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LETTER TO THE EDITOR

Resonant coupling effects observed in independently contacted triple-quantum-well structures

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Abstract. Independent contacts have been produced to all three two-dimensional electron gases (2DEGs) in a triple-quantum-well structure. This has been achieved by using *in situ* focused ion beam implantation followed by molecular beam epitaxial regrowth. Lateral transport studies of the individual layers have demonstrated resonant coupling between the high-mobility 2DEGs. Large resistance changes are observed due to coupling between the layers and these can be enhanced by having all three 2DEGs on resonance. A versatile device can thus be fabricated for studying electron interactions.

In the last few years there has been a rapid increase in the study of closely spaced electron gases. In particular, there have been many investigations of double quantum wells (DQWs) [1, 2] in which the interactions of the two conducting layers can be probed. The high mobilities obtainable by molecular beam epitaxy (MBE), in combination with the precision of growth, have enabled a systematic study to be made of a number of effects. These have included studies related to interlayer wavefunction coupling [3] and Coulomb interactions [4]. An important ingredient for developing the studies of DQW structures has been the ability to contact the two conducting layers independently, thereby enabling measurements of the layers to be made separately [5] as well as tunnelling between the layers [6]. This has led to the observations of a Coulomb gap [7, 8] in the tunnelling in a magnetic field, Coulomb drag between layers [9] and incompressibility phenomena [10].

These DQW structures have also exhibited properties that may lead to the fabrication of quantum effect devices. The lateral transport of the individual layers is found to show regions of positive and negative transconductance, which are a direct result of the interlayer tunnelling [5]. The short times associated with this tunnelling process mean that the devices can be driven at high speed and thus may be used for generation of harmonics at high frequency [11]. In addition, the tunnelling can be used to transfer current between the layers, which may lead to the development of a high-speed current switch. Finally, measurement of the tunnelling process reveals regions of negative differential resistance (NDR) [6] which are similar to those seen in double-barrier resonant tunnelling diodes (DBRTDs). One major difference between our structures and more conventional DBRTDs is that the carrier densities in the emitter and collector regions can be continuously changed, with front and back gates, so altering the threshold voltage for the NDR region.

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The natural extension of this work is the inclusion of a third quantum well to produce three two-dimensional electron gases (2DEGs) in a triple-quantum-well (TQW) structure. This adds a further degree of freedom for designing devices, which can be used to enhance the device performance. Alternatively, this provides a parameter for investigating the interlayer interactions [12]. In this letter, we present the first results from such a structure, demonstrating independent contacting of each 2DEG. An *in situ* focused ion beam implantation process [13] is used to define a patterned back gate which, in combination with front gates, is used to produce the independent contacts to the different layers. A versatile device can thus be fabricated where the carrier densities in the top and bottom 2DEGs can be controlled by front and back gates respectively. In addition, all voltage probes can independently contact *any* of the three 2DEG layers. This has enabled us to measure all three 2DEGs separately and study the interlayer coupling between the different 2DEGs.

Devices were grown by MBE, with the layer sequence shown in figure 1(b). After growth of the n^+ GaAs layer, the wafer was transferred under ultrahigh-vacuum conditions to a separate chamber for ion implantation. Here a 30 keV Ga focused ion beam was used to pattern selectively the n^+ GaAs layer, rendering the exposed areas insulating [13]. Separate conducting regions can thus be defined, which are used as back gates (B_g) to control the carrier density under the mesa, or as back depleting gates (B_{dg}) which lie under the arms of the voltage probes and are used to achieve independent contacting. The various regions of the back gate are shown in the plan and cross sectional diagrams of the device shown in figure 1.

After implantation the wafer was returned to the growth chamber where the subsequent layers were grown. These consisted of three quantum wells in which modulation doping was used to form high-mobility 2DEGs. This particular design of the TQW structure was chosen to ensure that all three QWs would be populated with carriers. In order to determine the type of structured needed, test data were obtained using a one-dimensional self-consistent Poisson and Schrödinger simulation. The results indicated that for equal-sized QWs, and modulation doping on either side of the outer wells, the middle QW would be unpopulated. This is a result of the band bending introduced by the electrons that occupy the outer QWs; this causes a lowering of the Fermi energy in the middle QW to below the ground-state energy. If the middle QW is, however, made thicker than the outer QWs, the ground-state energy of the middle 2DEG can be lowered with respect to the outer QWs, and the middle QW can then be populated. The outer QWs were therefore made 11 nm thick, which is sufficiently wide that interface scattering, which becomes significant for QWs less than 10 nm, would not degrade the 2DEG mobility. A middle QW of 20 nm then allows all three QWs to be populated.

