Direct measurements of the spin and the cyclotron gaps in a 2D electron system in silicon

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Using magnetocapacitance data in tilted magnetic fields, we directly determine the chemical potential jump in a strongly correlated two-dimensional electron system in silicon when the filling factor traverses the spin and the cyclotron gaps. The data yield an effective $g$ factor that is close to its value in bulk silicon and does not depend on filling factor. The cyclotron splitting corresponds to the effective mass that is strongly enhanced at low electron densities.

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A two-dimensional (2D) electron system in silicon metal-oxide-semiconductor field-effect transistors (MOSFETs) is remarkable due to strong electron-electron interactions. The Coulomb energy overpowers both the Fermi energy and the cyclotron energy in accessible magnetic fields. The Landau-level-based considerations of many-body gaps [1,2], which are valid in the weakly interacting limit, cannot be directly applied to this strongly correlated electron system. In a perpendicular magnetic field, the gaps for charge-carrying excitations in the spectrum should originate from cyclotron, spin, and valley splittings and be related to a change of at least one of the following quantum numbers: Landau level, spin, and valley indices. However, the gap correspondence to a particular single-particle splitting is not obvious [3], and the origin of the excitations is unclear. In a recent theory [4], the strongly interacting limit has been studied, and it has been predicted that in contrast to the single-particle picture, the many-body gap to create a charge-carrying (iso)spin texture excitation at integer filling factor is determined by the cyclotron energy. This is also in contrast to the square-root magnetic field dependence of the gap expected in the weakly interacting limit [1,2].

A standard experimental method for determining the gap value in the spectrum of the 2D electron system in silicon metal-oxide-semiconductor field-effect transistors (MOSFETs) is remarkable due to strong electron-electron interactions. The Coulomb energy overpowers both the Fermi energy and the cyclotron energy in accessible magnetic fields. The Landau-level-based considerations of many-body gaps [1,2], which are valid in the weakly interacting limit, cannot be directly applied to this strongly correlated electron system. In a perpendicular magnetic field, the gaps for charge-carrying excitations in the spectrum should originate from cyclotron, spin, and valley splittings and be related to a change of at least one of the following quantum numbers: Landau level, spin, and valley indices. However, the gap correspondence to a particular single-particle splitting is not obvious [3], and the origin of the excitations is unclear. In a recent theory [4], the strongly interacting limit has been studied, and it has been predicted that in contrast to the single-particle picture, the many-body gap to create a charge-carrying (iso)spin texture excitation at integer filling factor is determined by the cyclotron energy. This is also in contrast to the square-root magnetic field dependence of the gap expected in the weakly interacting limit [1,2].

In this paper, we report the first measurements of the chemical potential jump across the spin and the cyclotron gaps in a 2D electron system in silicon in tilted magnetic fields using a magnetocapacitance technique. We find that (i) the $g$ factor is close to its value in bulk silicon and does not change with filling factor, in contrast to the strong dependence of the valley gap on $\nu$; and (ii) the cyclotron splitting is determined by the effective mass that is strongly enhanced at low electron densities. We also verify the systematics of the gaps in that the measured $\nu = 4, 8$, and 12 cyclotron gap decreases with parallel magnetic field component by the same amount as the $\nu = 2, 6$, and 10 spin gap increases.

Measurements were made in an Oxford dilution refrigerator with a base temperature of $\approx 30$ mK on high-mobility (100)-silicon MOSFETs (with a peak mobility close to 2 m$^2$/Vs at 4.2 K) having the Corbino geometry with diameters 250 and 660 $\mu$m. The gate voltage was modulated with a small ac voltage 15 mV at frequencies in the range 2.5–25 Hz and the imaginary current component was measured with high precision using a current-voltage converter and a lock-in amplifier. Care was taken to reach the low frequency limit where the magnetoca-
pacitance, \( C(B) \), is not distorted by lateral transport effects. A dip in the magnetocapacitance at integer filling factor is directly related to a jump, \( \Delta \), of the chemical potential across a corresponding gap in the spectrum of the 2D electron system, and therefore we determine \( \Delta \) by integrating \( C(B) \) over the dip in the low temperature limit where the magnetocapacitance saturates and becomes independent of temperature [12].

