Critical tunnel currents and dissipation of Quantum-Hall bilayers in the excitonic condensate state

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Abstract.
Transport and tunneling is studied in the regime of the excitonic condensate at total filling factor one using the counterflow geometry. At small currents the coupling between the layers is large making the two layers virtually electrically inseparable. Above a critical current the tunneling becomes negligible. An onset of dissipation in the longitudinal transport is observed in the same current range.

1. Introduction
Two-layer quantum-Hall systems in which the lowest Landau level in each layer is approximately half-filled may form a superfluid state. This can be visualized by considering the filled and unfilled electron states in the Landau levels of the two layers as excitons which condense into a coherent ground state \([1, 2, 3]\). The first experimental evidence of an unusual state at the total (combined) filling factor one had already been reported early on as a distinct minimum in the longitudinal and a plateau in the Hall resistance \([4]\). This was later verified by several other groups. In counterflow experiments where equal but oppositely directed currents were passed through the two layers, a nearly complete vanishing of both Hall and longitudinal resistance was observed \([5, 6, 7]\). The coherence of the condensed excitons is thought to be responsible for the enhanced tunnel conductance at zero bias \([8, 9, 10]\) and the Josephson-like tunneling with a large critical current which became observable in samples with sufficiently large tunneling probability and area \([11, 12]\).

Theoretically this state has been described by theories resembling the BCS theory of superconductors with the Cooper pairs being replaced by the excitons. Condensation takes place at sufficient low temperatures if the magnetic length \(l_B = \sqrt{h/eB}\) becomes comparable to the layer separation \(d\). The existence of an energy gap of the condensed state manifests itself by the observation of the phenomena of the Quantum-Hall effect at the total filling factor one.

In this contribution we report on the critical tunnel current in the counterflow geometry \([13]\) and discuss its relation to the onset of dissipation in the in-plane transport.
Figure 1. (a) A schematic of the measurement set-up. Current is first injected into the top layer and then redirected via a loop resistor into the bottom layer and then guided into ground. At \( d/l_B = 1.37 \) (b and c) and \( d/l_B = 1.68 \) (d and e) \( I_{\text{Tunnel}} \) & \( I_{\text{Loop}} \) and \( V_{xx} \) are plotted versus \( I_{\text{Total}} \).

2. Experimental details

The double quantum well system used in this study have been grown by molecular beam epitaxy. Two 19 nm GaAs wells are separated by a 9.6 nm superlattice barrier layer consisting of alternating layers of AlAs (1.7 nm) and GaAs (0.28 nm). The quantum wells are populated by Si-doped sheets placed 300 nm below and 280 nm above the wells, yielding intrinsic densities of approximately \( 4.0 \times 10^{10} \, \text{cm}^{-2} \) in the upper and \( 4.6 \times 10^{10} \, \text{cm}^{-2} \) in the lower quantum well. Mobilities at these densities are \( 4.3 \times 10^5 \, \text{cm}^2\text{V}^{-1}\text{s}^{-1} \) and \( 4.1 \times 10^5 \, \text{cm}^2\text{V}^{-1}\text{s}^{-1} \), respectively. A Hall bar device with a length of 880 \( \mu \text{m} \) and a width of 80 \( \mu \text{m} \) is prepared by optical lithography. Independent electrical contacts to the two layers are achieved by applying appropriate negative voltages to the pre-patterned buried back gates and the metallic front gates crossing the contact arms (selective depletion technique [14, 15]). With the intrinsic densities, the interlayer resistance at zero magnetic field and 4.2 K is around 380 k\( \Omega \). The densities in the two layers can be adjusted independently by additional front and back gates and are balanced in all data shown. The ratio \( (d/l_B) \) of the layer separation \( (d = 28.6 \, \text{nm}) \) to the magnetic length \( l_B \) is set to values between 1.37 and 1.68. All data were taken in a dilution refrigerator at a bath temperature of 20 - 30 mK.

Counterflow experiments are performed by passing two oppositely directed currents through the two layers as shown in Fig. 1(a) similar as in previous experiments [5, 6, 7]. We use a dc input current \( I \) which is generated by applying a voltage to a large resistor (100 M\( \Omega \), not shown) in series to the bilayer system. The current passes first through the top layer, is redirected via
a loop resistor (10 kΩ) into the bottom layer in the opposite direction, and finally guided via another resistor (10 kΩ) into ground. The total $I_{\text{Total}}$ and the loop $I_{\text{Loop}}$ currents follow from the voltage drops across the 10 kΩ resistors. The interlayer tunneling current $I_{\text{Tunnel}}$ is the difference $I_{\text{Total}} - I_{\text{Loop}}$.

