Strong enhancement of the valley splitting in a two-dimensional electron system in silicon

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Using magnetocapacitance data, we directly determine the chemical potential jump in a strongly correlated two-dimensional electron system in silicon when the filling factor traverses the valley gap at $\nu=1$ and $\nu=3$. The data yield a valley gap that is strongly enhanced compared to the single-particle value and increases *linearly* with magnetic field. This result has not been explained by existing theories.

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A two-dimensional (2D) electron gas in (100)-silicon metal-oxide-semiconductor field-effect transistors (MOSFET's) is a unique double-layer electron system with strong interlayer interactions. Indeed, the valley index is identical with the isospin quantum number, and one can therefore try to apply to this system a good deal of recent theoretical work on double-layer electron systems. In a double-layer system with small layer separation compared to the interelectron distance in either layer, strong interlayer correlations are predicted to give rise to the appearance of both novel ground states and novel excitations.[1,2] In quantizing magnetic fields strong enough to fully polarize real electron spins, two cases as determined by the isospin system symmetry are discussed: (i) at finite layer separation the symmetry is U(1) corresponding to an ''easy-plane'' anisotropy and (ii) at vanishing layer separation the symmetry transforms to SU(2) and the anisotropy disappears. In the first (second) case the lowest-energy charge-carrying excitations are merons (Skyrmions), which are isospin textures with charge $e/2$ (e), where e is the electron charge.[1,2] There is little doubt that the valley splitting in the 2D electron system in silicon MOSFET's should be of many-body origin at least for lowest odd filling factors because the electron-electron interactions (and correlations) in this system are strong; particularly, in accessible magnetic fields, the Coulomb energy exceeds significantly the cyclotron energy. However, this is the strongly interacting limit in which existing theories are not valid and, therefore, they cannot be directly applied to silicon MOSFET's. The origin of the excitations for the valley splitting is unknown so far.

Experimental investigations of the valley splitting were performed largely[3] at high filling factor $\nu \geqslant 9$ based on analysis of the beating pattern of Shubnikov–de Haas oscillations in tilted magnetic fields.[4–7] The gap value, its linear dependence on substrate bias,[5] and its insensitivity to parallel magnetic field[8] are consistent with single-particle theoretical considerations for an asymmetric potential well that contains a 2D electron gas.[9,10]

In this paper, we perform low-temperature measurements of the chemical potential jump across the valley gap at the lowest filling factors $\nu=1$ and $\nu=3$ in a 2D electron system in silicon using a magnetocapacitance technique. The valley splitting is found to exceed strongly the single-particle value, decaying with filling factor. Unexpectedly, the data are best described by a *linear* increase of the valley gap with magnetic field, which is similar to the proportional magnetic field dependence of the enhanced spin gap for the 2D electrons in AlGaAs/GaAs heterostructures.[12,13]

Measurements were made in an Oxford dilution refrigerator with a base temperature of ≈ 30 mK on high-mobility (100)-silicon MOSFET's [with a peak mobility close to 2 $m^2/(V\,s)$ at 4.2 K] having Corbino geometry with diameters 250 and 660 μm. The gate voltage was modulated with a small ac voltage of 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 is not distorted by lateral transport effects. A dip in the magnetocapacitance at integer filling factor is directly related to a jump of the chemical potential across a corresponding gap in the spectrum of the 2D electron system.[14,15]

Typical traces of the magnetocapacitance $C(B)$ at different electron densities n_s are displayed in Fig. 1. It oscillates as a function of filling factor, $\nu=hcn_s/eB$, reflecting the modulation of the thermodynamic density of states (DOS) in quantizing magnetic fields. Narrow dips in the magnetocapacitance at integer ν are separated by broad maxima where the value C approaches in the high-field limit the geometric capacitance C_0 between the gate and the 2D electrons, in agreement with previous studies[14]:

