Anomalous state of a 2DEG in vicinal Si MOSFET in high magnetic fields

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We report the observation of an anomalous state of a 2D electron gas near a vicinal surface of a silicon MOSFET in high magnetic fields. It is characterised by unusual behaviour of the conductivities $\sigma_{xx}$ and $\sigma_{xy}$, which can be described as a collapse of the Zeeman spin splitting accompanied by a large peak in $\sigma_{xx}$ and an anomalous peak in $\sigma_{xy}$. It occurs at densities corresponding to the position of the Fermi level above the onset of the superlattice mini-gap inherent to the vicinal system. The range of fields and densities where this effect has been determined, and it has been shown that it is suppressed by parallel magnetic fields.

More than twenty years after the discoveries of the QHE and FQHE, the properties of two-dimensional electron systems remain one of the most important subjects in condensed matter physics \textsuperscript{1,2}, with much attention paid to the problem of electron-electron interactions. Examples include recent experiments indicating the formation of the quantum Hall ferromagnetic states in double 2D layers \textsuperscript{3} and in multi-valley 2D systems \textsuperscript{4}. The object of our study is a high-mobility 2DEG near a vicinal surface - one that is tilted by a small angle with respect to the widely studied (100)Si. It is known that such tilting creates a superlattice on the Si surface which enhances the inter-valley interaction \textsuperscript{5,6}. The effect of this enhancement is a subject of our study. An indication of the importance of increased valley interaction has been found in earlier works where the anomalously large value of the superlattice minigap \textsuperscript{5,6} and anomalies in the $\rho_{xx}$ and $\rho_{xy}$ in strong magnetic fields \textsuperscript{7,8} have been observed.

We focus our study on properties of a 2DEG near a vicinal silicon surface in strong perpendicular and parallel magnetic fields, and compare its behaviour with that of a 2DEG on (100)Si. We have observed strong anomalies in the magneto-transport of the vicinal system which are characterised by a collapse of the Zeeman splitting. It occurs at electron densities close to the superlattice minigap and persists at higher densities. We suggest that the primary reason for this behaviour is the interplay between enhanced inter-valley and electron-electron interactions.

The studied samples are MOSFET Hall bars on vicinal and (100) silicon surfaces fabricated on the basis of the same technology. The vicinal surface is tilted by the angle $9^\circ$ to (100)Si around the direction [011]. This surface has a superlattice structure with a period of 1.62 nm. The peak mobility is about 25000 cm$^2$/Vs at $T = 1$ K. Measurements have been carried out in a standard four-terminal arrangement with currents $I = 1 - 10$ nA, in magnetic fields up to 15 T and in the temperature range from 50 mK to 4.2 K. All results on the vicinal sample have been qualitatively the same for the two orientations of the Hall bar - along and perpendicular to the superlattice axis, and below we will only discuss the latter case.

The inset to Fig. 1 shows the conductivity $\sigma_{xx}$ versus electron density at zero magnetic field and $T \sim 50$ mK. A well known “Ω feature” \textsuperscript{5,6} appears at electron density $N_s = 2.6 \times 10^{12}$ cm$^{-2}$ due to the superlattice minigap. The longitudinal conductivity $\sigma_{xx}$ and Hall conductivity $\sigma_{xy}$ in high magnetic field $B = 11$ T are plotted in Fig. 1 (a) as functions of electron density $N$. A change in $\sigma_{xx}$ is clearly seen when the filling factor $\nu$ increases from 10 to 14: instead of the spin-splitting dip corresponding to $\nu = 14$, a large peak appears at this filling factor. The peak in $\sigma_{xx}$ is accompanied by a peak in $\sigma_{xy}(N_s)$, instead of the usual quantisation plateau. The magnitude of the peak in $\sigma_{xy}$ significantly exceeds the classical value: $\sigma_{xy} > eN_s/B$, Fig. 1 (c). Note that the ordinary (100)Si MOSFET does not show such features around $\nu = 14$, where the ordinary spin splitting minimum in $\sigma_{xx}$ and plateau in $\sigma_{xy}$ are seen. Importantly, both systems have identical behaviour up to the filling factor $\nu = 12$, with spin splitting minima in $\sigma_{xx}$ and corresponding plateaus in $\sigma_{xy}$.

