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The Relevance of Extrinsic Effects in GaInAsP Devices

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New experimental results on emission, absorption, gain and lifetime investigations show that the bandstructure of undoped GaInAsP is not parabolic and exhibits pronounced extrinsic features. Low energy tails or acceptor like states exist which have a considerable influence on the time response, the mode behaviour of lasers and the intensity saturation of light emitting diodes. Extrinsic effects are a general feature associated with all quaternary GaInAsP materials and devices.

Introduction

The material properties of quaternary GaInAsP-compounds have gained considerable interest in recent times in connection with the performance of long wavelength optoelectronic components. We have investigated the optical properties of GaInAsP-lasers, LED's, and LPE-layers with various optical techniques which reveal the existence and influence of pronounced tail states and corresponding extrinsic recombination effects. These tail states[1] are a general feature of GaInAsP, and they are present even in undoped materials. They change with doping level, and they have a strong influence on the performance of optoelectronic devices.

We have investigated the density of states near the bandedge, which shows characteristic extrinsic structures, with the following methods:

1) Temperature and excitation dependent emission spectroscopy
2) Temperature dependent near edge absorption spectroscopy
3) Temperature dependent gain spectroscopy
4) Carrier lifetime measurements as a function of carrier density and temperature

All these experimental methods lead to evidence for strong deviations from a simple intrinsic parabolic density of states.

Experiments and Discussion

Fig.1 shows a set of luminescence spectra obtained on a nominally undoped GaInAsP/InP double heterostructure (DHS). The spectra were measured at 57 K and at five different excitation levels. Two emission lines are clearly resolved. The existence of these two lines can only be interpreted if an additional band-acceptor recombination is assumed besides the normal band-to-band transition. The band-acceptor transition involves an acceptor like state ΔE = 13 meV above the valence band. Above 57 K, the emission spectra broaden, and the individual transitions cannot be resolved. In samples with higher doping concentration, we could not resolve two seperate emission lines. Instead, we observed an unusually broad emission spectrum.

These facts which were found in luminescence studies were further confirmed by near edge absorption measurements.

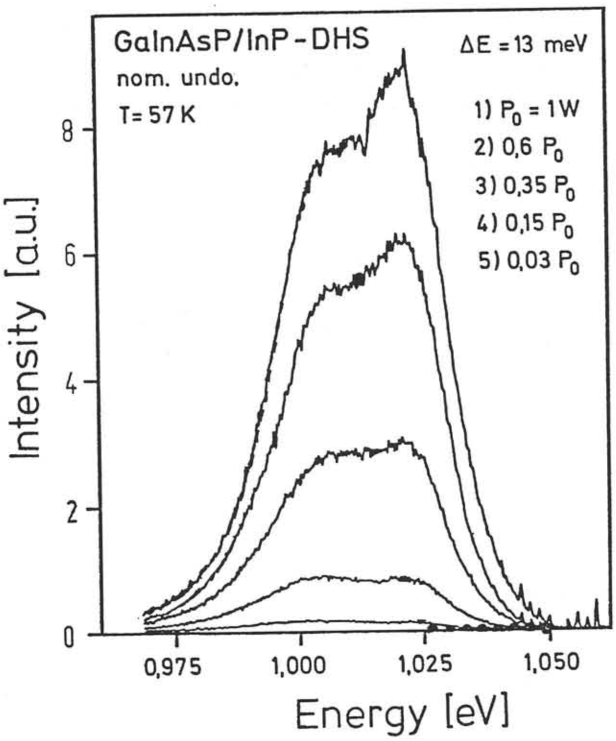

Fig.1 Spontaneous emission spectra of a GaInAsP/InP-DHS with an active layer thickness of 0.2 μm at low optical excitation levels. Low threshold injection lasers were made from the same wafer for comparison.

Fig.2 depicts an absorption spectrum obtained on a 3.8 μm thick nominally undoped GaInAsP epitaxial layer ($|N_D-N_A|=8\cdot10^{15}cm^{-3}$) at T = 84 K. Again, an energy state with an absorption coefficient of about 100cm^{-1} is observed below the normal band edge. Also plotted in Fig.2 is the expected square root dependence for a normal band-to-band absorption. In highly n and p doped samples, a pronounced low energy tail was measured ($N_D,N_A > 8\cdot10^{17}cm^{-3}$) instead of the characteristic impurity absorption structure of Fig.2.

In comparison to the situation in GaAs at similar doping levels, tail states in GaInAsP extend over a much larger energy range, until 100 meV at $N_A = 2\cdot10^{18}cm^{-3}$.

