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Observations of nascent superfluidity in a bilayer two-dimensional electron system at $\nu_T = 1$

M. Kellogg[a], J.P. Eisenstein[a,*], L.N. Pfeiffer[b], K.W. West[b]

[a]Condensed Matter Physics, California Institute of Technology, Pasadena, CA 91125, USA
[b]Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974, USA

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Abstract

Single-layer longitudinal and Hall resistances have been measured in a bilayer two-dimensional electron system at $\nu_T = 1$ with equal but oppositely directed currents flowing in the two layers. At small effective layer separation and low temperature, the bilayer system enters an interlayer coherent state expected to exhibit superfluid properties. We detect this nascent superfluidity through the vanishing of both resistances as the temperature is reduced. This corresponds to the counterflow conductivity rising rapidly as the temperature falls, reaching $\sigma_{xx}^{\mathrm{CF}} = 580(e^2/h)$ by $T = 35\,\mathrm{mK}$. This supports the prediction that the ground state of this system is an excitonic superfluid.

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1. Introduction

A unique quantum state arises in double-layer two-dimensional electron systems (2DES) when the density n of electrons in each layer is equal to one-half of the degeneracy eB/h of the lowest spin-resolved Landau level *and* the layers are sufficiently close together so that interlayer Coulomb interactions are comparable to the intralayer interactions [1]. Under these conditions, in the low-temperature regime, the system achieves a lower total energy when electrons in one layer are configured opposite to the vacancies (holes) in the half-filled Landau level in the other layer. These electrons and holes bind together forming a system of interlayer excitons [2].

Unlike conventional excitons (conduction electrons bound to valence band holes), which are unstable against recombination into photons, the interlayer excitons in the present case consist of holes in one layer (a particle–hole transformation is performed on the half-filled Landau level) binding onto electrons in the half-filled Landau level in the other layer, and do not recombine. These stable excitons can theoretically condense into a BEC with well-understood properties [3–6], at least in the absence of disorder. Among the features anticipated is a superfluid mode manifesting as equal but oppositely directed dissipationless electrical currents flowing through the two layers—which can be thought of as arising from a superfluid flow of the interlayer excitons [2,7].

An alternate view of this state is one in which every electron exists in an identical superposition of the two layer states: $|\rightarrow\rangle = |\uparrow\rangle + e^{i\phi}|\downarrow\rangle$, with $|\uparrow\rangle$ denoting an electron located in the top layer, $|\downarrow\rangle$ an electron in the bottom layer, and ϕ a phase angle, arbitrary in the limit of zero interlayer tunneling. These superposition states are eigenvectors of pseudospin, lying in the xy-plane of pseudospin space. Since the pseudospins of all electrons are the same, the system is a ferromagnet, and may be viewed as a completely filled Landau level ($\nu_T = hn_T/eB = 1$ where n_T is the total density of the two layers combined) of pseudospin-aligned electrons [5,6]. As in an ordinary itinerant ferromagnet, the exchange energy is responsible

*Corresponding author.
E-mail address: jpe@caltech.edu (J.P. Eisenstein).

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for enforcing this order. Spatial gradients in the phase ϕ represent pseudospin supercurrents or, equivalently, excitonic supercurrents.

This interlayer coherent state has been studied previously, exhibiting an integer quantized Hall effect (QHE) [8], an unusual textural phase transition [9], an extremely large peak in the interlayer tunneling conductance at zero interlayer bias [10], and precise quantization of the Hall component of Coulomb drag [11].

In the early QHE measurements [8,9], the longitudinal and Hall resistances were measured in the conventional way—the current was sent through the two layers going in the same direction. But if the currents were to be sent through the two layers going in opposite directions, a superflow of excitons should result (if the layers are close enough together) and be detectable as a vanishing of not only the longitudinal resistance, but also of the Hall resistance. In this paper we report on observations of this dramatic effect. Our results strongly support the existence of nearly dissipationless exciton transport at $\nu_T = 1$.

