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WEAK FIELD HALL RESISTANCE AND EFFECTIVE CARRIER DENSITY ACROSS METAL-INSULATOR TRANSITION IN Si-MOS STRUCTURES

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We studied the weak field Hall voltage in Si-MOS structures with different mobility, across the metal-insulator transition. In the vicinity of the critical density on the metallic side of the transition, the Hall voltage was found to deviate by 6–20 % from its classical value. The deviation does not correlate with the strong temperature dependence of the diagonal resistivity $\rho_{xx}(T)$. In particular, the smallest deviation in R_{xy} was found in the highest mobility sample exhibiting the largest variation in the diagonal resistivity ρ_{xx} with temperature.

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In the framework of the quasiclassical description of Si-MOS structures [1], the charge of the inversion layer Q_{inv} is proportional to V_g, as in a plain capacitor formed by the metallic gate and the 2D layer. This prediction was confirmed by the measurements of the Shubnikov – de Haas effect in perpendicular field [2]. At low temperatures, when the bulk conductance is frozen out and the charge in the depletion layer does not vary with gate voltage, variation of the capacitor charge with V_g is related to the inversion layer charge only:

$$Q_{inv} = C(V_g - V_t). \tag{1}$$

Here $C = dQ/dV_g$ is the geometric capacitance between the gate and the 2D carrier layer, V_t is determined by the difference in work functions of the Al-gate film and the 2D carrier layer, by the energy of the bottom of the lowest subband in the confining potential well and by the charge trapped in depletion layer and at the interface [1]. The charge in Si-MOS structure Q_{inv} was measured directly [3] and was found to be equal (within 2 % uncertainty) to the charge of the 2D carrier layer $Q_{2D} = e \times n_{\rm ShdH}$, where $n_{\rm ShdH}$ is the density of carriers participating in the Shubnikov – de Haas or Quantum Hall effect (QHE), $n_{\rm ShdH} = (eB/h) \times i$, and i is the number of filled quantum levels in a given magnetic field B.

The issue on the carrier density was raised recently again in connection with the metal – insulator (M–I) transition in 2D carrier systems at $B = 0$. The transition occurs at a critical gate voltage V_{gc} (where $V_{gc} > V_t$) [4]. The critical gate voltage is interpreted to correspond to a critical carrier density $n_c = (dn/dV_g)(V_{gc} - V_t)$. Recently, an alternative interpretation was put forward [5] where the density of carriers participating in transport at $B = 0$ was suggested to be equal to $n_{eff} = (dn/dV_g)V_g - n_c$, so that $n_{eff} = 0$ at the transition, i.e. at $V_g = V_{gc}$.

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The effective number of carriers is not a well defined parameter close to the M–I transition, and may, apriori, be found different in different effects. In a weak magnetic field, the Hall resistance in the single-particle approximation [6] is inversely proportional to the number of carriers:

$$R_{xy} \approx \frac{\omega_c \tau}{\sigma_0}[1 - \frac{1}{(\omega_c \tau_0)^2}\frac{\Delta G(\epsilon_F)}{G}]. \tag{2}$$

Here $\sigma_0 = ne^2\tau/m^*$ is the diagonal conductivity at $B = 0$, $\omega_c = eB/m^*$ is the cyclotron frequency, and τ, the transport scattering time at $B = 0$. G and ΔG are the monotonic and oscillatory parts of the density of states. According to the theory [7, 8], electron-electron interaction affects R_{xy} in the same order as σ_{xx} and thus, $\delta R_{xy}/R_{xy} \approx 2(\delta\rho_{xx}/\rho^0_{xx})$.

