Independently contacted two-dimensional electron systems in double quantum wells

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A new technique for creating independent ohmic contacts to closely spaced two-dimensional electron systems in double quantum well (DQW) structures is described. Without use of shallow diffusion or precisely controlled etching methods, the present technique results in low-resistance contacts which can be electrostatically switched between the two-conducting layers. The method is demonstrated with a DQW consisting of two 200 Å GaAs quantum wells separated by a 175 Å AlGaAs barrier. A wide variety of experiments on Coulomb and tunnel-coupled 2D electron systems is now accessible.

Electrical transport phenomena in two-dimensional electron systems (2DES) have been exhaustively studied for over 20 years.[1] While fascinating new results continue to be uncovered in purely 2D systems, effort has begun to shift toward either quasi-one or three-dimensional systems. Quasi-1D conductors are frequently fabricated by laterally confining an otherwise 2D electron gas.[2] Three-dimensional systems have been approximated by elaborating on the epitaxial techniques used to create the 2DES. Multiple quantum well structures, with any desired amount of interlayer tunneling, and wide parabolic single wells[3] with several occupied subbands, are notable examples. Novel correlated electron states are anticipated in many of these systems.[4,5]

Perhaps the simplest extension of the standard 2DES that promises to afford interesting new phenomena is the double quantum well (DQW). In this structure two 2D electron gases are established parallel to one another with a thin barrier between them. Recent magnetotransport experiments on DQW samples with substantial interlayer tunneling have already revealed evidence for a new kind of correlated electron state in the quantum Hall regime.[6] Even in the absence of tunneling, simple Coulomb interactions should give rise to novel ground states exhibiting the fractional quantum Hall effect.[5]

Most transport experiments on closely spaced (< 200 Å, say) quantum wells are restricted to "parallel" studies, i.e., those in which simultaneous electrical contact to all the quantum wells is forced by the difficulty of making reliable contact to the individual layers. Inability to perform independent transport measurements on both layers in a DQW, for example, rules out a wide class potential experiments. In this letter we demonstrate a new means of providing low-resistance ohmic contacts to the individual layers in a DQW. Beyond overall simplicity, this technique has the added advantage of allowing the contacts to be electrostatically switched between the two conducting layers.

To describe the technique, we first consider an idealized sample containing two quantum wells, each of width W and separated by a barrier of thickness D. This is illustrated in the upper inset to Fig. 1. Suitable doping is used to establish a 2DES in each well. Standard diffused In

contacts are made, and these contact both 2D layers simultaneously. Next, gate electrodes are evaporated both on the top and bottom of the sample. Although not shown in the figure, a standard mesa etch is used to define the conducting path and the gates are applied so as to fully cross the path.

Application of a negative bias potential V_t to the top gate electrode will result in depletion of the electrons within the quantum wells underneath the gate. For small $-V_t$ the depletion occurs only within the upper quantum
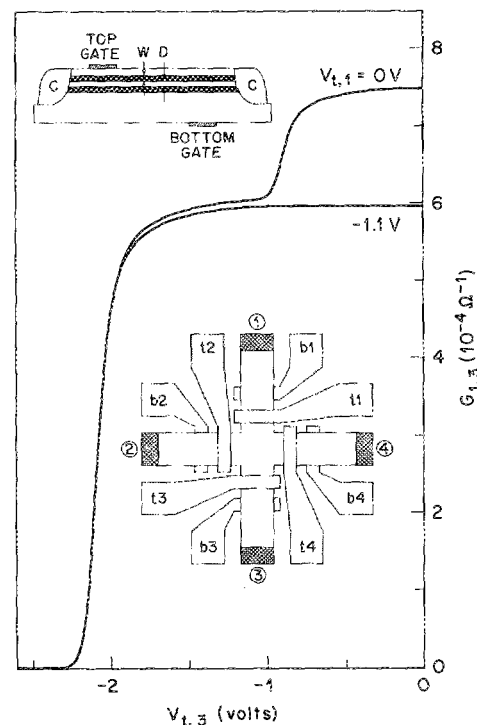

FIG. 1. Upper inset: idealized view of double quantum well structure fitted with two ohmic contacts C and top and bottom gates. Each quantum well is of width W and is separated from the other by a barrier of thickness D. Lower inset: sample mesa and gate configuration. At each end of the cross-shaped mesa a diffused In contact (No. 1–No. 4) is made. Each arm is fitted with top and bottom gates as shown. Data: Conductance $G_{1,3}$ vs top gate bias $V_{t,3}$ for two bias voltages $V_{t,1}$ on the "upstream" top gate. Side arms 2 and 4 are cut off by large (− 3 V) biases on their top gates. Data taken at 1.2 K. Substantial series resistances (leads and contacts) are included in the measured conductance.

well. Continued increase of $-V_t$ eventually fully depletes the upper well and begins depletion of the lower well. Therefore, a range of top gate bias voltages exists in which the two ohmic contacts are connected together only via the lower quantum well.

