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 in the centre. In this system unbalanced by gate depletion, at temperatures $T \gtrsim 30$ mK we observe two sets of quantum oscillations: 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 common gap presence down to the point of one- to two-subband transition and their non-trivial magnetic field dependences point to magnetic-field-induced hybridization of electron subbands.

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A soft two-subband electron system, or double electron 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 effect. 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 large $d \gtrsim a_B = \varepsilon\hbar^2/me^2$. Since pioneering papers [1,2] much attention is 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. [3,4] as due to the Coulomb-interaction-induced destruction of symmetric-antisymmetric splitting in strong magnetic fields. Observation was reported of the bilayer many-body IQHE at filling factor $\nu = 1$ [5,6] and FQHE [7–10] whose origin, alternatively, was attributed to interlayer correlation effects [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 behaviour" and explained this in terms of charge transfer between two electron subbands without appealing exchange and correlation effects.

Here, using a capacitive spectroscopy method, we investigate the spectrum of two-dimensional electrons at 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 both 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 two parts of the well) and a gate on the crystal surface with area 120×120 μm^2. The presence of the gate electrode enables us both 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 dependences of the imaginary current component on gate voltage at different magnetic fields are shown in Fig. 1(a). In zero magnetic field at $V_{th}^b = -0.7$ V $< V_g < V_{th}^f = -0.31$ V electrons fill only one subband in the back part of the well, relative to the gate. With increasing $V_g > V_{th}^f$ a second electron subband starts to collect

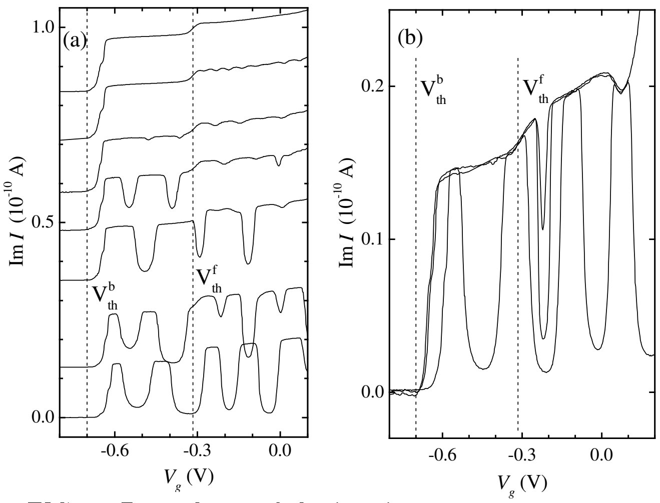

FIG. 1. Dependence of the imaginary current component on gate voltage at $f = 110$ Hz at different temperatures and magnetic fields: (a) $B = 0, 0.67, 1.34, 1.84, 2.51, 3.68, 4.34$ T at $T = 30$ mK, the lines are shifted proportionally to steps in B; (b) $T = 30, 620, 880$ mK at $B = 6$ T.

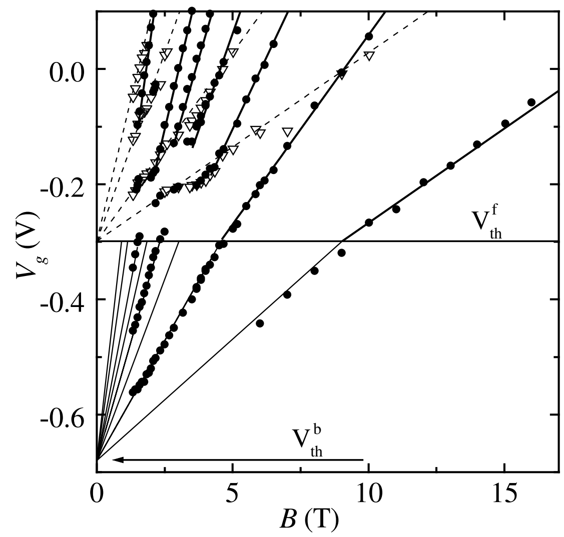

FIG. 2. Landau level fan chart as found from the minima of the density of states in the upper electron subband (open symbols, dashed lines) and of the conductivity of the lower electron subband (filled symbols, solid lines) and of the conductivity of the double-layer electron system (filled symbols, 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.

electrons in the front part of the well, which 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 $V_g > V_{th}^f$ 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. [16,17]) and depend only weakly on temperature in the regime investigated. Second, the oscillations at $V_g < V_{th}^f$ originate from the conductivity oscillations in the lower electron subband and so these are accompanied by peaks in the real current component. With increasing the magnetic field one more set of oscillations emerges formed by additional minima at $V_g > V_{th}^f$ (Fig. 1(a)). The small values of capacitance at the oscillation minima as well as the non-zero active current component reflect that the conductivity σ_{xx} vanishes for both electron subbands. Since related 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. 1(b), the weak oscillations reflecting the thermodynamic density of states in the upper subband persist after the appearance of the common oscillations. In particular, these do not change at all, when located between deep minima, as the latter develop. For coincident positions, the minima for the two kinds of oscillations trigger with changing temperature.