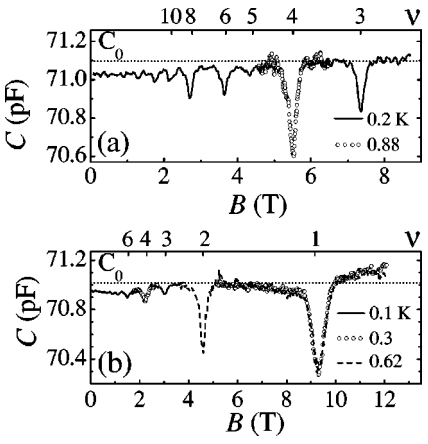

FIG. 1. Magnetocapacitance in the low-frequency limit for electron densities 5.3×10^{11} cm^{-2} (a) and 2.2×10^{11} cm^{-2} (b). The level of the geometric capacitance C_0 is indicated by a dotted line.

$$\frac{1}{C}=\frac{1}{C_0}+\frac{1}{Ae^2D}, \tag{1}$$

where A is the sample area, $D=dn_s/d\mu$ is the thermodynamic DOS, and μ is the chemical potential. We have checked that in the range of electron densities used, the value $D(B=0)$, which is calculated from the magnetocapacitance in the high-field limit (C_0) and that in $B=0$, corresponds to $2m/\pi\hbar^2$, where $m=0.19m_e$ and m_e is the free electron mass. Note that at the high-field edge of the dip in $C(B)$, the capacitance C can overshoot C_0, forming a local maximum (so-called negative compressibility effect[16]), the effect being not so pronounced at $\nu=3$ as at $\nu=1$; see Fig. 1.

Integrating Eq. (1) over a dip at integer $\nu=\nu_0$ yields a jump Δ of the chemical potential between two neighboring quantum levels:[15]

$$\Delta=\frac{Ae^3\nu_0}{hcC_0}\int_{\text{dip}}\frac{C_0-C}{C}dB, \tag{2}$$

where the integration over B is equivalent to the one over n_s as long as the dip is narrow. We note that, experimentally, it is easier to analyze $C(B)$ traces: while being independent of magnetic field, the geometric capacitance C_0 increases slightly with n_s as the 2D electrons are forced closer to the interface.

Apparently, if the capacitance C does not reach C_0 (i.e., the maximum thermodynamic DOS is insufficiently large), the jump Δ will be smaller than the level splitting by the level width. While the jump Δ is still determined by the area of the dip in $C(B)$ [see the inset of Fig. 2(a)], we estimate the level splitting including the level width contribution with the help of a similar integration of Eq. (1) between the magnetic fields $B_1=hcn_s/e(\nu_0+1/2)$ and $B_2=hcn_s/e(\nu_0-1/2)$.

In Fig. 2(a), we show the $\nu=3$ minimum in the $C(B)$ curve for $n_s=3.85\times10^{11}$ cm^{-2} at different temperatures. As the temperature T is lowered, the minimum deepens appreciably and becomes narrower until it saturates in the low-T limit, which is consistent with temperature smearing of the thermodynamic DOS. In a similar way, the maximum capacitance decreases with temperature departing from the geometric capacitance C_0. In insufficiently high magnetic fields, the (positive) difference between C_0 and C at the low-field edge of the dip is larger compared to that at the high-field edge. Therefore, we determine the jump Δ by replacing the reference level C_0 in Eq. (2) by the capacitance value at the low-field edge of the dip as depicted in the inset to Fig. 2(a). This gives somewhat underestimated values of Δ for such minima whose weakly asymmetric shape persists more or less, irrespective of magnetic field.

The chemical potential jump $\Delta(T)$ across the $\nu=3$ valley gap for the data of Fig. 2(a) with and without allowing for the temperature-dependent level width is displayed in Fig. 2(b). The value Δ increases with decreasing T and saturates in the low-temperature limit, this temperature dependence being weaker compared to that of the minimum magnetocapacitance (and the minimum D). The estimated valley splitting including the level width contribution is practically independent of temperature, as expected. It is clear that the experimental uncertainty of the determination of the valley splitting is the smallest in the low-temperature limit where the modulation of the thermodynamic DOS is maximal.

