Magnetotransport studies of the single and bilayer two dimensional electron gas in the quantum Hall regime
Galistu, G.M.

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6 Magnetotransport and optical properties of GaAs/InGaAs/GaAs quantum wells with a thin central AlAs barrier

6.1 Introduction

In recent years quantum wells with a complex potential profile have become of substantial interest. Thin barriers grown in the center of a quantum well and thus forming coupled quantum wells can tune the subband structure and in this way allow for desirable optical properties. Optical studies with thin AlAs or Al$_{1-x}$Ga$_x$As barrier layers incorporated in the well region demonstrated that the energy spectrum of the two-dimensional electrons could be tuned by changing either the barrier thickness or its height [1,2]. Such a tuning is utilized, for instance, in infrared photodetectors and lasers [3]. For practical use of quantum well structures high electron mobilities are desirable, and therefore it is of paramount importance to suppress electron-phonon scattering, which is dominant in modulation doped quantum well structures at temperatures above 100 K. Inserting a thin barrier in the quantum well that acts as a phonon wall is predicted to reduce the electron-phonon scattering. In transport experiments an increase in the electron mobility was observed when three AlAs barriers were inserted into a GaAs/AlAs multiple quantum well (QW) [4]. The reduction in scattering rate was attributed to the confinement of optical phonons [4], but in a theoretical paper [5] the effect was explained by a modulation of the electron states. In several theoretical papers [6-9] it has been calculated that the introduction of thin AlAs barriers in rectangular QWs leads to suppression of intersubband scattering by optical phonons, which in turn enhances the electron mobility. Other theoretical work has argued against an observable enhancement of the mobility [10-11]. Clearly consensus is lacking. In this chapter we will focus on single- and double sided delta doped GaAs/InGaAs/GaAs pseudomorphic quantum wells of different width and doping levels. This chapter is divided in two parts that correspond to two different series of measurements. In the first part we will report how inserting a thin central AlAs barrier, which acts as a phonon wall, changes
both the transport as well as the optical properties of the system [2]. This changing of transport and optical properties by the phonon wall is ascribed to the influence it has on the electron-optical phonon coupling and how this in turn influences the intra- and inter-subband electron scattering [3,6,10,11]. Three pairs of samples have been measured. In each pair the width of the QW and the doping level are the same. What is different is that only one sample of each pair has a central AlAs barrier (Fig. 6.1). We will present the magnetotransport data and how the presence of the phonon barrier reveals itself in comparing the transport parameters for the two components of each pair. Photoluminescence spectra will be shown for all six samples. The results will be compared with those of the transport measurements. Later on we will present the results of self-consistent numerical calculations of the subband structure and envelope wave functions for the measured samples [12]. Finally a comparison will be made between transport- and photoluminescence data and numerical simulations. The abovementioned experiments and simulations pointed out an undesired feature of our GaAs/InGaAs/GaAs structures, namely the occurrence of additional V-shaped potential wells coinciding with the regions of the delta-doped layers. This feature occurs due to both high doping level by Si at the delta-doped layers and insertion of the AlAs central barrier. As a consequence the spatial distribution of the wave functions has been changed, whereby some have extended over both the InGaAs and the delta-doped layer quantum wells and some have become localized within the delta-doped layer quantum wells. This feature has drastic consequences for the mobility of the structure (due to the change in scattering mechanism) and adds undesired phenomena such as parallel conductivity. In order to deal with this problem a new series of samples, using the compounds AlGaAs/InGaAs/GaAs, has been grown consisting out of a single quantum well with one-sided delta doping in the AlGaAs cladding barrier and its counterpart where the dopant layer is additionally confined by two AlAs barriers of 1 nm thickness. As shown with the first series of samples the AlAs barriers are a tool to push the energy levels up and reshape the wavefunctions. In this way we should be able to relocate the wave-functions in the main quantum well. The parameters extracted from the transport data and the results of numerical band-structure calculations will show in how far we have succeeded in this. Finally some suggestions will be made for future experiments.
6.2 First series of samples

