Electron mobility in selectively doped GaAs/InxGa1-xAs multiple quantum well structures

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Electron Mobility in Selectively Doped $GaAs/In_xGa_{1-x}As$ Multiple Quantum Well Structures

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The photoluminescence, the temperature dependence of the electrical conductivity ($0.4 < T < 300\ K$), the magnetoresistance and the Hall effect were investigated in selectively doped $GaAs/In_xGa_{1-x}As$ multiple quantum well (MQW) structures. The dependencies of the electron mobility on the width of the quantum wells and on temperature were measured. It is shown that in narrow MQW structures the value of mobility is restricted by interface roughness scattering. In wider MQW structures, the alloy scattering has a detrimental effect on the low magnetic field transport properties. A negative magnetoresistance was observed in low magnetic fields. From a detailed comparison between theory of weak localisation and experiment the wave function relaxation time τ_φ and its temperature dependence were evaluated. The quantum Hall effect was investigated in all samples in the temperature interval $0.4\ K \div 4.2\ K$ in magnetic fields up to 40 T.

1. INTRODUCTION

Interest in semiconductor multiple quantum well (MQW) structures originates from a one-dimensional periodic potential provided through a periodic variation of alloy composition, with a period shorter than the electron mean free path. The predicted peculiarities in the optical and

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transport phenomena originate from the splitting of the conduction and valence bands into narrow minibands. Physical properties of strained quantum wells and superlattices are currently of great scientific interest. In thin $GaAs/In_xGa_{1-x}As$ layers, the lattice mismatch is accommodated by a biaxial strain, which leads to a change in the band gap and to a splitting of the valence band at the Γ point. Therefore, strained MQW structures display interesting phenomena that are different from those of lattice-matched quantum wells. A study of the photoluminescence under hydrostatic pressure showed that the pressure coefficients of the 2nd conduction subband are larger than those of the 1st subband and that the pressure coefficients of the exciton peaks increased with reduced well width.[1] Although the interest to $GaAs/In_xGa_{1-x}As$ MQW structures arose due to their technological importance,[2–4] little attempt has been made to understand the transport properties of the two-dimensional (2D) electron gas formed in such structures. The introduction of modulation doping in $GaAs/In_xGa_{1-x}As$ modified its physical properties and it extended the physical effects to new phenomena including the quantum Hall effect (QHE) and the quantum corrections to conductivity. In determining the physical properties of MQW structures the principal role is played by the character of electron scattering processes. The mobility of the electrons may be reduced by charge impurity scattering or by interface roughness scattering. For example, in doped superlattices photoluminescence spectroscopy showed the line width to increase when compared to undoped samples. It has been shown that in GaAs/GaAlAs structures at low temperatures the electron mobility is limited by the remote ionised impurities in the GaAlAs layer and that the mobility can be improved by increasing the layer thickness of the spacer which separates the carrier channel from the donors. However, since the channel in the InGaAs pseudomorphic structure is a ternary compound, the electron mobility is expected to be largely affected by the scattering related to alloy disorder. The electron scattering mechanism may be investigated by optical or galvanomagnetic methods. In this paper we report on the photoluminescence, the galvanomagnetic properties, the quantum Hall effect (QHE) and the Shubnikov de Haas (SdH) oscillations of $GaAs/In_xGa_{1-x}As$ multiple quantum well structures with different well widths in the temperature range $0.4\,K < T < 100\,K$ and in magnetic fields $B \leqslant 40$ up to 40 T.

2. EXPERIMENTAL

All samples were grown by liquid phase epitaxy. The structures had a quantum well thickness less than the critical value for the formation of

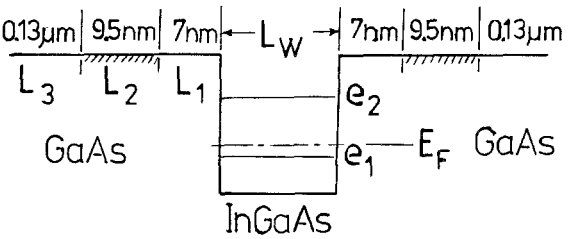

Fig. 1. Schematic drawing of the GaAs/$In_xGa_{1-x}As$ structure (only one well shown). e_1 and e_2 indicate the positions of the two energy levels. Layers L_1, L_2 and L_3 are described in the text.

