Mask pattern interference in AlGaInAs selective area metal-organic vapor-phase epitaxy: Experimental and modeling analysis

N. Dupuis,¹,α J. Décobert,¹ P.-Y. Lagrée,² N. Lagay,¹ F. Pointg,¹ C. Kazmierski,¹ A. Ramdane,³ and A. Ougazzaden⁴
¹Alcatel Thales III-V Lab., Route de Nozay, F-91461 Marcoussis, France
²CNRS, UPMC Univ Paris 06, IJLRA, F-75005, Paris, France
³CNRS LPN, Route de Nozay, 91460 Marcoussis, France
⁴Georgia Tech - CNRS , 2 rue Marconi, 57070, Metz, France

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We studied selective area growth modeling and characterization of the AlGaInAs material system. We used a three-dimensional vapor phase diffusion model to extract the effective diffusion lengths of Al, Ga, and In species from measured thickness profiles of the three binaries AlAs, GaAs, and InP. Our growth conditions yield to 50, 85, and 10 μm for Al, Ga, and In, respectively. Based on these values, we achieved a precise prediction of AlGaInAs thickness, composition, band gap, and biaxial strain variations in different selective area growth conditions. Particular attention was paid to the influence of neighboring cells in the case of high mask density. This configuration occurs in practical component mask layout. High mask density leads to interferences between masked cells and enhances the effect of the long diffusion length of aluminum and gallium species. Then, the biaxial strain is tensile shifted and the band gap is blue shifted in the vicinity of a mask, compared to reference material features grown away from the mask. High-resolution micro-photoluminescence and optical interferometer microscopy measurements confirmed the validity of simulated band gap and thickness variations for both bulk and multi-quantum well layers.


I. INTRODUCTION

Selective area growth (SAG) attracts considerable interest as a powerful tool for monolithic integration of active and passive photonic functions, opening the way to the achievement of reduced cost InP-based photonic integrated circuits. With this technology, different band gap materials can be defined simultaneously in a single epitaxial growth, thereby leading to well-controlled simplified processing in comparison with etch-regrowth-based methods such as the butt-joint technique.¹ SAG is based on metallorganic vapor phase epitaxy (MOVPE) on dielectric patterned substrates. Provided the active precursors do not nucleate on dielectric amorphous surfaces, they diffuse and induce a growth rate enhancement in the vicinity of the masked zone. In the case of ternary or quaternary alloys, the mask induces a spatial compositional shift due to the different decomposition and diffusion rates of group III element precursors in the vapor phase. This shift produces a band-gap variation around the mask, especially in the case of multi-quantum well (MQW) structures where the electronic transitions also depend on the well’s thickness. An appropriate design of the mask pattern then allows integration of different band-gap areas on the same wafer. For example, an integration of an active and passive waveguides such as a spot size converter with both thickness and refractive index tapering² is possible, allowing expansion of the optical mode and hence, reduction of the component to optical fiber coupling losses. The SAG technique has been used by many research groups in different integration schemes.

Examples of such integrations are distributed feedback laser/ electroabsorption modulator (EAM),³ integrated tunable distributed Bragg reflector laser/EAM,⁴ semiconductor optical amplifier/EAM,⁵ ⁶ or more complex devices such as selectable wavelength light sources for dense wavelength division multiplexing.⁷

In order to realize and control complex monolithic integrations with SAG band-gap engineering, we report here on the development of a predictive modeling tool. This work was carried out in two steps. First, we built a two-dimensional model which calculates material thickness across infinite dielectric stripes. This model has been used to determine the effective diffusion lengths of different species corresponding to specific growth conditions. This was achieved by fitting experimental thickness values for simple binary materials. Second, the knowledge of effective diffusion lengths was used to develop a three-dimensional model suitable for the simulation of SAG growth (thickness, composition, wavelength, strain) around an arbitrary mask shape. In practical component fabrication masks a periodic layout is often adopted where each mask pattern is surrounded by identical neighbors that may influence SAG. These proximity effects, also called interference effects,⁵ have to be taken into account in the component design and have thus been included in our model. Our primary interest was focused on the AlGaInAs material system which has a growing industrial importance for the new generation of low-cost telecommunications components. This is due to a large conduction/valence band discontinuity split (∆Ec/∆Eg = 0.7), resulting in a high electron confinement which leads to improved gain, absorption, and dynamic and thermal characteristics of components.