6.2.1 Sample structure (1)

All samples described in this chapter were grown at the Institute of Ultrahigh Frequency Semiconductor Electronics by G.B. Galiev and I.S. Vasil'evskii. The first series of samples consists out of pseudomorphic In$_{0.12}$Ga$_{0.88}$As quantum wells with and without central AlAs barrier, grown on semi-insulating (001) GaAs substrates with the use of molecular-beam epitaxy (MBE). The samples consist out of the following layers: a GaAs buffer layer 0.6 µm thick, a Si $\delta$-doping layer, a GaAs spacer layer 8.5 nm thick. The In$_{0.12}$Ga$_{0.88}$As quantum well with well widths $L_{QW}$ of 8 or 12 nm, a GaAs spacer layer 8.5 nm thick, an upper Si $\delta$-doping layer, and an i-GaAs layer 75 nm thick. The latter was grown to eliminate surface potential effects. The structures were covered with a cap layer of Si-doped GaAs 10 nm thick. The substrate temperature was 510 °C for the pseudomorphic QW and 590 °C for the other layers. Samples were prepared with $\delta$-doping layers with Si concentrations of $3.2 \times 10^{12}$ cm$^{-2}$ (heavily doped, samples #1 and #2) and $1 \times 10^{12}$ cm$^{-2}$ (moderately doped, samples #3 - #6). Samples without barrier (#1, #3, #5) and with barrier (#2, #4, #6) were prepared. The barrier consists of three monolayers of AlAs grown in the center of the QW. The structural and electro-physical characterization of the samples has been reported in Ref. [13]. In order to carry out transport measurements all samples were prepared in Hall bar geometry by conventional lithography and wet etching. In order to attach current and voltage leads, AuGe/Ni/Au ohmic contact pads were made on the samples. The structures are schematically shown in Fig. 6.1.

6.2.2 Transport properties

In Fig. 6.2 the temperature dependence of the sheet resistance measured for $T = 4.2$-300 K for all samples is shown. These curves where measured at the Low Temperature Physics Department of the Moscow State University by V.A. Kulbachinskii and co-workers. For the heavily doped samples #1 and #2 the resistance attains lower values and has weaker temperature dependence than the moderately doped samples (#3 - #6). The samples #3 and #5, with no barrier show metallic behavior from 300 K down to $\sim$70 K, where the resistance decreases approximately linearly with decreasing temperature.
Figure 6.1 Schematic sample structure for the In
to GaAs quantum wells: (a) without AlAs-barrier (samples #1, #3 and #5) and (b) with AlAs central barrier (samples #2, #4, #6). The width of the QW is 12 nm for sample #1 and #2 and 8 nm for samples #3-#6.

The temperature and magnetic field variation of the resistance below 70 K can be attributed to weak localization effects. The insertion of the barrier has a pronounced effect on the sheet resistance, notably in the moderately doped samples. In samples #4 and #6 the value of the resistance at 4.2 K increases by a factor 3 and 7 compared to samples #3 and #5 respectively. This large difference in resistance decreases with increasing temperature. The resistance values of the single QW sample #5 are smaller than those of sample #3, even though the well width is smaller (8 nm compared to 12 nm). This is due to the slightly larger carrier concentration in sample #5 (~5%) as determined by the low temperature Hall data (see Table 6.1). The Hall densities $n_H$ and Hall mobilities $\mu_H$ were determined at temperatures of 4.2, 77 and 300 K for all samples. An overview of the results is presented in Table 6.1. The Hall density $n_H$ is derived from the linear part of $\rho_{xy}$ according to:

$$n_H = -\frac{B}{\rho_{xy} e}$$

The Hall mobility is derived from:
\[
\mu_H = \frac{\partial \rho_{xy}}{\partial B} \frac{1}{\rho_{xx}(B=0)}
\]  

(6.2)

