Letter

# Nonequilibrium phenomena in bilayer electron systems

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(Received 26 October 2022; revised 16 December 2022; accepted 9 January 2023; published 17 January 2023)

In the present Letter, we have used magnetocapacitance and magnetoresistance measurements to investigate nonequilibrium phenomena in a bilayer electron system based on GaAs/AlGaAs heterostructures. The magnetic field ramping drives the bilayer electron system out of equilibrium, leading to magnetoresistance hysteresis and spikes. Unlike magnetoresistance, magnetocapacitance results intriguingly show hysteresis even when both layers are in the quantum Hall state. The hysteresis is accompanied by interlayer charge transfer, but the disequilibrium is not limited to interlayer imbalance. Results show that the edge-bulk imbalance can be the initial ground for the appearance of hysteresis. In addition, the nonequilibrium states are observed in which the total, rather than individual, layer densities determine the magnetic field and gate voltage dependencies.

DOI: 10.1103/PhysRevB.107.L041302

Bilayer electron systems representing parallel two-dimensional electron gases (2DEGs) formed in GaAs/AlGaAs heterostructures attract significant interest because they can be used as a versatile experimental platform to study the effects of interlayer coupling caused by both tunneling and Coulomb interactions. Many theoretical and experimental studies were focused on investigating their properties at high magnetic fields corresponding to low filling factors. Among the effects observed in this regime are Bose-Einstein exciton condensation [1], quantization of Coulomb drag resistance [2], and bilayer quantum Hall states observed at filling factors 1 and 1/2 [3,4].

In relatively uncoupled bilayer systems with a large interlayer separation (tens of nm), longitudinal and transverse (Hall) resistances can exhibit hysteresis and spikes as a function of magnetic field, when only one of the 2DEGs is in the quantum Hall effect (QHE) regime [5–9]. These observations are often interpreted as a manifestation of the breaking of interlayer equilibrium by a magnetic field sweep. Although wide (tens of μm) single-layer Hall bars are usually free from magnetoresistance hysteresis, it can appear in submicron-wide single-layer constrictions of a 2DEG [10,11]. This hysteresis can be explained by the absence of equilibrium between the edge and the bulk. Despite several reports of nonequilibrium phenomena in single- and bilayer systems, its origin remains mostly unclear and demands further investigation.

In both single- and bilayer systems, if the filling factors of all the 2DEGs involved are close to integer values, magnetoresistance hysteresis is usually not observed. However, in this state, magnetoresistance becomes a less reliable indicator of equilibrium or its absence, as longitudinal and Hall resistances are fixed at zero and at a quantized plateau, respectively, and insensitive to perturbations. Moreover, physical quantities, such as the electrochemical potential [12,13], electron density [14], and magnetization [15], may display a prominent hysteresis under these conditions in single 2DEGs, indicating that the system is driven out of equilibrium. Similarly, the velocity of surface acoustic waves has been shown to be hysteretic when both 2DEGs in a bilayer system are in the QHE regime [16]. These results show that alternative new experimental approaches, complementary to magnetoresistance measurements, are required to establish a possible interpretation of nonequilibrium phenomena in single- and bilayer systems.

In the present Letter, we use magnetoresistance and magnetocapacitance measurements [17] to study a bilayer electron system with a large (30 nm) interlayer separation. A combination of these two methods gives further insight about the system and the origin of nonequilibrium phenomena.

Experimental samples were fabricated from a heterostructure containing two parallel 2DEGs residing in 15-nm-thick GaAs layers separated by a 30-nm-thick $Al_{0.33}Ga_{0.67}As$ barrier to ensure the 2DEGs are uncoupled. The upper 2DEG is around 275 nm beneath the heterostructure surface. The samples have the shape of Hall bars with a length of 1.8 mm and width of 80 μm. Ohmic contacts were annealed in both 2DEGs, shortening them at the edges. The Hall bar is covered by a Ti/Au top gate having a length of 860 μm (see the inset in Fig. 1). The mobility of both the 2DEGs is approximately $1.2 \times 10^6$ $cm^2/V\,s$.

The samples were characterized using the four-terminal lock-in measurement of magnetoresistance at a frequency of 77 Hz and an amplitude of excitation current of 10 nA. The measurements were done at a base temperature of 23 mK in a cryofree dilution refrigerator equipped with an 8 T superconducting magnet, with a ramp rate set to 5 T/h.

