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Composition modulations in tensile strained $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ films grown on (100) InP substrates

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Abstract

The correlation between compositional modulations and surface morphology has been studied by transmission electron microscopy (TEM) and atomic force microscopy (AFM) for a series of tensile strained $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ films grown by molecular beam epitaxy (MBE) on (100) InP substrates. At low values of strain (0.6%), both a quaternary $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}_{0.6}\text{P}_{0.4}$ film and ternary $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ film show anisotropic behavior (both with regards to composition modulation and surface morphology) between $[0\ 1\ 1]$ and $[0\ \bar{1}\ 1]$ cross-sections. The composition modulation and surface undulation are prominent only in the $[0\ \bar{1}\ 1]$ cross-section. The $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ films develop a coarse faceted structure on $(4\ 1\ 1)$ and $(4\ \bar{1}\ \bar{1})$ planes after ~ 100 nm of film growth. Composition modulations (scaling with the size of the facets) are observed in films $0.1\text{--}1\ \mu\text{m}$ thick, but in thicker films ($> 1\ \mu\text{m}$) the faceted structure disappears while the scale of the compositional modulations decays to that found in unstrained films. On the other hand 2% tensile strained $\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$ and $\text{In}_{0.72}\text{Ga}_{0.28}\text{P}$ films show pronounced faceting with no evidence for compositional modulations, and 2% tensile strained $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}_{0.5}\text{P}_{0.5}$ films show composition modulation without scaling and no faceted surface. The results are discussed in terms of the interplay between thermodynamic driving force, leading to segregation and faceting, and kinetic factors. © 2001 Published by Elsevier Science B.V.

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1. Introduction

There are many interesting results on the nature of composition modulations in $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$

heteroepitaxial strained films [1–8]. Early studies, in samples grown by liquid phase epitaxy, suggested that the composition modulations always occurred in $\langle 001 \rangle$ directions [1,2]. However, later studies have shown that the composition modulation in thin films grown by vapor deposition on solid substrates occurs along $\langle 011 \rangle$ directions, not the elastically soft $\langle 001 \rangle$ directions, and is anisotropic between $[011]$ and $[0\ \bar{1}\ 1]$ directions [4–7]. The presence of a composition modulation

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also depends on the sign of strain built into the strained layer: the composition modulation in a film under tension is much stronger than that in a film grown under compression but with the same stress magnitude [8]. Moreover, composition modulations coupled with morphological undulations have been observed in InGaAsP films grown by chemical beam epitaxy (CBE) [7]. The explanation for the origin of this composition modulation is controversial. In_{1-x}Ga_xAs_yP_{1-y} alloys have a high chemical spinodal temperature T_{chem} , e.g. $T_{\text{chem}} = 1000 \text{ K}$ for $x = y = 0.5$ [9]. The film growth temperatures are generally lower than T_{chem} , so the observed composition modulation has often been attributed to spinodal decomposition. However, a calculation of the coherent spinodal in In_{1-x}Ga_xAs_yP_{1-y} alloys [10] accounting for the bulk strain energy associated with newly formed InAs- and GaP-rich region having different lattice-constants (using Cahn's coherent spinodal theory [11]) shows that the growth temperature is well above the coherent spinodal temperature T_{Cahn} . More accurate calculations [12], taking into account the elastic strain energy due to the misfit between the film and substrate, showed that the critical temperature against phase separation (T_{Glas}) in In_{1-x}Ga_xAs_yP_{1-y} films lies above T_{Cahn} , e.g. $T_{\text{Glas}} = 480 \text{ K}$ for $x = y = 0.5$. However, the film growth temperature, typically 450–500°C in molecular beam epitaxy (MBE), is still well above this critical temperature T_{Glas} .

