Conductance asymmetry of a slot gate Si-MOSFET in a strong parallel magnetic field

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We report measurements on a Si-MOSFET sample with a slot in the upper gate, allowing for different electron densities $n_1, n_2$ across the slot. The dynamic longitudinal resistance was measured by the standard lock-in technique, while maintaining a large DC current through the source-drain channel. We find that the conductance of the sample in a strong parallel magnetic field is asymmetric with respect to the DC current direction. This asymmetry increases with magnetic field. The results are interpreted in terms of electron spin accumulation or depletion near the slot.

1 Introduction

The objective of this work was to probe the influence of strong parallel magnetic field on electron transport across an interface between regions with different electron densities, $n_1$ and $n_2$, in a single Si-MOSFET sample. The sample has a narrow slot in the upper gate, which allows one to apply different voltages to separate gates. Previously, the longitudinal conductivity of a slot-gate Si-MOSFET sample was measured in a perpendicular magnetic field in the quantum Hall effect (QHE) regime [1]. For equal gate voltages, the presence of the slot did not cause any measurable decrease in conductance, implying that the slot does not act as a potential barrier for electrons [1].

The effect of a parallel magnetic field on the conductance of a two-dimensional electron gas (2DEG) in spatially uniform Si-MOSFET samples had been investigated earlier [2–4] in the context of metal-insulator transition studies. The conductance asymmetry with respect to the direction of the electric current (always parallel or antiparallel to the magnetic field), reported here, is a novel effect associated with the non-uniform properties of our slot-gate sample. Phenomenological interpretation of our results (involving current-induced spin accumulation or depletion near the slot) suggests that this asymmetry is directly related to the physical mechanism underlying the parallel-field magnetoresistance of a Si-MOSFET 2DEG.

2 Experiment

The sample used in our experiments was investigated earlier (see Ref. [1]). A narrow slot (100 nm) had been made in the upper metallic gate, allowing one to apply different gate voltages to different parts of the gate and thereby to independently control the electron density in the two areas of the sample. Measuring the transverse Hall resistivity, $\rho_{xy}$, and longitudinal resistivity, $\rho_{xx}$, as functions of the gate voltage $U_G$ in a perpendicular magnetic field yields the dependence of the electron density $n$ on $U_G$: $n = 1.43 \cdot 10^{15} (U_G - 0.64 \text{ V}) \text{ m}^{-2}$, at $n = 1.62 \cdot 10^{16} \text{ m}^{-2}$, electron mobility equals $\mu = 1.46 \text{ m}^2/\text{(V} \cdot \text{s)}$. 
Fig. 1 (a) Sample conductance as a function of DC current at $B = 0, 7, \text{and} \pm 14\,\text{T}$. $U_G(1) = 7\,\text{V}$, $U_G(2) = 18\,\text{V}$. (b) and (c) show symmetric and asymmetric parts of $\sigma(I_{DC}) - \sigma(0)$.

For the next series of measurements, the sample was mounted along the magnet axis, so that the current flow would be parallel to the magnetic field. The misalignment between the two was estimated with the help of Hall effect measurements. Whereas the Hall voltage must vanish in an ideal parallel geometry, the small value registered corresponds to a minute misalignment of $\sim 0.1^\circ$.

Our experimental scheme enables one to pass a DC current, $I_{DC}$, of up to $1\,\mu\text{A}$ through the source-drain channel, while measuring the dynamic resistance at $12.7\,\text{Hz}$ via a standard lock-in technique with an AC current of $\sim 50\,\text{nA}$. The sample temperature was maintained at $300\,\text{mK}$.

We fix the gate voltages at $U_G(1) = 7\,\text{V}$ (corresponding to $n_1 = 0.9 \cdot 10^{16}\,\text{m}^{-2}$ in area 1 of the sample) and $U_G(2) = 18\,\text{V}$ ($n_2 = 2.5 \cdot 10^{16}\,\text{m}^{-2}$ in area 2). Fig. 1(a) displays the conductance $\sigma$ of our sample measured as a function of $I_{DC}$ in the absence of a magnetic field, at $B = 7\,\text{T}$, and at $14\,\text{T}$. One can see the following features:

1) At zero $I_{DC}$, positive magnetoresistance (PMR) or negative magnetoconductance (NMC) is observed: the conductance decreases with increasing magnetic field. The magnitude of NMC is $|\sigma(B = 0) - \sigma(B)|/\sigma(B = 0) = 1.5\%$ for $B = 7\,\text{T}$, and $3.9\%$ for $B = 14\,\text{T}$.