Where \(\rho_{xy}\) and \(\rho_{xx}\) are the Hall resistivity and longitudinal resistivity’s of the 2DEG. For the heavily doped samples #1 and #2 the Hall density amounts to 2.6-2.7x10^{12} \text{ cm}^{-2} and is roughly temperature independent (to within \(\sim 10\%\)). Also the mobility is quite low, which indicates that ionized impurity scattering is dominant. For the moderately doped single QWs (#3 and #5) the temperature variation of \(n_H\) and \(\mu_H\) is consistent with the metallic behavior observed in the resistance. The overall increase of the mobility with decreasing temperature is attributed to the reduction in the phonon scattering rate. However, in the samples with barrier, #4 and #6, the Hall mobility on the whole decreases with decreasing temperature. At low temperatures (4.2 K and 77 K) the insertion of the barrier leads to a strong reduction of mobility by a factor 3-5, although the Hall density is roughly constant or even shows an increase (<20%).

![Figure 6.2 Temperature dependence of the sheet resistance for the In\(_{0.12}\)Ga\(_{0.88}\)As quantum wells with (#2, #4, #6) and without (#1, #3, #5) the AlAs-central barrier.](image-url)
Table 6.1: Structural and transport parameters (at $T = 300$ K, 77 K and 4.2 K) of the InGaAs QW samples; ‘b’ indicates the presence of the AlAs-barrier.

<table>
<thead>
<tr>
<th>sample</th>
<th>$L_{QW}$ (nm)</th>
<th>$N_d$ (Si) $10^{12}$ cm$^{-2}$</th>
<th>$T = 300$ K</th>
<th>$T = 77$ K</th>
<th>$T = 4.2$ K</th>
</tr>
</thead>
<tbody>
<tr>
<td>#</td>
<td></td>
<td>$n_H$ $10^{12}$ cm$^{-2}$</td>
<td>$\mu_H$ cm$^2$/Vs</td>
<td>$n_H$ $10^{12}$ cm$^{-2}$</td>
<td>$\mu_H$ cm$^2$/Vs</td>
</tr>
<tr>
<td>1</td>
<td>12</td>
<td>3.2</td>
<td>2.72</td>
<td>3830</td>
<td>3.0</td>
</tr>
<tr>
<td>2</td>
<td>12+b</td>
<td>3.2</td>
<td>2.6</td>
<td>3150</td>
<td>2.33</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>1.04</td>
<td>0.54</td>
<td>5740</td>
<td>0.79</td>
</tr>
<tr>
<td>4</td>
<td>12+b</td>
<td>1.04</td>
<td>0.42</td>
<td>4810</td>
<td>0.78</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>1.1</td>
<td>0.53</td>
<td>5910</td>
<td>0.76</td>
</tr>
<tr>
<td>6</td>
<td>8+b</td>
<td>1.1</td>
<td>0.50</td>
<td>4000</td>
<td>0.87</td>
</tr>
</tbody>
</table>

Magnetotransport data

The longitudinal- and Hall resistance has been measured for all the samples up to 12 T in the temperature range of 0.25-4.2 K using the lock-in technique. In Figs. 6.3a-f, we present the results obtained for samples #1 to #6 respectively. In the heavily doped samples #1 and #2, the overall behaviour of the longitudinal resistance shows positive quadratic field dependence. The longitudinal component of samples #3-#6 exhibits a negative linear magnetoresistance, which is indicative of weak localization in low-density two-dimensional semiconductor structures. Samples #1-#5 display pronounced Shubnikov - de Haas (SdH) oscillations. After subtracting the background and performing a Fast Fourier Transform on the SdH oscillations as function of $1/B$ we obtain the frequencies of the oscillations. Every frequency ($f$) corresponds to a (partially) filled subband. Making use of the relation [14]

$$n_\nu = \frac{2e}{h} \frac{1}{T}, \quad (6.3)$$

where $T$ is the period of the SdH-oscillations in the $\rho_{xx}$ vs. $1/B$ plot, we can relate the frequencies to the electron density of the respective subband. Usually only subbands with a high quantum mobility are visible in the SdH oscillations. The subband densities obtained in this way are shown in Fig. 6.3. For samples #1-#5 only one frequency peak is observed, which means that the SdH-oscillations correspond to one subband. For sample #6 no clear
frequency is present in the FFT, which is due to the low mobility (see Table 6.1) and the long oscillation period. In the heavily doped samples #1 and #2 the SdH density decreases from 1.35x10^{12} cm^{-2} to 0.63x10^{12} cm^{-2} due to barrier insertion. This will be explained in section 6.2.6. The SdH density approaches the Hall density in the moderately doped samples #3-#6, but is much lower than the Hall density for the heavily doped samples #1-#2, especially for sample #2, indicating that several subbands are populated.

