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The quantum Hall effect in modulation doped $\text{In}_{0.53}\text{Ga}_{0.47}\text{As-InP}$ heterojunctions

Y. Guldner (*), J. P. Hirtz (**), J. P. Vieren (*),
 P. Voisin (*), M. Voos (*) and M. Razeghi (**)

(*) Groupe de Physique des Solides (+) de l'Ecole Normale Supérieure, 24, rue Lhomond, 75005 Paris, France

(**) Laboratoire Central de Recherche, Thomson-C.S.F., 91401 Orsay, France

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Résumé. — Nous décrivons la première observation à 4,2 et 1,5 K de l'effet Hall quantique dans les hétérojonctions $\text{In}_{0.53}\text{Ga}_{0.47}\text{As-InP}$ à dopage modulé. Ces résultats sont ensuite comparés à ceux obtenus sur une hétérojonction $\text{GaAs-Al}_x\text{Ga}_{1-x}\text{As}$ ayant des caractéristiques électroniques semblables.

Abstract. — We report the first observation of the quantum Hall effect in modulation doped $\text{In}_{0.53}\text{Ga}_{0.47}\text{As-InP}$ heterojunctions at 4.2 and 1.5 K. The results are then compared to data obtained in a $\text{GaAs-Al}_x\text{Ga}_{1-x}\text{As}$ heterojunction having similar electronic characteristics.

The quantum Hall effect (QHE), which has recently provided [1, 2] a very accurate determination of the fine structure constant, has been observed up to now in Si metal-oxide-semiconductor field-effect transistor [1] and in modulation-doped $\text{GaAs-Al}_x\text{Ga}_{1-x}\text{As}$ heterojunctions [3]. In such systems, a two-dimensional electron gas (2 DEG) is formed at the Si-SiO₂ or $\text{GaAs-Al}_x\text{Ga}_{1-x}\text{As}$ interface, and the QHE manifests in the occurrence of plateaus in the Hall resistance (ρ_{xy}) of this 2 DEG when the magnetic field B , perpendicular to the interface, is swept or when the electron density, n , is varied under constant magnetic field. These plateaus correspond to quantized values of ρ_{xy} , namely $\rho_{xy} = h/ie^2$, where $i = 1, 2 \dots$ is the number of filled Landau levels of the 2 DEG, and, simultaneously, the magnetoresistance, ρ_{xx} , vanishes.

Under magnetic field, the 2 DEG energy is quantized into Landau levels broadened by scattering, each level having a degeneracy $d = eB/h$. When i Landau levels are filled, the gap between empty and filled Landau levels prevents scattering to occur and the density of states at the Fermi level, E_F , tends to vanish, so that the diagonal conductivity σ_{xx} , as well as ρ_{xx} , is equal to zero at $T = 0$. In this case, the off-diagonal conductivity is $\sigma_{xy} = ne/B$ with $n = id$, so that $\sigma_{xy} = ie^2/h$, leading to $\rho_{xy} = h/ie^2$. The observation of plateaus implies that E_F is pinned between Landau levels over finite ranges of B or n , instead of jumping from one Landau level to the following one when B or n is swept. Several theoretical models have been proposed to account for the QHE,

(+) Laboratoire associé au C.N.R.S.

E_F being pinned either by shallow impurities [4], or by localized states [5-9] in the tails of the broadened Landau levels, as a result of potential fluctuations.

We report here the first observation of the QHE in another system, namely in modulation-doped $\text{In}_{0.53}\text{Ga}_{0.47}\text{As-InP}$ heterojunctions. More than ten pronounced plateaus in ρ_{xy} are detected, yielding thus at least as good data as in $\text{GaAs-Al}_x\text{Ga}_{1-x}\text{As}$ structures [3]. The temperature dependence of the QHE is studied, and the electron g factor is found to be enhanced from the observation of an additional splitting in ρ_{xx} at high magnetic fields. Finally, we compare our results to those obtained in a modulation-doped $\text{GaAs-Al}_x\text{Ga}_{1-x}\text{As}$ heterojunction having comparable electronic characteristics.

