Magnetic-field-induced hybridization of electron subbands in a coupled double quantum well

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We employ a magnetocapacitance technique to study the spectrum of the soft two-subband (or double-layer) electron system in a parabolic quantum well with a narrow tunnel barrier at the center. In this system, when unbalanced by gate depletion, two sets of quantum oscillations are observed at temperatures $T \gtrsim 30$ mK: one originates from the upper electron subband in the closer-to-the-gate part of the well, and the other indicates the existence of common gaps in the spectrum at integer fillings. For the lowest filling factors $\nu = 1$ and $\nu = 2$, both the presence of a common gap down to the point of the one- to two-subband transition and their nontrivial magnetic field dependences point to magnetic-field-induced hybridization of electron subbands.

A soft two-subband electron system, or electron double layer, is the simplest system having a degree of freedom, which is associated with the third dimension, in the integer (IQHE) and fractional (FQHE) quantum Hall effects. As compared to a conventional two-subband electron system with vanishing distance d between electron density maxima, such as the one in single heterojunctions, in the double layer the energy spacing between subbands is very sensitive to intersubband electron transfer because of the large $d \gtrsim a_B = \varepsilon\hbar^2/me^2$. Since the pioneering papers of Refs. 1 and 2, much attention has been paid to the investigation of balanced systems with symmetric electron density distributions. While in this case the origin of the IQHE at even integer filling factors is trivial, the symmetric–antisymmetric level splitting caused by tunneling gives rise to the IQHE at odd integer filling factors. The absence of certain IQHE states at low odd integer fillings[1,2] was interpreted in Refs. 3 and 4 as being due to the Coulomb-interaction-induced destruction of symmetric–antisymmetric splitting in high magnetic fields. There have been reported observations of both the bilayer many-body IQHE at filling factor

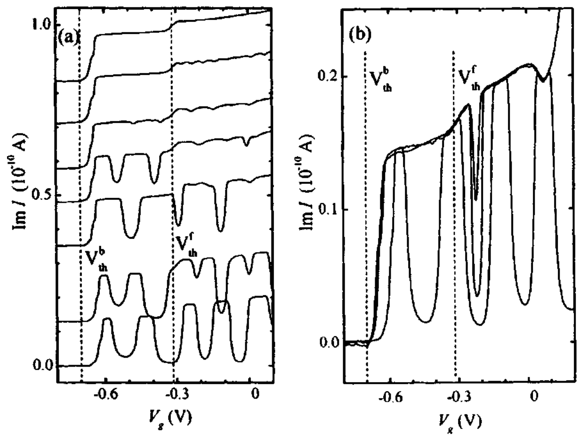

FIG. 1. Imaginary current component versus gate voltage at $f=110$ Hz at different temperatures and magnetic fields. a: $B=0$, 0.67, 1.34, 1.84, 2.51, 3.68, and 4.34 T at $T=30$ mK, the lines are shifted proportionally to steps in B; b: $T=30$, 620, and 880 mK at $B=6$ T.

$\nu=1$ (Refs. 5 and 6) and the FQHE (Refs. 7–10), whose origin, alternatively, has been attributed to interlayer correlation effects (Refs. 11–14). The case of an unbalanced system with strongly asymmetric electron density distributions was studied in Ref. 15. At relatively high filling factors the authors[15] observed an interplay between ''single- and double-layer behavior'' and explained this in terms of charge transfer between two electron subbands, without appealing to exchange and correlation effects.

Here, using a capacitive spectroscopy method, we investigate the spectrum of two-dimensional electrons in a quantizing magnetic field in a parabolic quantum well that contains a narrow tunnel barrier for the electron systems on either side. In the gate-depletion-unbalanced double-layer system, new gaps with unusual magnetic field dependences have been detected at filling factors $\nu=1$ and $\nu=2$. We argue that these emerge as a result of magnetic-field-induced hybridization of electron subbands.

