Intersubband absorption in δ-doped GaInAs-InP multi quantum wells

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Abstract

We report on intersubband absorption in lattice-matched $Ga_{0.47}In_{0.53}As$ *multi quantum well structures. Four* δ*-doped samples were grown by metal-organic vapour-phase epitaxy, the well-thickness variing between 5 and 11 nm. Experimental results are presented for bound-to-bound and bound-to-continuum transitions. The measured intersubband transition energies are in very good agreement with an effective-mass-approximation model including nonparabolicity effects.*

1 Introduction

Mid-infrared unipolar semiconductor lasers based on intersubband transitions have become very popular since the first quantum cascade laser (QCL) was realized in 1994 [1]. Several QCLs were grown by molecular beam epitaxy (MBE) in the $Ga_xIn_{1-x}As$/ $In_{1-x}Al_xAs$ and $Al_{1-x}Ga_xAs$/GaAs systems. $Ga_xIn_{1-x}As/In_{1-x}Al_xAs$ is a good choice because of the very large conductionband offset (≈560 meV and more) which allows a wide range of emission wavelengths. The advantage of $Al_{1-x}Ga_xAs$/GaAs is the huge experience in bandstructure engineering and MBE growth. Although the GaInAsP system is the standard for near-infrared applications there is limited knowledge of the subbandstructure of $Ga_{0.47}In_{0.53}As$/InP multi quantum wells (MQWs). As far as we know, there are no intersubband absorption measurements in n-doped MQWs published yet. Even the measured conductionband offset differs in the literature between 190 and 530 meV [2]. The main advantage of GaInAsP for laser production is the large experience in high quality layer growth employing industry-oriented metal-organic vapour-phase epitaxy (MOVPE) technology.

2 Samples

The most natural and direct way to determine the subbandstructure are absorption measurements. If the first subband of a quantum well is occupied by electrons, mid-infrared radiation fitting the energy difference between the upper subband E_2 und the lower subband E_1 lifts electrons from the first to the second subband. For intersubband absorption it is very important to have a more or less occupied ground level and an empty second level, which is the case at sheet carrier-densities of about 10^{11} cm^{-2}. 20-period MQWs with a constant barrier-thickness of 25 nm and well thicknesses t between 5 and 11 nm were grown on semiinsulating (100) oriented InP substrates by MOVPE. In the center of each barrier, we interrupted the InP growth by switching from TMIn to SiH$_4$ for a given time [3]. This technique of δ-doping has the advantage of trapping the electrons in the wells while the donor atoms remain in the barriers. Series of samples were grown employing different duration of δ-doping and different values of silane partial pressure. Mobilities of about 40 000 cm^2/Vs were achieved. Additional information on the crystalline quality and interband-transition energies were obtained by photoluminescence measurements between 13 and 300 K. Full-width-at-half-maximum of less than 10 meV at cryogenic temperatures (similarly grown but undoped samples) indicate a high crystalline quality of the samples. The thicknesses of the layers were determined by their growth-duration in our MOVPE.

3 Experimental method

The absorption spectra were measured with Bruker IFS113 and IFS66 Fourier-transform infrared (FTIR) spectrometers. The samples were mounted in a liquid-helium flow cryostat, where the temperature can be varied between 5 and 300 K. Only the normal-to-the-layers component of the electric field of the incident wave significantly contributes to intersubband transitions [4].

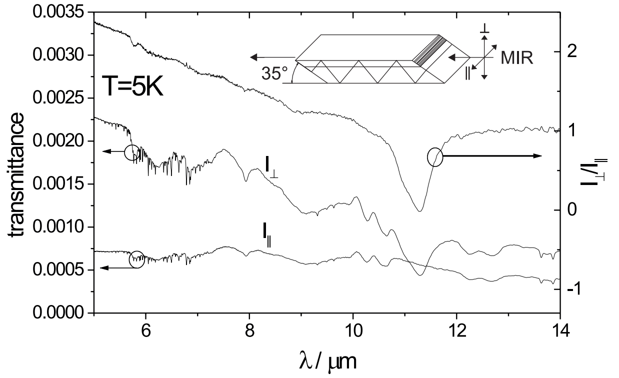
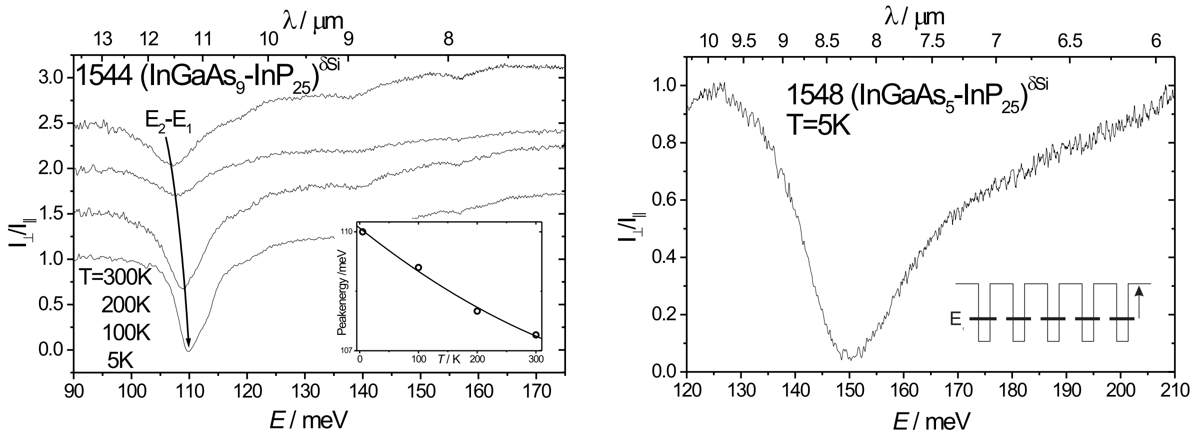


