Influence of mask design on the optical transition energy of InGaAs/InAlAs quantum wells grown by selective area epitaxy

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Introduction

The InGaAs/InAlAs multiple quantum well (MQW) system is of paramount importance for the development of amplitude modulators for operation at 1.55 μm for telecommunication applications. The smaller valence band offset of the InGaAs/InAlAs structure, compared to InGaAs/InP, shortens the escape time of holes from the quantum wells making this material suitable for high intensity signal applications. Such structures have already given excellent performance characteristics as far as low operation applied voltage [1-3], large Stark shift [1,2], small chirp parameter [4] and polarization independence [2,3]. The monolithic integration of such a modulator with other devices has an enormous potential to both decrease its insertion losses and increase its operation frequency. Selective area growth is the most promising technique for monolithic optoelectronic integration. This technique consists of growing epitaxial layers on a patterned substrate and it is based on two effects, namely: enhancement of growth rate and modification of alloy composition. InGaAs/InAlAs MQW structures to be used in the fabrication of modulators to operate at 1.55 μm should have a precise lowest optical transition energy. This energy depends on both the growth enhancement and the alloy composition. The possibility of selectively growing InGaAs/InAlAs MQW structures by low-pressure metalorganic vapor phase epitaxy (LP-MOVPE) has already been demonstrated [5]. However, to controllably grow such structures by this technique, a better understanding of the growth enhancement and alloy composition as a function of the growth parameters and mask design is required.

The purpose of this work is to investigate both growth enhancement and alloy composition as a function of growth parameters and mask geometry for InGaAs, InAlAs and InGaAs/InAlAs MQW structures grown by selective area epitaxy on different patterned InP (100) substrates.

Experimental Details

A horizontal low pressure, 100 mbar, MOVPE AIX 200 reactor was used for growing the samples. The total gas flow and temperature were 9800 sccm and 650^{o}C, respectively. The sources for the III elements were TMIn, TMGa and TMAl. AsH_3 was used as source for As with a mole fraction of 7.6 x 10^{-3} in all runs. The InP (100) oriented substrates were processed using specially designed masks with a fixed 20 μm wide window, which guarantees that selective area growth occurs in the gas phase diffusion regime. The width of the masked region varied between 5 and 75 μm and its length was 1mm in the [100] direction. The masks were obtained by depositing 0.2 μm of silicon oxide. An unpatterned substrate was always simultaneously introduced in the reactor to serve as a reference sample.

Several bulk InGaAs and InAlAs layers, as well as InGaAs/InAlAs MQW structures, were grown with input fluxes ratio [TMIn/(TMIn + TMGa(Al))] varying from 0.5 to 0.7. The different MQW structures had 15 or 20 periods, each unit had barriers 50 or 100 Å wide and quantum wells with thickness varying from 60 to 120 Å. The typical growth rate on unmasked substrates was about 1.5 to 2.0 Å/s.

The samples were characterized by spatially resolved photoluminescence (PL), x-ray diffraction and spatial profiler. The stylus spatial profiler was used to determine the growth enhancement in the patterned regions. The 514 nm line of an Ar ion laser was used for excitation in the PL measurements. The laser beam was focused using a microscope objective lens of 25 mm focal length producing a beam diameter on the sample of 3 μm. The emitted signal was dispersed by a 250 mm monochromator and

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detected by a liquid nitrogen cooled Ge photodetector. The conventional lock-in technique was used for detection. Measurements were carried out at 77 and 300 K with excitation power density up to 40 KW/cm^2. X-ray experiments were performed on a commercial double crystal diffractometer.

Results and Discussion

The growth enhancement for both InGaAs, InAlAs and for the InGaAs/InAlAs MQW structures varied linearly for mask widths up to 75 μm for all the investigated samples. The growth enhancement data were obtained with respect to the reference sample. The total thickness of the samples on the unpatterned substrates varied from 0.2 to 0.4 μm. On the patterned substrates, the thickness measurements were always performed in the middle of the 20 μm window. It has been observed that the layer grown within the window was essentially flat starting at 2 microns from the mask borders. The growth enhancement (*GE*) as a function of mask width in microns (*W*) follows the expression given below for all samples. The deviation on the angular coefficient is smaller than 15%.

$$GE = 1 + 0.0150 \cdot W \qquad (1)$$

Figures 1 and 2 show the change in Ga and Al content as a function of mask width for InGaAs and InAlAs samples with different [TMIn / (TMIn + TMGa(Al))] fraction in the gas phase. The experimental points were determined from the PL band edge peak energy, where 77 and 300 K PL spectra were used for InGaAs and InAlAs, respectively. The so determined alloy composition for the reference sample was compared to x-ray diffraction data and they were in fairly good agreement. The dotted lines are exponential decay fits. One observes that the In incorporation in the alloys is enhanced for increasing mask width, as previously reported [5]. Also, signs of saturation of the In content in InAlAs for large masks, for the [TMIn / (TMIn + TMGa(Al))] ratios used, is seen in figure 2. This means that the incorporation of In in InAlAs in the window of the masked regions depends solely on the growth conditions if the masks are made large enough. One does not see such effect for InGaAs (figure 1) most likely because of the smaller activation energy for the decomposition of TMGa as compared to that of TMAl. One should note that the dependence of both growth enhancement and alloy composition on the mask width are evidence of growth limited by vapor phase diffusion effects.