The Hall resistance was measured earlier, in low mobility p- and n-type Si-MOS structures [9, 10, 1] and was found to *remain finite and non-activated through the transition to the temperature activated conduction regime.* In high mobility n-type Si-MOS samples, the Hall resistance was measured across the QHE-insulator transition [11 – 13] and found also to be close to its classical value [12] $R_{xy} = B/ne$ with n given by Eq. (1). Low frequency (~ 3 Hz) ac-measurements of the capacitance "gate-2D layer" [11] have shown that the capacitance remains unchanged, within a few %, across the QHE-insulator transition. With such a precision, the number of carriers participating in charging-discharging is described by the same Eq. (1) both, in the insulating and metallic phases. This observation also sets an upper estimate for possible variation of the trapped charge in the vicinity of the M–I transition: $dV_t/dV_g < 10\%$.

The above measurements of R_{xy} and of the capacitance, however, were done in *quantizing magnetic field.* In this paper we report measurements of R_{xy} performed in such *weak magnetic fields*, where Landau levels are not resolved, $\Delta G/G \ll 1$. We found that the *weak-field Hall voltage remains finite across the M–I transition.* Deviation of R_{xy} from the quasiclassical value is within $(6 - 20)\%$ for different samples. In the assumption that the inverse Hall voltage is a measure of the effective number of carriers, n_{eff}, the latter does not decrease to zero at the M–I transition.

We studied three samples from different wafers: Si22 (with the peak mobility, $\mu = 33.000\,\text{cm}^2/\text{Vs}$ at $T = 0.3\,\text{K}$), Si4/32 ($\mu = 8.000\,\text{cm}^2/\text{V·s}$) and Si-46 ($\mu = 1.350\,\text{cm}^2/\text{V·s}$). All samples had oxide thickness of 200 ± 30 nm, and, correspondingly, $dn/dV_g = (1.05 \pm 0.15) \cdot 10^{11}\,/\text{V·cm}^2$. The samples had potential probes lithographically defined with accuracy of $1\,\mu$m. Top view of the samples is shown in the inset to Fig.1, where $w = 800\,\mu$m and $l = 1250\,\mu$m are the channel width and intercontact distance, and $d = 25\,\mu$m is the width of the bulk diffusion area contacting the 2D layer. For Hall voltage measurements at low density, we used battery operated electrometric amplifiers with input current $< 10^{-14}$ A. Four-probe measurements were taken by ac lock-in technique at $(3 - 7)$ Hz, and partly by dc-technique.

Fig.1 demonstrates that minima in the Shubnikov – de Haas oscillations in ρ_{xx} are equidistant in the gate voltage scale. The carrier density calculated from the minima is independent of magnetic field (in the range 0.5 to 5 T) and of temperature (for 0.3 to 1.4 K), within uncertainty of $(1 - 2)\%$. Hall voltage was measured in field of $0.2 - 0.3$ T which is large enough to suppress the quantum interference corrections to conductivity [14], and is low enough to keep the oscillatory part in the density of states small, for all gate voltages and temperatures down to 30 mK.

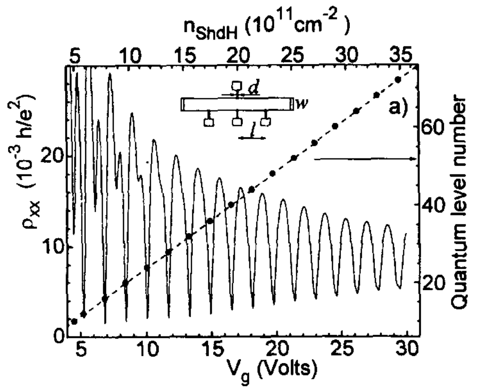

Fig.1. Shubnikov – de Haas oscillations in ρ_{xx} vs gate voltage at $T = 0.29\,\mathrm{K}$ and $B = 2\,\mathrm{T}$. Dashed line and full dots demonstrate a linear dependence between the number of the quantum level and the gate voltage, from which the n_{ShdH} density is calculated. Inset shows the sample geometry