The sample is grown by molecular beam epitaxy on 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 the two parts on either side. The symmetrically doped well is capped by 600 Å AlGaAs and 40 Å GaAs layers. The sample has two Ohmic contacts (each of them is connected to both electron systems in the two parts of the well) and a gate on the crystal surface with area 120×120 μm^2. The presence of the gate electrode makes it possible to tune the carrier density in the well and to measure the capacitance between the gate and the well. For capacitance measurements we apply an ac voltage $V_{ac}=2.4$ mV at frequencies f in the range 3 to 600 Hz between the well and the gate and measure both current components as a function of gate bias V_g, using a home-made I–V converter and a standard lock-in technique. Our measurements are performed in the temperature interval between 30 mK and 1.2 K at magnetic fields of up to 16 T.

The dependence of the imaginary current component on the gate voltage at different magnetic fields is shown in Fig. 1a. In zero magnetic field at $V^b_{\rm th}=-0.7$ V$<V_g<V^f_{\rm th}=-0.31$ V electrons fill only one subband in the back part of the well, relative to the

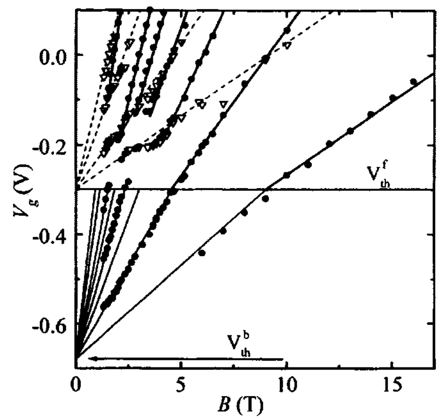

FIG. 2. Landau level fan chart as found from the minima of the density of states in the upper electron subband (open symbols, dashed lines) and of the conductivity of the lower electron subband (filled symbols, solid lines) and of the conductivity of the double-layer electron system (filled symbols, bold lines). The bold line disruptions signify the absence of common gaps. At crossing points of the dashed and bold lines the corresponding minima trigger with changing temperature.

gate. With increasing $V_g > V_{\mathrm{th}}^f$ a second electron subband starts to collect electrons in the front part of the well, as is indicated by an increase of the capacitance. In magnetic fields of about 1.3 T at low temperatures we observe two sets of quantum oscillations: first, the oscillations at $V_g > V_{\mathrm{th}}^f$ are due to the modulation of the thermodynamic density of states in the upper electron subband. They are typical of a three electrode system (see, e.g., Refs. 16 and 17) and depend only weakly on temperature in the regime investigated. Second, the oscillations at $V_g < V_{\mathrm{th}}^f$ originate from the conductivity oscillations in the lower electron subband, and so these are accompanied by peaks in the real current component. With increasing magnetic field, one more set of oscillations emerges, formed by additional minima at $V_g > V_{\mathrm{th}}^f$ (Fig. 1a). The small values of capacitance at the oscillation minima and the nonzero active current component indicate that the conductivity σ_{xx} vanishes for both electron subbands. Since they arerelated to σ_{xx}, these common oscillations are strongly temperature-dependent, whereas the measured capacitance in between the deep minima depends weakly on temperature. As seen from Fig. 1b, the weak oscillations reflecting the thermodynamic density of states in the upper subband persist after the appearance of the common oscillations. In particular, when located between deep minima, these do not change at all as the latter develop. For coincident positions, the minima for the two kinds of oscillations trigger with changing temperature.

Figure 2 presents a Landau level fan diagram in the (B, V_g) plane for our sample. Positions of the density of states minima in the upper electron subband are shown by open symbols. These minima correspond to the filling factors $\nu_2 = 1, 2, 4, 6$ in the upper subband. The conductivity minima are marked in Fig. 2 by solid symbols. In the gate voltage interval $V_{\mathrm{th}}^b < V_g < V_{\mathrm{th}}^f$ we see the filling factors $\nu_1 = 1, 2, 4, 6$ in the lower subband. Furthermore, for $V_g > V_{\mathrm{th}}^f$ the common oscillations define a third Landau level fan. The straight lines of this fan are parallel to those for the upper electron subband and correspond to $\nu = 1, 2, 3, 4, 5, 6, 8, 10$, which is the filling factor defined in terms of the electron density N_s in the quantum well. In the (B, V_g) plane the different slopes of the

