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Conductivity of a spin-polarized two-dimensional electron liquid in the ballistic regime

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In the ballistic regime, the metallic temperature dependence of the conductivity in a two-dimensional electron system in silicon is found to change non-monotonically with the degree of spin polarization. In particular, it fades away just before the onset of complete spin polarization but reappears again in the fully spin-polarized state, being, however, suppressed relative to the zero-field case. Analysis of the degree of the suppression allows one to distinguish between the screening and the interaction-based theories.

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I. INTRODUCTION

Much interest has been attracted recently to the anomalous properties of low-disordered, strongly correlated two-dimensional (2D) electron systems. The effects of electron-electron interactions are especially strong in silicon metal-oxide-semiconductor field-effect transistors (MOSFETs) (for recent reviews, see Refs. [1, 2]), but they are also pronounced in other systems like GaAs/AlGaAs [3] and Si/SiGe heterostructures [4]. Interactions lead, in particular, to critical behavior of the Pauli spin susceptibility [5, 6] and sharply increasing effective mass at low electron densities [7, 8, 9]. These phenomena (at least in Si MOSFETs) are not dominated by spin exchange effects, since the Landé g factor is found to be close to its value in a bulk semiconductor and the effective mass is insensitive to the degree of spin polarization. At the same time, spin effects are the origin of the strong positive magnetoresistance in parallel magnetic fields (see, e.g., Refs. [10, 11]). Therefore, one can probe the spin effects by studying peculiarities of a spin-polarized 2D electron system. The case of complete spin polarization of the electron system is especially interesting because it is the simplest from the theoretical point of view.

It is known that application of a parallel magnetic field causes giant (orders of magnitude) positive magnetoresistance and fully suppresses the metallic state near the 2D metal-insulator transition [10, 11, 12]. However, if the electron density is not too low (ballistic regime, $k_B T \gtrsim \hbar/\tau$ [13]), the metallic temperature dependence of conductivity has been found to persist in the fully spin-polarized state [14, 15, 16]. (Note that in silicon-based devices studied in these papers, electrons possess the valley degree of freedom, which survives in the fully spin-polarized state.) Conductivity of silicon MOSFETs in this regime was studied in Ref. [16]. However, for much of their data (particularly at relatively high tem-

peratures and/or electron densities), the complete spin polarization was in fact not reached as a result of the insufficiently high magnetic fields used.

Theoretically, linear-in-temperature corrections to the zero-field conductivity in the ballistic regime were calculated in Ref. [17]. In the newer theory [13], the exchange interaction terms were treated more carefully. However, it turned out that at $B = 0$, both the screening [17] and the interaction-based [13] theories describe the temperature-dependent conductivity equally well [18]. To distinguish between them, studies of the effect of the parallel magnetic field on conductivity may be helpful.

Here we experimentally study the transport properties of a 2D electron system in silicon in parallel magnetic fields at different degrees of spin polarization in the ballistic regime. We show that in a completely spin-polarized state, disorder effects are dominant when approaching the regime of strong localization, which is in contrast to the behavior of the unpolarized state in low-disordered 2D electron systems. The temperature-dependent correction to the elastic relaxation time is found to change strongly with the degree of spin polarization, reaching a minimum just below the onset of full spin polarization, where the conductivity is practically independent of temperature. In the fully spin-polarized state, the correction mentioned above is about two times weaker than that in $B = 0$ at the same electron density. This is consistent with what one expects according to the simple version of screening theory [19].

II. EXPERIMENTAL TECHNIQUE AND SAMPLES

Measurements were made in an Oxford dilution refrigerator on (100)-silicon MOSFETs with peak electron mobilities of about $3 \text{ m}^2/\text{Vs}$ at 0.1 K. The resistance was measured with a standard 4-terminal technique at a low frequency (1 Hz) to minimize the out-of-phase signal. Ex-

