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INEQUIVALENCE OF STAGGERED INTERFACES IN InAlAs/InP MULTI QUANTUM WELL STRUCTURES

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We investigate the electronic structure and the gain characteristics of lattice matched InAlAs/InP multi quantum wells by means of time-integrated and time-resolved photoluminescence and optical gain spectroscopy. Varying the doping profile we observe luminescence from either the 'normal' InAlAs on InP or the 'inverted' InP on InAlAs interfaces which show different optical properties. Optical gain measurements reveal values of up to 70 cm^{-1} for the normal interface but only absorption for the inverted interface transition.

1. Introduction

Heterojunctions made of InAlAs/InP are of growing interest because of their staggered band lineup leading to tunable below gap light emission.[1] The structural quality of interfaces becomes more important in this system as compared to nested heterostructures, because of the carrier localization at the interfaces and the optical transitions which are all spatially indirect. For realistic devices not only a single interface has to be considered but the physics of multiples of them have to be understood. We focus here on the comparison of the optical properties of normal and inverted interfaces in such InP/InAlAs MQW structures, which we suspect to be structurally inequivalent similar to the AlAs/GaAs case.[2]

2. Experimental

Photoluminescence measurements were performed at temperatures between 1.8K and 200K using a cw Ar^+-Laser for excitation and a cooled Ge-detector. Time resolved PL was carried out with a ps laser system consisting of a dye laser synchronously pumped by a Nd:YAG laser. The signal is detected by a Si avalanche photodiode employing time correlated single photon counting. The overall time resolution of this setup is 100ps. Optical gain measurements were made employing the well known stripe length method[3] with the second harmonic of a mode locked Nd:YAG laser (532nm) and excitation densities varied between $40kW/cm^2$ and $810kW/cm^2$. The gain spectra are derived from two spectra recorded at different stripe lengths below saturation.

Samples were grown using low pressure metalorganic chemical vapour deposition (MOCVD). The three samples A,B,C discussed here have basically the same structure, consisting of 250nm buffer layer grown on a (100) InP substrate, followed by 10 periods of 20nm InP/ 20nm $In_{0.47}Al_{0.53}As$ quantum wells, and capped by a an InP layer. Different doping profiles were applied to study the effects of internal electric fields on the emission and gain characteristics. Sample A has a 500nm p^+-cap and a n^+-buffer, B a 500nm n^+-cap and a p^+-buffer, C an undoped cap of only 50nm and a buffer that is undoped as well. The MOCVD growth conditions were described elsewhere.[4] The switching sequence at both the normal and inverted interfaces was symmetrical.

3. Results and discussion

A comparison of the low temperature PL spectra of the doped samples described in section 2.1 is shown in Fig. 1. Sample B which is strongly n-doped in the cap layer exhibits a luminescence at 1.2eV (lines I,II). Emissions at this energy from the lattice matched InAlAs/InP system are well known to arise from the spatially indirect recombination across the normal interface.[5]