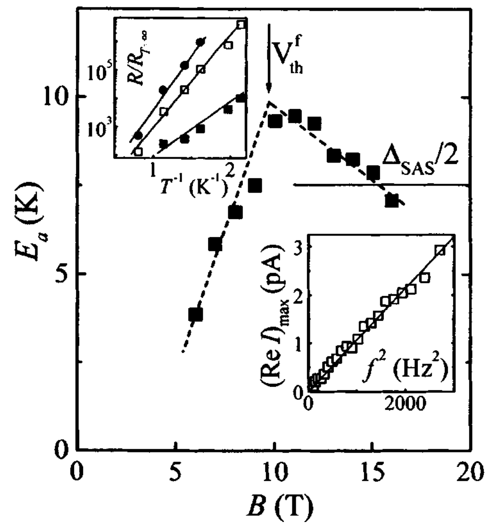

FIG. 3. Activation energy as a function of magnetic field at filling factor $\nu=1$. The insets display the frequency dependence of the active current component peak (bottom) and Arrhenius plot of the peak amplitude for $B=6$, 10, and 14 T (top).

fan lines below and above $V_g=V_{\rm th}^f$ (Fig. 2) correspond to the capacitance values before and after the jump near $V_g=V_{\rm th}^f$ (Fig. 1). One can see from Fig. 2 that despite the fact that upon variations in the gate voltage $V_g>V_{\rm th}^f$ the electron density changes substantially in the front part of the well, as is indicated by the fan line slopes, it is for integer ν that common gaps are observed in the double-layer system.

The activation energy in the common oscillation minima is found from the temperature dependence of peaks in the active current component, which accompany capacitance minima. In the limit of vanishing active current component the peak amplitude is expected to be proportional to $f^2\sigma_{xx}^{-1}$. To make sure that the measuring frequency is sufficiently low, we investigate the frequency dependence of the active current component (see the bottom inset to Fig. 3). In the frequency range where the above relation holds, the activation energy is simply determined from Arrhenius plot of the peak amplitude (the top inset to Fig. 3). Figure 3 displays the magnetic field dependence of the activation energy for filling factor $\nu=1$. This dependence is quite nontrivial: the activation energy is a maximum at about $V_g=V_{\rm th}^f$, where a second electron subband starts to be filled, and then it monotonically decreases with magnetic field up to the balance point. A similar behavior is found also for filling factor $\nu=2$. Although the gaps at filling factors $\nu>2$ are also maximal near the threshold voltage $V_{\rm th}^f$, at higher fields, unlike the gaps at $\nu=1$ and $\nu=2$, they vanish in some intervals of B (or V_g). This is indicated by disruptions of the fan lines in Fig. 2.

The band structure of our sample in the absence of magnetic field is known from far-infrared spectroscopy and magnetotransport investigations on samples fabricated from the same wafer.[18,19] It agrees with the result of self-consistent Hartree calculation of energy levels in a coupled double quantum well (Fig. 4). In the calculation one reasonably assumes that all electron subbands have a common electrochemical potential which

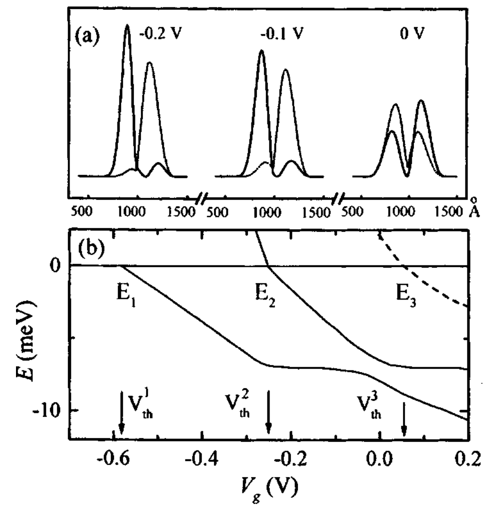

FIG. 4. Calculated at $B=0$, electron density distributions for the two lower energy bands in the quantum well (a) and positions of the energy band bottoms as a function of the gate voltage (b). The dotted and solid lines in case (a) correspond to E_1 and E_2, respectively.

