2D Electron Transport in Selectively Doped GaAs/In$_x$Ga$_{1-x}$As Multiple Quantum Well Structures

V. A. Kulbachinskii*, V. G. Kytin, T. S. Babushkina, I. G. Malkina
Low Temperature Physics Department, Moscow Lomonosov State University, 119899, Moscow, Russia

Received July 21, 1995

Photoluminescence, temperature dependence of conductivity ($0.4 < T < 300$ K), magnetoresistance in selectively doped GaAs/In$_x$Ga$_{1-x}$As multiple quantum well (MQW) structures were investigated. The dependence of electron mobility on the width of the quantum wells and temperature were measured. It was shown that in narrow MQW structures the value of mobility is restricted by interface roughness scatterinsg. In wider MQW structures neither interface roughness scattering nor charge impurity scattering can describe the values and temperature dependences of mobilily. Negative magnetoresistance was observed. From detailed comparison between theory of weak localization and experiment the relaxation time of the wave function phase τ_φ and temperature dependence of τ_φ were evaluated. Quantum Hall effect was investigated in all samples at T=0.4-4.2K in magnetic fields up to 40T.

I. Introduction

Interest in MQW structures originates from a one-dimensional periodic potential by a periodic variation of either impurities or alloy composition in semiconductors, with the period shorter than the electron mean free path. The predicted peculiarities of optical and transport phenomena originate from a 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$_x$Ga$_{1-x}$As layers, the lattice mismatch is accommodated by a biaxial strain, which leads to a change in the band gap and 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. Although the interest to GaAs/In$_x$Ga$_{1-x}$As MQW structures arose due to their technological importance[1], little attempt has been made to understand the transport properties of the 2D electron gas formed in such structures. The introduction of modulation doping in GaAs/In$_x$Ga$_{1-x}$As modifies its physical properties, and it gives rise to new phenomena including such as quantum Hall effect (QHE) and quantum correction to conductivity. The principal role in the transport properties of MQW structures plays the character of electron scattering. The mobility of electrons may be reduced for example by a charge impurity scattering or interface roughness scattering. In undoped superlattices the photoluminescence spectrum showed a narrower line width when compared to doped samples. The electron scattering mechanism may be investigated by optical or galvanomagnetic methods. In this paper we investigated photoluminescence, galvanomagnetic properties, quantum Hall effect and Shubnikov de Haas (SdH) oscillations of GaAs/In$_x$Ga$_{1-x}$As multiple quantum well structures in the temperature range 0 4K<T<60K in magnetic fields B<40 T.

II. Experimental

All samples were grown by liquid phase epitaxy. 15 periods of quantum wells In$_x$Ga$_{1-x}$As with the width

---

*Address correspondence to: prof. V.A.Kulbachinskii, Low Temperature Physics Department, Physics Faculty, Moscow State University, 119899, Moscow, Russia Fax: +7 (095) 932-8876, e-mail: kulb@mig.phys.msu.su

L_w(5.2nm < L_w <10.2nm) were separated by GaAs barrier with the width 165nm.

A single quantum well of the sample structure is shown in Fig. 1. The GaAs layers, denoted by L_2, were doped with Ge in concentrations up to 7 x 10^{17} cm^{-3}. The doped GaAs was separated from the quantum well by an undoped GaAs layer with width L_1 = 7 nm. The structure was separated from the GaAs(Cr) substrate by an i-GaAs buffer 0.08-0.14 μm width.

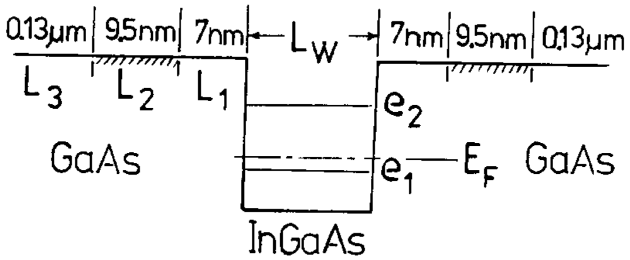

Figure 1. A single quantum well of a sample structure, e_1 and e_2 are the positions of the two energy levels.

We measured the temperature dependences of conductivity lor 0.4 < T < 300K, and the Hall effect and magnetoresistance for 0.4<T<60K. Low magnetic field up to 6T were produced with a superconducting solenoid, high magnetic field up to 40T we produced by a pulsed magnet.