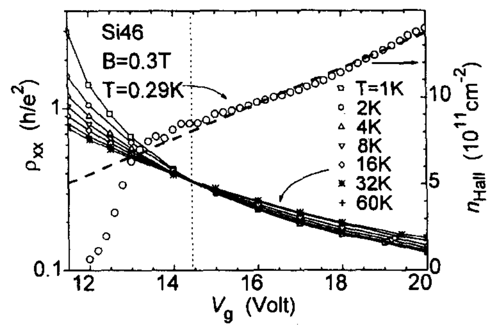

Fig.2. Resistivity at $B = 0$ (left Y-axis) vs gate voltage for the sample Si46 for seven temperature values. Hall density (right Y-axis) as a function of gate voltage at $B = 0.3\,\mathrm{T}$ and $T = 0.29\,\mathrm{K}$. Dotteded line depicts V_{gc}, dashed line is for the density n_{ShdH}

For the samples Si22 and Si4/32, the resistivity exhibited the exponential drop for $V_g > V_{gc}$ as temperature decreased [4, 15]. For the most disordered sample Si46, resistivity $\rho(T)$ is activated in the insulating state (for $V_g < V_{gc}$) and has a weak, almost linear, "metallic" temperature dependence for $V_g > V_{gc}$ [15], as demonstrated in Fig.2. The effective "Hall-density", $n_{\mathrm{Hall}} = B/eR_{xy}$, calculated from R_{xy} at $T = 0.29\,\mathrm{K}$ is shown in Fig.2. The dashed line depicts n_{ShdH} vs gate voltage, calculated from the period of oscillations. As V_g decreases, the effective Hall-density deviates from the classical linear dependence, and then falls quickly to zero, deep in the insulating state. This is consistent with the earlier results of Ref. [10]. Just at the critical gate voltage $V_{gc} = 14.4\,\mathrm{V}$, the Hall-density is by 5% *larger* than the classical value given by Eq.(1).

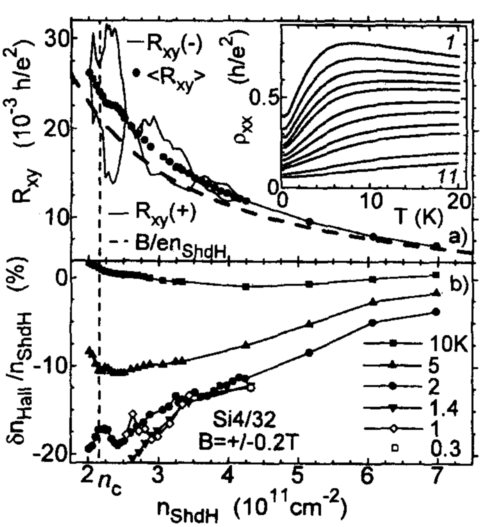

Fig.3. a) Hall resistance vs carrier density, measured at two opposite field directions at $T = 2\,\mathrm{K}$ and $B = \pm 0.2\,\mathrm{T}$. Dotted curve represents an averaged resistance, $< R_{xy} >= (R_{xy}(+B) - R_{xy}(-B))/2$. Bold dashed curve – classical dependence B/ne. b) Deviation in the "Hall-density", δn_{Hall}, measured at $B = \pm 0.2\,\mathrm{T}$ for six temperatures. Vertical dashed lines mark the critical density n_c. The inset shows ρ_{xx} vs temperature for 11 densities, 2.4, 2.5, 2.6, 2.7, 2.8, 3, 3.2, 3.4, 3.7, 4.7, 5.7, in unites of $10^{11}\,\mathrm{cm}^{-2}$

For samples with higher mobility, the critical density n_c is lower and the critical resistivity ρ_c is higher [15]. By this reason, the admixture of the longitudinal voltage produces large distortions of the measured Hall voltage. As Fig.3a shows, the admixture can be reduced substantially by subtracting the results taken for opposite magnetic field directions. The Hall resistance for sample Si4/32 at low density is larger than the quasiclassical value B/en_{ShdH}. The deviation in the effective Hall-density, $\delta n_{\text{Hall}} = n_{\text{Hall}} - n_{\text{ShdH}}$, calculated from the measured R_{xy} values for six temperatures is plotted in Fig.3b. At high density and high temperature, the deviation in the Hall-density tends to zero. As temperature decreases to 0.3 K, the deviation raises to almost 20%, and seems to saturate.

