Fabrication of GaInAsSb/GaAlAsSb Double Heterostructure Lasers Emitting at 2.2μm

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Received July 12, 1993

We ieport the developement of $Ga_{0.86}In_{0.14}As_{0.13}Sb_{0.87}$/ $Ga_{0.73}Al_{0.27}As_{0.02}Sb_{0.98}$ 2.2μm stripe geometry lasers grown by Liquid Phase Epitaxial. Using transverse far field patterns and theoretical calculation for tlie fundamental mode we estimated the value of the active layer refractive index as 3.78, confirming the good optical cofinement for this heterostructure. We also show that tlie stripe geometry lasers have tlie threshold current (I_{th}) limited by all excessive current spread in tlie low resistivity p-type active layer. This is partly solved by making the active region n-type. The minimum I_{th} obtained for oxide stripe n-type active layer lasers was 290mA compareci to 800mA for p-type active layers, the broad area threshold current being tlie same ($3kA/cm^2$) in hotli cases. Recent results for low mesa stripe n-type active layer lasers show minimum I_{th} = 170mA.

I. Introduction

Diode lasers with emission wavelengths in the range of 2 to 3μm are potentially useful foi a variety of applications, including possibility of optical communications employing low-loss fluoride based fibers and laser radar. These lasers are also needed for molecular spectroscopy in general and remote sensing of atmospheric gases in particular. Double Heterostructures (DH) composed of GaInAsSb as active layer and GaAlAsSb as confining layers matched to GaSb substrates have been developed as efficient room temperature diode lasers emitting in this wavelength region.

The first broad area DH $Ga_{1-x}In_xAs_ySb_{1-y}$/ $Ga_{1-x'}Al_{x'}As_{y'}Sb_{1-y'}$ lasers were reported by Bochkarev et al[1], in 1985 with 15% Al ($x' = 0.15$) in the confining layers. The threshold current density J_{th} increasec from 13kA/cm^2 to 20kA/cm^2 as the emissioii wavelength was varied (by changing the active region composition) from 1.99μm to 2.29μm. In 1986 this group reported[2] lasers with 26% Al in the confining layers that showed a minimum J_{th} = 7.6kA/cm^2. Caneau et al reported[3] in 1985 DH lasers with 27% in the confining layers tliat showed a minimum room temperature J_{th} = 6.9kA/cm^2. In 1987 Drakin et al reported[4] DH lasers wdth 27% Al in the confining layers and emission wavelength varying from 1.8μm to 2.4μm. They obtained a miniinum J_{th} in the range of 5 to 7kA/cm^2 independent of lasing wavelength. All these laser growths were done by Liquid Phase Epitaxial. Tlie maximum value of 27% Al in the confining layers was dictated by the difficulty to grow lattice matched layers at 530°C with higher values of x'. So further increase of Al to 40% required higher growth temperatures or the use of intermediate layers. Caneau et al[5], in 1986, increasing values of Al ($x' \approx 0.34$), improved the optical and electrical confinement and reduced the J_{th} to 3.5kA/cm^2. Caneau et al[6] in 1987 obtained J_{th} = 1.7kA/cm^2 with intermediate layers and

*Supported by CNPq
†Now at: Instituto de Física. U. A. de Puebla. Mexico
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using 40% Al in the confining layers. Values as low as $J_{th} = 1.5\text{kA/cm}^2$ were attained by Bochkarev et al[7], in 1988, using $x' = 0.55$. Iii 1989, Zyskind et al[8] presented lasers with the same cornposition of ref. [6] but with higher uniformity, making the complete DH growth over a narrow temperature range. Iii this way, they could avoid the intermediate cladding layers aiid use a simpler structure. The minimun J_{th} obtained was 2.6kA/cm^2 with better yield than Caneau et al[6]. It has been our experience and also that of others who have worked with Liquid Phase Epitnxial, that tlie growth of these DH structures with more than ≈30% Al in tlie confining layers is difficult to dominate iii a reproducible manner, although scattered good results can be obtained. The more sophisticated growth technique of Molecular Beam Epitaxy (MRE) does not suffer from this restriction of Al in the confining layer and was used by Choi et al[9] to obtain lattice matched coiifining layers with $x' = 0.75$ and resulted in very low values of $J_{th} = 0.94\text{kA/cm}^2$.

