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Low-temperature investigations of the quantum Hall effect in $In_xGa_{1-x}As$–InP heterojunctions

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We report investigations of the temperature dependence of the quantized Hall effect in modulation-doped $In_xGa_{1-x}As$–InP heterojunctions. The diagonal conductivity σ_{xx} is studied at several maxima and minima of the magnetoresistance ρ_{xx} down to 50 mK. An interesting result is the observation of a hopping conduction mechanism when the Fermi level is in the tail of the broadened Landau levels.

The quantum Hall effect (QHE), first observed in Si MOSFET's (metal-oxide-semiconductor field-effect transistors)[1] and, then, in modulation-doped GaAs-$Al_xGa_{1-x}As$ (Ref. 2) and $In_xGa_{1-x}As$–InP (Ref. 3) heterojunctions, has recently stimulated a great deal of experimental and theoretical investigations. In heterojunctions, this effect manifests at low temperature in the occurrence of plateaus in the Hall resistance ρ_{xy} when the magnetic field B perpendicular to the interface, is swept. These plateaus correspond to quantized values of ρ_{xy}, i.e., $\rho_{xy}=h/ie^2$, where $i=1,2\ldots$ is the number of filled Landau levels of the two-dimensional electron gas (2D EG) formed at the interface in the narrow gap material. Furthermore, the ρ_{xy} plateaus are accompanied by a vanishing of the magnetoresistance ρ_{xx}. These observations imply that the Fermi level is pinned between Landau levels over finite ranges of B, the pinning of E_F being due to shallow donors[4] in wide gap material or to localized states[5] in the tails of the broadened electron Landau levels.

Quite recently, low-temperature studies below 1 K have been reported in GaAs-$Al_xGa_{1-x}As$ heterojunctions,[6] and have given interesting information on this effect. We wish to report here the first investigations of the temperature dependence of the QHE performed down to 50 mK in modulation-doped $In_xGa_{1-x}As$–InP heterojunctions. We have observed a logarithmic variation with temperature of the conductivity σ_{xx} at different magnetoresistance maxima, which is consistent with the theoretical model of Girvin, Jonson, and Lee,[7] who studied the effect of Coulomb interactions in a 2D EG under high magnetic field. We have also obtained the temperature dependence of σ_{xx} at several magnetoresistance minima, which is consistent with a hopping conduction mechanism.

The $In_xGa_{1-x}As$–InP heterojunctions used here correspond to $x=0.53$, and were grown by low-pressure metal-organic chemical vapor deposition[8] on (100) semi-insulating Fe-doped substrates. The InP layer, 2000 Å thick, was n type with $N_D-N_A \sim 3\times10^{16}\ \mathrm{cm}^{-3}$. The $In_xGa_{1-x}As$ layer was also n type with $N_D-N_A\sim1.5\times10^{15}\ \mathrm{cm}^{-3}$, its thickness being equal to 1 μm. Standard Hall bridges were used to measure ρ_{xx} and ρ_{xy}. The sample was cooled in a dilution refrigerator, and the magnetic field, perpendicular to the interface, was provided by a superconducting coil and could be swept continuously from 0 to 9 T. Low-field Hall measurements gave electron mobilities typically equal to 9700, 31 000, and 33 000 $\mathrm{cm^2 V^{-1} s^{-1}}$ at 300, 77, and 4.2 K, respectively.

Figure 1 shows data obtained at 1.85 K and 55 mK for ρ_{xy} and ρ_{xx} as a function of B for a current equal to 10^{-8} A. Using standard procedures, we get from the periodicity in $1/B$ of the ρ_{xx} oscillations an electron density n_s equal to $4.5\times10^{11}\ \mathrm{cm}^{-2}$. The temperature dependence of the QHE is mainly characterized by an increased width of the ρ_{xy} plateaus and by a narrowing of the associated ρ_{xx} peaks when the temperature is decreased. Figure 2 gives the variation with temperature of σ_{xx} obtained at different maxima of ρ_{xx}. For quantum numbers $n\geqslant2$, we have observed between 0.2 and 2 K the logarithmic dependence $\delta\sigma_{xx}=0.8\times10^{-5}\ln T$ (in units of mho), analogous to what has been observed in GaAs-$Al_xGa_{1-x}As$ heterojunctions[6] between 50 and 300 mK for $n\geqslant4$. Recently, Girvin *et al.*[7] have calculated $\delta\sigma_{xx}$, taking into account Coulomb interactions in the 2D EG in the high magnetic field limit, and have