We would like to emphasise that the anomalies in the vicinal 2DEG are essentially different from the triple ‘cusp’-structure \textsuperscript{5} seen at large densities ($N_s \sim 5 \times 10^{12}$ cm$^{-2}$) in ordinary 2DEGs on (100)Si, Fig. 1(d). Firstly, the cusp feature in the middle of the Landau level is a weak triple feature. In the vicinal sample, however, the three peaks are well resolved and the central peak is more than two times larger than the side peaks. Secondly, the cusp feature in (100)Si MOSFETs is not accompanied by a peak in Hall conductivity, Fig. 1(d).

For further consideration it is convenient to present the data in terms of the directly measured longitudinal resistivity $\rho_{xx}$, which qualitatively has the same character as the conductivity $\sigma_{xx}$. Fig. 2(a) shows the $N_s$-dependence of $\rho_{xx}$ at $B = 6$ T where we study in detail how the anomalous state appears with increasing density. At $N_s < N_c$ the curve $\rho_{xx}(N_s)$ exhibits conven-
tional deep minima corresponding to cyclotron- and spin-splitting gaps. At \( N_s \approx N_c \), the behaviour of \( \rho_{xx}(N_s) \) significantly changes. The deep spin-splitting minimum disappears and a weak structure appears in the middle of the Landau level (LL) (later we will refer to this shape of \( \rho_{xx} \) as the ‘intermediate’ state). Importantly, the intermediate state corresponds to \( N_c \approx N_s^{\Delta} \). As the density increases further, a large central maximum develops accompanied by two side minima that are very similar in their position to the usual valley-splitting minima.

A similar transition from the ‘normal’ to ‘anomalous’ state is seen with decreasing magnetic field at fixed electron density \( N_s = 2.57 \times 10^{12} \text{ cm}^{-2} \) close to both \( N_s^{\Delta} \) and \( N_c \). Fig. 2(b). Magnetic field \( B_c \) corresponds here to the ‘intermediate’ state, therefore the appearance of the ‘intermediate’ state is determined by both the electron density and magnetic field. In Fig. 2(c) we plot the values of \( N_c \) and \( B_c \), obtained as described above (black symbols). The resulting relation is linear and can be treated as the boundary between two ‘phases’: one is a spin-split state, and the other is a spin-collapsed state.

This diagram allows us to come to the following conclusions: i) the anomalous state exists only at electron densities exceeding some density \( N_c \approx 2 \times 10^{12} \text{ cm}^{-2} \sim N_s^{\Delta} \); ii) a small increase of \( N_s \) leads to a significant increase of the critical magnetic field \( B_c \).

Fig. 3 (a, b) shows the evolution of the spin-split state into the anomalous state around \( \nu = 14 \) in the fourth LL as \( N_s \) is varied by small increments and the Landau level shifts to higher fields and changes its shape. There is an interesting fact in Fig. 3 (a, b) which is not reflected in the phase diagram in Fig. 2 (c): the transition from the normal (spin-split) into the intermediate state requires a significantly larger change of the electron density compared with the transition from the intermediate to the anomalous state. (In the case presented in Fig. 3 (a, b) the first transition requires \( \Delta N_s \sim 40\% \), while the second occurs with \( \Delta N_s \sim 5\% \).) This means that the anomalous
state develops rapidly when the Fermi level is lifted in the minigap. To obtain more detailed information on how spin-splitting disappears, the temperature dependence of $\sigma_{xx}$ was measured. In Fig. 3 (f) we present the results for minima at $\nu = 10$. It is seen that as $N_s$ increases, it is not only the depth of the minimum $\sigma_{xx}^{\min}$ that becomes smaller, but also the character of the temperature dependence changes. For the deepest minimum it is the dependence $\sigma_{xx}^{\min} = A \exp[-(T_0/T)^x]$, with $x$ close to 1/2 or 1/3 (comparison with 1/3 is shown in Fig. 3(f) and the same agreement is obtained for $x = 1/2$). This behaviour corresponds to variable-range hopping via localised states often observed in the QHE regime. As the density is increased and the minimum becomes less pronounced, the temperature dependence becomes linear with saturation at lowest $T$, Fig. 3(g), which indicates a change of electron transport from hopping to metallic. Note that this change in the character of transport occurs before the appearance of the intermediate state, when the spin-splitting in SdH oscillations is still clearly seen.

