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Quantum Hall effect in $In_{0.53}Ga_{0.47}As$-InP heterojunctions with two populated electric subbands

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Quantum-Hall-effect and Shubnikov–de Haas measurements are presented for $In_xGa_{1-x}As$-InP heterojunctions with two populated electric subbands and low electron density ($n_s \leq 5\times10^{11}$ cm^{-2}). The Shubnikov–de Haas oscillations clearly show two different periodicities. An anomalous behavior of the quantum Hall effect is observed, in particular some plateaus are missing and other plateaus are enhanced. Precise measurements of the Hall resistance have been performed and it is shown that the resistance of the $i=2$ plateau is equal to its theoretical value $h/2e^2$ with an uncertainty of $\sim10^{-8}$.

I. INTRODUCTION

The quantum Hall effect (QHE) in modulation-doped heterojunctions has stimulated a great many investigations in both GaAs-$Al_xGa_{1-x}As$ and $In_xGa_{1-x}As$-InP systems because of the high mobility of the two-dimensional electron gas (2DEG) occurring at the interface. Most of the experiments previously reported were done in heterojunctions (HJ's) in which only the ground electric subband of the 2DEG was populated at low temperature and zero magnetic field. The electron gas is then purely two dimensional; under magnetic field, plateaus in the Hall resistance ρ_{xy} appear, corresponding with a very high accuracy to the quantized values[1] $\rho_{xy}=h/ie^2$, where $i=1,2,\ldots$, and the minima of the magnetoresistance ρ_{xx} become simultaneously very small. Values as small as $\rho_{xx}\sim5\times10^{-7}$ $\Omega/\square$ have been reported.[2] We present here new investigations of the QHE in modulation-doped $In_xGa_{1-x}As$-InP HJ's with two populated electric subbands at zero magnetic field and low electron density $n_s\leq5\times10^{11}$ cm^{-2}. The Shubnikov–de Haas oscillations show two different periodicities which clearly reveal the occupation of two electric subbands in the 2DEG. When the magnetic field is increased, depopulation of the higher subband is observed and corresponds to the reduction of intersubband scattering. An anomalous behavior of the QHE is observed, in particular some plateaus are missing and other plateaus are enhanced. Precise measurements of the Hall resistance have been performed, and it is shown that the resistance of the $i=2$ plateau is equal to its theoretical value $h/2e^2$ in the limit $\rho_{xx}=0$.

TABLE I. Characteristics of the heterojunctions used in this work.

Sample	Hall mobility (cm^2/V sec) 300 K	77 K	4 K	n_s (cm^{-2}) 4 K
S1	10 000	50 000	60 000	4.2×10^{11}
S2	11 800	55 000	70 000	5.4×10^{11}
S3	9500	41 000	55 000	5.4×10^{11}

The $In_{0.53}Ga_{0.47}As$-InP HJ's used here were grown by low-pressure metal-organic chemical-vapor deposition[3] on (100) semi-insulating Fe-doped substrates. The InP layer, ~1000 Å thick, was n type with $N_D-N_A\sim3\times10^{15}$ cm^{-3}. The $In_xGa_{1-x}As$ layer was also n type with $N_D-N_A\sim2\times10^{15}$ cm^3, its thickness being equal to 1 μm. Electrons are transferred from InP into $In_xGa_{1-x}As$ and an accumulation layer is formed at the interface.[4] The mobility of the 2DEG and the electron density at 4 K are obtained from low-field Hall measurements and are listed in Table I for each sample. Standard Hall bridges were used to measure ρ_{xx} and ρ_{xy} between 1.3 and 4.2 K. The magnetic field B, provided by a superconducting coil, could be swept from 0 to 10 T and could be applied either perpendicularly to the interface or tilted by an angle θ from the normal to the interface.

