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LAMP SERIES REPORT

(Laser, Atomic and Molecular Physics)

VARIATION OF THE REFRACTIVE INDEX FOR THE ACTIVE LAYER OF THE DOUBLE HETEROSTRUCTURE GaAlAsSb/GaInAsSb/GaAlAsSb IN INJECTED MODE

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Preface

The ICTP-LAMP reports consist of manuscripts relevant to seminars and discussions held at ICTP in the field of Laser, Atomic and Molecular Physics (LAMP).

These reports aim at informing LAMP researchers on the activity carried out at ICTP in their field of interest, with the specific purpose of stimulating scientific contacts and collaboration of physicists from Third World Countries.

If you are interested in receiving additional information on the Laser and Optical Fibre activities at ICTP, kindly contact Professor Gallieno Denardo, ICTP.

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Abstract

This work reports on the influence of the injected current on the refrective index in the active layer of GaInAsSb/GaAlAsSb laser diodes. These diodes present at threshold a full beam width at half power $\theta_\perp$ of about 52°. The fluctuation of the refractive index caused by the injection of free carriers was studied on the basis of the evolution of $\theta_\perp$ as a function of the injected current. It was shown that the inversion of the population which follows the rising of the gain, causes a slight decrease of the refractive index.

1 INTRODUCTION

The schematic representation of the double heterostructure laser which was studied is shown in Figure 1. It is constituted of an active layer obtained from the quarternary $Ga_{0.83}In_{0.17}As_{0.15}Sb_{0.85}$. The active zone, seat of the radiating recombinations is sandwiched by two lateral zones, called confinements, obtained from the alloying $Ga_{1-x}Al_xAs_ySb_{1-y}$.

During the course of previous studies [1], the interest shown in these diodes has been explained.
It has been shown [2-5] that such lasers would be useful for a variety of applications.
Fermi-Dirac statistics show that the number of carriers injected in the active zone above the threshold stabilizes at the level of the threshold value. In consequence, the gain is quasi-constant as well as the full beam width at half power must remain practically constant for $I > I_{th}$. On a purely experimental level, the variation of the refractive index caused by the injection of free carriers through the study of the full beam width at half power $\theta_\perp$ near the threshold as a function of the injected current was studied. This study showed that the inversion of the population which accompanies the increase in gain limits the optical confinement.

2 PRESENTATION OF RESULTS

Figures 2 and 3 illustrate the evolution of the far field perpendicular to the interface of the laser diodes as a function of the injected current.
The threshold current I_{th} of the diodes is contained between 350 and 400 mA, with the exception of the 462-4 where the threshold is contained between 130 and 135 mA.
Only one lobe is observed which means that the diodes work on the order of mode zero. As a matter of fact, the order m of the mode which can propagate in a double symmetric heterostructure laser is given by the expression:

$$m < \frac{K_0 d}{\pi}\sqrt{n_{act}^2 - n_{conf}^2} \qquad m = 0, 1, \ldots$$

The calculation for these diodes gives $m < 0.85$. Thus, on a purely theoretical level, only the mode of order zero can propagate on the orthogonal plane at the junction. Such a theoretical prediction is therefore in agreement with our experimental results.
The diodes 462-4 and 462-6 present respectively at threshold a full beam width at half power $\theta_\perp$ of about $52.5 \pm 1°$ and $51 \pm 1°$.
In order to appreciate the variation of the refractive index caused by the injection of free carriers, the evolution of $\theta_\perp$ as a function of the injected current near and far from the threshold, has been represented in Figures 4 and 5. A decrease of $\theta_\perp$ is noticed, followed by a region of no change of values at higher currents.