Low-field Shubnikov–de Haas oscillations of longitudinal resistance $R_{xx}$ were used to calculate the densities of the top $n_t$ and bottom $n_b$ 2DEGs, as well as their dependence on the gate

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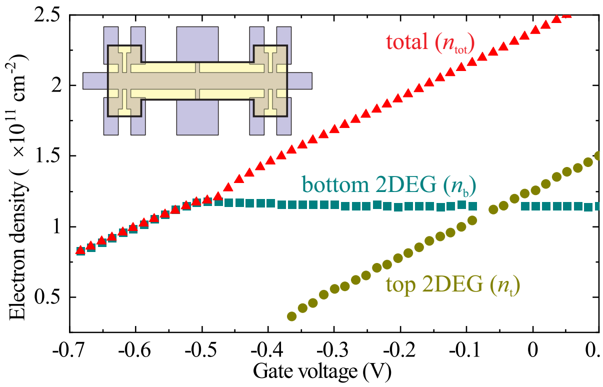


FIG. 1. The densities of top and bottom two-dimensional electron gases evaluated from Shubnikov–de Haas oscillations and the total electron density evaluated from the Hall resistance. Inset Layout of the Hall bar. The mesa (top gate) is shown in blue (yellow) color.

voltage $V_G$ (see Fig. 1). The total electron density $n_{tot}$ calculated from the Hall resistance $R_{xy}$ is also shown in Fig. 1. At a gate voltage $V_G > -0.4$ V, $n_t$ linearly decreases with decreasing $V_G$, while the bottom 2DEG is screened from the gate, and its density remains almost constant ($1.1 \times 10^{11}$ cm$^{-2}$) [18–20]. At $V_G < -0.5$ V, when the top 2DEG is depleted, the gate voltage starts influencing $n_b$.

Figures 2(a)–2(d) show the dependencies of $R_{xx}$ and $R_{xy}$ on increasing and decreasing magnetic field $B$ measured at several selected $V_G$ values. $R_{xx}$ and $R_{xy}$ curves display zeros and plateaus, respectively, both exhibiting integer and fractional QHE regimes. The grayscale plots in Figs. 2(e) and 2(f) show $R_{xx}(B, V_G)$ dependence for all the range of $V_G$ with two distinct superimposed patterns of bright stripes, corresponding to the transitions between quantum Hall states. The pattern corresponding to the top 2DEG is the fan originating from the $B = 0$, $V_G \approx -0.5$ V point. The pattern corresponding to the bottom 2DEG is a series of stripes vertical at $V_G > -0.5$ V and sloped below it, where the top 2DEG has been depleted.

Both $R_{xx}$ and $R_{xy}$ magnetoresistance curves in Figs. 2(b)–2(d) show hysteresis similar to that observed previously in bilayer electron systems [5–9]. This anticoercive hysteresis appears in the vicinity of integer filling factors of the top and bottom 2DEGs. The hysteresis is not seen in Fig. 2(a), where $n_b = n_t$, but it appears when electron densities of the 2DEGs are different. Similar to previous results [9], the observed hysteresis cannot be characterized with a single relaxation time [21]. The hysteretic behavior is reproducible in various cooldowns.

The hysteretic regions can also be seen in the grayscale plots in Figs. 2(e)–2(h). For example, when the magnetic field is swept forward [see Figs. 2(e) and 2(g)] and approaches $B \approx 4.6$ T ($\nu_b = 1$ line), the bright stripes lying at $V_G = -0.4 \ldots - 0.1$ V gradually bend up and follow the lines corresponding to constant total filling factor $\nu_{tot} = \nu_t + \nu_b$, rather than $\nu_t$. At a slightly higher magnetic field, this gradual bending ends up with an abrupt return of the bright stripes to lower $V_G$ values. When the magnetic field is swept backward [see Figs. 2(f) and 2(h)], the trend is opposite: The bright stripes gradually bend down when $B$ approaches 4.6 T from the right, and they abruptly return to higher $V_G$ values slightly to the left from the $\nu_b = 1$ line [22].