II. EVIDENCE FOR TWO POPULATED SUBBANDS

Figure 1(a) shows the B dependence of ρ_{xx} for sample S2 at low magnetic field ($B<1$ T) applied perpendicularly to the interface and $T=1.6$ K. Pronounced Shubnikov–de Haas oscillations are observed for $B>0.2$ T and two different oscillation periodicities appear clearly, which, we believe, originate from two populated subbands $E1$ and $E2$ in the 2DEG. Figure 1(b) gives the reciprocal field corresponding to the oscillation maxima as a function of the Landau-level index. Two linear dependences are observed and are associated with the two periodicities in B^{-1}. From the slopes of the two linear variations, the population $n_1=4.1\times10^{11}$ cm^{-2} and $n_2=1.1\times10^{11}$ cm^{-2} are calculated for $E1$ and $E2$, respectively. The total electron density $n_1+n_2=5.2$

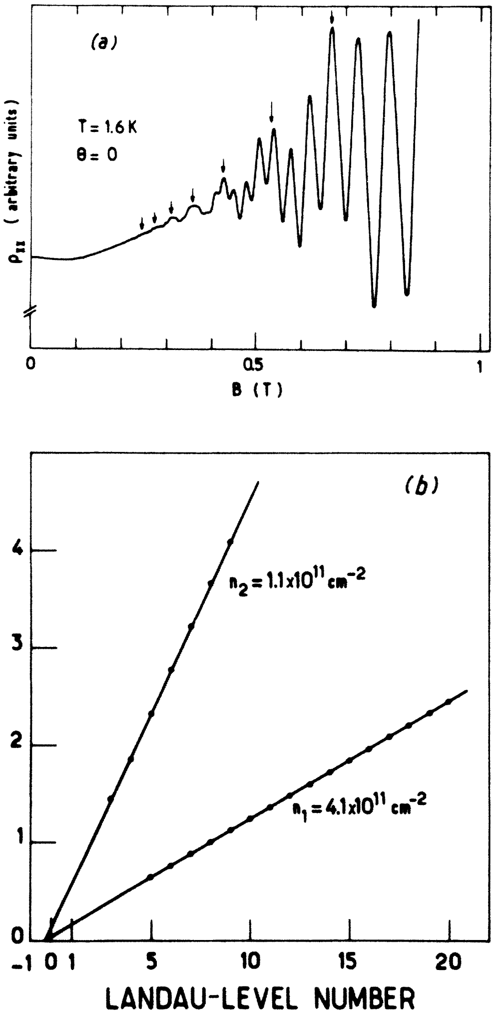

FIG. 1. (a) Shubnikov—de Haas oscillations at low magnetic field ($B < 1$ T) in sample S2. The maxima of the low-frequency oscillations are indicated by arrows (see text). (b) Reciprocal magnetic field at maxima of the high- and low-frequency oscillations versus the Landau-index number.

$\times 10^{11}$ cm^{-2} deduced from the Shubnikov—de Haas data is in good agreement with the value $n_s = 5.4\times 10^{11}$ cm^{-2} obtained from low-magnetic-field Hall measurements at 4 K in sample S2. Using $m^* = 0.047m_0$ for the 2DEG effective mass,[4] we get the Fermi energies $E_{F,1} = 21$ meV and $E_{F,2} = 5.5$ meV, measured from the bottom of the two subbands E1 and E2, respectively. The subband separation is then ~ 15.5 meV and the higher subband E2 starts to be occupied at $n_s \sim 3\times 10^{11}$ cm^{-2}. Similar results are obtained in sample S1 ($n_1 = 3.5\times 10^{11}$ cm^{-2}, $n_2 = 0.6\times 10^{11}$ cm^{-2}) and S3 ($n_1 = 4.6\times 10^{11}$ cm^{-2}, $n_2 = 0.9\times 10^{11}$ cm^{-2}). However, in previous experiments performed on HJ's grown by the same method, we had observed[4,5] only one occupied subband for $n_s \sim 4.5\times 10^{11}$ cm^{-2}. On the other hand, two populated subbands were evidenced[6] in $Al_xIn_{1-x}As$-$In_xGa_{1-x}As$ HJ's grown by molecular-beam epitaxy for $n_s \gtrsim 4.5\times 10^{11}$ cm^{-2}. The reason why a second subband is occupied for the low values of n_s reported here is not yet understood, but we would like to suggest a possible explanation. Indeed, it is important to note that, in the case of an accumulation layer in an n-type material, the potential profile, i.e., the subband position, is mainly defined at low temperature by the fixed charges which are the minority acceptor impurities.[7] As a result, the subband separation between E2 and E1, and therefore the critical concentration for which E2 becomes occupied, strongly depends on the minority acceptor concentration in the $In_xGa_{1-x}As$ layer which is unknown but may vary from sample to sample. If this suggestion is correct, this means that there are fewer acceptors in the $In_xGa_{1-x}As$ layers of samples S1, S2, and S3 than in the samples we used in Refs. 4 and 5, so that the HJ's investigated here would be of better quality. This is supported by the fact that, despite the intersubband scattering, the electron mobility in samples S1, S2, and S3 is higher than in our previous heterostructures.[4,5]