3 INTERPRETATION OF RESULTS

According to the general theory of the system of equations describing conduction in heterojunctions and taking into account the different mechanisms of recombination generation which appear in the active zone, it has been shown that the product of densities of carriers N and P in the active zone at the pre-threshold rate can be written as:

$$N_0 P_0 = NP \exp(E_{FP} - E_{FN})/KT$$

where N_0 represents the density of electrons at equilibrum and P_0 that of holes at equilibrum.
When $I > I_{th}$, it is essential to make use of the Fermi-Dirac statistics:

$$N = N_c f(\frac{E_{FP} - E_c}{KT}) \qquad P = N_v f(\frac{E_v - E_{FP}}{KT})$$

where N_c and N_v are the effective state densities and f is the Fermi integral of order 1/2. It is percieved that the number of injected carriers in the active zone depends directly on the separation of the Fermi-quasi-levels.
The observed behaviour of the curves is unexpected. In general, beyond the threshold, the electronic concentration in the active zone becomes stable at the level of its threshold value so that all the surplus pumping in connection with its threshold value is used to increase the photon density. In consequence, the gain is quasi-constant, thus the full beam width at half power would have to remain practically constant for $I > I_{th}$.
Let us recall that in any case, the notion of the constant gain of the threshold current is strongly connected on one hand to the quality of alloyings forming the double heterostructure laser, in particular the layer of the active zone, and on the other hand to the longitudinal homogeneity of the waves propagating in the Fabry-Perot cavity.
As a mather of fact, between the modes which are strongly excited, a strong concurrence is manifested, so that the multimode rate is overcome by the errors of spatial and temporal homogeneity of the field prevailing in the resonator. Meanwhile, an interpretation of the results through the effect of free carriers is attempted. In general (on a purly theoretical level), a plane wave propagating in the semiconductor exerts an action

on the free carriers of density N and causes a complex refractive index of which the real part can be set in the form of two terms.
The first term which represents the anormalous dispersion contribution to the effective (modal) differential refractive index is calculated using a Kramers-Kronig transformation [6].

$$\frac{dn_{eff}(E')}{dN} = \frac{hc}{2\pi^2} \int_0^\infty \frac{dg(E)/dN}{(E+E')(E-E')} dE$$

where n_{eff} is the effective refractive index, N the density of free carriers in the well, h Planck's constant, c the speed of light in vacuum and E' the photon energy.
The second contribution to dn/dN is due to the plasma effect [7,8], in which free carriers, responding to the optical electric field, induce an additional polarization, which reduces the refractive index proportional to the carrier density. For each type of carrier the change in differential refractive index due to the plasma effect is approximated as:

$$\Delta n(free\ carrier) = -\left[\frac{q^2 \lambda^2 N_i}{8\pi^2 \epsilon_0 n_0 c^2 m_i^*}\right]$$

where q is the unit charge, λ the wavelength, ϵ_0 the vacuum permittivity, n_0 the effective (modal) index in the absence of free carriers, m_i^* the effective mass and N_i the carrier density of the appropriate type of carrier.
The previous equation clearly shows the variation of the index of the active zone as a function of the number of the injected carriers due to the plasma effect.
In general, the full beam width at half power $\theta_\perp$ depends on the difference $\Delta n = n_{act} - n_{conf}$ [9-11]. This means, that the higher Δn, the greater the full beam width at half power of the emitted field will be. If we suppose that there exists a slight variation of free carriers above the threshold due to the contribution of other bands (e.g. impurity band), then the decrease of $\theta_\perp$ can be associated to the decrease of Δn for the values of current which are slightly superior to the value at threshold.
As the variation of the refractive index n_{conf} of the passive layer is negligible, the decrease of Δn can be attributed to a slight variation in the number of carriers which causes a decrease of the index n_{act} of the active layer.
The level observed on the curve would correspond to complete saturation. The work cited in reference [12] shows that in a situation of weak injection

of free carriers, the refractive index increases up to a maximal value and then decreases from a level of injection.

The experimental results of Figures 4 and 5 are in very good agreement with the theoretical predictions and show that the inversion of population which follows the increase in gain limits the optical confinement.

4 CONCLUSION

This research showed that complex phenomenon which are sometimes difficult to interpret can appear in the injection mode, particularly when the current is increased beyond the threshold level.

The longitudinal inhomogeneities of the EM field (provoked by the stationary waves at the nodes where the radiative transition speed is below the average speed) and the non-linear character of the interaction of modes can be the cause of the observed instabilities.

The decrease of the full beam width at half power $\theta_\perp$ as a function of the injection current near the threshold for $I > I_{th}$ shows, that the inversion of population which follows the rising of the gain, is a factor which limits the confinement of light in the active layer and causes a slight decrease in its refractive index.

