Refractive index dependence on free carriers for GaAs

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This work reports on the influence of the injected free carriers on GaAs refractive index N at 297 °K. The variation of N caused by injected free carriers was theoretically calculated in a more complete way than has been performed earlier. New results were obtained rather than those of a reducing effect on N in a linearlike dependence on the injected free carrier concentration n. They are: (1) linearlike dependence of N on n occurs only beyond a certain value n_1 and (2) an increasing effect on N is caused by the injected free carriers for concentrations in the range between $n = 0$ and a certain value of $n = n_c$ ($n_c < n_1$). In the range $n_c < n < n_1$ a nonlinear decreasing effect was obtained. Effect (2) has not been noticed up to now, so far as the authors know.

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The influence of free carriers on the refractive index of GaAs has been invoked to explain some phenomena observed in GaAs lasers.[1-4] One important phenomena, for practical applications, is the laser waveguide formation[3,4] in the direction parallel to the junction plane.

In this case, injected free carrier perturbation on the refractive index dominates processes.[4] Up to now the refractive index variation with injected carriers $\Delta N(n)$ has been taken as directly proportional to the injected carrier density n. The proportionality constant[5,6] includes the plasma effect and the Burnstein shift of the absorption edge. Some experimental data[7,8] have shown agreement with this relation between ΔN and n. This relation was obtained by Thompson[5] with an approximate calculation. Another indirect approximate calculation of N as a function of injection current was made by Cross and Adams[9] by using an analytic fit to Marples's refractive index data and considering the carrier exchange interaction and the injection only through an "effective band-gap energy".

THEORETICAL FRAMEWORK

In this work we present the results of a detailed calculation of the refractive index variation with free carriers, using a modified Kramers-Kronig analysis of a theoretical absorption coefficient calculation using Stern's treatment.[10] This calculation takes into account the band gap shrinkage caused by free carriers,[11] and the influence of the injected carriers on the bandtails and on the matrix element developed by Stern in Ref. 12. This matrix element describes the change from selection rule transitions for high energies, when parabolic bands take place, to nonselection rule transitions that occur for low-energy transitions, when bandtails are involved. Besides the band-to-band absorption, our calculation of the refractive index includes lattice absorption and intra and interband absorption. These effects were calculated using the following expressions:[10]

$$\Delta N_{1v} \simeq -9\times 10^{-4}/NE^2, \tag{1}$$

$$\Delta N_{\text{intra(holes)}}(E) \simeq -1.8\times 10^{-21} p/NE^2, \tag{2}$$

$$\Delta N_{\text{intra(electrons)}}(E) \simeq -9.6\times 10^{-21} n/NE^2, \tag{3}$$

$$\Delta N_{\text{inter(holes)}}(E) \simeq -6.3\times 10^{-22} p/E^2. \tag{4}$$

RESULTS

In this section, results of our calculations will be shown. In Fig. 1 is shown the spectral absorption coefficient corresponding to band-to-band transitions using bandtail densities of states, including the negative absorption part of the curve (or gain coefficient) for different injected carriers densities n.

In Fig. 2, the refractive index as a function of the photon energy, for different injected carrier densities, is shown. The refractive index shown in this figure was calculated by using the data of Fig. 1, including the effects described by Eqs. (1)–(4).

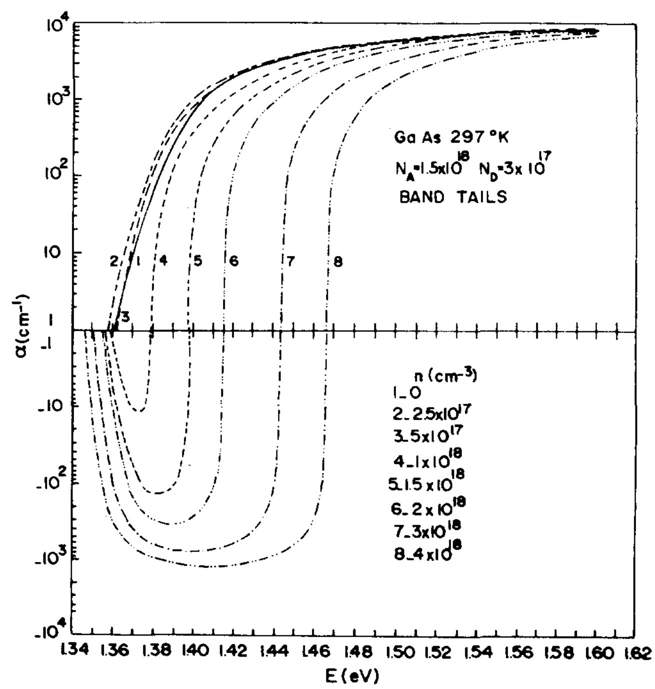

FIG. 1. Absorption coefficient vs photon energy as calculated by using a bandtail model for different injected carrier densities in the range n:0–4×10^{18} cm^{-3}.