The widths of the barriers separating the QWs were chosen on the basis of two requirements. If the barriers are made too small, the non-resonant tunnelling becomes large and independent contacting becomes unfeasible. The barrier also has to be sufficiently thin that significant resonant tunnelling can still be observed. This led to the choice of 14 nm barriers separating the QWs, for which the calculated symmetric–antisymmetric energy splitting Δ_{SAS} for two adjacent QWs is of the order 0.5 μeV. This is within the range where wavefunction coupling effects are minimal but resonant tunnelling should still be significant [15].

After growth, conventional optical lithography was performed to define a mesa and produce AuGeNi ohmic contacts. These contacts penetrate deep into the sample and therefore contact all three 2DEGs simultaneously. To prevent these contacts shorting to the back gate, they are formed over regions where the back gate layer has been ion damaged (see figure 1(b)). The back gate regions were also contacted with AuGeNi ohmic contacts,

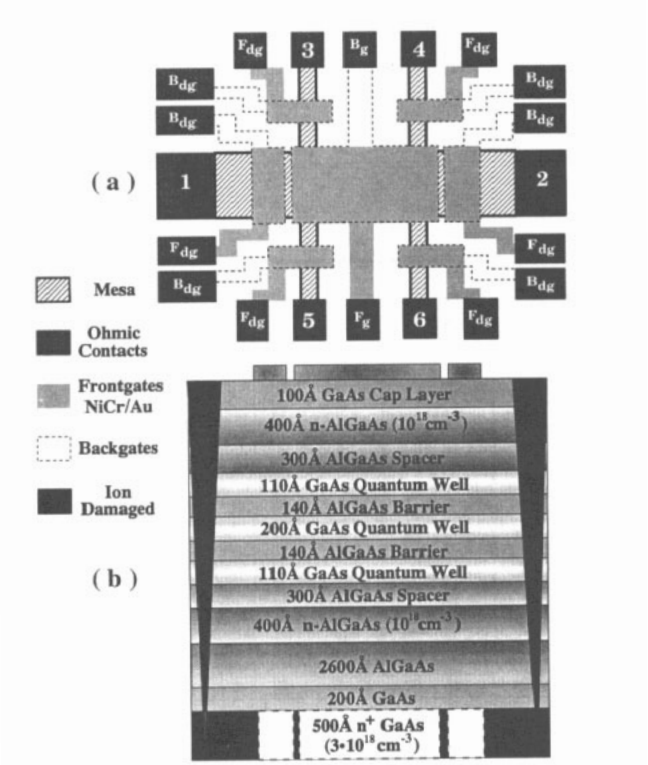

Figure 1. The plan (a) and cross sectional (b) diagrams of the TQW structure are drawn. The diagram shows six voltage probes (labelled 1 to 6) each of which has an associated front (F_{dg}) and back depleting gate (B_{dg}). There are also full front (F_g) and back gate (B_g) to control the carrier densities in the active area.

but in this case the contacts were formed off the mesa and so connect to the n^+ layer only. Using the technique of *in situ* focused ion beam lithography, the back gate could be placed close to the conducting layers and still operate reliably at low temperatures with negligible leakage current over a wide range of voltages. For the TQW structure, the back gate is located 350 nm from the bottom conducting layer, and voltages in excess of −2.5 V can be applied with the leakage remaining below 1 nA. This voltage range is found to be sufficient to deplete all the conducting layers of the TQW structure.

Schottky gates of NiCr (20 nm) followed by Au (100 nm) were patterned on the surface. These are used to control the carrier density in the mesa region (F_g) and produce depleting gates (F_{dg}) which lie on top of the arms of all the voltage probes (see figure 1(a)). Each voltage probe, therefore, has a front and back depleting gate that can be used to pinch off the conduction in the different layers of the TQW. The front depleting gate can be used to deplete the top and middle 2DEGs to produce an independent contact to the bottom 2DEG. Similarly, the back depleting gate can be used to deplete the bottom and middle 2DEGs to enable independent contacting of the top 2DEG. Finally, depletion of the top 2DEG with the front gate and bottom 2DEG with the back gate allows contact to the middle 2DEG alone. In this manner, any of the voltage probes can be used to probe any of the three 2DEGs by merely altering the associated depleting gate voltages. Using this method for producing independent contacts, the magnetoresistance of the three individual layers were measured separately, as shown in figure 2. The graphs show the characteristic Shubnikov–de Haas effect for a four-terminal constant current measurement. The traces show no signs of a low-field positive magnetoresistance or beating in the period of the oscillations, which are seen when two or more layers are measured in parallel [14]. Instead, a single oscillation is observed, the period of which can be used to determine the carrier density in the 2DEG. The individual carrier densities, and the calculated mobilities of the three different 2DEGs, are marked on the traces in figure 2.