The $\text{In}_{0.53}\text{Ga}_{0.47}\text{As-InP}$ heterojunctions used here were grown by low-pressure metalorganic chemical vapour deposition [10] on (100) semi-insulating Fe-doped InP substrates. A typical structure is shown schematically in figure 1a. The InP and $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ epilayers were n-type with $N_D - N_A \sim 3 \times 10^{16}$ and $2 \times 10^{15} \text{ cm}^{-3}$, respectively. Standard Hall bridges (Fig. 1b) were used to measure ρ_{xx} and ρ_{xy} . The magnetic field, perpendicular to the interface, was provided by a superconducting coil, and could be swept continuously from 0 to 10 T. Low field Hall effect measurements gave electron mobilities equal to 9 000, 37 000 and 50 000 $\text{cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ at 300, 77 and 4.2 K, respectively.

Previous Shubnikov-de Haas and cyclotron resonance measurements have shown [11] that a 2 DEG is actually formed at the interface between InP and $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$. As in modulation doped $\text{GaAs-Al}_x\text{Ga}_{1-x}\text{As}$ heterojunctions [12], electrons from the donors in the wide band gap material (InP) are transferred in the narrow gap one ($\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$), so that E_F is constant throughout the structure. This results in a 2 DEG confined in the potential well due to the band bending near the interface which is caused by the spatial separation of positive (ionized donors) and negative (electrons) charges, as shown in figure 1c.

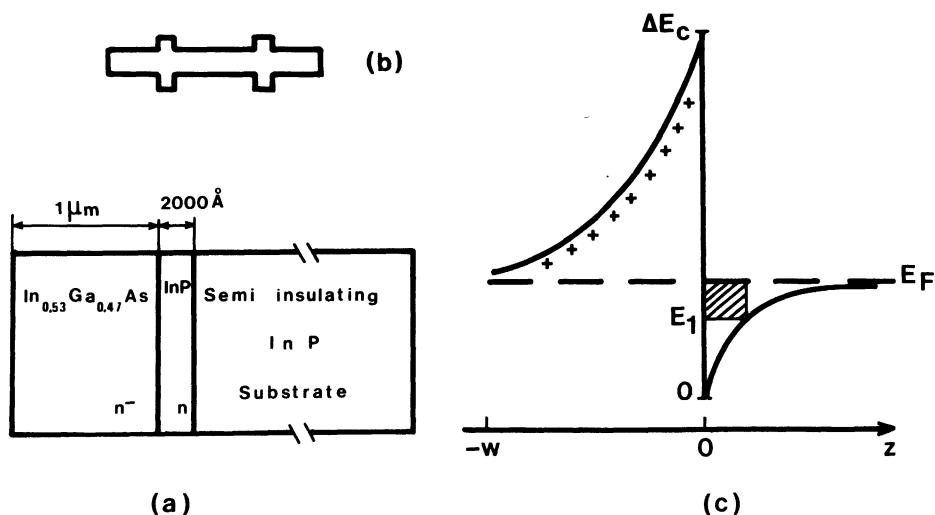


Fig. 1. — a) Configuration of the modulation doped $\text{In}_{0.53}\text{Ga}_{0.47}\text{As-InP}$ heterojunctions used here. b) Geometry of the Hall bridge used here; ρ_{xx} is measured along the length of the sample, and ρ_{xy} perpendicular to it. c) Schematic energy band diagram corresponding to modulation-doped heterojunctions. The interface is at $z = 0$, $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ and InP being situated, respectively, on the right and left hand side of the interface. E_1 and E_F are the ground electron subband and Fermi level, respectively. ΔE_c is the conduction band discontinuity, at $z = 0$, and W is the width of the depletion layer in InP corresponding to the region where donors are ionized (crosses). The hatched area represents the two-dimensional electron gas.

