Design and simulation of 1μm Al-free quantum-well SOA

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The semiconductor optical amplifier (SOA) is an active device integrated inside an optical phased array (OPA). It finds numerous applications, notably in LiDARs for automotive industry and smart devices. While many research works study 1.55μm wavelength OPA, only a few address OPA at 1μm wavelength and none, SOA at 1μm, whereas 1μm waves offer sharper sensitivity of Si photodetectors (for detection of returning signal from OPA), lower water absorption and solar background noise. Besides, large scale integration of common compounds with aluminum is prone to oxidation during fabrication. Therefore it is also of interest to seek alternatives of active layer structures without Al. This work analyzes several layouts of single quantum wells at 1μm and optimize the active region to achieve the desired features. Two structures are proposed, one with Al as a reference, one without.

Parameters that can be adjusted to engineer the bandgap of the active region include well and barrier alloys, width of the well and strain. Because no SOA at 1μm are documented, we tested multiple active regions of direct-gap III-V lasers. To simulate the material g and differential a gains of multi-layer devices, we implemented a model in Python. The code takes the alloy composition and width of layers as input and returns g and a, as well as the strain applied on each layer, lattice-matched to a given substrate. It also features calculation of density of states, gain spectrum, band offsets and alloy parameters. The model implements a new equation of a probability-weighted inverse mass in the plane transverse to <100>, derived by 1st order perturbation of the Hamiltonian.

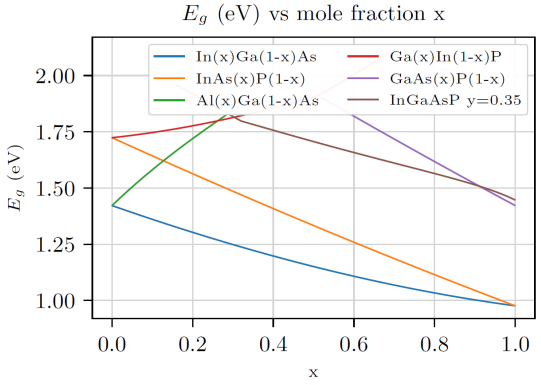

Figure 1: Band-gap E_g (eV) as a function of mole fraction x for various ternary alloys and InGaAsP.

Energy gaps (E_g) of compounds matched to GaAs calculated by the Python library are illustrated in fig. 1. It clearly appears that InGaAs is the sole compound candidate for wells below E_g=1.24eV which corresponds to 1μm. $InAs_xP_{1-x}$ is another one but its strain for high mole fraction is beyond critical levels. This motivated our choice for $In_{0.27}Ga_{0.73}As$ well. Because we considered single wells for now, we focus on barriers with 0-strain to obtain a low average strain thanks to thick barriers. Table 1 shows the main simulated properties of the SQW with four 0-strain alloys for barriers: the wavelength λ, the material gain g and the differential gain a. Among the alloys lattice-matched to GaAs without strain, $In_{0.12}Ga_{0.88}As_{0.76}P_{0.24}$ has the most similar properties to AlGaAs. We obtain the lowest g and a for GaAs, and the highest g (without Al) for $In_{0.52}Ga_{0.48}P$. For SQW, this table is exhaustive because there are no other ternary alloys lattice-matched to GaAs without strain. For MQW, more choices of alloys, in particular with a tensile strain, would be available.

In this study, we introduced a new structure for SOA with adequate parameters: $In_{0.27}Ga_{0.73}As$ well 5.5nm wide with compressive strain of 1.9% and strain-less $Al_{0.35}Ga_{0.65}As$ barrier, and an alternative without aluminum that exhibits similar characteristics using a $In_{0.12}Ga_{0.88}As_{0.76}P_{0.24}$ barrier. For saturation output power maximization, an important property for SOA, differential gain should be lower. Regarding only this criteria, a simple GaAs barrier is also thought to be a good option, but the considerably lower gain should be taken into account.

Barrier alloy	Strain (%)	E_g (eV)	N_θ ($10^{12}cm^{-2}$)	E (eV)	λ (μm)	a (10^{15} cm^2)	g (10^4 cm^{-1})
$Al_{0.35}Ga_{0.65}As$	0.0	1.90	0.56	1.25	0.99	4.88	0.71
GaAs	0.0	1.42	0.94	1.22	1.02	2.28	0.58
$In_{0.52}Ga_{0.48}P$	0.0	1.92	0.70	1.25	0.99	3.78	0.71
$In_{0.12}Ga_{0.88}As_{0.76}P_{0.24}$	0.0	1.57	0.60	1.23	1.01	4.46	0.69

Table 1: Barrier candidates for GaAs-matched $In_{0.27}Ga_{0.73}As$ well with strain=-1.9%, E_g=1.12eV, and a width of 55Å. Barrier gaps impact the effective bandgap of the well, E, and its equivalent wavelength λ, corresponding to the first transition Eigen-energy. $a = \frac{\partial g}{\partial N}$ is computed at the threshold carrier density level N_θ. g is computed for a carrier density $N = 10 \times 10^{12} cm^{-2}$.