Critical tunneling currents in the regime of bilayer excitons

L Tiemann¹, W Dietsche, M Hauser and K von Klitzing
Max-Planck-Institut für Festkörperforschung, Heisenbergstraße 1, 70569 Stuttgart, Germany
E-mail: L.Tiemann@fkf.mpg.de

New Journal of Physics 10 (2008) 045018 (10pp)
Received 25 January 2008
Published 30 April 2008
Online at http://www.njp.org/
doi:10.1088/1367-2630/10/4/045018

Abstract. We have investigated the tunneling properties of an electron double quantum well system where the lowest Landau level of each quantum well is half filled. This system is expected to be a Bose condensate of excitons. Our four-terminal dc measurements reveal a nearly vanishing interlayer voltage and the existence of critical tunneling currents $I_{\text{critical}}$ which depend on the strength of the condensate state.

Contents

1. Introduction ........................................ 2
2. Samples ......................................... 2
3. Tunneling set-up ................................... 3
4. Experimental data .................................. 3
   4.1. Ac modulation of a dc interlayer bias ....... 3
   4.2. Pure dc interlayer tunneling ................. 3
   4.3. Parallel tunneling: ‘The load configuration’ 8
5. Summary and conclusion ......................... 9
Acknowledgments .................................... 9
References .......................................... 9

¹ Author to whom any correspondence should be addressed.
1. Introduction

Macroscopic quantum systems such as superconductors and superfluids are the remarkable consequences of many of bosonic particles occupying the same lowest energy state, and thus forming a Bose–Einstein condensate (BEC). The design of closely spaced two-dimensional electron systems (2DES) which can be contacted independently is the foundation to create a BEC of excitons in semiconductors \[1, 2\]. Exposed to a strong perpendicular magnetic field \(B\), the density of states of each of the 2DES will condense into a discrete set of sub-bands, the Landau levels. The total number of occupied states is then parameterized by the filling factor \(\nu = \frac{hn}{eB}\). If the electron densities \(n\) are tuned to be identical in both layers, the filling factors will simultaneously be at 1/2 at a particular \(B\). Governed by Coulomb interactions, the bilayer system can then be viewed as a Bose condensate of interlayer quasi-excitons by coupling an electron from layer 1 to a vacant state from layer 2 and vice versa. Since these excitons have an infinite lifetime, their properties can be investigated via electrical transport experiments.

Transport experiments in the counter-flow configuration \[3, 4\], where constant currents of equal magnitude but opposite direction are imposed on the two layers have indeed shown that exclusively if \(\nu_{\text{layer 1}} + \nu_{\text{layer 2}} \approx 1\) (denoted as ‘total filling factor 1’, or simply ‘\(\nu_{\text{tot}} = 1\’) , the Hall and longitudinal voltages across both layers (nearly) vanish. While this by itself can be interpreted as the result of a dissipationless flow of charge–neutral electron–hole pairs in one direction, interlayer tunneling experiments \[5\]–\[8\] have shown an \(I/V\) characteristic that has an astonishing resemblance to one of the Josephson effects. However, the bilayer at \(\nu_{\text{tot}} = 1\) is only partially analogous to a Josephson junction \[9\], and it is important to recognize the experiment as tunneling between two electron systems that only as a whole \[10\] form the correlated state. This fact might also explain why no true dc supercurrent at zero bias has been observed so far. Suitable bilayer samples are required for weak tunneling \[8\], however, they only possess a very small single electron tunnel splitting \(\Delta_{S,AS}\) of up to approximately 100 \(\mu\)K. Even though interlayer phase coherence is completely spontaneous only for \(\Delta_{S,AS} \to 0\), it has been demonstrated \[11\] that single electron tunneling can co-exist with this correlated state which is still dominated by Coulomb interactions.

Our interlayer tunneling experiments indicate that the Bose condensation strongly changes the nature of the tunneling process. More specifically, we exploit a pure dc tunneling configuration which reveals the existence of critical tunneling currents \(I_{\text{critical}}\). These critical currents terminate the regime of interlayer phase coherence, i.e. when the total current \(I\) exceeds the threshold value of \(I_{\text{critical}}\), the four-terminal interlayer resistance abruptly increases by many orders of magnitude.

