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# Optimization of Optical Gain in $In_x Ga_{1-x}Sb$/GaSb unstrained quantum well structures

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**Abstract**

In this paper we study the effects of In concentration, temperature, quantum well width and carrier density on optical gain for GaSb/$In_xGa_{1-x}Sb$/GaSb untrained quantum well structures. This system was chosen as it is useful in infrared emission, finally, we introduce the optimum structure of quantum well to obtain the maximum optical gain, at room temperature and infrared emission particularly 2.3 (µm), for the use this structure in application of spectroscopic analysis of the gases specially $CH_4$. This structure can be used for light absorption to increase the solar cell efficiency a based on a quantum well and multi-junction.


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*Keywords:* Quantum well; $In_{1-x} Ga_x$ Sb; optical gain; Laser; detection;

## 1. Introduction

The use of semiconductor lasers and detectors operating at room temperature can greatly reduce costs and consider devices for the detection of compact and transportable gas. Such components exist in the spectral range 0.6-1.6 um (components based of GaAs or InP).Unfortunately for these wavelengths the bands of absorption gas is weakly absorbing and large sensitivity of detection cannot be achieved. the spectral region (2-2.5 um) appears to be much more interesting in terms of gas detection by laser diode spectrometers (SDL) because the gas absorption lines are more intense than in the field of short wavelength, and the optical absorption of the methane is 100 to 1000 times higher than 1.3 or 1.6 microns [1]. For emission in the infrared, the semiconductor lasers can be made of different

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materials mainly based III-V compound (GaAs, InSb, GaSb). GaSb and related materials have achieved growing interest in recent times for potential new device applications originating from their excellent optical and electronic properties, one particular GaSb-based easy-to-grow ternary is InGaSb [2]. The quantum well structure based GaInSb/GaSb provides the range of wavelengths (2.1-4.5 µm). In this work we have study the effect of (In) concentration, temperature, quantum well width and carrier density on the optical gain.

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| **Nomenclature** | |
|---|---|
| $E_g$ | Energy gap at T = 300 K |
| $E_{g0}$ | Energy gap at T = 0 K |
| $\varepsilon_r$ | Dielectric constant |
| Δ | Spin-orbit interaction energy |
| T | Temperature |
| $m_c$ | Effective electron mass |
| $m_v$ | Effective heavy hole mass |

The data used for the calculations, as given in Table1, have been linearly interpolated from that of InSb and GaSb.

Table 1. Values of physical parameters binary materials used in the calculation

| | GaSb | InSb | Ref |
|---|---|---|---|
| $m_v/m_0$ | 0.267 | 0.263 | [3] |
| $m_c/m_0$ | 0.042 | 0.0145 | [4] |
| Eg(eV) | 0.725 | 0.172 | [5] |
| Δ (eV) | 0.77 | 0.81 | [6] |
| $\varepsilon_r$(eV) | 14.44 | 15.86 | [7] |
| α(meV/K) | 0.417 | 0.32 | [8] |
| β (K) | 140 | 170 | [8] |
| $Eg_0$ (eV) | 0.812 | 0.235 | [9] |

## 2. Theory approach

### *2.1. Energy levels in QW structure*

On the outside of the well, the energy of electrons which are in the band conduction and holes in the valence band can take any value (continuum). For against, within the potential well, the wave equation describing the movement of the particles may be solved only to some values energy. These eigenvalues are given by solving the system of equations transcendental following [10].

$$\left[\frac{m_{cb}}{m_{cw}}\frac{\Delta E_c - E_{cn}}{E_{cn}}\right]^{1/2} = \begin{Bmatrix} \tan \\ -\cot \end{Bmatrix} \left[\frac{\mathrm{L\,p}\sqrt{2\mathrm{m_{cw}E_{cn}}}}{2\hbar}\right] \begin{Bmatrix} \mathrm{n;\ even} \\ \mathrm{n;\ odd} \end{Bmatrix} \quad (1)$$

$$\left[\frac{m_{hb}}{m_{hw}}\frac{\Delta E_v - E_{vm}}{E_{vm}}\right]^{1/2} = \begin{Bmatrix} \tan \\ -\cot \end{Bmatrix} \left[\frac{\mathrm{L\,p}\sqrt{2\mathrm{m_{hw}E_{vm}}}}{2\hbar}\right] \begin{Bmatrix} \mathrm{m;\ even} \\ \mathrm{m;\ odd} \end{Bmatrix} \quad (2)$$

Where $m_{cb}$ is the effective mass of electrons in the potential barrier, $m_{cw}$ is effective mass of electrons in the well.

