Gas-source molecular beam epitaxy growth of $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ on GaAs for photonic and electronic applications

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Abstract – Gas-source molecular beam epitaxy growth of $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ layers lattice-matched to GaAs is reported. X-ray diffraction, photoluminescence, and Hall measurements show that the layers are of good quality. High-performance Al-free (In)GaAs(P)/ $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ quantum well lasers, emitting at $0.8 \leq \lambda \leq 1.1 \mu\text{m}$, and GaAs/ $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ heterojunction diodes are also demonstrated. The results are comparable to those obtained for the best AlGaAs based materials and devices. In particular, we report on the first tensile-strained GaAsP/GaInAsP/GaInP quantum well laser.

1. Introduction.

Lattice-matched $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ quaternary layers grown on InP and GaAs substrates have energy band gaps varying in a wide range [1]. The $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ layers on InP have been studied extensively and utilized in infrared ($1.3 - 1.6 \mu\text{m}$) lasers and photodiodes for optical fiber communication [2, 3]. The $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ layers on GaAs are known to be suitable for light emitting devices operating from near infrared to the green region of spectrum [4, 5]. The $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ layers on GaAs have attracted relatively little attention so far. This is because the band gap range of AlGaAs in the most common AlGaAs/GaAs system fully covers that of lattice-matched $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ and because growth of AlGaAs is much easier than growth of $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$. On the other hand, lattice-matched $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ /GaAs has many interesting properties. It possesses a direct band gap and high luminescence efficiency at all compositions from GaAs to $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ (covering the energy range from 1.42 to 1.90 eV) [1]. In particular, it is likely that there exists a large valence-band offset (ΔE_v) at the (In)GaAs/ $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ interfaces (e.g., ΔE_v as large as 0.24 eV has been reported for GaAs/GaInP, Ref. [6]), providing novel low-dimensional physical properties which may be useful for photonic and electronic devices. Moreover, $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ is not as easily oxidized as AlGaAs [7]. Therefore, the $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ materials lattice matched to GaAs deserve detailed studies of epitaxial growth as well as device performances. Several groups have grown $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ on GaAs using metalorganic chemical vapor epitaxy (MOCVD) and liquid phase epitaxy (LPE) techniques [4,5,8,9]. The present work investigates gas-source molecular beam epitaxy (GSMBE) growth of $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ /GaAs and their optoelectronic properties for device applications.

2. GSMBE growth and material properties.

In GSMBE growth, we used conventional effusion cells of Ga, In, Si and Be. Molecular beams As_2 and P_2 were produced by thermal decomposition of AsH_3 and PH_3 in a high-pressure cracker cell held at 950°C . The group III fluxes were monitored with a nude ion gauge at the growth position. Substrate (growth) temperature was measured by a narrow-bandwidth pyrometer. In the present work, the substrates of $16 \times 16 \text{ mm}^2$ in size were cut from (100) GaAs wafers and attached to a substrate holder without using indium solder. The $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ layers were grown at temperatures between 500 and 515°C . The growth rate was varied from 0.6 to $1.5 \mu\text{m/h}$ for different experiments.

Fig. 1. Energy band gap of the lattice-matched $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ on GaAs versus the indium composition. A: obtained from room temperature photoluminescence measurements of our GSMBE-grown samples with $-200 \leq \Delta a/a \leq 1000$ ppm. The solid line is used to guide an eye; B: calculated from $E_g = 1.35 + 0.68x - 1.17y + 0.758x^2 + 0.18y^2 + 0.75xy - 1.14x^2y - 0.789xy^2 + 0.819x^2y^2$ (eV) (Ref. [8]).

We have grown $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ (abbreviated as GaInAsP later) with various compositions. Figure 1 shows the energy band gap (E_g), determined from room temperature photoluminescence (PL), of GaInAsP versus the indium composition. The values of E_g are somewhat smaller than those calculated from Eq. 4 in Ref. [8]. Garbzove *et al.*[4] have reported $E_g = 1.51$, and 1.83 eV for LPE-grown layers $x = 0.13$ and 0.43 , respectively. Groves [9] reported an $E_g = 1.65$ eV for MOCVD-grown layer with $x = 0.3$. These E_g values reasonably agree with our data shown in Fig. 1.