Narrow stripe lasers grown by Liquid Pliase Epitaxial showed low values of threshold current (I_{th}) when index guiding structures like ridge and buried structures are used. Lower values of I_{th} were obtained by Baranov et al[10], in 1988, with $I_{th} = 240\text{mA}$ for buried structure and $x' = 0.34$ and by Bochkarev et al[7], in 1988, with $I_{th} = 80\text{mA}$ for a ridge structure using 55% Al. The lowest value of $I_{th} = 29\text{mA}$ was obtained by Clioi et al[11], in 1902, for a Molecular Beam Epitaxy (MBE) growth quantum well ridge structure.

We have reported[12] the fabrication of $2.2\mu m$ double heterostructure (DII) emitting lasers made of GaAlAsSb cladding layers and GaInAsSb active layer grown by Liquicl Phase Epitaxial on GaSb substrates. For the GaAlAsSb confining layers we use 27% Al. The lasers showed a room temperature minimum $J_{th}= 2\text{kA/cm}^2$ (L = $300\mu m$). We report in this work laser characterization measurements to obtain some important parameters of these structures.

Fitting of the measured Full Width at Half Power (FWHP) and the shape of the far field patterns allowed the estimation of tlie active layer refractive index. The value obtained is higher than previous theoretical predictions, resulting in a index step $\Delta n/n = 4.2\%$, relative to tlie confining layer.

From the stripe width dependence of the threshold current. and by electrical measurements we will show that the p-type active layer has very low resistivity (p $\approx 10^{-3}\Omega$ cm) and it give a large contribution to the lateral current spreading, causing the high threshold current for narrow stripe geometry lasers. This low resistivity can be the limiting factor for achieving CW room temperature operation. We show that this problem can be overcoine by making the active layer n-type and changing the junction position. With these new oxide stripe lasers, a minimum I_{th} of 290mA (stripe width $\approx 15\mu m$ is achieved compared to 800mA (stripe width $\approx 25\mu m$) for p-type active layer lasers, the broad area J_{th} being 3kA/cm^2 in both cases. Lasers of this n-type active layer show external quantum efficiency of 6 - 10% per facet.

II. Experimental

Tlie laser structures shown in figure 1 were grown by Liquicl Phase Epitaxial under H_2 atinosphere. The growth was at a temperature near 530°C on (100) Te-doped GaSb ($N_A - N_D = 1-3 \times 10^{17}\ cm^{-3}$) wafers, using a cooling rate of 0.3°C/min. The solid composition of the active and confining layers was determined to be $Ga_{0.86}In_{0.14}As_{0.13}Sb_{0.87}$ and $Ga_{0.73}Al_{0.27}As_{0.02}Sb_{0.98}$ by microprobe analysis. Double-crystal X-ray diffraction rocking curves from GaInAsSb and GaAlAsSb layers showed narrow peaks with a $\Delta a/a \leq 3 \times 10^{-4}$ and $\Delta a/a \leq 7 \times 10^{-4}$, respectively. The non-intentionally doped active layer is p-type with residual concentration of $2 \times 10^{17}\text{cm}^{-3}$ and the n-type active layer and GaAlAsSb layers were Te-doped at 1×10^{17} and $5 \times 10^{17}\text{cm}^{-3}$, respectively.

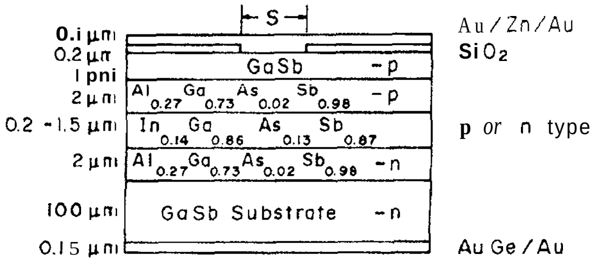

Figure 1: Schematic diagram of the DH stripe heterostructure laser.

