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Properties of the Quantum Hall Effect of the Two-Dimensional Electron Gas in the n-Inversion Layer of InSb Grain Boundaries under High Hydrostatic Pressure

By

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The magnetotransport properties of the two-dimensional electron gas (2DEG) confined at the interface of the grain boundary in p-type InSb bicrystals are investigated. Under high hydrostatic pressures and in high magnetic fields ($B > 5$ T) the integral quantum Hall regime is reached, where the Hall resistance ϱ_{xy} is quantized to h/e^2j (j is the number of filled Landau levels of the 2DEG). In this high field regime detailed measurements are given of the resistivity ϱ_{xx} and the Hall resistance ϱ_{xy} as function of temperature T and current density j_x. An unexpected high accuracy of the Hall resistance ϱ_{xy} at magnetic field values close to a fully occupied Landau level is found, despite the high value of the diagonal resistivity ϱ_{xx}. At high current densities j_x in the quantum Hall regime ($j = 1$) a sudden breakdown of the quantized resistance value associated with a jump-like switching to the next lower quantized value $h/2e^2$ is observed. A simple macroscopic picture is proposed to account for these novel transport properties associated with the quantum Hall effect.

Es werden die Magnetotransporteigenschaften des zweidimensionalen Elektronengases (2DEG) in der Inversionsschicht einer Korngrenze von p-leitenden InSb-Bikristallen untersucht. Unter hohem hydrostatischen Druck und in hohen Magnetfeldern ($B > 5$ T) werden experimentelle Bedingungen realisiert, bei denen der integrale Quanten-Halleffekt auftritt, d. h. der Hallwiderstand ϱ_{xy} in Werten von h/e^2j (j Zahl der besetzten Landau-Niveaus) quantisiert ist. In diesem Hochfeldregime werden detaillierte Messungen des Längswiderstandes ϱ_{xx} und des Hallwiderstandes ϱ_{xy} als Funktion der Temperatur T und der Stromdichte j_x durchgeführt. Es wird eine unerwartet hohe Genauigkeit des Hallwiderstandes ϱ_{xy} bei Feldwerten, die voll besetzten Landau-Niveaus entsprechen, gefunden, obwohl der Diagonalwiderstand ϱ_{xx} in diesem Feldbereich relativ hohe Werte annimmt. Im Gebiet des Hall-Plateaus ($j = 1$) wird bei hohen Stromdichten ein plötzlicher Zusammenbruch des quantisierten Wertes für den Hallwiderstand $\varrho_{xy} = h/e^2$ beobachtet, der mit einem sprunghaften Umschalten auf den benachbarten quantisierten Wert $h/2e^2$ verbunden ist. Es wird ein einfaches makroskopisches Bild für die Erklärung der beobachteten Transporteigenschaften in der Nähe des Hallplateaus vorgeschlagen.

1. Introduction

The two-dimensional electron gas (2DEG) formed in silicon MOSFET's [1] and also in various semiconductor heterostructures [2 to 4] has proved to be an excellent system for the experimental study of new interesting physical phenomena as e.g.

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the integral and fractional quantum Hall effect (QHE). The experiments previously reported in the literature demonstrate that in high magnetic fields and at low temperatures the Hall resistivity ϱ_{xy} of a 2DEG exhibits a series of plateaus at the quantized values $\varrho_{xy} = h/e^2 j$ ($j = 1, 2, \ldots$ is the number of filled Landau levels of the 2DEG), when the external magnetic field or the carrier density is varied. Simultaneously the minima of the magnetoresistance ϱ_{xx} become very small ($\varrho_{xx} \to 0$ in the low-temperature limit). According to the present view the occurrence of the quantized values of ϱ_{xy} is closely related to the problem of disorder and Anderson localization in strong magnetic fields [5]. When a 2DEG is placed in a strong transverse magnetic field at low temperatures, the density of states takes the form of nearly discrete extended states in the middle of the corresponding Landau subbands separated by localized states in the tails of each level. If the electron density and the magnetic field are such that the Fermi energy E_F lies in the region of localized states between the Landau levels, the Hall resistance ϱ_{xy} is precisely quantized. Despite the various degrees of disorder in the various semiconductor devices, the quantization of ϱ_{xy} is fulfilled with extreme accuracy and this result suggests that the QHE is a fundamental property independent of experimental details. The physical nature of the integral QHE and the extreme accuracy of the Hall quantization is now fairly understood as being due to the nearly complete absence of carrier dissipation in the quantized Hall regime. However, many aspects of the QHE, e.g. the nature of the localized states in strong magnetic fields, the role of various dissipative effects in higher electric fields, and the relationship between the disorder and the plateau width is not well understood and has not yet been very widely investigated.