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Figure captions

Figure 1: Schematic representation of the double heterostructure laser diode.

Figure 2: Evolution of the far field (perpendicular to the junction plane) as a function of the injected current for the DH laser 462-4.

Figure 3: Evolution of the far field (perpendicular to the junction plane) as a function of the injected current for the DH laser 462-6.

Figure 4: Evolution of $\theta_\perp$ as a function of the injected current for the DH laser 462-6.

Figure 5: Evolution of $\theta_\perp$ as a function of the injected current for the DH laser 462-4.

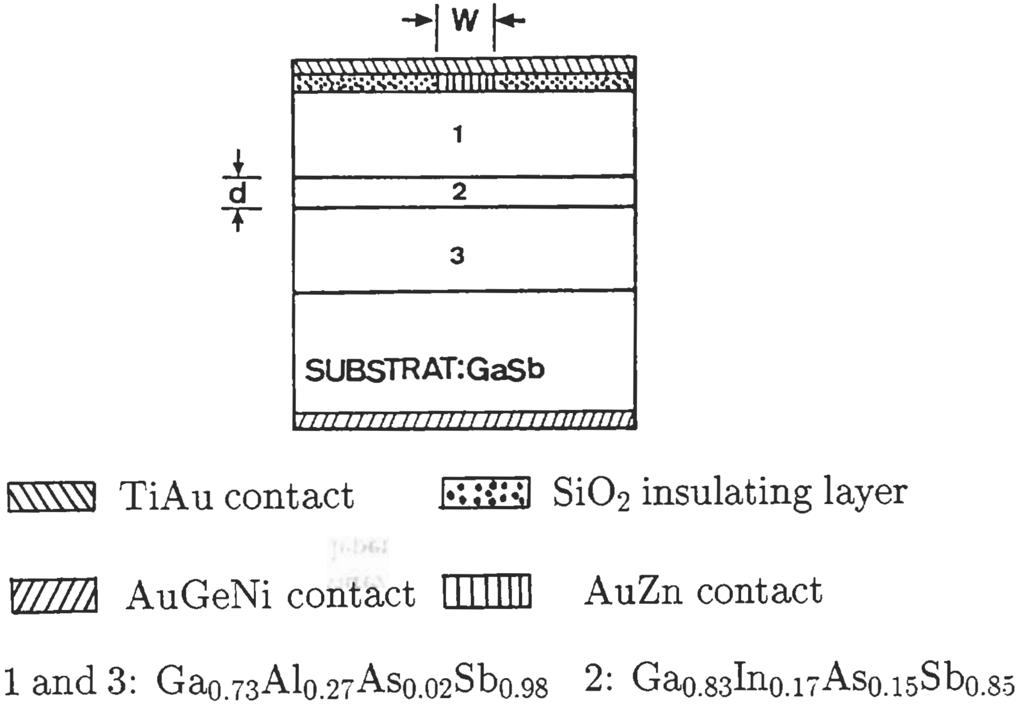

Figure 1.