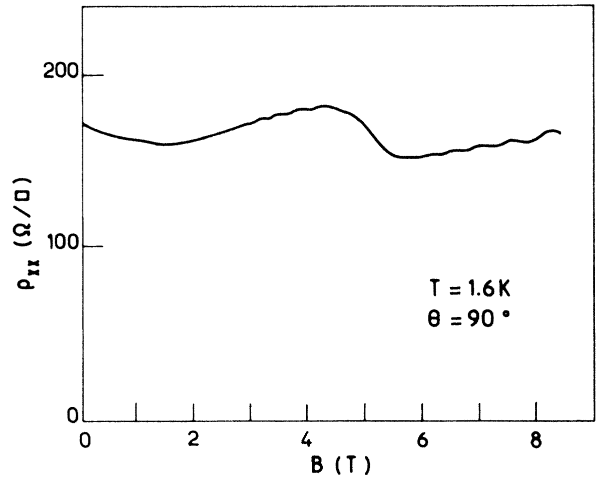

FIG. 2. Magnetoresistance of sample S2 with B parallel to the interface.

The existence of two populated subbands gives rise to intersubband scattering as calculated[8] and observed[9] in $GaAs$-$Al_xGa_{1-x}As$ HJ's. The influence of intersubband scattering can be demonstrated from magnetoresistance experiments with B parallel to the interface ($\theta = 90°$). The effect of a parallel magnetic field is to increase the subband separation and, finally, to depopulate[10,11] E2. Figure 2 shows the magnetoresistance ρ_{xx} as a function of B for $\theta = 90°$ in sample S2, which exhibits a fall of 20% about in the resistance occurring at $B \sim 5$ T. This fall corresponds to the magnetic depopulation of the higher subband E2 and to the reduction of the intersubband scattering. Similar results were obtained[12] in $Al_xIn_{1-x}As$-$In_xGa_{1-x}As$ HJ's and also in the resistance of $GaAs$-$Al_xGa_{1-x}As$ HJ's as a function of the electron concentration.[9]

III. QUANTUM HALL EFFECT

Figure 3 shows ρ_{xx} and ρ_{xy} in sample S1 at 1.3 K as a function of B applied perpendicularly to the interface. Striking features are observed in ρ_{xy} as compared to the usual QHE curves reported[5,13] in similar samples with

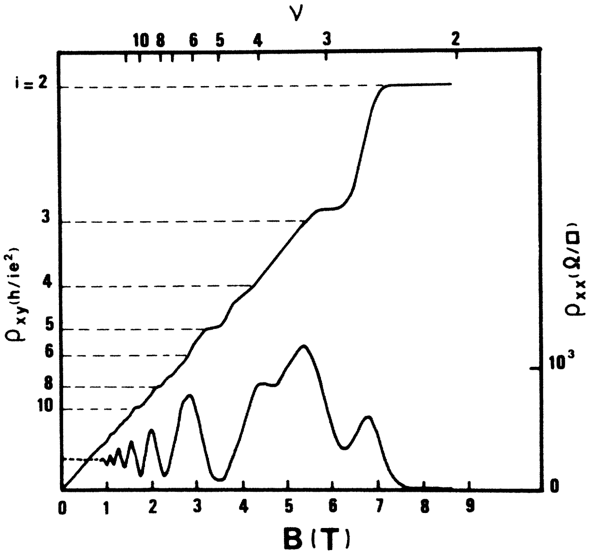

FIG. 3. Hall resistance ρ_{xy} and magnetoresistance ρ_{xx} as a function of B and the filling factor ν in sample $S1$ ($T=1.3$ K).