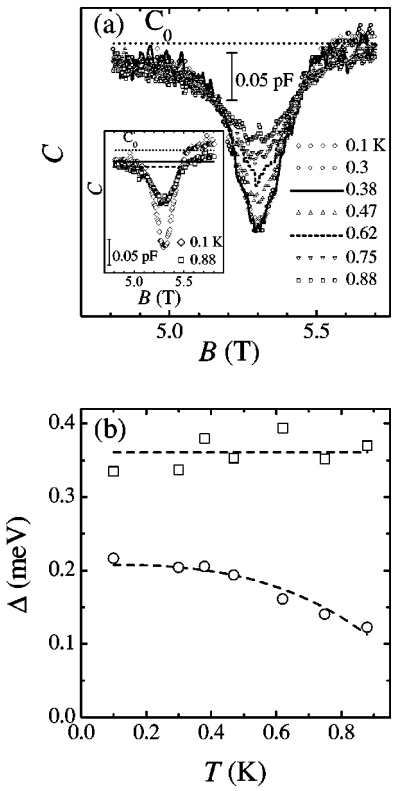

FIG. 2. The temperature dependence of the $\nu=3$ minimum in the magnetocapacitance at $n_s=3.85\times10^{11}$ cm^{-2} (a) and of the chemical potential jump with (squares) and without (circles) the level width contribution (b). The dashed lines in (b) are guides to the eye. The inset shows the same minimum in $C(B)$ along with the shifted reference level (solid and dashed lines) used to determine the jump Δ of Eq. (2) when the geometric capacitance C_0 (dotted line) is not attained.

In Fig. 3, we show the $\nu=1$ and $\nu=3$ valley splitting measured in the low-temperature limit as a function of both magnetic field and electron density. For both filling factors, the value of valley gap turns out to be strongly enhanced compared to the single-particle value[9] [solid line in Fig. 3(b)]. The valley gap enhancement decays rapidly with ν so that almost no enhancement is observed for $\nu=5$. To our surprise, the data are best described by a *linear* increase of the valley gap with B (or n_s). This fact is reliably established for $\nu=3$ where the geometric capacitance C_0 is attained in the entire range of magnetic fields used except for the lowest B, which is indicated by systematic error bars in Fig. 3 that correspond to the level width contribution. Extrapolation to $B=0$ of the linear magnetic field dependence of the $\nu=3$ gap yields a value which is consistent with the single-particle splitting. For filling factor $\nu=1$, the dependence of Δ on B (or n_s) can also be described by a linear function, although

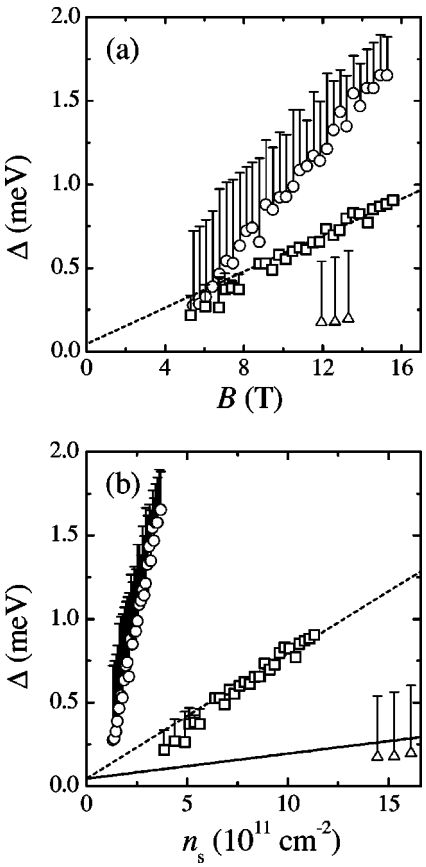

FIG. 3. The valley gap for $\nu=1$ (circles), $\nu=3$ (squares), and $\nu=5$ (triangles) as a function of magnetic field (a) and electron density (b). The systematic error bars correspond to the level width contribution, see text. A linear fit of the $\nu=3$ data is shown by a dashed line. The solid line in (b) is the expected linear n_s dependence of the single-particle valley gap Ref. 9 for depletion layer charge density 1×10^{11} cm^{-2}.

the experimental uncertainty (estimated from data dispersion) of the data for $\nu=1$ is markedly larger than that for $\nu=3$.

