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Composional Latching in $GaAs_{1-x}P_x$/GaAs MOVPE

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MOVPE growth studies of $GaAs_{1-x}P_x$ (x=0.05-0.40) on GaAs substrates, combined with X-ray diffraction analysis and secondary-ion mass spectroscopy, have demonstrated a "compositional latching" effect in thin layer growth, where the incorporation of P from vapor to solid is suppressed due to lattice strain on the growing surface. A growth model based on strain-dependent incorporation probabilities for P and As have been proposed.

1. Introduction

The epitaxial growth of $GaAs_{1-x}P_x$ on GaAs substrates involves a lattice-mismatch, which will give rise to specific growth effects due to lattice strain on the growing surface. One of such effects is "compositional latching" as found in the MOVPE growth of thin $GaAs_{1-x}P_x$ layers on GaP substrates[1]. On the GaP substrate, the thin $GaAs_{1-x}P_x$ layer is strained compressively parallel to the layer for coherent growth. Then the As atoms from vapor are considered to experience steric hindrance to adsorption, resulting lower As content in the grown layer as compared with thick relaxed layers[1]. In the case of $GaAs_{1-x}P_x$ on GaAs, grown layers will suffer from tensile strain parallel to the layer. Strain effects for this system, however, have not been clear in previous work[2,3].

In this work, the strain effect in the $GaAs_{1-x}P_x$ MOVPE growth on GaAs substrates has been studied by growing thin strained layers as well as thick relaxed layers.

2. Experimental

The MOVPE growth of $GaAs_{1-x}P_x$ (x=0.05-0.40) was performed in a low-pressure (60 Torr) reactor, using trimethylgallium (TMG), AsH_3 and PH_3 as sources with H_2 as carrier. The growth temperature ranged from 650 to 800 °C. The TMG flow rate was 9.2×10^{-6} mol/min. The V/III ratio was varied from 60 to 150 depending on the solid composition x. The reactor operated with a vent-run pipeline configuration which assured an abrupt change of gas flow components. The growth rate was typically 3.4µm/h. With these growth conditions, relatively thick layers (thickness ~2µm) as well as thin layers (thickness ~0.06µm) were grown on (100) GaAs substrates.

The solid composition and the lattice strain of the grown layers were determined from the X-ray double crystal asymmetric (511) diffraction, in which lattice parameters for both parallel ($a_{\parallel}$) and perpendicular ($a_{\perp}$) to the surface were known. The secondary-ion mass spectroscopy (SIMS)

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was used to examine the solid composition profile along the growth direction.

3. Results and discussions

3.1 Thick-layer growth

The grown-surface features for the thick layers are classified into the four types of surface morphology, depending on the solid composition and the growth temperature, as shown in Fig. 1. In region (a), where the lattice mismatch is relatively small and the growth temperature is not very high, crosshatch patterns along the [011] and [01$\bar{1}$] directions are noticeable. In region (b), island feature with short edge lines is dominant. In region (c), smooth surfaces without any prominent features are obtained. The grown surfaces are roughend when the lattice-mismatch is increased for higher growth temperatures as in region (d).

As these thick layers were grown to much above the critical thicknesses[4] for elastic accomodation of strain, the lattice strain was considered to be largely relaxed by generating misfit dislocations. From the X-ray diffraction, it has been known that the lattice relaxation ratio, δ/f, amounts to above 90 % for these thick layers, where f is the relative mismatch between layer and substrate and δ the amount of mismatch accomodated by misfit dislocations[1]. We refer to these thick layers as relaxed layers.

3.2 Thin-layer growth

For the thin-layer growth, the grown surfaces had the two types of distinct features as dependent on the solid composition and the growth temperature as shown in Fig. 2. The estimated values for the lattice relaxation ratio in % are indicated for each data point. Very smooth surfaces with weak crosshatch patterns were obtained when the lattice relaxation ratio

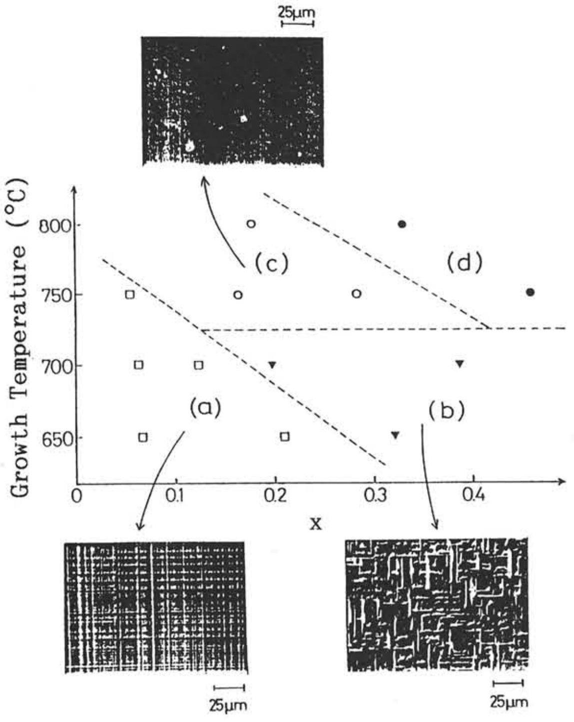

Fig. 1 Surface features for the thick layer growth.