Recently it was already demonstrated by magnetotransport investigations of the electronic properties of grain boundaries in n-Ge [6, 7], p-InSb [8], p-$Hg_{1-x}Mn_xTe$ [9], and p-$Hg_{1-x}Cd_xTe$ [10] that the defects (charged traps) in the grain boundary region lead to the formation of a inversion layer in which the degenerate carrier gas forms a quasi-two-dimensional system. In this system the carrier gas is confined in a symmetric V-like potential well which quantizes the motion of the carriers in the direction perpendicular to the grain boundary interface into a set of electric subbands. In addition, we have found from our magnetotransport measurements a remarkable change of the electronic properties of the n-inversion layer in InSb bicrystals under hydrostatic pressure [11]. A rapid decrease of the carrier concentration in the inversion layer is observed when pressure is applied. Under high pressures and in high magnetic fields convenient experimental conditions for the observation of the integral QHE are verified. It was shown in [11] that under high pressure, if only the ground electric subband of the 2DEG was populated, plateaus in the Hall resistance ϱ_{xy} appear, corresponding with high accuracy, to the quantized values $\varrho_{xy} = h/e^2 j$.

In the present paper we report on new detailed investigations of the 2DEG in the quantized Hall regime in the inversion layer of InSb bicrystals under high hydrostatic pressure. Precise measurements of the Hall resistance have been performed and some anomalous features of the QHE of 2DEG in the grain boundary interface are observed.

2. Experimental Details

The InSb bicrystal sample containing a single straight grain boundary was grown by the horizontal zone melting method with a double-seed technique. Some characteristic parameters of the sample (sample geometry, orientation of the bicrystal and the grain boundary) and some experimental details have been reported in a previous publication [8].

All measurements of the resistivity and the Hall constant of the sample were done with the standard dc technique with separate current and potential leads. The current fed to the sample was adjusted to levels where Ohmic behaviour was guaranted. The potentials are measured with a high impedance Keithley-type nanovoltmeter model 616. For the SdH-type experiments and investigation of the quantum Hall effect, magnetic fields up to 15 T were applied by a superconducting solenoid.

For measuring the electrical properties under hydrostatic pressure the bicrystal sample was mounted in a high pressure cell. All parts of the pressure vessel are made of a hardened Be–Cu alloy suited to low-temperature application in high magnetic fields. High pressures (up to 10^3 MPa) have been generated at room temperature and subsequently the pressure cell was placed into the cryostat and slowly cooled down to 4.2 K.

The excess acceptor concentration $p = N_A - N_D$ and the carrier mobility μ of the bulk material were determined from the Hall constant measured at 77 K with a magnetic field strength of 1 T ($p_{77K} = N_A - N_D = 5.8 \times 10^{15}$ cm^{-3}; $\mu_{77K} = 4.6 \times \times 10^3$ cm^2/Vs). The characteristic parameters of the inversion electrons in the interface region have been reported in our previous publication [8].

3. Experimental Results and Discussion

3.1 Quantum Hall effect under hydrostatic pressure

It has been reported in our previous paper [11, 14] that in the inversion layer of InSb grain boundaries at high pressures a rapid decrease of the 2D electron density results, as the pressure increases. It was demonstrated by our magnetotransport experiments that the decrease of electron concentration due to the application of pressure leads to a drastic change in the quantum properties of the 2DEG. Under conditions where only the ground electric subband of the 2DEG is populated ($p > 4.5 \times 10^2$ MPa) the Hall resistance ϱ_{xy} takes quantized values $\varrho_{xy} = h/je^2$. For $p = 4.2 \times 10^2$ MPa the ($j = 1$) ($\varrho_{xy} \approx 25.8$ kΩ) and the ($j = 2$) ($\varrho_{xy} \approx 12.9$ kΩ) resistance plateaus are observed in the magnetic field intervals 12 T $< B <$ 14 T and 7.1 T $< B <$ 7.8 T, respectively. For lower pressures (higher electron densities) the resistance plateaus with Hall resistance quantum numbers up to $j = 6$ are identified [11]. However, in the pressure range $p < 4 \times 10^2$ MPa an anomalous behaviour of the QHE and the Shubnikov-de Haas oscillations is observed at some fixed pressures (cf. [11, 12]), in particular, some plateaus are missing and other plateaus are enhanced. From a detailed analysis of these results and some numerical calculations [13], we concluded that the anomalous properties of ϱ_{xy} and ϱ_{xx} can be explained by the existence of several occupied electric subbands at $B = 0$ [14]. Similar results were obtained recently in InGaAs/InP heterojunctions [15].

For the measurements reported in this paper the attention is confined to the high-pressure range $p = (4$ to $6) \times 10^2$ MPa, where only one electric subband is populated ($n_s < 5 \times 10^{11}$ cm^{-2}).

Fig. 1 shows the pressure dependence of the electron density n_s in the inversion layer for pressures $p > 4.8 \times 10^2$ MPa. In this figure the solid line represents the results of a simple calculation based on the assumption of a constant density of positively charged interface states in the grain boundary region and a linear increase of the gap energy E_g with pressure ($\partial E/\partial p = 0.15$ meV/MPa).

