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Magnetoconductivity of a spin-polarized two-dimensional electron gas near the (1 1 1) silicon surface

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Abstract

The magnetoresistance of a disordered and highly interacting two-dimensional electron gas (2DEG) in a silicon (1 1 1) MOSFET has been measured in the presence of a magnetic field parallel to the surface of the 2DEG. For high electronic densities, a linear negative magnetoconductance has been observed. The field of complete spin saturation has been found to depend linearly on the density. From this result, we have determined the g^*m^* product, which has been shown to decrease as the density is reduced.

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During the last decade, transport properties of strongly correlated and disordered two-dimensional electron systems (2DES) have attracted much interest: indeed, in contrast to the theoretical expectations for non [1] or weakly [2] interacting particles, the resistivity of a high mobility (1 0 0) MOSFET has been found to decrease with temperature [3] and an apparent metal to insulator transition has been observed. Today, the nature of the ground state of the system still remains undetermined: at intermediate densities, a ferromagnetic Fermi liquid characterized by a full spin polarization may take place [4] but no direct experimental evidence of this theoretical prediction has been found yet.

In the frame of the Fermi-Liquid theory [5], spin exchange interactions lead to a renormalization of the Landé g factor and of the effective mass m: their effective values are noted respectively g^* and m^*. A good way to probe the appearance of a paramagnetic ground state is the measurement of the g^*m^* product. Indeed, an increase of this product when the density is lowered, as has been measured in (1 0 0) Si MOSFET by several groups [6], may indicate a spontaneous trend of spin polarization for densities lower than a critical value.

In this paper, we focus on the parallel magnetoconductance of a 2DEG in a Si MOSFET near the (1 1 1) surface: this disordered and highly interacting system is characterized by a very large value of the r_s parameter, about 50, and a nonmonotonic behavior of $\rho(T)$ has recently been observed [7], from which a negative value of the Fermi liquid constant, $F_0^\sigma \approx -0.3$, has been derived.

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The in-plane magnetoresistance has been measured up to high fields and in a very broad range of density. For all concentrations, a linear positive magnetoconductance has been obtained at low field, in agreement with recent theories based on screening effects. More surprising, the g^*m^* product determined from the field of complete spin polarization has been shown to decrease as the density is increased, in contradiction with most of the experiments made on (1 0 0) Si MOSFET.

The structures we have studied are Silicon MOSFET grown on a (1 1 1) surface by means of conventional Si technology. The surface orientation has been determined by X-ray diffraction within an accuracy of 10 min. The samples have a Hall bar geometry whose width is 400 μm, equal to the spacing between the voltage probes. A metallic gate covers the entire structure. Two samples have been fabricated on the same model, both have been mounted on a single axis rotation stage, one has been measured in a dilution fridge with a superconducting magnet (T=30 mK and B=0–15 T) and the second in an ^{4}He pumped bath mounted in the center of a 20 MW resistive magnet ($T = 1.7$ K and $B = 0$–28 T). Experiments have been performed in the low-temperature limit, for electronic densities at which the magnetoconductance becomes roughly temperature-independent [8]. The measurements were made by standard four terminal low frequency lock-in techniques. In both cases, the experimental procedure was the following: firstly, in magnetic field perpendicular to the plane of the 2DEG, the electronic density was determined at different gate voltages from the slope of the Hall voltage. Then, it was turned to parallel field (precisely determined by minimizing the Hall voltage) and the in-plane magnetoresistance was measured in a broad range of density.

Fig. 1 shows the mobility of the 2DEG versus the electronic concentration, at $T = 1.7$ K. At low concentration ($N_s < 14 \times 10^{11}$ cm^{-2}), the mobility strongly increases with the density: in this region, the dominant scattering mechanism is the scattering by charged impurities [9]. At higher densities $N_s > 14 \times 10^{11}$ cm^{-2}, the mobility decreases with increasing density. In this strong inversion régime, the distance of the carriers to the interface becomes smaller and interface roughness scattering dominates. The transition between these two regimes occurs at $N_s \sim 14 \times 10^{11}$ cm^{-2} which corresponds to the peak mobility $\mu \sim 2400$ cm^2/V.s.

