Magnetoresistance of Si(001) MOSFETs with high concentration of electrons

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We have studied magnetoresistance of Si(001) MOSFETs with high density of electrons in the inversion layer, well above the onset of occupation of the excited subbands.

Silicon is an indirect gap semiconductor having six minima (valleys) in the conduction band. In the case of (001)-oriented wafers, two of the Fermi ellipsoids have the long axes perpendicular to the $x-y$ plane of a Si/SiO_2 interface (with $m_z = 0.916$), while the long axes of other four are parallel ($m_z = 0.19$). A quantum well is formed at the interface by applying a positive voltage U_g to the gate, and the electron motion in z direction is quantized. The difference in m_z causes a splitting of the energy spectrum of bound states into two independent ladders of levels: the twofold-degenerate ladder of eigenenergies $E_0, E_1, E_2, \cdots$ and a fourfold-degenerate ladder $E_{0'}, E_{1'}, E_{2'}, \cdots$. Due to the higher effective mass in the z-direction, the lowest energy level in the potential well is E_0. The self-consistent calculations predict that the excited levels $E_{0'}$ and E_1 are very close on energy scale to the Fermi energy E_F and become occupied at the carrier concentration $N \approx 0.5 \times 10^{13}\mathrm{cm}^{-2}$. While $E_F - E_1$ increases linearly with U_g, the fourfold-degenerate $E_{0'}$ stays "pinned" to the Fermi energy and $E_F - E_{0'}$ stay almost constant even for the highest possible gate voltages. In both cases the difference between energies of excited levels and the Fermi energy is at most a few percent of total E_F for all gate voltages.

In our experiments we have employed the samples of Russian provenance, with 200 nm thick gate oxide and the top mobilities μ around $25000\mathrm{cm}^2/\mathrm{Vs}$. The concentration of electrons in the inversion layer is related to the gate voltage by $dN/dU_g \approx 1.1 \times 10^{11}\mathrm{cm}^{-2}\mathrm{V}^{-1}$ with the threshold voltage close to $0.5V$. The samples are 0.25 mm wide and 0.5 mm long with the distance between potential leads 0.625 mm. The highest concentration of carriers $N \approx 1.3 \times 10^{13}\mathrm{cm}^{-2}$, reached for $U_g = 120\mathrm{V}$, is well above the concentration where the excited subbands become occupied. The magnetoresistance was measured as a function of the magnetic field B up to 11 T for a series of fixed gate voltages in the bath of pumped ^{3}He. Anomalous behavior was observed for gate voltages corresponding to occupied excited subbands.

First, the novel series of SdH oscillations appeared, most pronounced at highest gate voltage 120 V where the amplitude of SdH oscillation of the first subband is very small. The oscillations are periodic in $1/B$ but their period is almost independent of U_g.

Second, a strong negative magnetoresistance and the nonlinear field dependence of the Hall resistance accompany the novel oscillations at high carrier concentrations. Both phenomena are most pronounced for the lowest temperatures ($T \approx 0.4$ K) and the smallest density of current ($I_{ac} = 0.5\mu\mathrm{A}$) used in our measurements. The heating of the 2D electron layer either by large current or by increase of the bath temperature leads to suppression of both effects. At T=4.2 K they can be observed only for the highest gate voltages.

We attribute the observed anomalies to the large difference between the electron structure of the ground subband and excited subbands. The twofold-degenerate ground subband contains many Landau levels even for highest magnetic fields. The occupation of excited subbans is very small and we assume that the subband attached to the level E_1 is emptied at relatively week B and thus the density of states of electrons belonging to the twofold-degenerate ladder is halved and so their scattering rate, which leads to the negative magnetorestance.

On the other hand, we believe that the fourfold-degenerate subband is not emptied by increasing B and it is responsible for the novel oscillations the period of which does not depend on U_g.

With increasing the temperature the energy k_BT becomes comparable with the separation between Landau levels. The electron-electron scattering increases and the anomalies observed are suppressed.