Some parameters of the samples investigated are listed in table 1. The electron concentration (n_1) is given per quantum well.

III. Results

The semiwidth of the photoluminescence peak at T=77K was approximately 35-55 meV for doped and 15-20 meV for undoped structures with the same geometrical parameters. Typical photoluminescence spectra of the MQW structures are shown in Fig. 2 at 300K and 77K. The electron mobility increases when the width of well is increased (see table 1).

For all samples the conductivity increases when temperature decreases. When the temperature is decreased below 30K the conductivity σ decreases. For T < 15K the dependence $\sigma(T)$ is a linear function in coordinates $\sigma - \ln T$. The sheet conductivity $\sigma_\square$ per well for three samples is shown in Fig. 3. Negative magnetoresistance were observed in low magnetic fields B < 0.1T. The negative magnetoresistance depended quadratically on the magnetic field in very low fields followed by logarithmical dependence on magnetic field. The lowering of T reduced the range of quadratic dependence. For T > 50K the magnetoresistance became positive with a quadratic dependence on the magnetic field.

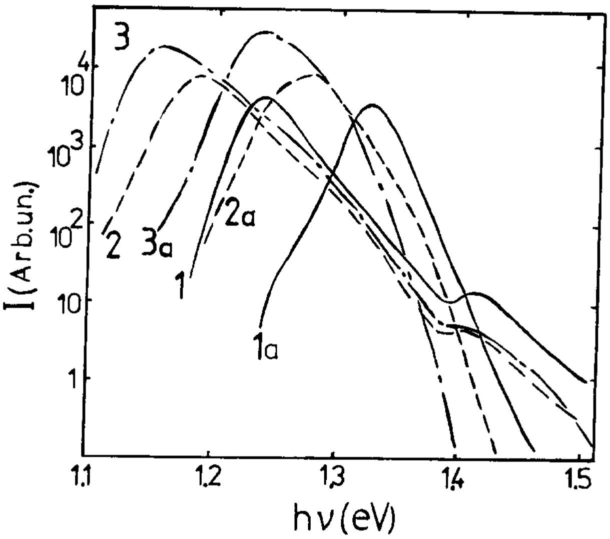

Figure 2. Photoluminescence spectra of MQW structures at T=300K (1,2,3) and T=77K (1a,2a,3a). Numbers correspond to numbers of samples in the table 1.

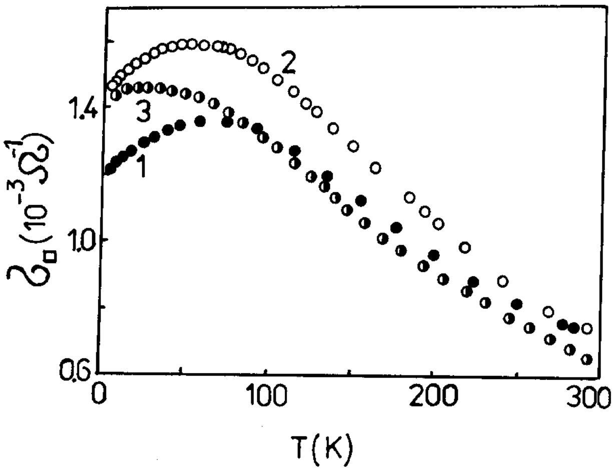

Figure 3. Temperature dependence of sheet conductivity. Numbers correspond to numbers of samples in table 1.

Table 1 Composition (x), well width (L_w), Fermi energy (E_F), electron concentration per well (n_1), experimental and calculated values of mobility (μ), the lateral roughness (Λ), the semiwidth of photoluminescence spectra (δE) and experimental (δE_c) and calculated (δE_c) the energy difference between two subbands in well ($\delta E = e_1 - e_2$) for samples No.1, No.2, and No.3 at T=4.2K.