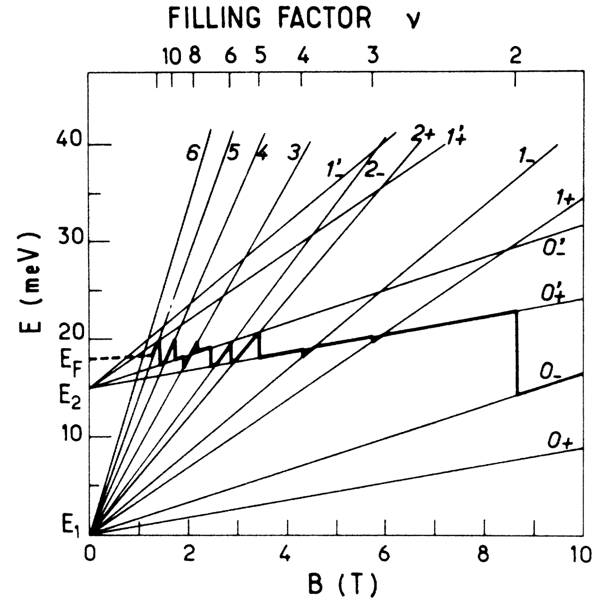

FIG. 4. Schematic diagram of the Landau levels $N_\pm$ and $N'_\pm$ arising from the two ground subbands $E1$ and $E2$. (The subscripts + and − refer to spin up and down, respectively.) For the sake of simplicity, the spin splitting of the levels is not presented for $N \geq 3$. The variation of the Fermi energy E_F assuming infinitely sharp Landau levels and a constant electron concentration $n_s=4.2\times10^{11}$ cm^{-2} is also shown (dotted line).

only one occupied subband. While the $i=2$, 8, and 10 plateaus are well developed at $B \sim 8.5$, 2.2, and 1.75 T, respectively, the $i=4$ and $i=6$ plateaus are nearly missing. Moreover, the width of the $i=5$ plateau occurring at $B \sim 3.5$ T is anomalous. Indeed, in experiments previously reported[5] on $In_xGa_{1-x}As$-InP HJ's with similar values of n_s and of the electron mobility but with only one occupied subband, the $\rho_{xy}=h/5e^2$ plateau was not observed even at very low temperature, because the spin splitting of the $N=2$ Landau level was not resolved. Remarkable features are also observed in the ρ_{xx} dependence as a function of the filling factor $\nu=n_sh/eB$. Figure 3 shows that ρ_{xx} minima occur for $\nu=2,5,8,10,12$ but only smaller structures are observed at $\nu \sim 3,4,6$. Furthermore, the only vanishing ρ_{xx} minimum occurs at $\nu=2$. The anomalous behavior of ρ_{xy} can be explained by the existence of two occupied electric subbands at $B=0$. Figure 4 shows a schematic diagram of the Landau levels $N_\pm$ and $N'_\pm$ arising from the two occupied subbands $E1$ and $E2$, respectively. The calculations are done for $\theta=0$ using 15 meV as the subband separation, $m^* \simeq 0.047m_0$,[4] and an enhanced Landau factor[13] $g \sim 10$, independent of the Landau level index and B. The resulting variation of the Fermi energy E_F, assuming infinitely sharp Landau levels, is also shown for a total electron concentration $n_s=4.2\times10^{11}$ cm^{-2}. The middle of each ρ_{xy} plateau and the ρ_{xx} minima in Fig. 3 must correspond to vertical jumps of E_F from one level to the next one occurring for integral values of ν. Figure 4 shows that the two Landau levels $0'_+$ and 1_- overlap in the vicinity of $\nu=4$ ($B \sim 4.4$ T), yielding no significant jump of E_F. This is consistent with the absence of the $i=4$ plateau in ρ_{xy} and the observation of a small dip instead of a real minimum in ρ_{xx} at $\nu \sim 4$ (Fig. 3). Similarly, the crossover of the 1_+ and $0'_+$ levels in the vicinity of $\nu=3$ ($B \sim 5.8$ T) strongly perturbs the ρ_{xy} plateau occurring at $B \sim 6$ T whose value is significantly larger than $h/3e^2$. The well-developed $i=5$ plateau appears when the $0_\pm$, $1_\pm$, and $0'_+$ Landau levels are completely filled and corresponds to the jump of E_F from $0'_+$ to $0'_-$. Note that in previous experiments[5,13] in $In_xGa_{1-x}As$-InP HJ's with only one occupied subband, the $i=5$ plateau would have corresponded to the jump of E_F between the two $N=2$ spin components which are not experimentally[5,13] resolved in samples with an electron mobility less than 70 000 cm^2/V sec.

