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Exchange-driven bilayer-to-monolayer charge transfer in an asymmetric double-quantum-well

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Abstract

We present data which shows for the first time that an exchange-driven bilayer-to-monolayer transition occurs in an externally biased double quantum well system at $B = 0$ as the total carrier density is *increased*. This transition is due to the negative compressibility of the low density carrier systems and the layer imbalance caused by external gate biases. © 2002 Elsevier Science B.V. All rights reserved.

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Bilayer 2D systems formed in double quantum well structures exhibit a wide variety of collective phenomena which either have no counterpart, or cannot be directly examined, in single-layer systems. One problem that has attracted considerable interest is the possibility of an interaction-induced exchange instability in bilayer 2D systems at $B = 0$. Initial theoretical studies of balanced bilayer systems suggested that at low densities and layer separations a re-arrangement of charge would occur, with all the charge spontaneously transferring to one of the quantum wells [1,2]. However, more detailed calculations indicate that this bilayer–monolayer instability does not occur; instead a bilayer phase coherent state forms with equal charge distributions in the two quantum wells [3,4]. In this work we investigate a related question: can many body interactions cause a transition from a bilayer state to a monolayer state in a biased (asymmetric) double quantum well system?

Samples were taken from an ultra-high-quality GaAs–AlGaAs heterostructure grown by MBE on the (3 1 1)*A* plane. The structure contains two 150 Å quantum wells, separated by a 25 Å AlAs barrier. The samples are of exceptional quality, with peak mobilities in excess of 1.25×10^6 cm^2 V^{-1} s^{-1} in each well. Tunnelling between the two wells is extremely weak, due to the large hole mass ($m^* \approx 0.3m_e$) and potential barrier height, with the tunnelling gap Δ_{SAS} less than 7 μeV. Front and back gates provided independent control over the carrier density in the upper and lower quantum wells. Measurements were performed in a dilution refrigerator with a base temperature below 30 mK.

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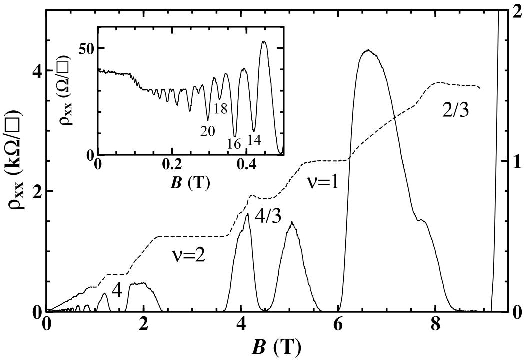

Fig. 1. Diagonal and Hall resistivities at a balanced total carrier density of $p_s = 1.4 \times 10^{11}$ cm^{-2}. The inset shows the low-B data, which exhibits standard SdH oscillations, but with no ν=odd states.

We begin by demonstrating the high quality of these samples, and the absence of interlayer tunnelling. Fig. 1 shows magnetotransport data under symmetric well occupation conditions, at a total carrier density of $p_s = 1.4 \times 10^{11}$ cm^{-2}. At low magnetic fields (see the inset to Fig. 1), Shubnikov–de Haas (SdH) oscillations periodic in $1/B$ are seen. Only even-ν ρ_{xx} minima occur when the carrier densities in the two layers are equal, due to the double-layer degeneracy (here ν refers to the total filling factor of the system). The absence of odd-ν minima, which would be produced by a Δ_{SAS} tunnelling gap, confirms that tunnelling is negligible. At higher magnetic fields, fractional quantum Hall states are visible, but again only with even-numerator states such as $\nu = \frac{4}{3}$ and $\frac{2}{3}$. The sole exception is the bilayer $\nu = 1$ state, which arises from the interplay of interlayer and intralayer interactions, rather than from tunnelling [5,6].

We now examine the transition from bilayer-to-monolayer occupation at much lower carrier densities, where interaction effects are stronger. We start with asymmetrically biased gates at a very positive front-gate bias V_{fg}, so that only the back quantum well is occupied. The total hole density is then increased by reducing the front-gate bias V_{fg}, and magnetoresistance data is studied to determine how the additional charge is distributed between the two quantum wells.

