SOA Characteristics Using Different Quaternary Compounds

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Abstract The semiconductor optical amplifier (SOA) is modeled and investigated. Interpolation is used to estimate the active region material parameters. SOA characteristics are obtained for InGaAsP and InGaAlAs in the wavelength band 1450-1650 nm. The effect of molar fraction of active region material elements on material gain characteristics is also studied.

Keywords: Semiconductor optical amplifier SOA, active region, molar fraction, interpolation method, material gain.

1. Introduction

The increased interest shown lately in studying semiconductor optical amplifiers (SOAs) is due to their potential of performing amplification of ultrahigh bandwidth optical signals without employing the customary detection, electronic amplification, and generation cycle. Such amplification is very attractive in, e.g., wavelength division multiplexed (WDM) systems. Another area of application of light amplifiers is optical networks based on integrated optics devices where different types of losses (waveguide, coupling, power splitting) severely limits the possibilities of generating complex optical systems [1].

The scarce of experimental and standard data for semiconductor materials parameters makes difficulties to study their characteristics when used as SOA active region materials. The purpose of this paper is to estimate the physical parameters of compounds that are used in the active region of the SOA and study the effect of molar fractions concentration of active region compound elements on the material gain.

In Sec.2, we present the model used to estimate material gain and net gain coefficients, which are essential to study the steady state characteristics of the SOA. Interpolation method for calculating the physical parameters of quaternary semiconductor compounds is investigated in Sec.3. In Sec.4, illustration and comparison between the results of standard and interpolated parameters for $InP/In_{1-x}Ga_xAs_yP_{1-y}$ at a certain value of molar fraction are presented. This is followed by results at different values of elements molar fraction in the active region. Section 5 shows a comparison between $Al_zGa_xIn_{1-x-z}As$ and $Al_yGa_xIn_{1-x-y}As$ at different molar factions in the active region. Section 6 gives an example of arrangement between carrier density and molar fraction to get a peak material gain centered at 1550 nm. The main results are summarized in Sec. 7.

2. Mathematical Model

SOAs are used mainly in the 1.3 μm and 1.55 μm wavelength regions. They are fabricated from the same materials used to fabricate laser sources in these regions. These materials are the III-IV semiconductors, which include InP, InGaAs, InGaAsP, AlGaAs and InAlGaAs.

2.1 Bulk Material Gain Coefficient

SOAs with an active region whose dimensions are significantly greater than the deBroglie wavelength ($\lambda_0 = h/p$ where p is the carrier momentum) of carriers is termed as a bulk device. When the active region has one or more of its dimensions of the order of λ_B, the SOA is termed a quantum-well device [2].

The device structure consists of a central active region of width W, a thickness d and a length L. The gain model is adopted for the semiconductor material. In this work, we consider the active region of a SOA to be fabricated from a bulk direct bandgap material. The model allows one to calculate the stimulated emission and stimulated absorption coefficients, from which the material gain coefficient is obtained as [3]:

$$g_m(\nu,n)=\frac{c^2}{2\pi\nu^2 n_r^2}\left(\frac{2m_e m_{hh}}{\hbar(m_e+m_{hh})}\right)^{3/2}\cdot \sqrt{\nu-\frac{E_g}{\hbar}}\left[F_c(E_a)-F_v(E_b)\right] \quad (1)$$

This equation can be decomposed into two components: a gain coefficient, g'_m, and an absorption coefficient, g''_m, that result from the downward and upward transitions, respectively. The material gain coefficient, g_m, is given by the difference between these two components, which are given by:

$$g'_m(\nu,n)=\frac{c^2}{2\pi\nu^2 n_r^2}\left(\frac{2m_e m_{hh}}{\hbar(m_e+m_{hh})}\right)^{3/2}\cdot \left(\sqrt{\nu-\frac{E_g}{\hbar}}\right)F_c(E_a)\left[1-F_v(E_b)\right] \quad (2)$$

and

$$g''_m(\nu,n)=\frac{c^2}{2\pi\nu^2 n_r^2}\left(\frac{2m_e m_{hh}}{\hbar(m_e+m_{hh})}\right)^{3/2}\cdot \left(\sqrt{\nu-\frac{E_g}{\hbar}}\right)F_v(E_b)\left[1-F_c(E_a)\right] \quad (3)$$