αElectronic mail: nicolas.dupuis@3-5lab.fr.
However, compared with the standard GaInAsP material system which has been widely investigated by SAG,8–14 only few reports deal with the AlGaInAs alloys.15–18

Here, binaries, ternaries, and quaternaries of the AlGaInAs material system were selectively grown and their characteristics systematically compared. Details on the growth conditions and characterization results are developed in Sec. II. Section III introduces the governing equations and boundaries of the vapor phase diffusion model and then explains the periodicity of the computed SAG cell. In Sec. IV we present the effective diffusion length extraction of Al, Ga, and In species in our growth conditions. Section V is devoted to the predictive modeling of ternary and quaternary AlGaInAs alloys. This includes the calculation of thickness enhancement and compositional variations. The influence from nearest neighbors in a periodic SAG cell is also investigated with a specifically designed mask layout. In the last section, an actual integration case is reported with an AlGaInAs MQW structure selectively grown on a periodic mask with a high cell density.

II. EXPERIMENTAL

All investigated samples were grown in a horizontal AIX200/4 MOVPE reactor, designed for three 2 in. wafers, using trimethylaluminum (TMAI), trimethylgallium (TMGa), trimethylindium (TMIn), arsine (AsH3), and phosphine (PH3) as growth precursors.19 Bulk layers including InP, InAs, GaAs, AlAs binary, AlInAs, GaInAs, GaAlAs ternary, AlGaInAs quaternary alloys, and AlGaInAs MQW structures were selectively grown in lattice-matched conditions on various InP, InAs, and GaAs (001) appropriately patterned substrates. The SiO2 mask stripes were processed using conventional photolithography and reactive ion etching. The mask pattern consists of two parallel dielectric stripes aligned along the [110] crystallographic direction. The cell geometry (Fig. 1) is defined by the stripe length (L), the stripe width (Wm), and the opening width (Wo) between two stripes. Wx and Wy define the free area size around the two stripes that are reproduced periodically from cell to cell. Three masks were used in this study. All the dimensions will be quantified later in the paper.

(i) The first mask, named A, is used for the parametrical study. L, Wx, and Wy are kept constant and are large compared with Wo and Wm, which vary monotonously. Therefore, the different patterns are sufficiently separated to avoid any influence on each other.

(ii) The second mask, named B, is for the periodicity study. Wm, Wo, and L are kept constant. Wx and Wy are changed to evaluate the interference between the nearest-neighbor patterns.

(iii) The third mask, named C, is used for our optoelectronic device integration. The density of integration is high and the stripes are very long compared to Wm and Wo.

The growth conditions for all samples are: temperature of 650 °C, pressure of 150 mbar, and nominal growth speed of 0.1 nm/s for binaries and 0.2 nm/s for ternaries and quaternaries. These conditions were optimized for AlGaInAs material growth on InP and have previously been reported.20 In this study, they were kept constant for all alloys in order to fix the vapor phase diffusion lengths of species and therefore allow direct comparison and extrapolation between samples. The SiO2 dielectric mask led to a perfect selectivity (i.e., no polycrystalline deposition on the mask) for all mask widths and for all samples, including the more aluminum-rich ones (e.g., AlAs). For each sample, thickness enhancement and overgrowth near the mask were characterized by optical interferometer microscopy (OIM) with a high vertical resolution (±5 nm). For ternary, quaternary alloys and MQW structures, the emission spectra were measured by microphotoluminescence (µ-PL) at room temperature with a 680 nm laser diode providing a spot size of 2–3 μm. In the field region (i.e., far away from the masked areas) high resolution x-ray diffraction (HRXRD) measurements were used to obtain the amount of lattice mismatch for ternary and quaternary alloys as well as for the MQW stack.