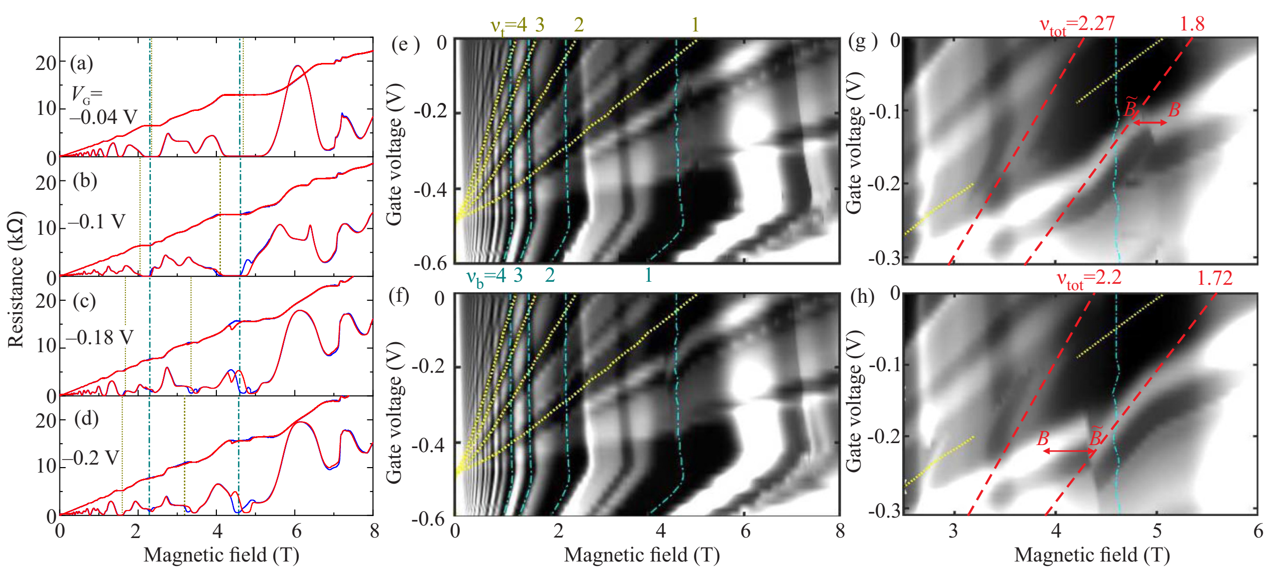


FIG. 2. (a)–(d) Longitudinal (bottom curves) and Hall (top curves) resistances measured as functions of perpendicular magnetic field at the gate voltages shown in the plots. Blue (red) curves represent the values measured at increasing (decreasing) magnetic fields. Vertical dotted-yellow (dashed-dotted cyan) lines show the magnetic fields corresponding to filling factors 1 (right) and 2 (left) of the top (bottom) layer. (e), (f) Grayscale plots showing the dependence of longitudinal resistance on magnetic field and gate voltage for increasing (e) and decreasing (f) magnetic fields. Yellow (cyan) lines show the states corresponding to integer filling factors (values for the top $\nu_t$ and bottom $\nu_t$ layers are shown near the plot). (g), (h) More detailed measurements in a reduced range of magnetic field and gate voltage. The ends of the red arrows show equilibrium ($B$) and nonequilibrium ($\tilde{B}$) states corresponding to the same filling factor of the top layer. The red dashed lines correspond to constant total filling factors $\nu_{tot} = \nu_t + \nu_b$.