Since the intermediate state has a characteristic fourfold feature with small oscillations of equal magnitude, we assume that it corresponds to the situation with the following relation between valley- and spin-splitting: $\Delta_s \approx \Delta_s/2$ (see Fig. 3c). Using the theoretical dependence $\Delta_s(N_s)$ from [5], in Fig. 2 (c) we plot the corresponding $B_c(N_s)$ required to provide the equality $\Delta_s \approx \Delta_s/2$ in the ordinary (100) structures (also the experimental points from [5] obtained for (100) samples) and compare it with the $B_c(N_s)$ dependence in our vicinal sample. The $B_c(N_s)$ in (100)Si starts from the origin and has a significantly smaller slope, while the experimental diagram $B_c(N_s)$ has a distinct threshold character. The two dependences intersect at $N_c \approx 2.3 \times 10^{12}$ cm$^{-2}$ – the value which is close to $N_{A}^{\Delta}$. This clearly indicates the relation between the anomalous state in the vicinal sample and the presence of the minigap in it.

To prove the spin-related nature of the anomalous state, we have studied the effect of a parallel field on it. Fig. 4(a) shows the results of measurements of $\rho_{xx}(N_s)$ in a fixed perpendicular magnetic field, $B = 7$ T, with the parallel component $B_{\parallel}$ changing gradually from 0 to 8 T. It is clearly seen that the parallel field destroys the anomalous state for a particular LL with $N = 5$ and transforms it into the intermediate state. The fact that parallel field affects only one LL can be easily understood in terms of the “phase” diagram in Fig. 2(c). The position of the Landau level with the triplet shape (marked by “1”) corresponds to the ‘anomalous’ side of the diagram.

**FIG. 3:** (a) $\rho_{xx}(B)$ for Landau level $N = 4$ at different $N_s$ in the transition from a spin-split state to an intermediate state at $\nu = 14$ (curve “1” - $N_s = 2.15 \times 10^{12}$ cm$^{-2}$, “2” - $N_s = 2.57 \times 10^{12}$ cm$^{-2}$, “3” - $N_s = 2.85 \times 10^{12}$ cm$^{-2}$). (b) Transition from the intermediate state to a spin-collapsed state (“4” - $N_s = 2.85 \times 10^{12}$ cm$^{-2}$, “5” - $N_s = 3.13 \times 10^{12}$ cm$^{-2}$). (c, d, e) The energy diagrams illustrating the transformation of LL with increasing valley splitting. (f, g) Temperature dependence of $\sigma_{xx}$ at the minimum $\nu = 10$ at different densities, in the transition from state (c) to state (d), see text.
Applying the parallel field shifts the state up in the vertical direction until the boundary is reached, “3”. (Plotting the position of the state “3” on the diagram, with the total magnetic field $B_c = 10.6 \text{ T}$, $N_c = 3.05 \times 10^{10} \text{ cm}^{-2}$, shows that it falls exactly on the $B_c(N_s)$ line.) Clearly, other LLs in Fig. 4 (a) are far away from the boundary line, and hence they cannot be moved by parallel field into the intermediate state. A similar result has been obtained at a perpendicular field of 10 T and total magnetic field 15 T. Both cases are plotted in Fig. 2(c) by grey symbols. The transition for one of the Landau levels, $N = 5$, now from the intermediate to the normal spin-split state, is shown in Fig. 4 (b). Here the parallel component of magnetic field is increased from 0 to 6.9 T at a constant perpendicular field of 6 T.