2. Samples

Our data originate from three different samples from the same wafer. The double quantum well structure consists of 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). The quantum wells have an intrinsic electron density of about \(4.5 \times 10^{14} \text{m}^{-2}\) and a low-temperature mobility which exceeds 40 \(\text{m}^2\ (\text{V s})^{-1}\). While sample A is a standard Hall bar geometry with a length of 880 \(\mu\)m and a width of 80 \(\mu\)m, samples B and C are patterned into a quasi-Corbino ring \[12\], both with an outer diameter of 860 \(\mu\)m and a ring width of 270 \(\mu\)m. A commonly used selective depletion technique \[13, 14\] was used to provide separate contacts to the layers. The densities
in the two layers are balanced with a front and back gate which cover the entire region of the structures including the edges.

3. Tunneling set-up

The modulation of a tunable dc bias $V_{dc}$ with a low amplitude ac sine wave $V_{ac}$ which is applied between the two layers (i.e. the interlayer bias) is a convenient and commonly used method to determine the differential conductance $dI_{ac}/dV_{ac}$. While a $V_{dc} \neq 0$ counter-shifts the Fermi energies of both systems, $V_{ac}$ is used to induce an ac (tunneling) current which can be detected via a sensitive lock-in technique. In the zero magnetic field case, if both layers have identical densities and $V_{dc} \approx 0$, the Fermi energies of both layers align, and owing to momentum and energy conservation, electron tunneling becomes possible. Under the application of a magnetic field, however, it generally requires a finite energy $eV_{dc}$ to add/extract an electron to/from one of the correlated 2DES [15]. This means that no peak in $dI/dV$ centered around $V_{dc} = 0$ is expected under application of a (strong) perpendicular magnetic field.

4. Experimental data

4.1. Ac modulation of a dc interlayer bias

Figure 1 shows the results of the common tunneling experiment as previously described. The tunable dc bias was modulated with a small ($\approx 7 \mu V$) ac voltage. The current was detected by measuring the voltage drop across a 10 kΩ resistor connected towards common ground. These measurements were performed on sample A (Hall bar) at $T_{bath} \approx 25$ mK and $n_{tot} = 1$ with balanced carrier densities in the two layers leading to three different $d/l_B = \{1.85, 1.78, 1.71\}$. This ratio of the center-to-center distance $d$ between the layers (here 28.9 nm) and the magnetic length $l_B = \sqrt{\hbar/eB}$ characterizes the strength of the $n_{tot} = 1$ state due to Coulomb interactions.

For figure 1, we use the common notation where we plot the 2-point (2pt) differential conductance $dI/dV$ versus the 2pt voltage $V_{dc}$, i.e. the curve illustrates the measured $dI_{ac}$ induced by the ac modulation of 7 \mu V versus the variable dc interlayer bias. The peaks centering $V_{dc} = 0$ can be identified as the familiar enhanced tunneling anomaly [8] of the $n_{tot} = 1$ state. From high to low values of $d/l_B$, the full width at half maximum (FWHM) in these three cases is about 60, 160 and 200 \mu V. While an increase of the tunneling amplitude upon decreasing $d/l_B$ was to be expected based on earlier reports, it is yet remarkable that its FWHM appears to increase as well. As we will show next, the answer to this apparent inconsistency is hidden in the modality of a two-terminal tunneling experiment where the interlayer resistance becomes much smaller than other series resistances.

4.2. Pure dc interlayer tunneling

Using a sufficiently sensitive dc measurement set-up, the tunneling experiment can be simplified by measuring the dc current directly. In addition, with a separate pair of contacts, a 4-point (4pt) set-up is possible to probe the dc voltage that drops across the barrier as well. Figure 2 illustrates these 4pt measurements, performed again on sample A at $n_{tot} = 1$ for a single $d/l_B$ of 1.44. The current was again detected by measuring the voltage drop across a resistor connected towards the common ground. The left panel thus illustrates this dc current as a function of the 2pt dc
Figure 1. Differential tunnel conductance for $d/l_B = 1.85$ (dotted line), 1.78 (dashed line) and 1.71 (solid line). In addition to its amplitude, the width also increases with decreasing $d/l_B$. These data were produced on sample A at $T_{\text{bath}} \approx 25$ mK.

Voltage. Consistent with the prior observation of an enhanced tunneling conductance at small bias voltages, the dc current displays a relatively steep slope around $V_{dc} = 0$ which abruptly terminates when the current exceeds values of approximately $-1.5$ or $+1.25$ nA.\textsuperscript{2} The existence of such a critical current had already been predicted [9, 10] but had not been clearly demonstrated. Most strikingly, the 4pt measurements on the right panel reveal a plateau in the probed dc voltage close to zero which accompanies the region where the current flow is enhanced.