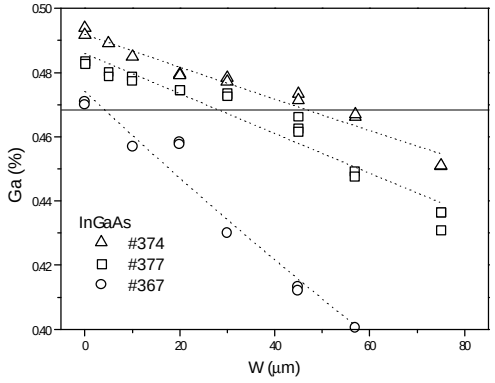

Fig. 1: Ga content of the InGaAs alloy for samples grown with different [TMIn / (TMIn + TMGa)] fraction in the gas phase as a function of mask width (*W*). The dotted lines are exponential decay fits. The horizontal line refers to lattice matched InGaAs grown on InP substrates.

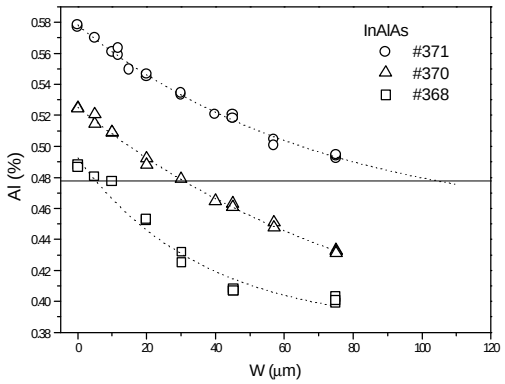

Fig. 2: Al content of the InAlAs alloy for samples grown with different [TMIn / (TMIn + TMAl)] fraction in the gas phase as a function of mask width. The dotted lines are exponential decay fits. The horizontal line refers to lattice matched InAlAs grown on InP substrates.

A substantial decrease of the input [TMIn / (TMIn + TMGa)] fraction in the gas phase was found as a function of the mask width for obtaining InGaAs and InAlAs layers lattice matched to InP, as shown in figure 3, where the solid lines are exponential decay fits which serve as a guide for the eyes. The region above the lines correspond to compressive strained layers (In rich), while the region below the lines

correspond to tensile strained samples (Ga or Al rich). The experimental points in this figure were obtained from figures 1 and 2. One can conclude from these results that as long as the masks are larger than a certain value (around 100 microns for our growth conditions), the alloy composition is not influenced by the mask geometry, as already expected from the data in figure 2. This effect is probably related to the extent of the decomposition of the gas phase of In containing species during lateral diffusion above the mask in the presence of AsH_3 [6]. One also notices that the relative TMIn fluxes for obtaining lattice matched InGaAs are smaller than those for InAlAs. This result is most likely due to the larger temperature of TMAl pyrolis compared to that of TMGa.

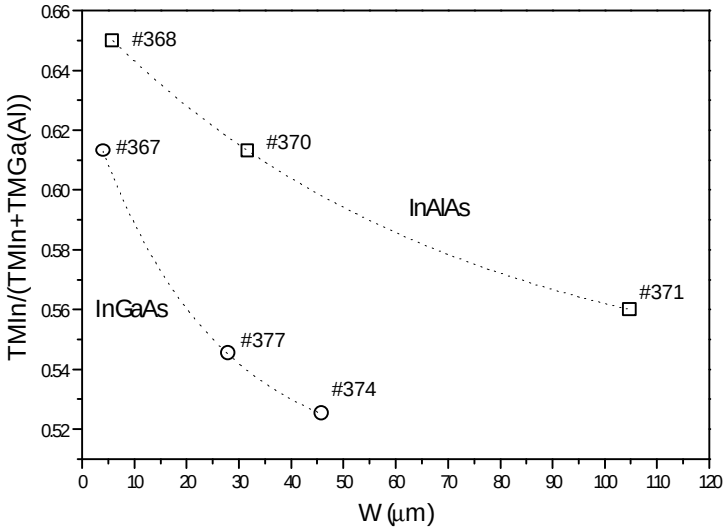

Fig. 3: [TMIn / (TMIn + TMGa(Al))] fraction in the gas phase as a function of mask width (*W*) for lattice matched InGaAs and InAlAs grown on patterned (100) InP substrates. The dotted lines are exponential fits, which serve as a guide for the eyes.