Let us now discuss possible origins of the anomalous state. Spin-splitting collapse, in the presence of disorder, was considered for a 2DEG in [12]. This theory, however, cannot explain the main features of the phenomenon we have observed. In particular, it does not predict the presence of the triplet-like shape of $\sigma_{xx}$. It also does not explain the change of the transport mechanism when the spin-split minimum is still pronounced, Fig. 3 (f, g).

For further consideration we make a suggestion that the dissipative conductivity is determined by the density of states ($\sigma_{xx} \propto D(E_F)$). Then the presence of the triplet-like feature in $\sigma_{xx}$ (or $\rho_{xx}$) allows one to speculate about the reconstruction of the spin states in the presence of strong inter-valley interaction. At $N_s > N_c$ the electron state originating from mixing of two interacting valley states with different spins, can be constructed as a singlet-like and triplet-like spin states. Then the central peak of $\sigma_{xx}$ corresponds to the superposed singlet and the state $S_z = 0$ of the triplet. Zero spin explains the absence of spin-splitting in this case. Also, this explains the larger magnitude of the central peak compared with the side peaks - this peak corresponds to the state with double degeneracy (two states with zero spin), while the side peaks represent single states with $S_z = \pm 1$. The energy diagram of the transformation of a Landau level with increasing density (increasing the valley splitting) is shown in Fig. 3 (c, d, e) and corresponds respectively to the curves “1”, “3” and “5” in Fig. 3 (a, b).

There is an important result, which has not been discussed above. This is the observation of the peak in Hall conductivity in the center of the LL (Fig 1 b), where $\sigma_{xy}$ exceeds its classical value $e N_s / B$. According to the conventional theories of 2DES in high magnetic fields (from the early theories [2] to the modern theories of integral QHE [15, 16, 18]), at the maximum of $\sigma_{xx}$ the Hall conductivity always obeys the following condition: $\sigma_{xy} \leq e N_s / B$. To date numerous experiments [14] for different 2D electron systems including (100) Si-MOSFETs [20] (see also Fig. 1 d) supported this relation. It also remains valid in the FQHE regime [15, 16, 18], that is in the case of strongly interacting electrons. The peak in Hall conductivity exceeding $e N_s / B$ and accompanying the peak in longitudinal conductivity indicates that in the anomalous state this fundamental relation between $\sigma_{xx}$ and $\sigma_{xy}$ breaks down. Presumably this is a signature of some collective state resulting from the interplay between electron-electron and inter-valley interaction enhanced in vicinal Si-MOSFETs. One can naively speculate about an enhancement of the effective charge $e^*$ of the quasiparticles in this state, which is larger than the free electron charge ($e^* > e$). However, such a simplified assumption has to be proved theoretically, and we believe that a description of the observed anomalies is important and challenging task for the theory of correlated multi-valley electron systems.

In summary, we have performed a detailed investigation of an unusual state of a 2D electron gas near Si vicinal surface. This state is characterised by large peak in $\sigma_{xx}$ and anomalous peak in $\sigma_{xy}$, and can be described as collapse of the Zeeman spin-splitting at electron densities when the Fermi level enters the superlattice minigap. We have shown that the transition to the spin-collapsed state is dependent on electron density and magnetic field and have found the boundary $B_c(N_s)$ between the normal and anomalous states. We suggest that the anomalous state is caused by the electron-electron interaction in the condition of enhanced inter-valley interaction in the 2DEG on the vicinal surface.

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