We emphasize that the unexpected increase in width of the differential tunneling conductance curves in figure 1 is now explainable in terms of a strongly reduced 4pt dc voltage. In view of this reduction, which affects the 4pt ac modulation as well, the $dI/dV$ curves would rescale to a very narrow peak with a very high amplitude if plotted versus $V^{4pt}$ and with $dV = V^{4pt}_{ac}$. Please note that at no other (total) filling factor is such a behavior observable, i.e., the strong reduction of the 4pt interlayer voltages is a peculiarity of the $\nu_{\text{tot}} = 1$ state.

We associate the range in which $V^{4pt}$ is small with a state in which interlayer coherence is established. Its width apparently depends on the sum of all series resistances $R_s$ in the system, such as contact arms and the series resistance for the current measurement. If $R_s$ is large compared to the 4pt interlayer resistance, the experiment is essentially performed by controlling the current so that the existence of critical currents can be resolved. In a voltage-controlled experiment on the other hand, critical currents are concealed in the limit of vanishing (interlayer) resistances.

Figure 3 demonstrates how the tunneling process evolves upon reducing the ratio $d/l_B$ from high to low values, i.e. upon reducing the electron densities in both layers simultaneously and adjusting the magnetic field. These data were produced on sample B (Corbino geometry) where

\textsuperscript{2} The very sharp jump of the current and voltage at about 400 $\mu$V in figure 2 cannot be directly compared to the results in figure 1 which are measured at a different value of $d/l_B$. In addition, we observed a hysteretic behavior which may lead to a smearing of the curves in ac modulated measurement.
Figure 2. Left panel: measured current plotted versus the 2pt interlayer bias $V$. Clearly visible are critical currents below which the characteristic has a steeper slope. Right panel: 4pt voltage $V^{4pt}$ which was measured simultaneously versus $V$. A plateau exists around zero bias where the 4pt voltages are nearly zero. The plateau terminates at exactly the same 2pt voltages where the critical currents occur. The inset shows a schematics of the experiment with the source (S) and drain (D) contacts and the location of the voltage probes $V_{A,B}$. Shaded contacts connect to the lower layer. These data were produced on sample A at a $d/l_B$ of 1.44 and $T_{\text{bath}} \approx 25$ mK.

the voltage $V$ was applied between the two outer circumferences of the upper and lower layer. Moving from high to low values of $d/l_B$, plateaus in the 4pt voltage appear which progressively take on lower values. At the same time the critical currents grow. The resulting 4pt interlayer resistance has, at the lowest $d/l_B$, a value of only about 200 $\Omega$ at $T_{\text{bath}} \approx 25$ mK. Once the critical current is exceeded, the 4pt interlayer resistance is nearly of the same magnitude for all $d/l_B$, which suggests that the condensate is destroyed and the current is maintained by bare electron tunneling. The observed asymmetry which is particularly pronounced in sample B for low $d/l_B$ is due to a strong hysteresis.

The question of the lowest obtainable 4pt resistance and/or its accuracy is directly related to the question of which factors influence the 4pt voltage. In addition to a temperature-activated behavior, it is relevant where exactly the potential is probed (see insets in figures 2 and 4) because residual resistances come into play. More precisely, \textit{any} current $I$ that crosses the boundary of a 2DES under quantum Hall (QH) conditions will produce a voltage difference across the contact of the order of the Hall voltage $h/e^2 \cdot I (\approx 25 \, \mu V \, \text{at} \, I = 10^{-9} \, \text{A})$. Since the sign of the Hall voltage depends on the sign of the magnetic field $B$, it should be possible to account for its influence by inverting the magnetic field. And indeed, depending on the choice of contacts to probe the voltage, the inversion from $+B$ to $-B$ also inverted the slope of $V^{4pt}$ around $V = 0$. The mean value calculated from the curves at $+B$ and $-B$, however, did not completely cancel out $V^{4pt}$ within the plateau region. This might be caused by longitudinal resistance components, if the current flows through dissipative regions [16]. Nevertheless, as we have shown, this (residual) voltage and the resulting 4pt interlayer resistance was a lot smaller for sample B (Corbino). For this sample, the voltage was probed in a 'longitudinal' configuration, i.e. the voltage was probed (across the barrier) at contacts that lie between the source and drain, and at the same side of the current flow.

