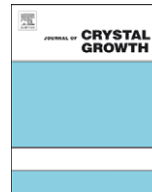




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## Demonstration of planar thick InP layers by selective MOVPE

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### ABSTRACT

We studied the selective metal-organic vapor-phase epitaxy of thick InP bulk layers. The work focused on the obtention of planar thick layers by an adjustment of the growth conditions. We showed that reduced pressure and temperature in the reactor allowed to decrease the sharpness of the thickness profiles in the vicinity of the mask. This approach is consistent with the vapor phase diffusion model and the kinetic theory. Thick InP layers generally show huge overgrowths at the edges of the dielectric stripes. These overgrowths were suppressed by reducing the growth rate. All samples' thickness profiles were characterized by means of optical interferometer microscopy and surface profiler. Scanning electronic microscopy was used in the observation of the edge overgrowths and highlighted the complexity and anisotropy of the growth at these edges.

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### 1. Introduction

Selective area growth (SAG) is an important process step for the integration of optoelectronic devices. In SAG, the growth occurs on a wafer partially covered with a dielectric material. As no species can deposit on the amorphous surface of the dielectric, a concentration gradient appears in the vapor phase and the active species diffuse from above the masked areas toward the open areas. Compared with a region far away from any dielectric mask perturbation, the two main effects are thickness enhancement and compositional variations in the case of ternary and quaternary alloys. These two effects are widely used in photonic integrated circuits where a SAG dielectric mask can be tailored in order to integrate different active/passive optical functions. Usually the selectively grown layers are complex stacking including a multiple-quantum well section embedded in separate confinement heterostructures (SCH) and InP layers. The InP buffer layer avoids starting the epitaxial growth directly with a quaternary material, typically the SCH. InP is also commonly used as a spacer for distributed feed back or tunable distributed Bragg reflector lasers. In the SAG regime, the thick InP layers are known to be difficult to handle [1,2]. First, in standard growth conditions, the indium precursor has a very small diffusion length [3] which gives rise to very sharp thickness profiles in the vicinity

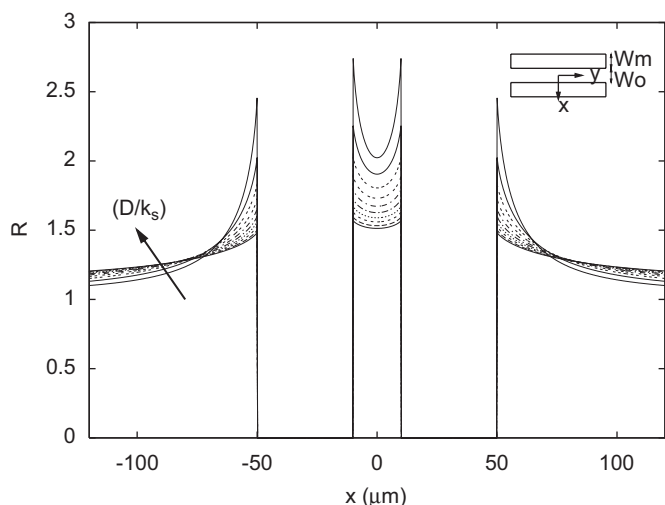
of the mask. Second, in the case of thick enough InP layers (300 nm and more), huge overgrowths appear at the edges of the dielectric stripes as shown by Sugiyama et al. [1]. These overgrowths should be suppressed as they can lead to major problems in devices fabrication. In this paper, we focus on the selective area growth conditions of thick InP layers in order to improve the flatness of the thickness profiles and to reduce the overgrowths at the edges.

