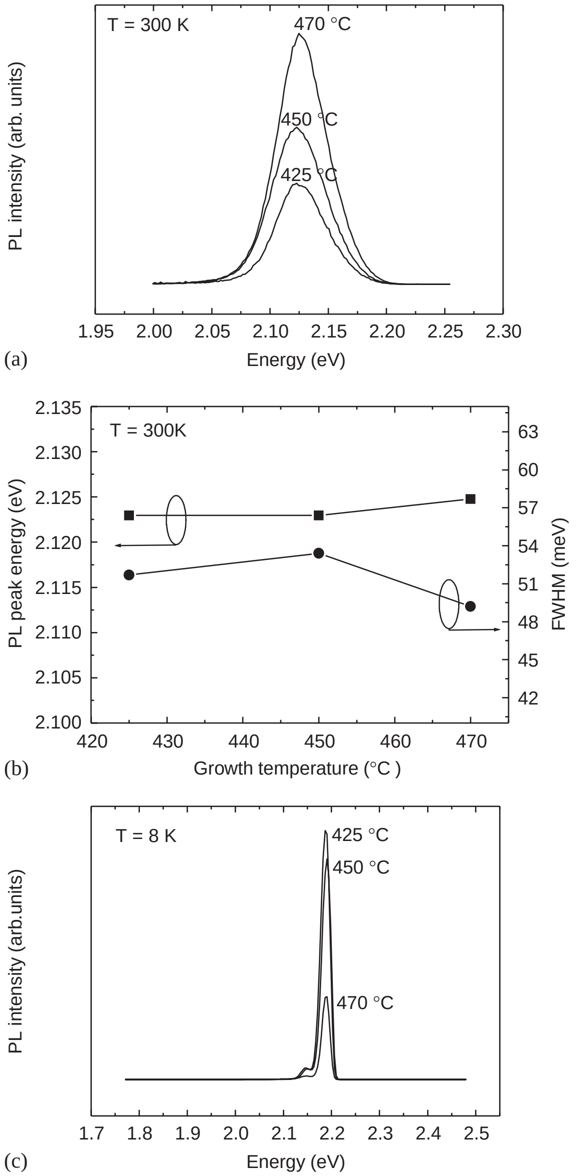


Fig. 3. (a) 300 K-PL spectra of digital-alloy $In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ as a function of growth temperature. (b) PL peak energy and line width of digital-alloy $In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ as a function of growth temperature. (c) 8 K-PL spectra of digital-alloy $In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ as a function of growth temperature.

width were not changed significantly as shown in Fig. 3(b). The difference of PL peak energy for samples between 425 and 470 °C was 2 meV as shown in Fig. 3(b). This result was not observed in the case of analog-alloy InGaP and InGaAlP, which have the variation in band gap caused by the enhancement of ordering effect as growth temperature was increased [13,14]. This means that the growth temperature does not change the band gap energy significantly for digital-alloy InGaAlP. For samples of $In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ grown at 425–470 °C, 8 K-PL spectra was also measured as shown in Fig. 3(c). 8 K-PL spectrum shows two peaks—higher (H)- and lower (L)-energy peaks—like digital-alloy InGaAlAs reported by Song et al. [9]. However, the intensity ratios of L peak to H peak (I_L/I_H) were 0.046, 0.048, and 0.043 for 425, 450, and 475 °C, respectively. The small I_L/I_H means that digital-alloy InGaAlP can be virtually treated as bulk material rather than superlattices [9].

For applications to red laser diodes, the quantum well structure was grown using digital-alloy $In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$. As shown in Fig. 4(a), the quantum well structure consists of three wells separated by 15 nm-thick $In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$, which are sandwiched between two 100 nm-thick $In_{0.51}Al_{0.49}P$ layers. The well layers ($In_{0.49}Ga_{0.51}P$) are 8 nm-thick. Fig. 4(b) shows the 300 K-PL spectrum of digital-alloy $In_{0.49}Ga_{0.51}P/In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ MQW grown at 450 °C. PL peak energy of 1.911 eV and line width of 38 meV were obtained, respectively. Recently, Toikkanen et al. [4] reported that the line width of ~44 meV was obtained from tensile-strained $In_{0.42}Ga_{0.58}P$(6.5 nm)/$In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ MQW grown on GaAs (1 0 0) using MBE system. Moreover, it was reported by Dong et al. [15] that the line width of 35 meV was obtained from $In_{0.51}Ga_{0.49}P$(10 nm)/$In_{0.48}(Ga_{0.6}Al_{0.4})_{0.52}P$ MQW grown on GaAs (1 0 0) 7° off toward (1 1 1)A to suppress the spontaneous ordering in InGaP and InGaAlP using LP–MOCVD system. These groups have used an analog-alloy method for the growth of barrier layers. On the other hand, a digital-alloy method for the growth of $In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ barrier and lattice-matched InGaP well were used in our experiment. Fig. 4(c) shows transmission electron microscopy (TEM) image of $In_{0.49}Ga_{0.51}P/In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ MQW structure. As shown in Fig. 4(c), it was observed that the interfaces in the MQW structure were clear.