$m_{hb}$ is the effective mass of holes in the potential barrier, $m_{hw}$ is the effective mass of holes in the well. $\Delta E_c$ is the difference between the conduction energy barriers and that the well. $\Delta E_v$ is the difference between the valence energy barriers and that the well. $E_{cn}$ are the eigenvalues for the energy of the electrons in the conduction band (n=1). $E_{vm}$ are the eigenvalues for the energy of holes in the valence band (m=1), and $L_p$ is the width of the well.

In (2) the light-hole band is neglected, and the transition between the electrons and the heavy holes are considered.

### *2.2. Optical gain*

The model of the optical gain used in this study for a single quantum well structure GaSb/$In_xGa_{1-x}$Sb/GaSb is the model of Asada [10]:

$$g(\omega) = \omega\sqrt{\frac{\mu}{\varepsilon}}\sum_{n=1}\left(\frac{m_r}{\pi\hbar^2 L_z}\right)\int_{E_g+E_{cn}+E_{vn}}^{\infty}\langle R_{cv}^2\rangle(f_c - f_v)\ F_\tau(E_{cv})dE_{cv} \tag{3}$$

Where ω is the angular frequency of the light, μ the permeability, ε the dielectric constant, $m_r$ the reduced effective mass given by $(m_{cw}.m_{vw})/(m_{vw+} m_{cw})$, $E_{cv}$ the transition energy. $R_{cv}$ is the modulus squared of the dipole moment formed by the electron-hole pair [11].$f_c$ and $f_v$ are the Fermi functions which express the probability of finding a particle that has the same energy. $F\tau$ ($E_{cv}$) is a function expressing the enlargement transition [12], Where $\tau_{in}$ is the relaxation time intra-band, $\tau_{in}=1.10^{13}$ s. The wavelength corresponding to the transition between a conduction electron and a heavy hole at each subband edge is given by [13,14]:

$$\lambda_n = \frac{1.24}{[E_g+E_{cn}+E_{vn}]} \tag{4}$$

### *2.3. Varshni model*

This model [15] has considered that when the temperature increases the energy gap decreases as is shown per following empirical relationship:

$$E_g(x, T) = E_g(x, 0) - \left(\frac{\alpha(x)T^2}{\beta(x)} + T^2\right) \tag{5}$$

Where α, ß are coefficients of Varshni

## 3. **Results and discussion**

The Figure (1) shows the energy difference between the first quantized level of the conduction band and the first quantized level band of heavy holes as a function of the width of the quantum well. We find that the effect of quantization is obviously much larger than the width of the well is low. The curve from 25nm which is substantially the limit of quantification for alloys InGaSb. In Figure 2, the calculated wavelengths corresponding to the first transition (n = m = 1) between electrons and heavy holes are shown as a function of the (In) fraction, for three widths of wells, the wavelength increases as the concentration (In) decreases, and it is observed that the augmentation of the well width causes the increase of wavelength. As seen in Fig. 3, the $In_xGa_{1-x}$ Sb /GaSb QW laser operates in infrared emission with variation of (In ) concentration. In Figure 3, we have plotted the optical gain as a function of wavelength for three different concentration x=0.3, 0.7 and 0.9. it is found that when the In concentration increases the optical gain Decreases considerably, and also There is a shift of gain spectrum toward higher wavelengths. The main reason for this resonance shift is the increment in energy interval of two different electronic states between which an optical transition occurs. Figure 4 shows the optical gain as a function of wavelength for different of InGaSb wells width. It clearly seen that the optical gain will be reduced significantly with increasing the well width. This is due to the stronger electrons and holes are separated by increasing the well width, thereby reducing optical gain as well as spontaneous emission.