Generally, for lower pressures $p < 5.5 \times 10^2$ MPa a good agreement between the results of different experimental methods and the calculations has been obtained (the results for $p < 4.8 \times 10^2$ MPa are published in our previous paper [11]). However, for pressures $p > 5.5 \times 10^2$ MPa remarkable differences between the values n_s

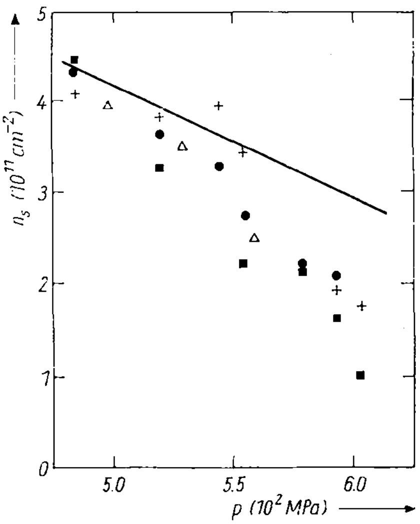

Fig. 1. Electron density n_s of the inversion layer vs. hydrostatic pressure. The solid line is a theoretical curve obtained from a simple calculation based on the assumptions mentioned in the text. The various experimental points are obtained by different experimental methods: + Shubnikov-de-Haas oscillations in high magnetic fields, ● position of the quantum Hall plateaus in high magnetic fields, ■ Hall effect in low magnetic fields ($B = 1$ T), △ quantum oscillations $d\varrho_{xx}/dB$ in low magnetic fields [14]

determined by different experimental methods are observed. Furthermore, the experimental values are tendentious smaller than the calculated ones, and the decrease of n_s with increasing pressure becomes stronger than expected from the simple model mentioned above. The reason for the different results obtained for n_s by the application of several experimental methods may be an inhomogeneous distribution of the inversion electrons along the sample axis x (cf. also Fig. 3a and the remarks given below). A possible explanation of the higher pressure coefficient of n_s at high pressures could be given by the assumption of a variable (increasing) density of the grain boundary interface states at higher energies [16].

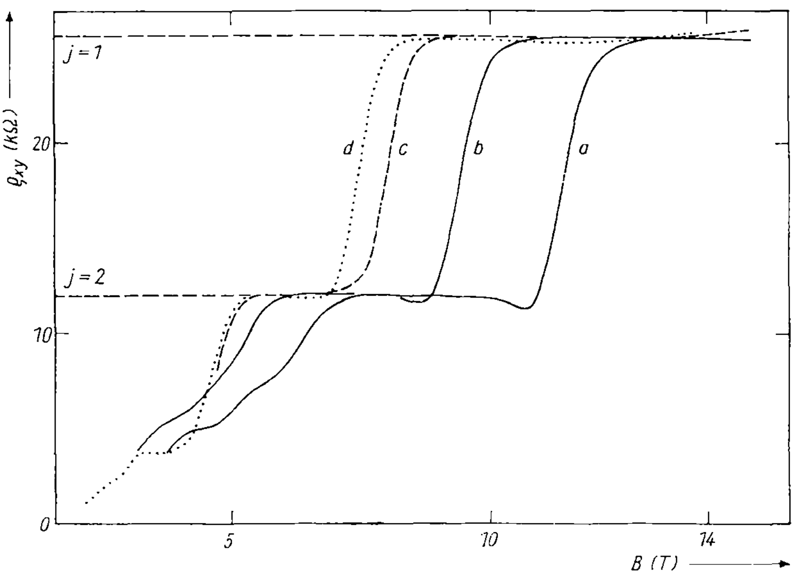

Fig. 2. Hall resistivity ϱ_{xy} vs. magnetic field for several pressures $p > 4.8 \times 10^2$ MPa (the experimental curves for $p < 4.5 \times 10^2$ MPa are published in [11]); $T = 1.47$ K, $I_x = 0.5$ μA

Fig. 2 shows experimental curves for the Hall resistivity $\varrho_{xy} = R_H$ as a function of magnetic field at fixed values of the carrier density n_s corresponding to various pressures p ($p > 4 \times 10^2$ MPa). Well-defined and extensive Hall plateaus with quantum numbers $j = 1$ and $j = 2$ are visible. The Hall plateaus are much more pronounced as at lower pressures (cf. [11]) and occupy a very wide field range, e.g. at $p = 5.9 \times 10^2$ MPa the ($j = 1$) plateau occupies a field range ΔB of approximately 7 T. As reported in our previous papers [11, 14] a remarkable shift of the Hall plateaus towards lower magnetic fields is observed as the pressure is increased.

The diagonal component ϱ_{xx} exhibits pronounced Shubnikov-de Haas oscillations at low magnetic fields ($B < 6$ T). In the quantum Hall regime $j = 1$ and $j = 2$ ϱ_{xx} usually drops to a pronounced minimum. However, despite the relatively high accuracy of the observed Hall plateau quantization (cf. Section 3.3) the resistivity component ϱ_{xx} remains finite and attains values > 1 kΩ. Fig. 3 represents this experimental situation at $T = 1.47$ K for two various values of hydrostatic pressure. For $p = 5.95 \times 10^2$ MPa (Fig. 3b) two extended Hall plateaus $j = 1$ and $j = 2$ are observed, while the ϱ_{xx} component monotonically increases over the whole field range ($B > 8$ T) reaching a resistance value up to 1 MΩ at 13 T.

