Quantum Hall Effect in a Wide Parabolic Quantum Well

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We investigate the activated conductivity for Landau levels at filling factors ν=1,2 in a parabolic Al_xGa_{1-x}As well down to 30 mK. We obtain a very small activation energy $\sim$ 0.02 meV, which is almost 1-2 orders of magnitude smaller than the expected values for energy gaps in a wide quantum well. The resistivity minima vanish completely when a parallel component of magnetic field is applied. The collapse of the energy gaps in the wide parabolic well occurs due to the new electron correlated state, probably the charge density wave state predicted for a uniform wide electron slab in high magnetic field.

I Introduction

The Quantum Hall effect (QHE) is characterized by narrow resistivity peaks separated by deep minima [1]. These resistivity minima arise due to the localization of the electron states at the Fermi energy, when it lies in the gaps between Landau or spin split levels. In this regime the resistivity is determined by the electron thermal activation with an energy gap $\hbar\omega_c$ where ω_c =eB/m_c- cyclotron frequency for Landau levels and gμB/2 for spin split levels. Here μ is the Bohr magneton, g is the effective Lande factor, which is strongly enhanced in a two-dimensional electron gas due to the electron-electron interactions. The temperature dependence of the resistivity minima can therefore be used to study energy gaps in the quantum Hall effect. Several experiments have been performed to study the exchange enhanced Landau and spin splitting [2], composite Fermions cyclotron energy [3] and skyrmions [4]. In a conventional picture the quantum Hall effect is predicted to disappear for a sufficiently wide quantum well. Fig.1 shows the energy spectrum as a function of magnetic field B for a wide square quantum well. At sufficiently high B the Fermi energy crosses the energy levels corresponding to the lowest Landau level of each subband. Therefore, it is expected that for a wide quantum well the last resistivity minima could be due to the energy gap between electric subbands, and not to Landau levels. In a real system the energy levels will have finite widths because of the disorder, therefore the last resistivity minima disappear for a sufficiently thick layer, when corresponding electric subbands overlap. However, the magnetoresistance should show oscillations as the Fermi energy crosses degenerated Landau subbands. A three dimensional electron gas (3DEG) in the presence of a strong magnetic field is also expected to show interesting properties. It has been predicted a charge-density wave or a Wigner crystal at high magnetic fields for such a system [5]. However, in doped three dimensional semiconductors the electron impurity interaction is very strong and can destroy these exotic ground states. The system which can be used in order to study the evolution of states of a quasi-two-dimensional toward a three dimensional behavior is a wide partially filled parabolic quantum well. Considerably larger mobility in comparison with conventional bulk three dimensional electron gas has been achieved by removing the dopant atoms from the quantum well [6]. Recently the electron-electron interaction in a wide parabolic quantum well has been studied in the Hartree-Fock aproximation [7]. It has been shown that the ground state of the quasi-2DEG in the strong magnetic field, applied perpendicular to the electron slab and corresponding to the filling factor ν=1 is a charge density wave state. It leads to the destruction of the ν=1 minima the Hall plateau in the Quantum Hall effect. The critical thickness, when the system undergoes a phase transition, varies with the curvature of the parabolic potential ω_0. For the published magnetotransport experiments with sample parameters $\hbar\omega_0$ =2.9 meV the critical thickness was found to be d_c=1000 $\AA$. However, the destruction of the ν=1 plateau has not been observed in experiments in wide well structures with thickness ~ 1500 $\AA$ [6]. We perform our experiments with thicker electron slab.

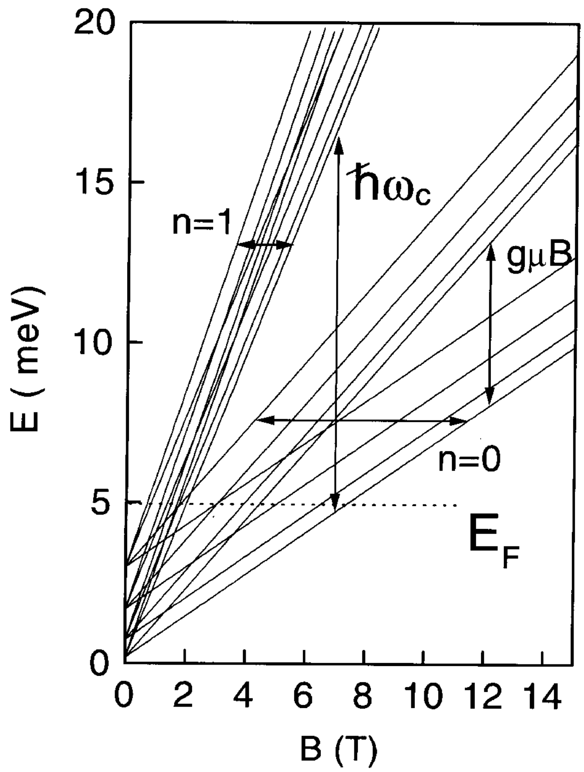

Figure 1. Energy diagram for a wide square well. The cyclotron, Zeeman and subband energies are indicated.