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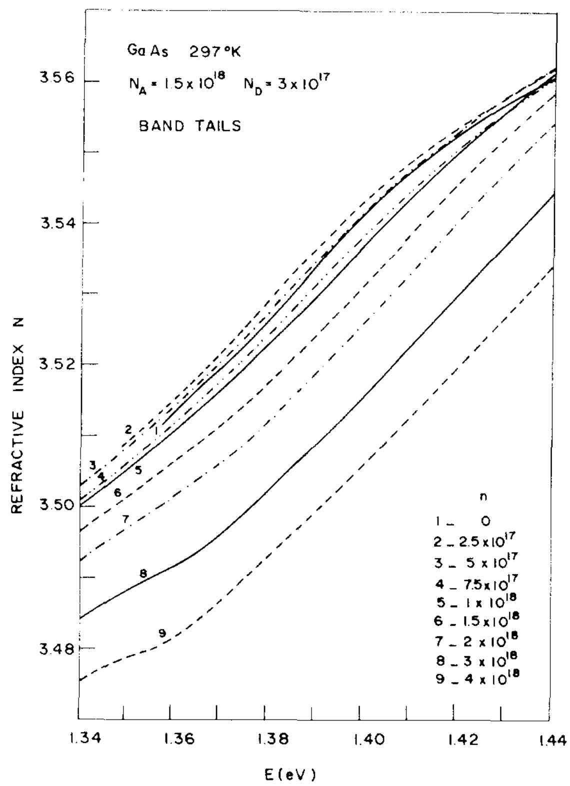


FIG. 2. Resulting refractive index from the modified Kramers-Kronig analysis of the absorption for different injected carrier densities.

The refractive index as a function of the injected carrier density is shown in Fig. 3, where we present curves for differ-

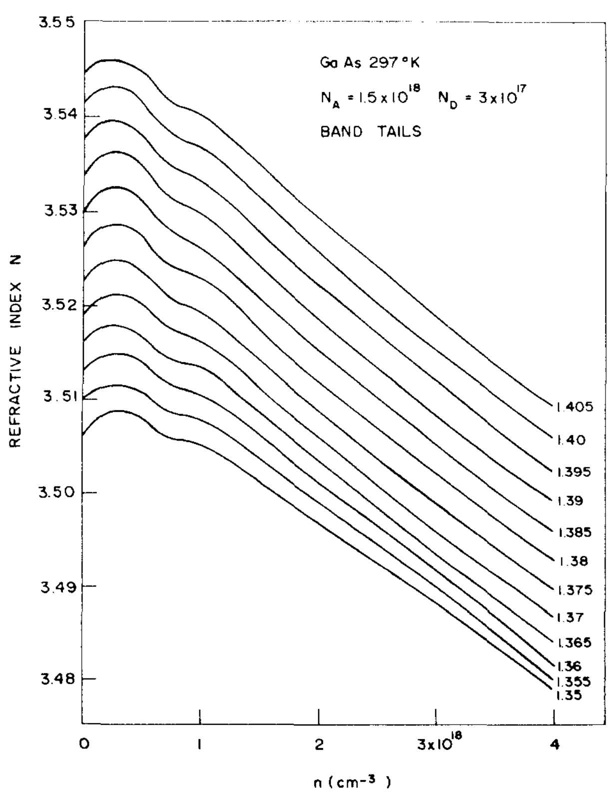


FIG. 3. Refractive index as a function of the injected carrier density for different photon energies.