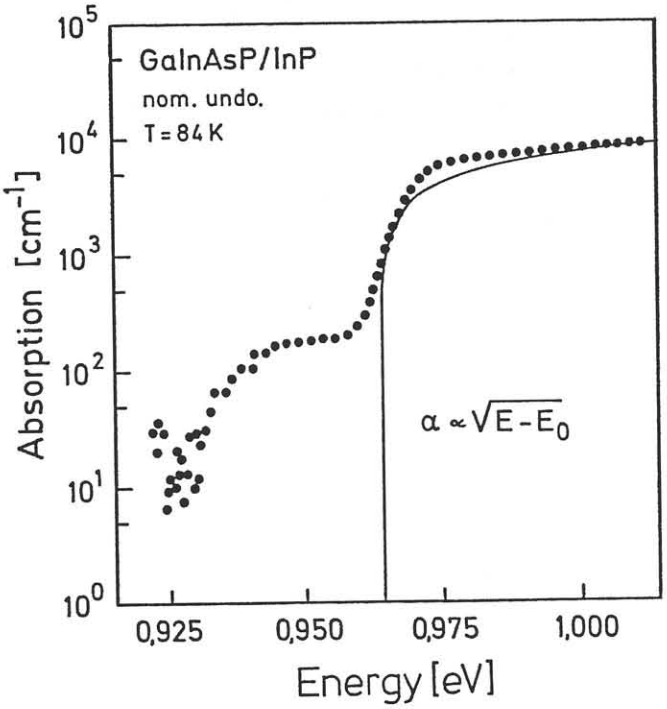

Fig.2 Absorption spectrum of a nominally undoped GaInAsP ($|N_D-N_A| = 8\cdot10^{15}cm^{-3}$), epitaxial layer.

A more sensitive and quantitative method to investigate these always present extrinsic states is the following: The spontaneous emission of a semiconductor with direct energy gap is given by

$$r_{sp} = \frac{4\pi ne^2E}{\varepsilon_o m^2h^2c^3} \; |M|^2 \; \varrho_{join} \; f^{CB} \; (1-f^{VB})$$

where ϱ_{join} is the joint density of states. The absorption coefficient of the same semiconductor is given by

$$\alpha = \frac{e^2\pi h}{\varepsilon_o nm^2cE} \; |M|^2 \; \varrho_{join} \; (f^{VB}-f^{CB})$$

By selfconsistent calculations including the measured spontaneous emission and absorption spectra of the same sample, at the same excitation intensity and temperature, the joint density of states as a function of energy can be determined. Fig.3 shows the result of an evaluation obtained on an unintentionally doped ($|N_D-N_A| \simeq 10^{16}cm^{-3}$) LPE-GaInAsP epitaxial layer at T = 82 K. A distinguished acceptor like band can be observed about 12 meV below the band edge. This feature is present in undoped materials and becomes enhanced with increasing p-doping level.

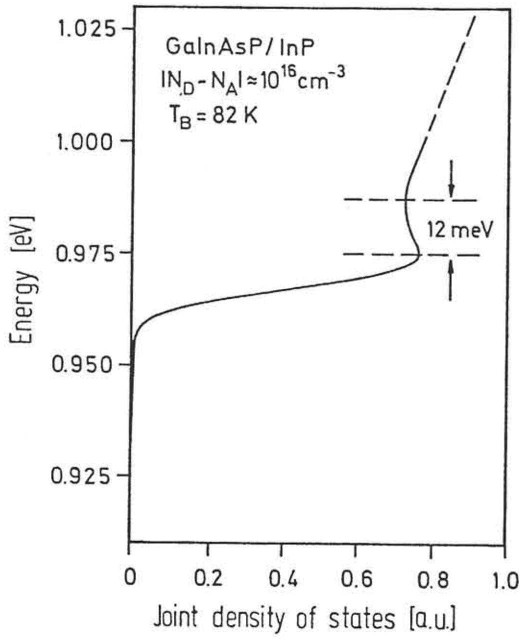

Fig.3 Joint density of states for undoped GaInAsP derived from spontaneous emission and absorption data.

For a physical characterization of semiconductor lasers, it is desirable, to know if the observed localized states give rise to optical amplification. In order to check this question we have performed spectrally resolved gain measurements. GaInAsP-DHS were optically excited with a slit of variable length and the gain was determined by the method of single pass amplification of spontaneous emission.[2] Fig.4 depicts an example of this gain spectrum obtained on a nominally undoped GaInAsP/InP-DHS at T = 260 K. The gain spectra demonstrate that the acceptor like states have an optical net gain of $200cm^{-1}$ up to $300cm^{-1}$ at low temperatures $T \leq 200K$. At higher temperatures $T \geq 200K$, however, the optical gain of the band-to-band transition dominates. The relative importance of the extrinsic and intrinsic gain contribution can be derived in a direct and convenient way from this typ of gain analysis at different temperatures. These details of the gain spectra have an immediate influence on the mode behaviour of quaternary multimode lasers.