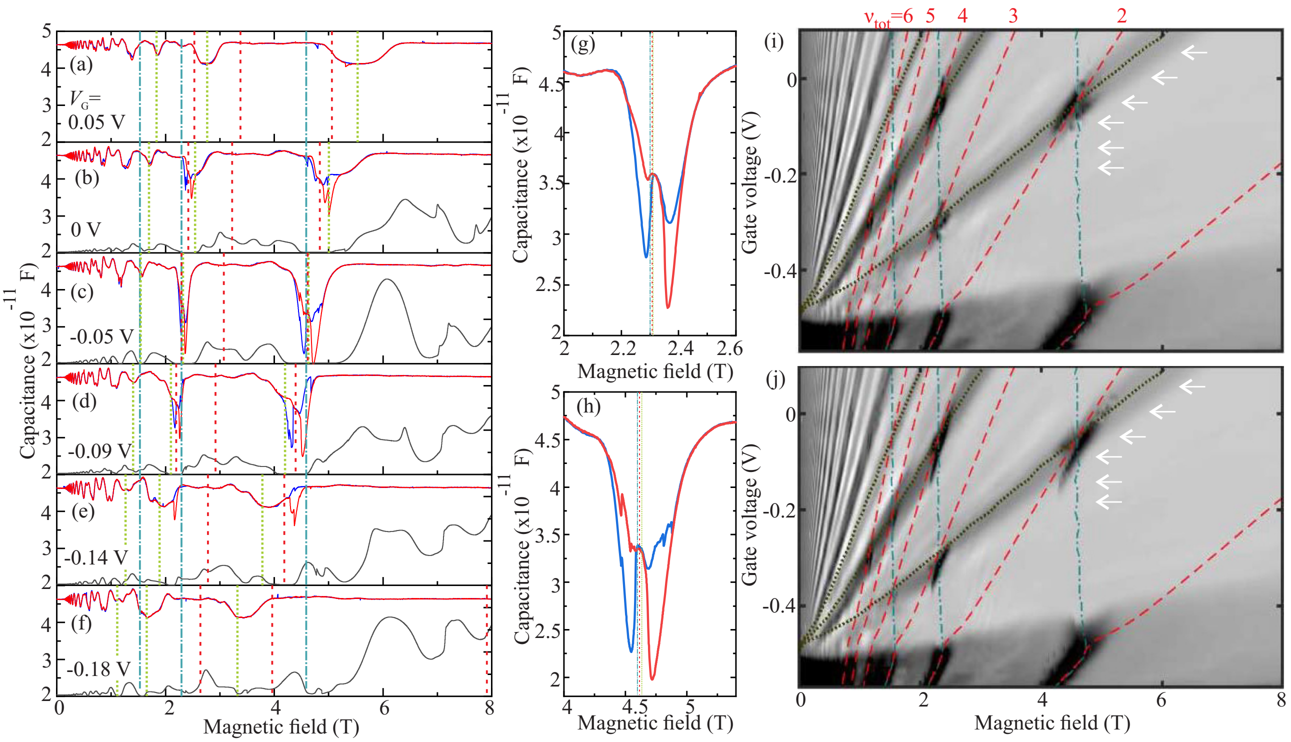


FIG. 3. (a)–(f) Capacitance between the gate and the bilayer system measured as a function of perpendicular magnetic field at the gate voltages shown in the plots. Blue (red) curves represent the values measured at increasing (decreasing) magnetic fields. Magnetocapacitance minima are observed at the same fields as in the magnetoresistance curves (for comparison, magnetoresistance curves in gray are shown for increasing magnetic field only). The dashed red vertical lines added to the plots denote the positions of integer total filling factors. (g), (h) Magnified views of magnetocapacitance minima observed in (c). (i), (j) Grayscale plots showing the dependence of magnetocapacitance on magnetic field and gate voltage for increasing (i) and decreasing (j) magnetic fields. The dark doubled regions corresponding to magnetocapacitance minima are oriented along the dashed red lines of integer total filling factors $\nu_{\rm tot}$ (values are shown near the top plot). The white arrows show the gate voltages at which the curves shown in (a)–(f) were measured.

The observed distortion of the bright stripes corresponding to a fixed filling factor $\nu_{\rm t}$ indicates that when the bottom 2DEG is in the quantum Hall state, the magnetic field sweep makes the density of the top 2DEG $\tilde{n}_{\rm t}$ different from its equilibrium value $n_{\rm t}$, with the signs of deviation $\tilde{n}_{\rm t} - n_{\rm t}$ being opposite for different magnetic field sweep directions. A maximal density deviation can be estimated from the magnetic fields corresponding to the same filling factor $\nu_{\rm t} = n_{\rm t}h/eB$ in equilibrium ($B$) and nonequilibrium ($\tilde{B}$) states [see Fig. 2(g) and 2(h)]. The nonequilibrium density can be estimated as $\tilde{n}_{\rm t} = n_{\rm t}\tilde{B}/B$. This estimate gives the density deviations $\tilde{n}_{\rm t} - n_{\rm t} = -6$ and $+8 \times 10^9$ cm$^{-2}$ for increasing and decreasing magnetic fields, respectively, while equilibrium $n_{\rm t}$ values are 1 and $0.65 \times 10^{11}$ cm$^{-2}$ at the considered $V_{\rm G}$ values $-0.11$ and $-0.22$ V. The observed change in $\tilde{n}_{\rm t}$ can be interpreted as direct experimental evidence of the previously proposed hypothesis associating the magnetoresistance hysteresis and spikes in bilayer electron systems with interlayer charge transfer [5,6,9]. In addition, the absence of hysteresis and spikes in the balance condition ($n_{\rm t} = n_{\rm b}$) aligns with the hypothesis. Thus, our results show that when the filling factor of one of the 2DEGs approaches an integer value, and another 2DEG is in a compressible state with nonzero $R_{\rm xx}$, the equilibrium of the system is broken. The fact that the features observed in Figs. 2(e)–2(h) follow the lines of constant total filling factor suggests that in the nonequilibrium state the system behaves as a single 2DEG with electron density $n_{\rm tot} = n_{\rm t} + n_{\rm b}$ and, in this case, the nonequilibrium state is collective. Does the system stay in an equilibrium state when both the 2DEGs are in the QHE regime? To investigate this, we performed magnetocapacitance measurements [17,23].