Figure 1: FTIR absorption spectra of a 20-period Ga$_{0.47}$In$_{0.53}$As/InP MQW. The thickness of the quantum wells is 9 nm.

In order to increase the net absorption we fabricated multipass waveguides by cleaving the bars and polishing both ends at an angle of 35^o (inset of figure 1). To eleminate instrumental, substrate and free-carrier contributions to the spectra, normal (I$_\perp$) and in-plane polarized transmittance (I$_{||}$) were measured and divided by each other (right ordinate of figure 1). Pronounced peaks caused by intersubband absorption were observed (figure 1). The descending base-lines at longer wavelengths in figure 1 is due to nonlinearities of the KRS-5 polarizer employed.

4 Results

Figure 2(a) shows the measured bound-to-bound absorption peaks of the sample with the 9 nm-MQW at four different temperatures. With increasing temperature, a slight decrease of the transition-energy is observed. This is due to the decrease of the InP and Ga$_{0.47}$In$_{0.53}$As bandgap energy with rising temperature what has a small effect on the bound states in the quantum wells. Figure 2(b) shows a low-temperature absorption-peak of the sample with the 5 nm-MQW. At well-widths of 6 nm and less, only one bound state in the quantum wells is expected. Figure 2(b) validates this assumption. The peak is very



(a) FTIR absorption spectra of a 20-period $Ga_{0.47}In_{0.53}As$/InP MQW. The thickness of the quantum wells is 9 nm.

(b) FTIR absorption spectra of a 20-period $Ga_{0.47}In_{0.53}As$/InP MQW. The thickness of the quantum wells is 5 nm.

Figure 2: Absorption spectra of a 5 nm (a) and a 9 nm (b) MQW. Figure 2(a) shows absorption caused by bound-to-bound transition, figure 2(b) is an example of a narrower well with only one bounded state in the wells.

wide and asymmetric with a long high-energetic 'tail', which is typical for absorption into the continuum [4].

Figure 3 shows the experimental results by circles as a function of the well-thickness t. The calculations given as curves were done analytically by solving Schroedinger's equation [5]. The nonparabolicity was taken into account by using a model of the effective mass m_e^* as a linear function of energy [6]:

$$m_e^*(E) = m_{e0}^*\left(1 + \alpha E\right) \qquad (1)$$

where $m_{e0}^* = 0.044m_0$ is the effective mass at the bottom of the conduction band. $\alpha = 1.35$ is the nonparabolicity parameter.

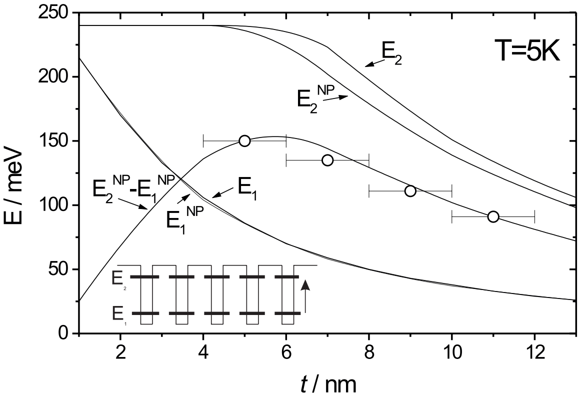


Figure 3: The first two (electron) energy levels E_1 and E_2 in $Ga_{0.47}In_{0.53}As$/InP quantum wells and bound to bound or bound to continuum absorption energy, calculated with and without nonparabolicity effects (index NP). The experimental data obtained from absorption measurements are in good agreement with the theoretical ones taking into account effects of nonparabolicity.

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