Exciton condensate at a total filling factor of one in Corbino two-dimensional electron bilayers

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Magnetotransport and drag measurements on a quasi-Corbino two-dimensional electron bilayer at a total filling factor of 1 (ν_T=1) reveal a drag voltage that is equal in magnitude to the drive voltage as soon as the two layers begin to form the expected ν_T=1 exciton condensate. The identity of both voltages remains present even at elevated temperatures of 0.25 K. The conductance of the drive layer vanishes only in the limit of strong coupling between the two layers and at $T \rightarrow 0$ K which suggests the presence of an excitonic circular current.

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When two closely spaced two-dimensional electron systems (electron bilayer) are exposed to a perpendicular magnetic field B so that each layer has a filling factor of close to $1/2$ and the relative distance between interlayer electrons, parametrized by the ratio d/l_B (d: layer separation; $l_B = \sqrt{\hbar/eB} = 1/\sqrt{2\pi n_T}$: magnetic length with n_T as the total density), is sufficiently small, a quantum Hall (QH) state characterized by the total filling factor of 1 (ν_T=1) can be observed. Both theoretically and experimentally, it is found that this state in bilayers occurs at a d/l_B ratio of less than ≈ 2.[1,2] In the limit of comparably small tunneling, its origin is dominated by Coulomb interactions, where the electrons in the two layers form a strongly correlated many-body state to minimize their exchange energy. In this state and in the low temperature limit, spontaneous interlayer phase coherence develops, driving all electrons in a quantum mechanical superposition of the layer eigenstates sharing the same macroscopic phase ϕ.[3,4] However, the predicted Kosterlitz-Thouless type of phase transition[12] has not yet been unequivocally demonstrated in experiment. After a particle-hole transformation that changes the sign of the interactions from repulsive to attractive, this state can be regarded as an excitonic condensate, where each electron is bound to a "vacant state" in the opposite layer. Interlayer drag experiments, where a constant current is passed through one of the layers ("drive layer") and the induced longitudinal and transverse voltage drop in the other layer ("drag layer") is measured,[2] have revealed a Hall drive and drag which approaches a quantized value of h/e^2 at ν_T=1 in a temperature-activated fashion. The quantization of the Hall drag is an indirect indication of a superfluid mode of excitons,[5] which can be viewed as either a uniform flow of interlayer excitons or as a counter flow of electrons in the opposite layers.

In standard Hall bars, the occurrence of the ordinary integer QH effect with the vanishing of the longitudinal resistance and the quantization of the Hall resistance can be explained in terms of one-dimensional (dissipationless) edge channels.[6,7] However, in the case of ν_T=1 and its associated superfluid transport mode, it cannot be ruled out from the Hall bar data that a dissipationless quasiparticle current at the sample edges is responsible for the observed effects.[8]

In this Brief Report, we present interlayer drag measurements on a *quasi*-Corbino electron bilayer with independent contacts to both layers. An *ideal* Corbino structure allows direct measurement of the conductivity σ_{xx} in contrast to the common Hall bar geometry where the resistivities are measured. We observe that at ν_T=1, a voltage develops in the drag layer that equals in sign and magnitude the voltage across the drive layer. We find that the identity of the drag and drive voltages is maintained up to high temperatures or large d/l_B where the single layer current flow shows nearly no trace of the ν_T=1 QH effect. Due to the absence of sample edges connecting source and drain contacts in a ring, the current is driven selectively through the bulk of the ν_T=1 system. At low temperatures, drive and drag voltages remain identical and the drive current nearly vanishes. The Corbino experiments thus open a venue to explore the bulk property of the ν_T=1 system.

Our two-dimensional electron bilayer is confined in two 19 nm GaAs quantum wells, separated by a 9.9 nm superlattice barrier composed of alternating layers of AlAs (1.70 nm) and GaAs (0.28 nm). Each quantum well has an intrinsic electron density of about 4.3×10^{14} m^{-2} and a low-temperature mobility of 67 (45) m^2/V s for the upper (lower) quantum well (measured on a Hall bar fabricated from the same wafer). Since the ideal Corbino geometry is not compatible with the selective-depletion technique[9,10] for independently contacting each layer, we instead employ a quasi-Corbino geometry with four contact arms attached to each ring, as depicted in Fig. 1. The back gates were patterned *ex situ* from a Si-doped GaAs epilayer before growing an insulating GaAs/AlGaAs superlattice and the bilayer on top. Electrical isolation between the two layers is achieved by applying appropriate negative voltages to the buried back gates and metallic front gates crossing the contact arms. One set of contacts can then be used to pass a current and another one to measure the voltage across the ring. The densities in each layer can be adjusted independently by using another set of front and back gates (not shown) covering the active region of the Corbino ring including the ring edges.