This result is in sharp contrast to experiments in Si MOSFET's [1] and $Ga_{1-x}Al_xAs/GaAs$ heterojunctions [2, 3], which have already demonstrated that at low temperatures $\varrho_{xx} \to 0$ in the quantum Hall regime. Furthermore, a linear relationship between the finite resistivity ϱ_{xx}(min) and the small deviations of $\Delta\varrho_{xy}$ from the precise quantized Hall value should exist. The results for Si MOSFET's [17] and p-HgCdMnTe bicrystals [18] indicates that cooling the sample down to 0.3 to 0.5 K is important in order to approach the ideal conditions $\varrho_{xx} \to 0$. Our investigations of

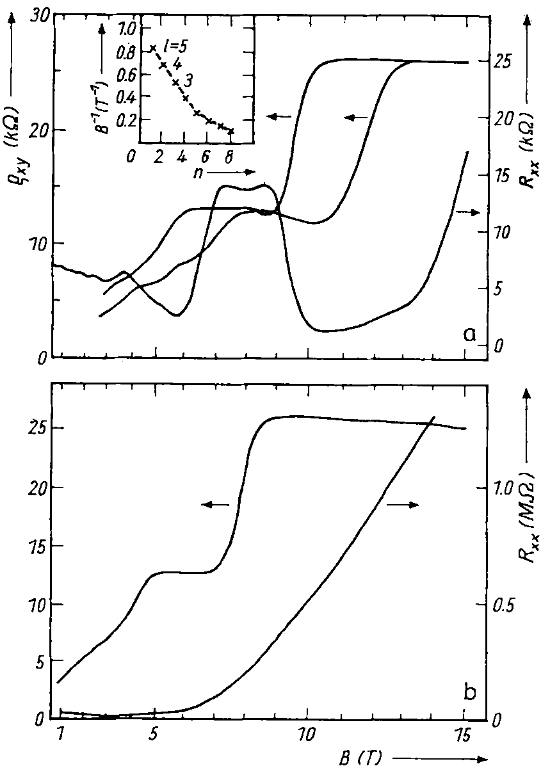

Fig. 3. Typical experimental curves for the Hall resistivity ϱ_{xy} and the longitudinal resistance R_{xx} as functions of the magnetic field at two fixed values of hydrostatic pressure corresponding to fixed carrier densities n_s of the inversion layer in the high-pressure range $p > 5 \times 10^2$ MPa, $T = 1.47$ K. a) $p = 5.2 \times 10^2$ MPa ($n_s = 3.85 \times 10^{11}$ cm^{-2}). The two distinct curves for ϱ_{xy} have been taken from experiments using different pairs of Hall probes of the sample; this result suggests that an inhomogeneous distribution of inversion electrons may exist at various points of the sample. b) $p = 5.95 \times 10^2$ MPa ($n_s = 2.2 \times 10^{11}$ cm^{-2}). The inset of Fig. 3a shows the standard plot of the inverse of the field positions of the extrema of Shubnikov-de Haas oscillations vs. their index; $l = 3, 4, 5 \ldots$ are the Landau quantum numbers of the magnetoresistivity oscillations ϱ_{xx} in high magnetic fields. In high magnetic fields spin splitting of the last Landau levels is observed

the temperature dependence of the ($j = 2$) Hall plateau ($p = 6.1 \times 10^2$ MPa, $B \approx \approx 6$ T) at low temperatures down to 180 mK indicates that the Hall plateau is more pronounced at lower temperatures, however, the value of the diagonal resistance $\varrho_{xx}^{\min}$ appears to be affected only weakly by temperature (at $T = 180$ mK $\varrho_{xx}^{\min}$ decreases by 20% at all).

From investigations on bulk semiconductors it is well known that a strong external magnetic field shrinks the atomic orbit and enhances the binding energy of the impurity atom. Magnetooptical and galvanomagnetic investigations of impurities in quantum wells show that, in this case also, the presence of the magnetic field enhances the impurity binding energy [19, 20]. Thus in magnetic fields $B > 12$ T the magnetic-field-induced metal–nonmetal transition (magnetic freeze-out of free carriers in shallow impurity states) may occur. However, for a M–NM transition defined in this way a rapid (exponential) variation of ϱ with temperature is expected. Such a dependence has not been confirmed by our experimental results (on the contrary, for $B = 12$ T ϱ_{xx} slightly decreases with decreasing temperature).

It is worth noting that inhomogeneities of the carrier density (series of quantized and nonquantized regions) may cause a nonvanishing diagonal resistivity ϱ_{xx} even if the quantized Hall conditions are realized in a part of the sample [21]. This is the most likely explanation for the unexpected behaviour of the diagonal resistance ϱ_{xx}. However, it is not clear yet whether this effect can yield resistance values >1 MΩ in the quantized plateau region. To clarify this point detailed measurements of ϱ_{xy} and ϱ_{xx} at more potential contacts attached to the grain boundary interface are required.