Typical magnetocapacitance traces taken at different electron densities, temperatures, and tilt angles are displayed in Fig. 1 near the filling factor \( \nu = \hbar c n_s / e B_\perp = 4 \) and \( \nu = 6 \). The magnetocapacitance shows narrow minima at integer \( \nu \) which are separated by broad maxima, the oscillation pattern reflecting the modulation of the thermodynamic density of states, \( D \), in quantizing magnetic fields: \( 1/C = 1/C_0 + 1/Ae^2D \) (where \( C_0 \) is the geometric capacitance between the gate and the 2D electrons, and \( A \) is the sample area) [10]. As the magnetic field is increased, the maximum \( C \) approaches the geometric capacitance indicated by the dashed lines in Fig. 1. Since the magnetocapacitance \( C(B) < C_0 \) around each maximum is almost independent of magnetic field, this results in asymmetric minima of \( C(B) \), the asymmetry being more pronounced for \( \nu = 4, 8, \) and 12. The chemical potential jump at integer \( \nu = \nu_0 \) is determined by the area of the dip in \( C(B) \):

\[
\Delta = \frac{Ae^3\nu_0}{\hbar e C_0} \int_{\text{dip}} \frac{C_{\text{ref}} - C}{C} dB_\perp,
\]

where \( C_{\text{ref}} \) is a step function that is defined by two reference levels corresponding to the capacitance values at the low and high field edges of the dip as shown by the dotted line in Fig. 1. The so-determined \( \Delta \) is smaller than the level splitting by the level width. The last is extracted from the data by substituting \( (C_0 - C_{\text{ref}})/C \) for the integrand in Eq. 1 and integrating for the case of resolved levels between the magnetic fields \( B_1 = \hbar c n_s / e (\nu_0 + 1/2) \) and \( B_2 = \hbar c n_s / e (\nu_0 - 1/2) \).

Tilting the magnetic field allows us to verify the systematics of the gaps in the spectrum and probe the lowest-energy charge-carrying excitations. As the thickness of the 2D electron system in Si MOSFETs is small compared to the magnetic length in accessible fields, the parallel field couples largely to the electrons’ spins while the orbital effects are suppressed [17]. Therefore, the variation of a gap with \( B_\parallel \) should reflect the change in the excitation energy as the Zeeman splitting, \( g_\text{\mu} B \), is increased: the excitation energy change is determined by the difference between the spin projections onto magnetic field for the ground and the lowest excited states. Within single-particle picture, e.g., one can expect that with increasing \( B_\perp \) at fixed \( B_\parallel \), the spin gap will increase, the valley gap will stay constant, and the cyclotron gap, which is given by the difference between the cyclotron splitting and the sum of the spin and the valley splittings, will decrease. In contrast, for spin textures (so-called skyrmions), the dependence of the excitation energy on \( B_\parallel \) should be much stronger compared to the

FIG. 1: Magnetocapacitance traces for \( n_s = 3.65 \times 10^{11} \text{ cm}^{-2} \) (left panel) and \( n_s = 7.21 \times 10^{11} \text{ cm}^{-2} \) (right panel). Also shown are the geometric capacitance \( C_0 \) (dashed lines) and the step function \( C_{\text{ref}} \) (dotted line).

FIG. 2: (a) Chemical potential jump across the spin gap as a function of magnetic field. The slope of the solid line gives a lower boundary for \( g \approx 1.75 \). (b) Change of the spin gap with \( B_\parallel \) at different values of \( B_\perp \). The level width contribution is indicated by systematic error bars, see text. The solid line corresponds to an effective \( g \) factor \( g \approx 2.6 \) and \( B_2 = \hbar c n_s / e (\nu_0 - 1/2) \).

\[ \Delta = \frac{Ae^3\nu_0}{\hbar e C_0} \int_{\text{dip}} \frac{C_{\text{ref}} - C}{C} dB_\perp, \]
single-particle Zeeman splitting \[\Delta_{\text{S}}\] in bulk silicon points to the single spin-flip origin of the excitations for the \(\nu = 2, 6,\) and 10 gaps.