Below, we present data from two samples from the same wafer, which show essentially the same behavior. Sample A consists of a quasi-Corbino ring with an outer diameter of d_O=600 μm and a ring width of w=140 μm, while sample B is characterized by d_O=780 μm and w=230 μm. For all samples, interlayer tunneling is small; the interlayer resis-

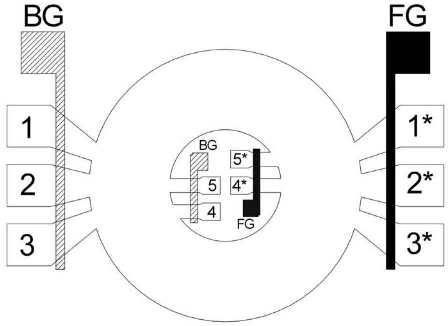

FIG. 1. Schematic view of the Corbino geometry used in this experiment. Application of appropriate voltages to the back gates (marked as "BG") and front gates ("FG") will lead to contact separation; i.e., contacts 1–5 will connect to the upper quantum well and 1^*–5^* to the lower one.

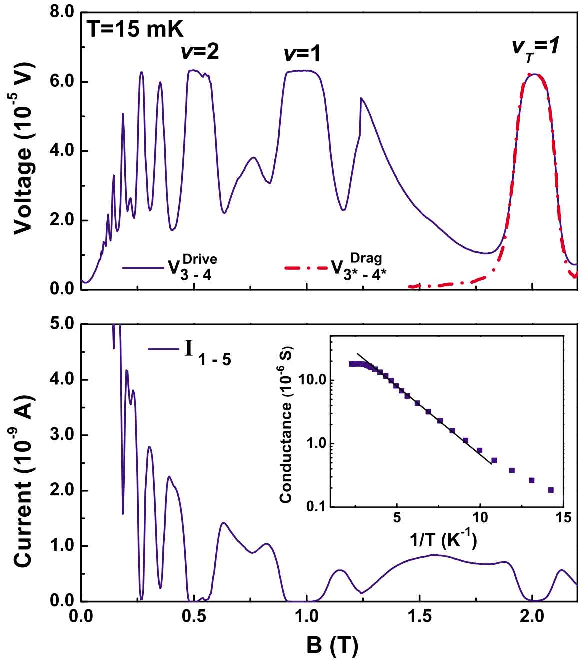

FIG. 2. (Color online) Top panel: measured drive (solid line) and drag (dash-dotted line) voltages at $T_{bath}=15$ mK on sample B. The (integer) filling factors $\nu \leq 2$ and $\nu_T=1$ $(d/l_B=1.62)$ are labeled. Bottom panel: measured current in the drive layer. The inset plots the temperature dependence of the radial conductance G; the line is a fit using $G \propto \exp(-E_{gap}/T)$.

tance (at zero magnetic field and 0.25 K) is of the order of (10^7-10^8) Ω. Transport measurements were performed by using a standard lock-in technique with the sample mounted at the cold finger of a dilution refrigerator or a ^{3}He system. For all measurements, the electron densities in the two layers were adjusted to be equal. A small excitation voltage V_{exc} [60–65 μV, 3–5 Hz (Ref. 19)] was applied radially across one layer (the drive layer) through an isolation transformer, and the induced current through this layer was measured with a small resistance connected in series. We would like to stress that the total current has a radial and an azimuthal part. These two parts oscillate anticyclically as a function of the magnetic field, i.e., in a QH state, the radial fraction is zero while the azimuthal (circular) part is maximal. Hence, the (radial) voltage dropping over the drive layer changes in response to the radial current as well. For that reason, the voltage across the drive layer was monitored using a separate pair of contacts in a quasi-four-terminal geometry together with the induced voltage in the drag layer. This excludes also the effects of the finite resistances of the Ohmic contacts and the contact arms. The measurements were reproducible upon interchanging contacts and upon interchanging drive and drag layers.