Figure 4 shows how the PL peak energy for several InGaAs/InAlAs MQW structures varies with mask width. The TMGa flow and growth time were modified in this series of samples. One observes that an optical transition energy shift exceeding 200 meV with respect to the sample simultaneously grown on a reference unpatterned InP substrate was achieved for the wider mask and the MQW structure with a 60 Å QW width and 50 Å barrier (sample 384 in figure 4). This result is comparable to the best values reported [5].

The width of the individual layers of the MQW structure in the window of the patterned regions can be evaluated by determining the width of the entire MQW structure with the stylus profiler and by taking into account the fact that the growth enhancement is essentially the same for both InGaAs and InAlAs, as discussed before. Knowing the QW thickness and the lowest optical transition energy, it is possible to calculate the QW alloy composition by solving the Schrödinger equation within the one band effective mass approximation. The strain effects are included in the calculations. The results for two samples with different TMGa flows are plotted in figure 5, where one can see the variation of the Ga content in the QW alloy as a function of mask width. The dotted lines are exponential decay fits. A clear saturation of the In content is observed for mask widths between 40 and 50 μm. Thus, two regimes can be distinguished. For masks with width smaller than 40 μm both growth enhancement and changes in alloy composition influence the optical transition energy, while for masks wider than 50 μm, the alloy composition remains stable and the selectivity is essentially due to the growth enhancement. With appropriate mask design, it should then be possible to have two integrated QW devices with the same alloy composition, lattice matched, for instance, and different optical transition energies. Larger masks should make the selective area growth control and integrated devices' design simpler, since the growth enhancement dominates the selectivity. It should be noted that this effect is much more significant for the

QWs than for the bulk samples, as one notices when comparing figure 5 to figures 1 to 3. This point is yet poorly understood and requires further investigation.

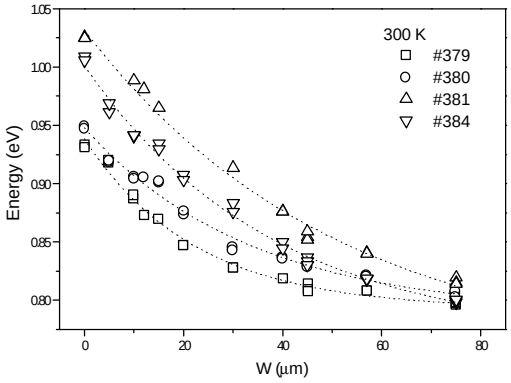

Fig. 4: Lowest optical transition energy for a series of InGaAs/InAlAs MQW structures grown with various [TMIn / (TMIn + TMGa)] fraction in the gas phase and growth times as a function of mask width (*W*). The dotted lines are exponential decay fits.

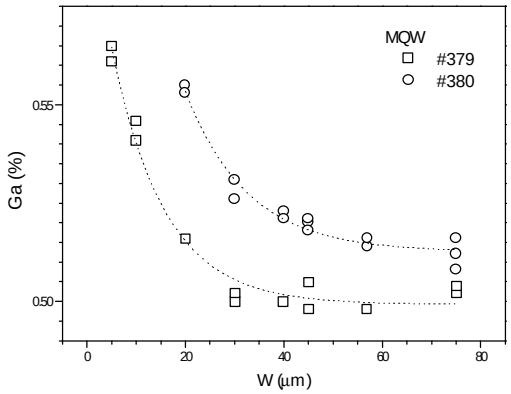

Fig. 5: Ga content in the InGaAs QW alloy for two InGaAs/InAlAs MQW structures grown with different [TMIn / (TMIn + TMGa)] fraction in the gas phase as a function of mask width (*W*). The dotted lines are exponential decay fits.

Conclusion

A detailed investigation of the selective area growth of InGaAs, InAlAs and InGaAs/InAlAs MQW structures for optoelectronic integration has been performed. For the growth conditions and mask geometries used in this work, the same linear growth enhancement dependence on mask width was observed. The In incorporation in the layers grown on the patterned substrates relative to the ones grown on the unmasked substrates is enhanced. A saturation of the alloy composition of the QW material in the MQW structures was observed for masks wider than 50 μm. This implies that for masks larger than this value, the alloy composition remains unchanged and growth enhancement dominates the selective area growth of InGaAs/InAlAs MQW. Signs of such alloy composition saturation effect can be seen for bulk InAlAs, as well, but such condition is reached for larger masks.

References

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