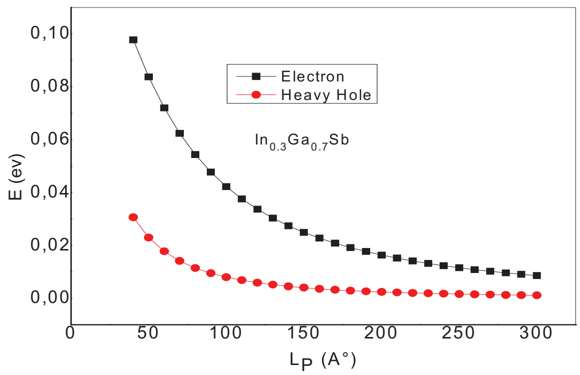


Fig. 1. Variation of Energy quantization as function of well width for ( n=m= 1 )

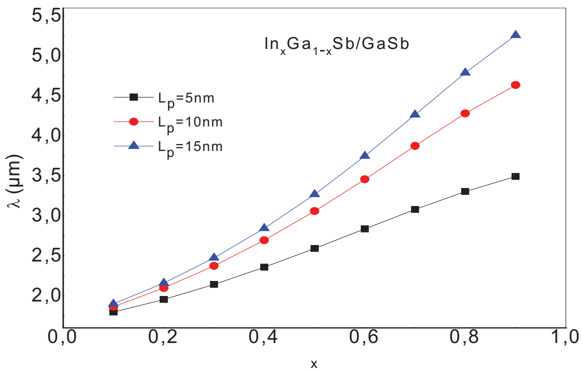


Fig. 2. Wavelengths corresponding to the first transition (n=1) between the quantized energy levels of electrons and heavy holes as a function of (In) fraction for $In_x Ga_{1-x} Sb/GaSb$ quantum well structure with well widths $L_P$ = 5, 10 and 15 nm.

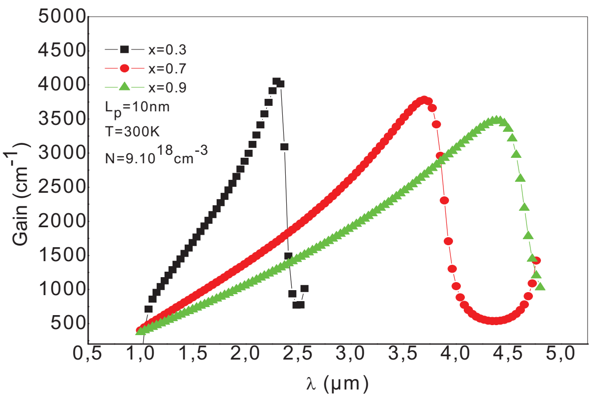


Fig 3. Variation of the gain as a function to wavelength for deferent concentrations of In

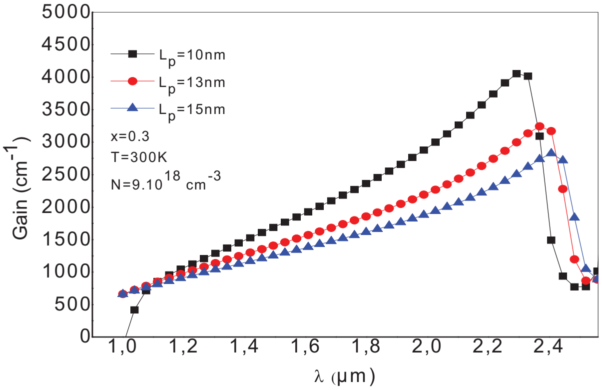


Fig 4. variation of the gain as a function to wavelength for deferent well width.

Figure 5 shows the optical gain as a function of wavelength for different temperatures. When the temperature increases, the gain decreases, this is due to the scattering of the carriers to another subband, from the curve we also find that we have a displacement of the gain spectrum when uses the model of Varshni, unlike the not used of this model, because this last reduces the gap significantly.

