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Direct observation of an electronic phase transition in a double quantum well

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We report *in situ* tuning of electron density through an electronic phase transition in a double quantum well. As density is increased, the well-formed quantum Hall state at energy-level filling factor $\nu=3$ is replaced by a gapless correlated bilayer state. These observations establish that a phase transition exists which is driven by electron correlation (not, e.g., by the disorder potential). Activation energies in the transition region reveal a threshold density, above which the excitation gap decreases rapidly to zero.

Consider a system consisting of electrons in two widely separated (uncoupled) quantum wells. This double quantum well (DQW) will exhibit the same magnetotransport phenomena familiar from single two-dimensional electron layers, including the integral and fractional quantum Hall effects.[1,2] If the separation between the two wells is decreased to a few 100 Å, the electron layers will couple through the Coulomb interaction. One resulting phenomenon is interwell Coulomb drag: A current confined entirely in one well gives rise to an induced voltage of the opposite sign in the other well, due to Coulomb-mediated momentum transfer between the two wells.[3] Other manifestations would be fractional quantum Hall states predicted in DQWs which are not present in single electron layers (e.g., Hall plateaus at $2h/e^2$ and $4h/e^2$).[4,5]

If the separation between wells is decreased further, to a few 10 Å, direct electron tunneling between the wells results in symmetric and antisymmetric DQW eigenstates [see Fig. 1(a)], separated by an energy gap, Δ_{SAS}. Within a single electron model, the magnitude of Δ_{SAS} is unaltered by a high magnetic field perpendicular to the DQW plane. However, recent experiments reveal a regime characterized by missing quantum Hall states, which suggests that Δ_{SAS} collapses in a sufficiently high perpendicular magnetic field.[6,7] The collapse is believed to occur when Coulomb-driven interwell density fluctuations overwhelm the single-electron Δ_{SAS} tunneling gap.[8,9] This model predicts a phase transition upon increasing electron density in a DQW while keeping Δ_{SAS} and energy level filling factor, ν, constant.

In this paper, we directly observe this phase transition and establish the dominant role of Coulomb interactions in driving the transition. Previous observations fall short of these goals: (i) They compare different quantum Hall states, which occur at widely separated magnetic-field positions. High-field states are missing, while low-field states remain well formed. Such comparisons cannot establish the existence of a density-driven phase transition, in part because Landau-level and band-mixing effects are different for each quantum Hall state. (ii) They compare the same quantum Hall states among three samples of different Δ_{SAS}. The smaller Δ_{SAS}, the more missing quantum Hall states. Unfortunately, for these samples, there is also a correlation with electron mobility: the lower the electron mobility of a sample, the more missing quantum Hall states. This raises the concern whether disorder potentials played the dominant role in destroying quantum Hall states at high magnetic fields.

The magnetotransport measurements presented here avoid these complications because all observations are at the $\nu=3$ filling factor of a single DQW sample. At low electron densities, the $\nu=3$ quantum Hall state is well formed, presenting an accurately quantized Hall plateau, $R_{xy}=h/3e^2$, and a thermally activated minimum in the longitudinal resistance, R_{xx}. Upon increasing electron