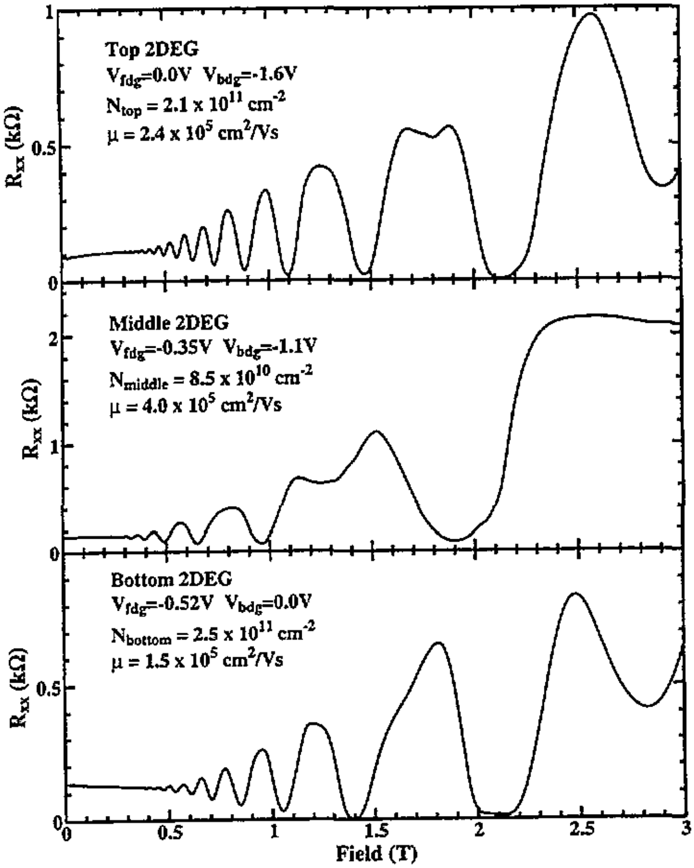

Figure 2. The longitudinal magnetoresistance measured at 1.6 K for the three 2DEGs separately. The characteristic periodic magneto-oscillations are observed from which the carried density can be directly calculated, the results of which are shown for each 2DEG. The mobility of each layer has also been calculated and the outer QWs are found to have a similar mobility and carrier concentration. The middle 2DEG has a much lower carrier density but still has a higher mobility, indicating that this is the highest quality layer.

The degree of coupling between the layers was measured by performing lateral transport measurements of the independently contacted middle 2DEG. The resistance of the middle 2DEG is plotted as a function of the back gate in figure 3(a) and as a function of the front gate voltage in figure 3(b). As the back gate voltage is altered, the number of carriers in the bottom well changes approximately linearly with voltage, as can be determined from magnetoresistance characterization of the device. The effect on the number of carriers in the middle layer, though, is small due to the screening of the electric field by the charge in the bottom 2DEG. The middle 2DEG carrier concentration therefore remains approximately constant as the gate voltage is altered. A large dip in the measured middle 2DEG resistance occurs, however, when the number of carriers in the bottom 2DEG matches that in the middle 2DEG. This decrease has been seen before in DQW structures [5] and is associated with tunnelling between the two 2DEGs. This is a resonant process since the electrons must conserve both energy and momentum, a condition that is only satisfied when the carrier densities in the two layers are matched. The onset of tunnelling provides an extra current path that results in a decrease in the resistance that is measured. As the back gate voltage is made even more negative, the bottom layer has a lower carrier concentration than the middle and the resonant tunnelling drops, resulting in a rise of the resistance. Similarly, when the front gate voltage is varied, a resonance between the middle 2DEG and the top 2DEG can be probed as seen in figure 3(b). The size of the resistance change is similar in the two cases which reflects the fact that the top and bottom 2DEGs are of similar mobility.

