Two-Dimensional Metallic State in Silicon-on-Insulator Structures

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In silicon-on-insulator metal oxide semiconductor structures with a peak mobility of 25,000 cm^2/Vs a strong drop of the resistivity towards low temperature has been observed. This metallic effect can be fitted by a linear-in-T term, which can be interpreted with both, the ballistic interaction corrections and the temperature dependent screening of impurity scattering. At low temperature and density in addition a strong increase of the resistivity towards lower T was observed, which is attributed to the contact regions of the sample.

Introduction

The metallic state (MS) in Si-metal oxide semiconductor (MOS) structures and other two-dimensional (2D) electron structures was completely unexpected as the influence of electron-electron interaction effects was probably strongly underestimated in the past. In order to investigate the effects in a similar structure as Si-MOS, we performed experimental work on the metallic state in high-mobility silicon-on-insulator (SOI) MOS structures. By comparing the differences in the behavior of the two systems, one can get information on the underlying physical mechanisms.

Experiment and Analysis

Recently, new SOI-MOS structures became available, which reach a maximum electron mobility of 25,000 cm^2/Vs at 0.3 K – a value comparable to many investigated high-mobility Si-MOS structures in the literature.
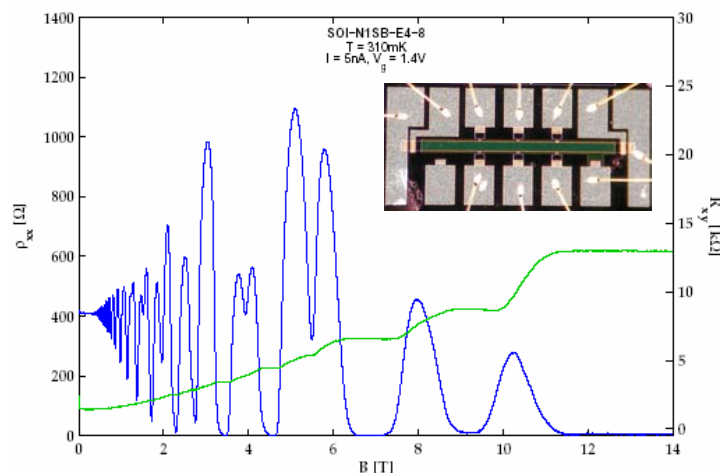

Fig. 1: Shubnikov-de Haas and Quantum Hall effect of high-mobility SOI-MOS structure at a temperature of 300 mK (inset shows etched Hall bar).

Our SOI-MOS samples were fabricated on commercially available bonded SOI. After the processing steps, the final SOI film thickness was just 40 nm with a gate oxide of also 40 nm. The resistivity and Hall measurements on such samples were performed in a ^{3}He-cryostat down to 0.3 K.

As can be seen in Fig. 2 (a), at high electron densities the typical resistivity drop in $\rho(T)$ towards low T is observed. However, at low densities $\rho(T)$ shows a strong non-monotonic behavior with a strong increase below 2 K towards lower T. The latter effect can probably be described by contact resistivity effects, whereas the decreasing parts towards lower T represent the interesting metallic behavior.

We further observed a non-monotonic behavior of $\rho(n)$ in the 'insulating' part at low T, which is shown in Fig. 2 (b). The observed fluctuations can be reproduced at 0.26 K by sweeping the gate voltage V_g up and down. Only at an elevated T of e.g. 1.26 K, the fluctuations become weak and finally disappear. Such fluctuations in $\rho(n)$ might be due to universal potential fluctuations (UFC), despite it is surprising that such fluctuations exist over large distances of 800 μm between the potential probes.