III. VAPOR-PHASE DIFFUSION MODEL

AlGaInAs alloys have three group III elements (Al, Ga, and In) for only one group V element (As). The organometallic precursors for these elements provide different vapor and surface decomposition rates and different diffusion coefficients in the vapor phase. In conventional epitaxy, these differences are not important as any desired AlGaInAs composition can be achieved by an adjustment of the precursor flow. In SAG, as the precursors cannot react on the mask, extra material is available over the masked zone and a lateral concentration gradient builds-up. This gradient leads to extra lateral diffusion of species around the mask and to a local enhancement of the growth rate. Thus, in the SAG regime, diffusion rates and surface reaction rates of Al, Ga, and In precursors become measurable. This is especially true with ternary and quaternary alloys where spatial compositional variation occurs around the mask.

A simple approach to model the selective growth regime is to consider only vapor phase diffusion (VPD) as the source of material supply.12,13 This assumes a laminar flow, the existence of a stagnant layer in contact with the wafer surface, and the absence of deposition on mask surface. The molecules diffuse and are incorporated onto the exposed crystal surface. Surface diffusion on the mask is ignored in the present model since it occurs within only a few micrometers.
of the dielectric edge. The Laplace equation of the concentration $\nabla^2 N = 0$ is solved in three dimensions with specific boundary conditions (see Fig. 2). On the mask, as no species are incorporated, the flux is equal to 0, hence $(\partial N / \partial z)_{z=0} = 0$. On the crystal, the Langmuir isotherm-like condition $D (\partial N / \partial z)_{z=0} = k_x N$ is assumed with $D$ being the diffusion coefficient of the reactants in the vapor phase and $k_x$ a sticking rate constant which depends on the reactivity of source molecules on the crystal surface. At the top of the stagnant layer $(H)$, the concentration is assumed constant $N(H) = N_0$ (i.e., infinite diffusion source). Finally, the periodicity of the domain leads to $(\partial N / \partial z)_{z=0} = 0$ for left and right boundaries. These boundary conditions are depicted in Fig. 2. Note that without any mask, the solution is linear in $z$ and we readily obtain

$$N(z) = N_0 \frac{k_x H}{D} + 1.$$

To solve the full problem, we investigated several numerical approaches: finite differences, finite elements, and fast Fourier transform (FFT). In each case, the numerical results were identical. In practice, results presented in the following were obtained using the FFT method. To implement this last method we worked on

$$n(x, y) = \int \int \hat{n}(k_x, k_y) e^{i(k_x x + k_y y)} dk_x dk_y,$$

which represents the perturbation from the equilibrium concentration Eq. (1) induced by the mask where $k_x$ and $k_y$ are the Fourier modes. The effective concentration on the crystal surface is then

$$N_{\text{eff}}(x, y) = N(0) + n(x, y).$$

The latter concentration profile strongly depends on the geometrical dimensions $W_m$ and $W_o$. The dimensions of the calculation window $(W_x$ and $W_y)$ define the periodicity of the domain which is natural in the FFT method: in the calculation the cell in Fig. 1 is assumed to be surrounded by identical cells with the same dimensions $W_x$ and $W_y$. These close cells actually play an important role as they will interfere with each other. This periodicity is fundamental to model the SAG process, especially for device integration, where a large number of closely spaced components is usually desired. Inherent to the FFT method is the problem of the Fourier modes $k_x=0$ and $k_y=0$, which are solved by applying the Green–Ostrogradsky formula on the calculation domain.