2.2 Net Gain Coefficient

The total loss coefficient, $\alpha(n)$, of an SOA active region can be modeled as [3]:

$$\alpha(n) = K_0 + \Gamma K_1 n \quad (4)$$

where Γ is the optical confinement factor, K_0 and K_1 are carrier independent and carrier dependant absorption loss coefficients, respectively. K_0 is given by [4]:

$$K_0 = \frac{\mu\sigma c}{n_r} \quad (5)$$

where σ is the intrinsic conductivity of the active region and μ is the permeability of the semiconductor material. The net gain coefficient g(v,n) of an SOA is expressed as[4]:

$$g(\nu,n) = \Gamma g_m(\nu,n) - \alpha(n) \quad (6)$$

The optical confinement factor, Γ, is involved since not all the photons are expected to interact with the electron population in the p-n junction.

3. Estimation of Physical Parameters

3.1 Material Parameters of Binary Semiconductors

A variety of semiconductor compounds are achieved by mixing elements of the third group (Al, Ga, In,.....) with that of the fifth group (P, As, Sb,.....) in the same lattice such as InxGa1-xAsyP1-y and In1-x-yGaxAlyAs,....., where x and y are the molar fractions of the elements (x=0,....,1; y=0,.....,1). *Any variation in x or y leads to a different compound with new material parameters.* Because of the random distribution of elements from the same group within the alloy lattice, exact calculations of material parameters are hardly possible.

To estimate the physical parameters of ternary or quaternary, a linear interpolation of the relevant binary semiconductors is used. The material parameters of the binary semiconductors are given in Table 1[4-8].

3.2 Interpolation Method

If we have the two compounds $A_{1-x}B_xC_yD_{1-y}$ and $A_{1-x-y}B_xC_yD$, where A, B, C and D are symbols for the elements in III-V semiconductor compounds, the interpolation for a physical parameter Z for the compound $A_{1-x}B_xC_yD_{1-y}$ has the form [6]:

$$Z[A_{1-x}B_xC_yD_{1-y}] = Z[BC]xy + Z[BD]x(1-y) + Z[AC](1-x)y + Z[AD](1-x)(1-y). \quad (7)$$

While for the compound $A_{1-x-y}B_xC_yD$, the same parameter has the form [6]:

$$Z[A_{1-x-y}B_xC_yD] = Z[AD](1-x-y) + Z[BD]x + Z[CD]y. \quad (8)$$

Three physical quantities are calculated separately for the corresponding binary for semiconductor materials before applying (7) or (8); namely the radiative carrier recombination lifetime, τ, the electric conductivity, σ and the refractive index, n_r. Firstly, τ can be calculated from [3]:

$$\tau = (B_{rad}\, n)^{-1} \tag{9}$$

Then, σ is given by [7]:

$$\sigma = e\sqrt{n_r n_v}\exp\left(\frac{-E_{go}}{2k_B T}\right)(\mu_e + \mu_h) \tag{10}$$

Finally, n_r is calculated from [4]:

$$n_r = \left[\frac{1}{2}c^2\mu\left(\left[1+\left(\frac{\sigma}{2\pi\nu\varepsilon}\right)^2\right]^{1/2}+1\right)\right]^{1/2} \tag{11}$$

where, ε is the permittivity of the semiconductor material, μ_e and μ_h are, respectively, the electron and hole mobilities.

4- Results and Discussion

4.1 Using Standard and Interpolated Parameters

In this section, a comparison between results due to standard and interpolated parameters is carried out. Available standard parameters are used for the $InP/In_{1-x}Ga_xAs_yP_{1-y}$ and the material gain coefficient is obtained, Fig.1 [9]. While, when the interpolation method is used for the same compound and conditions, the results of Fig.2 are obtained.

Figures 1 and 2 show the spectral variation of the material gain coefficient g_m, emission coefficient, g'_m and absorption coefficient, g''_m for $InP/In_{0.58}Ga_{0.42}As_{0.892}P_{0.108}$ at arsenide molar fraction, y=0.892. For lattice matching between the cladding and active region substrates, i.e., both have the same lattice constant and lattice structure, $x=0.47y$. Lattice matching allows the growth of one substrate on the other.