3. Results

In Fig. 1(b) we plot $I_{\text{Tunnel}}$ and $I_{\text{Loop}}$ as function of the total (dc) input current for a $d/l_B=1.37$ at $\nu_T=1$. Strikingly, at small total currents, we find that $I_{\text{Loop}}$ is nearly zero. This is equivalent to almost all current tunneling before reaching the end of the Hall bar. With increasing total current, a critical current value $I_C=1.5$ nA is reached, where $I_{\text{Tunnel}}$ suddenly becomes negligible and nearly all current flows through the loop resistor. At the same current the longitudinal voltage ($V_{xx}$) measured along one of the layers jumps from almost zero to a finite value and continues to increase rapidly with increasing $I_{\text{Total}}$ (Fig. 1(c)). Below $I_C$ the interpretation of the $V_{xx}$ data is difficult because the current might tunnel before passing both voltage probes. At larger $d/l_B$ values, Fig. 1(d) and (e), the transition at the critical current is less sharp but the general behavior is similar.

![Figure 2. Longitudinal resistance of the sample of Fig. 1 at different ac-current amplitudes.](image_url)

We estimate from the increase of the loop current at $I_C$ that the effective interlayer resistance must be less than 300 Ω below $I_C$. The values of both $I_C$ and the interlayer resistance are comparable to the ones reported in Ref.[11].

Naively, one would expect that reaching the maximum current for dissipationless tunneling signals the collapse of the condensed exciton state. This is, however, not the case as becomes obvious from data like the ones presented in Fig. 2 which shows several traces of $R_{xx}$ vs the magnetic field $B$ in the same counterflow geometry as shown in Fig. 1. For this set of data ac-current is used. The respective peak values of the sinusoidal excitation currents are given in the figure. The value of $d/l_B$ was set to $=1.37$ where $I_C=1.5$ nA. Each trace corresponds to a $B$-sweep with a different $I_{\text{peak}}$ value. It is striking that upon increasing $I_{\text{peak}}$ above $I_C$ the formerly deep and nearly complete minimum in $R_{xx}$ weakens but does not disappear. Furthermore, although not shown here, $R_{xy}$ remains small and nearly constant (at around 2 kΩ) as observed in the earlier counterflow experiments. This result corresponds also to earlier results [5, 6, 7] where clear signatures of the $\nu_T=1$ were found in counterflow experiments while the observed tunneling conductance was much less than reported here.

In another, more recent experiment with a different sample we studied the current dependence of the longitudinal transport. This sample was grown with a thinner (7.6 nm) tunneling barrier.
between the two layers. The density was adjusted for $d/l_B = 1.65$ at a magnetic field of 2.6 T. The longitudinal resistance was monitored as function of the ac current amplitude. Results are shown in Fig. 3. For the black curve with square markers the two layers were electrically separated by the gating technique. The red trace was obtained with the gates being turned off and the current being fed into both layers simultaneously. Strikingly, both traces are very similar. At small currents, the $R_{xx}$ values are small and independent from current. Exceeding about 20 nA, both traces show a sharp upturn indicating a rapid increase in dissipation. The identity of the two traces is another sign that at small currents the two layers are virtually indistinguishable. The $R_{xx}$ values at the largest currents in the figure are still small compared with those at other (unquantized) filling factors. The critical tunnel currents have not yet been measured with this sample and a comparison with the critical current for the onset of dissipation seen in Fig. 3 is not yet possible. It is nevertheless intriguing to speculate that its value would be similar to that observed in longitudinal transport. The identity of the critical current for longitudinal transport and tunneling has actually been predicted theoretically [16] but has not yet been verified experimentally.

4. Conclusions
In conclusion, our findings show that exceeding the critical tunnel current does not cause the breakdown of the $\nu_T=1$ quantum Hall state. It marks, however, the beginning of an increasing dissipation along the current-carrying layers. Recent theoretical suggestions attribute the dissipation in these exciton condensates to the unbinding and the current-induced motion of vortices connected to charged quasiparticles (merons) [17, 18, 19, 20] or to vortices parallel to the layers which move dissipatively if there is a bias voltage difference [21]. Below the critical current the bilayer system is indistinguishable from a single layer system.

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