### 2. Experiment

All investigated samples were grown in a horizontal AIX200/4 MOVPE reactor, designed for three 2 in wafers using trimethylindium (TMIn), arsine (AsH<sub>3</sub>), and phosphine (PH<sub>3</sub>) as growth precursors. The InP wafers were pre-processed with 350 nm thick SiO<sub>2</sub> dielectric stripes using conventional plasma enhanced chemical vapor phase deposition (PECVD), photolithography, and reactive ion etching (RIE). The SAG mask layout included various patterns. Basically, the SAG pattern consists of two parallel dielectric stripes aligned with the [110] crystallographic direction.  $W_m$  is defined as the width of the stripes and  $W_o$  as the opening width between stripes (see inset in Fig. 1). The patterns were very long (900 μm) and sufficiently separated to avoid any influence on each other [4]. The different samples were selectively grown with various temperature and pressure conditions which will be described latter in the paper. Different growth rates were also investigated by changing the input TMIn flow rate at constant

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**Fig. 1.** Calculations in VPD of the growth rate enhancement  $R$  along  $x$  direction with  $(D/k_s)$  varied from 10 to 100  $\mu\text{m}$  every 10  $\mu\text{m}$  steps.  $W_m$  is fixed to 40  $\mu\text{m}$  and  $W_o$  to 20  $\mu\text{m}$ . The calculations show the evolution of the  $R$  profile which goes smoother (see arrow) while increasing  $(D/k_s)$ .

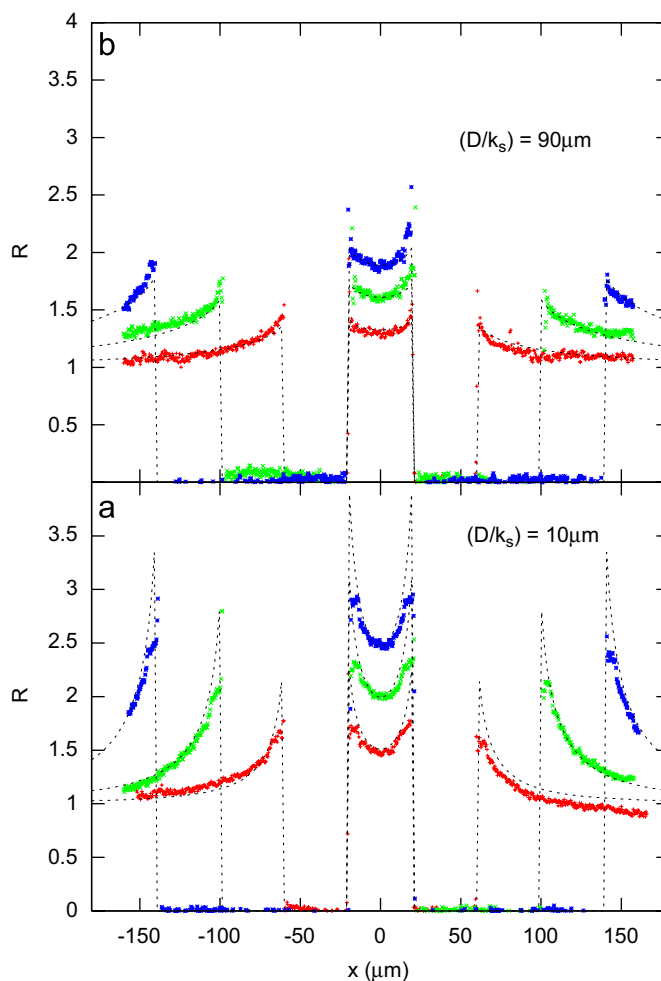
$\text{PH}_3$  flow (100 sccm). In the field region (i.e far away from any mask perturbation), all the investigated samples had the same thickness sequence that is a 97 nm InP/ 3 nm InAsP stack repeated seven times leading to a global thickness of 700 nm. The markers were added for convenience with scanning electronic microscopy (SEM) observations. In order to characterize the thickness profiles around the mask, both optical interferometer microscopy (OIM) and surface profiler have been used, the latter one being much more adapted to precisely measure the overgrowths at the edges of the mask.