Fabrication of broad area and stripe geometry devices was carried out. To define tlic stripe geometry contact. SiO_2 and standard photolithographic procedures were used. Some devices were processed with Zn skin diffusicn and low mesa-stripe structure before the SiO_2 deposition. Following this, the wafers were metallized with Au-Zn on tlic p-side. After lapping the back side to a thickness of $100\mu m$, tlie a metallization of the n-side with the eutetic Au-Ge alloy was performed. Low resistance ohmic contacts were obtained after alloying at 375°C for 3min. Individual devices were cleaved in $300\mu m$ long cavities. The device series resistance for tlie conventional oxide stripe laser was in tlic range of 4 to 8Ω for stripe width between 50 and $5\mu m$, respectively. Low mesa-stripe structures with Zn diffusion showed series resistance around 2Ω for stripe widths iii the range of 10 to $25\mu m$.

III. Results

In Figure 2 we show the variation of J_{th} vs. d ($d \equiv$ active layer thickness) for our broad area p-type active layer lasers. The solid line in the same figure corresponds to the theoretical equation[13]:

$$J_{th} = \frac{J_0 d}{\eta} + \frac{d}{\eta \Gamma \beta'} \left[\alpha + \frac{1}{L} \ln \frac{1}{r} \right] \qquad (1)$$

where:

$J_0 = 1050 A/cm^2\mu m$ is the transparency current

η usually taken as 1 is tlie internal quantum efficiency

Γ is tlie confinement factor

$\alpha = 30 cm^{-1}$ represents tlie internal losses

$\beta' = 0.033 cm/A\ \mu m$

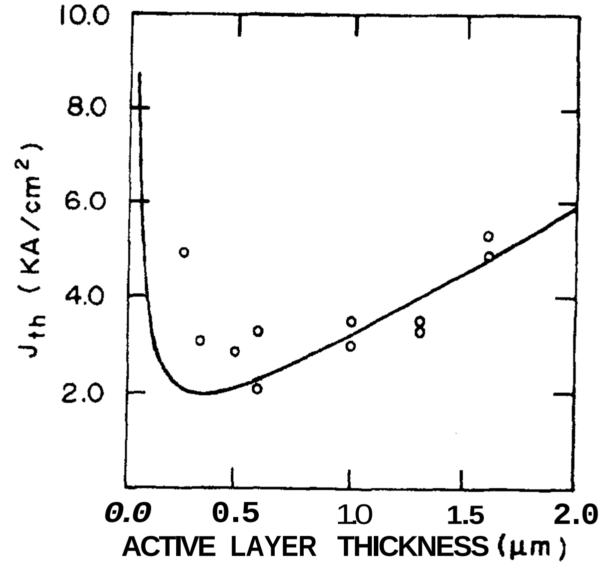

Figure 2: J_{th} vs Active Layer Thickness d. The solid line is a theoretical fit.

We can see, in tlie figure 2, that the experimental minimum occurs at about d = $0.5\mu m$, in good fit to tlie theoretical curve. J_0, α and β' were chosen to give the best fit to the experimental data. This value of α is in the range of the best performance GaInAsSb/GaAlAsSb DH lasers grown by MBE[14], indicating good quality materials and interfaces for our Liquid Phase Epitaxial growths.

The active layer refractive index value, $n_2 = 3.78$, was determined experimentally by us as described be-l o ~ Its value is greater than has been previously assumed (≈ 3.72)[15] and it gives a good fit to our experimental points for equation (1) when used in the confinemet factor calculation. We must observe in figure 2 that our experimental minimum (2 - 3kA/cin^2) of J_{th} vs. d is much lower - by a factor of three - than previously published results[2-4] and also occurs at a lower value of d($\approx 0.5\mu m$) coinpared to $\approx 1\mu m$ previously obtained. The previous workers had ascribed their poor results to a possible lack of good optical confiiiement when using 27% Al in the confinement layers. Our measurement of the refractive index step Δn and also the fit with experimental data of J_{th} vs. d, using this value of Δn demonstrates that this is not true.