In exact analogy, the bottom gate can be negatively biased so that the lower quantum well above it is fully depleted but the upper well is not. If the top gate is not simultaneously depleting the upper well, the two contacts are connected only via the upper well. If both gates are suitably biased a condition is obtained in which the contacts are disconnected but neither gate depletes both wells.

In a more general multiprobe geometry, each ohmic contact can be surrounded by both top and bottom gates. These contacts might be along the edge of a mesa or in its interior. With appropriate bias voltages on the gates any contact can be connected to the bulk of the sample through either, or both, quantum wells. By extension, contact to any single quantum well, or contiguous set of wells, within a multiple quantum well structure should be achievable by appropriately biasing both the top and bottom gates. Independent transport measurements on the individual wells are thus possible.

The sample we have employed to demonstrate this technique is a GaAs/AlGaAs DQW growth by molecular beam epitaxy. Aside from two 200 Å GaAs wells separated by an undoped 175 Å AlGaAs barrier ($x \sim 0.3$) Si δ-doping layers are placed both below the lower well and above the upper well. Combined Shubnikov-de Haas and Hall effect magnetotransport measurements on unprocessed segments of the wafer yield 2D carrier concentrations in each well of around $N_s \sim 1.3 \times 10^{11}$ cm^{-2}, the two wells being equal to within 30%. An average mobility of approximately $\mu \sim 3 \times 10^6$ cm^2/V s is determined via the van der Pauw method.

Simple photolithographic techniques are employed to pattern a mesa structure on the sample top surface and to provide masks through which the top and bottom gates (aluminum) are evaporated. Before depositing the bottom gates the entire sample (5×5 mm) is thinned to a total thickness of 50 μm. A simple cross mesa, depicted in the lower inset to Fig. 1, is employed. Standard diffused In contacts are placed at the end of each arm. These make simultaneous electrical connection to both 2D electron systems in the DQW. In the central region of the mesa the arms are 100 μm wide, and each is crossed by 50-μm-wide top and bottom gates as shown. With these gates we can choose which 2DES layer is continuous from any contact in to the mesa center.

To demonstrate the action of the gates, we first render the device effectively two-terminal by biasing the top gates on arms 2 and 4 to -3 V (relative to their associated indium dot). This voltage is sufficient to fully deplete both quantum wells underneath the gate, thereby "cutting off" the contact. The conductance $G_{1,3}$ between arms 1 and 3 is now measured, using a constant 0.2 mV, 24 Hz excitation and a 100 Ω current-sensing resistor in series. As a two-terminal measurement, series lead (~ 300 Ω) and contact (~ 200 Ω) resistances influence the measured conduc-

tance. Figure 1 shows $G_{1,3}$ as a function of the top gate bias $V_{t,3}$ on arm 3 for two different fixed voltage $V_{t,1}$ on the top gate on arm 1. With $V_{t,1} = 0$, $G_{1,3}$ at first remains roughly constant as the bias $V_{t,3}$ is increased. At about $V_{t,3} = -0.9$ V of $G_{1,3}$ drops rapidly to a lower plateau. Further increase of, $-V_{t,3}$ eventually leads to a sharp drop of the conductance to zero around -2.3 V. These data clearly show the ability of the top gate to sequentially deplete the quantum wells.

Figure 1 also shows $G_{1,3}$ vs $V_{t,3}$ with the "upstream" top gate on arm 1 set at $V_{t,1} = -1.1$ V. This value provides complete depletion of the upper quantum well under top gate 1, while leaving the lower well nearly full. Now as $-V_{t,3}$ is increased from zero there is no drop to a lower plateau when the upper well under top gate 3 depletes. This is simply because the upper well is carrying no current since it is severed upstream by top gate 1. Only when top gate 3 begins to cut the lower well, around -2 V, does $G_{1,3}$ begin its drop to zero.

The data in Fig. 1 convincingly demonstrate our ability to switch the current injection from both wells to only the lower well using a top gate and a simple In contact. The data also prove there are no unintentional "shorts" between the wells in the region between top gates 1 and 3. Studies with larger mesa dimensions gave strong evidence for such shorts. Their existence was obvious: the same plateau structure was observed in $G_{1,3}$ vs $V_{1,3}$ regardless of whether top gate 1 was deleting the upper quantum well or not. Apparently the shorts were associated with visible defects on the sample surface since using smaller mesas and avoiding the defects solved the problem. We can simulate the effect of a short by removing the barrier to one of the side arms of the mesa and allowing access to the In contact (or any other conducting defect) on that arm. This is demonstrated below.