We start by showing data at lowest temperatures. Figure 2 presents data at $T_{bath}=15$ mK on sample B. The bottom and top panels plot the measured (radial) current in the drive layer and the corresponding drive and drag voltages as a function of the magnetic field. The electron densities in the two layers were adjusted to be equal, producing a total density of 4.8×10^{14} m^{-2}. Below 1.5 T, the current oscillates reflecting the varying filling factors and integer QH states. At a total filling factor of 1 which occurs here at about 2.0 T, we observe a strong minimum in the current like at the ordinary QH states at lower magnetic fields. As a result, the voltage drop over the drive layer almost equals the source voltage (top panel). Meanwhile, a large drag voltage develops over the region of the correlated $\nu_T=1$ phase, with the sign and magnitude identical to that of the drive layer. Since the radial component of the current in the drive layer is nearly zero, one possible explanation for the observed drag voltage is the existence of an azimuthal (i.e., circling) current in the drive layer, in analogy to the ordinary QH states. Owing to the excitonic coupling, it would trigger an azimuthal current of the same magnitude in the drag layer, leading to identical voltages across both layers. However, we neither know the nature of this excitonic current nor where it flows. It could be homogeneously distributed throughout the bulk or rather concentrated at the sample edges. Nevertheless, the well-established model of electron-hole pairing around $\nu_T=1$ implies that such a transport mode in Corbino bilayers might be possible. Supported is that notion by the fact that the Ohmic contacts of the drag layer in our geometry are located at the opposite side of the ring, i.e., approximately 1 mm away from the Ohmic contacts of the drive layer. In previous drag experiments using a standard Hall bar geometry, identical Hall voltages in the drag and drive layers were also considered to be signaling the underlying excitonic superfluidity.

The origin of identical voltages could equivalently be attributed to the special nature of the excitonic state. Since an excitonic wave function would have to exist across the barrier, quasiparticle transfer between the layers would become possible as soon as the system reaches a total filling factor of 1. While standard tunneling spectroscopy experiments[1] performed on very similar electron bilayer samples indeed indicate that tunneling becomes resonantly enhanced in the vicinity of $\nu_T=1$, identical voltages could only be explained if the interlayer resistance became insignificantly small compared to the bulk resistance. This, however, is inconsistent with tunneling experiments[1,13,14] on common electron bilayer

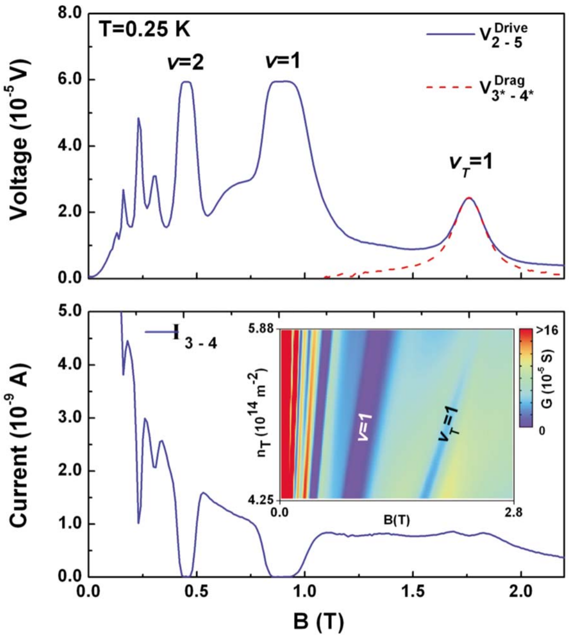

FIG. 3. (Color online) Top panel: drive (solid line) and drag (dash-dotted line) voltages versus the magnetic field at T=0.25 K measured on sample A. Bottom panel: the current in the drive layer measured simultaneously. The inset illustrates the conductance G of the drive layer as a function of the magnetic field and the total density. Clearly visible is how the conductance at ν_T=1 decreases as the total density n_T is reduced.

