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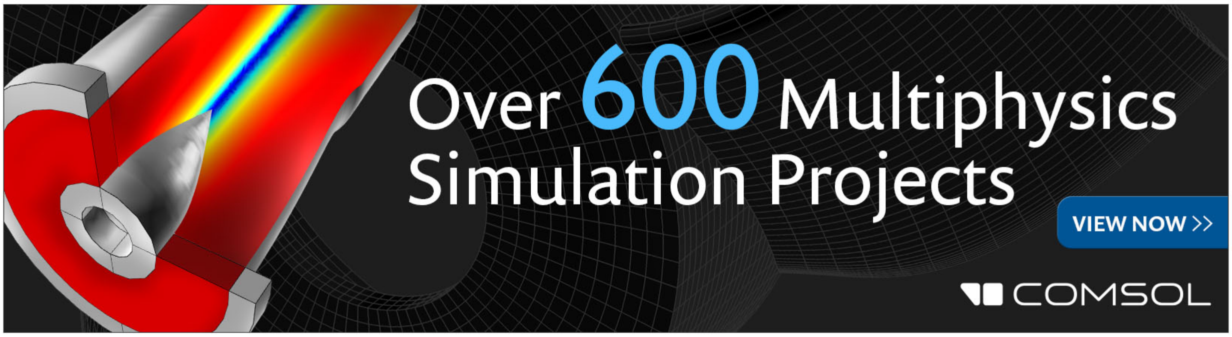

Gas-source molecular beam epitaxy growth of highly strained device quality InAsP/InP multiple quantum well structures

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$InAs_xP_{1-x}$/InP strained multiple quantum wells with strain as high as 2.5% were grown by gas-source molecular beam epitaxy. Successful control of the arsenic composition over a wide range was achieved by two different growth techniques. Structural and optical studies, such as high-resolution x-ray rocking curve, cross-sectional transmission electron microscopy, photoluminescence, and absorption measurement, indicate that we have obtained high quality multiple quantum wells that are suitable for optoelectronic applications.

$In_{1-x}Ga_xAs_yP_{1-y}$ grown on InP is a promising material for optoelectronic applications because its fundamental band gap is suitable for infrared emitters and detectors operated between 0.9 and 2.0 μm.[1] Extensive studies of the growth and characterization as well as device applications have been presented based on this material system.[2-4] In contrast, $InAs_xP_{1-x}$/InP, a special case of quaternary $In_{1-x}Ga_xAs_yP_{1-y}$/InP, has received little attention from various advanced crystal growth techniques, such as organometallic vapor phase epitaxy (OMVPE)[5,6] or molecular beam epitaxy (MBE). The growth of $InAs_xP_{1-x}$ reduces difficulties in the composition control of quaternary $In_{1-x}Ga_xAs_yP_{1-y}$, and provides a new degree of freedom for device design by tailoring the band structure with built-in biaxial strain. Moreover, an independent control of the layer thickness and alloy composition can be achieved since the former is determined only by the indium beam flux, while the latter can be controlled properly by adjusting the AsH_3 and PH_3 flow-rate fraction in gas-source MBE (GSMBE) growth. However, the difficulty in obtaining pseudomorphic growth of $InAs_xP_{1-x}$ arises from the accurate control of the hydride flow-rate fraction since As incorporates with In much more significantly than P does.[7] In this letter we report a successful growth of device quality $InAs_xP_{1-x}$/InP strained multiple quantum wells (SMQWs) by GSMBE. High quality materials were characterized by high-resolution x-ray rocking curves, transmission electron microscopic (TEM) images. Photoluminescence (PL) and absorption spectra show the application possibility of optoelectronic devices, such as modulator or laser, based on such a material system.

The $InAs_xP_{1-x}$/InP SMQW structures were grown on (100)Fe-doped semi-insulating InP substrates in a modified Varian Modular Gen-II MBE machine. The growth was performed with elemental indium and thermally cracked hydrides, AsH_3 and PH_3, at a substrate temperature of 460 °C. The gas-source supplies (100% arsine and 100% phosphine) were introduced into the growth chamber through a single Varian four-channel hydride injector, which was operated nominally at 1000 °C. The growth chamber was equipped with a 2200 ℓ/s cryopump and a 220 ℓ/s ion pump. The typical working pressure was 1×10^{-5} Torr. The indium flux was set such that the growth rate was about 1 μm/h as determined by intensity oscillations of reflection high-energy electron diffraction (RHEED).