### 3. Results and discussion

In selective epitaxy, the shape of the concentration profiles around the mask is known to be strongly dependent on the growth conditions [5–8]. As a first approximation, the vapor phase diffusion (VPD) model is well adapted to calculate the concentration profiles around any masked areas [6,9]. In this model, the diffusion equation  $D\nabla^2 N = 0$  is solved with the proper boundaries on the mask,  $\partial N/\partial z = 0$ , and on the crystal,  $D\partial N/\partial z = k_s N$ . The former boundary condition on the flux implies a perfect selectivity that is no deposition on the mask. The second one is a mixed condition which states the equilibrium between the reaction on the wafer and the incident flow. It also introduces the main driving parameter of the model namely the  $(D/k_s)$  parameter.  $D$  ( $\text{m}^2 \text{s}^{-1}$ ) is the diffusion coefficient of the reactants in the vapor phase and  $k_s$  ( $\text{m s}^{-1}$ ) a sticking rate constant which depends on the reactivity of source molecules on the crystal surface. Therefore,  $(D/k_s)$  expresses an effective diffusion length and is commonly expressed in  $\mu\text{m}$ . As an example, Fig. 1 shows different concentration profiles along a cross section of the mask ( $x$  axis, see inset on Fig. 1) extracted from VPD calculations with various  $D/k_s$  values. These calculations were realized for  $W_m = 40 \mu\text{m}$  and  $W_o = 20 \mu\text{m}$ . The profiles were normalized to the far field reference to get the growth rate enhancement ( $R$ ). As seen in Fig. 1, short (long)  $D/k_s$  give rise to sharp (extended) profiles. The operating conditions ( $p$  and  $T$ ) will have an influence on both  $D$  and  $k_s$ . The  $D$  coefficient can be evaluated from kinetic theory and one can easily show that  $D \propto (k_B T)^{3/2}/p\sigma^2$  with  $k_B$  the Boltzmann constant,  $T$  the temperature,  $p$  the pressure and  $\sigma$  the collision diameter of the diffusing molecule. The  $k_s$  rate constant is a

median macroscopic constant which involves many different chemical reactions and cannot be easily expressed. This constant will mainly depend on the growth temperature.

Clearly, in the SAG regime, a first step to improve the flatness and decrease the sharpness of the thickness profiles is to obtain a large  $D/k_s$  for a given diffusing precursor. We now compare two different thick InP layers in two different growth conditions (GC). In GC<sub>1</sub> (GC<sub>2</sub>) the growth temperature was set to 650 °C (590 °C) and the reactor pressure to  $p = 150$  mbar ( $p = 50$  mbar). For both conditions, good morphology and high selectivity on the mask were observed. Fig. 2 sketches measured thickness profiles along  $x$  direction with OIM setup for the two different growth conditions: GC<sub>1</sub> (a) and GC<sub>2</sub> (b). The VPD model was used to fit the experimental profiles and to deduce the characteristic diffusion lengths  $D/k_s$  of each GC. The extracted values,  $(D/k_s)_1 = 10 \mu\text{m}$  and  $(D/k_s)_2 = 90 \mu\text{m}$ , clearly show the strong influence of the reactor pressure and temperature. The reduced pressure and temperature in GC<sub>2</sub> increase  $D/k_s$  and as a consequence improve the flatness of the concentration around the mask. This explains the strong decrease of the thickness profiles sharpness in the vicinity of the dielectric, as seen on (b) profiles. The reduced pressure is consistent with an increase of the mean-free path of the molecules which lead to a faster diffusion process (higher  $D$ ). The main effect of the reduced temperature is the decrease of molecules reactivity (smaller  $k_s$ ) on the crystal surface. Note that



**Fig. 2.** InP growth rate enhancement fitting (dots) with VPD model (dashed lines) for two growth conditions: (a) GC<sub>1</sub> and (b) GC<sub>2</sub>; in both cases, the fit is repeated for three mask widths  $W_m = 40/80/120 \mu\text{m}$ ; the opening  $W_o$  is kept constant,  $W_o = 40 \mu\text{m}$ .