The bottom gates show similar depletion characteristics to the top gates; only the voltages required are about 100 times larger. Figure 2(a) again shows $G_{1,3}$ with arms 2 and 4 cut off by large negative biases on their respective top gates. In the figure, sweeps of $G_{1,3}$ vs $V_{t,3}$ are shown for several values of the bias $V_{b,1}$ on the upstream bottom gate. The basic two-step shape of $G_{1,3}$ remains intact until $V_{b,1}$ reaches about -120 V. Beyond -120 V the lower plateau in the conductance, for which all the current flows in the lower quantum well, has essentially disappeared. In this condition the bottom gate has fully depleted the lower well above it. Obviously, since there is still substantial conductance when the top gate bias $V_{t,3} = 0$, the upper well is not significantly depleted at $V_{b,1} = -130$ V. From Fig. 2(a) we conclude that for $V_{b,1} = -130$ V and $1.1 < -V_{t,3} < 2.2$ V a situation has been obtained wherein In contact No. 1 is connected to the central region of the mesa only via upper quantum well, and In contact No. 3 is so connected only via the lower well. That negligible current flows in this situation demonstrates the high degree of isolation obtained between two 200 Å wells separated by a 175 Å barrier. The small residual conductance observed around 2×10^{-5} Ω^{-1} suggests the presence of weak shorts between the quantum wells. Whether these shorts repre-
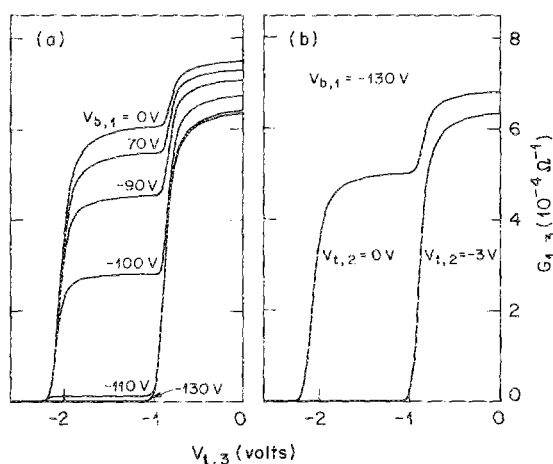
FIG. 2. (a) Conductance $G_{1,3}$ vs top gate bias $V_{t,3}$ for several voltage $V_{b,1}$ on the "upstream" bottom gate. By $V_{b,1} = -120$ V complete depletion of the bottom quantum well above the gate has been reached. Side arms 2 and 4 are cut off. (b) Effect of inducing a "short" between the quantum wells. Side arm 2 is opened up when $V_{t,2}$ is raised from -3 V to zero.

sent simple or impurity-assisted tunneling or some other mechanism, requires further study.

An additional check on these conclusions is obtained by opening up one of the side arms on the cross mesa. Figure 2(b) shows the result of setting the top gate bias $V_{t,2}$ on arm 2 to zero. In effect this provides a short between the quantum wells, either via In contact No. 2 or some conducting defect beyond gate 2. As the figure shows, the result is the return of the two-step characteristic of $G_{1,3}$ vs $V_{t,3}$, even though bottom gate 1 is depleting the lower well ($V_{b,1} = -130$ V). The lower plateau now re-

sults from current injection into the upper well only, some of which transfer to the lower well at the short, followed by collection downstream beyond top gate 3.

With the four-probe geometry employed here, a number of other transport configurations can be realized. For example, we have measured the carrier concentrations of the two wells independently, corroborating our earlier estimates made without the benefit of independent contacts to the individual quantum wells. Several additional experiments can be envisioned. these include tunneling studies in DQW structures, "Coulomb drag" experiments in which a current in one quantum well produces a drag voltage in the other well, studies of the fractional quantum Hall effect in the presence of a nearby parallel conducting plane, etc. All of these require a scheme for providing independent contact to closely spaced 2D electron gas layers.

To summarize, a simple technique has been demonstrated for producing low-resistance ohmic contacts to closely spaced 2D electron gas layers. With use of top and bottom gates a contact can be switched between either individual 2D layer or be allowed to connect to both layers simultaneously. A new class of experiments is now possible.

[1] For a review, see T. Ando, A. Fowler, and F. Stern, Rev. Mod. Phys. 54, 437 (1982).
[2] See Nanostructure Physics and Fabrication, edited by M. A. Reed and W. P. Kirk (Academic, San Diego, 1989).
[3] M. Sundaram, A. C. Gossard, J. H. English, and R. M. Westervelt, Superlatt. Microstuc. 4, 683 (1988); M. Shayegan, T. Sajoto, M. Santos, and C. Silvestre, Appl. Phys. Lett. 53, 791 (1988).
[4] B. I. Halperin, Jpn. J. Appl. Phys. 26, Suppl. 26-3, Part 3 (1987).
[5] See, for example, A. H. MacDonald, Surf. Sci. 229, 1 (1990).
[6] G. S. Boebinger, H. W. Jiang. L. N. Pfeiffer, and K. W. West, Phys. Rev. Let. 64, 1793 (1990).