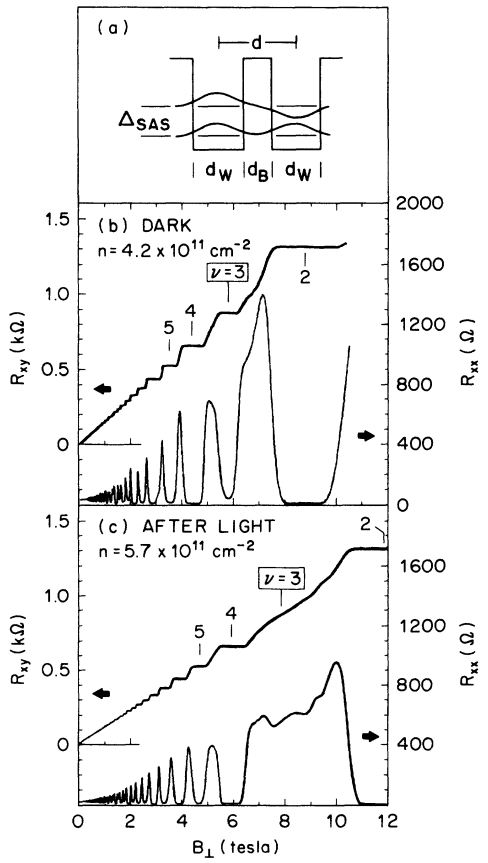

FIG. 1. (a) The symmetric and antisymmetric states of the double quantum well. Magnetoresistance, R_{xx}, and Hall resistance, R_{xy}, at $T=0.3$ K (b) before illumination and (c) after illumination. Illumination increases the electron density, n, and completely destroys the $\nu=3$ quantum Hall state.

density, there is a phase transition at $\nu=3$: the activation energy collapses and the quantum Hall state is replaced by a gapless correlated bilayer state. We rule out a disorder-driven transition, because the electron mobility of the sample *increases* with increasing electron density.

Our sample consists of nominally identical GaAs wells of width $d_W=139$ Å, separated by a $Al_{0.3}Ga_{0.7}As$ barrier of thickness $d_B=40$ Å [see Fig. 1(a)]. The sample is grown by molecular-beam epitaxy with electrons provided by remote delta-doped donor layers ($N_{Si}=4\times10^{11}$ cm^{-2}) set back from each side of the DQW by ~450-Å-thick $Al_{0.3}Ga_{0.7}As$ spacer layers. The sample is sandwiched between frontside and backside gates, each 0.5 mm away from the DQW and consisting of a Au layer on an insulating GaAs substrate.

The electron densities in each well are balanced by applying a bias to the backside gate until the beating in the Shubnikov-de Haas oscillations is minimized.[7] [The residual beating is due to the two different electron densities occupying the symmetric and antisymmetric states.] The total electron density can be shifted by applying a bias to the frontside gate and rebalancing the wells using the backside gate. In this manner, the electron density of our DQW is continuously tunable from $3.44\leq n\leq5.45\times10^{11}$ cm^{-2} while maintaining the electron balance between the two wells. The electron density can be further increased to 5.75×10^{11} cm^{-2} by shining a red light-emitting diode (LED) on the sample and subsequently balancing the wells with the backside gate. The electron mobility, μ, is 640000 cm^2/Vs at $n=4.55\times10^{11}$ cm^{-1}. It increases with increasing density in accord with the empirically established relationship, $\mu\propto n^{\alpha}$, where $\alpha\sim0.7$.[10,11] Although similar to a sample studied previously,[6,7] this sample has thinner undoped spacer layers and fewer total silicon dopants, resulting in a higher electron density and an increased range of accessible densities (including gateability even after LED illumination). These features prove critical for observing the electronic phase transition. We emphasize that all data in this paper are taken with the electron density balanced between the wells.

Within a single-electron model, application of a magnetic field perpendicular to the plane of the DQW forms a fan of spin-split Landau levels originating from the symmetric state. A second fan, originating from the antisymmetric state, is shifted to higher energy by Δ_{SAS}. Quantum Hall states occur at magnetic fields corresponding to the Fermi energy lying in either the cyclotron, Zeeman, or Δ_{SAS} energy gaps.[6,7] In the regime where the Zeeman energy is larger than Δ_{SAS} ($B\gtrsim1$ T for our sample), each Landau level is comprised of four energy levels: the lowest-energy state is the spin-aligned symmetric state, followed by the spin-aligned antisymmetric state, the spin-reversed symmetric state, and the spin-reversed antisymmetric state. The same pattern continues in higher Landau levels. The number of filled energy levels is given by the filling factor $\nu=nh/eB$, where n is the total electron density in the DQW and B is the perpendicular magnetic field. Thus, $\nu=1,3,5,7,\ldots$ correspond to the Fermi energy lying in the Δ_{SAS} energy gap; $\nu=2,6,10,14,\ldots$ correspond to the Zeeman gap; and $\nu=4,8,12,16,\ldots$ correspond to the cyclotron gap. [This pattern breaks down for $B\lesssim1$ T, because the Zeeman energy is smaller than Δ_{SAS}.]