The active layer refractive index was measured using two methods. The first one was a direct measurement of reflectivity as a function of incidence angle[16], similar to that of ref. [li]and gave a value of 3.78. In the second method, transverse far field pattern measurements of lasers were used to extract the refractive index following the equations for the far field pattern $I(\theta)/I(O)$[13] and for tlie FWHP $\theta_\perp$ [18] as follows:

$$\frac{I(\theta)}{I(O)} = \left[\gamma\kappa^2\left(\frac{\gamma\cos[k_0(d/2)\sin\theta] - k_0\sin\theta\sin[k_0(d/2)\sin\theta]}{(\kappa^2 - k_0\sin^2\theta)(\gamma^2 + k_0^2\sin^2\theta)}\right)\right]^2 \qquad (2)$$

where

$$k_0 = \frac{2\pi}{\lambda_0} \qquad \lambda_0 = 2.2\mu m$$

κ and γ are the eigenvalue for the fundamental even TE mode symmetric three-layer slab waveguide

$$\theta_\perp = \frac{0.65D\sqrt{n_2^2 - n_1^2}}{1 + 0.086\mathcal{K}D^2} \quad \text{for} \quad 0 < D < 1.5 \qquad (3)$$

where:

$$D \equiv \frac{2\pi}{\lambda}\sqrt{n_2^2 - n_1^2}$$

$$\mathcal{K} = \frac{2.52\sqrt{n_2^2 - n_1^2}}{\tan^{-1}(0.36\sqrt{n_2^2 - n_1^2}}$$

In figure 3, the continuous line shows the experimental transverse far field pattern for a DH $Ga_{0.86}In_{0.14}As_{0.13}Sb_{0.87}$ / $Ga_{0.73}Al_{0.27}As_{0.02}Sb_{0.98}$ laser with $0.2\mu m$ thickness active layer and $5\mu m$ stripe. The dashed line shows the far field pattern calculated from equation (2). The FWHP is $\theta_\perp = 26°$. Both the shape and the FWHP of the far field pattern are in good agreement with the experimental measurement, using $n = 3.78$. Far field patterns of other lasers with different active layer thicknesses were measured and fitted by equations (2) and (3). These data are shown in Table I.

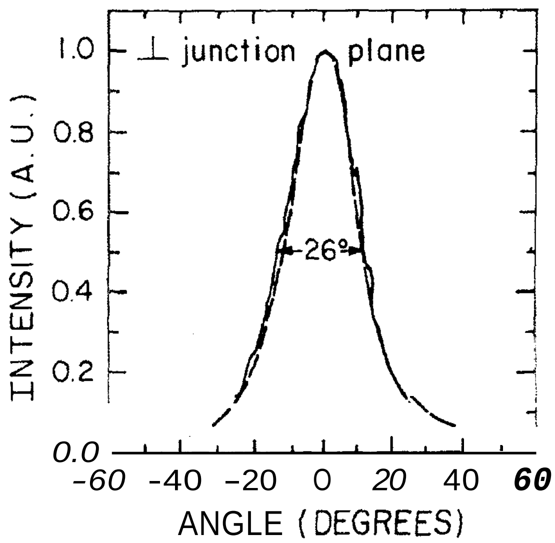

Figure 3: Transverse Far Field Pattern for a $0.2\mu m$ active layer thickness DH GaInAsSb/GaAlAsSb laser shown in the solid line. The dashed line represents a theoretical fit.

Table I: Beam Divergence and Waveguide Parameters for $Ga_{0.86}In_{0.14}As_{0.13}Sb_{0.87}$ active layer diode lasers (300K).

active layer thickness $d(\mu m)$	heam divergence $\theta_\perp$ (degrees)	refractive index n_2
0.2	26	3.78
0.3	34	3.78
0.4	38	3.77

Taking the confining layers refractive index as 3.62 [17], we have a refractive index step An = 0.16 for the above compositions of tlie GaInAsSb/GaAlAsSb DH lasers, confirming the good optical confinement..