Our previous growth studies of $GaAs_{1-x}P_x$ grown on GaAs[8] show that arsenic incorporates into $GaAs_{1-x}P_x$ much more significantly than phosphorus when both are present. This is especially true for $InAs_xP_{1-x}$ growth with AsH_3 and PH_3 because the effective adsorption rate of As to P is higher in InAsP than in GaAsP.[9] Therefore, it is necessary to use a relatively large PH_3 flow rate, compared to AsH_3, to *dilute* the arsenic fraction in the flux on the growth front so as to achieve a proper control of the arsenic composition. We fixed the AsH_3 flow rate at 0.6 sccm, varied PH_3 flow rates from 3 to 5 sccm, and grew a series of SMQW samples with a typical structure of 15-period $InAs_xP_{1-x}$(80 Å)/InP(150 Å). Correspondingly, the arsenic composition in $InAs_xP_{1-x}$ was varied from 0.65 to 0.20.

Instead of using the usual run-vent technique, the growth was interrupted at each interface. Shown in Fig. 1 is a diagram of the shutter operation sequence. The interruption duration t_1 was 20 s typically to allow switching the AsH_3 and to stabilize the beam flux of arsenic. t_2, t_3, t_4, varying from 3 to 10 s, are interruption durations for recovering the growth front and purging the residual gas. However, achieving an $InAs_xP_{1-x}$ layer with a very small As composition by this growth method is limited by the stability of the mass flow controller at very low flow rate. Therefore, an alternative method was employed. As shown at the lower part of Fig. 1, AsH_3 was alternatingly introduced during InP growth so that the As composition in the $InAs_xP_{1-x}$ quantum well layer was averaged to a smaller value by these short-period (2–5 monolayers per period) InAsP/InP superlattices. The x can be controlled with the ratio of open and close durations of AsH_3 easily by using this technique.

The growth rate, therefore, the thickness of $InAs_xP_{1-x}$, is constrained only by the indium beam flux at a group-V overpressure, so the layer thickness of

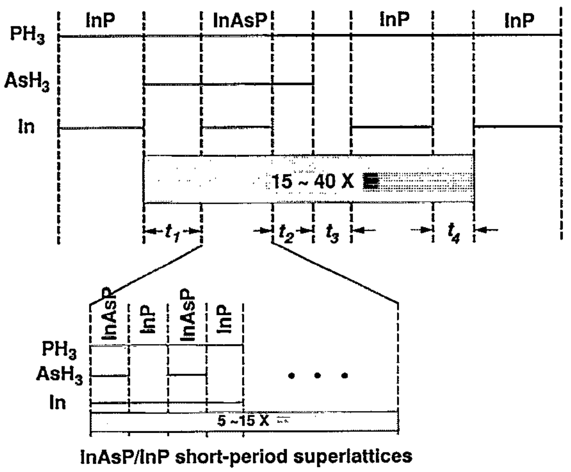


FIG. 1. Diagram of the growth sequence of multiple quantum well structures. The lower part indicates the growth of $InAs_xP_{1-x}$ layer by short-period superlattices.

