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Opening an Energy Gap in an Electron Double Layer System at the Integer Filling Factor in a Tilted Magnetic Field[1]

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We employ magnetocapacitance measurements to study the spectrum of a double layer system with gate-voltage-tuned electron density distributions in tilted magnetic fields. For the dissipative state in normal magnetic fields at filling factor ν = 3 and 4, a parallel magnetic field component is found to give rise to the opening of a gap at the Fermi level. We account for the effect in terms of parallel-field-caused orthogonality breaking of the Landau wave functions with different quantum numbers for two subbands. *© 2000 MAIK "Nauka/Interperiodica".*

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Much interest in electron double layers is attracted by their many-body properties in a quantizing magnetic field. These include the fractional quantum Hall effect at filling factor ν = 1/2 [1], the many-body quantum Hall plateau at ν = 1 [2], broken-symmetry states at fractional fillings [3], the canted antiferromagnetic state at ν = 2 [4], etc. Still, the single-electron properties of double layer systems that can be interpreted without appealing to exchange and correlation effects are no less intriguing. A standard double layer with an interlayer distance of about the Bohr radius is a soft two-subband system, if brought into the imbalance regime in which the electron density distribution is two asymmetric maxima corresponding to two electron layers. In such a system, a small interlayer charge transfer significantly shifts the Landau level sets' positions; in particular, the transfer of all electrons into a single quantum level would lead to a shift as large as the cyclotron energy. In a double layer system with gate-bias-controllable electron density distributions at normal magnetic fields, peculiarities were observed in the Landau level fan chart: at fixed integer filling factor ν > 2, the Landau levels for two electron subbands pin to the Fermi level over wide regions of a magnetic field, giving rise to a zero activation energy for the conductivity [5, 6]. The pinning effect is obviously possible due to the orthogonality of the Landau level wave functions with different index and, therefore, it might disappear if the orthogonality were lost for some reason. In contrast, at ν = 1 and 2, the gap was found to be similar to the symmetric–antisymmetric splitting at balance and having a finite value for any field. This was explained by subband wave function reconstruction in the growth direction [6].

Here, we study the electron spectrum of a gate-voltage-tunable double layer in tilted magnetic fields. We find that for the dissipative state at filling factor ν = 3 and 4 in a normal magnetic field, the addition of a parallel field component leads to the appearance of a gap at the Fermi level, as indicated by activated conductivity. These findings are explained in terms of a wave-function orthogonality-breaking effect caused by the parallel magnetic field component.

The samples are grown by molecular beam epitaxy on a semi-insulating GaAs substrate. The active layers form a 760-Å-wide parabolic well. In the center of the well, a 3-monolayer-thick $Al_xGa_{1-x}As$ ($x = 0.3$) sheet is grown, which serves as a tunnel barrier between both parts on either side. The symmetrically doped well is capped by 600-Å AlGaAs and 40-Å GaAs layers. The symmetric–antisymmetric splitting in the bilayer electron system, as determined from far-infrared measurements and model calculations [7], is equal to Δ_{SAS} = 1.3 meV. The sample has ohmic contacts (each of them is connected to both electron systems in two parts of the well) and two gates on the crystal surface with areas 120 × 120 and 220 × 120 μm^2. The gate electrode enables us to tune the carrier density in the well, which is equal to 4.2×10^{11} cm^{-2} at zero gate bias, and simultaneously measure the capacitance between the gate and the well. For the capacitance measurements, we additionally apply a small ac voltage V_{ac} = 2.4 mV at frequencies in the range 3–600 Hz between the well

[1] This article was submitted by the authors in English.

and the gate and measure both current components as a function of gate bias V_g in normal and tilted magnetic fields in the temperature interval between 30 mK and 1.2 K. An example of the imaginary current component is depicted in Fig. 1; also shown in the inset is the calculated behavior of the conduction band bottom for our sample.

The employed experimental technique is similar to magnetotransport measurements in Corbino geometry: in the low frequency limit, the active component of the current is inversely proportional to the dissipative conductivity σ_{xx}, while the imaginary current component reflects the thermodynamic density of states in a double layer system. Activation energy at the minima of σ_{xx} for integer ν is determined from the temperature dependence of the corresponding peaks in the active current component.