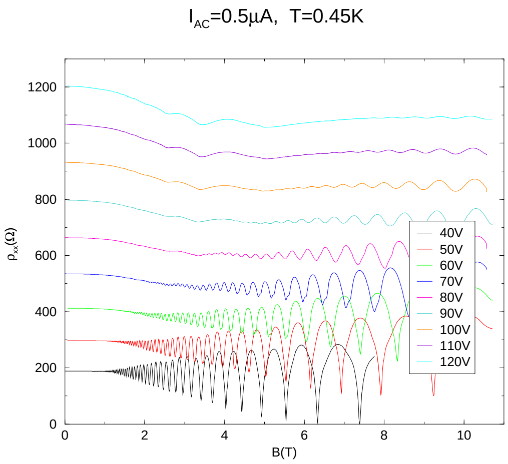

Figure 1: The magnetoresistance of Sample A for different gate voltages with two series of SdH oscillations.

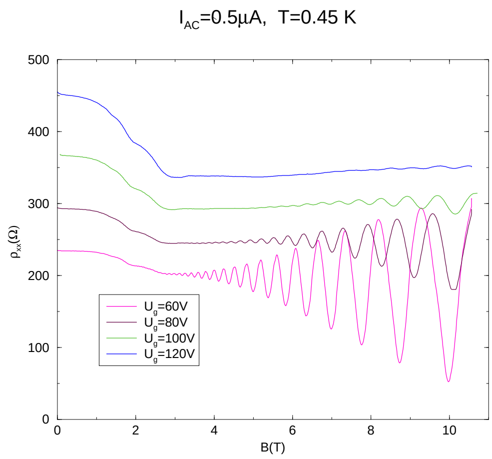

Figure 3: The magnetoresistance of Sample B for different gate voltages with two series of SdH oscillations.

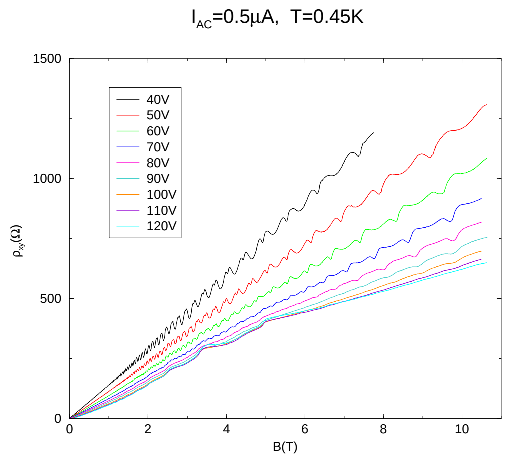

Figure 2: The Hall resistance of Sample A for different gate voltages deviates from the linear dependence for large U_g.

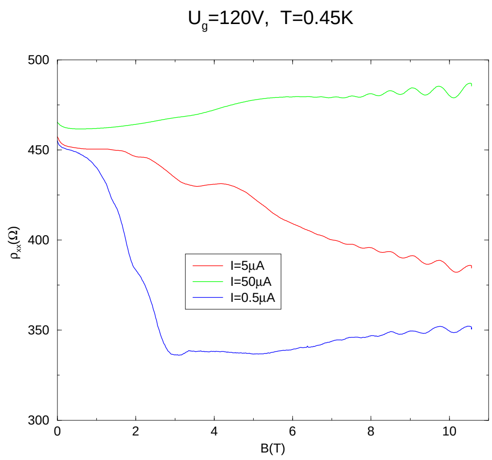

Figure 4: The magnetoresistance of Sample B for different gate voltages with two series of SdH oscillations.

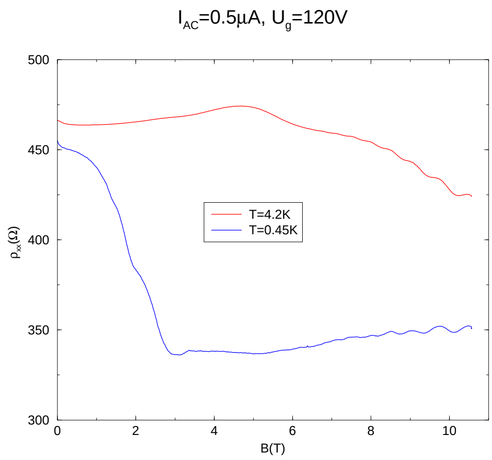

Figure 5: The magnetoresistance of Sample B for different gate voltages with two series of SdH oscillations.