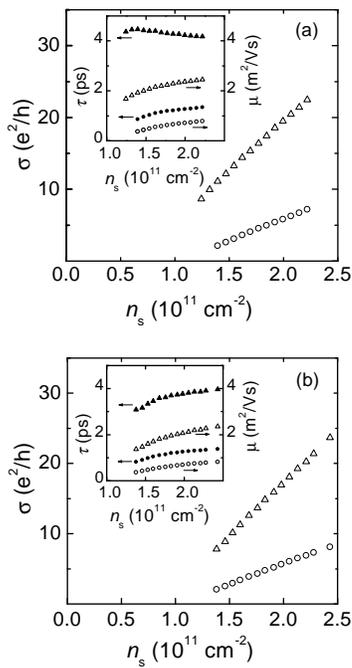


FIG. 1: Conductivity, mobility, and elastic scattering time vs. electron density at a temperature of 0.1 K for spin-unpolarized (triangles) and fully spin-polarized (circles) states in two slightly different samples A at $B = 0$ and 9.5 T (a) and B at $B = 0$ and 14 T (b).

citation current was kept low enough (below 1 nA) to ensure that measurements were taken in the linear regime of response. Contact resistances in these samples were minimized by using a split-gate technique that allows one to maintain a high electron density in the vicinity of the contacts (about $1.5 \times 10^{12} \text{ cm}^{-2}$), regardless of its value in the main part of the sample.

In Fig. 1, we show low-temperature conductivity as a function of electron density, n_s , in the metallic regime (i.e., when the conductivity $\sigma > e^2/h$) for fully spin-polarized and spin-unpolarized states in two slightly different samples. As the electron density is decreased, the conductivity significantly drops as a result of a decrease in the electron mobility μ (insets to Fig. 1). This mobility decrease originates from the effects of both disorder and electron-electron interactions. The former determines the elastic relaxation time, τ , while the latter is responsible for the enhanced effective mass [7, 8, 9]. Taking the effective mass values from Ref. [8], we have calculated τ as shown in the insets to Fig. 1. For the spin-unpolarized state, the behavior of τ for the two samples is qualitatively different, although the mobilities are very similar. In sample A, the decrease in μ at low densities is dominated by electron-electron interactions (increasing effective mass), while in sample B, disorder effects are more pronounced and lead to τ decreasing at low n_s . In the fully spin-polarized state, the disorder effects prevail in both samples.

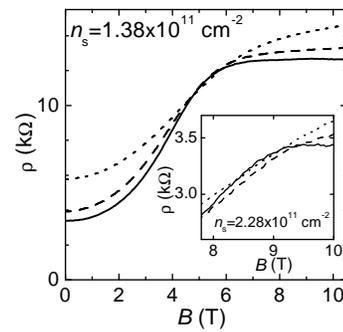


FIG. 2: Magnetoresistance at temperatures 0.5 (solid line), 0.8 (dashed line), and 1.2 K (dotted line) on sample B. The inset shows a detailed view of the magnetoresistance just before the onset of complete spin polarization.

III. RESULTS

Experimental traces of the parallel-field magnetoresistance at different temperatures are displayed in Fig. 2. The low-temperature resistivity, ρ , rises with B and saturates above a certain n_s -dependent magnetic field, $B_{\text{sat}}(0)$, corresponding to the onset of complete spin polarization of the 2D electrons [20]. Increasing the temperature leads to smearing the dependences so that the resistance saturation occurs at higher magnetic fields. In other words, the saturation field increases as the temperature is increased [6]. The resistivity rises appreciably with increasing temperature in both $B = 0$ and $B > B_{\text{sat}}$, here the saturation field B_{sat} corresponds to the highest temperature used in the experiment. The magnetoresistance at two electron densities measured at the highest temperature used, $T \approx 1.2$ K, is shown in the inset to Fig. 3. The fact that the magnetoresistance saturates at sufficiently high magnetic fields confirms that the full spin polarization is reached in our experiment even at this temperature. As seen from Fig. 2, just below $B_{\text{sat}}(0)$ the resistivity practically does not depend on temperature up to the highest temperatures used. The validity of this effect, which has also been observed in Refs. [15, 16], has been verified at ten electron densities in the range between 1.38×10^{11} and $2.42 \times 10^{11} \text{ cm}^{-2}$. We would like to emphasize that the flattening of $\sigma(T)$ just below the onset of complete spin polarization makes it difficult to analyze the data for $\sigma(T)$ obtained in a fixed magnetic field or in a narrow field region [15, 16] as the complete spin polarization may have not been reached at higher temperatures and/or electron densities.