Figure 1(b) shows R_{xy} and R_{xx} for the DQW with the relatively low density of $n=4.2\times10^{11}$ cm^{-2}. Note that all the quantum Hall states from $\nu=2$ to 12 are well formed. Upon illumination, the electron density increases to $n=5.7\times10^{11}$ cm^{-2}, shifting the filling factors to higher magnetic field, as shown in Fig. 1(c). Note that the $\nu=3$ state is now completely missing, despite the existence of all other states from $\nu=2$ to 12. Both sets of data in Fig. 1 were taken at $T=0.3$ K.

We attribute the destruction of the $\nu=3$ state to Coulomb-driven interwell density fluctuations:[8,9] (i) At $\nu=3$, the lowest single electron excitation consists of exciting an electron from a symmetric state to an unoccupied antisymmetric state across the Δ_{SAS} energy gap. This excitation locally unbalances the electron density between the two quantum wells. (ii) The Coulomb interaction can mix the antisymmetric states immediately above the Fermi energy into the many-body ground state, thereby allowing electrons in the same well to be more strongly correlated than electrons in different wells. (iii) If the Coulomb energy reduction per mixed-in antisymmetric state exceeds the Δ_{SAS} cost, the symmetric to antisymmetric excitation gap will vanish. The quantum Hall state will be replaced by a correlated bilayer state characterized by very weak interwell and strong intrawell correlations. Hartree-Fock calculations suggest the new bilayer state is a charge-density wave,[9] although a gapless quantum-fluid state seems equally possible.

Since Δ_{SAS} is fixed for a given DQW, increasing Coulomb interactions by increasing electron density should eventually result in a phase transition at $\nu=$odd.[8] Figure 2 provides an experimental observation of this phase transition. Here, the electron density has been continuously tuned by biasing the front and backside gates. The horizontal axis has been scaled by the density to vertically align filling factor. As in Fig. 1, all traces were taken at $T=0.3$ K. Note that the phase transition is quite sudden at $\nu=3$: for $n=4.63\times10^{11}$ cm^{-2}, the quantum

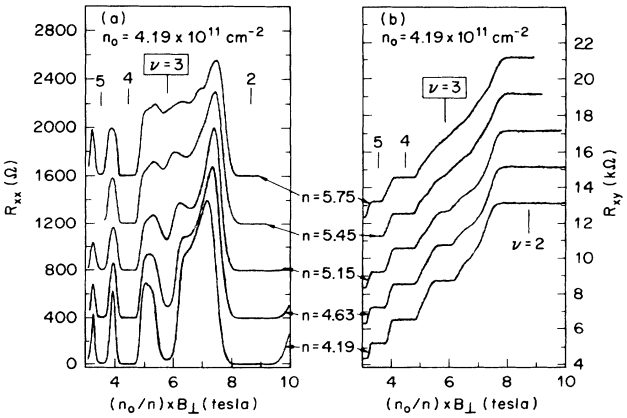

FIG. 2. Tuning the electron density through the $\nu=3$ phase transition. All data are taken at $T=0.3$ K; n is given in units of 10^{11} cm^{-2}. Traces are offset for clarity and the magnetic-field axis is scaled to vertically align filling factors.

Hall plateau is well formed, yet an 18% increase, to 5.45×10^{11} cm^{-2}, leaves only a residual inflection. Note also that $\nu=5$, like $\nu=3$, corresponds to the Fermi energy in the Δ_{SAS} gap, yet the $\nu=5$ state does not exhibit the phase transition. This is evidence that only the electrons in the highest occupied symmetric state can correlate (lower-energy electrons being frozen out). Thus, at $\nu=3$, there is an effective electron density of $n/3$, sufficient to drive the phase transition, while at $\nu=5$, $n/5$ is too low an effective density. Finally, the quantized states at $\nu=2$ and 4 exhibit no density dependence, since interwell fluctuations are not energetically favorable with the Fermi energy in the Zeeman ($\nu=2$) or cyclotron ($\nu=4$) energy gaps.

