Josephson Currents in the Bilayer Exciton Condensate

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Reducing the dimension of an electronic charge system from three to two leads to the emergence of intriguing phenomena like the integer and fractional quantum Hall effect (QHE) or special forms of superconductivity . Two-dimensional electron gases (2DEG) in GaAs quantum wells embedded in AlGaAs buffer layers are unique because of their extreme high purity characterized by electron and hole mobilities of several million $\mathrm{cm}^2/\mathrm{Vsec}$. In recent years it has been demonstrated, both experimentally and theoretically, that bilayers produced from two 2DEGs in such a system can even undergo a transition into a BCS state where (quasi)-excitons of full and vacant electron states play the role of the Cooper pairs. This novel state exhibits signatures of both the QHE and of a Josephson-like coherent coupling between the layers [1].

In conventional superconductors it is well known that two Josephson junctions connecting two superconductors show quantum interferences because the junctions are coupled via the coherence of the groundstate wavefunction. It is a long-standing question if a similar coupling can be realized in the bilayer excitonic BCS state. Here we report that it is indeed possible to manufacture devices where almost no electric current flows between two different Josephson circuits but where the exchange of ground state excitons leads to an intricate coupling between them. These devices are ring-shaped (Corbino) structures as shown in Fig. 1(a) where contacts can be placed at different edges of the sample. Therefore, almost no electrical current flows between the two edges in the excitonic BCS state.

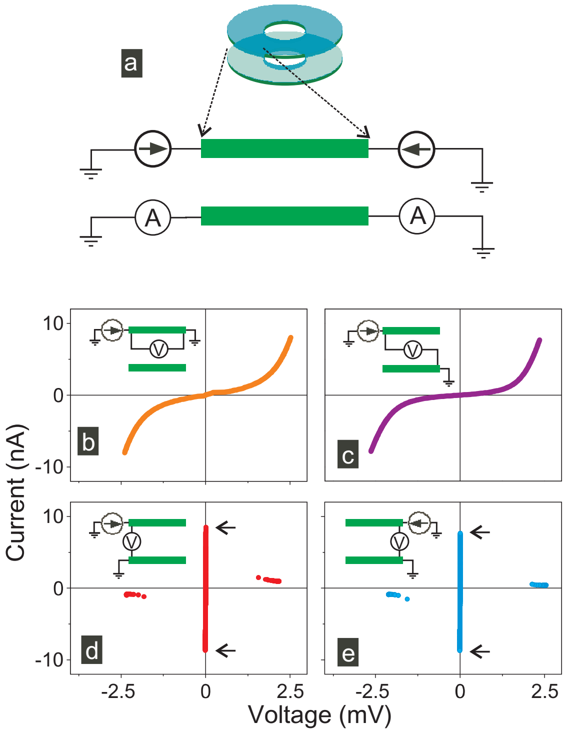

Figure 1: (a) Schematic of the Corbino device. Individually controlled currents can be fed in by contacts placed at the inner and the outer edge, respectively. The currents are measured both at the inputs and the outputs of the device. Voltages between the two layers and between the edges are measured by separate contacts, not shown in the schematic. (b)-(e) Current-voltage characteristics measured with the Corbino device at $\nu_T = 1$ temperatures below 50 mK. The respective configurations are shown in the inserts. Nearly no current is flowing if contacts at separate edges are used, even with voltages up to 2 mV (b) and (c). With contacts at the same edge, a Josephson-like I/V is measured, (d) and (e).

For our experiments we use bilayer quantum Hall systems consisting of two 2DEGs based upon MBE-grown GaAs/AlGaAs heterostructures separated by a few nm. Charge densities and the perpendicular magnetic field B are set such that the filling fraction of the Landau levels $\nu = hn/eB$ is approximately $1/2$ in each layer. At high temperatures or at large separations, the two layers behave like independent 2DEGs. At smaller interlayer separations the electrons and holes (the occupied and the vacant states in the respective lowest Landau level) become correlated forming excitons which condensate in a BCS-like state at temperatures below a few 100 mK. This state prevails even if the tunneling probability between the layers is negligibly small as long as the d/l_B ratio is less than about 2 where d is the average distance between the 2DEG layers and $l_B = \sqrt{\hbar/eB}$ is the magnetic length. The excitonic condensate state is usually called the $\nu_T = 1$ state.