2. Experimental details

These experiments were conducted using a GaAs/AlGaAs heterostructure consisting of two GaAs wells 18 nm wide separated by a 10 nm wide $Al_{0.9}Ga_{0.1}As$ barrier. The as-grown electron density in each well is $5.4 \times 10^{10}\,\mathrm{cm}^{-2}$ with a low-temperature mobility of about $1 \times 10^{6}\,\mathrm{cm}^2/\mathrm{Vs}$. Using standard photolithographic techniques, we etched a $160\,\mu\mathrm{m} \times 320\,\mu\mathrm{m}$ mesa with seven arms extending out from it (see Fig. 1). Aluminum gates above and below the arms allow for in situ control over which layer each arm contacts [12]. Arms 1–4 make up the two Y-shaped projections at the opposite ends of the bar and are used for injecting current symmetrically into the layers; arms 5–7 are for probing the longitudinal and Hall voltages in the main mesa region. The longitudinal probes (5, 6) are spaced $160\,\mu\mathrm{m}$ apart, the width of the mesa, and so we are measuring along "one square". Large aluminum gates were also evaporated above and below the central mesa area allowing us to reduce the electron density in each well by as much as a factor of 2.5. The sample was thinned to $49\,\mu\mathrm{m}$

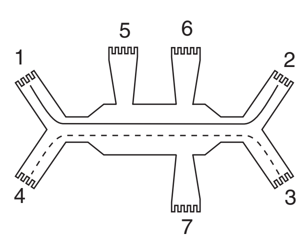

Fig. 1. A schematic illustration of the mesa region: arms 1–4 are for driving currents through the electron layers and arms 5–7 are for measuring the resulting voltages. For the counterflow configuration, a current is sent through the bottom layer by arms 1 and 2 (the solid line shows the route) and then an oppositely directed current goes through the top layer through arms 3 and 4 (the dashed line). Gate electrodes omitted for clarity.

during processing. The tunneling resistance at resonance in zero magnetic field was measured to be $R_{\mathrm{tun}} \approx 100\,\mathrm{M\Omega}$.

A 2.3 Hz, 0.5 nA current is sent first through the bottom layer (via arms 1 and 2 shown in Fig. 1) and then redirected to go through the top layer (via arms 3 and 4) going either in the same direction (the parallel configuration) or in the opposite direction (the counterflow configuration). Because the interlayer coherent state exhibits enhanced tunneling [10], we measure the current before it enters the first layer and then after it has left the first layer but before entering the second layer—the difference between the two represents the loss due to the interlayer tunneling current. This loss is roughly 5 pA when the system is at $\nu_T = 1$, consistent with other measurements of the interlayer coherent tunneling in the sample. In the counterflow configuration, this will not affect the relative magnitudes of the currents in the layers, they will still carry equal but opposite currents despite the small tunneling leakage.

The voltages are measured in just one of the layers using arms (5, 6) and (6, 7). The longitudinal (Hall) voltage V_{xx} (V_{xy}) divided by the injected current, yields the longitudinal (Hall) resistance R_{xx} (R_{xy}). Superscripts $\parallel$ and CF indicate whether the current is in the parallel or counterflow configuration, respectively.

3. Data

Fig. 2 displays the primary result of this experiment. The main figure shows the Hall resistance at $n = 2.46 \times 10^{10}\,\mathrm{cm}^{-2}$ per layer and $T = 30\,\mathrm{mK}$ for both the parallel (dotted line) and counterflow (solid line) configurations. This density corresponds to $d/\ell = 1.55$ when calculated at $\nu_T = 1$, where $\ell = (\hbar/eB)^{1/2}$ is the magnetic length, and $d = 28\,\mathrm{nm}$ is the center-to-center spacing between the quantum wells. The ratio d/ℓ is the effective layer separation and

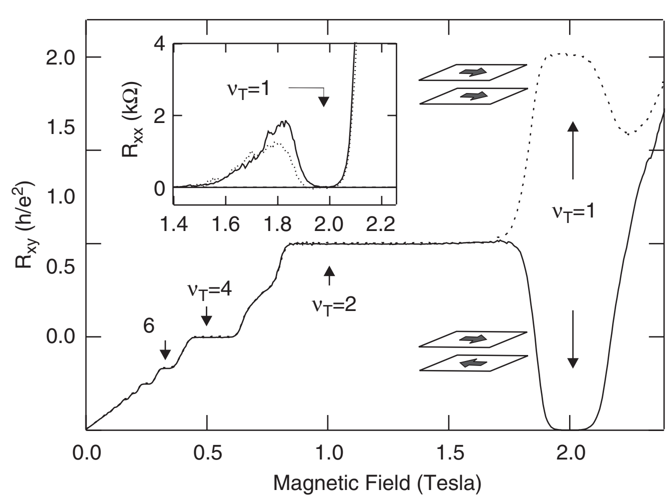

Fig. 2. Main figure shows the Hall resistance versus magnetic field in the parallel (dotted line) and counterflow (solid line) configuration for $n = 2.46 \times 10^{10}\,\mathrm{cm}^{-2}$ and $T = 30\,\mathrm{mK}$. The inset shows the longitudinal resistances. Voltages are measured in one layer only.