New Journal of Physics 10 (2008) 045018 (http://www.njp.org/)
Figure 3. The top panel plots the measured tunneling current versus the 2pt interlayer bias $V$ for a set of six different $d/l_B = \{1.99, 1.92, 1.85, 1.78, 1.70$ and 1.44\}. The middle panel shows the probed 4pt voltage $V_{4pt}$ which was not measured simultaneously, and the bottom panel illustrates the calculated 4pt interlayer resistance. The enhanced noise around $V = 0$ originates from the noise in detecting small voltages.
Figure 4. The current plotted versus the measured 4pt voltage $V^{4pt}$ for $d/l_B = 1.44$ (sample B). Only red dots are actual data points, the black dashed lines are used to guide the eye. The inset shows a simplified schematic of the experiment where the contacts to probe the voltage and the source and drain contacts are marked. Shaded contacts connect to the lower layer. Unused Ohmic contacts are disregarded.

Figure 4 finally shows the current plotted versus the 4pt voltage for $d/l_B = 1.44$. In this representation our data resemble earlier reports [7] where, however, the maximal current was of the order of 20 pA, or about 1000 times smaller. Note that in [7] the $I/V$ characteristic was deduced from integrating the differential tunneling conductance data which may have masked the critical current behavior reported here. Even though the sample characteristics differ only marginally (QW/barrier/QW width in [7] is 18/9.9/18 nm) which yields a comparable value of $\Delta_{S,AS}$, the effective single particle tunneling amplitude in our samples appears to be larger. Hence, we assume that the different magnitudes of the maximal currents can be attributed to a different bare interlayer tunneling which strongly influences the tunneling anomaly at $\nu_{tot} = 1$ [9].

For reasons of completeness, we would like to elaborate on an experimental detail. Generally, the application of an interlayer bias will imbalance the electron densities of both layers, while the total density $n_{tot} = n_{layer\ 1} + n_{layer\ 2}$ remains constant. This has the consequence that the regular QH states will shift to lower/higher fields, owing to a higher/lower density in the respective single layer. The $\nu_{tot} = 1$ QH state on the other hand depends only on $n_{tot}$ and thus does not shift to a different magnetic field. Using the Shubnikov–De Haas oscillations in transport experiments in the low field regime, we were able to adjust front and back gate voltages while sweeping the interlayer bias to keep the density in each of the two layers constant. However, interlayer tunneling experiments did not significantly differ from unadjusted measurements. The bias-induced tunneling for the electron bilayer system in question is $\approx 4\%$
4.3. Parallel tunneling: ‘The load configuration’

In a different experiment, sample C (Corbino ring) was set-up in a drag experiment as described in [11], where a voltage is applied across only one layer (drive layer), while the other (drag) layer is kept as an open circuit. Only at a total filling factor of one has this been shown to produce a voltage drop of equal sign and magnitude across the adjacent drag layer. At the same time, the conductance through the drive layer vanishes, i.e. the bulk is in a gapped state.

In this situation, we applied a variable resistor $R_{\text{Load}}$ between the inner and outer circumference of the drag layer as shown in the inset of figure 5. For $R_{\text{load}} \to \infty$ the system behaves as before. However, upon decreasing $R_{\text{Load}}$ from $\infty$ to $0 \,\Omega$, a current begins to flow through the bridge connecting the inner and outer circumference of the drag layer. Simultaneously, a current of equal magnitude in the circuit of the drive layer can be measured. In the light of the strongly reduced 4pt interlayer resistance we demonstrated with figures 2–4, these results can be explained in terms of parallel-tunneling at both sample edges carried by quasiparticles [17, 18].

