# Interlayer charge transfer in double-quantum-well systems

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As the front-layer density in a bilayer electron or hole system is depleted by the application of a biased front gate, the density in the back layer increases due to the exchange term in the energy. For the sample parameters we studied, a self-consistent calculation using the local-density approximation predicts a discontinuous charge transfer that is not observed experimentally. We discuss possible origins of this discrepancy. [S0163-1829(97)01416-1]

Bilayer electron systems (BLES's), coupled by the interlayer Coulomb interaction, are good candidates in which to observe many-body phenomena.[1–3] For idealized two-dimensional electron sheets, Ruden and Wu predicted that at sufficiently small densities and interlayer separations, the BLES would become bistable, with all of the charge residing in one layer or the other, due to the dominance of the negative exchange term over the positive kinetic-energy term at low densities.[4,5] It would be difficult to observe the bistability directly, however, because the small density and interlayer separation required are very hard to achieve experimentally. Here we describe our study of a related problem, namely, the behavior of the layer densities as one layer is depleted by a biased front gate. We focus on the possibility of an exchange-induced *discontinuous* charge transfer from the front layer to the back layer, as the front layer is depleted.[6,7]

Our study is motivated by previous work on this subject. Katayama *et al.*[6] observed a sharp and significant ($\sim$50%) drop in the in-plane resistance of a BLES as the front layer was depleted, and interpreted this observation as a signature of a sudden interlayer charge transfer. Systematic Shubnikov–de Haas (SdH) measurements of the layer densities in similar samples by Ying *et al.*,[7] however, revealed only a gradual charge transfer from the front layer to the back layer. This gradual transfer also results from the dominance of the exchange energy; indeed, Ying *et al.* found their data to be in good quantitative agreement with the results of self-consistent calculations which include the exchange energy via a local-density approximation (LDA).[7–9] Figure 1 exhibits an example of the measured and calculated densities for sample A, used in Ying's study. The sample parameters are listed in Table I. Note that in the SdH measurement the *subband* densities are measured; in Fig. 1 these are compared to the subband densities calculated with the LDA.[10] The remarkable feature of Fig. 1 is the excellent agreement between the experimental data and the LDA calculations in the entire density range, and in particular near the front-layer depletion where both the data and calculations show a gradual charge transfer from the front to the back layer. Also shown in Fig. 1 (dotted curves) are the results of a simulation where the layers are taken to be *ideal* two-dimensional electron sheets centered in the quantum wells. This simulation uses the same method as the calculations done by Ruden and Wu[4] and Katayama *et al.*[6] It is clear that this simpler simulation does not match the experimental data as well as the LDA simulation.

Shown in Fig. 2 are the results of an LDA simulation for a BLES with different parameters, namely, lower layer densities and a slightly smaller interlayer distance (sample B in Table I). For these low electron densities, a pronounced, discontinuous charge transfer to the back layer is predicted by the LDA calculations. The experimental data, on the other hand, are in good agreement with the calculation except right before the front-layer depletion. Specifically, they do not exhibit the abrupt transfer predicted by the LDA simulation. In the remainder of this paper we provide more experimental details and data, and then discuss possible origins of the discrepancy between the experimental results and the LDA predictions. For completeness, the results of an *ideal* BLES simulation are also shown in Fig. 2 as dotted curves. In the region very near the depletion of the front layer, these results appear to agree with the experimental data better than the

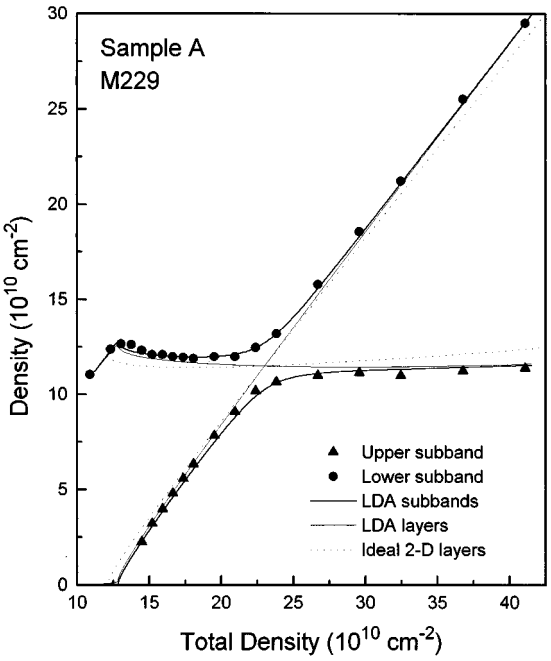


FIG. 1. The measured (symbols) and LDA simulation results (thick solid curves) for the subband densities in a double-quantum-well sample. Note the excellent agreement between the experimental data and the LDA results over the whole density range. The solid curves show the layer densities deduced from the LDA simulation. The dotted curves are from a simulation where the layers are taken to be ideal two-dimensional sheets.