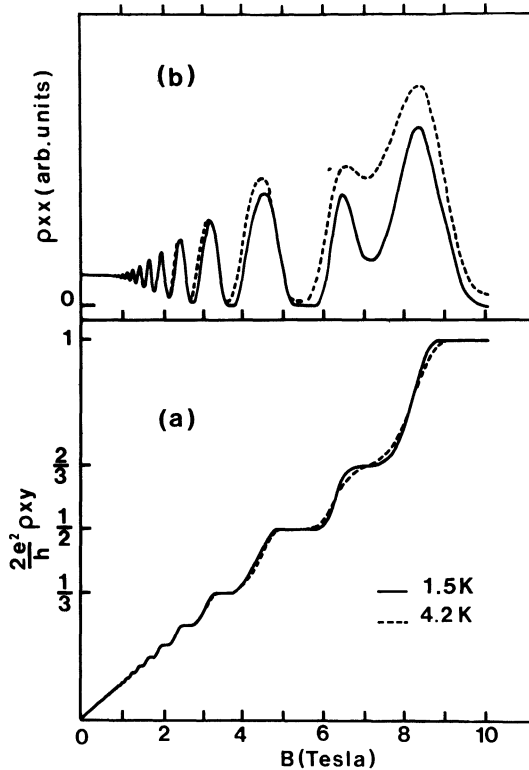


Fig. 2. — a) Typical results obtained in an $\text{In}_{0.53}\text{Ga}_{0.47}\text{As-InP}$ heterojunction. ρ_{xy} as a function of B at 4.2 (dashed line) and 1.5 K (solid line), with $h/2e^2 = 12\,906\ \Omega$. b) ρ_{xx} as a function of B at 4.2 (dashed line) and 1.5 K (solid line).

Figure 2 gives ρ_{xx} and ρ_{xy} at 4.2 K and 1.5 K. These results are quite typical of the QHE [1, 2], since they show unambiguously the vanishing of ρ_{xx} and plateaus in ρ_{xy} . The oscillations in ρ_{xx} are periodic in $1/B$, as in usual Shubnikov-de Haas measurements, and the electron density at the interfaces deduced from the period is here $n = 5.3 \times 10^{11}\ \text{cm}^{-2}$. One can see distinctly in figure 2a at least ten plateaus in ρ_{xy} corresponding to quantized values of the Hall resistance, such as $h/2e^2, h/3e^2 \dots$. The first two steps in ρ_{xy} occurring around 8 T correspond to the spin-split $N = 1$ Landau levels, and the plateau $h/3e^2$ to the gap between these two spin-split levels. The magnetic field separation between the midpoints of the two neighbouring steps of this plateau yields an effective electron g factor of the order of 10 at 1.5 K. The g factor is thus enhanced with respect to its bare value which is ~ 3 in $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ [13]. This is certainly due, as in Si MOS structures [14] and $\text{GaAs-Al}_x\text{Ga}_{1-x}\text{As}$ heterojunctions [15], to exchange interactions in the 2 DEG [16]. Note that we cannot distinguish plateaus corresponding to $h/5e^2, h/7e^2 \dots$ because, for the corresponding values of the magnetic field, the spin splitting of the associated Landau levels is too small and cannot be resolved.

We have also done the same experiments in a modulation-doped $\text{GaAs-Al}_{0.25}\text{Ga}_{0.75}\text{As}$ heterojunction grown by molecular beam epitaxy, in which the electron density ($n = 4 \times 10^{11}\ \text{cm}^{-2}$) and mobility ($\mu = 50\,000$ at 4.2 K) were comparable to their values in the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As-InP}$ heterojunctions studied here. We have obtained data quite similar to those shown in figure 2, the most striking feature being that, for each quantized value of ρ_{xy} which could be observed in our $\text{GaAs-Al}_{0.25}\text{Ga}_{0.75}\text{As}$ and $\text{In}_{0.53}\text{Ga}_{0.47}\text{As-InP}$ heterojunctions, the

range ΔB of magnetic field over which the corresponding plateaus extend (i.e. the width of the plateaus) were the same in both structures. This is indeed somewhat surprising because, except for n and μ , the two systems under study here, which were not grown by the same epitaxial method, are actually different. We believe, in fact, that the biggest difference is that the 2 DEG is either confined in $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ or in GaAs. Thus, one might expect to have potential fluctuations due to alloy disorder in $\text{In}_{0.53}\text{Ga}_{0.47}\text{As-InP}$ heterojunctions which would help in localizing carriers leading [5], for example, to wider plateaus than in $\text{GaAs-Al}_x\text{Ga}_{1-x}\text{As}$ heterojunctions. However, carrier localization is a difficult and subtle problem, and it is not possible to assert definitely from these simple observations, which we cannot explain at the present time, that localization is not involved in the QHE.

To conclude, we think that more experimental and theoretical investigations are clearly required to have a complete understanding of the quantum Hall effect, which is certainly a very interesting and stimulating aspect of semiconductor physics.

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