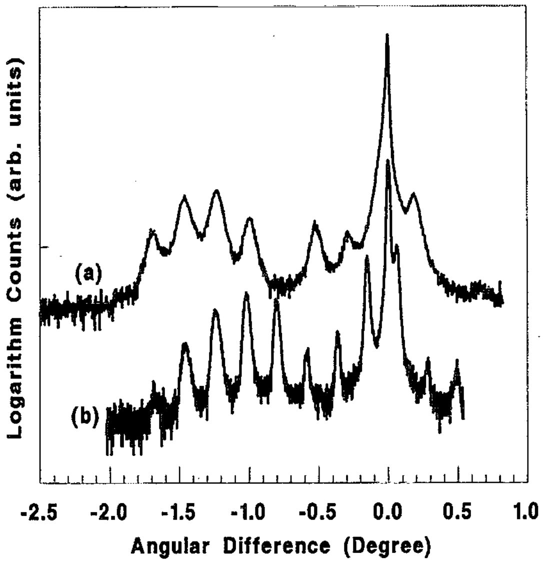


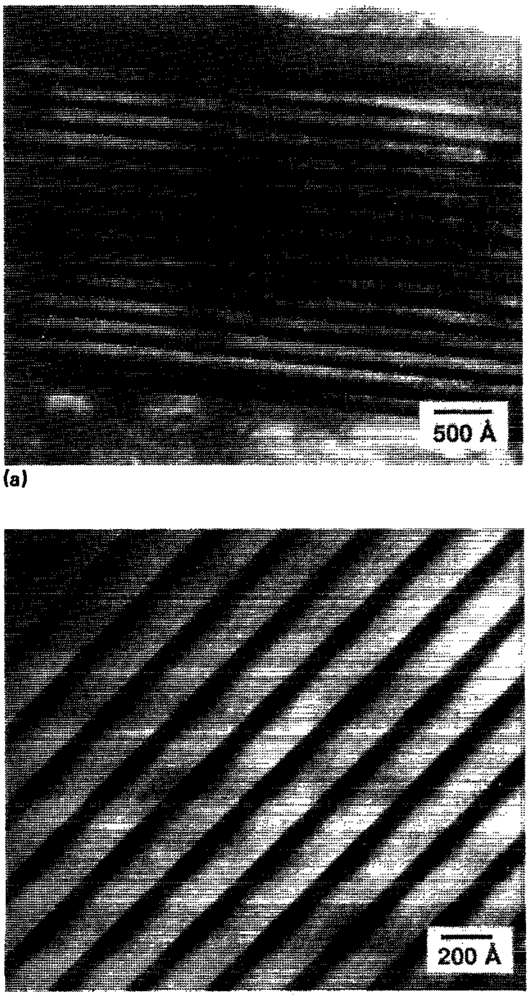
FIG. 2. High-resolution x-ray rocking curves with (004) diffraction taken from (a) sample 1 and (b) sample 2, SMQW structures grown by different methods.

$InAs_xP_{1-x}$ can be controlled independently of the composition, which is related to only the AsH_3 and PH_3 flow-rate fraction. Featureless surface morphology was obtained for all the samples over a wide composition range grown with both techniques. Two SMQW samples grown with the two different methods, respectively, were used in the present studies. Sample 1 was grown with 0.6 sccm AsH_3 and 4 sccm PH_3, and it consists of 16-period $InAs_{0.6}P_{0.4}$(78 Å)/InP(144 Å) quantum wells. Sample 2 was grown with a continuous supply of 3 sccm PH_3 and an alternating supply of 2 sccm AsH_3, and it consists of 15-period $InAs_{0.5}P_{0.5}$(76 Å)/InP(162 Å) quantum wells. In sample 2 the $InAs_{0.5}P_{0.5}$ layer was composed of 5 periods of 2.5 -monolayer $InAs_yP_{1-y}$ (y is greater than 0.5) and 2.5 monolayer InP. The V/III ratio on the substrate surface during growth was typically 4:1 as determined from the group-V- and group-III-induced RHEED oscillations.[8,10]

High-resolution x-ray rocking curves were recorded with symmetric (004) diffraction from a monochromatic Cu $K\alpha_1$ line through four Ge crystals for the two samples, as shown in Figs. 2(a) and 2(b). Satellite peaks, resulting from diffraction of SMQWs, can be observed up to the seventh order, and they are sharp and distinct. This suggests that good periodicity of these multilayered structures was obtained, even with strain as high as 2.3%. The slight broadening of the peaks in Fig. 1(b) is attributed to the partial relaxation of the strain and As carryover into the InP layer at the interface during the growth interruption.[6] By assuming an abrupt interface in the quantum well structure and a strain-free InP layer, a simulation based on the dynamic theory was carried out. It turns out that the structural parameters determined from the growth condition agree with those determined from x-ray diffraction. Furthermore, the ratio of layer thicknesses of InAsP to InP is exactly the same as the ratio of growth durations of these two layers, because the growth rates of both InAsP and InP are determined only by the indium flux. Moreover, it appears that little phosphorus was incorporated in the $InAs_yP_{1-y}$ during short-period superlattice growth with 2 sccm AsH_3 present since the As composition in $InAs_{0.5}P_{0.5}$ layer is the average of InP and InAs.