the temperature decrease will also naturally affect  $D$  and at least reduce it. However, comparing the ranges  $p = 150\text{--}50\text{ mbar}$  and  $T = 650\text{--}590^\circ\text{C}$ , one easily convinces himself that the reduced temperature will have a negligible effect on  $D$  compared with the reduced pressure. Kinetic theory gives the relation between  $D_1$  and  $D_2$  and as a consequence the relation between  $k_{s1}$  and  $k_{s2}$ . Assuming that for both growth conditions, the same growth precursors diffuse in the vapor phase we have

$$\frac{D_1}{D_2} \approx \left(\frac{T_1}{T_2}\right)^{3/2} \left(\frac{p_2}{p_1}\right) = 0.4 \quad (1)$$

then

$$\frac{k_{s1}}{k_{s2}} \approx 3.3 \quad (2)$$

As seen with Eqs. (1) and (2), the pressure and temperature adjustments have a strong effect on both coefficients  $D$  and  $k_s$ . From GC<sub>1</sub> to GC<sub>2</sub>,  $D$  is increased by 50% while  $k_s$  is decreased by about 70%. Oh et al. found similar results in a study concerning  $(D/k_s)$  dependence on growth temperature and pressure for GaAs in SAG [10]. It should be noted that the ratio found from Eq. (2) cannot be used to calculate an activation energy for the TMIn precursor since the partial pressure was not the same in GC<sub>1</sub> and GC<sub>2</sub> ( $p_{\text{TMIn}(1)} \approx 3p_{\text{TMIn}(2)}$ ). VPD and kinetic theory show the advantages of low pressure/temperature in the case of InP growth.

At the dielectric's edges, the situation is much more complicated. The adjustment of the growth temperature and the reactor pressure was not effective to suppress the huge overgrowths. Note that these overgrowths were not observable with OIM setup (Fig. 2) because of the small lateral resolution of this technique ( $\approx 1.5\ \mu\text{m}$  for  $\times 20$  magnification) and therefore were measured with the surface profiler. The edge overgrowths were found to depend strongly on the growth rate. In Fig. 3, we present measurements of the overgrowths along the  $[01\bar{1}]$  crystallographic direction ( $x$ -axis) for two different field growth rates  $v_1 = 0.4\ \text{nm/s}$  (a) and  $v_4 = 0.1\ \text{nm/s}$  (b). The growth temperature and reactor pressure were the same as in GC<sub>2</sub>. In both cases (a) and (b), the measurement was repeated for several  $Wm$  configurations while the opening width  $W_0$  was kept equal to  $40\ \mu\text{m}$ . The high growth rate  $v_1$  (a) leads to huge overgrowths especially for large  $Wm$  while in the case of  $v_2$  (b), planar profiles were observed. Another convenient way to observe these results is to plot the overgrowth dependence with  $Wm$  (Fig. 4) for different growth rates:  $v_1 = 0.4\ \text{nm s}^{-1}$ ,  $v_2 = 0.3\ \text{nm s}^{-1}$ ,  $v_3 = 0.2\ \text{nm s}^{-1}$  and  $v_4 = 0.1\ \text{nm s}^{-1}$ . In Fig. 4, the edge overgrowth thickness ( $h_e$ ) is normalized to the center thickness measured between the two dielectric stripes ( $h_c$ ) at  $x = y = 0$  leading to  $OG = (h_e/h_c) - 1$ , as detailed in the Fig. 4 inset. The  $Wm$  comparison is interesting since the growth rate enhancement in the vicinity of the masked area is known to have a linear dependence with  $Wm$  (see Ref. [6]). As a consequence, in the VPD model the ratio  $h_e/h_c$  should theoretically be a constant. The increase of  $OG$  with both  $v$  and  $Wm$  shows the development of the overgrowth. As an example, with  $Wm = 230\ \mu\text{m}$  and  $v_4$ , the overgrowth is  $\approx 150\%$  of the total thickness measured between the two dielectric stripes. This corresponds to an overgrowth of up to  $2\ \mu\text{m}$  at the edges of the dielectric (see Fig. 3). Fig. 4 clearly shows that only the lower growth rate  $v_4$  avoids the edge overgrowth development over the whole  $Wm$  range. Similar results were observed in the  $[110]$  crystallographic direction from  $Wm = 20$  to  $100\ \mu\text{m}$ . The dependence of  $OG$  with the growth rate was slightly different but the lower growth  $v_4 = 0.1\ \text{nm s}^{-1}$  also gives rise to planarized profiles. For larger  $Wm$ , we observed that  $OG$  begins to increase with  $Wm$ . For the moment, we do not have a clear explanation of this phenomena. Due to its simplicity, VPD model cannot precisely fit the thickness in the vicinity of the mask [6] and explain the edge