Magnetocapacitance curves $C(B)$ measured at selected gate voltages are shown in Figs. 3(a)–3(f), while the whole $C(B, V_{\rm G})$ dependence is represented as grayscale plots in Figs. 3(i) and 3(j). The latter plots do not display the pattern of vertical stripes originating from the bottom 2DEG, unlike the magnetoresistance data in Figs. 2(e) and 2(f). As the top 2DEG screens the bottom one from the gate, magnetocapacitance becomes sensitive to the state of the bottom 2DEG only if the top 2DEG is depleted ($V_{\rm G} < -0.5$ V), or if both 2DEGs are in the quantum Hall state [see the caption of Figs. 3(i) and 3(j)]. At $V_{\rm G} = 0.05$ and $-0.18$ V neither of these conditions is satisfied, and the corresponding magnetocapacitance curves [Figs. 3(a) and 3(f)] show relatively shallow and wide dips only in the vicinity of integer $\nu_{\rm t}$ marked by vertical yellow lines. In these dips, the bulk of the top 2DEG is in the insulating state, and the measured signal reflects the capacitance between the gate and the bottom, a more distant 2DEG.

The curves measured at other gate voltages [see Figs. 3(b)–3(e)] show deeper dips when both 2DEGs are in the QHE regime. Figures 3(g) and 3(h) show magnified views of Fig. 3(c). We note the following: (1) The dips have double-minima structures taking a peak in the middle. (2) The magnetocapacitance curves are hysteretic in both minima. The left minimum structure is more prominent with increasing $B$, and the right one is deeper at decreasing $B$. (3) At the peak between the minima, the hysteresis is generally absent. (4) The curves show hysteresis at $V_G = -0.05$ V, where $n_t \approx n_b$, unlike the case of magnetoresistance curves measured at similar balanced conditions [see Fig. 2(a)]. (5) The paired minima are centered with respect to the magnetic fields corresponding to integer total filling factors $\nu_{tot} = \nu_t + \nu_b$, marked with red dashed lines [Figs. 3(b)–3(d), 3(g), and 3(h)]. In the grayscale plots [Figs. 3(i) and 3(j)], the dips appear as paired black regions intersected by the lines of the integer $\nu_{tot}$ and oriented along them. This orientation is promising, as it shows that the system undergoes a transition into a collective bilayer state when both 2DEGs are in the QHE regime. As the features observed in both magnetoresistance and magnetocapacitance in the nonequilibrium states are oriented along constant $\nu_{tot}$ lines, they most likely have the same origin.

The results obtained cannot be explained by the previously proposed hypothesis [5,16] which assumes that (1) the hysteresis is caused by the delayed charging of the bulk of the 2DEG in the QHE regime and (2) the second 2DEG acts as an electron reservoir [24,25]. First, the observed hysteresis is anticoercive, and the system response does not lag behind, but outstrips the changing magnetic field. Second, an increasing (decreasing) magnetic field leads to a negative (positive) change in the density of the top 2DEG $\tilde{n}_t - n_t$. If electrons are provided by the bottom 2DEG, then $\tilde{n}_b - n_b$ should have the opposite signs, contrary to those predicted by the hypothesis. Third, at $n_t = n_b$, magnetocapacitance hysteresis is not expected under these assumptions.

To explain our results, we assume that (1) the model of an electron reservoir [24,25] is applicable, and (2) the initial origin of hysteresis is the disequilibrium between the edge and the bulk driven by a changing magnetic field when the 2DEG is in the quantum Hall state [13]. This imbalance, often associated with nonequilibrium currents [7], is known to lead to anticoercive magnetoresistance hysteresis. In the case of increasing (decreasing) magnetic field, it should result in the transfer of electrons from (to) the edge to (from) the bulk of the 2DEG in the QHE state. As the edges of the 2DEGs are shortened via the Ohmic contacts, the second, compressible 2DEG should decrease (increase) its density to compensate the nonequilibrium edge charge in the first 2DEG, in agreement with our results. Finally, disequilibrium between the edge and the bulk can be expected even when $n_t = n_b$.

