

MOVPE Waveguide Regrowth in InGaAsP/InP with Extremely Low Butt-Joint Loss

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InP photonic circuits are becoming increasingly complex and require different layer-stacks for different applications like interconnecting, switching or amplification. This integration requires epitaxial regrowth steps of different waveguide material-compositions with low butt-joint loss. In this paper we present experiments with transparent InGaAsP/InP waveguides which were grown using a two step MOVPE process. The propagation loss in the waveguides which were grown in the first step and in the second step showed no significant difference. In addition, the loss in the butt-joints between the two materials was below 0.1 dB.

Introduction

InP photonic integrated circuits (PICs) require the integration of at least two waveguide materials for the different active (laser, amplifier, modulator, etc.) and passive elements (e.g. interconnection waveguides, wavelength (de) multiplexers, couplers, etc.). Among the integration techniques, the butt-joint coupling technique offers maximum flexibility in the design, i.e. compositions, thicknesses, doping concentrations. In the butt-joint technique, the coupling is made by first growing one waveguide layer (e.g. the laser or amplifier active layer), locally removing it by etching and regrowing the second waveguide layer (e.g. modulator, passive waveguide) in the etched regions. For InP based devices, this technique is facilitated by the high tolerance towards regrowth steps for Metal Organic Vapour Phase Epitaxy (MOVPE) in the InP/InGaAsP system.

Previously, we reported butt-joint couplings showing no excess loss as compared to continuous waveguides [1,2]. One of the conditions for the fabrication for these extremely low loss couplings is that the layer thicknesses (active or passive guide layer plus InP cladding) do not exceed the value of 0.3 μm . This procedure limits the thickness of the guide layers to about 0.2 μm , which in general is not sufficient for polarization-insensitive performance of the PIC. In this paper, we present a procedure for the fabrication of butt-joint couplings for waveguide thicknesses of 0.5 μm and higher as needed for polarization insensitive PICs.

In the study, the butt-joint couplings obtained from different layer stacks and etched step heights are compared by scanning electron microscopy (SEM) and optical transmission measurements. Also the influence of the crystallographic direction of the waveguides containing the butt-joints is investigated.

Design and fabrication of test-waveguides

All epitaxy steps for the test waveguides containing butt-joint couplings were performed by Low-Pressure MOVPE (LP-MOVPE) at 625°C. In the first epitaxy step, a 500 nm thick $\lambda = 1250$ nm InGaAsP layer and either a 100 nm or 200 nm thick InP layer are grown. Both layers are nominally undoped. In this way, optical losses due to free carrier

absorption are minimized, thus lowering the detection limit for other loss factors such as scattering at butt-joints.

In the test waveguides fabricated for this study, the $\lambda = 1250$ nm InGaAsP layer represents the 500 nm thick SOA active layer stack of the full active-passive PIC, see e.g. [3].

Next, mesa blocks (500 μm long, 20 μm wide spaced by 500 μm) are defined by lithography and wet chemical etching using a SiO_2 layer as etching mask. In this mask also uninterrupted mesa blocks running over the full wafer and “empty” spaces are included in order to obtain reference waveguides not containing butt-joints, see fig. 1. Then undoped $\lambda = 1250$ nm InGaAsP and InP layers are grown by selective area LP-MOVPE using the same SiO_2 layer as mask. The thicknesses of both layers are matched to the original thicknesses and the etch depth.

Table 1: overview of values of layer thicknesses and etch depths (all in nm). The etch depth in wafer 4 was controlled by a 20nm InP etch-stop layer.

	wafer #1	wafer #2	wafer #3	wafer #4
thickness p-InP	300	300	400	300
thickness i-InP	200	200	100	200
etch depth $\lambda = 1250$ nm InGaAsP	200	300	200	300 (*)

Finally, after removing the SiO_2 mask, a p-InP ($p = 5 \times 10^{17} \text{ cm}^{-3}$) layer is grown over the entire wafer, bringing the total InP thickness to 500 nm. Table 1 gives an overview of the layer thicknesses and etch depths investigated in this study. Ridge waveguides with a width of 2 μm and a height of 600 nm were etched by Reactive Ion Etching.