misfit dislocations.[5,6] The sample structure for a single quantum well is shown in Fig. 1. The 15 quantum wells $In_xGa_{1-x}As$ ($0.27 < x < 0.3$), with width L_W varying between 5.2 and 10.2 nm were separated by GaAs barriers (i.e. layer $L_1L_2L_3L_2L_1$) with a total width of 163 nm. Modulation doping of the GaAs layer labeled L_2, with a width of 9.5 nm by Ge up to a concentration of $7*10^{17}$ cm^{-3} at both sides of every well was performed. The doped GaAs layer was separated from the quantum wells by undoped GaAs layers with width $L_1 = 7$ nm. The structure was separated from the GaAs(Cr) substrate by an *i*-GaAs buffer with width 0.08–0.14 μm. The thickness of the wells were determined from the precisely known rate and time of the growth. We tried to grow samples with the same In content. Occasionally, the In concentration slightly differs between samples. This influences only the depth of the well and hence the position of the energy levels, which may be easy determined by photoluminescence. For the investigation of the dependence of the electron mobility on the width of the quantum wells this difference is not important.

TABLE 1

Composition (x), Well Width (L_w), Fermi Energy (E_F), Electron Concentration per Well (n_1), Experimental (μ_{exp}) and Calculated (μ_{calc}) Values of Mobility, the Lateral Roughness (Δ), the Semiwidth of Photoluminescence Peak (δE), the Experimental (ΔE_e) and Calculated (ΔE_c) the Energy Differences Between the Two Levels in Well ($\Delta E = e_1 - e_2$) for Samples N1, N2, and N3. All Data are at $T = 4.2$ K. n is the Concentration of Doping by Ge

N	x	L_w (nm)	E_F (meV)	n_1 (10^{11} cm^{-2})	μ_{exp} (cm^2/Vs)	μ_{calc} (cm^2/Vs)	Λ (nm)	δE (meV)	ΔE_c (meV)	ΔE_e (meV)	n (10^{17} cm^{-3})
1	0.27	5.2	31	9.1	8750	8900	17	35	—	—	7
2	0.28	8.0	37	11	9600	190000	17	55	101	100	7
3	0.30	10.4	34	10	10300	530000	17	53	80	100	7

We have measured the temperature dependencies of the electrical conductivity for $0.4\ \mathrm{K} < T < 300\ \mathrm{K}$, Hall effect and the magnetoresistance for $0.4\ \mathrm{K} < T < 60\ \mathrm{K}$. Low magnetic field up to 6 T were produced with help of a superconducting solenoid. High magnetic field up to 40 T were produced by a pulse magnet, using the facilities of the university of Amsterdam. Some relevant parameters of the investigated samples are listed in Table 1, where the electron concentration (n_1) is given per quantum well.

3. RESULTS

The semiwidth of the photoluminescence peak at $T = 77\ \mathrm{K}$ was approximately 35–55 meV for the doped and 15–20 meV for the undoped structures with the same geometrical parameters. Typical photoluminescence spectra of MQW structures at 300 K and 77 K are shown in Fig. 2. Near $1.4 \div 1.5$ eV a shoulder peak appears in the photoluminescence data taken at 300 K. Detailed measurements of photoluminescence in GaAs/InGaAs heterostructures showed that this peak may be ascribed to GaAs.[7] The intensity of this peak is always lower than well-resolved peaks, corresponding to the wells.

The electron mobility increases when the width of the well increases (see Table 1). For all samples the conductivity σ increases when the

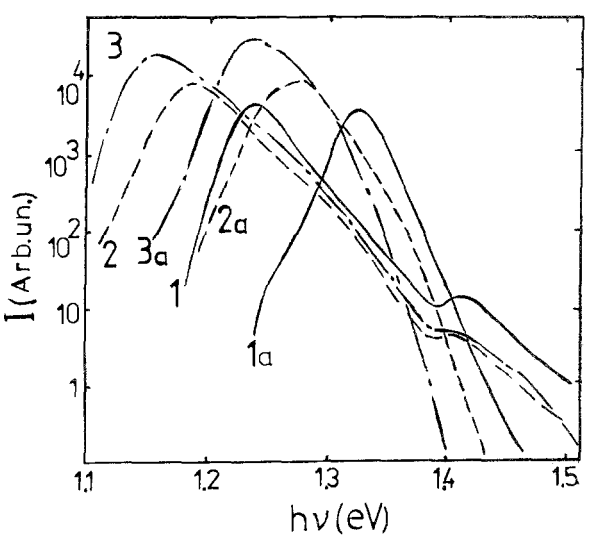

Fig. 2. Photoluminescence spectra of GaAs/$In_xGa_{1-x}As$ MQW structures at 300 K (1, 2, 3) and 77 K (1a, 2a, 3a). The labels correspond to the numbers of the samples as listed in Table 1.