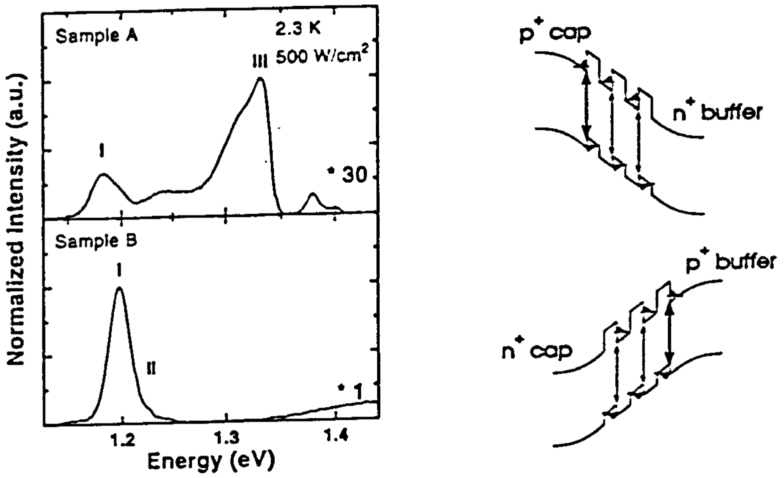

Figure 1. PL spectra of samples A, B and schematic plot of carrier localization

The luminescence spectrum of sample A with a strongly p-doped cap layer (Fig 1(a)) differs considerably from that of sample B. In addition to lines I and II two further maxima are observed, one at 1.245eV and the other at 1.320eV (line III), dominating the spectrum of sample A. At the expected position of the inner QW luminescence (~ 1.160 eV) only a weak line is found for all three samples. The 1.3eV emission from the InP/InAlAs system has been observed only recently and was ascribed inconsistently to either recombination across the inverted interface,[6] or a transition in the InP layer directly above the inverted interface.[7]

We ascribe the differences in the spectra of samples A and B to the localization of carriers at opposite interfaces, the inverted one for the case of sample A and the normal one for sample B. This effect is caused by the opposite doping profiles of these samples giving rise to band bending. In sample B the built in bias favours the localization of carriers at the normal interface so that only the line I and II emission appears. In sample A the high acceptor concentration in the cap layer leads to a bias with the opposite sign so that the luminescence is dominated by the 1.3 eV emission from the inverted interface.

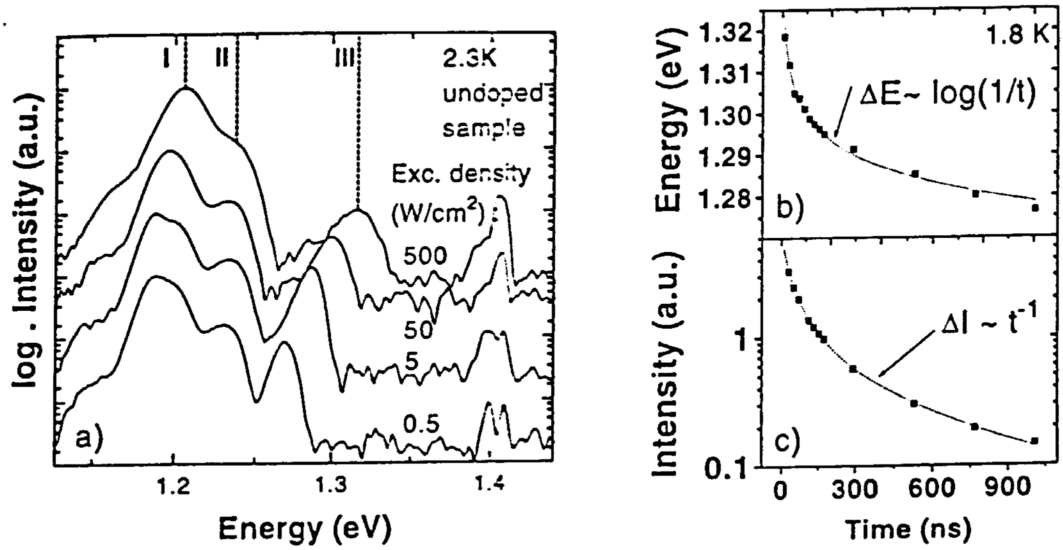

Figure 2. Excitation density dependence of PL spectra (a), transient (b) and time dependence of peak position of line III of sample C

A test of this interpretation is provided by the luminescence properties of the undoped sample C. The luminescence spectrum of this sample (Fig. 2a) exhibits both lines I,II and line III, that strongly shifts to higher energies increasing of excitation density. The integrated intensity of this luminescence saturates at high densities. The slight shift of line I is approximately proportional to the third root of excitation, which is predicted for an excess carrier induced triangular QW at a type II interface, in opposite to line III which shifts logarithmic with excitation. The luminescence transient of lines III deduçed from time delayed spectra follows a t^{-1} law in opposite to the normal interface luminescence which shows exponential decay with $\tau \sim 5$ - 15 ns depending on the doping profile. In agreement with the excitation dependent PL spectra line III shifts to lower energy with time. We ascribe the strong shift of line III to a combination of band bending change and band filling at the top inverted interface, because of the high density of photoexcited carriers at this interface. The transient behaviour of line III can be explained by dynamic band renormalization, which decreases wavefunction overlap and transition energy.