A good agreement between interpolated and standard results is clearly obtained. The small difference between standard and interpolated results has a negligible effect on the signal output power and fiber-to-fiber gain, when compared with literature and experimental work reported by [2].

4.2 Using Different Molar Fractions and Carrier Densities

Now, one can study the effect of different arsenide molar fractions in the active region of the compound $InP/In_{1-x}Ga_xAs_yP_{1-y}$, Fig.3, using interpolation method.

Using Eq.(6), it is possible to calculate the net gain coefficient at different arsenide molar fractions, y, Fig.4. It is clear that the peak value of the net gain is smaller than the peak value of material gain coefficient. This is due to the material loss.

The peak material gain and the corresponding wavelength, of $InP/In_{1-x}Ga_xAs_yP_{1-y}$ as a function of the carrier density at different arsenide molar fractions, y, are displayed, respectively, in Figs.5 and 6.

It is evident that the peak gain coefficient is approximately a linear function of the carrier density, and increases with y. This refers to the increase of electrons that are stimulated from the valence band to the conduction band (CB) when the value of y is increased.

Figure 6 shows that the peak gain, λ_{peak}, is shifted to a shorter wavelength as the carrier density increases while, increasing the arsenide molar fraction, y, shifts the peak gain to a longer wavelength. The optimum value obtained if one uses a carrier density = 2.2×10^{24} m^{-3} and an arsenide molar fraction = 0.892.

To obtain higher material gain and at the same time maintain an optimum material gain window centered on the wavelength 1550 nm, one can increase the carrier density simultaneously with arsenide molar fraction.

5. Comparison between Two SOA Active Region Materials

The previous work is now repeated for $Al_zGa_xIn_{1-x-z}As/Al_yGa_xIn_{1-x-y}As$, which has recently been investigated as an SOA material.

For the lattice matching, the molar fractions in both the active region and cladding materials are related by x=1.1875y and w=1.1875z ,respectively. Table 2 summarizes the results of the two SOA active region materials, InGaAsP and AlGaInAs at different molar fractions of gallium, x.

From table 2, it is clear that, in InGaAsP, the material peak gain increases with the gallium molar fraction and shifts peak wavelength to a longer value. While, in AlGaInAs, the material peak gain decreases with the gallium molar fraction and shifts the peak gain wavelength to a shorter value.
When using AlGaInAs as an SOA active region, the maximum material gain coefficient at 1550 nm and at a carrier density of 3.5×10^{24} m^{-3} can achieved by adjusting the molar fraction of gallium to 0.15. The value of w in the cladding is taken 0.2.

6. Arrangement between Carrier Density and Molar Fraction

From the previous results, one can make an arrangement between carrier density and molar fraction of material elements to obtain a peak wavelength at 1550 nm. An example of this arrangement, Table 3, shows the peak material gain centered at 1550 nm wavelength for different values of carrier density and arsenide molar fraction (y) in InGaAsP.

It is clear that a higher peak material gain centered at 1550 nm wavelength can be obtained if the arsenide molar fraction is increased. This also requires increasing in the carrier density.

Similar arrangement can be made for the AlGaInAs to obtain a higher material gain at 1550 nm.

7. Conclusion

Changing the molar fraction of the active region material elements affects the characteristics of the SOA. Keeping the carrier density constant, it is found that, the material gain increases with arsenide molar fraction in the InGaAsP and decreases in AlGaInAs with the gallium molar fraction.

An arrangement between carrier density and molar fraction of active region material elements is carried out to obtain a higher material gain centered at 1550 nm. As an example, in InGaAsP, when the arsenide molar fraction is increased from 0.862 to 0.912, the carrier density must be increased from 1.54×10^{24} to 2.86×10^{24} m^{-3} to maintain material the peak gain centered at 1550 nm, Table 3.