In the following discussion, we will consider the normalized concentration $R$ also named growth rate enhancement,

$$R(x, y) = \frac{N_{\text{eff}}(x, y)}{N(0)}.$$

The main advantage of the VPD approach is to give a simple way to determine the effective diffusion length $(D / k_x)$ parameter which is, apart from the geometrical dimensions of the mask, the only adjustable parameter of the model.

IV. BINARY COMPOUNDS: AL, Ga, AND IN $(D / k_x)$ EXTRACTION

In the case of AlGaInAs alloys, three effective diffusion lengths are considered: $(D / k_x)_{Al}$, $(D / k_x)_{Ga}$, and $(D / k_x)_{In}$. The approach proposed here to determine these parameters is a fitting between OIM thickness measurements of the binary alloys (AlAs, GaAs, and InAs) and VPD calculations on mask A. A precise adjustment between the calculated and experimental thickness profiles leads to the $(D / k_x)$ parameter for each binary. In the case of $(D / k_x)_{In}$ extraction, both InAs and InP binaries were considered. We observed that InAs exhibits a slightly higher growth rate enhancement than InP. This small difference was already mentioned by Caneau et al. who studied the effect of group V elements for different binaries (InAs, InP, GaAs, GaP). They explained that the decomposition rate of TMIn (or TMGa) precursor is enhanced in the presence of AsH$_3$ compared to PH$_3$. However, the difference is quite small and the influence on $(D / k_x)_{In}$ is negligible. The fit was actually done with InP because of perturbed morphology in the case of InAs growth. We believe this problem arises from the fixed growth temperature chosen for our study $(T=650 \degree C)$, which is too high for InAs. Figure 3 shows the fit for the three binary compounds along the $x$ direction $(y=0)$ for two mask widths, $W_m=80$ and 120 $\mu$m, and with $W_o=30$ $\mu$m. The experimental thickness was measured using the OIM setup and normalized relatively to the field reference in order to deduce the experimental thickness enhancement (GRE) ratios $R_{AlAs}$, $R_{GaAs}$, and $R_{InP}$. In the following, these ratios are noted $R_A$, $R_G$, and $R_I$ in order to simplify notations. From these results the three extracted diffusion lengths in our growth conditions are $(D / k_x)_{Al}=50$ $\mu$m, $(D / k_x)_{Ga}=85$ $\mu$m, and $(D / k_x)_{In}=10$ $\mu$m. The indium and gallium values are in qualitative agreement with those already reported in the literature. The aluminum one is found intermediate between indium and gallium ones. This value for aluminum is clearly confirmed in Fig. 3. Indeed, in the vicinity of the mask, the slope of the AlAs thickness enhancement profile (a) appears steeper than the GaAs one (b). The extracted $(D / k_x)$ parameters control the thickness enhancement profile in the vicinity of a selective mask for the three binaries. They also appear as key parameters in predictive modeling of thickness and compositional changes.
variations for ternary and quaternary alloys. In the next section, we show that this modeling can be based on simple linear relations between binaries results.

V. TERNARY AND QUATERNARY ALLOYS

Selective growth modeling of ternary and quaternary alloys is more complex since two or three group III elements are mixed in the vapor phase. The simplest model is to assume no interaction between III elements and a linear dependence of the alloy GRE ratio (denoted $R_a$) with the binary GRE ($R_{Al}$, $R_{Ga}$, and $R_{In}$). For quaternary alloys, the notation $Al_{\alpha}Ga_{\beta}In_{1-\alpha-\beta}As$ is adopted in the text. The group III element compositional ratios ($\alpha$, $\beta$, and $1-\alpha-\beta$) depend on the position ($x, y$) in the cell. For ternary alloys, one of these ratios is simply equal to zero. In the field region the quaternary reference composition is written: $Al_{\alpha}Ga_{\beta}In_{1-\alpha-\beta}As$. This reference composition can be fully characterized with HRXRD and photoluminescence (PL) on an unmasked reference sample. For a ternary or quaternary alloy with ($\alpha$, $\beta$), reference composition, the growth rate enhancement $R_a(x, y)$ can be written as