3.2 Temperature and current dependence of the resistivity components ϱ_{xy} and ϱ_{xx} in the quantum Hall regime

The investigation of the dependence of the quantized Hall resistance on various measuring parameters such as temperature and current may provide a deeper understanding of the transport properties associated with the QHE. From several investigations [22, 23] it appears that both $\varrho_{xx}^{\min}$and the slope $\mathrm{d}R_\mathrm{H}/\mathrm{d}B$ show thermally activated behaviour at sufficiently high temperatures, i.e. both quantities are proportional to exp $(\Delta E/2kT)$, where ΔE is the spacing between two adjacent spin-splitted Landau levels. At lower temperatures ($T < 1$ K) deviations from the activated behaviour are observed which are interpreted as a variable-range hopping process.

In our experiments the Hall resistance ϱ_{xy} was determined as a function of magnetic field with longitudinal currents of 0.5 to 50 μA at two different temperatures $T = = 1.46$ and 4.2 K. Fig. 4 summarizes the results of the temperature dependence of the quantized values of ϱ_{xy} at magnetic fields in which the ϱ_{xy}-component showed a well-defined Hall plateau $j = 1$ (the Fermi energy E_F lies between the 0^+ and 0^- Landau levels). It is apparent from this figure that the measured values of ϱ_{xy} in the observed plateau region are in good agreement with those given by the equation $\varrho_{xy} = h/e^2$. The agreement is limited by the accuracy of our measuring equipment ($\approx$0.5 ‰). As expected, the plateau quantization is significantly more complete at 1.46 K than at 4.2 K.

From investigations on Si MOSFETs and semiconductor heterojunctions it is well known that increasing channel current yields similar effects as increasing temperature, e.g. $\varrho_{xx}^{\min}$ increases and the width of the Hall plateaus decreases at on increase of the current. If for a fixed filling factor ν (ratio of the number of electrons present to the number of states within the lowest Landau level) the current is increased, there is a critical current density j_cr at which the dissipation-less transport suddenly breaks

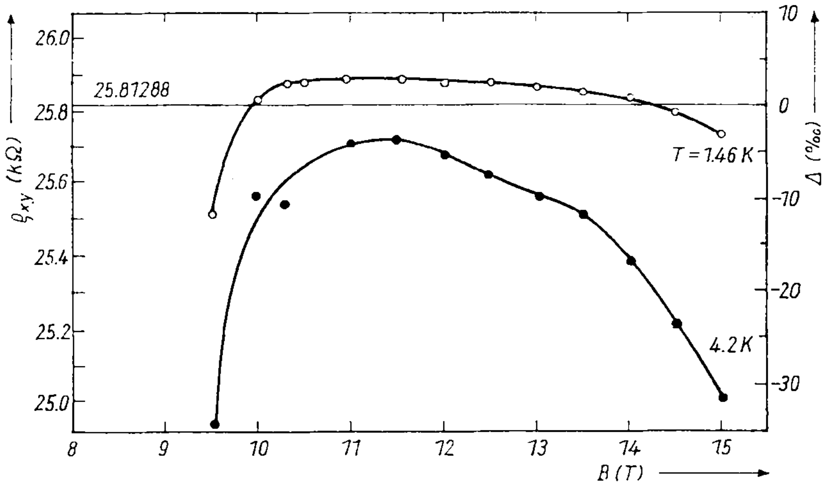

Fig. 4. Hall resistance values ϱ_{xy} and deviations $\Delta = (\varrho_{xy}^{\text{th}} - \varrho_{xy}^{\text{exp}})/\varrho_{xy}^{\text{th}}$ of the $(j = 1)$ quantized Hall step vs. magnetic field for two different temperatures T ($p = 5.4_5 \times 10^2$ MPa, $n_s = 3.9 \times 10^{11}$ cm^{-2}, $I_x = 0.5$ μA)

down and the longitudinal resistivity ϱ_{xx} increases by several orders of magnitude [24]. Ebert et al. [24] attribute this breakdown effect to an electron heating effect. However, other mechanisms like Zener tunneling [25], emission of acoustic phonons (if the drift velocity of the carriers exceeds the sound velocity) [26, 27], and electric-field-induced delocalization of carriers [28, 29] have been suggested to be the origin of the anomaly. Up to now the proposed mechanisms are qualitative and a definite understanding of the observed anomalous properties has not been achieved.

In this paper we present detailed and systematic measurements of the diagonal resistivity ϱ_{xx} and the Hall resistance ϱ_{xy} as a function of current I_x in the range of pressure p and magnetic fields in which the ϱ_{xy}-component exhibits the well-defined Hall plateaus $j = 1$ and $j = 2$.