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_c meV
1	0.27	5.2	31	9.1	8750	8900	17	35	-	-
2	0.28	8.0	37	11	9600	190000	17	55	101	100
3	0.30	10.4	34	10	10300	530000	17	53	80	100

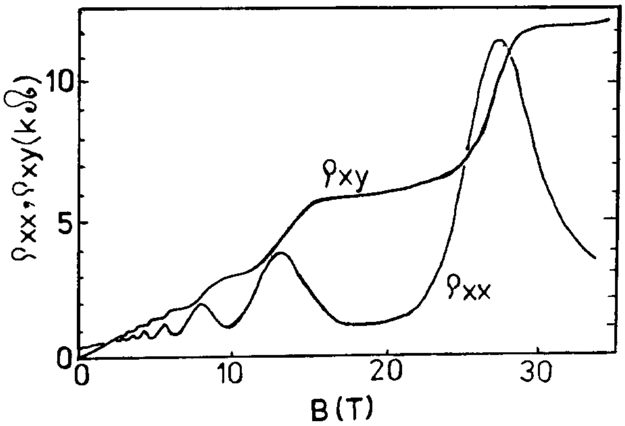

Figure 4. Shubnikov-de Haas oscillations ρ_{xx} and quantum Hall effect ρ_{xy} of a sample 1 at T=4.2K.

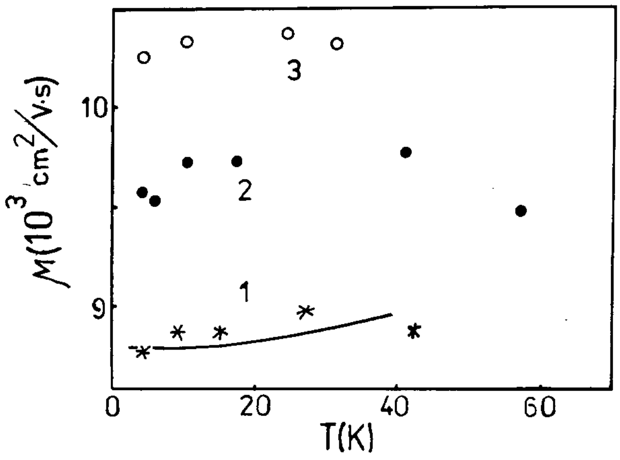

Figure 5. Temperature dependence of mobility. Numbers correspond to numbers of samples in table 1. Solid line represents a calculated dependence of $\mu(T)$ with help of formula (1) with parameter $\Lambda = 17$nm.

In high magnetic fields we observed the QHE. The dependences of the transverse magnetoresistance ρ_{xx} and Hall resistance ρ_{xy} on magnetic field are shown in Fig. 4 for sample No.1.

As it is seen in Fig. 4, all the parallel connected quantum wells exhibit the same electron density in the populated ground subband, which results in one observable period of Shubnikov-de Haas oscillations. The most sensitive to inhomogeneity the ρ_{xy} plateaus show no additional structures. The concentration of electrons evaluated from Shubnikov-de Haas oscillations is nearly the same as calculated from the Hall effect. The Hall effect measurements showed that for all samples the concentration of electrons does not depend on temperature at least up to $T \approx$20K. It means that in this temperature range the temperature dependence of conductivity must be attributed to a temperature dependence of the mobility. The dependence of mobility μ on T for all samples is plotted in Fig. 5.

IV. Discussion

The electron mobility μ in the investigated samples decreases very rapidly when the width L_w of the quantum well decreases In Ref. [2] it was proposed that in thin quantum wells (L_w <6nm) interface roughness scattering is the dominant scattering mechanism. In this case electron mobilities are proportional to L_w^6 and depend on the lateral width Λ of roughness and its height Δ:

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

where function g depends smoothly on temperature T, electron concentration n and parameter Λ. We calculated the temperature dependence of electron mobilities in two cases: for the dominant charge impurity scattering and the dominant interface roughly scattering. In the first case we used the formulas from Ref. [3] . The calculated values of the mobilities were about one order of magnitude higher than the experimental values and showed a different temperature dependence. For the second case we used formula (1) and fitted theoretical curve to the experimental points using Λ and Δ as fitting parameters. The result of such a fitting is shown in Fig. 5 for sample No. 3 by the solid line. The theoretical curve and the experimental points are in a good agreement. The same result for the temperature dependence of mobility in the case of dominant interface roughness scattering mechanism was obtained for AlAs/GaAs quantum wells[4] and for GaAlAs/GaAs quantum wells[5]. In quantum wells with $L_w > 6$nm (samples No. 1 and No. 2) neither interface roughness scattering nor charge impurity scattering may describe the absolute values and the temperature dependence of mobility. Reduction of experimental values of mobility in comparison with the calculated one (see table 1) may be explained by the additional scattering due to fluctuation in the alloy composition in the wells.