Figure 4 shows that, in the case of $S1$, the $i=6$ plateau would correspond to the spin splitting of $N=2$ which, again, is not experimentally resolved. This is consistent with the absence of the $i=6$ plateau in ρ_{xy} and the nonobservation of any ρ_{xx} minimum at $\nu=6$ (Fig. 3). Finally, the $i=8$ and $i=10$ plateaus correspond to the usual situation when pairs of spin-split Landau levels are completely filled ($0_\pm,0'_\pm,1_\pm,2_\pm$ for $i=8$ and $0_\pm,0'_\pm,1_\pm,2_\pm,3_\pm$ for $i=10$). Note that, above 8.75 T, the subband $E2$ is totally depopulated by the magnetic field (Fig. 4). The $i=2$ plateau and the $\nu=2$ minimum of ρ_{xx} in Fig. 3 correspond to the usual situation where only one subband is occupied. A complete redistribution of the energy levels is obtained in tilted magnetic fields ($\theta \neq 0$) since the Landau level separation is determined only by the B component perpendicular to the interface while the spin splitting comes from the total magnetic field. Figure 5 shows ρ_{xy} in sample $S1$ for $\theta=45°$. The $i=4,5,6,10,12$ plateaus are observed, but the $i=8$ plateau is now missing. Again the result could be qualitatively interpreted with a schematic diagram of the Landau level arising from the subband $E1$ and $E2$ at $\theta=45°$. For a more precise analysis of the results, it would be necessary to take into account the

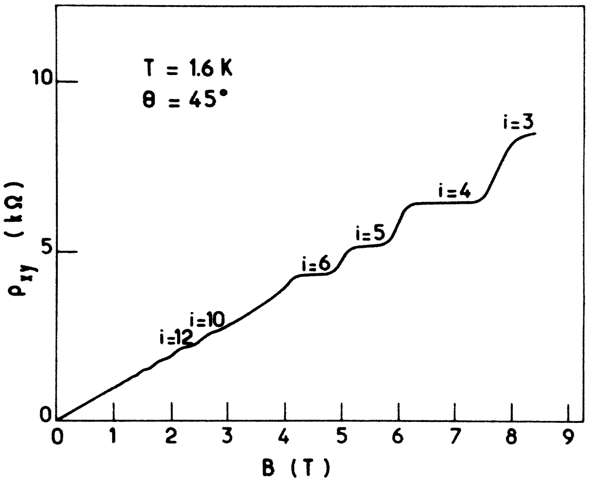

FIG. 5. Quantum Hall effect in tilted magnetic field ($\theta = 45°$) in sample $S1$.

broadening of the Landau levels, the exact dependence of the effective g factor on B and N, and, for $\theta \neq 0$, the shift of the $E1$ and $E2$ positions due to the introduction of a B component parallel to the interface.[10,11]

IV. PRECISE MEASUREMENT OF THE QUANTIZED HALL RESISTANCE

Precise Hall resistance measurements referred to a standard resistor were made at the Laboratoire Central des Industries Electriques at Fontenay-aux-Roses in France on sample $S1$. The experimental setup (a specially designed resistance-ratio measurement bridge using a cryogenic current comparator) was described elsewhere[14] and allows experiments with a 2.2×10^{-8} uncertainty (1σ). The $i = 2$ plateau which is associated with the smallest minimum of ρ_{xx} ($\rho_{xx}^{\min} \sim 10^{-3}$ Ω/□ at 1.3 K), was investigated between 2 and 1.3 K. At 1.3 K, the plateau is flat to better than $\pm 5 \times 10^{-8}$ over a 0.4-T range. The Hall resistance as a function of $\rho_{xx}^{\min}$ shows the linear variation:

$$\rho_{xy}(\rho_{xx}^{\min}) = \rho_{xy}(0) + 0.07\rho_{xx}^{\min} .$$

A similar linear law was previously observed[1] in GaAs-$Al_xGa_{1-x}As$ HJ's and may be due, at least partly, to the misalignment of the Hall probes. The most interesting result is that the extrapolated value $\rho_{xy}(0)$ in nondissipative conditions, i.e., at $\rho_{xx}^{\min} = 0$, is the same, within the experimental uncertainty, as the value obtained on GaAs-$Al_xGa_{1-x}As$ HJ's. $\rho_{xy}(0)$ is expected to be equal to the theoretical value $h/2e^2$. At 1.3 K, the correction $\Delta\rho_{xy}/\rho_{xy}(0)$ due to the finite value of $\rho_{xx}^{\min}$ is less than 10^{-8}. Detailed information about these precise ρ_{xy} measurements will be published elsewhere.[15]

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