Transport and tunneling measurements are shown in Fig. 1(b)-(e). Current-voltage (I/V) characteristics are obtained with the different contact configurations indicated by the respective inserts. In Fig. 1 (b), current is fed into the outer edge of the upper layer and led out from the inner edge of the same layer. At small voltages, the electric conductance across a layer is very small because only a very small charge current flows between the two edges. In the configuration Fig. 1(c) the tunnel conductance is also very small because charges still have to flow from edge to edge in this arrangement.

In contrast, the conductance increases by more than three orders of magnitude if current contacts at the same edge are used, Fig. 1 (d) and (e). This Josephson-like tunneling terminates at a critical current I_c and is a direct consequence of the coherent BCS-like excitonic condensate [2]. A popular picture of this Josephson current is based upon an Andreev-reflection like process where electrons injected into one layer "reflect" electrons out of the other layer, thereby forming excitons, i.e. an extra electron in one layer and an extra hole in the other. The excitons propagate as a dissipationless counterflowing current before tunneling removes the excess charges. In a recent theory, both the size of the Josephson conductance and of the critical current were connected to the magnitude of the small but finite bare tunneling probability and to a correlation length which is finite because of merons induced by defects [3].

It is important to note that the critical currents measured at the two edges (and also the conductances if the slopes in Fig. 1(d) and (e) are analyzed) are almost the same. This is striking, because the two edges are nearly completely electrically isolated from each other, as is evident from the results of in Fig. 1 (d) and (e). The fact that the two tunneling characteristics are identical cannot originate from edge phenomena because the lengths of the two edges differ by a factor of 2.7. Rather, the Josephson tunneling in the $\nu_T = 1$ state is a consequence of the excitonic groundstate which extends over all of the sample area.

In an excitonic Josephson tunnel experiment, the density of the groundstate excitons is brought out of equilibrium by the Andreev-like process mentioned above where the tunneling current is thought to be equivalent to the creation of extra excitons. The relaxation of the excess excitons via the small but non-zero tunneling leads to an equilibrium density of these. An important and interesting feature of the excess excitons in the $\nu_T = 1$ state is that they may have different "polarities", depending on the direction of the generating tunnel current. Rather than to rely on the tunneling process it should also be possible to reduce the excess exciton density by injecting excitons with opposite polarisation. This way one should be able to reach much larger critical currents than it is possible with one pair of contacts only.

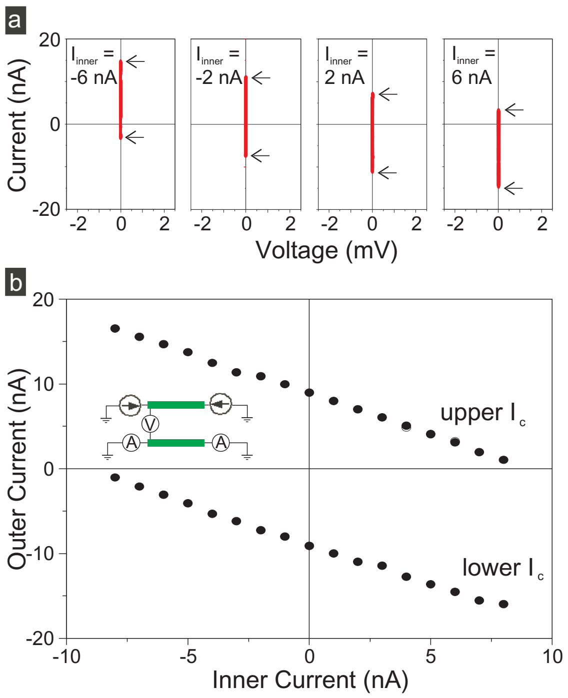

Figure 2: (a) Tunneling current-voltage characteristics of the outer contacts with different constant currents passing through the inner contacts. The critical currents through the outer contacts are increased (decreased) if an additional current flows through the inner contacts in the opposite (same) direction. (b) Upper and lower (positive and negative) critical currents measured at the outer contacts as function of the Josephson current passing through the inner ones (black dots).