Fig. 3b shows experimentally obtained unsaturated gain spectra of the normal InAlAs/InP interface (sample A) for various excitation densities. As the excitation intensity goes up the gain amplitude follows, accompanied by a pronounced shift of the zero gain position to higher energies. This second feature can be explained by band filling and manybody effects at higher carrier densities leading to a high energy shift of the chemical potential μ and an effective bandgap shrinkage. Both effects cause contrary energy shifts, resulting in a nearly constant spectral position of the maximum gain amplitude in respect to the width of the spectra.

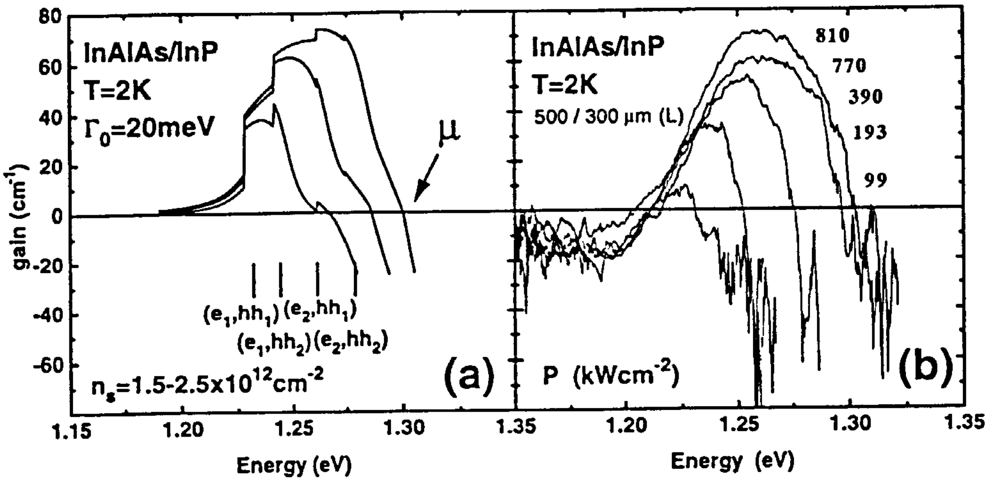

Fig. 3. (a) Calculated gain spectra for various sheet carrier densities and (b) measured unsaturated gain spectra at various excitation densities for sample B.

Contributions of higher subbands, which are present at about 1.25 eV are smoothed out and cannot be resolved, but with higher excitation density their contribution to the gain coefficient is increased. In contrast the transition at the inverted interface only shows absorption. A first order analysis of the experimentally derived gain spectra is achieved, based on the coupled Poisson and Schrödinger equations. For transitions which are indirect in r-space, gain is given by:

$$g(E) \approx \sum_{i,j=1} \left|\left\langle \Psi_i^e \middle| e \bullet \mathrm{grad} \middle| \Psi_j^{hh} \right\rangle\right|^2 \left|\left\langle \Psi_i^e \middle| \Psi_j^{hh} \right\rangle\right|^2 J_{i,j}(E)\left[f_e(E_A^i, kT) - f_{hh}(E_A^j, kT)\right] \quad (2)$$

Fig. 3a shows the result of our calculation using an broadening parameter of the Landsberg type Γ_0, in good agreement with the experimentally determined gain spectra.

Conclusion

In conclusion, we investigated the electronic stucture and the gain characteristics of type II InAlAs/InP multi quantum wells. The luminescence is found to be dominated by transitions at the top and lowest MQW interfaces. Normal and inverted interfaces show different optical transitions. Gain up to 70 cm^{-1} is found only for the normal interface transition.

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