Fig. 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 the figure by solid symbols. In the gate voltage interval $V_{th}^b < V_g < V_{th}^f$ we see the filling factors $\nu_1 = 1, 2, 4, 6$ in the lower subband. Furthermore, for $V_g > V_{th}^f$ the common oscillations define the 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 as determined by the electron density N_s in the quantum well. In the (B, V_g) plane the different fan line slopes below and above $V_g = V_{th}^f$ (Fig. 2) correspond to the capacitance values before and after the jump near $V_g = V_{th}^f$ (Fig. 1). One can see from Fig. 2 that despite with varying the gate voltage $V_g > V_{th}^f$ the electron density changes essentially in the front part of the well as indicated by the fan line slopes, it is the integer ν at which 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). Fig. 3 displays the magnetic field dependence of the activation energy for filling factor $\nu = 1$. This dependence is quite non-trivial: the activation energy is a maximum at about $V_g = V_{th}^f$, where a second

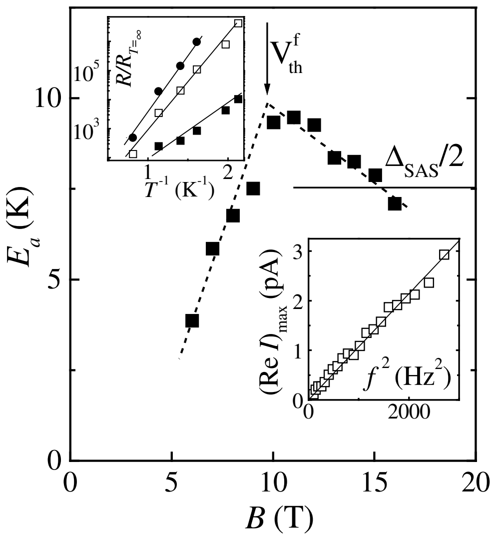

FIG. 3. Activation energy as a function of magnetic field at filling factor $\nu = 1$. The insets display the frequency dependence of the active current component peak (bottom) and Arrhenius plot of the peak amplitude for $B = 6, 10, 14$ T (top).

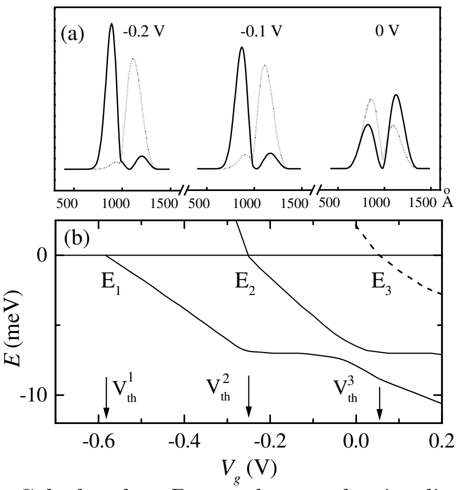

FIG. 4. Calculated at $B = 0$, electron density distributions for the two lower energy bands in the quantum well (a) and positions of the energy band bottoms as a function of gate voltage (b). The dotted and solid lines in case (a) correspond to E_1 and E_2, respectively.

electron subband starts to be filled, and then it monotonically decreases with magnetic field up to the balance point. A similar behaviour is found also for filling factor $\nu = 2$. Although the gaps at filling factors $\nu > 2$ are also maxima near the threshold voltage V_{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 corresponds to the zero-point on the energy scale in Fig. 4(b). In agreement with experiment, only one energy band is occupied by electrons in the range $V_{th}^1 < V_g < V_{th}^2$, two energy bands are filled at $V_{th}^2 < V_g < V_{th}^3$ and three of them are filled above $V_g = V_{th}^3$. The band splitting at a zero gate voltage is symmetric-antisymmetric splitting $\Delta_{SAS} = 1.3$ meV. Fig. 4(a) 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 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 relative shift of 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 a behaviour 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 behaviour". 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_{th}^f to the balance point (Figs. 2,3). We explain this behaviour 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, quantum level energies for two Landau level ladders can get 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 $\nu = 1, 2$ as well as for higher $\nu \neq 4m$ (m is integer) near the balance point. The absence of orthogonality implies that the bilayer system is described by the 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 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 $V_g > V_{th}^f$ (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 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, then, is determined by their competition which, in principle, may even lead to closing 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 zeroes 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} [17]. That stands to reason, it is the smaller splitting that corresponds to $\nu = 1$ (Fig. 3). For $\nu = 2$ the very similar behaviour 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 the 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 centre. 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, L.W. Engel, S.W. Hwang, and M. Shayegan, 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, L.N. Pfeiffer, and K.W. West, Phys. Rev. Lett. **72**, 728 (1994).
[6] T.S. Lay, Y.W. Suen, H.C. Manoharan, X. Ying, M.B. Santos, and M. Shayegan, Phys. Rev. B **50**, 17725 (1994).
[7] Y.W. Suen, L.W. Engel, M.B. Santos, M. Shayegan, and D.C. Tsui, Phys. Rev. Lett. **68**, 1379 (1992).
[8] J.P. Eisenstein, G.S. Boebinger, L.N. Pfeiffer, K.W. West, and S. He, Phys. Rev. Lett. **68**, 1383 (1992).
[9] Y.W. Suen, J. Jo, M.B. Santos, L.W. Engel, S.W. Hwang, and M. Shayegan, Phys. Rev. B **44**, 5947 (1991).
[10] Y.W. Suen, H.C. Manoharan, X. Ying, M.B. Santos, and M. Shayegan, 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, J.T. Nicholls, M.Y. Simmons, and D.A. Ritchie, 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, D. Schmerek, H. Drexler, W. Hansen, J.P. Kotthaus, and M. Holland, Phys. Low-Dim. Struct. **6**, 1 (1996); 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).
[18] M. Hartung, A. Wixforth, K.L. Campman, and A.C. Gossard, Solid State Electronics **40**, 113 (1996).
[19] G. Salis, B. Graf, K. Ensslin, K. Campman, K. Maranowski, and A.C. Gossard, Phys. Rev. Lett. **79**, 5106 (1997).
[20] T. Jungwirth, and A.H. MacDonald, Phys. Rev. B **53**, 9943 (1996).