$$R_a(x, y) = \alpha R_{Al}(x, y) + \beta R_{Ga}(x, y) + (1 - \alpha - \beta) R_{In}(x, y),$$

and the compositional ratio $C_e(x, y)$ of the e element (e = Al, Ga, In when $i = \alpha$, $\beta$, $1 - \alpha - \beta$, respectively) is

$$C_e(x, y) = \frac{i R_e(x, y)}{R_a(x, y)},$$

where $R_e$ denotes the GRE for element $e$. In order to obtain AlGaInAs $R_a(x, y)$ and $C_e(x, y)$, the FFT numerical calculation is repeated three times with the three diffusion lengths determined in the last section, to obtain $R_{Al}(x, y)$, $R_{Ga}(x, y)$, and $R_{In}(x, y)$ independently. The variations of band gap, biaxial strain, and electronic transitions are deduced from Eqs. (5) and (6).

From a theoretical point of view, these equations lead to some useful comments. First, in the case of a quaternary alloy with three group III elements such as AlGaInAs and when varying $W_m$, if the compositional ratio of one element remains practically unchanged, this implies that the corresponding species has an intermediate diffusion length value to the two other species. This is typically the case for aluminum. The interpretation is quite different in the case of the two group V elements of a quaternary alloy such as GaInAsP for which both As and P species have very large diffusion lengths, and the compositional ratio between As and P is constant. Second, we can also notice that in the AlGaInAs well and barrier heterostructures, the growth rate enhancement $R_{well}$ and $R_{barrier}$ can be very different since $\alpha$, $\beta$, and $1 - \alpha - \beta$ are different for well and barrier compositions.

A. Thickness enhancement

Thickness enhancement of ternary and quaternary alloys is successfully predicted with the simple linear approach described by Eq. (5). This equation uses the ($D/k_e$) value previously extracted from the binary alloys without any adjustment. Figure 4 shows an example for AlGaInAs quaternary (a) and AlInAs (b), GaAlAs (c) ternary alloys. The calculated GRE remarkably fit the OIM measured profiles (mask A). The reference compositions ($\alpha$, $\beta$) were deduced from...
HRXRD characterization for ternaries and from a combination of PL and HRXRD for the quaternary. As seen from these results, the simple approach of the linear model of the growth rate enhancement, as suggested by Eq. (5), appears quite appropriate. A comparison between $R_c(x, y)$ of GaAlAs from Fig. 4(c), and $R_{Al}(x, y)$ and $R_{Ga}(x, y)$ from Figs. 3(a) and 3(b) clearly shows that for the same mask pattern, the sharpness of the GaAlAs profile is intermediate between those of GaAs and AlAs. This gives weight to the arguments discussed in the previous section concerning the value of $(D/k_A)_{Al}$.