The in-plane magnetoconductance at high electronic density is shown in Fig. 2a: in the complete range of density, a negative linear behavior has been clearly observed, which slope is shown to decrease with increasing density. This result is in agreement with recent theoretical predictions based on screening effects due to the spin polarization of the 2DEG [10].

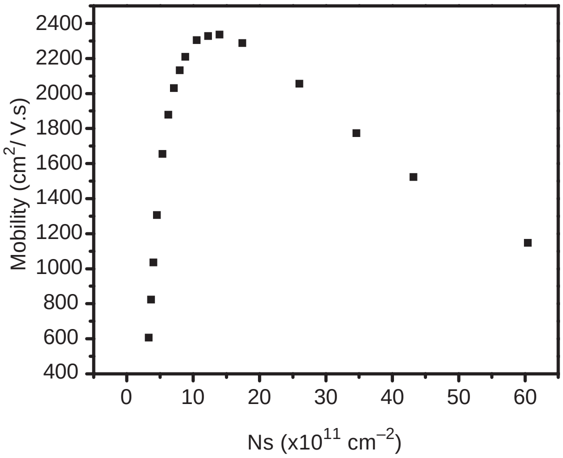

Fig. 1. Mobility of the 2DEG versus density, measured at $T = 1.5$ K.

For lower densities, (see Fig. 2b), the conductance decreases with $B_{\parallel}$ at low fields until it saturates at a density dependant field, previously identified as the field of complete spin polarization B_c [11]. The amplitude of the magnetoresistance decreases with increasing density, $\rho(B_c)/\rho(0) \sim 3.2$ at $N_s = 3 \times 10^{11}$ cm^{-2}, and ~ 2 at $N_s = 14 \times 10^{11}$ cm^{-2}.

The value of the valley degeneracy of a Si (1 1 1) 2DEG is a long standing question in the physic of 2D systems: indeed, the first experimental studies have led to $g_v = 2$, in contradiction with the predictions based on the effective mass approximation, $g_v = 6$. There have been many attempts to explain this discrepancy based for example on the appearance of strains at the Si/SiO_2 interface or on intervalley exchange scattering. An interesting set of information was given in [12] where $g_v = 6$ was found at zero magnetic field from thermopower measurements while, at non zero field, Shubnikov de Haas measurements led to $g_v = 2$.

A comparison of our results to the above mentioned theory [10] can give another argument to this controversy: indeed, in the impurity scattering regime, this theory foresees a positive magnetoresistance with $\rho(B_c)/\rho(0) = 4$ for the screening parameter $\eta \ll 1$ (where $\eta = \sqrt{4\pi N_s} a^* (g_s g_v)^{-3/2}$, g_s is the spin degeneracy and a^* the effective Bohr radius), and a negative magnetoresistance with a vanishing $\rho(B_c)/\rho(0)$