Quantum mobilities were determined from the envelope of the SdH-oscillations [15]. For the moderately doped samples the SdH- and Hall densities are comparable, indicating that transport is dominated by one high mobility subband. The Hall resistance (R_{xy}) is the most pronounced in the samples without barrier (odd numbers) because of the higher mobility. In samples #3-#6 we observe the quantum Hall effect regime with the integer plateaus corresponding to the filling factors ν = 2 and 4. The Landau Levels are non-spin split in this region of the magnetic field. At these integer filling factors R_{xy}=0, which demonstrates the absence of parallel conduction. In samples #1 and #2 parallel conduction is obviously present and hampers the observation of the QHE.

### 6.2.3 Photoluminescence

Photoluminescence (PL) measurements have been carried out on all six samples. The corresponding spectra at T = 77 K are shown in Fig. 6.5. These curves were measured at the Low Temperature Physics Department of the Moscow State University by V.A. Kulbachinskii and co-workers. The spectra of all six samples exhibit a maximum in the energy range 1.35-1.47 eV, which is below the transition energy in bulk GaAs (1.508 eV). Notice that insertion of the barrier leads to a significant upward shift of the peaks in the order of 0.05 eV, without a substantial decrease of the PL intensity. The peaks for the single QWs (#1, #3, #5) are relatively broad and asymmetric with respect to the peaks for the coupled QWs. This indicates that the spectra of the single QWs are composed of several peaks with closely spaced subband energies. The samples with barrier do not display any additional transitions. This is attributed to the decreasing energy differences between the subbands due to the barrier. These energy gaps between the two electron subbands become so small that photoluminescence measurements cannot resolve the different transitions. Also note that for the single QW samples #1 and #3, which have the same well width but
Figure 6.3 a)-f) Magnetotransport curves for the samples #1- #6 at $T = 0.25$ K. 

different doping levels, the transition energies differ slightly (by 0.02 eV). After insertion of the barrier this energy difference disappears.
6.2.4 Subband structure and wave function calculations

The conduction band profile and the subband structure and energy levels were calculated for all the structures by solving the Schrödinger and Poisson equations self consistently [12]. The width of the δ-doping layers has been taken 5 nm [16]. The results of these calculations for all six samples are presented in Fig. 6.6.
Figure 6.6 Calculated conduction band profiles, electron wave functions and subband energy levels for samples #1-#6.
Comparing the conduction band profile of the heavily doped samples (#1 and #2) and the moderately doped (#3-#6) we notice an important difference. In the heavily doped samples the δ-doped layers form additional V-shaped quantum wells almost of the same depth as the InGaAs QW. In sample #1 the ground state wavefunction $\Psi_0$ with energy $E_0$ is predominantly situated in the InGaAs QW, but partially penetrates the V-shaped QWs. The wavefunctions $\Psi_1$ and $\Psi_2$ are mainly confined in the V-shaped QWs and results in two decoupled subbands labeled $E_1$ and $E_2$. Insertion of the AlAs barrier (sample #2) causes a tunnel splitting of the central QW state $\Psi_0$ into the wavefunctions $\Psi_2$ and $\Psi_3$ and an upward shift of the subband energies $E_2$ and $E_3$ (before $E_0$). Hence the central QW states are no longer the ground state. The wave functions in the V-shaped QWs ($\Psi_0$ and $\Psi_1$) are less affected by the insertion of the barrier. Since wavefunction $\Psi_2$ and $\Psi_3$ are spread over the central QW and the V-shaped QWs, insertion of the barrier causes an increase of the electron density in the area of the V-shaped QWs and a decrease of the electron density in the area of the central QW. In the moderately doped QWs (#3 and #5) the V-shaped δ-layer QWs are significantly weaker. The conduction band profile is asymmetric. The ground state wavefunction is confined into the QW. As for the excited states, only states formed in the deeper V-shaped QW are below the Fermi energy. We observe that for sample #3 the ground state energy level $E_0$ lies below the deeper V-shaped QW, meaning that the electrons of the ground state subband are mainly confined in the central QW. Insertion of the AlAs barrier leads again to a redistribution of the wavefunction $\Psi_0$ towards the V-shaped QW. A similar redistribution of the wavefunction after insertion of the barrier can also be seen in samples #5 and #6.