The peaks in the middle of the magnetocapacitance dips were observed before [26,27] in single-layer 2DEGs, through which a dc current was passed. In our case, the nonequilibrium currents generated by the changing magnetic field and associated with the bulk-edge disequilibrium may be a possible reason for the appearance of the peaks. These currents are known [28] to be high enough to result in the breakdown of the QHE regime in the vicinity of integer filling factors, where the peaks are observed in our case. The breakdown occurs when the electric field associated with nonequilibrium currents reaches its critical value. When one of the 2DEGs is in the compressible state, it can partially screen the electrical fields in the second 2DEG, which is in the QHE regime. This may explain why the magnetocapacitance peaks are observed only when both the 2DEGs are in the QHE regime. However, the breakdown of the QHE regime is only one of the manifestations of the edge-bulk imbalance associated with nonequilibrium currents, and it does not explain all the observed effects.

Regarding the signatures of collective states observed at integer $\nu_{tot}$ in magnetocapacitance, we limit ourselves to a phenomenological comparison with similar effects reported before. First, in our case, these states are observed at high $\nu_{tot} = 2\dots6$, and can hardly be related to the exciton condensation reported for $\nu_{tot} = 1$ [1]. Previously, charge transfer between the layers was shown to lead to widening of the magnetocapacitance minima due to the retention of the chemical potential in the gap between the Landau levels [25]. However, our results are qualitatively different from that of widening. Collective states appearing in a wide, effectively bilayer, quantum well due to the interlayer charge transfer were observed using photoluminescence studies [29], however, only for the filling factors equal to integer multiples of 4. In our case, the collective phenomena are observed in the range $\nu_{tot} = 2\dots6$, and there are no dedicated multipliers. Paired conductivity features centered around integer filling factors of one of the layers were previously observed and interpreted as a signature of quasiparticle Wigner crystallization [30]. It is not clear at the moment whether the doubled magnetocapacitance dips observed in our case are related to Wigner crystallization.

In summary, nonequilibrium hysteretic phenomena arising at high magnetic fields in the quantum Hall effect regime are investigated in a bilayer electron system using magnetoresistance and magnetocapacitance measurements. Magnetoresistance measurements give a direct experimental evidence of interlayer charge transfer and the absence of equilibrium between the layers. Magnetocapacitance measurements, in addition, show that the system is driven out of equilibrium even when the layers are in a balance state. Experimental results show that the initial origin of disequilibrium in bilayer systems is the same as in the case of single-layer systems, namely, the charge transfer between the edge and the bulk associated with nonequilibrium currents generated by a changing magnetic field. Additionally, magnetocapacitance measurements show that at the integer total filling factor of the system as a whole, a distinct collective bilayer state is formed.

This work was funded by the United Kingdom Research and Innovation (UKRI) Future Leaders Fellowship (Ref. No. MR/S015728/1) and the Royal Society (IECR2202165, IECR1211166).

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[22] Similar hysteretic regions are also seen at different $(B, V_G)$ values in Figs. 2(e)–2(h), where only one of the 2DEGs is in the vicinity of the integer filling factors (see, for example, the regions at $B \approx 3.5$ T, $V_G \approx -0.15$ V and $B \approx 2.2$ T, $V_G \approx -0.4$ V), however, we will focus on the region described above, where the effects are most pronounced.

[23] In magnetocapacitance measurements, to determine the capacitance ($C = I_Y \delta V_G^{-1} \Omega^{-1}$) between the top gate and the bilayer electron system, we applied a sum of dc $V_G$ and ac $\delta V_G(t) = \delta V_G \cos \Omega t$ voltages to the gate, while measuring in-phase $I_x$ and quadrature $I_y$ components of the current flowing into one of the Ohmic contacts connected to the ground via a lock-in amplifier. The ac voltage had amplitude $\delta V_G = 10$ mV and frequency $\Omega/2\pi = 77$ Hz. The measured signal contains a parasitic component independent on $B$. Its value (≈13 pF) can be estimated from the expected geometrical capacitance 33 pF and the measured value 46 pF at $B = 0$. Our analysis, however, is based on the change in $C$ induced by magnetic field, rather than on its absolute value. The influence of finite two-terminal 2DEG resistance which is in series with the measured capacitance becomes noticeable at high (kHz) frequencies and at high magnetic fields, however, at the chosen frequency it is insignificant.

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