II Experimental results and discussion

The samples used are the GaAs-Al_xGa_{1-x}As parabolic quantum well grown by molecular-beam epitaxy. On the top of the semi-insulating substrate there is a 1000 nm GaAs buffer layer with 20 periods of a AlAs(5ML)GaAs(10ML) superlattice, followed by 500 nm GaAs-Al_xGa_{1-x}As with x varying from 0.07 to 0.27, 100 nm $Al_{0.3}Ga_{0.7}$As with δ-Si doping, $Al_{0.3}Ga_{0.7}$As undoped layer (spacer), the 200 nm -wide parabolic well with the alloy composition x in the range $0 < x < 0.19$. Two structures have been studied, A and B, the main difference between these is that the parabolic well A has a spacer with smaller thickness 100 $\AA$ in comparison with 400 $\AA$ for sample B. It leads to the difference in the electron density: sample A has concentration n_s in the dark 3.9×10^{11} cm^{-2}, sample B - 0.54×10^{11} cm^{-2}. After growth the substrate with the parabolic quantum well (PQW) was processed into Hall bars. Four-terminal resistance and Hall measurements were made down to 30 mK in magnetic fields up to 17 T. The distance between the voltage probes was 250 μm and the width of the bar was 100 μm. The measurements were performed with an ac current not exceeding 10^{-8} A. The resistance was measured for different angles between the field and thesubstrate plane in magnetic field using an in situ rotation of the sample. The three dimensional pseudocharge is $n_{3D}=2\Delta\epsilon/(\pi e^2 W^2)$, where W is the well width, ϵ =12.5 -dielectric constant for GaAs Δ =150 meV- height of the parabola. We find $n_{3D}=2.1\times10^{16}$ cm^{-3} which corresponds to the classical width of the 3D electron gas for the sample A $w_e = n_s/n_{3D}$=190 nm and w_e = 26 nm for sample B. Therefore we can compare the behaviour of the QHE for the narrow and for the wide electron layers. For the wide parabolic well the sample layer is close to the geometrical width of the well, therefore the energy spectrum E_i of a parabolic well can be roughly approximated by the spectrum of a square well $E_i = i^2(\hbar/w_e)^2/8m_e$, where m_e is a effective electron mass. The mobility of the electron gas in the well is 270×10^3 cm^2/Vs for sample B and 65×10^3 cm^2/Vs for sample A.

The magnetoresistance and Hall effect data for sample A at different temperatures are shown in Fig.2. We see that in strong magnetic fields and low temperatures the sample reveals the usual Quantum Hall effect. However, the resistance peaks at filling factors n=3/2 and 5/2 are completely smeared out at 0.5 K. For the parabolic well with smaller layer width (sample B) the QHE is still clearly seen at T=0.9 K. Fig. 3 shows the temperature dependence of the diagonal resistivity from 30 to 900 mK for sample A. The inset in Fig. 3a shows activated resistivity at ν=1 (circles) and 2 (squares) minima which can fit to an Arrhenius plot. Saturated behaviour is found at T< 50 mK, which could be due to sample heating. The energy gaps calculated from the Arrhenius plot are very small ~ 0.02 meV. Fig. 2b shows the temperature dependence of the low field diagonal magnetoresistance for the same temperature interval. We see that at B< 1.2 T the amplitude of the oscillations practically does not depend on the temperature below 0.5 K and minima between peaks are very pronounced. We do not find zero resistance at magnetic field B<7 T, however background magnetoresistance can not be explained by hidden disordered electron layer, because we obtain zero resistance at stronger magnetic fields. We can also see that at B> 1.2 T all oscillations have a much stronger temperature dependence than the oscillations at lower fields. The peak at

B=5 T (Fig.2 a) and the neighboring minima are also completely smeared out at T=0.5 K. We should note that for the sample B the energy gaps calculated from the Arrhenius plot for minima 1 and 2 are coincident with the gaps which are expected for Landau and spin splitting.

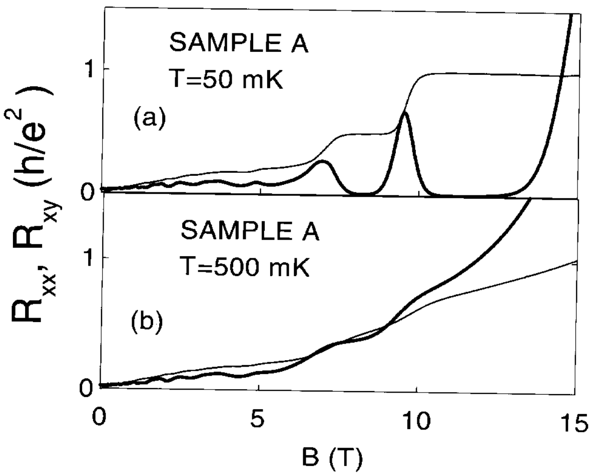

Figure 2. Longitudinal and Hall resistivities for a wide parabolic well at T=50 mk (a) and T=500 mK (b).