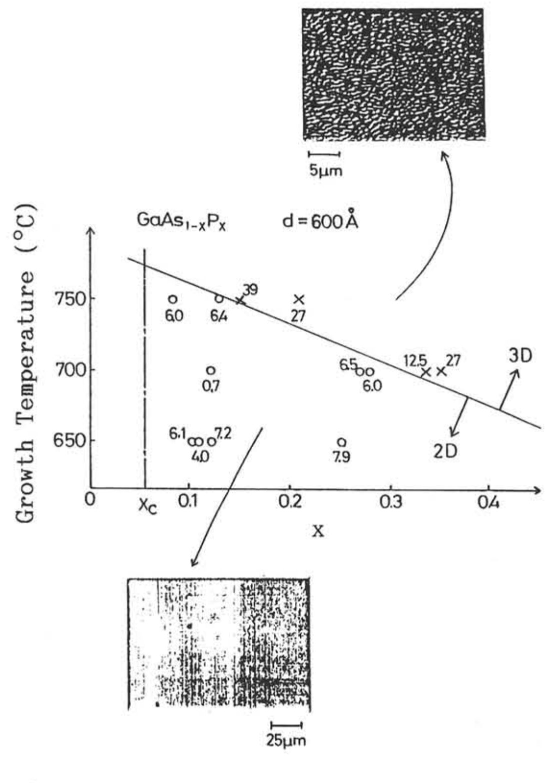

Fig. 2 Surface features and the lattice relaxation ratio (δ/f) for the thick layer growth.

was less than 10 % in spite that the layer thicknesses were a few times larger than the critical thicknesses. For these layers, the growth seems to be layer-by-layer two-dimensional (2D) like. For other layers, however, the lattice relaxation ratio was much above 10 %. The grown surfaces were not smooth and the growth mode seems to be three-dimensional (3D) like.

It is to be noted that the boundary between the 2D and the 3D regions almost coincides with the boundary between region (a) and others in Fig. 1. Namely, when the growth is done in the 2D region for thin layers, the grown layer will have considerable amount of residual strain which leads to the observed crosshatch patterns. We refer to these layers as strained layers. Whereas, in the 3D region, the lattice strain will be mostly relaxed for thick layers. After the strain is sufficiently relaxed, the growth mode will tend to be 2D like for higher growth temperatures resulting smooth surfaces as found in region (c).

3.3 Compositional latching

The solid versus vapor compositions for the growth of thick (relaxed) layers and thin (strained) layers at 650-750°C are plotted in Fig. 3. For the strained layers, the P content is suppressed compared with the relaxed layers, thus showing "compositional latching" effect. The variation in the P content from the initial strained layers to the relaxed layers is very evident in the SIMS depth profiles for the thick layers as shown in Fig. 4. For the 700°C growth, the larger the P content (i.e. the larger the lattice mismatch) the more emphasized the compositional latching, resulting a large

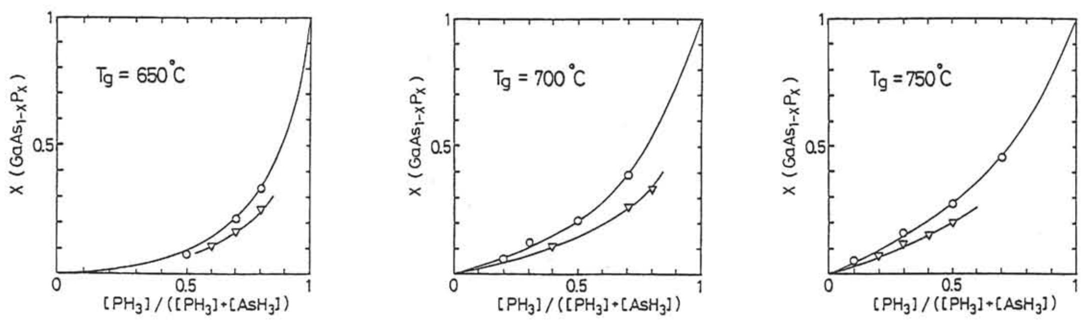

Fig. 3 Solid versus vapor compositions for the relaxed (○) and the strained (▽) $GaAs_{1-x}P_x$ layers.