At $\nu=3$, the temperature dependence of the R_{xx} minimum is consistent with thermal activation (see Fig. 3) throughout the experimental range of densities: $R_{xx}=R_0\exp(-\delta/T)$, where δ is the activation energy. Unshown data for $3.44<n<4.16\times10^{11}$ cm^{-2} essentially superimpose the $n=4.16\times10^{11}$ cm^{-2} data of Fig. 3. Figure 4 contains the measured activation energies at $\nu=3$ plotted versus electron density (top scale) and corresponding magnetic field (bottom scale). The data suggest that δ is independent of electron density until $n\gtrsim4.2\times10^{11}$ cm^{-2}. At higher densities, δ decreases monotonically, reaching zero at $n\sim5.5\times10^{11}$ cm^{-2}.

The inset of Fig. 4 contains the phase diagram proposed in Ref. 8 for the Coulomb-driven destruction of $\nu=$odd quantum Hall states in DQWs. The dashed line is the calculated phase boundary including a correction for the finite width of the experimental quantum wells. $d=d_B+d_W$ is the distance between well centers [see Fig. 1(a)], l is the magnetic length, and $e^2/\epsilon_0 l$ is the Coulomb energy scale. The solid arrows, labeled by d_B, depict trajectories for a given sample (fixed d_B and Δ_{SAS}) as B or n increases. Solid and open symbols denote observed and missing quantum Hall states, where the circles are data of Ref. 6 labeled by filling factor, $\nu=1$ or 3. The data of this paper all lie between the open and filled diamonds on the $d_B=40$ Å trajectory. Thus, at least for $d_B=40$ Å, the position of the experimental phase transition is in excellent quantitative agreement with the calculation.

In the absence of disorder, activation energies presumably measure half the quasiparticle pair creation energy at $\nu=3$. Under this assumption, we would assign $n\sim4.2\times10^{11}$ cm^{-2} as a threshold density marking onset of interwell density fluctuations. At higher densities, the δ decreases as additional antisymmetric states mix into the ground state, increasing the possibilities for short-range correlation. Finally, at $n\sim5.5\times10^{11}$ cm^{-2}, the Δ_{SAS} cost is entirely offset by Coulomb energy reductions and the correlated bilayer state is fully realized.

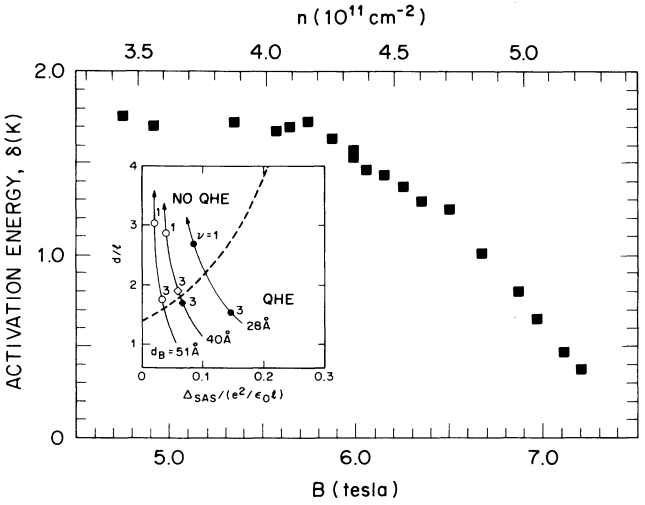

FIG. 4. Activation energies, δ, at $\nu=3$ as a function of electron density (top scale) and corresponding magnetic field (bottom scale). The inset contains the phase diagram from Ref. 8. The dashed line represents a Coulomb-driven DQW phase transition (see text). Solid and open symbols denote observed and missing quantum Hall states at filling factor ν. The phase transition reported in this paper occurs between the open and filled diamonds.

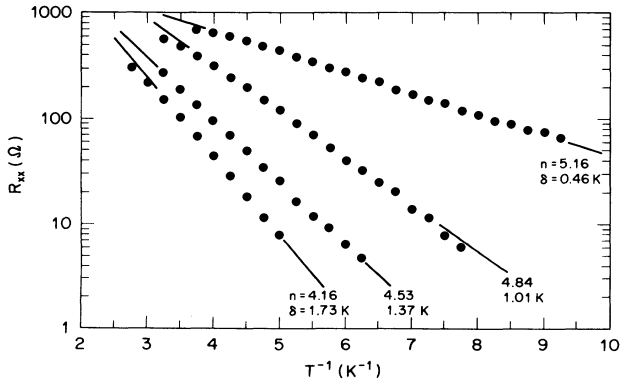

FIG. 3. Activated behavior of the $\nu=3$ minimum through the transition region. n is given in units of 10^{11} cm^{-2}. Data for $3.44<n<4.16$ essentially superimposes the $n=4.16$ data.