2) At $B = 0$, the conductivity decreases slightly with the DC current, and $\sigma(I_{DC})$ is almost symmetric with respect to the sign of $I_{DC}$.

3) At $B = 7$ and $14\,\text{T}$, the dependence $\sigma(I_{DC})$ is clearly asymmetric. This asymmetry does not depend on the direction of the magnetic field: the shape of the curves is identical for $B = 14\,\text{T}$ and $-14\,\text{T}$. This excludes the Hall voltage (which may arise due to the slight misalignment of the sample) as a possible origin of the asymmetry.

3 Discussion

We will now discuss the observed behaviour of conductance in more detail.

1. For Si-based two-dimensional systems, the NMC effect in a parallel magnetic field had been reported earlier [2–8]. The metallic-like conductivity of Si MOSFETs decreases with an increasing in-plane magnetic field and stabilises once the electrons are fully polarised [5, 6].

2. Figs. 1(b) and 1(c) show the decomposition of $\sigma(I_{DC})$ into symmetric $\sigma_s$ and antisymmetric $\sigma_a$ parts according to $\Delta \sigma_s = [\sigma(I_{DC}) + \sigma(-I_{DC})]/2 - \sigma(I_{DC} = 0)$, and $\Delta \sigma_a = [\sigma(I_{DC}) - \sigma(-I_{DC})]/2$. Copyright line will be provided by the publisher
At $B = 0$, the most likely source of $\Delta \sigma_s$ is the Joule heating caused by $I_{DC}$. In our case, both electron concentrations $n_1$ and $n_2$ correspond to metallic behaviour, with increasing temperature at $B = 0$ leading to a conductance decrease, $d\sigma/dT < 0$, which explains the experimental data. In a strong magnetic field, however, the conductivity of Si-MOSFETs does not depend on temperature [4], and heating by a DC current does not affect the conductance. We indeed see that in a field, values of $\Delta \sigma_s$ become much smaller. This is accompanied by a growth of the antisymmetric part, $\Delta \sigma_a$ (and hence of the overall asymmetry of $\Delta \sigma(I_{DC})$).

A small asymmetry observed at $B = 0$ (about $2.5 \cdot 10^{-4}$ of the net conductance at maximal current) can be explained by an additional voltage bias $V_{DC}$ induced by $I_{DC}$: $V_{DC} = I_{DC}/\sigma$. For our sample geometry, $V_{DC}$ at $I_{DC} = 0.4$ $\mu$A reaches $1$ mV which is, indeed, about $10^{-4}$ of the $U_G = 7$ V. In MOSFETs, $V_{DC}$ with an appropriate sign is added to the gate voltage. This leads to a small increase or decrease (depending on the sign of $I_{DC}$) of the electron density and hence to a change in $\Delta \sigma$. We emphasise that this mechanism cannot possibly account for the much more pronounced asymmetric behaviour of $\sigma(I_{DC})$ found in the presence of a strong magnetic field.

3. The observed enhancement of asymmetric behaviour of conductance in a parallel field [see Fig. 1(c)] can be understood in terms of electron spin accumulation/depletion near the interface. Consider, e.g., the case of $I_{DC} > 0$, corresponding to the flow of (appropriately spin-polarised) electrons from area 1 to area 2, where the relative spin polarisation is smaller. Below, we argue that such a current causes a local increase of spin polarisation in area 2 near the slot, resulting in a decrease of the overall conductance.

Within a simple Drude approach, applying in-plane magnetic and electric fields to a uniform strictly two-dimensional system gives rise to the magnetisation, electric current, and spin current densities:

$$M_0 = \frac{1}{2}(n_1 - n_2) = \frac{m_e \nu g \mu_B B}{4 \pi h^2}, \quad j = \frac{e^2 E_T}{m_e} (n_1 + n_1), \quad s = -\frac{e E_T}{2m_e} (n_1 - n_1).$$  \hspace{1cm} (1)

Here, $g$ is the Landé factor, $\nu = 2$ the number of valleys, $e = |e|$ and $m_e$ are electron charge and effective mass, and $n_1$ ($n_2$) density of spin-up (spin-down) electrons. The momentum relaxation time $\tau$ (assumed to be the same for both spin directions) is much shorter [9] than the longitudinal spin relaxation time $T_1$, and we will be faced with a situation in which the magnetisation $M$ deviates from its equilibrium value $M_0$. It is easy to see that the relationship $s = -jM/en$, where $n = n_1 + n_1$, persists in such a non-equilibrium case.