Recent modeling of kinetic instabilities suggests that the composition modulation may be correlated with surface undulations [13]: in this model the composition modulation has the same periodicity as the surface perturbation. The temperature for this deposition driven composition and surface instability (T_{dep}) lies above the bulk chemical spinodal temperature (T_{chem}) in In_{1-x}Ga_xAs_yP_{1-y} films. These calculations might offer an explanation of the composition modulations observed in III–V films. In this paper, we report on transmission electron microscopy (TEM) and atomic force microscopy (AFM) observations of composition modulations and surface morphology in 0.6% tensile strained In_{0.65}Ga_{0.35}As_{0.6}P_{0.4} and In_{0.45}Ga_{0.55}As films, and 2% tensile strained

In_{0.5}Ga_{0.5}As_{0.5}P_{0.5}, In_{0.25}Ga_{0.75}As and In_{0.72}Ga_{0.28}P films grown on (100) InP substrates.

2. Experimental procedures

A series of ternary and quaternary lattice-mismatched In_{1-x}Ga_xAs_yP_{1-y} films with 0.6% and 2% tensile strain were grown on an *n*-type exact (100) (singular) InP substrates at 480°C using gas-source MBE. The details of the growth procedures are described elsewhere [6,14]. The evaporation sources are used for the group III elements (In and Ga), while the group V constituents are supplied primarily in the form of AsH₃ and PH₃. A single, low pressure rhenium cracker, operating at 1000°C, was used for both AsH₃ and PH₃. All films were grown at a rate of 1 µm/h. The compositions of the films were determined by a technique combining double crystal X-ray diffraction and photoluminescence measurements. The mismatch (*f*) of an In_{1-x}Ga_xAs_yP_{1-y} film on an InP substrate is defined by $f = (a_s - a_f)/a_f$ where a_f and a_s are the lattice constants of In_{1-x}Ga_xAs_yP_{1-y} and InP in their natural states at room temperature. [011] and [0 $\bar{1}$ 1] cross-sections and (100) plan-view samples were prepared for TEM following standard procedures and examined in a Philips CM12 operating at 120 kV. The AFM studies were performed in air using a Digital Instruments Nanoscope III system.

3. Observations

3.1. Quaternary In_{0.65}Ga_{0.35}As_{0.6}P_{0.4} and In_{0.5}Ga_{0.5}As_{0.5}P_{0.5} films

Fig. 1a and b are 022 and 02 $\bar{2}$ dark field TEM images of [0 $\bar{1}$ 1] and [011] cross-sectional samples of a 20 nm thick, 0.6% tensile strained In_{0.65}Ga_{0.35}As_{0.6}P_{0.4} film. In the image taken from the [0 $\bar{1}$ 1] cross-section (Fig. 1a), a strong periodic bright and dark contrast lying parallel to the growth direction [100] and perpendicular to the [011] direction is visible. This is associated with a composition modulation along the [011] direction, having a wavelength of about 10 nm. In contrast,

Fig. 1. Dark field images of (a) $[0\bar{1}1]$ cross-section ($g = 022$), and (b) $[011]$ cross-section ($g = 022$) of an $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}_{0.6}\text{P}_{0.4}$ epitaxial layer with 0.6% tensile strain. The contrast associated with the composition modulation is visible only in $[0\bar{1}1]$ cross-section.

no periodic features are observed in the image taken from the $[011]$ cross-section (Fig. 1b), implying that the composition modulation is one-dimensional and anisotropic between the $[011]$ and $[0\bar{1}1]$ directions. This pattern of composition modulation was confirmed by plan-view TEM observations. A plan-view bright field image of an $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}_{0.6}\text{P}_{0.4}$ epitaxial layer in which a one-dimensional composition modulation can be clearly seen is shown in Fig. 2a. The composition modulation is limited to the $[011]$ direction. Fig. 2b is a $[100]$ zone axis diffraction pattern taken from the area shown in Fig. 2a. The $\{002\}$ family of diffraction spots are each marked by streaks extending in a $[011]$ direction, and can be associated with the composition modulation along the $[011]$ direction.

An AFM image of the surface of this film is shown in Fig. 3. The surface undulation is also anisotropic between the two $\langle 011 \rangle$ directions: the undulation is running predominately along the

Fig. 2. (100) plan-view bright field image ($g = 020$) of an $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}_{0.6}\text{P}_{0.4}$ epitaxial layer with 0.6% tensile strain (a) and a corresponding $[100]$ diffraction pattern (b). Four $\langle 002 \rangle$ diffraction spots are accompanied by streaks extending in $[011]$ direction due to the composition modulation in this direction.