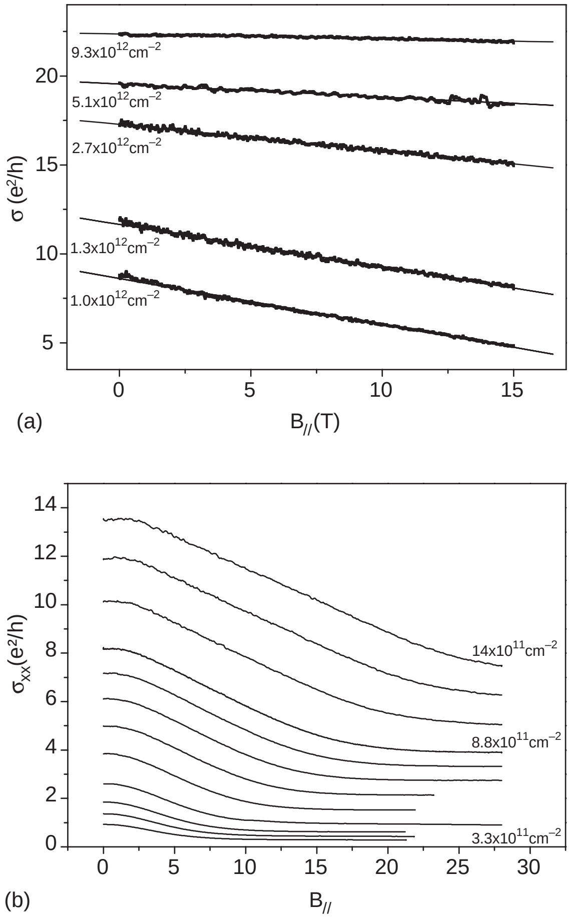

Fig. 2. In-plane magnetoconductance, (a) at high electronic density ($T = 30$ mK) and (b) at low density ($T = 1.5$ K).

for $\eta \gg 1$. With the parameters of Si (1 1 1) systems, one finds that the condition $\eta = 1$ is achieved, respectively at $N_s = 5.52 \times 10^{13}$ cm^{-2} for $g_v = 2$ and 1.5×10^{15} cm^{-2} for $g_v = 6$: clearly, the predictions for $g_v = 2$ lead to a much better agreement with the experimental results.

All these data force to make the assumption that applying both a normal or an in-plane magnetic field changes the valley degeneracy of a 2D electron gas near the Si (1 1 1) surface, from 6 to 2. However a complete understanding of this very interesting problem will obviously require further studies.

A non-linearity of the magnetoconductance at low field, as can be seen in Fig. 2b, has not been observed in our other measurements: we attribute it to a non-perfect setting of the parallel field position, leading to the appearance of a small perpendicular field contribution to the conductance.

As has already been mentioned, the g^*m^* product is a key parameter in the understanding of the nature of the 2DEG ground state. There are two main experimental ways to access this value (see for example Ref. [8] for a review): the first is based on the measurement of the Shubnikov–de Haas oscillations in tilted magnetic field or at different temperature. This method cannot be applied to our systems which mobility is too low to allow for the observation of well pronounced Shubnikov–de Haas oscillations.

The second way is a direct determination of B_c from measuring of the in-plane magnetoresistance. This method is mainly limited by the value of the saturation field which increases with the density and so, has been restricted up to $N_s < 7 \times 10^{11}$ cm^{-2} [13]. To overcome this limit, we have performed experiments on a 20 MW magnet at the Grenoble High Magnetic Field Laboratory, up to $B = 28$ T.

A striking feature of the in plane magnetoconductivity of Si MOSFET has been reported in [14]: it is the insensitivity of the scaled magnetoconductance versus scaled field, in broad ranges of density and temperature. Indeed, in these domains, the curves plotting the field dependent contribution of the magnetoconductivity, $\sigma(B) - \sigma(0)$ normalized by its complete spin polarization value $\sigma(\infty) - \sigma(0)$ versus scaled field B/B_c have been shown to collapse into a single curve. This method, a scaling with a single parameter B_c, is a very reliable way to access to $B_c(N_s)$: we have applied it to our measurements which indeed present very good scaling properties (see inset of Fig. 3). What is more, results obtained at T=30 mK and at T=1.8 K are similar in their common range of density: it confirms the weak temperature dependence of B_c already pointed in Ref. [14].

The $B_c(N_s)$ dependence deduced from scaling is shown in Fig. 3. It turns out that B_c is a strictly linear function of the electronic density, this result is in agreement with the behavior already pointed out in Si (1 0 0) MOSFETs [8] or in other 2D systems where a law $B_c \propto (N_s - N_\chi)$ was established. In these structures, N_χ is a finite electronic density close to the critical density N_c where a zero field metal–insulator transition (MIT) appends. In our case, however, this quantity was found to be negative. One has to approach this result to the absence of MIT in our Si (1 1 1) MOSFET, as pointed out by Ref. [7].