The linear magnetic field dependence of the enhanced valley gap observed in silicon MOSFET's is similar to the puzzling proportional B dependence of the enhanced spin gap in the 2D electron system in AlGaAs/GaAs heterostructures.[12,13] Before making a comparison with existing theories, we would like to emphasize that they are expected to hold in the limit of weak electron-electron interactions; i.e., the Coulomb energy $E_c=e^2/\varepsilon l$ [where $l=(\hbar c/eB)^{1/2}$ is the magnetic length] in a 2D electron system should be small compared to the cyclotron energy $\hbar\omega_c$. For real 2D electron systems, one determines that in a magnetic field of 10 T, the Coulomb and cyclotron energies are approximately equal to each other for the 2D electrons in GaAs, whereas in Si MOSFET's the energy E_c exceeds $\hbar\omega_c$ by a factor of 4. Therefore, even for the case of GaAs, the validity of the Landau-level-based considerations[1,2,11,17] is questionable. Formally, these cannot be applied to the case of Si MOSFET's. Bearing this in mind, we will make a qualitative comparison of our results with the aforementioned theories below.

Theoretically, the basic idea is that the gap enhancement is expected to be controlled by electron-electron interactions whose strength is characterized by the Coulomb energy E_c.[1,2,11,17] Hence, as long as the enhancement dominates the single-particle gap value Δ_0, the many-body enhanced gap should essentially be proportional to $B^{1/2}$. This law is in contradiction to the experiment, not to mention that the predicted values of the many-body gap are an order of magnitude larger than the experimental ones.

Two approaches to introduce corrections to the $B^{1/2}$ law have been formulated. Based on the traditional theory of exchange-enhanced gaps,[11] the authors of Ref. 17 took account of the corrections to the exchange energy due to the level overlap and finite 2D layer thickness as well as the correlation energy contribution. Knowing that in our case the level overlap is small,[13] we have verified that the approach[17] is unable to noticeably increase the power of the theoretical $B^{1/2}$ dependence of the gap.

In accordance with the other approach, in the limit $E_c \gg \Delta_0$, a possible formation of the isospin textures—Skyrmions[1] or merons[2] — is expected to lead to a reduction of the exchange-enhanced gap which is related to single isospin-flip excitations. We have verified that in the range of magnetic fields (or electron densities) used, the predicted crossover between the two regimes as governed by the ratio Δ_0/E_c (Ref. 1) has a weak effect on the theoretical square-root dependence $\Delta(B)$. Although the actual symmetry of the isospin system in Si MOSFET's is unknown, it is unlikely that the outcomes for the two textures[1,2] would be very different, because the layer separation is small.

Thus, for our case both approaches fail to modify appreciably the $B^{1/2}$ law and, therefore, they are not even able to give a qualitative account of our experimental data.

In summary, we have performed low-temperature measurements of the chemical potential jump across the valley gap at the lowest $\nu=1$ and $\nu=3$ in a 2D electron system in silicon. The valley splitting is found to be strongly enhanced compared to the single-particle value, decaying with filling factor. The data are best described by a linear increase of the valley gap with magnetic field. This result is similar to the proportional B dependence of the enhanced spin gap for the 2D electrons in GaAs.[12,13]

Recently, in the limit $E_c \gg \hbar\omega_c$, a remarkably different behavior of the many-body gap to create a charge-carrying spin texture excitation at integer ν has been predicted:[18] $\Delta_{st}=\nu|Q|\hbar\omega_c$, where Q is the integer topological charge. If the exchange effects play a similar role for the valley splitting,[9] the predicted linear B dependence of the gap is consistent with our findings. Still, both the gap value and its dependence on filling factor are not explained by the theory.[18]

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