corresponds to the zero-point on the energy scale in Fig. 4b. In agreement with experiment, only one energy band is occupied by electrons in the range $V_{\mathrm{th}}^1 < V_g < V_{\mathrm{th}}^2$, two energy bands are filled at $V_{\mathrm{th}}^2 < V_g < V_{\mathrm{th}}^3$, and three of them are filled above $V_g = V_{\mathrm{th}}^3$. The band splitting at a zero gate voltage is symmetric–antisymmetric splitting $\Delta_{SAS} = 1.3$ meV. Figure 4a shows the electron density profiles for the two lower energy bands in the quantum well at three different gate voltages. We note that for both energy bands, even far from the balance, the wave function is not completely localized in either part of the quantum well.

Experimentally, the possibility of all the electrons collecting in one part of the quantum well (so-called broken-symmetry states)[20] is excluded because of the coexistence of the Landau level fan for the upper subband and the one determined by common oscillations (Fig. 2).

One can tentatively expect that the experimental data find their interpretation in terms of a relative shift of the Landau level ladders corresponding to two electron subbands. At fixed integer ν, the conductivity σ_{xx} of a bilayer system should tend to zero in the close vicinities of Landau-level-fan crossing points in the (B, V_g) plane, at which both individual filling factors ν_f, ν_b are integers, as long as the Fermi level remains in a gap between quantum levels for two electron subbands. Obviously, in between the crossing points the common gap closes as soon as the Fermi level pins to both of the quantum levels. Such behavior is indeed observed in the experiment at filling factors $\nu > 2$ (see Fig. 2). We note that the presence (absence) of common gaps was identified in Ref. 15 as ''single (double) layer behavior.'' In contrast, for a conventional two-subband electron system with vanishing distance between electron density maxima, common gaps at integer ν are expected to close in negligibly narrow intervals on the Landau-level-fan lines where both quantum levels from two electron subbands cross the Fermi level.

However, such simple considerations fail to account for the common gaps at filling factors $\nu=1,2$ which do not disappear in the entire range from the threshold $V_{\rm th}^f$ to the balance point (Figs. 2 and 3). We explain this behavior as a result of magnetic-field-induced hybridization of the wave functions of two electron subbands, which gives rise to the creation of new gaps in the bilayer spectrum.

In a soft two-subband electron system, the quantum level energies for two Landau level ladders can become equal only if the corresponding wave functions are orthogonal, i.e., if the Landau level numbers are different. Apparently, this is not the case for $\nu=1,2$ or for higher $\nu\neq 4m$ (m is an integer) near the balance point. The absence of orthogonality implies that the bilayer system is described by a hybrid wave function that is a linear combination of the wave functions of two electron subbands. The appearance of new gaps, as a result, is crucially determined by intersubband charge transfer in magnetic field to make the band bottoms coincident. We note that this process is impossible in the conventional two-subband system as discussed above. Although in our soft two-subband system the distance between electron density maxima (Fig. 4) is close to the in-plane distance between electrons, the amount of charge transferred is estimated to be small. This is confirmed experimentally by the absence of appreciable deviations of the data points from the upper-subband-fan lines (Fig. 2) as determined by zero-magnetic-field capacitance at $V_g>V_{\rm th}^f$ (Fig. 1). It is clear that the magnetic-field-induced hybridization generalizes the case of symmetric electron density distributions corresponding to formation of Δ_{SAS}. From the first sight it seems natural to expect that the common gaps at $\nu=1,2$ decrease with magnetic field and approach Δ_{SAS} at the balance point (Fig. 3). Yet, for all the filling factors in question the situation is far more sophisticated, because the spin splitting, which is comparable to the hybrid splitting, comes into play. The bilayer spectrum is then determined by their competition, which, in principle, may even lead to the closing of common gaps in some intervals of magnetic field. For example, at $\nu=2$ the actual gap is given by the splitting difference, and so it vanishes for equal splittings. In our experiment, for the simplest case of $\nu=1$ one can expect that over the range of magnetic fields used, the many-body enhanced spin gap is large compared to Δ_{SAS} (Ref. 17). That stands to reason, since it is the smaller splitting that corresponds to $\nu=1$ (Fig. 3). For $\nu=2$ the very similar behavior of the gap with magnetic field hints that at these lower fields the hybrid splitting is dominant. As a result of interchange of the hybrid and spin splittings, odd $\nu>1$ near the balance in our case correspond to spin rather than hybrid gaps.