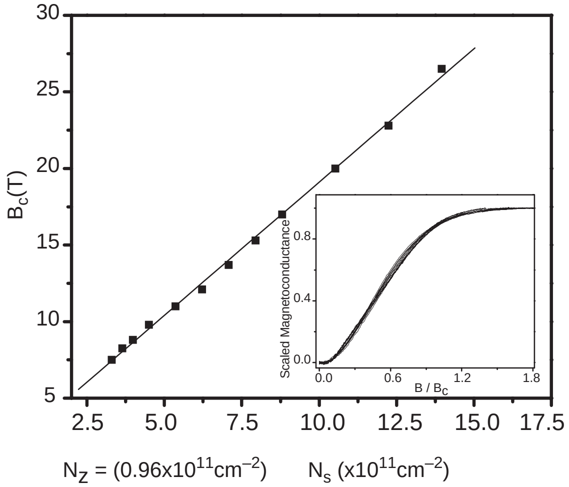

Fig. 3. Density dependence of B_c, field of complete spin polarization. Inset: Scaling of the magnetoconductance traces into one single curve ($T = 1.5$ K).

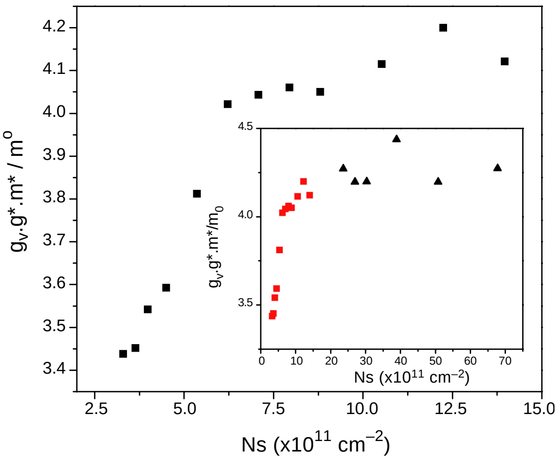

Fig. 4. $g^*m^*(N_g)$ deduced from scaling and in insert, from scaling (dots) and from theory [10] (triangles).

The $g^*m^*(N_s)$ dependence has then been deduced from $B_c(N_s)$ by writing that, when the complete spin polarization is reached, the Zeeman energy becomes equal to the Fermi energy: it leads to $B_c = h^2 N_s / 2\pi\mu_B g_v g^* / m^* m_0$ where μ_B is the Bohr magneton.

Fig. 4 shows the density dependence of $g_v g^* m^* / m_0$ in the broad range of electronic concentration allowed by the experimental setup. At high density, the product is shown to be roughly insensitive to the density and equal to ∼4.

At lower densities $N_s < 6 \times 10^{11}$ cm^{-2}, the g^*m^* product has been found to decrease with decreasing density. This surprising result, in contradiction with what has been observed in Si (1 0 0) MOSFETs [8], had only been reported before in GaAs very high mobility, dilute 2DEG [15], systems which have obviously few characteristics in common with disordered Si (1 1 1) MOSFET. Some more theoretical attention is required to explain this behavior.

In the high density region $N_s > 15 \times 10^{11}$ cm^{-2} where a linear magnetoconductance has been observed, g^*m^* can be estimated by fitting the slope of the conductance with the theory described in Ref. [10] which predicts $\sigma(B)/\sigma(0) = 1 - D_B(N_s)|B/B_c|$, where D_B is a coefficient expressed in Ref. [10]. Following this method, we have obtained a g^*m^* product independent on N_s within an accuracy of 5%. Its value can be normalized to the constant value of g^*m^* obtained from scaling, at the highest densities, by dividing it by a factor ∼1.15: in the frame of this theory, this small discrepancy could for example, be attributed to a non-zero thickness of the 2DEG.

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