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 the 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 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].

Numerous attempts to determine the splittings in the spectrum of the strongly interacting 2D electrons in silicon have been made over three decades. A standard experimental method for determining the gap value in the spectrum of the 2D electron system in a quantizing magnetic field is activation energy measurements at the minima of the longitudinal resistance [5–8]. Its disadvantage is that it yields a mobility gap which may be different from the gap in the spectrum. In Si MOSFETs, the activation energy as a function of magnetic field was reported to be close to half of the single-particle cyclotron energy for filling factor $\nu = 4$, while decreasing progressively for the higher ν cyclotron gaps [5–7]. At low electron densities, an interplay was observed between the cyclotron and the spin gaps, manifested by the disappearance of the cyclotron ($\nu = 4$, 8, and 12) minima of the longitudinal resistance [9]. On the contrary, for the 2D electrons in GaAs/AlGaAs heterostructures, the activation energy at $\nu = 2$ exceeded half the single-particle cyclotron energy by about 40% [8]. A direct method for determining the gap in the spectrum is measurement of the chemical potential jump across the gap [10–12]. It was applied to the 2D electrons in GaAs [10] and gave cyclotron gap values corresponding to the band electron mass [11]. Recently, the method has been used to study the valley gap at the lowest odd filling factors in the 2D electron system in silicon which has been found to be strongly enhanced and increase linearly with magnetic field [12,13].

The effective electron mass, m, and the g factor in Si MOSFETs have been determined lately from measurements of the parallel magnetic field of full spin polarization in this electron system and of the slope of the metallic temperature dependence of the conductivity in zero magnetic field [14]. It is striking that the effective mass becomes strongly enhanced with decreasing electron density, n_s, while the g factor remains nearly constant and close to its value in bulk silicon. This result is consistent with accurate measurements of m at low n_s by analyzing the temperature dependence of the Shubnikov–de Haas oscillations in weak magnetic fields in the low-temperature limit [15,16]. *A priori* it is unknown whether or not the so-determined values g and m correspond to the spin and the cyclotron splittings in strong perpendicular magnetic fields. The conventional theory [1], e.g., predicts that each gap in the spectrum is exchange enhanced, the enhancement decreasing with deviation of the filling factor from the integer value corresponding to the gap's midpoint.

In this Letter, 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 in disagreement with theoretical predictions, (i) the g factor is close to its value in bulk silicon and does not change with the filling factor, in contrast to the strong dependence of the valley gap on ν; and (ii) the cyclotron splitting is determined by the effective mass that is strongly enhanced at low electron densities.

Measurements were made in an Oxford dilution refrigerator with a base temperature of ≈ 30 mK on high-mobility (100)-silicon MOSFETs (with a peak mobility close to 2 m^2/Vs at 4.2 K and the oxide thickness 1310 Å) having the Corbino geometry with diameters 250 and 660 μm. 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 magnetocapacitance, $C(B)$, is not distorted by lateral transport effects. A dip in the magnetocapacitance at integer filling factor is directly related to a jump, Δ, of the chemical potential across a corresponding gap in the spectrum of the 2D electron system, and therefore we determine Δ by integrating $C(B)$ over the dip in the low-temperature limit where the magnetocapacitance saturates and becomes independent of temperature [12]. Note that this limit occurs at progressively higher temperatures as the gap increases.

Typical magnetocapacitance traces taken in the low-temperature limit at different electron densities and tilt angles as well as the temperature dependence of the magnetocapacitance are displayed in Fig. 1 near the filling factor $\nu = hcn_s/eB_\perp = 4$ and $\nu = 6$. The magnetocapacitance shows narrow minima at integer ν 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 the 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 $C(B)$:

$$\Delta = \frac{Ae^3\nu_0}{hcC_0}\int_{\rm dip}\frac{C_{\rm ref} - C}{C}dB_\perp, \qquad (1)$$

where the integration over $B_\perp$ is equivalent to the one over n_s as long as the dip is narrow. Here $C_{\rm ref}$ 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 Δ is smaller than the level splitting by the level width. The last is extracted from the data by substituting $(C_0 - C_{\rm ref})B_0^2/CB_\perp^2$ (where $B_0 = hcn_s/e\nu_0$) for the integrand in Eq. (1) and integrating for the case of resolved levels between the magnetic fields $B_1 = hcn_s/e(\nu_0 + 1/2)$ and $B_2 = hcn_s/e(\nu_0 - 1/2)$.