**B. Compositional variations and mask pattern interference**

The compositional ratios ($\alpha=$Al, $\beta=$Ga, and $1-\alpha-\beta=$In) display very different values depending on the mask geometry ($W_m$, $W_o$, and $L$), the position ($x, y$) in the cell, and the dimensions of the cell ($W_x$ and $W_y$). As expected, the indium species, which has the shortest effective diffusion length, highly enriches in the near vicinity of the mask. On the other hand, the other elements, aluminum and gallium, have an influence which extends further from the mask edge. Alam et al.\textsuperscript{13} described a similar analysis in the GaInAsP material system. They compared the long-range effect of the gallium element compared to the indium shorter range. In the AlGaInAs material family, this longer range effect applies to both aluminum and gallium species. This effect is, however, quite subtle to observe since the longer diffusion length of Al and Ga tends to homogenize their concentration distribution on a larger surface. Hence, their contribution to the alloy GRE ($R_a$) is generally lower than that of the indium precursor. With mask A, where $W_x$ and $W_y$ are large, this contribution is not observable since at the distance at which it occurs, the nominal growth rate is almost recovered (i.e., $R_a=1$). However, with mask B and smaller $W_x$ and $W_y$, the cells are influencing each other and the contributions of aluminum and gallium become detectable. This case is depicted in Fig. 5 through cross sections along the $y$ direction (at $x=0$) for an AlGaInAs quaternary alloy with the following reference composition, $\alpha_i=0.172$ and $\beta_i=0.313$. In this figure, we present the simulated variations of binaries GRE ($R_{Al}, R_{Ga}$, and $R_{In}$), the compositional ratios [$\alpha$, $\beta$, and $1-\alpha-\beta$ calculated with Eq. (6)], the biaxial strain $-\varepsilon_{xx}$, and the emission wavelength corrected for the strain for heavy/light hole bands ($\lambda_{hh}/\lambda_{lh}$). The mask geometry is $W_m=140\ \mu$m, $W_o=40\ \mu$m, and $L=300\ \mu$m. Only a half mask is represented since the profile is symmetric. A bold trace on the (a) and (b) upper graphs shows the SiO$_2$ mask ($y, z$) cross section.

In the following, we compare the compositional enrichment variations with respect to different mask configurations. To help with this comparison, we arbitrarily define three zones denoted I, II, and III which correspond to indium, aluminum, and gallium highest GRE, respectively. In zone I,
R_{In} > R_{Al}, R_{Ga}, in zone II, R_{Al} > R_{Ga}, R_{In}, and in zone III, 
R_{Ga} > R_{In}, R_{Al}. These three zones are separated in Fig. 5 by 
means of vertical dashed lines. Two calculated configurations are 
compared:

(i) In the first situation (a), Wx and Wy are large (Wx = Wy = 1000 μm) and zone I extends over a large interval (y ∈ [-170; 0]). In this zone, as seen on (a) middle graph left axis, an indium enrichment compared with the reference composition (see arrows on composition axis) is observed contrary to gallium and aluminum elements and, consequently, the biaxial strain −ε_{xx} (see middle graph right axis) shifts to compression. Therefore, the emission wavelength [upper (a) graph] is red shifted compared to the reference one (see arrow on wavelength axis). In zones II (y ∈ [-220; 
-170]) and III (y ∈ [-300; -220]), which are aluminum and 
gallium predominance areas, respectively, the nominal growth rate is almost recovered (R_{In} = R_{Al} = R_{Ga} = R_a ≈ 1.1) 
and the small extra aluminum and gallium incorporation does not significantly affect the wavelength (λ ≈ λ_c).

(ii) In the second situation (b), Wx and Wy are smaller (Wx = Wy = 400 μm) and the influence between cells now 
plays a major role. In this case, the concentration profiles 
R_{Al}, R_{Ga}, and R_{In} are enhanced compared with the previous 
configuration; in addition, the indium predominance (zone I) 
is occurring over a smaller part. Zone I is extending to 
y ∈ [-120; 0] and, similar to the first configuration (a), the 
indium species concentration is enriched in this zone. Due to 
neighbor cell’s influence, in the aluminum and gallium 
predominance zones (II and III), the nominal GRE is not 
recovered and a non-negligible aluminum and gallium enrichment 
is observed. Consequently, the biaxial strain is tensile shifted 
on the whole profile compared with situation (a). Moreover, 
in zones II (y ∈ [-145; -120]) and III (y ∈ [-200; -145]), a 
wavelength blue shift is observed: λ < λ_c.