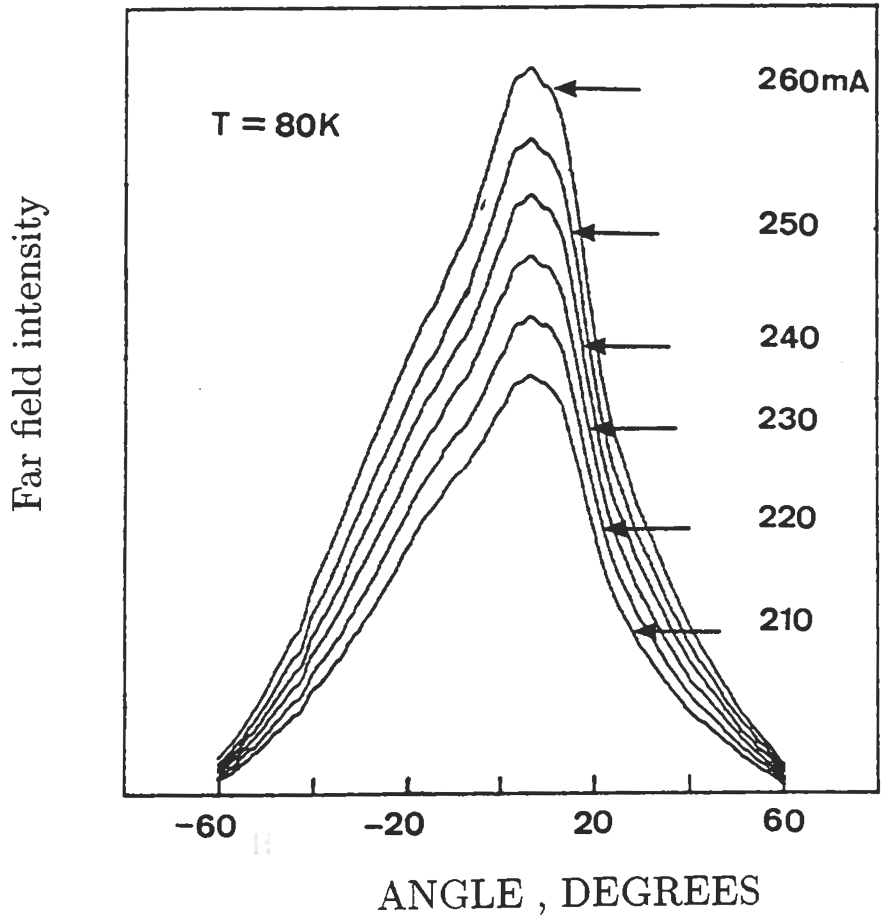

Figure 2

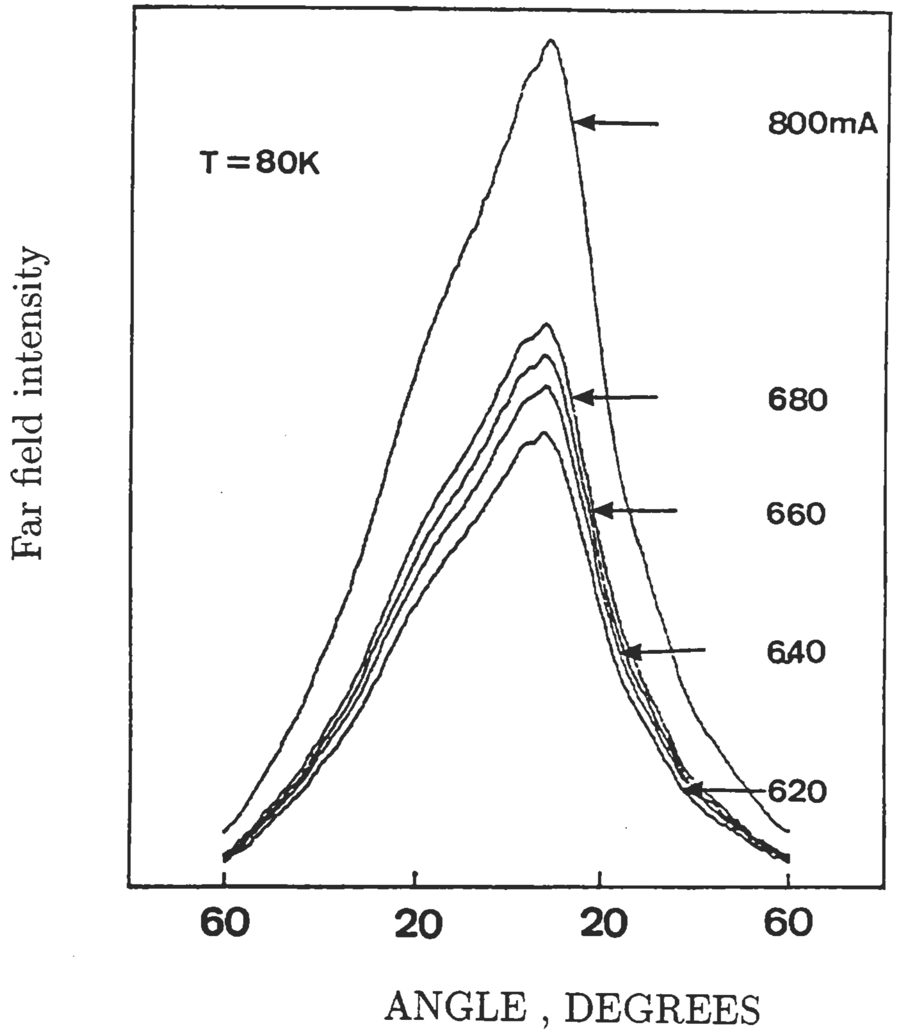

Figure 3.