$[011]$ direction, i.e. along the same direction as the composition modulation.

Fig. 4a and b are 022 and $02\bar{2}$ bright field TEM images of $[0\bar{1}1]$ and $[011]$ cross-sectional samples of a 20 nm thick, 2% tensile strained $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}_{0.5}\text{P}_{0.5}$ epitaxial film grown on (100) InP substrate. In contrast to the anisotropy of composition modulation found between the two $\langle 011 \rangle$ directions in the 0.6% tensile strained layer, the contrast associated with a composition modulation is now visible in both $[0\bar{1}1]$ and $[011]$ cross-sections. Plan-view TEM observations verified that the composition was modulated along the two $\langle 011 \rangle$ directions (Fig. 5). A plan-view dark field image of this film (Fig. 5a) clearly shows

Fig. 3. AFM image of an $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}_{0.6}\text{P}_{0.4}$ epitaxial layer with 0.6% tensile strain. The surface undulation dominated along $[0\ 1\ 1]$ direction.

that there is a modulation contrast along both of the $[0\ \bar{1}\ 1]$ and $[0\ 1\ 1]$ directions. Fig. 5b is the $[1\ 0\ 0]$ zone axis diffraction pattern taken from the area shown in Fig. 5a. The $\{002\}$ diffraction spots are accompanied by streaks extending in $[0\ \bar{1}\ 1]$ and $[0\ 1\ 1]$ directions, associated with composition modulations along $[0\ \bar{1}\ 1]$ and $[0\ 1\ 1]$ directions.

The AFM image of this film (Fig. 6a) shows surface undulation running along both $[0\ \bar{1}\ 1]$ and $[0\ 1\ 1]$ directions in contrast to that found in 0.6% tensile strained layer. However, the wavelength and magnitude of the undulations in the two $\langle 0\ 1\ 1 \rangle$ cross-sections are different: the wavelength is smaller while the magnitude is larger along the $[0\ 1\ 1]$ direction in the $[0\ \bar{1}\ 1]$ cross-section. Surface undulations running parallel to $\langle 0\ 1\ 1 \rangle$ are clearly seen in both cross-sections shown in Fig. 4a and b.

Fig. 7 is a $\mathbf{g} = 022$ dark field TEM image (where $\mathbf{g}$ is the operating reflection) of a $[0\ \bar{1}\ 1]$ cross-sectional sample of a 500 nm thick, 2% tensile strained $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}_{0.5}\text{P}_{0.5}$ film. Throughout the whole 500 nm thickness of the film, a fine scale composition modulation is visible. From the structure factor point of view, the contrast

associated with this composition modulation is not obvious with $\mathbf{g} = 200$, while strong contrast appears with $\mathbf{g} = 022$ for $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}_{0.5}\text{P}_{0.5}$ films. On the other hand $\mathbf{g} = 200$ is a good diffraction condition to observe the composition modulation contrast for ternary $\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$ and $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ films [15]. Additional TEM contrast associated with the composition modulation aligned normal to the $[0\ 1\ 1]$ direction, obtained with $\mathbf{g} = 022$, is due to the strain between two of different lattice parameter, i.e. the displacement is parallel to $[0\ 1\ 1]$, while there is no contrast due to the strain when $\mathbf{g} = 200$. The surface of the 500 nm thick, 2% tensile strained quaternary $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}_{0.5}\text{P}_{0.5}$ film is not faceted, but is undulated as shown in Fig. 7. AFM observations of the topology of this film confirmed that the surface of this quaternary film is not faceted (Fig. 6b).