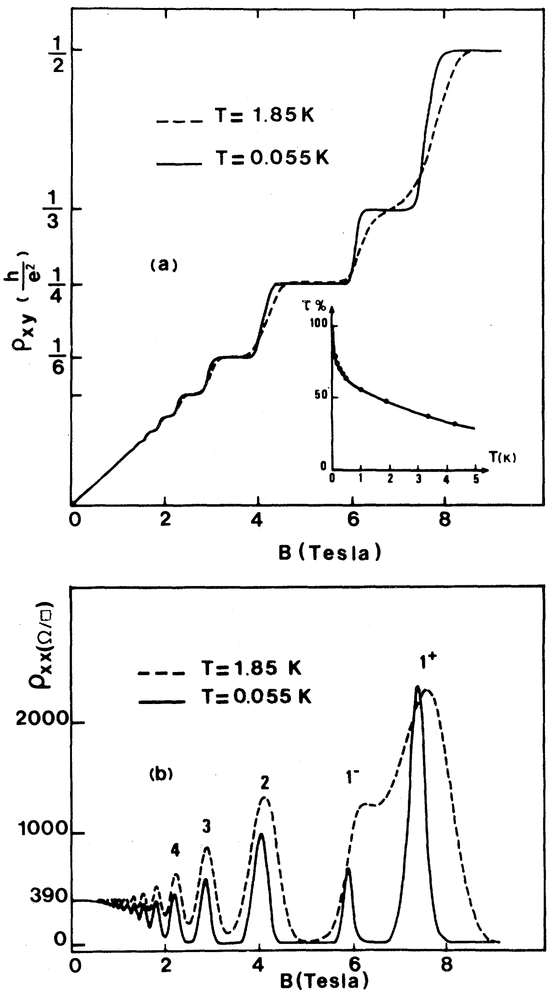

FIG. 1. (a) Hall resistance ρ_{xy} as a function of B at different temperatures. The inset shows as a function of temperature the ratio of the width of the $\rho_{xy}=h/4e^2$ plateau to its maximum possible width, as defined in the text. (b) Magnetoresistance ρ_{xx} as a function of B at different temperatures. The corresponding Landau levels are noted 1^+, 1^-, 2. . . .

obtained

$$\delta\sigma_{xx}=\frac{e^2}{2\pi h}(2-F)\ln T \ , \qquad (1)$$

where F is a quantity depending on the ratio of the screening length to the magnetic length. In our case, $F\sim 0.6$, yielding $\delta\sigma_{xx}\sim 0.86\times 10^{-5}\ln T$ (mho), in agreement with our experimental results. This logarithmic dependence has also been observed[9] in Si MOSFET's at $B=0$ in the weak localization regime. However, it should be noted that, as in Ref. 6, we have studied σ_{xx} at several ρ_{xx} peaks instead of measuring directly the temperature dependence of different σ_{xx} maxima, but the resulting discrepancy is clearly small for low values of n. It is also noteworthy that for $n\geqslant 2$ the spin splitting of the Landau levels is here unresolved as, in fact, in many other QHE experiments. At this stage, it is difficult to determine if this may influence the observed temperature dependence but, within the model of Girvin *et al.*,[7] this does not seem to strongly affect our analysis.

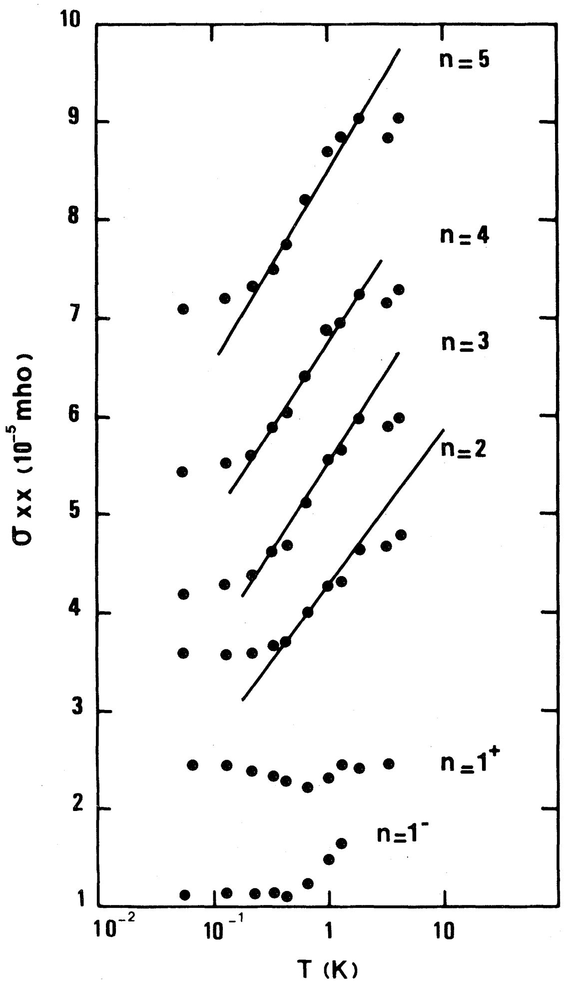

FIG. 2. Variation with temperature of σ_{xx} at different ρ_{xx} maxima.