Single-mode calculations suggest an alternate interpretation of the sharp experimental transition.[8,12] The $\nu=3$ DQW dispersion relation exhibits a minimum excitation energy at wave vector $ql\sim1$ corresponding to an electrically neutral magnetoroton (similar to the fractional quantum Hall effect in a single electron layer). The magnetoroton minimum collapses slowly to zero with increasing electron density; however, activation energies probably correspond to the pair creation energy at $ql\rightarrow\infty$. Though inaccurate in this limit, the single-mode calculation suggests that the pair creation energy remains relatively unchanged as the magnetoroton collapses. At the phase transition, the activation energy would discretely switch to the pair creation energy of the correlated bilayer state (which the data suggests is gapless). From this point of view, the finite width of the experimental transition probably results from inhomogeneous broadening as regions of the sample undergo the phase transition at slightly different densities.

Finally, we mention two other structures, wide square wells and wide parabolic wells, which introduce third-dimensional degrees of freedom to highly mobile electron layers. It is possible that these systems will also exhibit phase transitions driven by electron correlations. In wide square wells (~1000 Å wide), the electrons form layers

at the two sides of the well. These layers are weakly coupled through a thick, shallow tunneling barrier whose shape is determined solely by the self-consistent potential. As the electron density increases, Δ_{SAS} decreases. To date, it has been observed that wider wells (smaller Δ_{SAS}) have fewer quantum Hall states at ν=odd,[13] in qualitative agreement with the DQW data.

Wide parabolic wells exhibit behavior qualitatively similar to the $\nu=3$ data of this paper, but at fractional filling factors $\nu=\frac{1}{3}$ and $\frac{2}{3}$.[14] In wide parabolic wells, increasing density increases the electron layer *thickness,* while leaving the in-plane areal density essentially unchanged. Increasing thickness, however, reduces intersubband energy splittings, thereby increasing the possibility of band mixing. Although it is possible that a physically similar phase transition occurs in both parabolic wells and DQWs, there are several distinctions to be considered: (i) To date, correlation effects in the parabolic well involve only fractional quantum Hall states.[15] (ii) In DQWs, even-numerator fractional states (e.g., $\nu=\frac{2}{3}$) have been observed to survive the DQW phase transition while odd-numerator fractional states do not.[6,7] (iii) There is an alternate mechanism suggested for the parabolic well: Increasing layer thickness makes the electron wave functions more rodlike, weakening the short-range component of the Coulomb interaction which gives rise to the incompressibility of the fractional quantum Hall states.[14,16]

In summary, our double quantum well data exhibit a phase transition at filling factor $\nu=3$ upon *in situ* increase of the electron areal density. The data establish the existence of a phase transition driven by electron correlation. The activated temperature dependence at $\nu=3$ may provide an experimental measure of the excitation gap throughout the transition region.

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[15]We note that Ensslin *et al.* [Phys. Rev. B **43**, 9988 (1991)] have reported the destruction and recovery of *integer* quantum Hall plateaus in parabolic wells; however, the underlying physical mechanism is manifestly not electron correlation. Ensslin *et al.* find that quantum Hall states are missing when the Fermi energy lies at a degeneracy (or near degeneracy) of Landau levels from different confinement subbands. They further demonstrate that the Hartree potential plays a dominant role in determining subband energy splittings as a function of electron density and magnetic field in parabolic wells. In DQWs, these effects are negligible and play no role in the phase transition reported herein. In DQWs, the thickness of the electron layers is strongly fixed by the confinement potential, thus there is less than a 10% change in Δ_{SAS} (the DQW analog of the subband energy splitting) as the electron density is varied in our sample. Furthermore, Ensslin *et al.* show that the subband energy splitting in parabolic wells depends dramatically on the relative occupation of the two lowest subbands. In DQWs, this effect is virtually nonexistent because the two lowest subbands, the symmetric and antisymmetric states, are essentially identical except in the center of the barrier, where the amplitudes of both wave functions are quite small.

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