The positions of the σ_{xx} minimum for ν = 2, 3, and 4 in the ($B_\perp$, V_g) plane are shown in Fig. 2 for both normal and tilted magnetic fields. At the gate voltages $V_{th1} < V_g < V_{th2}$, at which one subband E_1 of the substrate side part of the well is filled with electrons, the experimental points fall onto straight lines with slopes defined by the capacitance between the gate and the bottom electron layer. Above V_{th2}, where a second subband E_2 collects electrons in the front part of the well, a minimum in σ_{xx} at integer ν corresponds to a gap in the spectrum of the bilayer electron system. In this case, the slope is inversely proportional to the capacitance between the gate and the top electron layer. Additional minima of the imaginary current component that are related solely to the thermodynamic density of states in the second subband are shown in Fig. 2 by dashed lines. Hence, each of the two different kinds of minima forms its own Landau level fan chart. In the perpendicular magnetic field, wide disruptions of the fan line at ν = 4 and termination of the line at ν = 3 indicate the absence of a minimum in σ_{xx} (Fig. 2a). As mentioned above, this results from a Fermi-level pinning of the Landau levels for two subbands.

Remarkably, switching on a parallel magnetic field is found to promote the formation of a σ_{xx} minimum at integer $\nu > 2$, particularly at ν = 3 and 4; see Fig. 2b. This implies that the parallel magnetic field suppresses the pinning effect, giving rise to the opening of a gap at the Fermi level in the double layer system.

Figure 3 represents the behavior of the activation energy E_a along the ν = 3 and 4 fan lines in Fig. 2 for different tilt angles Θ of the magnetic field. As seen from Fig. 3a, for filling factor ν = 4 in the normal field, the value of E_a is largest both at the bilayer onset V_{th2} and at balance. In between these it zeroes, which is in agreement with the disappearance of the minimum of σ_{xx} in the magnetic field range between 2.6 and 3.4 T; in the close vicinity of B = 3 T, E_a is unmeasurably small, but likely finite, as can be reconciled with the observed σ_{xx} minimum at the fan crossing point of ν = 4 and ν_2 = 1 (Fig. 2a). In contrast, for tilted magnetic fields, the activation energy at ν = 4 never tends to zero, forming a plateau instead (Fig. 3a).

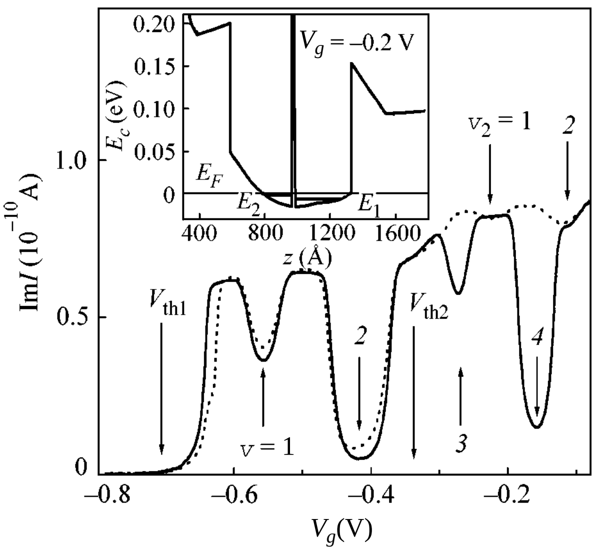

Fig. 1. Dependence of the imaginary current component on gate voltage at a frequency of 100 Hz and temperature of 30 mK for a normal (dashed line) and a tilted by Θ = 30° (solid line) magnetic field corresponding to the same $B_\perp$ = 3.3 T. The filling factors in the whole electron system and in the second subband are indicated. The threshold voltages are determined from Fig. 2 taking account of insignificant threshold shifts in different coolings of the sample. Inset: calculated band diagram of the sample at V_g = –0.2 V. Two electron subbands E_1 and E_2 in the quantum well are filled. The coordinate z is counted from the gate.

For ν = 3, the parallel field effects are basically similar to the case of ν = 4 with one noteworthy distinction. Near the balance point, the activation energy in a tilted magnetic field exhibits a minimum that deepens with increasing tilt angle, see Fig. 3b. This minimum is likely to be of many-body origin: at sufficiently large Θ it is accompanied by a splitting of the ν = 3 fan line, which is very similar to the behavior of the double layer at ν = 2 discussed as a manifestation of the canted antiferromagnetic phase [4]. This effect will be considered in detail elsewhere.