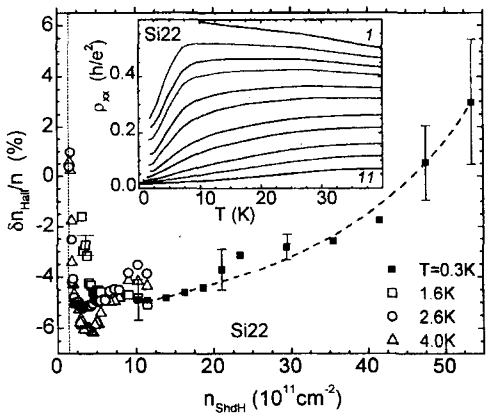

Fig.4. Deviation in the "Hall-density", δn_{Hall} measured at $B = \pm 0.2\,\text{T}$ with sample Si22 for four temperatures. Dashed line is a guide to the eye. Dotted vertical line marks the critical density n_c. The inset shows ρ_{xx} vs temperature for 11 densities, 1.5, 1.7, 1.8, 1.9, 2.1, 2.4, 2.9, 3.34, 4.3, 5.5, 7.9, in unites of $10^{11}\,\text{cm}^{-2}$

Finally, as shown in Fig.4, the deviation in the Hall-density for the high mobility sample Si22 depends on gate voltage and temperature 3 times weaker than for Si4/32. As V_g increases, the disagreement between n_{Hall} and n_{ShdH} becomes less than the measurement uncertainty. We must note that the absolute value of n_{ShdH}, and the true position of the "zero" on the vertical scales in Fig.4 and Fig.3 b, have the uncertainty $\sim (1-2)\,\%$ for Si22 and 4% for Si4/32. Although the deviation of the Hall-density is small for all samples, $\delta n_{\text{Hall}}/n_{ShdH} \ll 1$, it is much larger than the error bars. Due to the charge neutrality in Si-MOS structure, Eq.(1), the nonzero value of the δn_{Hall} indicates either a lack of the Drude-Boltzmann interpretation of the Hall voltage in the vicinity of V_{gc}, or a noticeable contribution of carriers exchange between the 2D layer and shallow potential traps at the Si/SiO_2-interface [16, 17].

In the framework of the Drude – Boltzmann model, the effective carrier density n_{Hall} for all samples remains close to the classical value over the metallic range of densities $V_g > V_{gc}$, where ρ_{xx} strongly varies with temperature. We conclude, in the same framework, that the strong exponential drop in $\rho_{xx}(T)$ as T decreases [4], is associated with an anomaly in the scattering time or in the transport mechanism, rather than with carrier density. The insets to Figs. 3a and 4 show that the variations of the diagonal resistivity with temperature are much larger than those in R_{xy}, over the same range of density and of temperature. The lack of the linear relationship between δR_{xy} and $\delta\rho_{xx}$ in the vicinity of V_{gc}, indicates that at least one of these two quantities is not related to the interaction quantum corrections [7] (with the reservation that the theory may be not valid for the strong interaction case, $r_s \sim 3 - 10$).

In conclusion, we have measured the weak field Hall resistance in n−Si-MOS samples across the metal-insulator transition. We found no signatures of a complete carriers freeze-out at $V_g = V_{gc}$. However, for low density and low temperatures, the Hall voltage in different samples was found to deviate from the classical value by about (6-20)%. The deviation in R_{xy} does not correlate with the strong temperature dependence of $\rho_{xx}(T)$. Particularly, the smallest value of the deviation in R_{xy} (by 6 %) was measured in the high mobility sample Si22, where the diagonal resistivity ρ_{xx} varies most strongly (by 5.5 times) in the same temperature range.

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