Towards an Integration Technology Platform at 1300nm: Ridge Waveguide Design

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A design study on the development of an integration technology platform on InP, propagating light with a wavelength around 1300nm is presented. This platform is being developed on the basis of the generic integration technology already present on InP operating around 1550 nm. By using simulations and measured absorption parameters, the effects of the width of a ridge waveguide as well as thickness and composition of the wave-guiding layer on propagation loss and optical modes were studied. An optimum passive waveguide design was found.

Introduction

The extension of a photonic integration platform on InP with active/passive capability to 1300 nm would enable the use of photonic integration in a larger number of applications e.g. in sensing, datacom and O-band telecommunications, and biophotonics. In particular this capability could be used for devices for the Optical Coherence Tomography (OCT) medical imaging technique. Light at 1300 nm is widely used for OCT imaging because water has a local minimum in its absorption spectrum around that wavelength, thus enhancing the light penetration in human tissues. The water absorption varies indeed from 1.2 cm^{-1} at 1260 nm to 3.7 cm^{-1} at 1360 nm [1].

A solution for a ridge waveguide layerstack on InP substrate propagating light at 1300 nm is presented here. The study is focused on addressing the changes in propagation of the fundamental TE-like mode as the result of varying the waveguide thickness (t), width (W) and the semiconductor energy bandgap of the waveguide core layer (Q-value). In particular it is important to consider the optical losses and the number of the modes that are allowed to be propagated through straight waveguides as function of those three parameters. An important boundary condition is that the structure must be compatible with a butt-joint active-passive integration scheme and the use of the waveguides as electro-refractive modulators. This requires the presence of p and n-doping outside the waveguiding layer.

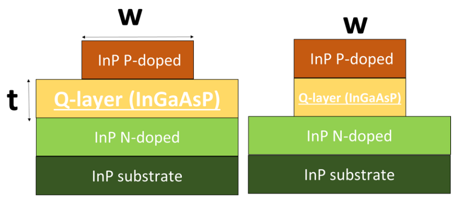

Figure 1 Schematic for the ridge waveguide in both shallow and deep etched technology

Methodology

The layerstack for the fabrication of the waveguides is grown on an n-doped InP substrate. Undoped InP has a refractive index of n=3.202 and an absorption coefficient of $\alpha = 0.04\ cm^{-1}$ at a wavelength of 1310nm [3].

In the ridge waveguide the light is guided by a quaternary semiconductor alloy, InGaAsP lattice matched to InP, with an engineered bandgap energy, sandwiched by n- and p-doped

InP. The change in the real part of the refractive index due to a doping concentration N is described by: $\Delta n = \frac{e^2\lambda^2 N}{8\pi^2 c^2 \epsilon_0 n\, m_{p,n}}$ where e is the elementary charge, ϵ_0 is the permittivity, n the refractive index of InP and $m_{p,n}$ is the effective mass of the charge carrier inside the crystal [2]. The main distinction between p- and n- doped materials is different effective masses for charge carriers. For the n-doped layers the charge carriers are electrons, and for p-doped layers are light and heavy holes. As a result of holes having an approximately 40 time higher effective mass than the electrons, the absolute change in refractive index is lower for the p-doped InP with respect to the n-doped InP. Wavelength dependent absorption also depends on the doping concentration. In the n-doped semiconductors the free electron absorption is dominant and it exhibits a quadratic wavelength dependence. On the other hand, in the p-doped InP, the absorption occurs due to the excitation of the light and heavy holes. It is linearly dependent on the doping concentration and it is described as: $\alpha_p(N) = 4.25 * 10^{-16} N e^{\frac{-4.53}{\lambda}}$ [4]. Since the p-doping levels should be maintained sufficiently high, to ensure a low series resistance in the active components, it is important to minimize the mode power fraction in the p-doped regions. It is important indeed to choose the correct waveguide parameters to ensure:

1. Low loss optical propagation ($Losses < 3\ dB/cm$).
2. Avoid the propagation of high order even modes (TE_{02}), which could easily overlap with the fundamental one (TE_{00}), resulting in a mode mixing.

Simulation results

Thickness sweep

The first parameter studied is the thickness of the waveguiding core layer. The idea is to track the number of modes and their effective refractive indices, for different waveguide thicknesses. Finite difference element numerical simulations [5] were performed fixing the width of the waveguide (W=2µm), and scanning the thickness of the waveguiding layer between 200 and 800 nm with a step size of 100nm, for different Q-values.

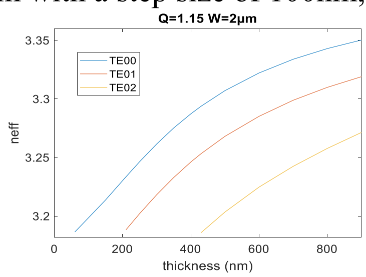

Figure 2 Effective index for different TE-modes as function of thickness for Q=1.15µm and W=2µm

As a result of this study, a thickness of 400 nm has been selected in order to have the waveguiding layer as thick as possible, to maximize the optical confinement, and at the same time to avoid the propagation of TE_{02}.

Width sweep

For a shallow etched ridge waveguide the choice of the width arises from a trade-off between the minimization of optical losses and the number of propagating modes. The width effects are simulated numerically through finite difference element method [5], keeping a step size of 200 nm, resulting from the fabrication tolerance.

As it can be seen from the graphs in figure 3, narrower waveguides introduce higher losses for the fundamental mode, due to its horizontal spread, and wider waveguides enable the propagation of the TE_{02}. The shallow etched waveguide width is chosen to be 2 µm, to keep the same width as for the 1550 nm platform in order to limit the changes in the fabrication processes. For the case of deep etched technology the waveguide width could be narrower, because the fundamental mode is more vertically extended and losses are less width dependent with respect to the shallow etched waveguides. The deep etched waveguide width is set to 1.5 µm, to keep the same fabrication processes, as discussed for the shallow etched technology.