3.2. Ternary $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$, $\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$ and $\text{In}_{0.72}\text{Ga}_{0.28}\text{P}$ films

Since the composition modulations and surface undulation are only observed in $[0\ \bar{1}\ 1]$

Fig. 4. Bright field images of (a) $[0\bar{1}1]$ cross-section ($g = 0\bar{2}2$), and (b) $[0\bar{1}1]$ cross-section ($g = 0\bar{2}2$) of an $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}_{0.5}\text{P}_{0.5}$ epitaxial layer with 2% tensile strain. The contrast associated with the composition modulation is visible in both $[0\bar{1}1]$ and $[011]$ cross-sections. The surface undulation is also visible in both $[0\bar{1}1]$ and $[011]$ cross-sections. There are microtwins in both cross-sections as well.

cross-section in 0.6% tensile strained $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ film [5], the study of these films concentrates on the dependence of the composition modulations and surface undulation behavior as a function of the film thickness in $[0\bar{1}1]$ cross-section.

Fig. 8a is a $[0\bar{1}1]$ cross-sectional TEM image of a $0.5\mu\text{m}$ thick, 0.6% tensile strained $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ film grown with a capping film. A faceted growth surface, composed of (411) and $(4\bar{1}\bar{1})$ facets was observed in this film (Fig. 8a). A composition modulation, coupled with the size of facets and aligned approximately normal to the $[011]$ direction is visible (Fig. 8a): the compositional modulations correspond to the lines of black and white contrast seen with $g = 200$ in the peak and valley regions of the faceted surface, respectively. The $g = 200$ dark field condition is particularly sensitive to abrupt composition variations. The black and white contrast lines corre-

Fig. 5. (100) plan-view bright field image ($g = 040$) of an $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}_{0.5}\text{P}_{0.5}$ epitaxial layer with 2% tensile strain (a) and a corresponding $[100]$ diffraction pattern (b). Four $\langle 002 \rangle$ diffraction spots are accompanied by streaks extending in $[0\bar{1}1]$ and $[011]$ direction due to the composition modulation in these two directions.

spond to regions that are much richer or leaner in Ga at the peaks and valleys, respectively than the mean film composition [5]. In this film, a composition modulation lying approximately parallel to the trace of the (411) and $(4\bar{1}\bar{1})$ facets can also be observed (Fig. 8a). Fig. 8b–e are a series of $[0\bar{1}1]$ cross-sectional TEM images taken from different locations of a $2\mu\text{m}$ thick, 0.6% tensile strained $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ film. The composition modulation is not uniform in this film. A fine scale composition modulation with a wavelength of about 10nm aligned normal to the $[011]$ direction is observed in the initial stage of film growth (Fig. 8b). The behavior of this composition modulation changes dramatically after the film

Fig. 6. AFM images of an $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}_{0.5}\text{P}_{0.5}$ epitaxial layer with 2% tensile strain. The surface undulation is visible in both $[0\ 1\ 1]$ and $[0\ \bar{1}\ 1]$ directions: (a) 20 nm thick film, (b) 500 nm thick film.

thickness reaches about 100 nm. For film thicknesses of 100 nm–1 μm , a composition modulation scaling with the size of facets at the growth surface and aligned approximately normal to the $[0\ 1\ 1]$ direction is visible (Fig. 8b and c). However, in the

upper section (1–2 μm) of this film, the wavelength of the composition modulation is gradually reduced as the film thickness increases (Fig. 8c and d). Finally, at the top of the film, fine scale composition modulations with a wavelength of

Fig. 7. $g = 0\ 2\ 2$ TEM image of $[0\ \bar{1}\ 1]$ cross-section of a 500 nm thick, 2% tensile strained $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}_{0.5}$ film.

about 10 nm re-appear (Fig. 8e). In addition to the composition modulation aligned normal to the $[0\ 1\ 1]$ direction, composition modulations along $[4\ 1\ 1]$ and $[4\ \bar{1}\ \bar{1}]$ directions, defined by the faceted growth surface, are again observed in the film thickness range of about 0.2–1 μm (Fig. 8b and c). The growth surface is highly faceted for film thicknesses in the range of 100 nm–1 μm (Fig. 8b and c), where the two types of composition modulation appear. In the upper part (1–2 μm) of the film, the faceted surface gradually disappears, being replaced by a slightly undulated surface. At the same time the wavelength of composition modulations aligned normal to the $[0\ 1\ 1]$ direction slowly diminishes as the film thickness increases (Fig. 8c and d). In addition, the composition modulations along $[4\ 1\ 1]$ and $[4\ \bar{1}\ \bar{1}]$ directions disappear, as the faceted growth surface is replaced by a nearly planar surface.