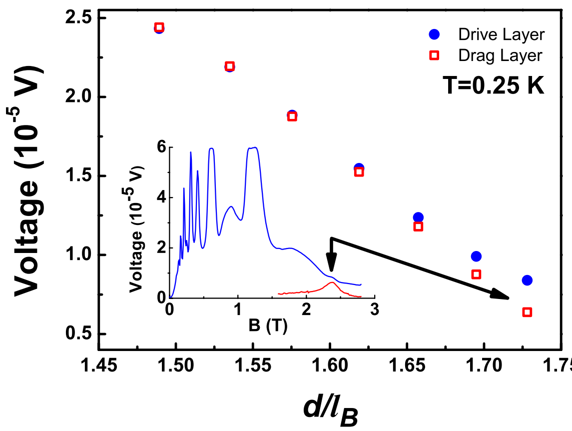

FIG. 4. (Color online) Drive (solid dots) and drag (open dots) voltages at ν_T=1 versus the parameter d/l_B at T_{bath}=0.25 K. Above d/l_B=1.65, the amplitudes of drive and drag voltage at total filling factor 1 diverge. The inset shows the corresponding field sweep for the last pair of points at d/l_B=1.73.

samples, showing resistances within the MΩ range instead.

Figure 3 plots data taken at a temperature of T=0.25 K on sample A. The densities in both layers are still equal but reduced to a total electron density of approximately 4.2×10^{14} m^{-2}. Now, ν_T=1 occurs at B=1.76 T which corresponds to d/l_B=1.49. At 0.25 K, the minimum in the current has almost entirely disappeared (bottom panel). Nonetheless, there is still a sizable peak in the drive voltage at ν_T=1 (solid line in the top panel). Surprisingly, the voltage over the drag layer (dash-dotted line) also displays a peak *with the same amplitude*. This striking observation of a nearly doubled dissipation in the drive layer accompanied by an identical drag voltage can be interpreted as evidence that both layers are in a state of commencing interlayer correlation. A previous report on drag experiments on Hall bar bilayers[2] has shown that identical voltages, i.e., the quantization of the Hall resistance to h/e^2, are only observable at lowest temperatures and low d/l_B ratios when the ν_T=1 QH state is fully developed. While this is in direct contrast to our data and might indicate a geometry dependence, the resilience of the ν_T=1 QH state to increasing temperatures yet is a behavior reminiscent of results obtained on bilayer two-dimensional *hole* gas samples[11] in counterflow configuration. We cannot offer any explanation for these similarities; however, it might simply be owing to the reported interlayer leakage or the larger effective mass of the holes.

We find that the ratio of both voltages remains 1 until d/l_B approaches a critical limit. We have traced the drag and drive voltages for a number of different (but matched) total densities at 0.25 K. The results are summarized in Fig. 4 which plots drag and drive voltages at ν_T=1 versus d/l_B. At 0.25 K, the identity of both drag and drive voltages can be tracked up to a d/l_B ratio of about 1.65 where the ν_T=1 QH state is collapsing owing to thermal fluctuations. For $d/l_B>1.65$, small peaks of different amplitudes can be observed as illustrated in the inset.

At some finite temperature, the collapse of the excitonic condensate at ν_T=1 in the bilayer can be observed. For sample B and temperatures below 0.25 K, the conductance $G=I/V$ is well described by thermal activation, i.e., $G\propto\exp(-E_{gap}/T)$, with an activation energy gap of approximately 0.5 K, as shown in the inset of Fig. 2. The magnitude of the extracted energy gap is in good agreement with earlier reports on comparable double quantum well structures,[2,15–17] where the activation energy was extracted from measurements of the temperature dependence of the longitudinal resistance in Hall bars.

In a theoretical letter, Stern and Halperin[18] suggested that the electron bilayer system at high d/l_B ratios is composed of puddles of strong interlayer correlation incorporated in the compressible fluids of the individual layers. Their model, albeit addressing specifically Hall bar geometries, appears to be connected with our observations as well. As long as these puddles are small in number and/or unrelated, a sizable current could flow through the bulk between source and drain contacts. As d/l_B is decreased, their number and/or size will increase until they eventually percolate, while the current through the bulk slowly diminishes. The smooth transition we observe in Corbino samples from a compressible to a nearly fully incompressible state upon decreasing the temperature and/or the parameter d/l_B appears to signify such a percolation.

In conclusion, we have conducted interlayer drag experiments on quasi-Corbino electron bilayers. At the lowest temperature and strong coupling, the ratio of drag and drive voltages is 1, while the conductance in the drive layer vanishes. These data imply a circular potential distribution along the sample edges owing to a circling (azimuthal) excitonic current in both layers. At elevated temperatures, the identity of both voltages is still present.

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