The low-temperature ratio $\rho(B_{\text{sat}})/\rho(0)$ vs. electron density is shown in Fig. 3. In agreement with the previously obtained data, it increases weakly with decreasing n_s , being close to the value $\rho(B_{\text{sat}})/\rho(0) = 4$ predicted by the theory of the spin-polarization-dependent screening of a random potential [19]. As seen from the inset, the ratio $\rho(B_{\text{sat}})/\rho(0)$ diminishes somewhat at higher temperatures.

The normalized conductivity as a function of tempera-

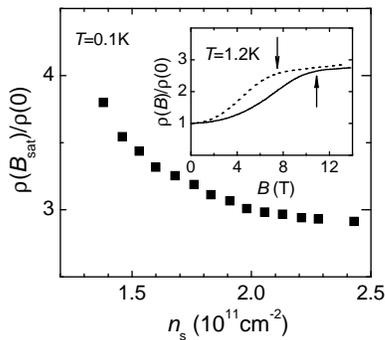


FIG. 3: Change of the resistance ratio, $\rho(B_{\text{sat}})/\rho(0)$, with electron density in sample B. The inset shows the normalized magnetoresistance, measured at the highest temperature used in this experiment, at electron densities $1.46 \times 10^{11} \text{ cm}^{-2}$ (dotted line) and $2.13 \times 10^{11} \text{ cm}^{-2}$ (solid line). The field of resistance saturation is marked by arrows.

ture in fully spin-polarized and spin-unpolarized states is depicted in the inset to Fig. 4. The correction to $\sigma/\sigma(0)$ is linear in temperature with the slope given by $A^* = -\sigma_0^{-1} d\sigma/dT$, where $\sigma_0 = \sigma(0)$ is obtained by linear extrapolation of the data to $T = 0$. We emphasize that the so-defined slopes do not depend on τ and are therefore different from the slopes defined in Ref. [16] as $d\sigma/dT$: the ratio of the slopes $r \equiv [d\sigma(B_{\text{sat}})/dT]/[d\sigma(0)/dT]$ used there is smaller by a factor of $\tau(0)/\tau(B_{\text{sat}}) \approx 4$ than the ratio $A^*(B_{\text{sat}})/A^*(0)$ used in this paper.

In Fig. 4, we show how the ratio of the slopes $A^*(B_{\text{sat}})/A^*(0)$ for completely spin-polarized and unpolarized states changes with electron density. Being approximately equal to 0.5 at low n_s , the slope ratio increases weakly with increasing n_s but remains less than one in the range of electron densities studied. Thus, the metallic behavior of the normalized conductivity is always suppressed in the fully spin-polarized state.

IV. DISCUSSION

We give a qualitative account of the absence of the $\sigma(T)$ dependence just below the onset of complete spin polarization. In the magnetic field $B = B_{\text{sat}}(0)$, the degree of spin polarization decreases linearly with temperature: $\xi = 1 - \gamma k_B T / E_F$ (where the factor $\gamma \sim 1$ and E_F is the Fermi energy of the spin-polarized 2D electrons). The increase in the number of electrons with opposite spin direction naturally leads to increasing conductivity. Therefore, near the onset of complete spin polarization there exists another contribution to the temperature-dependent conductivity, whose sign is opposite compared to the conventional screening behavior of $\sigma(T)$. In the simple version of the screening theory [19], the derivative $d\rho/d\xi$ at $T = 0$ tends to infinity as one approaches the field $B_{\text{sat}}(0)$ from below. This feature will obviously be smeared out at finite temperatures and/or due to the disorder present in real electron systems. It is clear that