AFM images from the 0.6% tensile strained $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ samples illustrate the change of surface morphology with film thickness. As noted in the XTEM study, the surfaces of the 20 nm thick film were already rough, but the roughening was much more marked along the $[0\ 1\ 1]$ than the $[0\ \bar{1}\ 1]$ direction (Fig. 9a). This behavior is similar to that found in the 0.6% tensile strained quaternary $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}_{0.6}\text{P}_{0.4}$ film. In a 500 nm thick film this anisotropy becomes most pro-

nounced, with the surface evolving into $(4\ 1\ 1)$ and $(\bar{4}\ 1\ 1)$ facets (Fig. 9b). However, these facets are no longer visible in the surface of the 2 μm thick film as noted in the XTEM study.

Fig. 10 compares $[0\ \bar{1}\ 1]$ cross-section TEM images of a 500 nm thick, 2% tensile strained $\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$ film (Fig. 10a) and a 100 nm, 2% tensile strained $\text{In}_{0.72}\text{Ga}_{0.28}\text{P}$ film (Fig. 10b). Although the morphology of the surface of these films is similar to that of the 0.6% tensile strained $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ film, i.e. composed of facets with plane indices close to $(4\ 1\ 1)$ and $(4\ \bar{1}\ \bar{1})$, no composition modulations are observed. Another characteristic feature these 2% strained samples is a high-density of twins and dislocations; this implies that considerable plastic relaxation of the growth strains has occurred.

4. Discussion

Several factors appear to play important roles in the composition modulation behavior in tensile strained $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ heteroepitaxial strained layers: the thermodynamic driving force for decomposition (e.g. the alloy composition in relation to the position of the chemical spinodal), the sign and magnitude of the strain field in the layer, and the rate of growth of the film. Of these three factors, the origin of the composition modulation in the present study appears to be primarily dependent on the position of the overall composition of the film with respect to the chemical spinodal. The alloy compositions of the two quaternary films, $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}_{0.6}\text{P}_{0.4}$ and $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}_{0.5}\text{P}_{0.5}$, and the ternary $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ film all lie within the chemical spinodal at the growth temperature of 480°C (Fig. 11). This is believed to be responsible for the fine scale composition modulations observed in these films. No composition modulation was observed in the 2% tensile strained $\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$ and $\text{In}_{0.72}\text{Ga}_{0.28}\text{P}$ films. The composition of these films lies outside the chemical spinodal at the growth temperature of 480°C. The magnitude of the strain plays little role on the initial fine scale composition modulation.

Fig. 8. $[0\bar{1}1]$ cross-section dark field TEM images of a $0.5\text{ }\mu\text{m}$ thick, 0.6% tensile strained $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ film with a capping film (a), and a $2\text{ }\mu\text{m}$ thick, 0.6% tensile strained $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ film of different locations (b, c, d, e). $g = 200$ for all images. Note that distances between the top of image and interface are $1\text{ }\mu\text{m}$ for (c), $1.6\text{ }\mu\text{m}$ for (d) and $2\text{ }\mu\text{m}$ for (e).

The observation of an anisotropy in both composition modulation and surface topology between the two $\langle 011 \rangle$ directions in the 0.6% tensile strained $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}_{0.6}\text{P}_{0.4}$ film found in this study agrees with previous observations in a 0.6% tensile strained $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ film [5]. Similar results have been reported by other authors in III–V and II–VI alloy epitaxy systems [3,4,7,16,17]. In this study, however, we observed another interesting phenomenon: with an increase in the misfit between substrate and film from 0.6% to 2% , the composition modulation and surface

undulation are no longer anisotropic but occur in both of the $[0\bar{1}1]$ and $[011]$ directions.