temperature decreases, while a shallow maximum is observed in the temperature range 30–70 K. For $T < 15$ K $\sigma(T)$ is a linear function in coordinates σ-ln T. The sheet conductivity per well, $\sigma_{\square}$, for all three samples is shown in Fig. 3. A negative magnetoresistance was observed in low magnetic fields ($B < 0.1$ T). The negative magnetoresistance depends quadratically on the magnetic field in very low fields, followed by a logarithmic dependence on B. Lowering the temperature reduced the range for the quadratic field dependence. For $T > 50$ K, the magnetoresistance became positive with a quadratic dependence on the magnetic field. In high magnetic fields, we observed the QHE. The dependencies of the transverse magnetoresistance ρ_{xx} and the Hall resistance ρ_{xy} on the magnetic field are shown in Fig. 4. As follows from Fig. 4, all the parallel connected quantum wells exhibit almost the same electron density in the populated ground subband, which results in one observable period of the Shubnikov-de Haas signal. The ρ_{xy} plateau, which are the most sensitive to inhomogeneity, shows only a weak additional structure for sample N3. The concentration evaluated from the Shubnikov-de Haas oscillations coincides well with the one calculated from the Hall effect. The Hall effect measurements showed that the concentration of electrons does not depend on temperature ($T < 60$ K) for all samples. This implies that the temperature dependence of the conductivity must be attributed to the temperature dependence of the mobility only. The temperature variation of the mobility μ is plotted in Fig. 5.

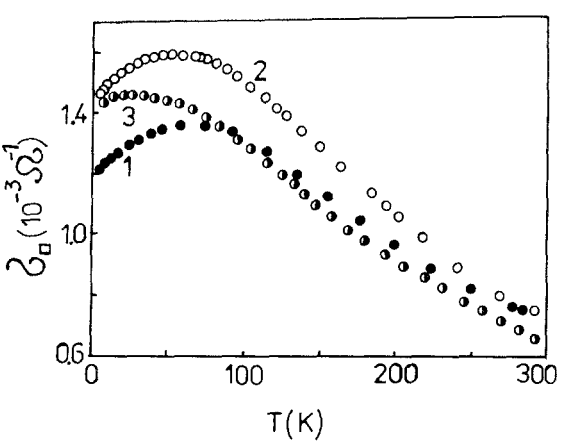

Fig. 3. Temperature dependence of sheet conductivity per well for GaAs/$In_xGa_{1-x}As$ MQW structures. The labels correspond to the numbers of the samples as listed in the Table 1.