The grown GaInAsP layers were studied by Nomarski optical microscopy and double crystal X-ray diffraction (DCXRD). The layers had spectacular, featureless surface under optical inspection. At the same time, lattice-mismatch between GaInAsP and GaAs was less than 1000 ppm determined from the DCXRD rocking curves. The full width at half maximum of the DCXRD peak for GaInAsP was about 30 arc sec. Figure 2 displays the DCXRD rocking curves recorded from InGaAs/GaInAsP, GaAs/GaInAsP, and GaAsP/GaAs multiple-quantum-well (MQW) structures grown on GaAs. Sharp and distinct satellite peaks are observed, suggesting very regular periodicity and abrupt interfaces in these MQW structures.

Fig. 2. Double crystal X-ray diffraction rocking curves for 10-period $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}(100 \text{ \AA})/\text{GaInAsP}(300 \text{ \AA})$, 10-period $\text{GaAs}(100 \text{ \AA})/\text{GaInAsP}(300 \text{ \AA})$ and 15-period $\text{GaAs}_{0.92}\text{P}_{0.08}(120 \text{ \AA})/\text{GaAs}(268 \text{ \AA})$ MQW structures. The GaInAsP layers are lattice-matched to GaAs and have an $E_g = 1.57 \text{ eV}$.

Fig. 3. Hall mobility of GaInAsP having $E_g = 1.57 \text{ eV}$ versus electron density. Solid line: room temperature; dashed line: 77 K.

Doping levels up to 10^{19} cm^{-3} were achieved by using Si as an n-dopant and Be as a

p-dopant. Figure 3 shows Hall mobilities of n-type GaInAsP at room temperature and 77 K. The undoped GaInAsP ($E_g = 1.57$ eV) is n-type with a net carrier density of $N_d - N_a < 5.0 \times 10^{14} \text{ cm}^{-3}$. Its Hall mobilities are 2 500 and 7 200 cm^2/Vs at 300 and 77 K, respectively. These mobilities are quite low, which may be due to the alloy scattering effect [2].

Fig. 4. Room temperature photoluminescence spectra from (A) $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}/\text{GaInAsP}$ (1.72 eV), (B) $\text{GaAs}/\text{GaInAsP}$ (1.72 eV), (C) $\text{GaAs}_{0.92}\text{P}_{0.08}/\text{GaInAsP}$ (1.72 eV), and (D) GaInAsP (1.57 eV)/ GaInAsP (1.83 eV) SCH-SQW laser structures. All the quantum wells are 12-nm thick.

Figure 4 displays room temperature PL spectra measured from compressive-strained $\text{InGaAs}/\text{GaInAsP}$, unstrained $\text{GaAs}/\text{GaInAsP}$ and $\text{GaInAsP}/\text{GaInAsP}$, and tensile-strained $\text{GaAsP}/\text{GaInAsP}$ single quantum well laser structures. The shapes and line widths of the PL spectra are similar to those obtained for high quality $(\text{In})\text{GaAs}/\text{AlGaAs}$ quantum well [10,11], and no emission related defects [12] was observed. We may conclude that the $(\text{In})\text{GaAs(P)}/\text{GaInAsP}$ quantum wells are of high quality.

3. Al-free $(\text{In})\text{GaAs(P)}/\text{GaInAsP}$ quantum well lasers.

Due to absence of easily oxidized AlGaAs [7] and low surface recombination velocity of GaInAsP [13], it is expected that Al-free $(\text{In})\text{GaAs(P)}/\text{GaInAsP}$ quantum well lasers have improved performances, such as long lifetime and low facet temperature rise [4,14], compared with their counterpart $(\text{In})\text{Ga(Al)As}/\text{AlGaAs}$ ones. We have fabricated compressive-strained (1.4 %) $\text{InGaAs}/\text{GaInAsP}/\text{GaInP}$, unstrained $\text{GaAs}/\text{GaInAsP}/\text{GaInP}$, and tensile-strained (-0.3 %) $\text{GaAsP}/\text{GaInAsP}$ separate-confinement-heterostructure single-quantum-well (SCH-SQW) lasers emitting at $0.8 \leq \lambda \leq 1.1 \mu\text{m}$. The active region consisted of a 12-nm thick SQW layer sandwiched between two 0.2- μm thick GaInAsP ($E_g = 1.72$ eV) confinement layers. The cladding layers are made of GaInP lattice-matched to GaAs .