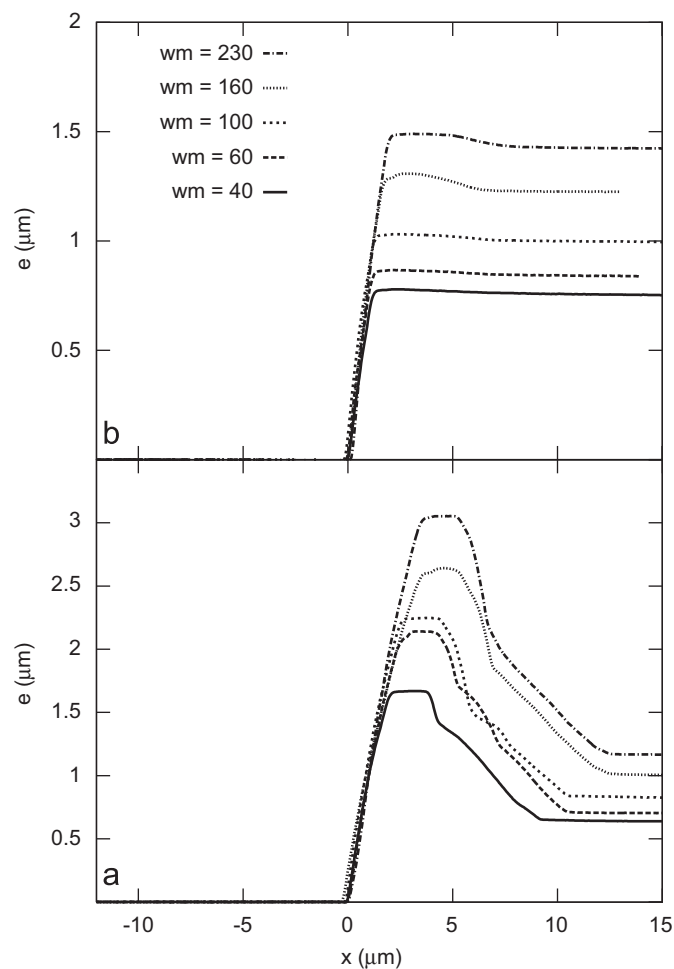


Fig. 3. Surface profiling along  $x$  direction at the edges of the mask for two different growth rates: (a)  $v = 0.4\ \text{nm/s}$  and (b)  $v = 0.1\ \text{nm/s}$ . For each growth rate, different mask widths are depicted:  $Wm = 40/60/100/160/230\ \mu\text{m}$ . The opening between masked stripes is  $W_0 = 40\ \mu\text{m}$ .