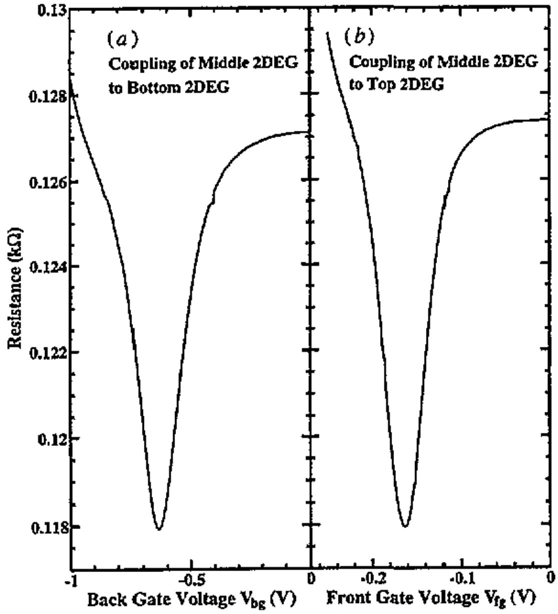

Figure 3. The device resistance as measured when independent contacts are made to the middle 2DEG. In (a) the resistance is plotted as a function of the back gate voltage with the minimum occurring when the carrier densities in the middle and bottom 2DEGs are matched. Similarly, in (b) the front gate voltage is altered, and the minimum resistance is now measured when the carrier densities in the middle and top 2DEGs are equal.

The resistance of the independently contacted middle 2DEG can therefore be used as a direct probe of the degree of coupling between the 2DEGs. This can be used to map out the coupling between all three layers. Figure 4 is a three-dimensional plot in which the resistance of the middle 2DEG is plotted as a function of the front and back gate voltages. The data shows minima in the resistance when the carrier density in the middle 2DEG is matched with that in the top *or* bottom 2DEGs. An even stronger resonance is observed when all three QWs have matched carrier densities. This corresponds to the large minimum in the centre of the plot. In this case, the current injected into the middle 2DEG can flow through two extra current paths; hence the current is divided between all three 2DEGs and the resistance is greatly reduced. In this way, the current flow through the top 2DEG can be controlled with the front gate, and the current through the bottom 2DEG with the back gate.

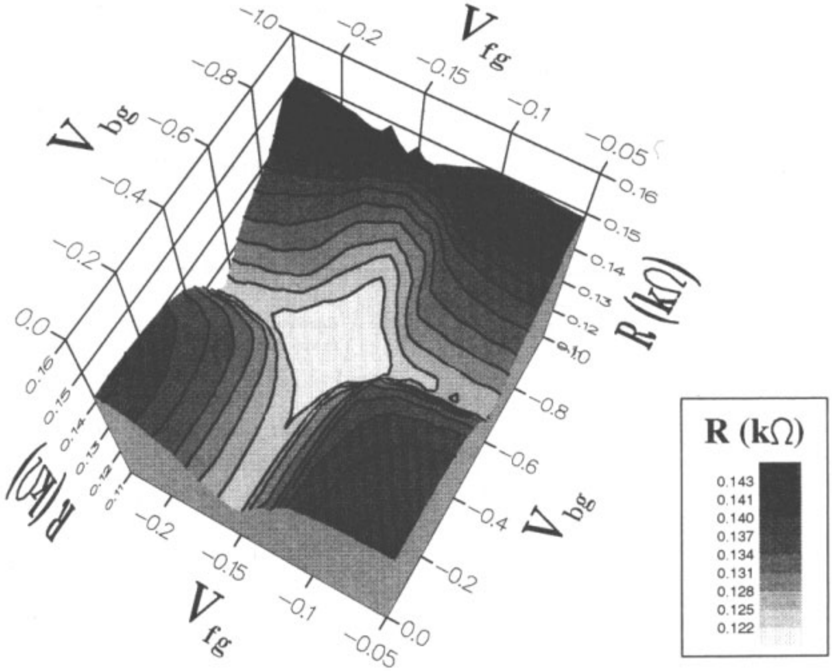

Figure 4. The dependence of the resistance of the middle 2DEG is plotted as a function of both the front gate (V_{fg}) and the back gate voltage (V_{bg}). The resistance is decreased by the coupling to the other 2DEGs and hence the resistance data shown in the figure can be used to directly map out the strength of the coupling.

We have demonstrated, for the first time, the ability to contact independently all three 2DEGs of a TQW structure. Each layer can be probed separately and the carrier concentrations in the top and bottom 2DEGs can be changed independently. This provides a very versatile device for studying electron interaction effects. In particular, we have been able to observe resonant coupling between the 2DEGs which causes large resistance changes. This effect can be enhanced by having all three 2DEGs on resonance. Although we have concentrated in this letter on the lateral transport through this structure, other measurements can readily be performed. These include direct tunnelling between the layers, Coulomb drag induced between the layers and studies of incompressibility. The added degree of freedom provided by the inclusion of an extra 2DEG, provides a new method for investigating fundamental electron interactions, as well as for designing new quantum effect devices.

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