For the analysis of the metallic state, we concentrate on the $\rho(T)$ dependence of that part where the fluctuations are not important. This is for high electron densities or for higher temperatures. In our analysis, the experimental data are compared with i) coherent interaction corrections in the ballistic regime and ii) temperature dependent screening of impurity scattering.
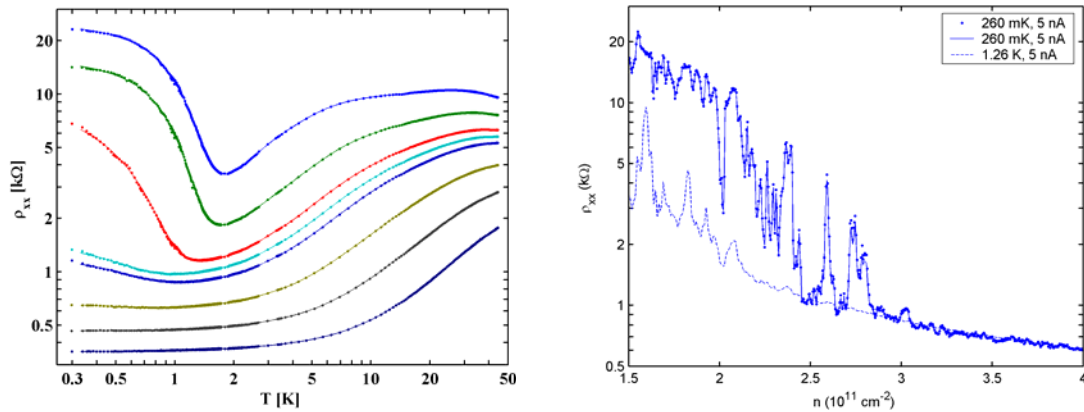

Fig. 2:   (a) Longitudinal resistivity $\rho(T)$ for SOI sample N1SB-E4-8. The electron density is in the range from 1.45 to 7.61x10^{11} cm^{-2} from top to bottom traces.
(b) Resistivity $\rho(n)$ at 260 mK from 1.5 to 4x10^{11} cm^{-2} (small dot symbols) and backward (full line) at 260 mK and at 1.26 K (dashed line).

The theory i) on ballistic interaction correction was recently introduced by Zala et al. [1] and describes the electron-electron interaction corrections at intermediate temperature where $k_B T > \hbar/T$. The corrections to the conductivity σ are due to the charge channel and due to the triplet channels with F_0^σ the characterizing Fermi liquid parameter. The correction is in first order linear in T. The 2-fold valley degeneracy for 2D n-type Si enters also into the analytic description.

According to recent works, there is some discrepancy whether F_0^σ in Si-MOS structures is rather towards -0.6 or closer towards -0.25. This discrepancy seems to depend largely on the detailed method of analysis. In the original work on the ballistic electron-electron interaction [1], the correction is given in terms of $\Delta\sigma$, whereas it was also argued that rather $\Delta\rho$ should be fitted. In the analysis of experimental data, both approaches were used.

In a linear approximation, the two corrections are related to each other as $\Delta\rho = -\rho_0^2\Delta\sigma$, with $\rho_0 = 1/\sigma_0$. As long as $\Delta\sigma/\sigma_0 \ll 1$ the two approaches are equivalent, but as soon as the deviation becomes large, there is a difference in fitting the data either with a linear-in-T term in $\Delta\sigma$ or in $\Delta\rho$.

We have performed true multi-parameter least-square fits for both $\Delta\sigma$ and $\Delta\rho$ in order to determine F_0^σ and the conductivity σ_0. The lower temperature boundary for the fit was chosen so that only data with a monotonic increase in $\rho(T)$ were taken into account, i.e. leaving out the region with the fluctuation as described above. As the upper limit, $k_B T = E_F/4$ was taken. The Fermi energy E_F was calculated with $m_0^* = 0.19 \, m_e$ and was thus not renormalized, whereas a renormalized mass of $m^* = (1 + 0.0585 r_s + 0.00522 \, r_s^2) \times m_0^*$ was used in order to calculate the momentum relaxation time τ ($r_s = 1/(a_B(p \, n)^{1/2})$ is the Wigner-Seitz or interaction parameter and a_B the effective Bohr radius.) With these values, the conductivity corrections due to the charge channel and the triplet channels could be calculated according to Zala et al. [1].