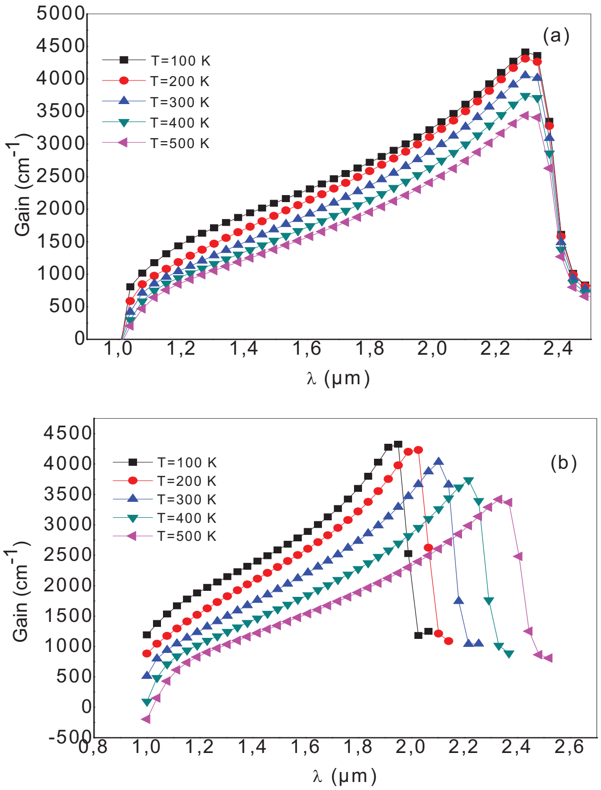


Fig 5. Variation of the gain as a function to wavelength for different temperature with N=9.10$^{18}$ (cm$^{-3}$), x=0.3, $L_p$=10nm.
(a) Without the use of the model varshni. (b) With the use of model varshni.

Figure 6 shows the spectrum of the optical gain in the TE mode for several of injection density of carriers, at a well width, and temperature fixed. The maximum of gain varies with the carrier density. Also a very small shift of the maximum gain towards the short wavelengths is observed when the carrier density increases. This phenomenon is related to the filling of the high states in the conduction and valence bands with the increase in the number of carriers. Figure 7 shows the variation of the maximum gain of $In_xGa_{1-x}Sb$/ GaSb as a function to the carrier density; we note that the maximum gain increases rapidly as soon as the threshold transparency is crossed.

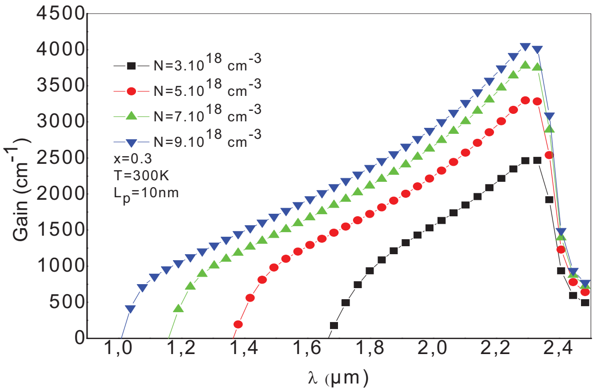

Fig 6: Variation of the gain as a function to wavelength for deferent carrier density

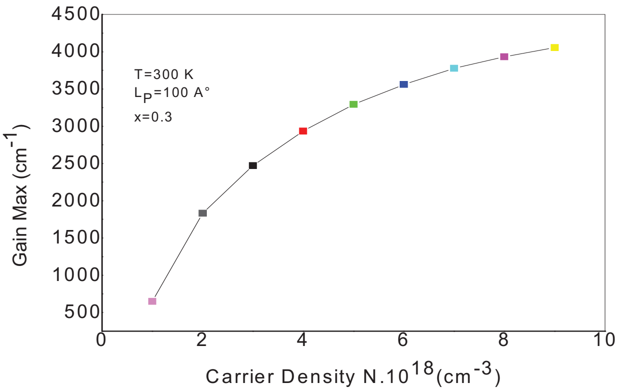

Fig 7. Gain max as a function to carrier density.

## 4. Conclusion

In this paper we have study the effects of In concentration, temperature, quantum well width and carrier density on optical gain for the unstrained quantum well structures of GaSb/ $In_xGa_{1-x}Sb$/GaSb. This structure has a significant gain at room temperatures. For a structure of $N = 9.10^{18}cm^{-3}$, $L_p$ =100nm, x = 0.3 and T=300K, the maximum optical gain is 4000 $cm^{-1}$ at infrared emission of $\lambda = 2.3$ µm. This work allowed us to optimize quantum well structures of $In_xGa_{1-x}Sb$/GaSb, to realize reliable laser diodes for spectroscopic analysis of the gases particularly $CH_4$. As a perspective, we can improve this material for the detection to 2.6 µm. We can improve the efficiency of a solar cell by increasing the absorption of the structure $In_xGa_{1-x}Sb$/GaSb .

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