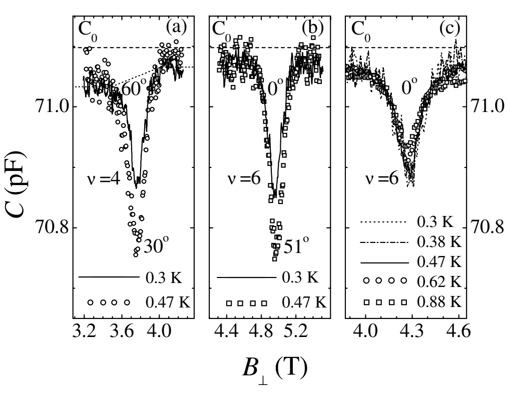

FIG. 1. Magnetocapacitance traces in the low temperature limit at different tilt angles for $n_s = 3.65 \times 10^{11}$ cm^{-2} (a) and $n_s = 7.21 \times 10^{11}$ cm^{-2} (b) and the temperature dependence of the magnetocapacitance at $n_s = 6.21 \times 10^{11}$ cm^{-2} (c). Also shown are the geometric capacitance C_0 (dashed lines) and the step function $C_{\rm ref}$ [dotted line in (a)].

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, $g\mu_B B$, is increased. Within the single-particle picture, e.g., one can expect that with increasing $B_\parallel$ at fixed $B_\perp$, 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 single-particle Zeeman splitting [2].

In Fig. 2(a), we show the value of the chemical potential jump, Δ_s, across the $\nu = 2$ and $\nu = 6$ gaps as a function of magnetic field for different tilt angles. It is insensitive to both the filling factor and the tilt angle, as expected for spin gaps. The data are best described by a proportional increase of the gap with the magnetic field with a slope corresponding to an effective g factor $g \approx 1.75$. The so-determined value obviously gives a lower boundary for the g factor because both the valley splitting at odd ν and the level width are disregarded.

In Fig. 2(b), we show how the $\nu = 6$ gap changes with $B_\parallel$ at different values of the perpendicular field component. It is noteworthy that the level width contribution, which is indicated by systematic error bars, depends weakly on parallel field, and the valley splitting has been verified to be independent of $B_\parallel$. This, therefore, allows more accurate determination of the g factor as shown by the solid line in Fig. 2(b). Its slope yields $g \approx 2.6$, which is in agreement with the data obtained for the $\nu = 2$ and $\nu = 10$ gaps. The fact that this value is close to the g factor $g = 2$ in bulk silicon points to the single spin-flip origin of the excitations for the $\nu = 2$, 6, and 10 gaps.

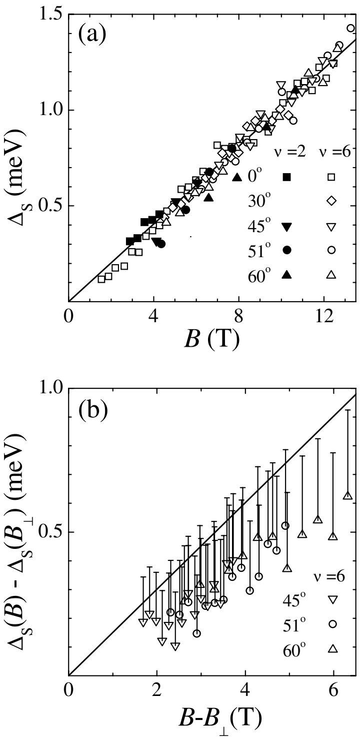

FIG. 2. (a) Chemical potential jump across the spin gap as a function of magnetic field. The slope of the solid line gives a lower boundary for $g \approx 1.75$. (b) Change of the spin gap with $B_\parallel$ at different values of $B_\perp$. The level width contribution is indicated by systematic error bars; see text. The solid line corresponds to an effective g factor $g \approx 2.6$.