 

TABLE I. Parameters for the samples.

| Sample | $d$ (Å) | $W$ (Å) | $N_{\mathrm{bal}}$ ($10^{10}$ cm$^{-2}$) | $\mu$ ($10^{6}$ cm$^{2}$/V s) | $\Delta_{\mathrm{SAS}}$ (K) |
|---|---|---|---|---|---|
| A($M229$) | 10 | 180 | 23 | 1.0 | 10 |
| B($MM083$) | 33 | 140 | 9.3 | 0.2 | 1.7 |

LDA results do, but the fit is worse in the other regions.[11] We believe that the agreement near the depletion in Fig. 2 is coincidental, and that the ideal BLES simulation is not accurate.[12]

Our samples were grown by molecular-beam epitaxy (MBE), and consist of two GaAs quantum wells of width $W$, separated by an AlAs barrier of width $d$. They are modulation doped with a wide spacer between the Si dopant atoms and the quantum wells. We studied double-quantum-well samples containing either electrons or holes. They were grown simultaneously on GaAs(100) and (311)A wafers which were placed side by side on the MBE substrate holder.[13] Contacts were made by alloying In:Sn for electrons or In:Zn for holes in a reducing atmosphere for 12 min at 440 °C. We then deposited a CrAu film which we used as a front gate. The measurements were made in a pumped $^{3}$He system and in a $^{3}$He/$^{4}$He dilution refrigerator. Samples from different areas of the wafer were taken. The relevant sample parameters, including the total balanced density $N_{\mathrm{bal}}$, are listed in Table I.

We measure subband densities by measuring the longitudinal resistance $R_{xx}$ as a function of perpendicular magnetic field $B$ using a lock-in amplifier. The resistance measurement shows SdH oscillations at low $B$ and the quantum Hall effect at higher $B$. The frequencies of the SdH oscillations, $f_i$, directly give the subband densities by the relation $N_i=(2e/h)f_i$. In the regions we are interested in, far from the balanced point, the subband densities are essentially equal to the layer densities.[7,10] The LDA simulation in Fig. 2 shows clearly that the subband and layer densities are almost identical near the abrupt charge transfer that we are looking for.

The experimental results shown in Fig. 2 agree with the LDA simulation at all densities except for where the discontinuous charge transfer is expected. We see that the back-layer density smoothly increases until the front layer is fully depleted, at which point the back layer starts depleting.

A few points regarding Fig. 2 are worth mentioning. The data in Fig. 2 were taken at a temperature of 25 mK on an electron sample with a Hall bar geometry. The Hall bar had 100-$\mu$m width, while the distance between the $R_{xx}$ contacts was 200 $\mu$m. To match the experimental data, the well width $W$ in the LDA simulation was taken directly from the MBE growth parameters, but we used a barrier width $d=33$ Å, as compared to the nominal growth value of 30 Å. Given an uncertainty in MBE growth of about $\pm 15\%$, this value is reasonable. The subband densities were measured at particular front-gate biases $V_{\mathrm{FG}}$. The total density $N_{\mathrm{tot}}$ at each point was obtained by adding the two measured subband densities wherever we were able to measure both subbands ($N_{\mathrm{tot}}>6.5\times10^{10}$ cm$^{-2}$). To deduce the total density where we could not detect both subbands in the SdH oscillations ($N_{\mathrm{tot}}<6.5\times10^{10}$ cm$^{-2}$), we used a line which was fitted to the measured $N_{\mathrm{tot}}$ vs $V_{\mathrm{FG}}$ (for $N_{\mathrm{tot}}>6.5\times10^{10}$ cm$^{-2}$).[14] There is a small change in capacitance between the front gate and the BLES at the depletion of the front layer, resulting in a change of the slope of the $N_{\mathrm{tot}}$ vs $V_{\mathrm{FG}}$ curve for $N_{\mathrm{tot}}<5.0\times10^{10}$ cm$^{-2}$. This change is only 3%, however, and can only affect the experimental points' positions on the $x$ axis of Fig. 2. Therefore it cannot affect the conclusion that the abrupt transfer was not observed.