We wish to emphasize now some experimental results which, we think, are striking but remain unexplained. (i) The relative height and width of the ρ_{xx} peaks noted 1^+ and 1^- in Fig. 1, which correspond to the $n=1$ spin-split Landau levels, is unexpected. Indeed, the $n=1^+$ peak is much wider and more intense than the $n=1^-$ peak, which is different from data obtained in GaAs-$Al_xGa_{1-x}As$ heterojunctions,[6,10] at least for the relative height of these two peaks. (ii) The step in ρ_{xy} associated with the $n=1^-$ ρ_{xx} peak (Fig. 1) is steeper than the step corresponding to the $n = 1^+$ ρ_{xx} peak. (iii) Though the data shown in Fig. 2 for the $n = 1^+$ and 1^- quantum numbers are not quite reliable above 1 K because the corresponding ρ_{xx} peaks broaden and overlap, they show nevertheless that the previous logarithmic dependence of $\delta\sigma_{xx}$ on temperature is not observed. In addition, our results are different from those of Paalanen, Tsui, and Gossard,[6] where a thermally activated conductivity is observed. (iv) As in Ref. 6 we observe a saturation of σ_{xx} in the low-temperature regime, namely, for $T < 200$ mK, which may be due to carrier heating.

Figure 3 shows the temperature dependence of σ_{xx} at three ρ_{xx} minima, namely, between the $n = 2$ and $n = 3$ (curve A), the $n = 1^-$ and $n = 2$ (curve B), and the $n = 1$ spin-split (curve C) Landau levels. Curves A, B, and C correspond to $B = 3.3$, 4.95, and 6.3 T, respectively. It can be seen that the data can be fitted to the following expression over a wide range of σ_{xx} between 50 mK and 1 K:

$$\sigma_{xx} \propto \frac{1}{T} \exp\left[-\left(\frac{T_0}{T}\right)^{1/2}\right] \quad . \qquad (2)$$

Such a good agreement would not be obtained over this range of temperature for $\sigma_{xx} \propto \exp[-(T_0/T)^{1/3}]$, which was, in fact, reported by Störmer *et al.*[11] in GaAs-Al_xGa_{1-x}As heterojunctions in a narrower and different temperature range. This behavior [Eq. (2)] was derived by Ono[12] for a hopping conduction in a two-dimensional electron gas under high magnetic field, using Gaussian localization for states close to the edge of the broadened Landau levels. Here T_0 is given by

$$T_0 \propto \frac{B}{D(E_F)} \quad , \qquad (3)$$

where $D(E_F)$ is the density of states at the Fermi energy E_F. From the experimental results, we obtain $T_0 = 11$, 70, and 7.8 K for curves A, B, and C, respectively. This difference is not explained by the magnetic field dependence of Eq. (3), but by the variation of the density of states $D(E_F)$ at the ρ_{xx} minima A, B, and C. Indeed, as can be inferred from Fig. 1(b), the overlap of the tails of the $n = 1^-$ and $n = 2$ levels, and thus $D(E_F)$, are smaller for the ρ_{xx} minimum B than that corresponding to the ρ_{xx} minima A and C. The observation of such a hopping behavior can be explained by the occurrence of localized states in the tails of the broadened electron Landau levels. The existence of such localized states has been found by Ando[13] from numerical simulations, and their influence on the QHE has been first discussed by Prange[5] and Aoki and Ando.[5]

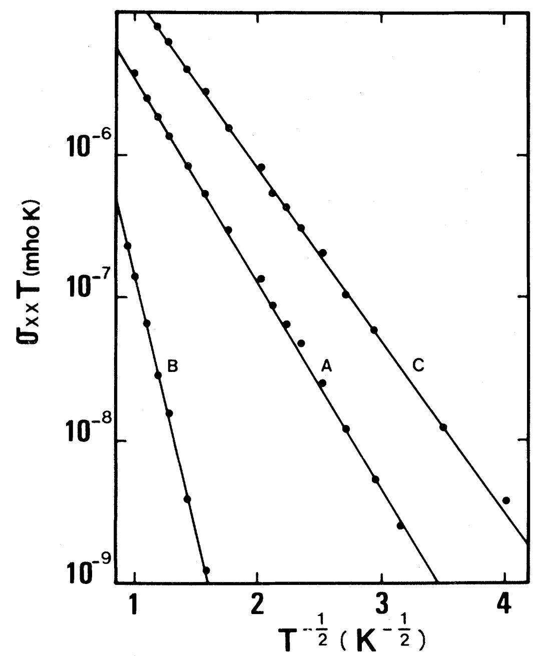

FIG. 3. Temperature dependence of σ_{xx} at ρ_{xx} minima A, B, and C, as defined in the text.

The ρ_{xy} plateaus occur when E_F lies in the localized states and, when the temperature is decreased, one can expect wider ρ_{xy} plateaus. We have investigated the width of the $\rho_{xy} = h/4e^2$ plateau between 4.2 K and 50 mK. As shown in the inset of Fig. 1(a), this width ranges, with an accuracy of the order of 0.5%, from 30% to 80% of its largest possible value obtained from the midpoints of the adjacent steps at 50 mK. These results cannot be explained by the model of Baraff and Tsui,[4] which cannot explain a strong temperature dependence of the QHE, but they show that an important fraction of the electron states are localized when T approaches zero, as already observed[6,10] in GaAs-Al_xGa_{1-x}As heterojunctions.

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