The value $M_0$ does not depend on the electron density $n$. Therefore for $j = 0$, at equilibrium, the quantity $P = 2M/n$ (the degree of polarisation) suffers a jump at the interface between the two parts of our sample [solid line in Fig. 2 where we assume $n_1 < n_2$ with $n = n_1$ ($n = n_2$) for $x > 0$ ($x < 0$)]. For the measurement shown in Fig. 1 the equilibrium value of $P$ at $B = 14$ T can be estimated to be $P = 0.19$ for $n = n_1$ and $P = 0.07$ for $n = n_2$. For $j \neq 0$, the continuity of the electric and spin currents dictates that $P$ must also be continuous at $x = 0$. Since the values of $n_1$ and $n_2$ are fixed by the gate voltages, this in turn implies that $M$ must deviate from $M_0$. Neglecting spin diffusion, we write for the steady state:

$$-\frac{\partial s}{\partial x} = \frac{j}{en} \frac{\partial M}{\partial x} = \frac{M(x) - M_0}{T_1} \Rightarrow \frac{M(x) - M_0}{M_0} = \begin{cases} \frac{\nu}{n_2} - 1 \theta(x) \exp\left(\frac{en}{jT_1}x\right), & j < 0, \\ \frac{\nu}{n_1} - 1 \theta(-x) \exp\left(\frac{en}{jT_1}x\right), & j > 0, \end{cases}$$  \hspace{1cm} (2)

with $\theta(x) = 1$ for $x > 0$ and 0 otherwise; we also denote $T_1(n_{1,2})$ by $T_1^{(1,2)}$. Schematic profiles of $P(x)$, shown in Fig. 2, reflect accumulation (depletion) of electron spin at $j > 0$ ($j < 0$).

In a spatially uniform situation, two physical mechanisms are known to contribute to the dependence of the resistivity $\rho(n, B)$ on $B$: (i) the effect of spin-polarisation on the screening properties [10] and on electron correlations in an interacting system [11, 12], and (ii) orbital effects in the out-of-plane direction [13]. In the first case only, $\rho$ depends on $B$ via the magnetisation $M_0(B)$; more precisely, $\rho$ depends not
on $B$ but on $M$, regardless of whether the latter equals the equilibrium value, $M_0$. Denoting by $\alpha \leq 1$ the relative contribution of this first mechanism, we may write

$$\rho(n, B, M) = \rho(n, B, M_0) + \alpha \frac{\partial \rho(n, B)}{\partial B} \left( \frac{dM_0}{dB} \right)^{-1} (M - M_0), \quad \rho(n, B, M_0) \equiv \rho(n, B). \quad (3)$$

Substituting Eqs. (2–3) into the expression $V_{DC} = j \int \rho[n, B, M(x)]dx$ for the bias voltage, after simple algebra we find the differential conductance:

$$\sigma(I_{DC}, B) = \sigma(0, B) - \frac{2I_{DC}B}{\epsilon d^2} \alpha [\sigma(0, B)]^2 \left( \frac{1}{n_1} - \frac{1}{n_2} \right) \times \begin{cases} T_1^{(1)} \frac{\partial \rho(n_1, B)}{\partial B}, & I_{DC} < 0, \\ T_1^{(2)} \frac{\partial \rho(n_2, B)}{\partial B}, & I_{DC} > 0 \end{cases}$$

where $d \sim 30 \mu m$ is the width of our sample. We see that $\sigma(I_{DC}, H) - \sigma(0, H)$ is proportional to $B$ and indeed changes sign at $I_{DC} = 0$, with different slopes for positive and negative $I_{DC}$. Very rough estimates suggest that the value of the coefficient $\alpha$ may be about $\alpha \approx 0.5$. Further theoretical and experimental work is clearly needed to justify the many assumptions made in this preliminary treatment.

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