Figures 5 shows threshold current density (J_{th}) versus reciprocal cavity length (L) for uncoated broad-area Fabry-Perot $(\text{In})\text{GaAs(P)}/\text{GaInAsP}$ lasers. Clearly, the 1.4 % compressive-strained laser has the lowest J_{th} . The -0.3 % tensile-strained laser has slightly higher J_{th} in short cavity region, but smaller J_{th} in long cavity region than the unstrained $\text{GaAs}/\text{GaInAsP}$ laser. This is mostly because the tensile-strained laser has a relative small

Fig. 5. Threshold current density *versus* reciprocal cavity length for compressive-strained (1.4%) $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}/\text{GaInAsP}$, unstrained $\text{GaAs}/\text{GaInAsP}$, and tensile-strained (-0.3%) $\text{GaAs}_{0.92}\text{P}_{0.08}/\text{GaInAsP}$ SCH-SQW lasers.

optical confinement factor. It is expected that the tensile-strained laser has a reduced J_{th} if it has a higher lattice strain in the quantum well or an equal optical confinement factor as does the unstrained laser. It is, of course, possible to reduce J_{th} for all lasers by properly designing the laser structures. For example, J_{th} as low as 72 and 150 A/cm^2 have been obtained for $\text{InGaAs}/\text{GaInAsP}/\text{GaInP}$ laser with single and three quantum wells, respectively [15]. As seen in Fig. 6, the compressive-strained and tensile-strained SQW lasers have higher external differential and internal quantum efficiencies than the unstrained SQW laser, while the internal waveguide loss is very small for all the lasers. These results are consistent with those obtained for $\text{InGaAs(P)}/\text{GaInAsP}/\text{InP}$ [16] and $\text{InGaP}/\text{AlGaInP}$ [17] lasers in which both compressive and tensile strains improve lasing performances such as reduced J_{th} and enhanced efficiency. It should be noted that the characteristics of these Al-free lasers are compared to those obtained for the best $(\text{In})\text{Ga}(\text{Al})\text{As}/\text{AlGaAs}$ lasers. Moreover, to the best of our knowledge this is the first report on tensile-strained $\text{GaAsP}/\text{GaInAsP}/\text{GaInP}$ QW lasers.

4. GaAs/GaInAsP heterojunction diodes.

We also fabricated $\text{GaAs}/\text{GaInAsP}$ heterojunction diodes to study device properties. The active region consisted of (i) 0.5 μm n-type GaAs with $n = 5.0 \times 10^{17} \text{ cm}^{-3}$, (ii) 0.1 μm p-type GaInAsP with $p = 5.0 \times 10^{16} \text{ cm}^{-3}$, and (iii) 0.4 μm p-type GaInAsP with $p = 5.0 \times 10^{17} \text{ cm}^{-3}$. The diode processing was the same as that of our $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$ avalanche photodiodes [18]. The current-voltage (I-V) characteristics of a diode of 500 μm in diameter are shown in Fig. 7. The forward I-V curve closely resembles that of $\text{GaAs}/\text{AlGaAs}$ heterojunction diodes [19]. In the low-bias region AB, the recombination current dominates. In the

high-bias region BCD, the diffusion current takes over, and in the region DE the current

Fig. 6. CW light output per facet *versus* injection current at room temperature for uncoated ridge waveguide lasers. η_i and α_i are the internal quantum efficiency and internal waveguide loss, respectively. η_d is the external differential quantum efficiency.

is limited by the spreading resistance of the diode. The reverse I-V shows that at low bias $\leq 5 \text{ V}$, the dark current is as small as 0.1 nA , i.e., a current density of only $5.1 \times 10^{-8} \text{ A/cm}^2$, which is mainly due to carrier generation-recombination via traps in the depletion region [20]. At higher reverse voltages ($> 5 \text{ V}$), the dark current is predominantly caused by

avalanche processing and tunnelling. An abrupt breakdown is observed at 22.4 V. These characteristics of the diode imply that the density of traps present in the GaInAsP layer and at the GaAs/GaInAsP interface is very low.

Fig. 7. I-V characteristics of a GaAs/GaInAsP heterojunction diode having a diameter of 500 μm . (a) forward bias; (b) reverse bias.

5. Summary.

In conclusion, lattice-matched GaInAsP on GaAs and the GaInAsP-based heterojunction and quantum well structures have been grown by GSMBE. All these structures exhibited very good structural and optoelectronic properties. These results, together with those obtained from experiments on heterojunction diodes and quantum well lasers, clearly point out that the GaInAsP is, indeed, a promising candidate for optoelectronic applications. In particular, we have demonstrated the first tensile-strained GaAsP/GaInAsP/GaInP quantum well laser.

Acknowledgements: This work was, in part, carried out within the framework of RACE-II WELCOME Project No. R2006. It was sponsored by the Technology Development Centre (TEKES, Finland) and the Academy of Finland. The authors would like to thank J. Näppi and A. Ovtchinnikov for their help in processing the laser diodes.

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