8. References

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9. Appendix

Table.1 Material parameters of some binary semiconductors

Material	AlAs	GaAs	InAs	GaP	InP
E_{g0}(eV)[a]	2.16 i[e]	1.43 *d*[f]	0.36 *d*	2.26 i	1.35 d
$m_c(m_0)$[b]	0.15	0.067	0.023	0.25	0.077
$M_{hh}(m_0)$	0.76	0.5	0.4	0.79	0.85
$M_{lh}(m_0)$	0.15	0.074	0.025	0.14	0.089
$\mu_e(m^2/V.s)$	0.12	0.85	2.26	0.03	0.4
$\mu_h(m^2/V.s)$	0.042	0.04	0.02	0.015	0.01
ε_r[c]	10.9	13.2	14.6	11.1	12.4
K_1 $(10^{-21}m^3/s)$[d]	---	3	4.7	32	4
B_{rad} $(10^{-16}m^3s^{-1})$	---	721	85	0.0537	1260

a. E_{g0} is measured at 300K.
b. M_0 is the free electron mass.
c. ε_r is the dielectric constant.
d. K_1 is measured at λ=9μm.
e. i is the indirect bandgap.
f. *d* is the direct bandgap.

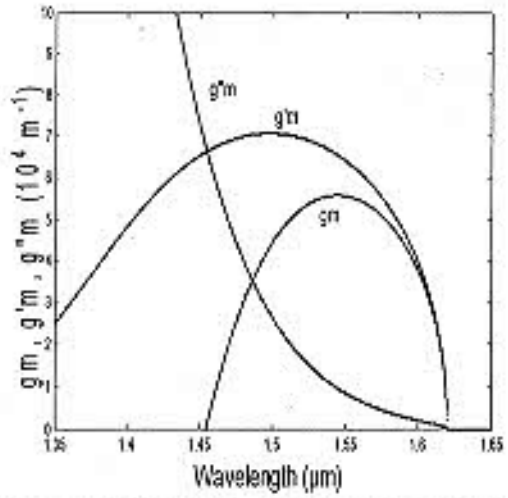

Figure 1 Material gain, emission and absorption coefficients for InGaAsP, using standard parameters and a carrier density of $2\times10^{24}m^{-3}$.

Table.2 Results of SOA active region materials

Material / Parameter	$(In_{1-x}Ga_xAs_yP_{1-y})^b$			$(Al_xGa_yIn_{1-x-y}As)^c$		
x[a]	0.4	0.42	0.44	0.13	0.15	0.17
$g_{speak}(10^4m^{-1})$	3.8	4.1	4.6	7.2	7.1	6.9
λ_{peak} (μm)	1.51	1.56	1.61	1.62	1.55	1.45
$g_{th}(10^3m^{-1})$	5.4	7.5	10	23.3	23	21.3

a. x is gallium molar fraction in SOA active region material
b. x=0.47y and n=2*10^{24} m^{-3} in InGaAsP material.
c. x=1.1875y and n=3.5*10^{24} m^{-3} in AlGaInAs material.

Table.2 Arrangement between carrier density and molar fraction

y[a]	0.862	0.872	0.882	0.892	0.902	0.912
λ_{peak}[b]	1.55	1.55	1.55	1.55	1.55	1.55
n[c]	1.54	1.78	2.02	2.32	2.62	2.86
g_{speak}[d]	1.431	2.636	4.109	6.249	8.728	10.978

a. y is arsenide molar fraction in InGaAsP.
b. λpeak is the peak wavelength in μm.
c. n is the carrier density in (10^{24} m^{-3}).
d. g_{speak} is the peak material gain at 1.55 μm wavelength, in (10^4 m^{-1}).

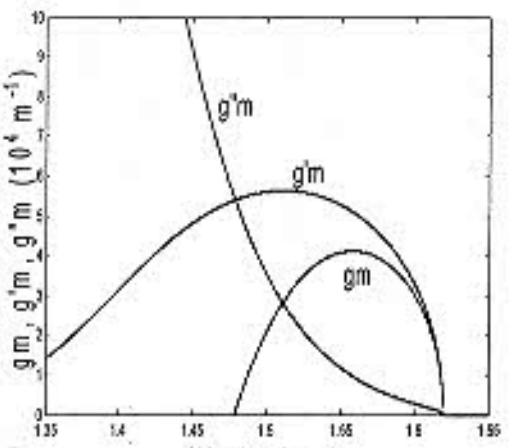

Figure 2 Material gain, emission and absorption coefficients for InGaAsP, using interpolated parameters and a carrier density of $2\times10^{24}m^{-3}$.