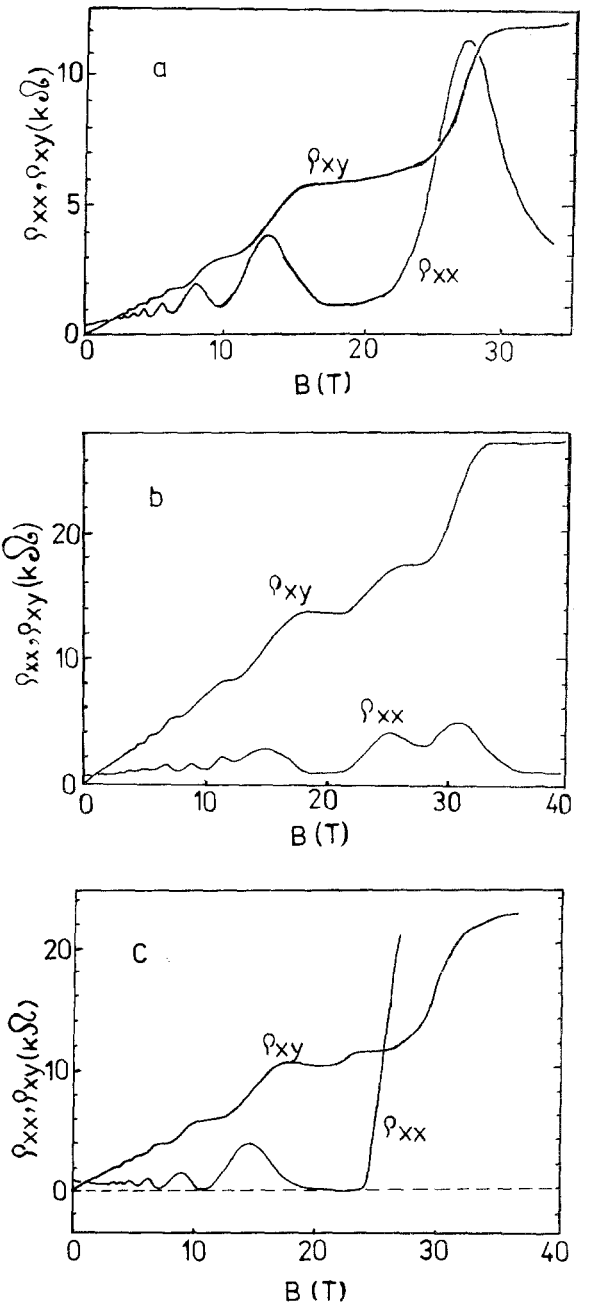

Fig. 4. The Shubnikov-de Haas oscillations (ρ_{xx}) and the quantum Hall effect (ρ_{xy}) for sample 1(a), 2(b) and 3(c) at $T = 4.2$ K.

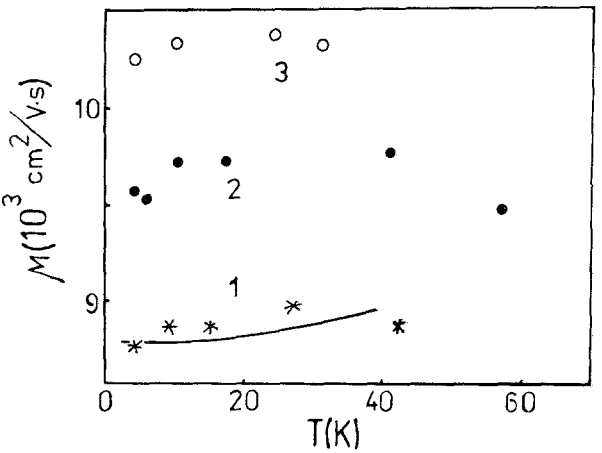

Fig. 5. Variation of mobility μ with temperature. The labels correspond to the numbers of samples as listed in Table I. The solid line represents calculated $\mu(T)$ with help of formula (1) using $\Lambda = 17$ nm.

4. DISCUSSION

The electron mobility μ of the investigated samples very rapidly decreases when the width L_w of the quantum well decreases. In Ref. 8 it was proposed that in thin quantum wells ($L_w < 6$ nm) interface roughness scattering is the dominant scattering mechanism. In this case electron mobilities are proportional to L_w^6 and depend on the lateral roughness width (Λ) and roughness height (Δ) through the relation:

$$\mu = \frac{L_w^6}{\Delta^2 \Lambda^2} g(\Lambda, n_1, T) \tag{1}$$

where the function g depends smoothly on the temperature T, the electron concentration n_1 and parameter Λ. We calculated the temperature dependence of the electron mobility for two mechanisms: for dominant charge impurity scattering and dominant interface roughness scattering. For the first case, we used the formulas of Ref. 9. It appeared that the calculated mobilities were about one order of magnitude higher than the experimental values and exhibited another temperature dependence. For the second mechanism, we used formula (1) and fitted the theoretical curve to the experimental points using Λ and Δ as fit parameters. The value of Δ was taken as the height of a single atomic layer. The results of such a fitting procedure for sample N1 is shown in Fig. 5 by the solid line. The

theoretical curve and experimental data points are in good agreement. Similar results for the temperature dependence of the mobility attributed to dominant interface roughness scattering mechanism were obtained for AlAs/GaAs[10] and GaAlAs/GaAs quantum wells.[11] In quantum wells with $L_w \gtrsim 6$ nm (samples N2 and N3) neither interface roughness scattering nor charge impurity scattering can account for magnitude of the mobility and its temperature dependence. The reduction of the experimental values of the mobility, as compared to the calculated ones (see Table 1) may be explained by the additional scattering related to the alloy disorder, which is an intrinsic process arising from the random distribution of alloy atoms at the available lattice sites. Due to alloy scattering, electron transport in InGaAs wells has failed to yield mobilities that rival those of GaAs.

We have also calculated the subband structure of the samples. The energy spectrum and the wave functions were calculated by the selfconsistent solution of the equations

$$\{(-\hbar^2/2m^*)\, d^2/dz^2 + E_c\}\, \psi_{sn}(z) = E_n \psi_{sn}(z) \tag{2}$$

$$d^2E_c(z)/dz^2 = -e^2\{N^+_{d(z)} - N^-_{a(z)} - n(z)\}/\varepsilon\varepsilon_o \tag{3}$$

Here $N^+_{d(z)}$, $N^-_{a(z)}$ and $n(z)$ are the donor, acceptor and electron concentrations, ε and ε_o are the dielectric constant of the medium and the vacuum, respectively. The main feature of the investigated structures is the existence of one single energy level in Sample No. 1 while Samples No. 2 and 3 have two electron energy levels. Moreover, the Fermi energy was found to be lower than the position of the upper level. Thus in the SdH oscillations we observed only one single frequency attributed to one occupied level.