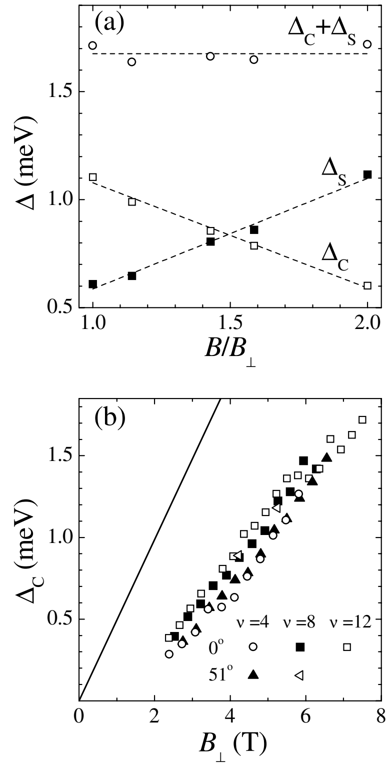

FIG. 3. (a) Change of the $\nu = 6$ spin and the $\nu = 4$ cyclotron gaps with $B_\parallel$ at fixed $B_\perp = 5.5$ T. The dashed lines are guides to the eye. (b) Chemical potential jump across the cyclotron gap as a function of perpendicular field component including the term that is responsible for the increase of Δ_s with $B_\parallel$. Also shown by a solid line is the difference between the single-particle cyclotron and Zeeman splittings.

Unlike spin gaps, the chemical potential jump, Δ_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 $B_\parallel$ at the 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 1.5×10^{11} cm^{-2}; and (ii) the g factor does not vary with filling factor ν. 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 ν based on activation energy measurements and made in line with theoretical predictions [1,18] under the assumption of $B_\parallel$-independent level width [5].

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 $B_\parallel$. The data coincidence confirms that the changing spin gap is the only cause for the dependence of the cyclotron gap on the parallel field component. As is evident from the figure, Δ_c is considerably smaller than the value $(\hbar\omega_c - 2\mu_B B_\perp)$ expected within the 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. 4 the difference, $(\Delta_c - \Delta_s)/2\mu_B B$, 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_s data using $g = 2.6$ is equal to $m \approx 0.23m_e$, which is close to the band mass of $0.19m_e$. As long as our g value is constant, the decrease of the normalized gap difference with decreasing n_s reflects the behavior of the cyclotron splitting,

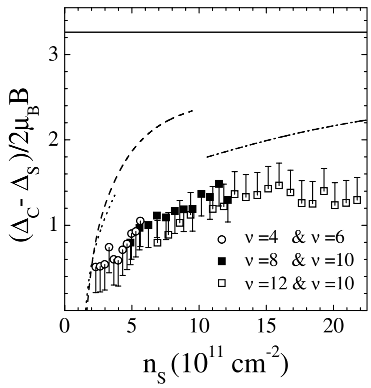

FIG. 4. Difference of the normalized values of the cyclotron and the spin gaps in a perpendicular magnetic field vs n_s. The resulting level width contribution is indicated by systematic error bars. Also shown is the value $(m_e/m - g)$ determined from the data of Ref. [14] (dashed line), Ref. [15] (dotted line), and Ref. [19] (dash-dotted line) as well as using the band electron mass and the g factor in bulk silicon (solid line).

which is in agreement with the conclusion of the strongly enhanced effective mass at low electron densities [14,15].

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 spectrum compared to the single-particle picture. Such a possibility has been supported by a recent theory [3] which shows the importance of the Jahn-Teller effect for the ground state of a 2D electron system in bivalley (100)-Si MOSFETs in quantizing magnetic fields. At $\nu = 2$, one expects a complicated phase diagram including three phases: spin-singlet, canted antiferromagnet, and ferromagnet. In our experiment, over the studied range of magnetic fields down to 3 T, we observe at $\nu = 2$ a spin-ferromagnetic ground state only.

The fact that we do not observe oscillations of the g factor as a function of ν is not too surprising, because our enhancement of g is relatively 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 [1], 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 [1].

The data for the cyclotron gap of Fig. 4 indicate unequivocally that the origin of the small Δ_c value in Fig. 3(b) is not related to valley splitting and level width. Instead, it is a renormalization of the effective mass and the 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 is in agreement with both the decrease of the ratio of the cyclotron and the spin gaps with decreasing n_s [9] and the sharp increase of the effective mass at low electron densities [14,15]. It is needless to say that the conventional theory [1] yields an opposite sign of the interaction effect on the cyclotron splitting.

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