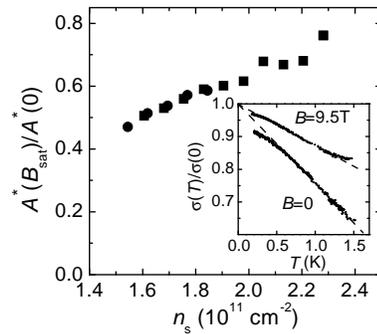


FIG. 4: The slope ratio as a function of electron density for samples A (circles) and B (squares). The inset shows the temperature dependence of the conductivity in both the fully spin-polarized state for $n_s = 1.85 \times 10^{11} \text{ cm}^{-2}$ and the unpolarized state for $n_s = 1.7 \times 10^{11} \text{ cm}^{-2}$ on sample A. The dashed lines are fits of the linear interval of the dependence.

depending on disorder strength, two opposite contributions to the linear-in- T correction to conductivity can in principle balance each other [21].

It is worth comparing the behavior of 2D electron system in Si MOSFETs to that in another two-valley system, Si/SiGe quantum wells. Transport properties of the latter system have been found to be very similar to those of silicon MOSFETs [4, 14, 22], although the disordered potential in both cases is different resulting, particularly, from the presence/absence of a spacer. However, the peculiarities near the onset of complete spin polarization are less pronounced in Si/SiGe quantum wells than in MOSFETs: only a weakening, but not absence, of the temperature dependence of the resistance has been observed in the metallic regime in a partially spin-polarized state [4]. Theoretically, the effect of the weakening of the $\sigma(T)$ dependence near the onset of complete spin polarization has been found for the 2D electrons in Si/SiGe quantum wells in the frames of screening approach [23].

We now compare the experimental ratio of the slopes $A^*(B_{\text{sat}})/A^*(0)$ with theoretical predictions. As we have already mentioned, in zero magnetic field, both the temperature-dependent screening theory [17] and the interaction-based theory [13] describe reasonably well the available experimental data for $\sigma(T)$ in silicon MOSFETs [2, 18, 24]. For the fully spin-polarized state, however, their predictions are very different. In theory [13], the ratio $A^*(B_{\text{sat}})/A^*(0)$ (for a two-valley 2D system) is formally equal to $(1 + 4F_0^\sigma)/(1 + \alpha F_0^\sigma)$ [25], once the effective mass, as well as the g factor, are independent of the degree of spin polarization [1, 2]. Here the interaction parameter F_0^σ is responsible for the renormalization of the g factor through $g = 2/(1 + F_0^\sigma)$, the coefficient $\alpha = 8$ if $T < \Delta_v$ and $\alpha = 16$ if $T > \Delta_v$, and Δ_v is the valley splitting. For negative F_0^σ , the observed slope ratio (Fig. 4) cannot at all be attained within the approach [13]: based on the $B = 0$ data for F_0^σ [7], considerably smaller values of the slope ratio are expected compared to the experiment. On the other hand, accord-

ing to the screening theory in its simple form (ignoring the local field corrections), the ratio $A^*(B_{\text{sat}})/A^*(0)$ is equal to 0.5, as inferred from doubling the Fermi energy due to the lifting of the spin degeneracy [19]. This value is close to the experimental finding. The observed decrease of the slope ratio at low electron densities is likely to be similar to the behavior of the resistance ratio mentioned above (see Fig. 3). Concerning the data for Si/SiGe quantum wells [4], one can evaluate the slope ratio for $n_s = 0.515 \times 10^{11} \text{ cm}^{-2}$ at about 0.45, which is consistent with our results.

V. CONCLUSION

In summary, we have found that in the ballistic regime, the metallic temperature dependence of the conductivity in a two-dimensional electron system in silicon changes non-monotonically with the degree of spin polarization. It fades away just below the onset of complete spin polarization but reappears again, being suppressed, in the

fully spin-polarized state. A qualitative account of the effect of the disappearance of the $\sigma(T)$ dependence near the onset of complete spin polarization is given. While in zero magnetic field both the temperature-dependent screening theory and the interaction-based theory provide a reasonably good description of experimental data for the temperature-dependent conductivity in the ballistic regime, the results obtained in the fully spin-polarized state favor the screening theory in its simple form.

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