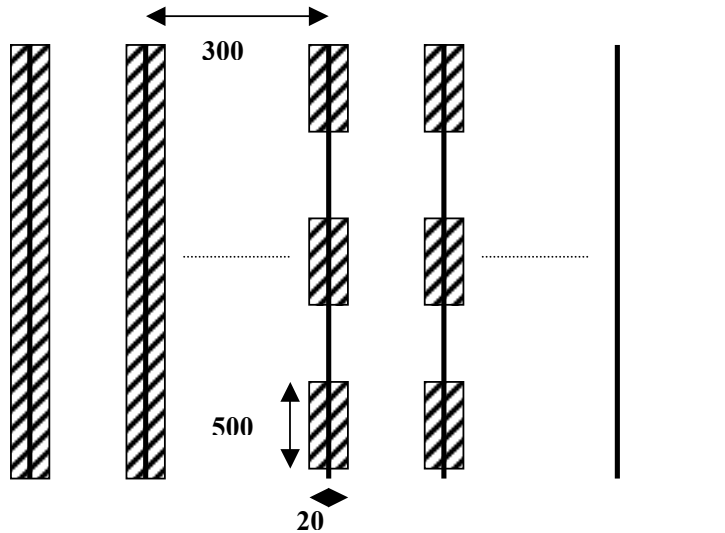


Figure 1: schematic mask layout for test waveguides showing mesa blocks (shaded rectangles) and waveguides (solid lines). Dimensions are in μm .

In fig. 2, SEM cross sections after stain etching in $\text{K}_3\text{Fe}(\text{CN})_6/\text{KOH}$ are shown for wafer #1 in both the [110] and the [-110] crystallographic direction. In both cases, but especially for [110], the irregularities at the butt-joint are extremely small. We do not observe any mass-transported material (e.g. InP) at the regrowth interface. The cross sections of the other wafers are similar, [-110] always having the larger of the slight irregularities.

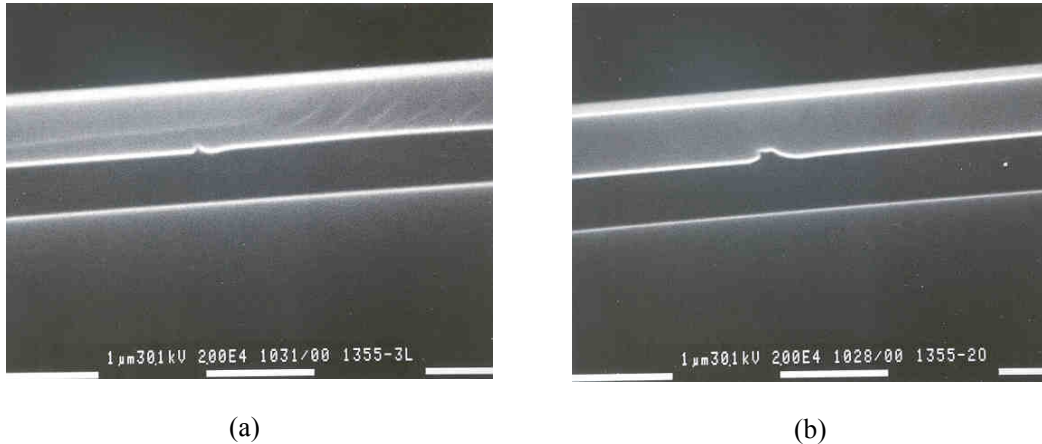


Fig.2. SEM micrographs of cross sections of butt joints of wafer 1, (a) $[110]$, (b) $[-110]$ direction.

Optical transmission measurements

To characterise the quality of the regrown structures a series of $2\ \mu\text{m}$ wide ridge waveguides was etched through the different regions as indicated in Figure 1. All waveguides were etched $100\ \text{nm}$ into the quaternary layer. The optical transmission losses in $5\ \text{mm}$ long waveguide sections from the four wafers were measured by recording the Fabry-Perot transmission spectra. The loss in the waveguide was determined from the amplitude of the extrema in the spectrum with the theoretical facet reflectivities as input parameter. The orientation of the measured waveguides that came from wafers 1 and 3, was parallel to the $[0\ 1\ 1]$ crystallographic plane. The orientation of waveguides from wafers 2 and 4 was parallel to the $[0\ -1\ 1]$ plane. Losses were measured of 15 to 25 waveguides per wafer fragment for each (TE and TM) polarisation. Total losses of the $5\ \text{mm}$ long waveguide sections range between 1 and 5 dB. The high values obtained for the $[0\ -1\ 1]$ oriented waveguides could partly be due to an underestimate of losses on the facets for this cleaving direction.