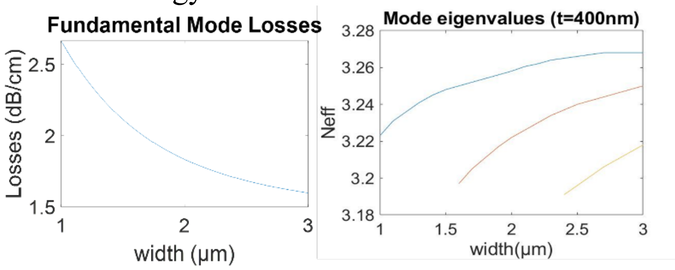

Figure 3 Optical loss for the fundamental mode TE_{00} and effective indices of the first three eigenmodes as function of width of a shallow etched ridge waveguide with thickness=400 nm

Quaternary semiconductor alloy choice

The last parameter investigated to determine the optimum layer-stack is the Q-value of the waveguiding layer. The Q-value is the direct energy bandgap of the quaternary alloy semiconductor (InGaAsP) and it's linked to its composition. The choice of the Q-value depends on many factors and parameters. This study is focused on the trade-off between the spatial confinement and the intrinsic absorption of the quaternary layer itself. The higher the Q-value the more the optical mode is confined inside the waveguiding layer, the smaller the overlap with the high absorbing layers (p-doped layers). However, also the waveguiding layer material absorption increases with the Q-value. The energy bandgap will be closer to the photon energy which will lead to an absorption:

$$\alpha = A\ exp\ [\frac{\sigma(\hbar\omega - \hbar\omega_0]}{k_b T}]$$

where ω_0 is the photon frequency, T the temperature and σ and A constants depending on the material [6]. In order to retrieve σ the approach is to measure the absorption tail of a straight waveguide in InGaAsP, with a Q-value=1.25µm realized in the standardized 1.55 µm technology. Light from a tunable laser is led through a straight waveguide with cleaved reflective facets ($R \approx 33\%$ for TE polarization) sweeping the wavelength from 1260 up to 1360 nm. The transmission formula is:

$$\frac{I_t}{I_{inc}} = \frac{(1-R)^2 e^{-\alpha d}}{1 + R^2 e^{-2\alpha d} - 2Re^{-\alpha d} cos\,(2kd)}$$

With $k = \frac{2\pi}{\lambda}$ wavenumber and d=4.6 mm cavity length [7]. From this measurements we retrieve $\sigma = 2.2\ \pm 0.2$, for InGaAsP Q=1.25µm.

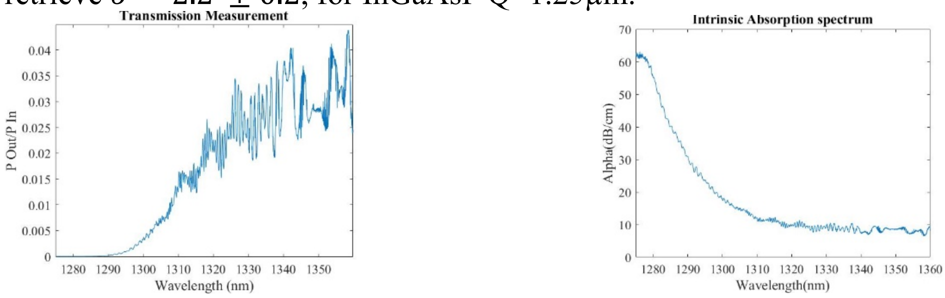

Figure 4 a) Measurement of transmission spectrum of a straight waveguide (4 mm long) with uncoated end facets close to the quaternary alloy bandgap, Q=1.25µm. b) Measured absorption coefficients as a function of wavelength.

It is then possible to separate the intrinsic absorption of the waveguiding layer from the absorption due to the excitation of the free carriers. This is possible since the free carrier absorption is weakly dependent on wavelength. Thus an absorption spectrum for each Q-value can be obtained, assuming $\alpha = A$ at the bandgap energy. The Q-value for which the trade-off between spatial confinement and optical losses is optimized is 1.1µm (Bandgap energy=1.12 eV). This is also the technological fabrication limit given by our foundry. However, lower Q-values do not improve losses, because they reduce optical confinement into the waveguiding layer.

Conclusions

As a result of these choices simulations predict it is possible to have a waveguide design with an optical propagation of the fundamental TE-mode with losses less than 2dB/cm in the whole O-band for both shallow and deep etched ridge waveguides. The propagation constant (β) of the fundamental mode in the deep etched straight ridge waveguide is presented in figure 5 as function of waveguide width and wavelength, for TE polarization, obtained by modeling the dielectric waveguide as a metallic one with $W_{eff} \approx W + \frac{\lambda}{pi\sqrt{n_s^2 - n_c^2}}\left(\frac{n_c}{n_s}\right)^{2\sigma}$, where $\sigma = 0$ for TE polarization, n_s is the slab refractive index and n_c the cladding one[8].

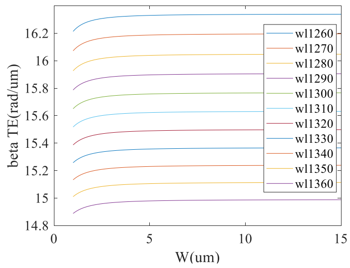

Figure 5 Propagation constants for the deep etched straight waveguide.

From this definiton it is possible to model further components, starting with waveguide bends.

Acknowledgements

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