In summary, we have performed magnetocapacitance measurements on a bilayer electron system in a parabolic quantum well with a narrow tunnel barrier in its center. For asymmetric electron density distributions created by gate depletion in this soft two-subband system we observe two sets of quantum oscillations. These originate from the upper electron subband in the front part of the well and from the gaps in the bilayer spectrum at integer fillings. For the lowest filling factors $\nu=1$ and $\nu=2$, the common gap formation is attributed to magnetic-field-induced hybridization of electron subbands, dependent on the competition between the hybrid and spin splitting.

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[1] G. S. Boebinger, H. W. Jiang, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **64**, 1793 (1990).
[2] Y. W. Suen, J. Jo, M. B. Santos *et al.*, Phys. Rev. B **44**, 5947 (1991).
[3] A. H. MacDonald, P. M. Platzman, and G. S. Boebinger, Phys. Rev. Lett. **65**, 775 (1990).
[4] L. Brey, Phys. Rev. Lett. **65**, 903 (1990).
[5] S. Q. Murphy, J. P. Eisenstein, G. S. Boebinger *et al.*, Phys. Rev. Lett. **72**, 728 (1994).
[6] T. S. Lay, Y. W. Suen, H. C. Manoharan *et al.*, Phys. Rev. B **50**, 17725 (1994).
[7] Y. W. Suen, L. W. Engel, M. B. Santos *et al.*, Phys. Rev. Lett. **68**, 1379 (1992).
[8] J. P. Eisenstein, G. S. Boebinger, L. N. Pfeiffer *et al.*, Phys. Rev. Lett. **68**, 1383 (1992).
[9] Y. W. Suen, J. Jo, M. B. Santos *et al.*, Phys. Rev. B **44**, 5947 (1991).
[10] Y. W. Suen, H. C. Manoharan, X. Ying *et al.*, Surf. Sci. **305**, 13 (1994).
[11] T. Chakraborty and P. Pietilainen, Phys. Rev. Lett. **59**, 2784 (1987).
[12] D. Yoshioka, A. H. MacDonald, and S. M. Girvin, Phys. Rev. B **39**, 1932 (1989).
[13] H. A. Fertig, Phys. Rev. B **40**, 1087 (1989).
[14] S. He, X. C. Xie, S. Das Sarma, and F. C. Zhang, Phys. Rev. B **43**, 9339 (1991).
[15] A. G. Davies, C. H. W. Barnes, K. R. Zolleis *et al.*, Phys. Rev. B **54**, R17331 (1996).
[16] R. C. Ashoori and R. H. Silsbee, Solid State Commun. **81**, 821 (1992).
[17] V. T. Dolgopolov, A. A. Shashkin, A. V. Aristov *et al.*, Phys. Low-Dimens. Semicond. Struct. **6**, 1 (1996); V. T. Dolgopolov, A. A. Shashkin, A. V. Aristov *et al.*, Phys. Rev. Lett. **79**, 729 (1997).
[18] M. Hartung, A. Wixforth, K. L. Campman, and A. C. Gossard, Solid-State Electron. **40**, 113 (1996).
[19] G. Salis, B. Graf, K. Ensslin *et al.*, Phys. Rev. Lett. **79**, 5106 (1997).
[20] T. Jungwirth and A. H. MacDonald, Phys. Rev. B **53**, 9943 (1996).