In order to confirm these proximity effects, a specific 
SAG mask was designed and fabricated. A part of this mask 
is shown in Fig. 6. The purpose of this design was to have, 
on the same sample, an identical mask pattern (W_m 
= 140 μm, W_0 = 40 μm, and L = 300 μm) in different 
neighborhood situations (different Wx and Wy values). We 
take into account the patterns respecting the periodicity 
criterion defined in the model (filled patterns in Fig. 6). These 
patterns have identical neighbors at the same Wx, Wy distance. 
We assume that only the nearest neighbors have a 
significant influence and that the other ones are far enough 
to neglect their effects. In Fig. 7, measured and calculated 

FIG. 6. Part of the mask B used for the periodicity measurements. On the 
figure, the cells respecting the periodicity criterion are filled. The character-
ized ones are surrounded by a dashed line.

FIG. 7. AlGaInAs quaternary (α = 0.172 and β = 0.313) measured (μ-PL) 
and calculated emission wavelength against Wx=Wy for different points: 
O(0,0), M(0,—Wy/2), N(Wx/2,0). The reference wavelength is indicated 
by an arrow and is λ_c = 1230 nm. Mask dimensions (mask B) are set 
to: W_m=140 μm, W_0=40 μm, and L=300 μm.

VI. INTEGRATION OF MULTI-QUANTUM WELL STRUCTURES

MQW structures are nowadays widely used in optoelec-
tronic devices. Lower threshold current for lasers, improved 
absorption properties based on the Stark quantum confined 
effect for electroabsorption modulators, or larger spectral 
bandwidths for semiconductor optical amplifiers (SOA) are 
few examples of the properties expected with these struc-
tures. Selectively grown MQW layer modeling is then a use-
ful tool for the engineering of optoelectronic devices. The 
electronic states of the heterostructure are calculated within 
the envelope function framework developed by Bastard and 
adapted for strained layers. This scheme is well suited 
as it includes the coupling between wells and the induced
tunneling effect across the barriers. This effect cannot be
neglected when the barrier becomes very thin (~5 nm),
which is generally the case in the outer region of the mask.
The GRE and compositional variations for the wells and bar-
riers are calculated with Eqs. (5) and (6) and reinjected in the
envelope function model, which leads to the variations of
the electronic transitions in the SAG window. In selectively
grown MQW structures two effects have a direct influence
on the emission wavelength. The first one is the composi-
tion variation which changes both wells and barrier material band
gaps. The second one is the thickness variation which
changes the quantum confinement energy.

We discuss here an example of an AlGaInAs MQW
structure with 10 compressive wells and 11 tensile barriers
calculated and measured along the y direction (x=0) on
mask C. Geometrical parameters of the mask are set in this
element to Wm=50 μm, Wo=40 μm, and L=1230 μm.
The cells density is high since x=250 μm and Wy
=1420 μm, which represents an actual integration scheme
configuration. On a reference unmasked sample, we deduced
from HRXRD the period of the MQW (10 nm) and from
combined HRXRD and PL (λc=1365 nm) characterizations,
the respective compositions of the barriers/wells:
Al0.32Ga0.59In0.12As/Al0.87Ga0.13In0.68As. It should be noted that
in this high-cell-density scheme, this reference material
was not recovered on the wafer and was measured on another
unmasked sample. Figure 8, from bottom to top, shows (a)
the calculated and measured GRE of the MQW, (b) the cal-
culated bulk heavy hole band gap for the well (Eg1-W)
and barrier (Eg1-B), and (c) the emission wavelength (calcu-
lated and measured) arising from the fundamental transition E1
−HH1. Similarly to the previous section, three zones I, II,
and III are defined in the figure by means of vertical dashed
lines, corresponding respectively to In, Al, and Ga enrich-
ment zones. Zone II extension is very small with this mask
design (y∈[−610;−604.5]) and is not shown for clarity. In
the close vicinity of the mask (zone I), the growth rate is
enhanced and both wells and barriers are enriched in indium.
However, in this mask scheme, this indium enrichment is
rather small. Consequently, the material band gaps of well
and barrier [see Fig. 8(b)] are nearly the same as in the field
region [see arrows for Eg1-Wr and Eg1-Br in Fig. 8(b)]. In
this design, Wo and Wm were selected to obtain similar GRE
of indium, aluminum, and gallium species in this zone (Rin
=RAi=RGa ≠ 1). One can easily check with Eq. (6) that
when y∈ zone I, C1(0, y)=1. Therefore in this zone, we can
infer that the emission wavelength variation compared to λc,
is not due to compositional changes. The wavelength red
shift [see Fig. 8(a)] is only due to the thickness effect (R>1),
which decreases the quantum confinement energy. In
zones II and III, due to the high cell density, two combined
effects are in competition. First, a non-negligible Al and Ga
enrichment occurs. This composition effect increases the
band gap of both wells and barriers [see Fig. 8(b)] and hence,
blue shifts the emission wavelength. In addition, the refer-
tence thickness is not recovered (R>1 [see Fig. 8(a)]. This
thickness effect decreases the quantum confinement energies
and red shifts the emission wavelength. The compositional ef-
fct is, however, in this present case, stronger and finally a