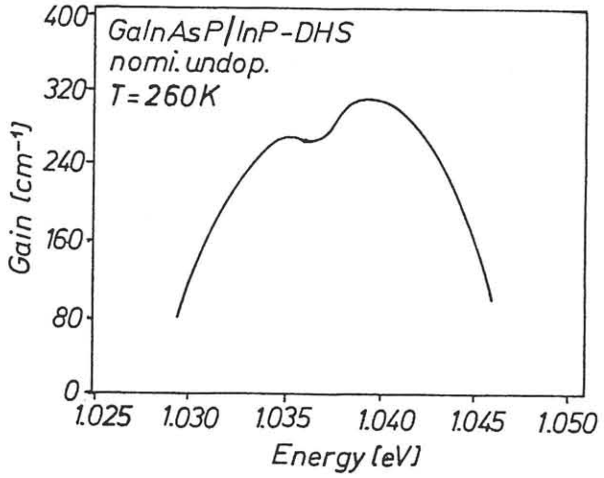

Fig.4 Gain spectra of an undoped GaInAsP/InP-DHS. The sample was pumped with 500 W by a pulsed dye laser.

Finally, with time resolved measurements we have determined the recombination coefficients A (extrinsic coefficient) and B (intrinsic band-to-band coefficient). For these measurements the samples were optically excited with a 25 ps laser pulse, and the decay of the emission intensity was studied. Fig.5a presents an example of these measurements obtained on a nominally undoped DHS at T = 60 K.

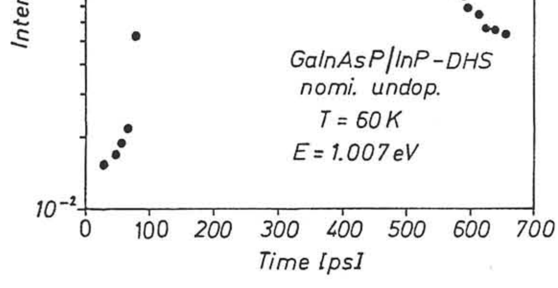

Fig.5a Time dependence of the emission intensity of a GaInAsP/InP-DHS after a very short optical excitation pulse.

The analysis of the time decay shows that the extrinsic recombination can be faster than the band-to-band recombination. In detail this depends on the doping level of the sample. The extrinsic recombination coefficient has values of $5 \cdot 10^{7}\ s^{-1}$ in nominally undoped samples and becomes as high as $10^{10}\ s^{-1}$ in p-doped material ($N_A = 2 \cdot 10^{18}\ cm^{-3}$). It is weakly temperature dependent. The band-to-band recombination coefficient, is about $8 \cdot 10^{-11} cm^3 s^{-1}$ at room temperature, and it increases strongly with decreasing temperature.

A narrow emission linewidth is connected with a fast extrinsic recombination. Linewidth values of about 20 meV at 60 K and at an injected carrier concentration of about $8 \cdot 10^{18}\ cm^{-3}$ are observed as Fig.5b demonstrates.

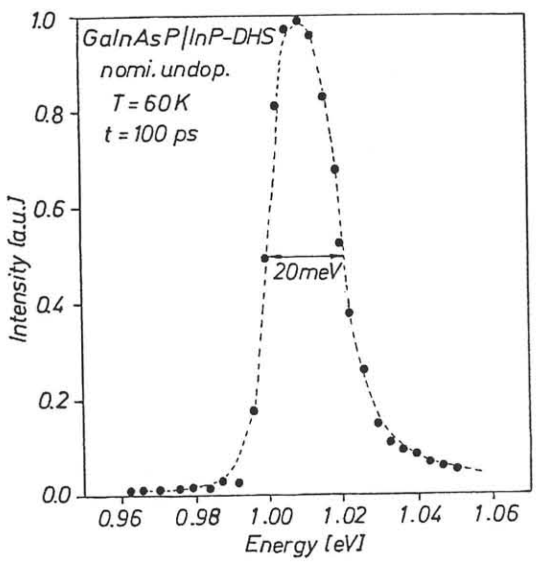

Fig.5b Emission spectrum 100 ps after the excitation. The same DHS as in Fig.5a was used.

A linewidth of about 260 meV would be expected for a spontaneous band-to-band emission and about 220 meV for stimulated transitions at the mentioned temperature and carrier concentration. The observed narrow emission line is a very strong argument for the presence of band-acceptor transitions.

Furthermore, in the case of the quantitative understanding of the intensity saturation effects of spontaneous surface emitting diodes, we can demonstrate that this extrinsic recombination rate must be included.

Conclusion

The combined experimental results presented in this paper are unambiguous evidence for strong deviations of the parabolic bandstructure of GaInAsP due to extrinsic states. An acceptor like state about 12 - 15 meV above the valence band was observed by different methods in different undoped and doped samples. We assume that these acceptor like states are not caused by residual impurities as zinc or carbon etc, but that they are a general feature of disordered quaternary alloys.

References

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