We have realized this by using all four current contacts shown in Fig. 1 (a). The I/V-characteristic at the outer edge is measured as before while a constant current is passed across the two layers at the inner edge. Results for different inner currents are shown in Fig. 2(a). Clearly, the tunneling I/V curves are shifted up and down depending on the current applied to the inner edges. Note, that a negative (positive) current I_{inner} increases (decreases) the respective positive (negative) critical current at the inner edge. Interestingly, the respective change of the I_cs is equal to the value of the I_{inner}. This linear dependence of I_c on I_{inner} becomes even clearer from Fig. 2(b) where the positive and negative critical currents are plotted as function of the inner current. It demonstrates the linear dependence of I_c on the inner Josephson current over the whole current range probed here.

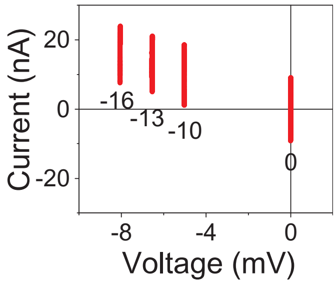

Figure 3: Tunneling characteristics with very large compensating currents passing through the inner contacts. The whole Josephson current regime can be shifted above zero current.

In Fig. 3 the range of the compensating currents is extended even further. It shows several I/V characteristics measured at the outer edge with compensating currents up to -16nA (the voltages of the different curves are offset for clarity). Amazingly, with compensating inner currents exceeding -9nA, both end points of the Josephson current range are now positive and the Josephson effect is now only observed if both current sources are simultaneously operating. Thus, measuring the traces of Fig. 3 requires the simultaneous increase of the oppositely directed currents at both edges up to the desired (inner) compensating current. Then the outer current is varied to trace one half of the I/V. Afterwards, all currents are set to zero, the procedure repeated, and the second half of the I/V measured.

Increasing the critical currents even further was not possible. It is intriguing to claim that at currents exceeding $\pm 16nA$ at the two edges, the excitons reach a critical velocity which, taking the charge density in the layers as the density of the excitons, would be about 20 cm/s. However, it is more likely that a more trivial phenomenon limits the Josephson tunneling at large compensating currents namely parasitic voltages which build up $between$ the edges and cause an inter-edge charge current.

In conclusion, we have used Corbino devices to separate electric charge currents from the flow of charge-neutral excitons which form the BCS-like groundstate in the Quantum-Hall bilayers at $\nu_T = 1$. In the bulk of the Corbino devices, the electric charge transport is effectively blocked while the excitons propagate nearly dissipationless. Equal critical currents at the two edges are have been found which is once more evidence that the excitonic Josephson current is a bulk effect.

Injecting oppositely polarized excitons at the two edges of the Corbino device leads to a dramatic enhancement of the critical Josephson currents because they compensate each other. The "natural" relaxation process of the excess excitons, namely the tunneling, remains active with compensating currents and determines the range between upper and lower (positive and negative) critical currents.

Our most important result is that the Josephson currents in the excitonic condensate can be controlled by the density and the polarity of the excitons which are injected into the Corbino structure. This is not conceivable in superconductors where only one type of a Cooper pair exists and the pair density can not be varied over a large range. More generally speaking, we demonstrated the interaction of two differerent currents via an excitonic condensate rather than electromagnetic fields or charged particles.

References:

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