Numerical calculations for a square well of width w_e=190 nm yield the following energies for the first 5 electric subbands : E_1=0.19 meV, E_2=0.75 meV, E_3=1.7 meV, E_4=3 meV, E_5=4.7 meV. We determine the electron density for the different occupied electric subbands from the Fourier power spectrum of the Shubnikov de Haas oscillations at low magnetic fields. We obtain densities 1.4× 10^{11} cm^{-2} , 0.9× 10^{11} cm^{-2} and 0.55× 10^{11} cm^{-2}. We should note that probably we are not able to separate oscillations corresponding to the 1/B frequencies from the first and second subbands. In this case it is reasonable to estimate the electron density for the second subband as 1.3-1.2× 10^{11} cm^{-2}. The upper subband has lower electron density and we are not able to detect it. The total density N_s= 4.05-4.15× 10^{11} cm^{-2} is in good agreement with the QHE high field data (N_s = 3.9× 10^{11} cm^{-2}) . The energy separations between subbands ($\Delta E_{21}\approx$ 0.5 meV, ΔE_{31}=1.8 meV, (ΔE_{41}=3 meV) also are in good agreement with theoretical values for the square well (ΔE_{21} = 0.56 meV, ΔE_{31}=1.5 meV, ΔE_{41}=2.8 meV). In a parallel magnetic field we observe 4 peaks in the magnetoresistance curve due to the magnetic depopulation of levels, which is also in accordance with our calculations. Within a single electron model, application of a magnetic field perpendicular to the plane of the quantum well forms a fan of Landau levels originating from the energy levels of each electric subband. Fig. 1 illustrates the magnetic field dependence of the energy levels of a square well with thickness 186 nm including Zeeman splitting. One can see here that at magnetic field B>5 T the Zeeman energy is larger than the separation between the second and third electric subbands in accordance with calculations of spin effects in a wide parabolic quantum well [8]. Thus, minima at ν =1, 2 correspond to the Fermi energy lying in the energy gap ΔE_{21} and ΔE_{31}. In strong magnetic fields only the last Landau level of the lower electric subband is occupied, thus the last minimum should be observed at B=16 T. Fig. 2 shows that at B>13 T the diagonal resistance starts to grow, however the well developed Hall plateau are still seen at higher magnetic fields. This behaviour corresponds to the metal-Hall insulator transition, which has been observed previously in narrow GaAsAlGaAs and InAs/GaAlInAs quantum wells [9]. Therefore for the last minimum in the diagonal resistance, the Fermi level does not lie in the center of the ΔE_{21} gap. This shift of the metal Hall insulator transition to the lower field could be due to the smallness of the ΔE_{21} energy gap. Also, as we mentioned above, Hartree Fock calculations suggest a new charge density wave state or a Wigner crystal [9] at strong magnetic fields. The minimum destruction and resistance growth could be due to the pinning of this sate by impurities.

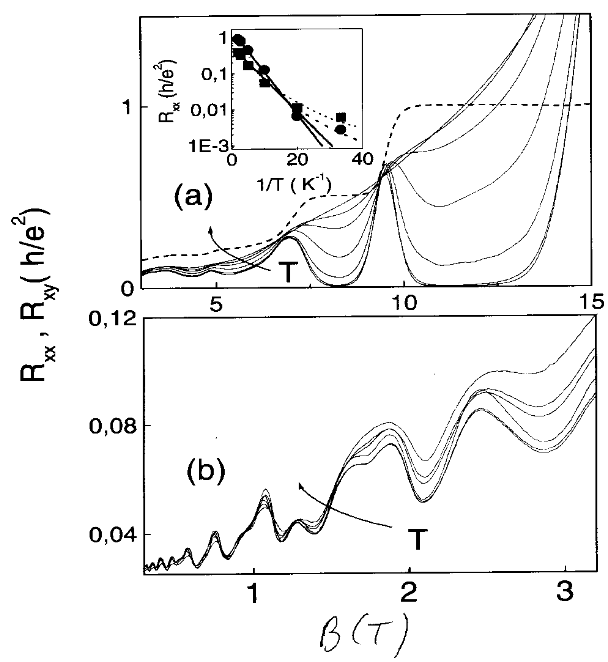

Figure 3. Longitudinal resistivity for different temperatures at strong (a) and low (b) magnetic fields. T=30, 100, 200, 350, 500, 750 and 900 mK. Insert : Arrhenius plot of Rxx at ν=1(circles) and 2(squares) vs 1/T.

III Conclusion

In summary, we measured the Quantum Hall effect in a wide quantum well and found very small activation in the resistivity minima energy at filling factors 1 and 2. Existing theory predicted such suppression in the ν=1 quantum limit due to the formation of a charge density wave. Small activation energies at ν=1,3 have been observed in a double quantum well [10], which also has been explained by phase transition to a charge density wave state [11]. We should note that the calculations also have been done only in the strong magnetic field corresponding to ν=1.

Acknowledgements

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