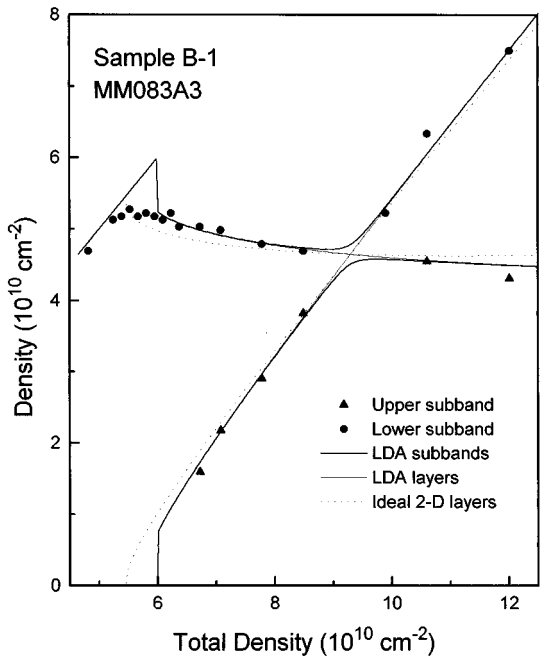


FIG. 2. Experimental results and the LDA simulation for a dilute bilayer electron system. The experimental data were taken at 25 mK. Note the excellent agreement at all points except those where the discontinuous charge transfer is predicted.

We have repeated this measurement with various parameters changed. We made another electron sample from a different piece of the wafer with an identical Hall bar, a back gate, and a front gate. We measured this sample at 0.3 K with back-gate biases of $-85$, 0, and 90 V. With these back-gate biases, $N_{\mathrm{bal}}$ was $7.2\times10^{10}$, $9.4\times10^{10}$, and $1.25\times10^{11}$ cm$^{-2}$, respectively. For these densities, the LDA simulations predict discontinuous increases in back-layer density of 17%, 13%, and 10%. We also repeated the experiment on a bilayer hole sample with $N_{\mathrm{bal}}=1.4\times10^{11}$ cm$^{-2}$, for which the LDA simulation predicts a discontinuous increase of 17%.[15] In all cases, the results were similar to those shown in Fig. 2, with good agreement between experiment and simulation except where the discontinuous charge transfer is predicted.

We also measured $R_{xx}$, capacitance, and subband densities vs $V_{\mathrm{FG}}$ in an electron sample with van der Pauw geometry at 0.3 K. Results are shown in Fig. 3. This is a different piece of sample B. The $R_{xx}$ and capacitance measurements show features near depletion which provide further evidence that depletion happens not abruptly where the LDA predicts, but more smoothly at a more negative $V_{\mathrm{FG}}$. The capacitance shows a decrease at depletion because the system is essentially a parallel-plate capacitor. When there is charge in the front layer, the capacitance is measured between the gate and the front layer, but when the front layer depletes, the capaci-

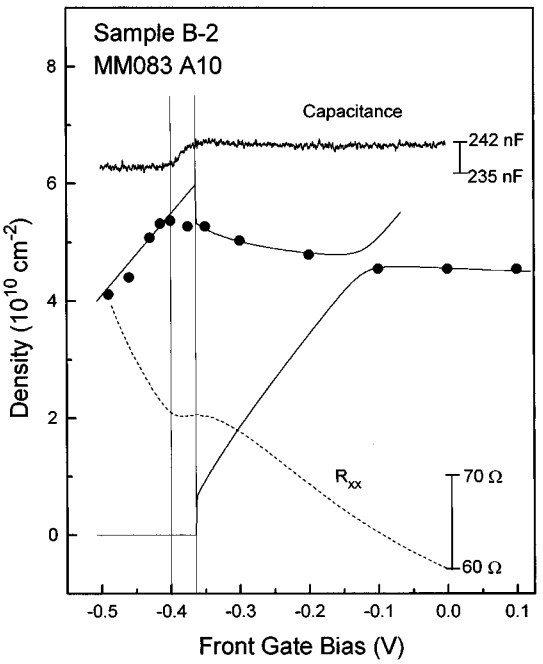


FIG. 3. Experimental data taken at 0.3 K, showing subband density $R_{xx}$ and capacitance as a function of $V_{FG}$. The capacitance and $R_{xx}$ were measured at $B=0$. The LDA simulation was fitted to the experimental data. All three data sets show that the front layer depletion happens at a more negative $V_{FG}$ than the LDA predicts.

tance is measured between the gate and the back layer, so the distance between the plates is larger and the capacitance is smaller. The front layer is not fully depleted until the capacitance reaches its smaller value. At the depletion of the front layer, the $R_{xx}$ trace shows a dip which may be explained as follows.[6] Just before depletion, the low-density front layer has a low mobility, and electron-electron scattering decreases the mobility for the back layer as well. When the front layer depletes fully, the back-layer electrons no longer scatter off of the front-layer electrons, so the mobility increases (before decreasing again at very low back-layer densities), resulting in a resistance minimum. All three measurements—$R_{xx}$, capacitance, and subband densities—indicate that there is no discontinuous charge transfer.

One possible explanation for the discrepancy between the LDA prediction and the experimental results is macroscopic sample inhomogeneity, a variation in areal density due to layer thickness and/or doping nonuniformities in the MBE growth. We believe that this is not the case here. The LDA simulations for sample B predict an abrupt increase in back-layer density of 13%. The density variation across a Hall bar of the size we used is expected to be less than 1%, so it should not be sufficient to completely mask the effect.