In figure 3 an overview of the results of the measurements is given. The four graphs show the losses per $500\ \mu\text{m}$ length of waveguide from each of the four wafers. In each graph the results are shown for TE and TM waves for waveguides that consist of material from the first growth (indicated as TE11 and TM11), waveguides with butt-joints between first growth and regrown material (TE12 and TM12) and waveguides that only have regrown material (TE22 and TM22). The loss is given per $0.5\ \text{mm}$ since there will be 1 butt-joint in this length of waveguide with joints and any increase in loss can be seen directly from the graphs. Note that the vertical scale on the graphs for wafer #2 and #4 is twice as large as the one for the graphs for wafers #1 and #3.

As can be seen there is almost no difference between loss of the uniform waveguides grown in the first step (11) and in the second step (22). By comparing the results from the 11, 12 and 22 type waveguides the influence of the butt-joints can be observed. One can see that the increase in loss by the butt-joints is hardly discernable in the measurements and is at most $0.1\ \text{dB}$ per butt joint, for both the $200\ \text{nm}$ (#1 and #3) and $300\ \text{nm}$ etch depths (#2 and #4).

One would expect a higher loss for wafer #3 for the TM waves since this wafer has a thinner intrinsic InP layer, but this was not observed. The results show overall higher losses for especially the TE waves in the $[0\ -1\ 1]$ oriented waveguides. The reason for this is not yet understood.

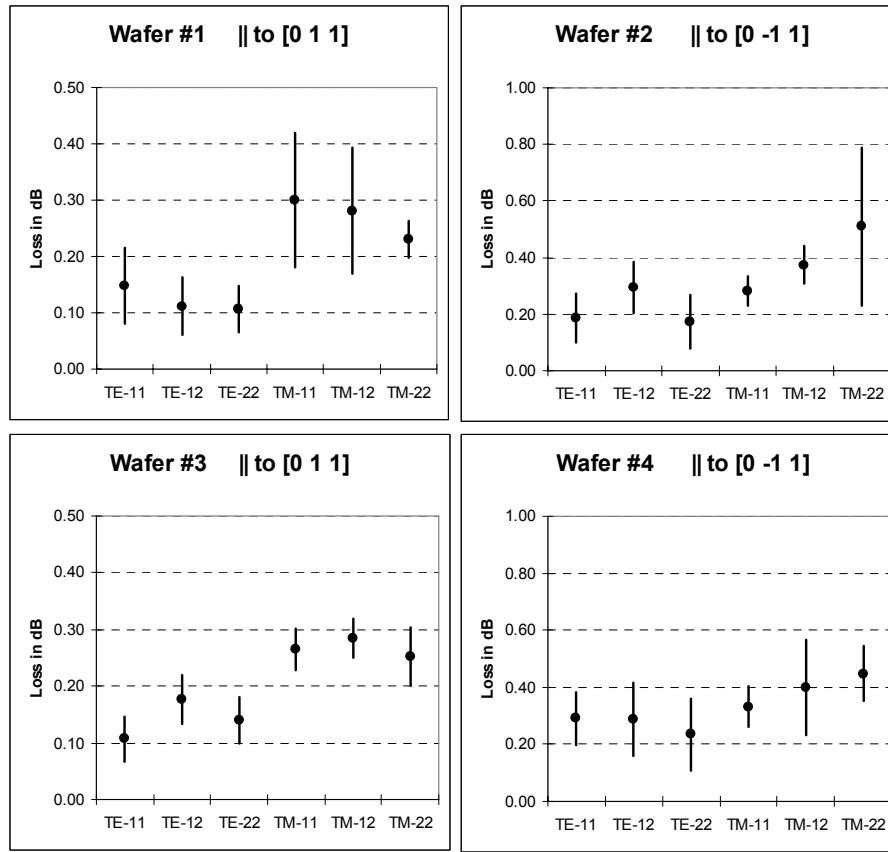


Fig. 3. An overview of the loss measurements. Plotted is the loss per 0.5 mm of waveguide for the four wafers investigated. Please note the scale on the graphs for #2 and #4 is twice that on the graphs for #1 and #3. The length of 0.5 mm of waveguide contains 1 butt-joint in the waveguides indicated with (12). In each graph the losses are shown for TE and TM polarised light in the waveguides from: a) first growth material (11); b) second growth material (22) and c) material with butt-joints and material from both growths(12).

Conclusions

It has been demonstrated that using MOVPE waveguide regrowth in InGaAsP/InP waveguides, butt-joints have been formed over a 500 nm discontinuity (300 nm Q1.25, 200 nm InP) with extremely low loss (≤ 0.1 dB per butt-joint). The overall thickness of the waveguide is 500 nm as is required for polarisation insensitive waveguides. This process is therefore very suitable for use in the production of photonic integrated devices.

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References

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