6.2.5 Comparison of transport measurements, PL and calculations

The predicted upward shift in energy levels is most clearly seen in the PL data where the energy shift is in the order of 0.05 eV. The transport measurements reveal a slightly more complicated situation. For the heavily doped sample #1 the electron density of the high mobility subband, associated with the central QW, indeed decreases considerably: from $1.35\times10^{12}$ cm$^{-2}$ to $0.63\times10^{12}$ cm$^{-2}$ (Fig. 6.4). However, in the moderately doped sample #3 the electron density decreases only by 10% after barrier insertion (Fig. 6.4). From the band structure calculations it becomes clear that there is a strong influence of the δ-doped layers, which act as V-shaped QWs. For sample #3 it means that insertion of the barrier causes the
central wavefunction $\psi_0$ to delocalize and to form a hybrid state occupying both the central QW and the V shaped QW. From the calculations (Fig. 6.7) it follows that the groundstate energy $E_0$ shifts only slightly after insertion of the barrier (<0.005 eV). In fact the hybridization of the wavefunction over the central QW and the V shaped QW is equivalent to an enlargement of the QW. This causes the energy-shift to be smaller than expected. This calculated shift in energy level of the ground state is much smaller than the measured PL shift of 0.05 eV, but the shift in the photoluminescence data is also due to the shift in hole subband energy. The hybridization of the wave function causes also a decrease in mobility (see Table 6.1). This is because the scattering mechanism changes from phonon scattering (dominant in the central QW) to ionized impurity scattering (dominant in the V-shaped QWs). In case of the narrowest QW (samples #5 and #6) this shift of the wavefunction to the V-shaped QW is the most drastic which results in sample #6 having the lowest mobility. Notice that the transport mobility of sample #1 hardly decreases after barrier insertion (for $T = 77$ K it even increases). This can be explained from the bandstructure calculations. We see that $\psi_0$ is hybridized into $\psi_2$ and $\psi_3$. The corresponding energy level $E_0$ is split and shifted upward drastically. The expected decrease in mobility does not occur since the V-shaped QWs are already occupied by $\psi_0$ and $\psi_1$. These wavefunctions provide effective screening from the ionized impurity potential, so the mobility in the third subband stays high. From this we can conclude that the observed frequency in the SdH oscillations of sample #2 is attributed to the third hybrid subband. So far we have encountered the undesired effects of the $\delta$-doped layer potential wells. There are several ways to deal with this. One way would be to make the central QW much deeper than the V-shaped QW, so that the wavefunctions are only localized in the central QW. In practice this is difficult to realize, since a material has to be found with a similar lattice constant as GaAs. One can also increase the cladding barrier height by using an Al$_x$Ga$_{1-x}$As compound layer. Another way is to make use of the same method described above: Inserting AlAs barriers around the $\delta$-doped layers in order to shift the energy levels upward and thus the wavefunctions out of the V-shaped QW. The last method has been adapted, together with the use of an Al$_x$Ga$_{1-x}$As compound layer as cladding barrier, and samples with two AlAs-layers of one nm in width surrounding the $\delta$ doped layers have been grown. The results obtained from these samples will be presented in the next sections.
6.3 Second series of samples
6.3.1 Sample structure (2)

The second series of sample structures was grown in order to find out if the effects of the V-shaped QW at the height of the δ doped layer(s) can be neutralized. Central in these new structures is a pseudomorphic Al$_{0.22}$Ga$_{0.78}$As/In$_{0.2}$Ga$_{0.8}$As quantum well. These six samples can be again divided in three pairs. In the first pair a single quantum well with one-side δ-doping is compared with the same structure, but with two additional AlAs barriers of one nm in width around the Si δ-doped layer (samples #416 and #417). The second pair is similar, only with a lower doping level (samples #440 and #444). The last two samples are double-sided δ-doped single quantum wells that differ in doping level (samples #397 and #407). No additional AlAs barriers are added here (Fig. 6.7).