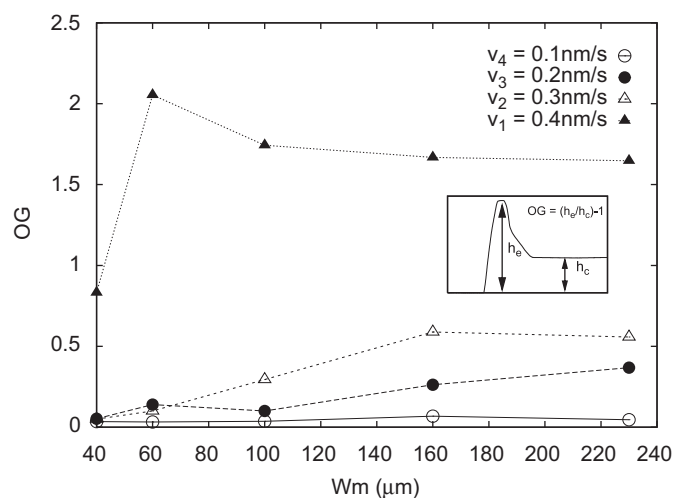
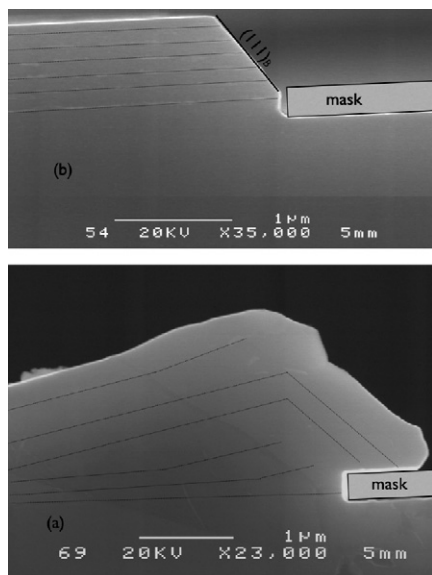


Fig. 4. Normalized edges overgrowth (OG) measured with the surface profiler against the mask width  $Wm$  for different growth rates. The opening between masked stripes is  $W_0 = 40\ \mu\text{m}$ .

overgrowths. To accurately fit these edges the model should include non-stationary boundaries, surface diffusion on both crystal and masked areas [1]. Cross sections of mask edges were



**Fig. 5.** SEM cross sections of mask edges for two different growth rates: (a)  $v = 0.4$  nm/s and (b)  $v = 0.1$  nm/s. Thin lines are superposed with the InAsP markers to guide the eyes. The SAG mask ( $W_m = 160$   $\mu$ m and  $W_o = 40$   $\mu$ m) is also depicted.

also observed with SEM. In Fig. 5 are shown the samples corresponding to  $GC_2$  with  $v_1$  (a) and  $v_4$  (b). The SAG mask geometry was in this case set to  $W_m = 160$   $\mu$ m and  $W_o = 40$   $\mu$ m. To guide the eyes, thin lines follow the InAsP markers and show the surface shape evolution. In the (a) cross section, the growth is very perturbed and complex anisotropy and crystallographic facets are revealed.

One can notice at least two different typical points. First is the huge overgrowth in the vicinity of the mask. This overgrowth agrees with the surface profiler edge measurements discussed above (see Fig. 3(a) for  $W_m = 160$   $\mu$ m). The second point concerns the lateral growth which appears over the mask and can be very problematic in the case of device fabrication. For example, a technology step with photoresist and dielectric deposition

followed by classical lithography and RIE will be difficult to handle. Indeed the dielectric material will be localized above the lateral overgrowth which makes it difficult to remove. In the case of (b) cross section no overgrowths and no lateral growth are observed. The profile is planar and one can observe the development of the  $(111)_B$  typical facet at the edge of the mask.

#### 4. Conclusion

We investigated different selective growth conditions to obtain planar thick InP layers. In order to improve the flatness and reduce the sharpness of the thickness profiles we tuned the temperature and pressure ranges to have a larger  $D/k_s$  parameter. This approach relied on a simple VPD approach and kinetic theory arguments. Thick selectively grown InP layers also showed some typical huge overgrowths at the edges of the dielectric. We studied the evolution of this overgrowth with the SAG mask width and showed that a reduced growth speed almost suppressed it. This work proposed a valuable step to obtain planar thick InP layers and can reasonably offer a key to simplify the devices technological post-processing.

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