We determine whether one or two layers are occupied from the low-field SdH oscillations. Fig. 2(a) shows data taken when the gates are asymmetrically biased ($V_{\mathrm{fg}} = 0.55$ V), so that only the back quantum well is occupied, with a rather low

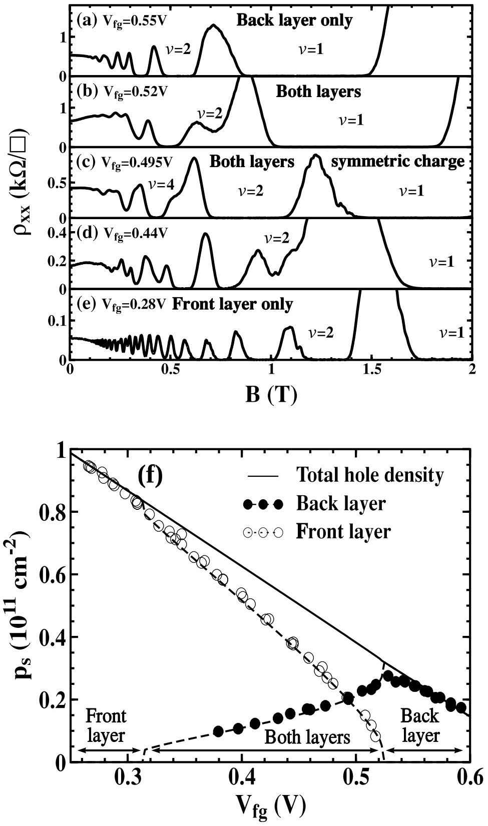

Fig. 2. (a–e): Magnetoresistance traces with (a) only the back layer occupied, (b)–(d) both layers occupied, and (e) only the front layer occupied. ($V_{\mathrm{bg}} = 2.05$ V). (f) Carrier densities as a function of V_{fg}. The symbols mark carrier densities in the two layers, and the solid line shows the total density. The dotted lines are theoretical fits described in the text.

carrier density of 2.5×10^{10} cm^{-2}. The data shows a weak negative magnetoresistance at low magnetic fields that is characteristic of single-layer occupation, with conventional SdH oscillations developing at higher magnetic fields. In Fig. 2(b), the front-gate bias is reduced to $V_{\mathrm{fg}} = 0.52$ V, which increases the carrier density, so that holes begin to populate the front quantum well. The magnetoresistance data shown in Fig. 2(b) now exhibits two clear signals of two layer occupation [7,8]. The low-field magnetoresistance is now positive, and the SdH oscillations are more complex (e.g. the ρ_{xx} minima at $\nu = 2$ is very weak). Upon further increasing the total density, the two-layer densities become equal at $V_{\mathrm{fg}} = 0.495$ V. The magnetoresistance data in Fig. 2(c) now exhibits standard SdH oscillations, except that only even-ν quantum Hall states are observed, due to the double-layer degeneracy. Increasing the total carrier density further with the front-gate bias causes the layer densities to become unequal again, signalled by the positive low-field magnetoresistance and the complex SdH oscillations in Fig. 2(d). Finally, as we continue to increase the total density, the magnetoresistance data returns back to the form that indicates *single*-layer occupancy, with a negative magnetoresistance and a single series of SdH oscillations that are periodic in $1/B$, as in Fig. 2(e). This transition back to single-layer occupancy with increasing total carrier density is not possible in a non-interacting system, and is entirely due to exchange and correlation effects.

To show the exchange-driven bilayer-to-monolayer transition more clearly, we plot the individual layer densities and the total carrier density as a function of the front-gate bias V_{fg} in Fig. 2(f). The layer densities are determined from the low-field SdH oscillations [6], and the total density from the low-field Hall effect. For $V_{\mathrm{fg}} > 0.53$ V, only the back layer is occupied. Reducing V_{fg} increases the total carrier density, and at 0.53 V the front layer starts to populate. Due to the negative compressibility of this layer, the hole density in the back layer now starts to decrease as the total carrier density is increased with the front gate. Thus there is only a finite range of densities over which both layers are occupied; below $V_{\mathrm{fg}} = 0.31$ V exchange effects drive the density in the back layer to zero, causing a transition back to single-layer occupancy with only the front layer populated.

Our observations are supported by theoretical fits to the experimental data using a robust model of bilayer 2D systems [4,9]. The model includes the electric-field energy between the layers, plus the kinetic, exchange, and correlation energies within each layer. Because Δ_{SAS} is so small, interlayer tunnelling is neglected. As the dashed lines in Fig. 2(f) show, this model yields excellent agreement with the experimental data, even though it slightly overestimates the abruptness of the bilayer-to-monolayer transition. The combined experimental and theoretical data thus provide the first evidence for an exchange-driven bilayer-to-monolayer transition with increasing density in a double quantum well system.

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