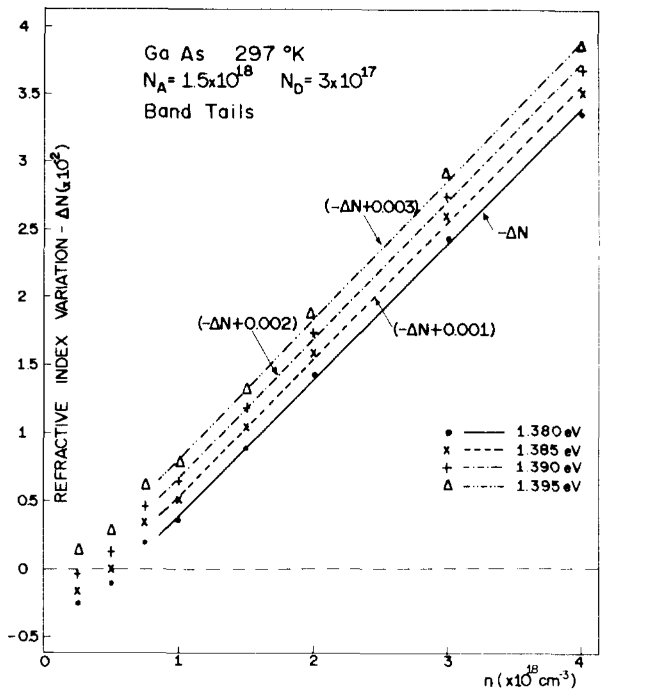


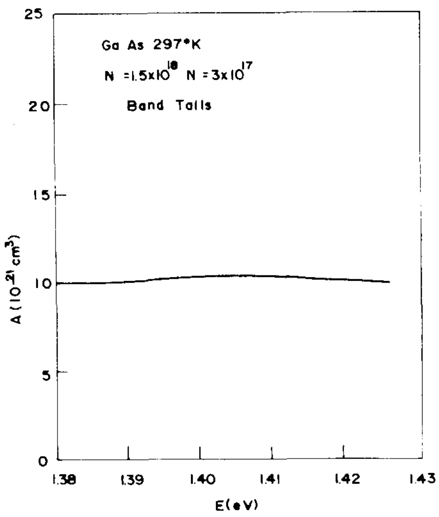
FIG. 4. Refractive index variation $-\Delta N$ as a function of the carrier injection n for different photon energies. Note that for $n < 7\times10^{17}$ cm^{-3}, ΔN is positive.

ent energies, mainly those close to typical lasing photon energies. The data shown in this figure were obtained from Fig. 2 by taking one energy and the refractive index corresponding to different carrier densities. We note in this figure that up to around 6×10^{17} cm^{-3}, the refractive index first increases with n reaching a maximum value which is photon energy dependent. Beyond the carrier-concentration value n_0 corresponding to this maximum value, the refractive index decreases with n crossing the value corresponding to the case of no injection ($n = 0$). For carrier concentration beyond this crossing point, the refractive index is a decreasing function of n: however, a linear behavior occurs only for values of n greater than a certain n_1 which is photon energy dependent. This can be seen clearly in Fig. 4 where the negative variation of the refractive index $-\Delta N$ is shown as a function of the injected carrier density n. In the case of the linear behavior of ΔN with n, the relation between them will be

$$\Delta N = -An + B(h\nu). \quad (5)$$

Here we must point out that this expression should be followed by the condition $n > n_1$, where n_1 is the value of n beyond which ΔN varies linearly with n; therefore, (B/A) here does not indicate the value of n for which ΔN equals zero. In some cases, depending on photon energy (and also depending on doping level), Eq. (5) approaches the behavior of ΔN with n between n_1 and n_0, and it may be used as a good approximation.

Figure 5 shows the two parameters A and B as functions of the photon energy. It can be observed that A is almost a constant parameter while B is not.



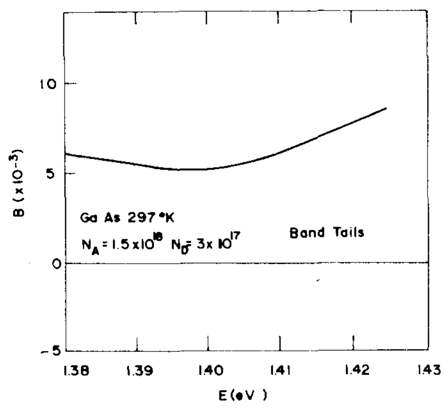


FIG. 5. Constants A and B used for the straight lines fitting of the points (ΔN vs n) shown in Fig. 4 as a function of the photon energy.

CONCLUSION

We have obtained with our calculations the refractive index perturbation caused by the injected free carriers. The results indicate that free carriers do not only reduce the refractive index in a linear way as was obtained by Thompson. For low injection levels free carriers increase the refractive index, and the decreasing effect only happens beyond a certain injection level. Also we observed that the decrease of refractive index with free-carrier concentration only occurs in an approximately linear way for carrier densities beyond a certain n_1. This indicates that in GaAs lasers, the refractive index variation from the center to the edges of the waveguide along the junction plane does not vary monotonically. This fact may influence the guided mode the narrower the stripe width is. The increasing effect of injected free carriers has not been noticed up to now, as far as we know. However, the refractive index calculated by Zoroofchi *et al.*,[13] from experimental absorption coefficient data for different n- or p-doped GaAs samples, shows an increasing effect with doping concentration similar to that which we have calculated in the energy range close to the gap. Also, experimental measurements of double-beam reflectance for n-type samples of GaAs made by Sell *et al.*[14] whose results in refractive index versus energy curves showed that in a certain energy range, the refractive index increases with n for low doping, and decreases as it is doped even more.

These data also suggest that the injected free-carrier effect that we calculated could be doping level dependent. The higher the doping level, the smaller the injected free-carrier effect. Calculations for different doping levels will be carried out. The differences observed among Thompson's results and our data can be related to the inclusion in the calculation of the band-gap shrinkage and tail length variation with free-carrier injection level not considered by him.

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