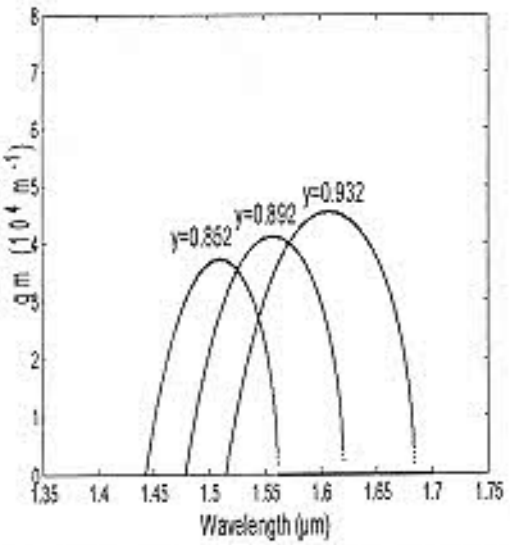

Figure 3 Material gain coefficient for InGaAsP at different arsenide molar fraction and a carrier density of 2×10^{24} m^{-3}.

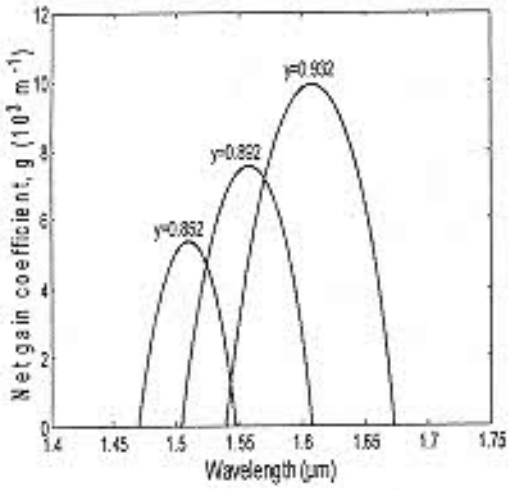

Figure 4 Net gain coefficient for InGaAsP at different arsenide molar fractions and a carrier density of 2×10^{24} m^{-3}.

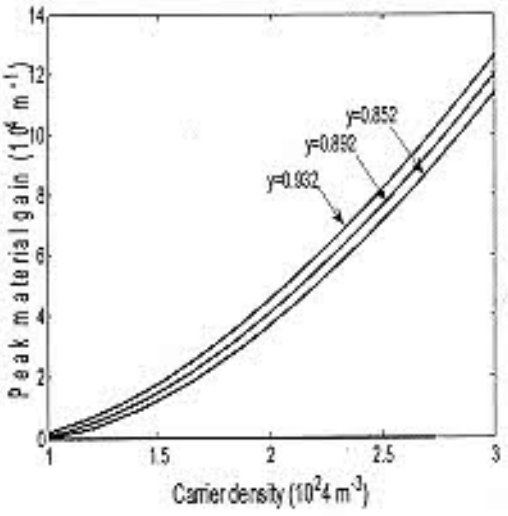

Figure 5 Peak gain coefficient versus carrier density at different arsenide molar fractions.

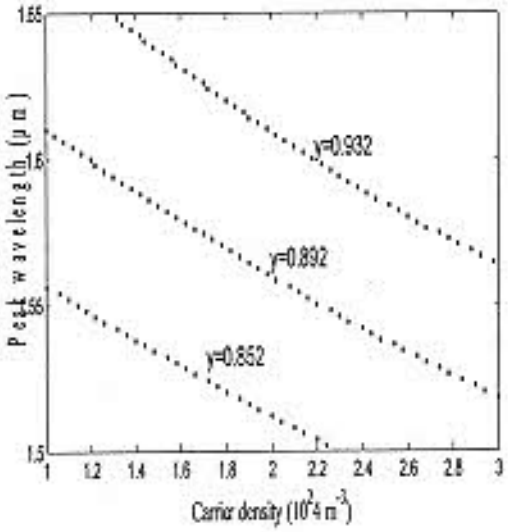

Figure 6 Peak wavelength versus carrier density for InGaAsP at different arsenide molar fractions.