FIG. 8. Calculations and measurements (mask C) along the y axis (x=0) in
the case of an AlGaInAs MQW structure with 10 compressive wells and 11
tensile barriers: (a) measured (OM) and calculated growth rate enhance-
ment (R) of the structure; (b) calculated bulk heavy holes band gap for well
Eg1-W and barrier Eg1-B; (c) measured (μ-PL) and calculated E1−HH1
transition. In this case Wm=50 μm, Wo=40 μm, L=1230 μm, Wr
=250 μm, and Wy=1420 μm. A bold trace sketches the position of the
selective mask.

small blue shift results. For instance, at point M(χ=0, y=−720), λc=1350 nm,
which leads to Δλ=(λc−λc)=−15 nm. The perfect agreement found between experimental measurements
and calculations for both thickness and wavelength variations
validates the model.

VII. CONCLUSION

The AlGaInAs material system was thoroughly investiga-
ted in the selective area growth regime. Aluminum-based
binary, ternary, and quaternary alloys were selectively grown
with different mask geometries. In our growth conditions,
the selectivity was perfect for each alloy of the family. Thickness
profiles of InP and GaAs binaries were fitted with a VPD
model in order to extract the indium and gallium character-
istic diffusion lengths (D/k). The values found, (D/k)Gal
=85 μm and (D/k)In=10 μm, are in qualitative agreement
with previously published values. In the same way, AlAs
binary alloy was measured to extract the aluminum diffusion
length value. We found, in our growth conditions (D/k)Al
=50 μm, an intermediate value between that of indium and
gallium. Computational analysis with a systematic compar-
ison with experiments was conducted to evaluate the growth

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rate enhancement and compositional variations of ternary and quaternary alloys. For these alloys, a simple linear dependence of the growth rate enhancement with the involved binaries was assumed. This perfectly matches our experiments and previous reports in the GaInAsP material system. We also brought new insights on Al and Ga long-range effects in the high-cell-density configurations. These effects were investigated with the model which included periodicity of the SAC cell as a boundary condition. A special mask, designed with varying periodicity of the SAC cell, was also investigated and showed that high-density integration schemes induce important proximity effects that cannot be neglected. For instance, we showed that blue/red shift of the wavelength and tensile/compressive shift of the biaxial strain, as compared to the field region reference, depend on the position (x,y) in the cell and on its periodicity. Highly resolved μ-photoluminescence confirmed the validity of these results. Finally, a MQW structure was selectively grown and analyzed with a specific mask design corresponding to a real integration scheme. In these integrated structures, the high cell density is a requirement and important proximity effects naturally occur between the different stages. We demonstrated that the VPD model is able to predict with a high accuracy the selective area growth effects for any AlGaInAs structure, including complex stacking like MQW layers. This study offers a very attractive tool for complex and precise engineering of SAC optoelectronic integrated devices.