![Sample structures of samples #397, #407, #417, #440, #416, and #444.](image)

*Figure 6.8 Sample structures of samples #397, #407, #417, #440, #416, and #444.*
The reason for adding two AlAs barriers surrounding the dopant layer (samples #417, #440) is that some separation is needed between the Si-donors and the AlAs layer, in order to prevent formation of DX-centers which would trap part of the donor electrons.

### 6.3.2 Transport data and band-structure calculation

Let us consider the first pair of samples (#416, #417). The transport data are presented in Figs. 6.9 and 6.10 below.

![Figure 6.9 Hall- and longitudinal resistivity](image)

*Figure 6.9 Hall- and longitudinal resistivity for #416 at temperatures of 0.25 K and 4.1.*

![Figure 6.10 Hall- and longitudinal resistivity](image)

*Figure 6.10 Hall- and longitudinal resistivity for #417 at temperatures of 0.25 K and 4.1K.*

In sample #416 the highest plateau corresponds to filling factor $\nu = 6$. In sample #417 the highest plateau corresponds to $\nu = 4$. The SdH oscillations for both samples are well pronounced. The SdH and Hall densities for all samples are shown in Table 6.2. For both samples #416 and #417 $n_{\text{SdH}}$ and $n_{\text{H}}$ coincide. This indicates that only one subband is filled. The decrease of both $n_{\text{SdH}}$ and $n_{\text{H}}$ after barrier insertion can be attributed to the previous mentioned DX centers formation due to the AlAs atoms, which trap part of the dopant electrons. Next we consider the subband structure calculation for both samples.
For sample #416 we see a wave function mainly confined to the V shaped QW ($\psi_1$), and a hybridized wavefunction ($\psi_2$). Inserting the AlAs barriers reconstructs the wavefunctions (Fig. 6.11b). The wavefunction $\psi_1$ is now fully confined to the QW together with $\psi_0$. The wavefunction $\psi_2$ is also reconstructed. The shift in energy levels after barrier insertion is minimal. However in both cases only one subband lies below the Fermi level.
Now let us consider sample pair #440 and #444. The transport data are shown in Figs. 6.12 and 6.13.

For sample #444 both the electron density \( n_{\text{e}} \) and transport mobility are low (see Table 6.2), resulting in a very weak presence of SdH oscillations. The slope of the linear part of the Hall resistance varies with temperature, which means there is a temperature dependence of the electron density. So for this sample either doping has been insufficient, or the DX-centers formation immobilizes a significant part of the electrons. A suggestion to overcome the second feature could be to illuminate the sample. In Fig. 6.14 we show the band structure of both samples #440 and #444.

Again in both samples there is only one subband below the Fermi level. The subband electron concentration has been determined in the usual way of subtracting a background from the SdH-oscillations, plotting the result vs \( 1/B \) and performing a FFT. The results of the Fourier transforms are shown in Fig. 6.15. For the double sided δ-doped samples we obtain the transport-data shown in Figs. 6.16a) and b).
Figure 6.14 Subband structure and wavefunctions for a) #444 and b) for #440.
SdH oscillations are very well pronounced in both samples. Now consider the subband structure shown in Fig. 6.17.
The addition of a second dopant layer indeed leads to a more symmetric QW. For both samples the second subband $\psi_1$ is close to the population edge. Since #397 has a higher doping level, the second subband is slightly filled by electrons. For sample #407 the second subband is already depopulated. This depopulation of the second subband in sample #407 explains $n_{\text{SdH}}$ and $n_{\text{H}}$ being similar for this sample.