Typical field dependences of the Hall resistivity ϱ_{xy} and its deviation $\Delta = (\varrho_{xy}^{\text{th}} - \varrho_{xy}^{\text{exp}})/\varrho_{xy}^{\text{th}}$ for various longitudinal currents I_x for the $(j = 1)$ and $(j = 2)$ plateaus are shown in Fig. 5. For the $(j = 2)$ plateau ($\varrho_{xy} = 12.90644$ kΩ) the well-known behaviour repeatedly observed on GaAs/GaAlAs heterojunctions has been observed. The width and the precision of the ϱ_{xy}-values substantially decrease with increasing current I_x.

However, for the $(j = 1)$ plateau ($\varrho_{xy} = 25.81288$ kΩ) a surprisingly distinct current dependence has been found (Fig. 5b). Very precise quantized values of ϱ_{xy}($\Delta < 0.5$‰) are obtained for the medium current range ($I_x = 5$ to 15 μA). In this case the agreement with the theoretical value $\varrho_{xy} = h/e^2$ is only limited by the accuracy of our measuring circuit. It is quite surprising that such a high precision of the ϱ_{xy}-values has been achieved despite the unusually high values of the diagonal component ϱ_{xx} attaining values up to 1 MΩ in the corresponding field range ($B > 12$ T).

Thus, it was explicitly verified that the usually accepted proportionality between the precision of the ϱ_{xy}-value and the value $\varrho_{xx}^{\text{min}}$ did not hold in our case. The high precision of the ϱ_{xy}-value observed in our experiments ($I_x = 5 \to 15$ μA), in our opinion, must be associated with an electron heating effect causing a slight but noticeable increase of the carrier concentration in the inversion layer. Such an interpretation has been supported by the non-ohmic behaviour of the I_x–U_x characteristic in this current range and the noticeable shift of the "onset" value of the plateau towards higher magnetic fields with increasing current I_x (cf. Fig. 5b).

Thus the present results suggest that an optimal carrier concentration may exist for the formation of a well-defined (accurately quantized) Hall plateau. A striking anomaly was observed at high current densities j_x. For values of the longitudinal current $I_x > 15\ \mu A$ in the quantum Hall regime ($j = 1$) a sudden breakdown of the quantized resistance value h/e^2 associated with a jump-like switching to the next

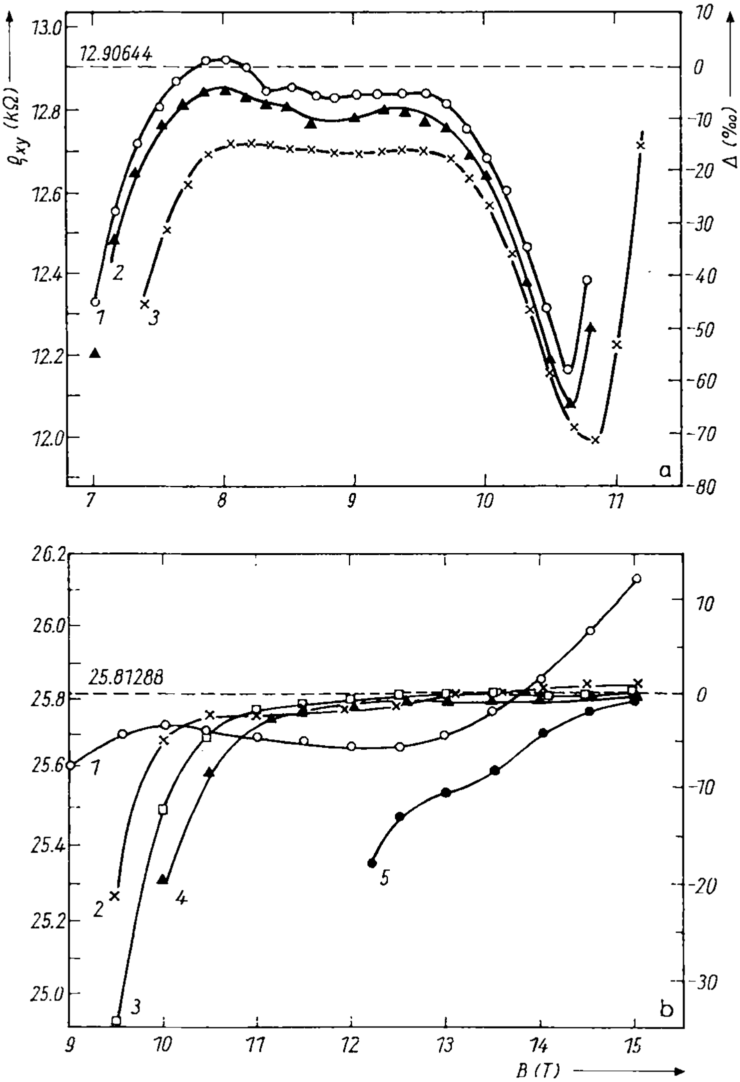

Fig. 5. Hall resistance values ϱ_{xy} and deviations $\Delta = \Delta\varrho_{xy}/\varrho_{xy}^{\text{th}}$ of the ($j = 1$) and ($j = 2$) quantized steps vs. magnetic field for different values of the longitudinal current I_x; $T = 1.47$ K. a) ($j = 2$) step ($\varrho_{xy} = 12.90644$ kΩ); $p = 4.85 \times 10^2$ MPa ($n_s = 4.2 \times 10^{11}$ cm^{-2}); (1) $I_x = 0.5$, (2) 15, (3) 20 μA. b) ($j = 1$) step ($\varrho_{xy} = 25.81288$ kΩ); $p = 5.8 \times 10^2$ MPa ($n_s = 2.4 \times 10^{11}$ cm^{-2}). (1) $I_x = 0.5$, (2) 5, (3) 10, (4) 15, (5) 20 μA