Figure 3 compares the fit for $\Delta\sigma$ and $\Delta\rho$, taking fully into account the two terms according to Zala et al. [1]. We find that the fit in $\Delta\sigma$ gives a clearly better agreement with the experimental data than the $\Delta\rho$ fit. As the corrections in $\Delta\sigma$ ($\Delta\rho$) are not so small any more, the prefactor of the corrections has to be different in order to fulfill the least-square condition of the fitting procedure. Accordingly, the deduced F_0^σ values are different for the two different fits as shown in Fig. 4.
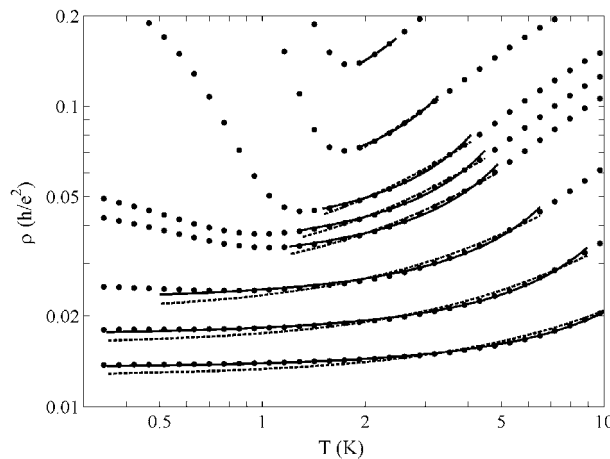

Fig. 3: Fit of $\rho(T)$ by $\Delta\sigma$- (full line) and $\Delta\rho$- (dashed line) approximations as described in the text.

For a comparison, we have also plotted the relation $F_0^\sigma \sim -r_s/[2(r_s+\sqrt{2})]$ (full line) according to the description of Eq. 2.16c in Ref. [1]. As one can see, the theoretically expected value of F_0^σ is closer to the $\Delta\rho$-fit than to the $\Delta\sigma$-fit. But neither the observation that the $\Delta\sigma$-fit gives a better description of $\rho(T)$ data nor the better consistency of F_0^σ for the $\Delta\rho$-fit can give a clear criterion what type of fit should be performed. It would be very helpful to have more rigorous theoretical arguments or to perform the theoretical calculations to higher order in T.

It can be concluded that the ballistic interaction corrections are able to describe the temperature dependence in r for SOI-MOS samples in the intermediate T-range. But due to the uncertainty whether $\Delta\rho$ or $\Delta\sigma$ should be fitted, there is also a relative large uncertainty for a precise determination of the Fermi liquid parameter F_0^σ.
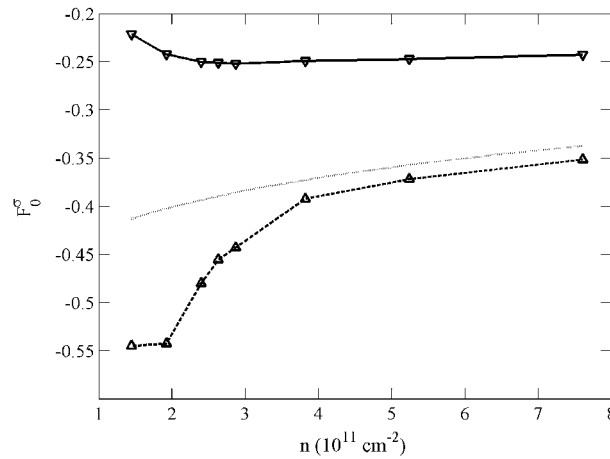
Fig. 4:   The Fermi liquid parameter F_0^σ as obtained from the $\Delta\sigma$- (full line) and $\Delta\rho$- (dashed line) fit. The theoretical estimate of F_0^σ (dotted line) is shown for comparison.

There is still the mechanism ii) of temperature dependent screening of impurity scattering under discussion. As this effect also leads to a linear-in-T term [2], the data can be fitted similarly well as with the ballistic interaction corrections. The prefactor of the linear T term is not in direct agreement with the earlier calculation, but a local field correction $G(2k_F)$ which takes into account both, exchange and correlation effects seems to be able to describe also the size of the slope [3].

Conclusion

Our experiments on silicon-on-insulator metal oxide semiconductor structures with a peak mobility of 25,000 cm^2/Vs show a clear metallic effect, i.e. a strong drop of the resistivity towards low temperature. This behavior can be described in principle with both, ballistic interaction correction and temperature dependent screening of impurity scattering as both theories give a leading linear-in-T term. A qualitative comparison of the slope has still some uncertainties for both theories. Further measurements and calculations should be performed in order to clarify the situation.

Acknowledgements

References

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