Narrow stripe lasers were constructed to reduce the threshold current and achieve CW room temperature operation. However, the oxide stripe structure presented a very high threshold current density in the narrow stripe lasers impeding the CW room temperature operation. To investigate this we prepared oxide stripe lasers with s (stripe width) varying from $5\mu m$ to $200\mu m$, and measured $J_{th}(s)$ (stripe dependent threshold current) as function of s. A typical set of data denoted by triangles for p-type active region lasers is presented in figure 4. A stripe width of $20\mu m$ would lead to J_s nearly to $2CkA/cm^2$.

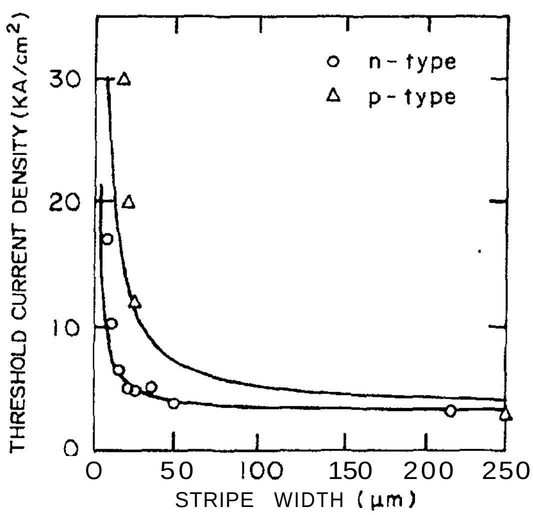

Figure 4: Var ation of $J_{th}(s)$ vs stripe width for p-type (triangle) antl n-type (open circles) active region lasers. Tlie solid lines cor:espond to a.fit to equation (4) using R_x = 312 and $R_x = 60\Omega$.

In this figure we also show a theoretical fit to the equation (4) [19]:

$$J_{th}(s) = J_{th} + [8J_{th}(\infty)/(3s^2R_x)]^{1/2} \qquad (4)$$

where

$J_{th}(\infty)$ is the Broad Area J_{th}

ti, is the Equivalent Spreading Resistence given by: $1/R_x = d_1/\rho_1 + d_2/\rho_2 + ..., d$ and ρ being, respectively, the thickness antl resistivity of the layers participating iii the spreading of tlie majority carriers up to the junction.

This fit for several wafers gave R_x in the range 252 to 20Ω antl did not change appreciably even if the contact layer was mesa-etched in tlic size of the stripe, avoiding spread in that layer. The resistivity of the $p\text{-}Ga_{0.73}Al_{0.27}As_{0.02}Sb_{0.98}$ ($\cong 5 \times 10^{-2}\Omega$ cm) is two orders too high to explain the low R,. Thus the nominaly undoped p active layer must be responsable for the excessive current spread and would have to have $\rho \cong 10^{-3}\Omega$ cm to give R_x in the measured range. We have measured ρ of tlie p active Iayer by the four point probe method and directly on long bars, obtaining ρ near $10^{-3}\Omega$ cm. This approximate concurrence is reasonable since we have neglected carrier outdiffusion and optical mode losses in fitting the data of figure 4.

The curreiit spread of the majority carriers should be limited up to the p-n junction, hence this problem of excessive current spread in tlie active layer should be avoided by making tlie active region n-type. We have carried out a calibration procedure for growing n-type GaInAsSb layers doped with Te. Next, we have grown laser structures incorporating this n-type GaInAsSb Iayers as the active region. The results obtained for these wafers processed as oxide stripe lasers are shown by the open circle data points in figure 4, and a fit to equation (4) gave R, $\cong 60\Omega$. In this case, a stripe width of $20\mu m$ leads to $J_s \cong 5$ kA/cm^L. The smaller diffusion length of holes compared with that of electrons also helps in improving the performance of stripe lasers with n active region. Results of EBIC measurements in GaInAsSb homojunction indicate diffusion lengths of $\geq 2\mu m$ for holes and $\geq 5\mu m$ for electrons. Tlie minimum I_{th} obtained for n-type active layers was 290mA compared to 800mA for p-type active layers, the broad area threshold current density being the same ($3kA/cm^2$) in both cases.