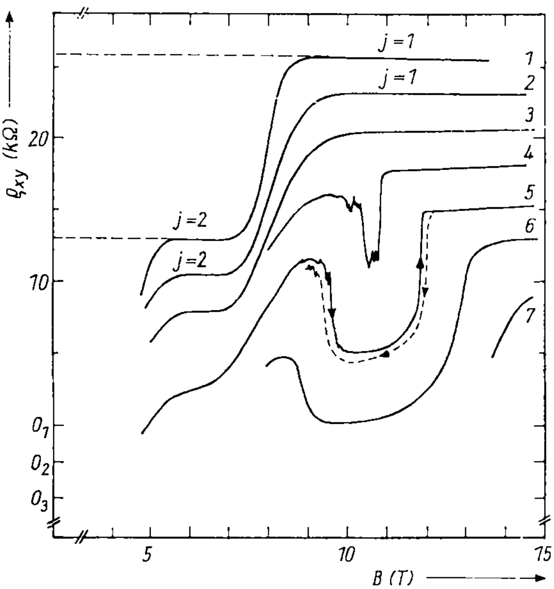

Fig. 6. Typical experimental curves for the Hall resistance ϱ_{xy} vs. magnetic field for different values of the longitudinal current I_x obtained in the high-pressure range ($p > 5 \times 10^2$ MPa); $p = 5.8 \times 10^2$ MPa ($n_s = 2.4 \times 10^{11}$ cm^{-2}); $T = 1.46$ K. (1) $I_x = 0.5$, (2) 5, (3) 15, (4) 18, (5) 20, (6) 25, (7) 50 μA. Note that the ordinate for each of the curves 2 to 7 is shifted downwards by 2.5 kΩ for clarity. The curves for $I_x = 18$ and 20 μA clearly illustrate the anomalous switching behaviour of the 2DEG in the quantum Hall regime ($j = 1$)

lower quantized value $h/2e^2$ has been observed. Fig. 6 shows the magnetic field dependence of the Hall resistivity ϱ_{xy} at $p = 5.8 \times 10^2$ MPa and $T = 1.46$ K for various longitudinal currents I_x. Qualitatively similar results are obtained at other pressures $p > 5 \times 10^2$ MPa. For $I_x < 15$ μA the normal step-like behaviour of the Hall resistivity ϱ_{xy} with pronounced plateaus $j = 2$ and $j = 1$ at magnetic fields $B > 5$ T has been observed. However, for $I_x > 15$ μA in the field dependences $\varrho_{xy}(B)$ spike-shaped instabilities appear at certain magnetic fields with a subsequent breakdown to a remarkably lower ϱ_{xy}-value. In higher magnetic fields ($B > 12$ T) a sudden jump-like reversal switching to the precise quantized value of the Hall plateau $j = 1$ occurs ($\Delta < 1‰$). Small hysteresis effects as shown in Fig. 6 (curve 5) are visible, when the sweep direction of the magnetic field is reversed. The jump-like behaviour in the field dependences is most pronounced in the relatively narrow current range $I_x = 20$ to 25 μA.

From an analysis of the experimental results it follows that the instabilities described here are directly connected with an S-shaped current–voltage characteristic.

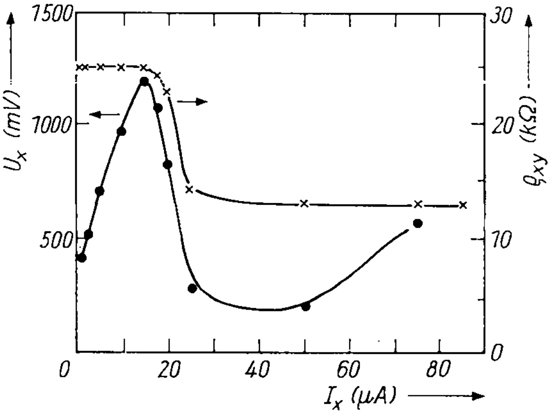

Fig. 7. U_x–I_x characteristic and current dependence of the Hall resistance ϱ_{xy} for $p = 5.9_5 \times 10^2$ MPa, $B \approx 10$ T (near the centre of the Hall plateau $j = 1$) and $T = 1.47$ K

Fig. 7 shows the I_x–U_x characteristic studied for a situation where the Fermi energy E_F lies between the two adjacent Landau levels 0^+ and 0^- (near the centre of the plateau $j = 1$). In the same figure the current dependence of the quantized value $\varrho_{xy}(I_x)$ measured under the same experimental conditions is shown.