Unlike spin gaps, the chemical potential jump, \(\Delta_{\text{c}}\), across the \(\nu = 4, 8,\) and 12 gaps decreases with parallel magnetic field component, as already seen from Fig. 1. In Fig. 3(a), we compare the behaviors of the \(\nu = 6\) and \(\nu = 4\) gaps with \(B_{||}\) at fixed perpendicular field component. For \(B_{\perp}\) between 2.7 and 6.6 T, the absolute values of the slopes of these dependences are equal, within experimental uncertainty, to each other so that the sum of the gaps is approximately constant even if the level width contribution is taken into account. These results lead to two important consequences: (i) the \(\nu = 4, 8,\) and 12 gaps are cyclotron ones, the conventional systematics of the gaps remaining valid in the studied electron density range down to \(1.5 \times 10^{11} \text{ cm}^{-2}\); and (ii) the \(g\) factor does not vary with filling factor \(\nu\). Although our value of \(g \approx 2.6\) is in agreement with the previously measured ones \(\[5, 14, 15\]\), we do not confirm the conclusion on oscillations of the \(g\) factor with \(\nu\) based on activation energy measurements and made in line with theoretical predictions \(\[1, 18\]\) under the assumption of \(B_{||}\)-independent level width \(\[14\]\).

In Fig. 3(b), we compare the data for the chemical potential jump across the \(\nu = 4, 8,\) and 12 gaps in perpendicular and tilted magnetic fields including the term \(g\mu_{B}(B - B_{\perp})\) that describes the increase of the spin gap with \(B_{||}\). The data coincidence confirms that the changing spin gap is the only cause for the dependence of the cyclotron gap on parallel field component. As is evident from the figure, \(\Delta_{\text{c}}\) is considerably smaller than the value \((\hbar\omega_{c} - 2\mu_{B}B_{\perp})\) expected within single-particle approach ignoring both valley splitting and level width.

To reduce experimental uncertainty related to the inaccurate determination of the level width, we plot in Fig. 1 the difference, \((\Delta_{\text{c}} - \Delta_{\text{s}}) / 2\mu_{B}B_{||}\) of the normalized values of the cyclotron and the spin gaps in a perpendicular magnetic field as a function of electron density. Assuming that the cyclotron splitting is determined by the effective mass \(m\), this difference corresponds to \((m_{e} / m - g)\), where \(m_{e}\) is the free electron mass. Using data for \(m\) and \(g\) obtained in both parallel \(\[14\]\) and weak \(\[15, 19\]\) magnetic fields, we find that the value \((m_{e} / m - g)\) is indeed consistent with our data, see Fig. 4. The effective mass determined from our high-\(n_{e}\) data using \(g = 2.6\) is equal to \(m \approx 0.23m_{e}\), which is close to the band mass of 0.19\(m_{e}\). As long as our \(g\) value is constant, the decrease of the normalized gap difference with decreasing \(n_{e}\) reflects the behavior of the cyclotron splitting, which is in agreement with the conclusion of the strongly enhanced effective mass at low electron densities \(\[14, 19\]\).

We now discuss comparatively the results obtained for the valley and the spin gaps. According to Ref. \(\[12\]\), the enhanced valley gap at the lowest filling factors \(\nu = 1\) and \(\nu = 3\) in Si MOSFETs is comparable to the single-particle Zeeman splitting. As our data for the spin gap correspond to the single-particle Zeeman splitting, this may lead to a different systematics of the gaps in the
From the data of Ref. [14] (dashed line), Ref. [15] (dotted line), and Ref. [19] (dash-dotted line) as well as using the band electron mass and the $g$ factor in bulk silicon (solid line), we observe at $\nu = 2$ a spin-ferromagnetic ground state only. This gives an estimate of the strength of the suggested mechanism for the valley splitting enhancement.

The fact that we do not observe oscillations of the $g$ factor as a function of $\nu$ is not too surprising, because our value of $g$ is close to the $g$ factor in bulk silicon so that those oscillations may be small. At the same time, our data for the $g$ factor allow us to arrive at a conclusion that at $\nu = 2$, the valley gap is small compared to the spin gap. Therefore, the valley splitting does oscillate with filling factor $\nu$, the conclusion being valid, at least, for the strongly enhanced gaps at $\nu = 1$ and $\nu = 3$. We stress that this effect occurs in the strongly correlated electron system, which is beyond the conventional theory of exchange-enhanced gaps \[ \[\text{[1]}\].