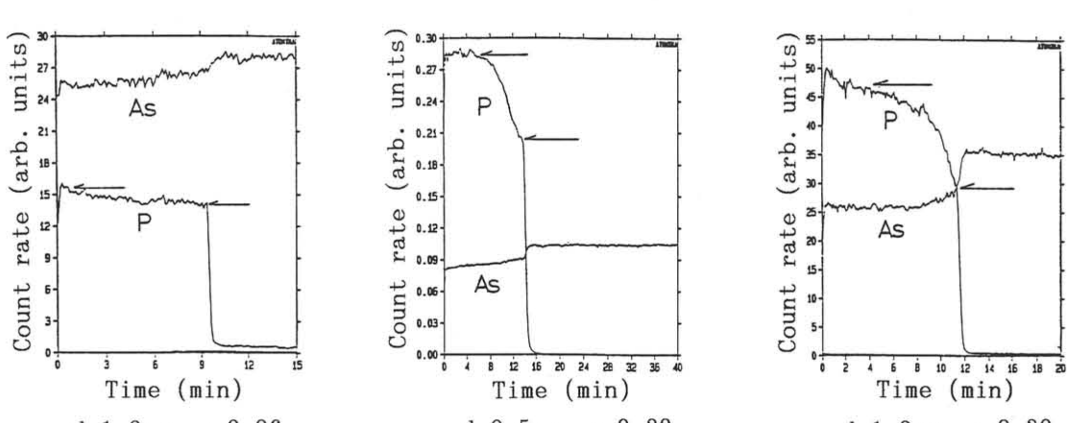

Fig. 4 The SIMS depth profiles of P and As for the thick layers grown at 700 °C.

variation in the P content along the growth direction. For higher growth temperatures (750°C and 800°C), the variation of the P content was more rapid due to the faster relaxation of the strain. The relaxed and the strained layers solid compositions are plotted for identical growth conditions in Fig. 5. It is found that the behavior is hardly dependent on the growth temperature.

In order to derive a growth model for the compositional latching in MOVPE, the strain-dependent incorporation probabilities for P and As from vapor into solid are assumed as

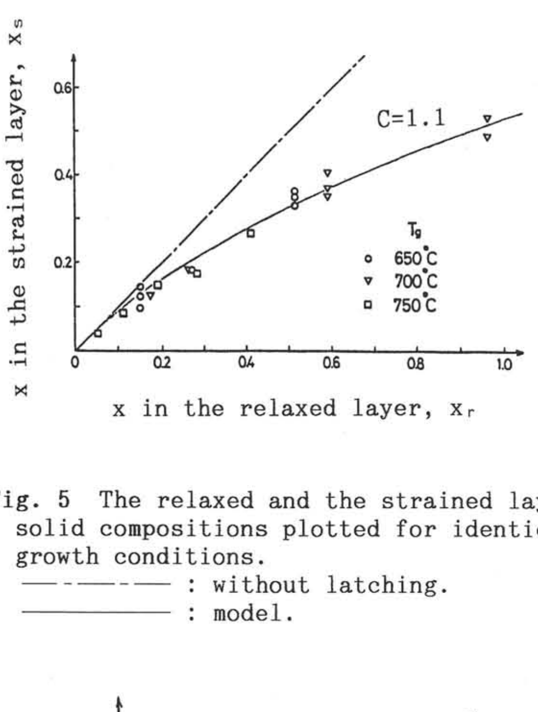

Fig. 5 The relaxed and the strained layers solid compositions plotted for identical growth conditions.
—·—·— : without latching.
——— : model.

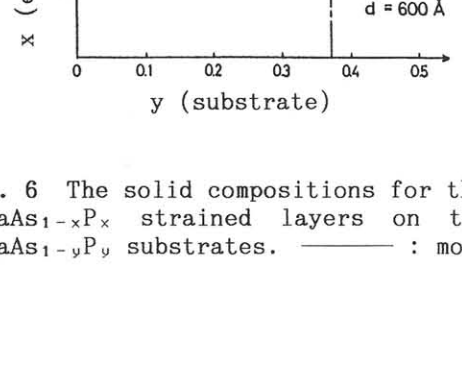

Fig. 6 The solid compositions for the $GaAs_{1-x}P_x$ strained layers on the $GaAs_{1-y}P_y$ substrates. ——— : model.

$$p_i = k_i \exp[\mp \frac{d_{sub} - a}{C(a_{GaAs} - a_{GaP})}], \quad (i=P, As) \quad (1)$$

(- for i=P, + for i=As)

where d_{sub} and a are the lattice constants of the growing surface and of the completely relaxed layer, respectively, k_i is the incorporation probability for relaxed layers [3], and C is a fitting parameter. With eq.(1), the relationship between the solid compositions of the strained layer, x_s, and of the relaxed layer, x_r, is expressed as

$$\frac{x_s}{1-x_s} = \exp[\frac{2(x_{sub} - x_s)}{C}] \frac{x_r}{1-x_r}, \quad (2)$$

where x_{sub} is the P content of the substrate. The data points in Fig. 5 are fitted with a curve when C=1.1.

In order to test the applicability of the model, the strained $GaAs_{1-x}P_x$ layers were grown on $GaAs_{1-y}P_y$ (100) relaxed substrates. The identical growth conditions as for the x=0.37 relaxed layer was used for y=0.08-0.37. The growth results are shown in Fig. 6. The solid line is the expected solid compositions from eq. (2). So far, much cannot be said for the agreement. The physical meaning of the model and its applicability are still to be studied.

4. Summary

Strain effects in the $GaAs_{1-x}P_x$ MOVPE on GaAs substrates have been studied. The grown surface morphology is strongly affected by the degree of relaxation of the lattice strain. For thin strained layers, compositional latching has been demonstrated.

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