We relate the appearance of a gap at integer $\nu > 2$ in the unbalanced double layer in tilted magnetic fields to orthogonality breaking of the Landau wave functions with different quantum numbers for two subbands. Indeed, interlayer tunneling should occur with in-plane momentum conservation, so that in a tilted magnetic field it is accompanied with an in-plane shift [8] of the center of the Landau wave function by an amount d_0 tanΘ, where d_0 is the distance between the centers of mass for electron density distributions in the two lowest subbands. Apparently, the thus-shifted Landau wave functions with different quantum numbers for two subbands become overlapped. In this case, the above-men-

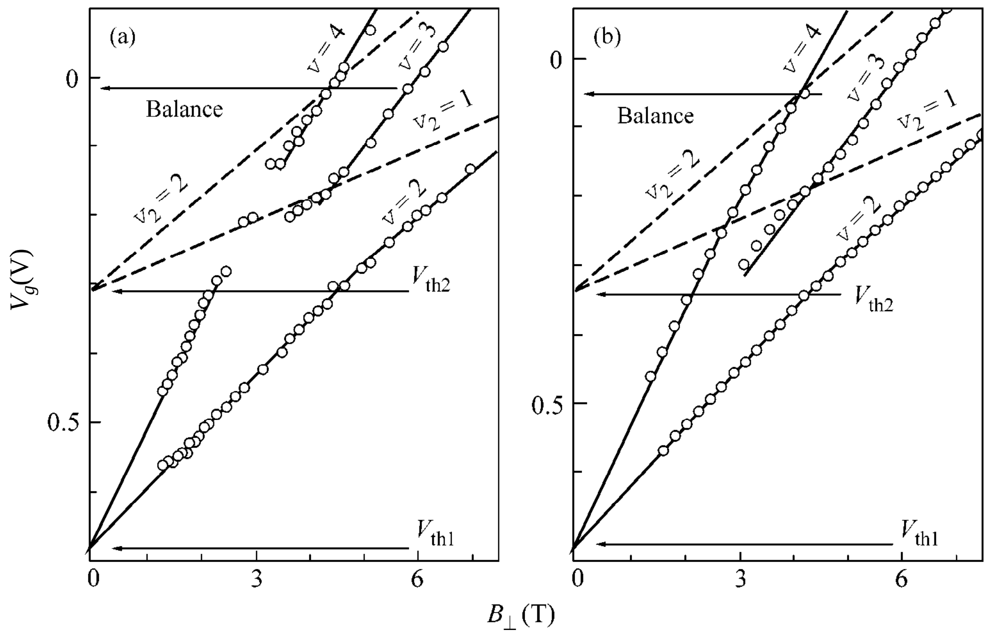

Fig. 2. Positions of the σ_{xx} minima at a temperature of 30 mK for different tilt angles: (a) Θ = 0°, (b) Θ = 30°. The dashed lines correspond to minima in the thermodynamic density of states for the second electron subband.

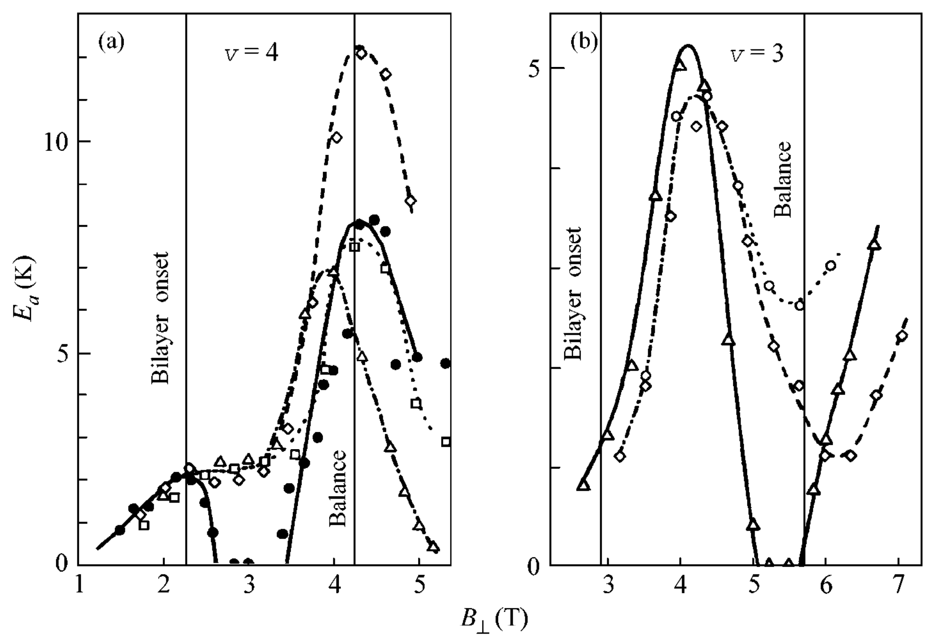

Fig. 3. Change of the activation energy with magnetic field at (a) ν = 4 for ν = 0° (dots), Θ = 30° (diamonds), Θ = 45° (squares), Θ = 60° (triangles); and (b) ν = 3 for Θ = 30° (circles), Θ = 45° (diamonds), Θ = 60° (triangles). The lines are guides to the eye.