The observables in any of these transport geometries are the currents and voltages in the leads [17], so we have no direct access to what is happening within the bulk. The ground state of our bilayer system in the correlated regime can be described by the Halperin (111) state [19], as the Laughlin wavefunction describes the ground state of the fractional quantum Hall effect.
And like in the FQHE, it is convenient to introduce the quasiparticle concept. These quasiparticles experience enhanced interlayer tunneling, just as the quasiparticle Hamiltonian of a superconductor has pair creation and annihilation terms. The quasiparticles in our system arise at the interface where the single particle electron current from the leads meets the correlated $\nu_{\text{tot}} = 1$ phase. Since for $\nu_{\text{tot}} = 1$ the bulk of the drive layer is in a gapped state, it prohibits any regular single electron current flow across the annulus. However, in a process which is analogous to Andreev reflection \[18\], the injection of a single electron leads to a condensate current, or an excited state from the condensate ground state, respectively. To put it simply, every incident single electron in the top layer excites an exciton in the bulk. To conserve the total charge in both layers, or to counter for this sudden net flow of excitons in the bulk, respectively, an electron must exit into the leads in the bottom layer. The Bose condensate thus changes the single electrons into quasiparticles which are easily transferred. This constant flow of quasiparticles is the process we would like to refer to as quasiparticle tunneling \[17\].

If the inner and outer circumference of the bottom layer are physically connected over a sufficiently small resistance $R_{\text{Load}}$, it offers a short cut path across the gapped bulk for reflected single electrons. Having passed that bridge, each electron will by itself undergo the same process of triggering condensate currents and quasiparticle tunneling at the other edge. While this model is able to account for our data, we cannot definitively say whether this configuration really allows us to trigger such an excitonic current through the bulk of the $\nu_{\text{tot}} = 1$ QH state or not. It is also possible that some still unknown (tunneling) process is taking place.

5. Summary and conclusion

We have presented dc tunneling experiments on electron double layer systems at a total filling factor of one which clearly show the existence of critical tunneling currents $I_{\text{critical}}$. When the total current $I$ exceeds the critical value, the 4pt interlayer resistance increases by many orders of magnitude. The results can be explained in terms of quasiparticle tunneling which is possible due to the Bose condensation. These observations could have grave consequences for the interpretation of the $\nu_{\text{tot}} = 1$ QH state and the transport experiment performed within this regime. This could be of particular relevance if the currents that are imposed in regular transport are smaller than $I_{\text{critical}}$.

Acknowledgments

We thank J G S Lok for the design of the Corbino geometry and J H Smet for giving us access to some of his equipment. Also, we would like to acknowledge the German Ministry of Research and Education (BMBF) for its financial support and gratefully thank both Allan H MacDonald and Ady Stern for discussions.

References

[1] Fertig H A 1989 Phys. Rev. B 40 1087
[2] MacDonald A H and Rezayi E H 1990 Phys. Rev. B 42 3224
[3] Tutuc E, Shayegan M and Huse D A 2004 Phys. Rev. Lett. 93 036802
[4] Kellogg M, Eisenstein J P, Pfeiffer L N and West K W 2004 Phys. Rev. Lett. 93 036801
[5] Champagne A R, Eisenstein J P, Pfeiffer L N and West K W 2008 Phys. Rev. Lett. 100 096801

New Journal of Physics 10 (2008) 045018 (http://www.njp.org/)
[6] Spielman I B, Kellogg M, Eisenstein J P, Pfeiffer L N and West K W 2004 Phys. Rev. B 70 081303
[7] Spielman I B, Eisenstein J P, Pfeiffer L N and West K W 2001 Phys. Rev. Lett. 87 036803
[8] Spielman I B, Eisenstein J P, Pfeiffer L N and West K W 2000 Phys. Rev. Lett. 84 5808
[9] Rossi E, Nunez A S and MacDonald A H 2005 Phys. Rev. Lett. 95 266804
[10] Park K and Das Sarma S 2006 Phys. Rev. B 74 035338
[11] Murphy S Q, Eisenstein J P, Boeinger G S, Pfeiffer L N and West K W 1994 Phys. Rev. Lett. 72 728
[12] Tiemann L, Lok J G S, Dietsche W, von Klitzing K, Muraki K, Schuh D and Wegscheider W 2008 Phys. Rev. B 77 033306
[13] Eisenstein J P, Pfeiffer L N and West K W 1990 Appl. Phys. Lett. 57 2324
[14] Rubel H, Fischer A, Dietsche W, von Klitzing K and Eberl K 1997 Phys. Rev. Lett. 78 1763
[15] Eisenstein J P, Pfeiffer L N and West K W 1992 Phys. Rev. Lett. 69 3804
[16] Fertig H A and Murthy G 2005 Phys. Rev. Lett. 95 156802
[17] Su J J and MacDonald A H 2008 Preprint arXiv:0801.3694
[18] MacDonald A H, private communication
[19] Halperin B I 1983 Helv. Phys. Acta 56 75