Sample disorder is a plausible explanation for the discrepancy that we cannot rule out. The LDA predicts that once the front layer reaches a density of less than roughly $7\times10^{9}$ cm$^{-2}$, it should deplete abruptly. This density corresponds to a Fermi energy of roughly 0.25 meV, which is comparable to the expected variations in the conduction band edge due to disorder caused by impurities in the sample and/or well width fluctuations. It is therefore possible that the front layer density is very nonuniform on a microscopic scale right before the expected discontinuous transfer, so as the gate bias is changed some regions deplete before others, and the depletion appears continuous as a result.

It is also possible that the absence of the abrupt charge transfer is ''intrinsic,'' and that the LDA simulation results are inaccurate. We note that the negative sign of the exchange-energy term is what causes the transfer of charge from the front layer to the back. If higher-order terms are included in the energy expansion, they might reduce the size of, or possibly eliminate, the predicted discontinuous charge transfer. Note that such higher-order terms are most important when the front layer is very dilute (near depletion), and should have little effect on the simulation results elsewhere. It also may be that interlayer and intralayer interactions are causing in-plane density variations which cannot be accounted for by a one-dimensional LDA simulation which assumes a uniform density in the plane. These in-plane density variations could eliminate the discontinuous charge transfer. In dilute single-layer electron systems, the in-plane interactions are known to play a key role and can lead to charge density wave (CDW) or Wigner crystal (WC) states.[16,17] In single-layer systems, such phenomena normally appear at densities more than an order of magnitude lower than those at which the discontinuous charge transfer we are discussing is expected to occur. Although there is no concrete theory, it is plausible that the presence of an additional nearby electron layer can enhance the threshold density for the formation of a CDW or WC. For the magnetic-field-induced WC, there exist data strongly suggesting a bilayer WC at higher Landau-level fillings than in the single-layer case.[3] Also, in an analogous system, a pair of parallel one dimensional quantum wires, a longitudinal CDW has been predicted to mask a charge-transfer instability between the wires.[18] The possibility of such intrinsic many-body interactions causing in-plane density fluctuations and eliminating a discontinuous charge transfer is very interesting, and merits further study.

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[9] Similar charge transfer and agreement with the LDA calculations was also found in compressibility measurements; see J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **50**, 1760 (1994).
[10] When the energy difference between the subbands is much larger than the symmetric-to-antisymmetric energy gap $\Delta_{SAS}$, the layer and subband densities are essentially equal; $\Delta_{SAS}$ is the subband separation when the layer densities are equal, i.e., when the BLES is ''balanced.'' In the LDA calculation, we define the *layer* density as the integral of the charge distribution in each quantum well. More details are given in Ref. 7.
[11] Note also the disagreement between the *ideal* BLES results and the experimental data in Fig. 1.
[12] It is at first glance surprising that the ideal BLES calculation always predicts a smaller charger transfer than the LDA, considering that tunneling is expected to reduce the charge transfer [H. Totsuji, Appl. Phys. Lett. **66**, 3343 (1995)]. This can be explained qualitatively by noting that the capacitive energy cost of transferring charge depends directly on the distance transferred. Taking sample B as an example, we note that the inside edges of the quantum wells are only 30 Å apart, the centers are 170 Å apart, and the outside edges are 210 Å apart. In the ideal calculation, all of the electrons must transfer across 170 Å. In the LDA, those that transfer across 30 Å pay a capacitive energy cost of less than one fifth of what the ideal case electrons pay, while those that transfer across 210 Å, pay about 1.24 times as much as the ideal case electrons. Because of this difference in energy cost, the broader layers should show a greater charge transfer than the ideal ones. Therefore, in going from the ideal to the real case, charge transfer is increased by the reduced energy cost more than it is decreased by the possibility of tunneling.
[13] On the (100) substrate, Si is incorporated as a donor, while on the (311)A substrate it is incorporated as an acceptor. See M. B. Santos, J. Jo, Y. W. Suen, L. W. Engel, and M. Shayegan, Phys. Rev. B **46**, 13 693 (1992), and references therein.
[14] We also deduced $N_{tot}$ from the low-$B$ Hall coefficient and the high-$B$ quantum Hall data. All the data indicate a $N_{tot}$ vs $V_{FG}$ which is linear to about 5%. The $N_{tot}$ from the sum of the subbands, however, is the most linear.
[15] The main difference between the bilayer electron and hole systems is the carrier effective mass in GaAs: $m_e^* = 0.067 m_e$, while $m_h^* = 0.40 m_e$. The larger $m_h^*$ results in a smaller $\Delta_{SAS}$, and a larger predicted abrupt charge transfer in a hole system compared to an electron system with the same sample parameters.
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