In figure 5 we show the Output Power vs. Current for one laser chip of this new active layer with $15\mu m$ stripe width. It shows low threshold current and high efficiency. The threshold current for this stripe geometry laser is $I_{th} = 290mA$ and the external quantum efficiency $\eta_{ext} = 10\%$ per facet. Recent progress in processing low mesa structure allowed us to attain the lowest threshold curreiit of 170mA, as we show in figure 6. This kind of laser should enable us to obtain index guiding ridge structure lasers to CW room temperature operation.

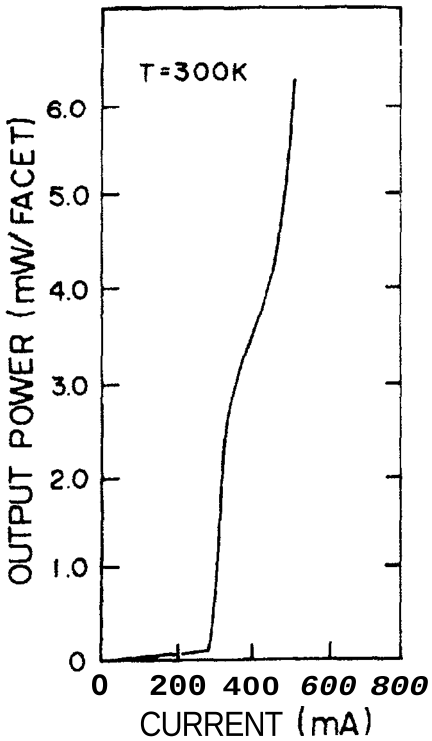

Figure 5: Output Power vs. Current for a oxide stripe n-type active region laser.

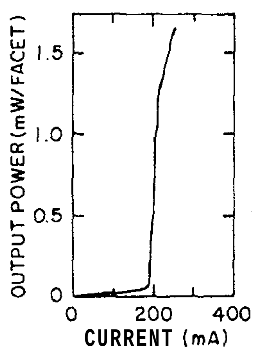

Figure 6: Output Power vs. Current for a low mesa stripe n-mesa active region laser.

IV. Conclusions

In this work we presented tlie more important characteristics of $Ga_{0.86}In_{0.14}As_{0.13}Sb_{0.87}/Ga_{0.73}Al_{0.27}As_{0.02}Sb_{0.98}$ DH broad area and oxide stripe lasers grown in our laboratories by Liquid Phase Epitaxial. We show that tlie lasers present very low tlireshold current density with a. minimum of $2kA/cm^2$ [12]. Using transverse far field patterns and theoretical calculation for the fundamental mode[13,18] we estirnated the value of the active layer refractive index as $n_2 = 3.78$. This value was obtained considering the measured valiie for the confining layers refractive index as $n_1 = 3.62$ [17]. The index step is $\Delta n/n = 4.2\%$, showing that there is a significant waveguiding in this Double Heterostructure.

We also show that the low value of the active layer resistivity ($\rho \approx= 10^{-3}\Omega cm$) is the main responsable for the current spreading, impeding a CW room temperature operation of these lasers. Making tlie active region n-type and changing the p-n junction position to ahove active region the lasers exhibited hetter performance, with external quantum efficiency in the range of 6 - 10% per facet and tlireshold ciirrent as low as 290mA.

Acknowledgements

This research was suported by TELEBRÁS. The authors wish to thank to E. I. F. Piza and E. F. Z. A. von Zuben for help with device fabrication, Prof. C. A. Ribeiro for microanalisys, W. Carvalho Jr. and H. Gazeta for X-Ray difraction analisys.

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