Let us finally discuss the results obtained for the cyclotron gap. The data of Fig. 4 indicate unequivocally that the origin of the small $\Delta_c$ value in Fig. 3(b) is not related to valley splitting and level width. Instead, it is renormalization of the effective mass and $g$ factor due to electron-electron interactions: the observed decrease of the gap difference with decreasing $n_s$ in Fig. 4 as well as the systematics of the gaps are in agreement with both the decrease of the ratio of the cyclotron and the spin gaps with decreasing $n_s$ \[ \[\text{[2]}\] and the sharp increase of the effective mass at low electron densities \[ \[\text{[14 15]}\]. Needless to say that the conventional theory \[ \[\text{[1]}\] yields an opposite sign of the interaction effect on the cyclotron splitting.

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[1] T. Ando and Y. Uemura, J. Phys. Soc. Jpn. 37, 1044 (1974); Yu. A. Bychkov, S. V. Iordanskii, and G. M. Elishashberg, JETP Lett. 33, 143 (1981); C. Kallin and B. I. Halperin, Phys. Rev. B 30, 5655 (1984); A. P. Smith, A. H. MacDonald, and G. Gumbs, Phys. Rev. B 45, 8829 (1992).

[2] K. Yang, K. Moon, L. Zheng, A. H. MacDonald, S. M. Girvin, D. Yoshioka, and S.-C. Zhang, Phys. Rev. Lett. 72, 732 (1994); K. Moon, H. Mori, K. Yang, S. M. Girvin, A. H. MacDonald, L. Zheng, D. Yoshioka, and S.-C. Zhang, Phys. Rev. B 51, 5138 (1995); L. Brey, H. A. Fertig, R. Cote, and A. H. MacDonald, Phys. Rev. B 54, 16888 (1996).

[3] S. Brener, S. V. Iordanskii, and A. Kashuba, cond-mat/0211214.

[4] S. V. Iordanskii and A. Kashuba, JETP Lett. 75, 348 (2002).

[5] T. H. Englert and K. von Klitzing, Surf. Sci. 73, 70 (1978).

[6] N. Kleinmichel, Diploma Thesis, TU München (1984).

[7] V. T. Dolgopolov, N. B. Zhitenev, and A. A. Shashkin, Sov. Phys. JETP 68, 1471 (1988).

[8] A. Usher, R. J. Nicholas, J. J. Harris, and C. T. Foxon, Phys. Rev. B 41, 1129 (1992).

[9] S. V. Kravchenko, A. A. Shashkin, D. A. Bloore, and T. M. Klapwijk, Solid State Commun. 116, 495 (2000).

[10] T. P. Smith, B. B. Goldberg, P. J. Stiles, and M. Heiblum, Phys. Rev. B 32, 2696 (1985).

[11] V. T. Dolgopolov, A. A. Shashkin, A. V. Aristov, D. Schmerek, W. Hansen, J. P. Kotthaus, and M. Holland, Phys. Rev. Lett. 79, 729 (1997).

[12] V. S. Khrapai, A. A. Shashkin, and V. T. Dolgopolov, Phys. Rev. B (2003, in press); cond-mat/0202505.

[13] An attempt to extract the gap value from the chemical potential jump measured in Si MOSFETs was made by V. M. Pudalov et al. (Sov. Phys. JETP 62, 1079 (1985)) based on a sophisticated model which did not allow reasonably accurate determination of the gaps.

[14] A. A. Shashkin, S. V. Kravchenko, V. T. Dolgopolov, and T. M. Klapwijk, Phys. Rev. Lett. 87, 086801 (2001); Phys. Rev. B 66, 073303 (2002); S. V. Kravchenko, A. A. Shashkin, and V. T. Dolgopolov, Phys. Rev. Lett. 89, 236601 (2002).
[15] A. A. Shashkin et al., cond-mat/0301187
[16] An evaluation of the effective mass at low electron densities was made by V. M. Pudalov et al. (Phys. Rev. Lett. 88, 196404 (2002)) in the high-temperature limit of Shubnikov-de Haas oscillations because of electron overheating in their experiment.

[17] D. Simonian, S. V. Kravchenko, M. P. Sarachik, and V. M. Pudalov, Phys. Rev. Lett. 79, 2304 (1997).
[18] T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. 54, 437 (1982).
[19] F. F. Fang and P. J. Stiles, Phys. Rev. 174, 823 (1968); J. L. Smith and P. J. Stiles, Phys. Rev. Lett. 29, 102 (1972).