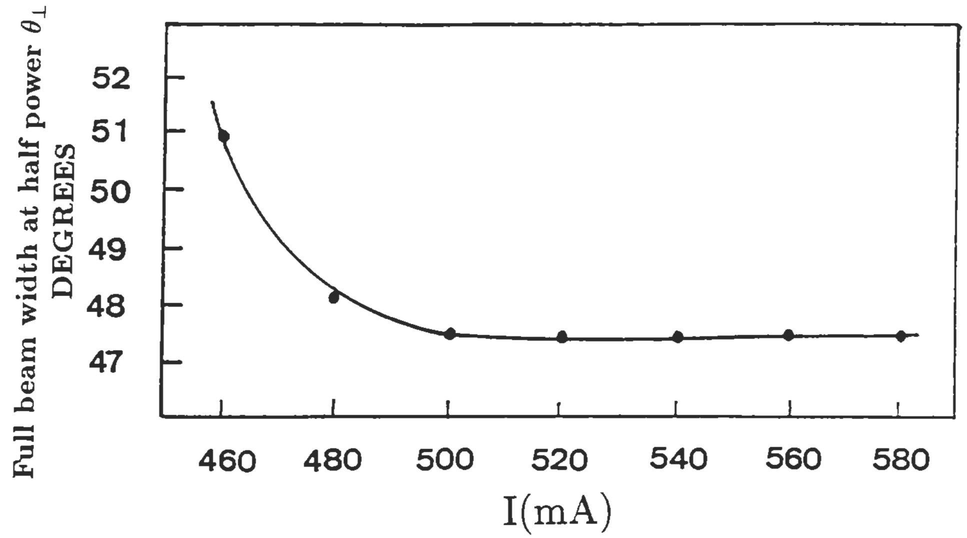

Figure 4

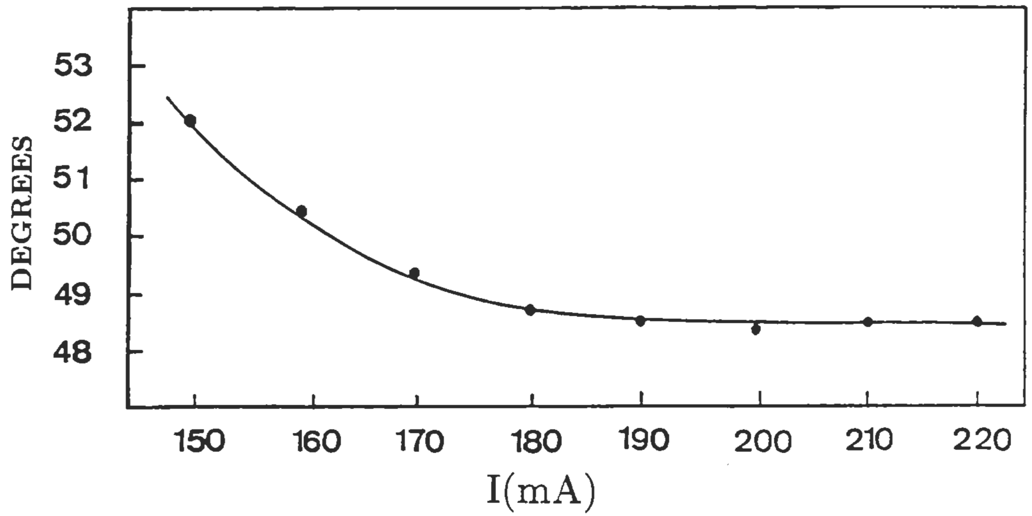

Figure 5