tioned pinning effect at integer $\nu > 2$ cannot occur any more. Instead, as will be discussed below, the wave functions get reconstructed, which is accompanied by level splitting.

We calculate the single-particle spectrum in a tilted magnetic field in self-consistent Hartree approximation without taking into account the spin splitting (supposing small g factor), as well as the exchange and correlation energies. The intersubband charge transfer when switching on the magnetic field is a perturbation potential in the problem that mixes the wave functions for two subbands. Account is taken of a shift of the subband bottoms due to a parallel component of the magnetic field, and the value of gap at the Fermi level is determined in the first order of perturbation theory in a

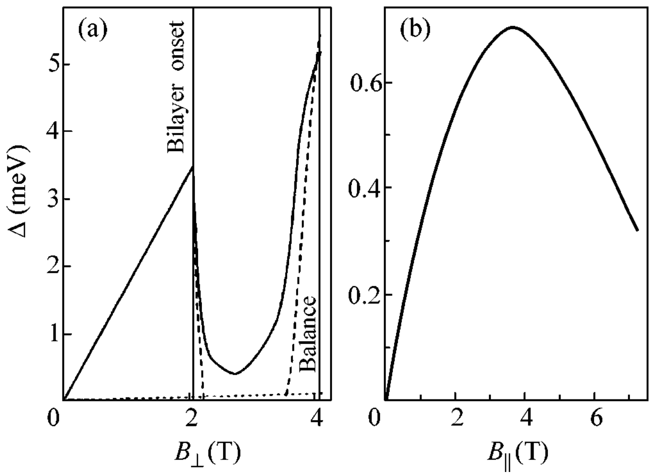

Fig. 4. The calculated gap at ν = 4 as a function of magnetic field for (a) fixed tilt angle Θ = 0° (dashed line) and Θ = 30° (solid line); and (b) fixed $B_\perp$ = 2.6 T. Also shown by a dotted line is the corresponding Zeeman splitting for Θ = 30°.

similar way to the ν = 1 and 2 cases for normal magnetic fields of [6].

The magnetic field dependence of the calculated gap Δ for filling factor ν = 4 is displayed in Fig. 4. At fixed tilt angle, the calculation reproduces well the observed behavior of the gap along the ν = 4 fan line (cf. Figs. 3a, 4a). The quantitative difference between the gap values can be attributed to the finite width of the Landau levels, which is disregarded in calculation.

The gap Δ as a function of parallel magnetic field component $B_\parallel$ at a fixed value of $B_\perp$ = 2.6 T is depicted in Fig. 4b. It reaches a maximum at $B_\parallel$ = 3.5 T and then drops with further increasing field ($B_\parallel$). It is clear that $\Delta(B_\parallel)$ reflects the dependence of the overlap of the Landau wave functions with different quantum numbers on their in-plane shift d_0 tanΘ: while at sufficiently small shifts the overlap rises with shift, at large shifts, the overlap is sure to vanish, restoring the wave function orthogonality.

The above explanation holds for filling factor ν = 3 as well. We note that, in a normal magnetic field, the ν = 3 gap for our case is of spin origin, since the expected spin splitting is smaller than Δ_{SAS} [6, 9]. Therefore, it can increase with $B_\parallel$ for trivial reasons. The point of importance is that the Landau wave function orthogonality has to be lost for the gap to open.

In summary, we have performed magnetocapacitance measurements on a double layer system with gate-voltage-controlled electron density distributions in tilted magnetic fields. It has been found that, for the dissipative state in normal magnetic fields at filling factor ν = 3 and 4, a parallel magnetic field component leads to the opening of a gap at the Fermi level. We attribute the origin of the effect to orthogonality breaking of the Landau wave functions with different quantum numbers for two subbands as caused by a parallel magnetic field. The calculated behavior of the gap is consistent with the experimental data.

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