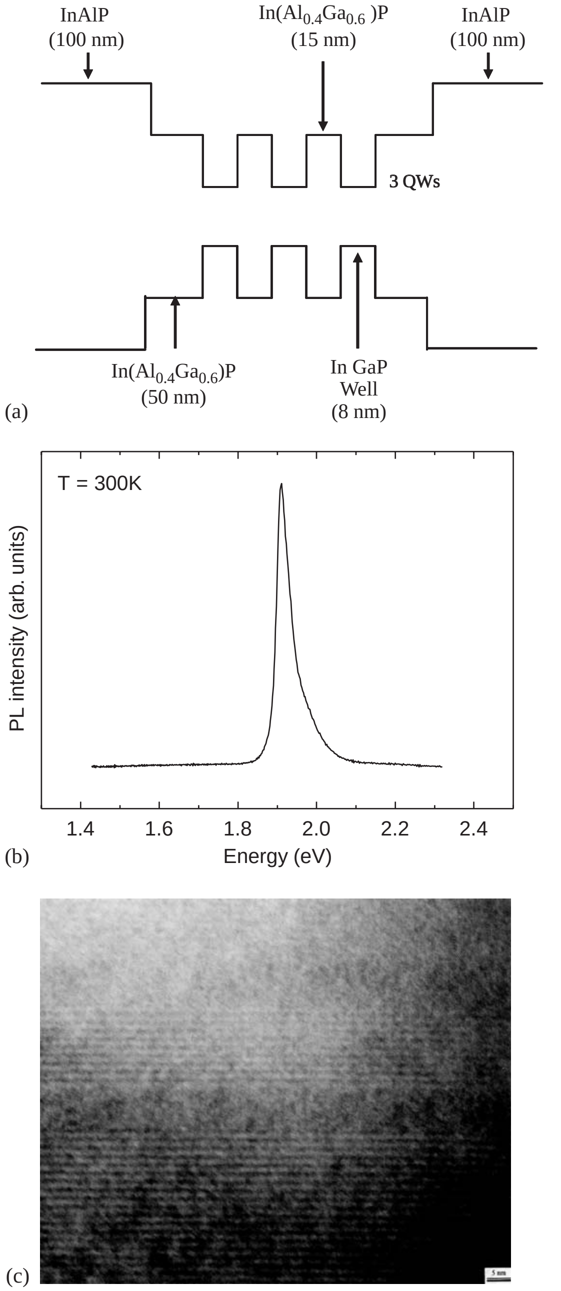


Fig. 4. (a) Digital-alloy $In_{0.49}Ga_{0.51}P/In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ MQW structure. The quantum well structure consists of three wells separated by 15 nm-thick $In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$, which are sandwiched between two 100 nm-thick $In_{0.51}Al_{0.49}P$ layers. The well layers ($In_{0.49}Ga_{0.51}P$) are 8 nm thick. (b) 300 K-PL spectrum of digital-alloy $In_{0.49}Ga_{0.51}P/In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ MQWs grown at 450 °C. (c) TEM image of digital-alloy $In_{0.49}Ga_{0.51}P/In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ MQWs grown at 450 °C.

$In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ layer and $In_{0.49}Ga_{0.51}P/In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ MQW through digital-alloy were successfully grown with good optical quality, as compared with results by Toikkanen et al. [4] and Dong et al. [15]. These results mean that the band gap control through a digital-alloy method can easily realize graded composition layers and separate-confinement heterostructure (SCH) with linear and graded index in the laser diode structures.

4. Conclusion

Digital-alloy $In_{0.49}(Ga_{1-z}Al_z)_{0.51}P$ and $In_{0.49}Ga_{0.51}P/In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ MQW structure with high quality were grown successfully by MBE and were characterized by 10 and 300 K-PL measurements. As Al compositions (z) of $In_{0.49}(Ga_{1-z}Al_z)_{0.51}P$ were increased from $z = 0.2$ to 0.6, the energy of PL peak increased from 2.0 to 2.167 eV. When the growth temperature of $In_{0.49}(Ga_{0.6}Al_{0.4})_{0.51}P$ was increased from 425 to 470 °C, the intensity of PL increased 2.5 times. However, the energy of PL peak and FWHM did not change significantly. Small ratio of I_L/I_H was also observed from 8 K-PL spectrum. PL peak energy of 1.911 eV and line width of 38 meV were obtained from InGaP/InGaAlP MQW structure grown at 450 °C. The band gap and compositions of InGaAlP were easily controlled by digital-alloy technique without degrading crystal quality.

Acknowledgements

The authors are grateful to J.H. Song and S.Y. Nam in GIST for PL measurements. This work was supported in part by KOSEF through UFON research center at GIST and the National Program for Tera-Level Nanodevices of the MOST as one of the 21st Century Frontier Programs.

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