The decrease of the conductivity when the temperature decreases and the negative magnetoresistance with a quadratic dependence on the magnetic field in low fields and a logarithmic one in higher fields may be fully described by the theory of quantum corrections to the conductivity for the 2D case,[12, 13] which is valid for $kT \ll E_f$. This gives a possibility to determine some electron parameters of the samples, for example, the electron wave function phase relaxation time τ_φ. The value of τ_φ depends on electron-electron or electron-phonon relaxation processes. The relationship between τ_φ and the energy relaxation time (τ_ε) and the inelastic scattering relaxation time (τ_i) was calculated in Refs. 14 and 15. The temperature dependence of the conductivity of two dimensional disordered systems in zero magnetic field, due to the occurrence of both weak localisation and electron-electron interaction effects, is given by

$$\sigma(T_2) - \sigma(T_1) = [\beta + (1-\beta)\, p + \lambda]\, \frac{e^2}{2\pi^2\hbar} \ln(T_2/T_1) \tag{4}$$

where λ is a constant describing the electron-electron interaction in a diffusion channel, p is the exponent of the temperature dependence of the wave function phase relaxation time τ_φ

$$\tau_\varphi = aT^{-p} \tag{5}$$

For electron-electron scattering in weakly disordered metals it was found that $p = d/2$ in contrast with the result $p = 2$ predicted in the clean limit whatever the dimensionality of the system. For electron-phonon scattering p ranges from 2 till 4 for the small mean free path limit at low temperatures. The coefficient β accounts for the scattering by superconducting fluctuations (Maki-Thompson corrections). The strength of the electron-electron interaction contribution is given by λ, where λ—which is a measure of the screening by other charge carries—has a value close to 1 in the limit of weak screening.

The corrections to the sheet conductivity σ in a magnetic field B has the form[12]

$$\sigma(B) - \sigma(0) = \frac{e^2}{2\pi^2\hbar}(1-\beta) f_2\left(\frac{4DeB\tau_\varphi}{\hbar}\right) \tag{6}$$

Here the function f_2 describes the localisation and depends on the diffusion coefficient D of the carries and the wave function phase relaxation time τ_φ. The function $f_2(x)$ behaves like $x^2/24$ for $x \ll 1$ while $f_2(x) \sim \ln(x)$ for $x \gg 1$.[12] According to Ref. 16 Eq. (6) is valid if the magnetic length $l_h = (h/eB)^{1/2}$ exceeds the mean free path l. For the investigated samples with low mobility it is possible to use formula (6) in low magnetic fields. The magnetic field dependence of λ is significant only in high magnetic fields ($g\mu_B B/kT > 1$) and may be neglected at low temperatures. We may analyse experimental data without corrections which describe electron-electron interaction (the second term in Eq. (6),[12] which we omitted).

Making use formula

$$\mu = eD/E_F \tag{7}$$

for the degenerate electron gas we calculate the value of D which is necessary for the calculation of τ_φ. Using τ_φ as a parameter we may fit the theoretical curves to the experimental negative magnetoresistance. From such a fitting we evaluated $\tau_\varphi(T)$. This dependence is described by the formula (3) with $p = 1$. It means that there is a strong electron-electron scattering in MQW GaAs/$In_xGa_{1-x}As$ structures.[14, 15]

5. CONCLUSION

We have investigated the dominant scattering mechanism in thin selectively doped $GaAs/In_xGa_{1-x}As$ multiple quantum well structures. The dependence of the electron mobility on temperature for the sample with $L_w = 5.2$ nm may be quantitatively explained by interface roughness scattering of electrons. In our quantum well structures with $L_w \gtrsim 6$ nm, alloy scattering decreases the electron mobility. It is shown that the quantum correction to conductivity for 2D case plays an important role for the explanation of the galvanomagnetic properties of $GaAs/In_xGa_{1-x}As$ multiple quantum well structures. In high magnetic field, we observed QHE, which showed that all the parallel connected quantum wells exhibit almost the same electron density in the populated ground subbands. The ρ_{xy} plateaux which are very sensitive to inhomogeneities show only weak additional structures. The temperature dependence of the conductivity is accounted for only by the temperature dependence of mobility.

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