The anisotropy of composition modulation and surface undulation observed in III–V epitaxial layers is thought to be related to surface reconstruction. It is well known that (100) surfaces of III–V semiconductors are usually reconstructed, e.g. the (2×4) reconstruction, so that the directions that were crystallographically equivalent before reconstruction are no longer so after reconstruction. A- and B-type steps running along $[011]$ and $[0\bar{1}1]$ directions on a vicinal (100)

Fig. 9. AFM observations showing the development of surface roughness in $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ films: (a) 20 nm thick film, (b) 500 nm thick film. Note the development of pronounced (411) and $(\bar{4}11)$ facets in the thicker film.

reconstructed surface have different characteristics, leading to anisotropic surface diffusivity [18]. This factor is believed to contribute also to the anisotropy of composition modulation and surface undulations between two $\langle 011 \rangle$ directions. The

reason why this anisotropy partly disappears in 2% strained epitaxial layers is not clear at this stage, although it might be related to another surface reconstruction that comes into play at higher tensile strains.

Fig. 10. $[0\bar{1}1]$ cross-section dark field TEM images of a 500 nm thick, 2% tensile strained $\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$ film (a), and a 100 nm thick, 2% tensile strained $\text{In}_{0.72}\text{Ga}_{0.28}\text{P}$ film (b). $g = 200$ for both images.

Fig. 11. Composition diagram for $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ alloys. Three lines represent the alloy compositions, which are lattice-matched ($f = 0$), 0.6% tensile strained ($f = +0.6\%$), and 2% tensile strained ($f = +2\%$) to InP. The curves are the chemical spinodal at 480°C . The alloy compositions used for this study are indicated by the solid circles.

Fig. 12. $[0\bar{1}1]$ cross-section TEM images of 2 μm thick, 0.6% tensile strained $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ film showing microtwins and dislocations. (a) $g = 022$ DF; and (b) $g = 022$ WBDF.

In this study, a faceted surface was observed in both 0.6% and 2% tensile strained, 500 nm thick ternary InGaAs films, and a 100 nm thick 2% tensile strained ternary InGaP film, while the surface was not faceted for the 500 nm thick, 2% tensile strained quaternary InGaAsP film. The reason for this behavior is unclear. The wavelength of surface faceting is almost the same for the 500 nm thick, 0.6% and 2% tensile strained InGaAs films although theory predicts that the wavelength of surface faceting should depend on the magnitude of the strain of the film [5]. At this film thickness, part of the strain was relieved by microtwins, misfit dislocations, and cracking in the 2% tensile strain film [19,20]; this might account for the observations.

For the 500 nm thick, 2% tensile strained $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}_{0.5}\text{P}_{0.5}$ film, since there is no faceted growth surface, a fine scale composition modulation with wavelength of about 10 nm is present throughout whole film. For the 2 μm thick, 0.6% tensile strained $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ film, considerable plastic strain relaxation has occurred after the film thickness exceeds 1 μm . Microtwins and misfit dislocations can be seen in this film (Fig. 12). As the strain is relieved with further film growth, the driving force for the surface faceting is reduced, and in turn the scaling of the composition modulation is diminished. As a result of this process, a fine scale composition modulation (~ 10 nm) re-appears near the top of this film, almost identical to that found in the first stage of the film growth. Both surface faceting and the compositional modulations associated with it are seen to be mutually dependent on the stresses in the film, as well as the overall film composition.

5. Conclusions

- (1) In the quaternary InGaAsP system where composition lies within the chemical spinodal at the growth temperature show composition modulations. No composition modulations are found in films whose composition lies outside the chemical spinodal.
- (2) A faceted growth surface is observed in all tensile strained ternary films, regardless of the magnitude of the strain and composition, while the quaternary films show island rather than faceted growth.
- (3) A clear correlation is found between the scaling of the composition modulation and strain-induced surface faceting: the composition modulations are found to scale with the size of facets in $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ films.
- (4) A 0.6% tensile strained quaternary $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}_{0.6}\text{P}_{0.4}$ film shows an anisotropy of composition modulation and surface morphology between the two $\langle 011 \rangle$ directions.

This anisotropy disappears in a 2% tensile strained quaternary $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}_{0.5}\text{P}_{0.5}$ film.

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