**Table 6.2**: Doping level and transport parameters at $T = 4.1$ K for samples #416, #417, #444, #440, #397 and #407.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Doping (cm$^{-2}$)</th>
<th>$n_{\text{H}}$ ($10^{12}$ cm$^{-2}$)</th>
<th>$\mu_{\text{H}}$ (cm$^2$/Vs)</th>
<th>$n_{\text{SdH}}$ ($10^{12}$ cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>416</td>
<td>$5.9 \times 10^{12}$</td>
<td>1.32</td>
<td>25880</td>
<td>1.31</td>
</tr>
<tr>
<td>417</td>
<td>$5.9 \times 10^{12}$</td>
<td>1.16</td>
<td>23100</td>
<td>1.16</td>
</tr>
<tr>
<td>444</td>
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<td>28790</td>
<td>0.4</td>
</tr>
<tr>
<td>440</td>
<td>$5.4 \times 10^{12}$</td>
<td>1.02</td>
<td>2310</td>
<td>1.0</td>
</tr>
<tr>
<td>397</td>
<td>$6.3 \times 10^{12}$</td>
<td>2.37</td>
<td>18364</td>
<td>2.25</td>
</tr>
<tr>
<td>407</td>
<td>$5.7 \times 10^{12}$</td>
<td>2.37</td>
<td>25708</td>
<td>2.37</td>
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</table>

Summarizing, for this second series of samples we can say that the main effect we hoped to observe after the insertion of the additional AlAs barriers in the V-shaped quantum wells...
does not show up in the data and calculations. Ideally, what we would like to see is the occurrence of parallel conduction in the V-shaped quantum well, for the samples without barriers. This parallel conduction should disappear after insertion of the barriers, since the energy levels will shift and the wavefunctions become reconstructed and should become fully localized in the main quantum well. Another expected effect of the barrier would be the increased transport mobility in the sample. This is due to the change in scattering mechanism (from ionized impurity scattering to phonon scattering). The reason for not observing this is that in all four samples with additional AlAs-barriers (# 416, #417, #444 and #440) the electron density is not high enough to have more than one subband filled. Only the lowest subband is filled, of which in all four cases the energy level lies below that of the V-shaped quantum wells (see Figs. 6.11 and 6.14). We do observe a reconstruction of $\psi_2$ in sample 417 (Fig. 6.11b). However this effect does not influence the transport data, since this subband is empty. Suggested future attempts, in order to show the uplifting of the energy-levels by barrier insertion, leading to reshaping the wavefunctions and re-localizing them in the central QW, could consist in trying to obtain samples with higher electron concentration. This can be achieved by illuminating the sample after cooling down, to use a gate electrode in order to fill the V-shaped quantum well or by growing sample structures with higher doping levels.

6.4 Conclusions

For the first series of samples measured, all three methods used, magnetotransport, photoluminescence and calculation of the bandstructure, reveal that insertion of a thin central AlAs barrier influences the spatial distribution of the electron wave functions and causes an upward shift of the corresponding energy levels. Since the delta doped layers themselves cause V-shaped quantum wells, the wavefunctions reshape into hybrid states spread over the main quantum well and the V-shaped $\delta$ doped layers. Because of this ‘spread’ of the wavefunctions, the dominant scattering mechanism changes from phonon scattering into ionized impurity scattering. This results in the lowering of the transport mobility. In the heavily doped samples (#1 and #2), the subband responsible for transport is effectively screened from this ionized impurity scattering by the electron subbands fully localized in the V-shaped quantum wells. Since these V shaped quantum wells hinder the original goal of our experiments, a second series of samples has been grown. The reasoning
behind these is that the same technique used in the first series of samples to shift the energy levels and reshape the wavefunctions (namely the central AlAs barrier), this time used in the V shaped δ layer quantum wells, should be able to reshape the wavefunctions in such a way that they become localized only in the quantum well. Calculations of the bandstructures show that this in principle should be possible. Unfortunately the electron density in the actual samples was not high enough to obtain convincing evidence for this. In future attempts to determine the effect of AlAs barriers on the energy levels of the subbands and the shape of the wavefunctions, we strongly recommend that samples with a higher electron density should be used.
6.5 References