We calculated the subband structure of the samples. The main feature of the investigated structures is the existence of single subband in sample No. 1 and two electron subbands in samples No. 2 and 3. The Fermi energy was lower then the threshold of the second subband. Thus in oscillations we observed only single frequency from one occupied subband.

The decrease of conductivity when temperature decreases and the negative magnetoresistance with a quadratic dependence on the magnetic field in low fields and a logarithmic one in high fields may be fully described by the theory of quantum correction to conductivity for the 2D case[6,7]. This gives the possibility to determine some electron parameters of samples, for example the relaxation time of the wave function phase τ_φ. The value of τ_φ depends on electron-electron or electron-phonon relaxation. The relationship between τ_φ and the characteristic values of the energy relaxation time and of the inelastic scattering relaxation time was calculated in [8,9]. The temperature dependence of τ_φ is given by

$$\tau_\varphi = aT^{-p} \qquad (2)$$

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 clear limit whatever the dimensionality of the system. For electron-phonon scattering p ranges from 2 to 4 at low temperatures in the limit of the small mean free path.

The corrections to the conductivity σ of a square in a magnetic field H has the form[6]

$$\sigma(H) - \sigma(0) = \frac{e^2}{2\pi^2\hbar}(1-\beta) f_2 \left(\frac{4DeB\tau_v}{\hbar}\right) \qquad (3)$$

where the function f_2 describes the localization, D is the diffusion coefficient of the carries, and τ_φ is the relaxation time of the wave function phase. The function $f_2(x) \sim x^2/24$ for $x << 1$ and $f_2(x) \sim ln(x)$ for $x >> 1$. Making use of the formula

$$\mu = eD/E_f \qquad (4)$$

valid for degenerate electron gas we calculate value of D which is necessary for calculation of τ_φ. Using τ_φ as a parameter we may fit theoretical curves to the experimental negative magnetoresistance. From such a fitting we evaluated τ_φ dependence on temperature. This dependence is well described by formula (2) with $p = 1$. It means that there is a strong electron-electron interaction in MQW GaAs/In$_x$Ga$_{1-x}$As structures.

V. Conclusion

It was shown that interface roughness scattering is the dominant scattering mechanism in thin quantum wells. It was shown that the quantum correction to conductivity for 2D case play important role for explanation of galvanomagnetic properties of GaAs/In$_x$Ga$_{1-x}$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} plateaus which are very sensitive to inhomogeneity show only weak additional structures.

The temperature dependence of conductivity deals only with the temperature dependence of the electron mobility. The dependence of electron mobility on the temperature for the sample with the L_w <6 nm may be quantitatively explained by interface roughness scattering of electrons. In quantum wells with Lw¿6nm neither interface roughness scattering nor charge impurity scattering may describe the observed temperature dependence of mobility.

References

1. K.J. Moore, G. Duggan, K. Woodbridge, and C. Roberts, Phys. Rev. B, **41**, 1090 (1990).
2. H. Sakaki, T Noda, K. Hirakawa, M. Tanaka, and T. Matsusue, Appl. Phys. Lett., **51**, 1934 (1987).
3. T. Ando, A.B. Fowler, and F. Stern, Rev. Mod. Phys., **54**, 437 (1982).
4. T. Noda, M. Tonaka, H. Sakaki, Appl. Phys. Lett., **57**, 1651 (1990).
5. V.A. Kulbachinskii, V.G. Kytin, V.I. Kadushkin, E.L. Shangina, and A. de Visser, J. Appl. Phys., **74**, 2081 (1994).
6. B.L. Altshuler, A.G. Aronov, A.N. Larkin, D.E. Khmelnitskii, JETP, **81**, 758 (1981) (Sov. Phys. JETP, **54**, 411 (1981)).
7. E. Abrahams, P. Anderson, D. Licciardello, and T.V. Ramacrichnan, Phys. Rev. Lett., **42**, 673 (1979).
8. B.L. Altshuler, A.G. Aronov - In: *Modern problems in Condensed Matter Science*, ed. by A.L. Efros and M. Pollak. Amsterdam. 1985. P.1-153.
9. A.G. Aronov, Physica B., **126**, 314 (1984).