For low currents $I_x < 15\ \mu A$ the resistivity component ϱ_{xy} precisely coincides with the value h/e^2. At a critical current $I_x^{cr} \approx 16\ \mu A$ U_x (and ϱ_{xx}) switches to a low-resistivity state and simultaneously the Hall resistance ϱ_{xy} switches to the next lower quantized value $h/2e^2$.

We believe that the observed breakdown of the QHE which is distinct in many features from the "ordinary" breakdown effect [24] (at which the dissipation less transport suddenly breaks down at a critical current density and the longitudinal resistivity increases by several orders of magnitude) can be accounted for by the following macroscopic picture.

According to our results it is highly probable that the breakdown is a consequence of the combined effect of the limited density of states in the lowest Landau level 0^+ ($N = eB/h$) and the sudden increase of the carrier concentration at a critical current density j_x^{cr}. At low currents and in high magnetic fields ($B > 9$ T) the electron density is such that the Fermi energy E_F lies at the localized states between the Landau levels 0^+ and 0^-, the Hall resistivity is precisely quantized. However, when sufficiently large electric fields are applied to the 2DEG the current–voltage instability provides a sudden increase of the carrier density of the 2DEG such that the Fermi energy moves to the region between the 1^+ and 0^- Landau levels providing the observed Hall resistivity $\varrho_{xy} = h/2e^2$ (Fig. 8).

In a magnetic field run (j_x = const) the critical electric field for such a switching effect can be generated by the increasing magnetic field due to the strongly increasing magnetoresistance ϱ_{xx} (see Fig. 3b), supposing that the increase of carrier concentration exceeds the growth of the degeneracy of the lowest Landau level. As the magnetic field is increased further in such a run, the degeneracy of the Landau level increases according to $N = eB/h$ whereas the carrier concentration remains nearly constant; the Fermi level is correspondingly reduced and the conditions for the quantized value h/e^2 are fulfilled thus leading to the observed reversal transition in higher magnetic fields. Since the two-dimensional density of states of the Landau levels increases linearly with the magnetic field, a slow and continuous transition between the quantized values may be expected. The observed sharp transitions clearly indicate that within the centre of the lowest Landau level an extremely narrow region of current carrying extended states must exist.

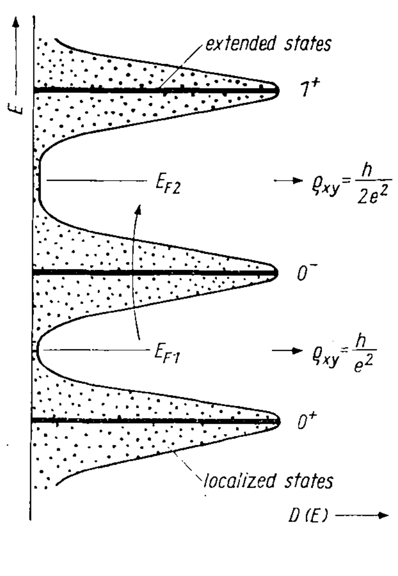

Fig. 8. Landau levels of a 2DEG in strong magnetic fields explaining the observed switching behaviour of ϱ_{xy}

On the other hand, for $B = \text{const}$ (under the Hall plateau condition $j = 1$) the voltage U_x strongly increases with increasing *current density* j_x and in a critical electric field the I–U instability occurs causing the switching effect mentioned above (Fig. 7).

Because for the occurrence of the I–U instability a large longitudinal voltage U_x is required, in our opinion, the observed switching effect at high magnetic fields is caused primarily by the high ohmic resistance in the quantum Hall regime.

The origin of the S-shaped current–voltage characteristic and the sudden increase of the carrier density of the 2DEG may be impact ionization of donor-like impurity states in high electric fields. However, it should be noted that the average electric field in the direction of current flow in the sample reaches values in the order of 1.5×10^4 V/m (for $B \approx 10$ T, $I_x = 15$ μA). Electric fields in this order of magnitude may cause a transport of inversion electrons from sample regions of higher electron density to depleted sample regions (i.e. tunneling or ballistic transport of carriers through potential barriers caused by the considerable inhomogeneities of the carrier distribution in the 2DEG), so that the sudden increase of the electron density between the Hall probes could be a combined effect of high electric fields and a local redistribution of the inversion electrons due to the inhomogeneities inside the sample.

Finally, we feel that our model of the observed breakdown effect is very simple and explains the experimental results only qualitatively. Many features of the effect remain poorly understood. In order to achieve a definite understanding of the phenomenon and to improve the interpretation of the results a detailed study of the transport properties in high magnetic fields are required.

4. Conclusions

To summarize, detailed investigations of the QHE in the inversion layer of InSb grain boundaries, on the one hand, demonstrate the universal two-dimensional properties of this effect, on the other hand, our experiments exhibit some striking anomalies of the QHE in this structure under high hydrostatic pressure. It is shown that a part of the found anomalies may be caused by inhomogeneities of the carrier density across the sample. The observed switching effect was suggested to be a direct consequence of the high ohmic resistance in the quantum Hall regime.

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