Figures 3(a) and 3(b) show the cross-sectional TEM images taken from samples 1 and 2, respectively. It is shown that SMQW interfaces are very flat and abrupt. However, as shown in Fig. 3(a), there is a contrast change in the InP buffer layer, adjacent to the epitaxial SMQWs. The appearance of these dislocation nets results from the large lattice mismatch (2.3%) of the InP substrate and the quantum well structure. These dislocations are located in the buffer layer and terminated at the first InAsP layer as the strained-layer superlattices can work as a threading dislocation barrier due to the alternating compressive and tensile strain in the strained epilayers.[11] In Fig. 3(b), no dislocation is observed in the quantum well layers, and the short-period superlattice structure in the $InAs_{0.5}P_{0.5}$ layer can be seen clearly.

PL measurements were carried out at 10 K with 0.5 mW argon ion laser excitation. The luminescence was dispersed with a 50 cm monochromator and detected by a cooled Ge photodiode. The sharp and intense peaks are observed with the full widths at half maximum (FWHM) of 9 and 5 meV for these two samples respectively, attributable to emissions from heavy-hole excitons confined in the quantum wells. These are among the best results which have been reported so far for this material system.[6] Figures 4(a) and 4(b) show absorption spectra taken from samples 1 and 2 at room temperature using a broadband halogen lamp. Very sharp and significant absorption can be seen at 1.55 and 1.4 μm, respectively. The absorption structures appearing at high energy side are from the transitions between higher subbands. It is interesting to note that sample 1 has a sharper PL peak but broader absorption peak, compared with sample 2. This is understood that a miniband was formed in the short-period superlattice composing the $InAs_xP_{1-x}$ quantum well layer in sample 2.



(a)

(b)

FIG. 3. TEM images taken from (a) sample 1 and (b) sample 2. Note that in (a) the misfit dislocations lie in the buffer layer and that in (b) fine structures corresponding to the short-period superlattice in the InAsP layer can be well resolved.

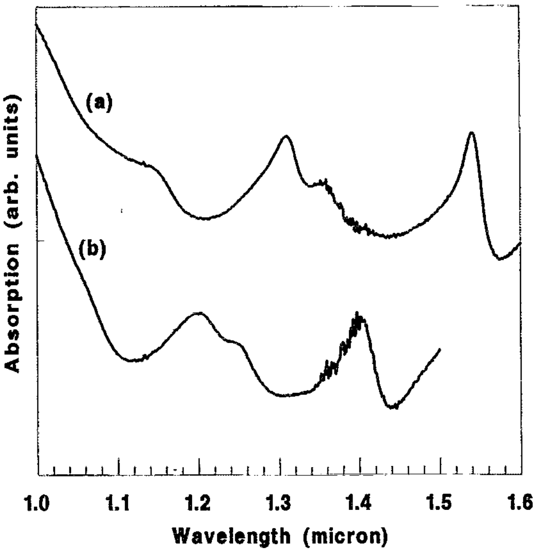


FIG. 4. Absorption spectra taken at room temperature by using a broadband halogen lamp for (a) sample 1 and (b) sample 2. The significant absorption peaks are from the excitonic transitions in the quantum wells.

Hence, the absorption peak, reflecting the density-of-state of the relatively broad miniband, is broader than that from sample 1, while the PL spectrum suggests that better periodicity of the SMQW structures was obtained for sample 2. These excitonic transitions from the confined heavy hole levels are extremely useful for optoelectronic device applications. Currently we are working on 1.3 and 1.55 μm modulator fabrications that are promising for fiber communications, and device results will be reported elsewhere.

In summary, $InAs_xP_{1-x}/InP$ strained multiple quantum wells with strain as high as 2.5% were grown with the GSMBE technique. The arsenic composition was successfully controlled either by using a high PH_3 flow rate to dilute the As to P incorporation ratio, or by using a short-period InAsP/InP superlattice to average the arsenic composition. Structural and optical studies, by high-resolution x-ray rocking curve, cross-sectional TEM, PL, and absorption measurements, indicate that we have achieved high quality SMQWs that are suitable for optoelectronic applications.

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