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**LETTER TO THE EDITOR**

# Gating schemes for controlling the electron wavefunction between GaAs and $In_{0.05}Ga_{0.95}As$ quasi-one-dimensional channels

**M D Godfrey[1,2,3], A Husmann[2], H E Beere[1], D A Ritchie[1], S N Holmes[2] and M Pepper[1,2]**

[1] Cavendish Laboratory, University of Cambridge, J J Thompson Avenue, Cambridge CB3 0HE, UK
[2] Toshiba Research Europe, 260 Cambridge Science Park, Milton Road, Cambridge CB4 0WE, UK

E-mail: mdg39@cam.ac.uk

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**Abstract**
The selective composition control of the electron wavefunction in a GaAs/InGaAs double quantum well device is presented for two different gating schemes. In particular, electron-beam defined surface gates schemes allow the definition of non-ballistic quasi-one-dimensional conduction channels in each of the quantum wells and result in the ability to electrostatically move the electron wavefunction between the two materials. The use of such a device as the basis for a spin qubit, due to the differing $g$-factors, and the investigation of other spin-related phenomena in one-dimension are discussed.

The development of III–V crystal growth techniques has led to the investigation of countless uniquely designed heterostructures. Of certain interest is the development of double quantum well (DQW) structures, where two quantum wells are separated by a narrow barrier 2–30 nm thick. Such structures have been used to investigate interaction effects, tunnelling and Coulomb drag between two-dimensional electron gases (2DEGs) [1, 2]. Recently, coherent spin transfer between two coupled quantum wells was measured optically [3], though spin transfer has yet to be measured through transport measurements alone. In general this work has been performed on samples consisting of two GaAs quantum wells separated by an AlGaAs barrier. A bilayer electron system in an $AlAs/Al_{0.1}Ga_{0.9}As$ heterostructure has been demonstrated [4]. The electrons lie in the X and Γ points of the Brillouin zone, respectively, creating a DQW structure without the need for a material barrier between the two wells, due to a suppression

[3] Address for correspondence: Cavendish Laboratory, University of Cambridge, J J Thompson Avenue, Cambridge CB3 0HE, UK.

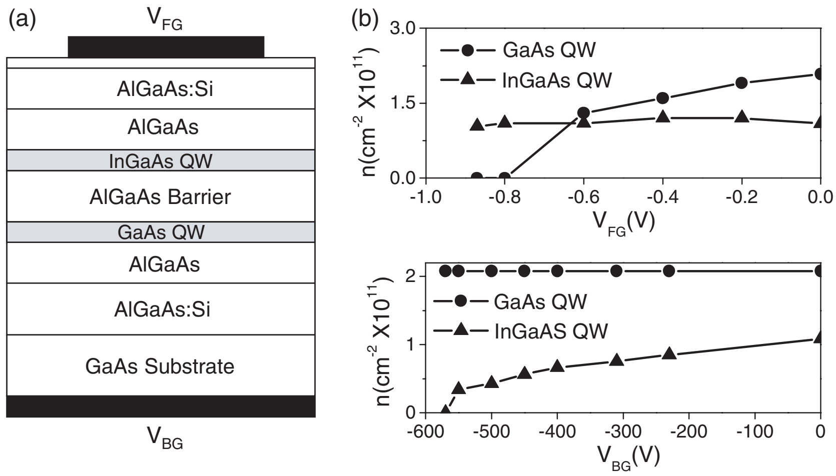


**Figure 1.** (a) Schematic diagram of device layer structure and gating arrangement. Evolution of carrier densities of the two quantum wells with applied electric field from (b) front gate or (c) back gate.

of tunnelling. In this letter we report on investigations into a DQW structure where the two quantum wells are formed in different materials, GaAs and $In_{0.05}Ga_{0.95}As$. Incorporating InGaAs causes certain limitations due to a lattice mismatch. However, previous studies have shown that for $In_xGa_{x-1}As$ with $x$ less than 0.3 pseudomorphic growth is possible [5]. Two-dimensional electron gases formed in InGaAs differ from those formed at a GaAs/AlGaAs heterojunction (high electron mobility transistor: HEMT) in that the mobility is limited by scattering due to the random potential from the alloy and the mobility is much lower than that of an equivalent GaAs/AlGaAs HEMT. However, the implementation of double quantum wells in separate materials, such as the AlAs/AlGaAs system described in [4] and the GaAs/InGaAs system described here, could have significance in the continued drive towards a semiconductor logic gate for quantum computing. This follows a proposal by Vrijen *et al* [6] where single qubit rotations are achieved by the movement of a single electron between regions of differing electron $g$-factor and the application of a constant external field. The electron $g$-factor is highly dependent on composition in both the GaAs–AlAs and GaAs–InAs material systems [7].

The structure investigated was grown by molecular-beam epitaxy and consists of 20 nm $Al_{0.33}Ga_{0.67}As$ (Si doped), 40 nm $Al_{0.33}Ga_{0.67}As$, 15 nm GaAs quantum well, 30 nm $Al_{0.33}Ga_{0.67}As$ barrier, 15 nm $In_{0.05}Ga_{0.95}As$ quantum well, 40 nm $Al_{0.33}Ga_{0.67}As$, 20 nm $Al_{0.33}Ga_{0.67}As$ (Si doped), and a 17 nm GaAs cap at the surface. This is shown schematically in figure 1(a). The 30 nm barrier separating the two conducting channels means that the quantum wells are uncoupled [8]. Ohmic contacts were made to the two quantum wells in parallel using evaporated and annealed Au/Ge/Ni. Two device designs are discussed in this letter, both of which are used to control the vertical position of the electron wavefunction. The first, device A, is in a Hall bar geometry and has a metallic back gate evaporated onto the substrate and a semi-transparent front gate. The second device design, device B, is used to achieve electron wavefunction control using surface gates only, utilizing quasi-one-dimensional channels in each of the quantum wells. In this case the surface gates are patterned by electron-beam lithography, and are in the split-gate midline geometry previously used in the investigation of double GaAs quantum wells [8].

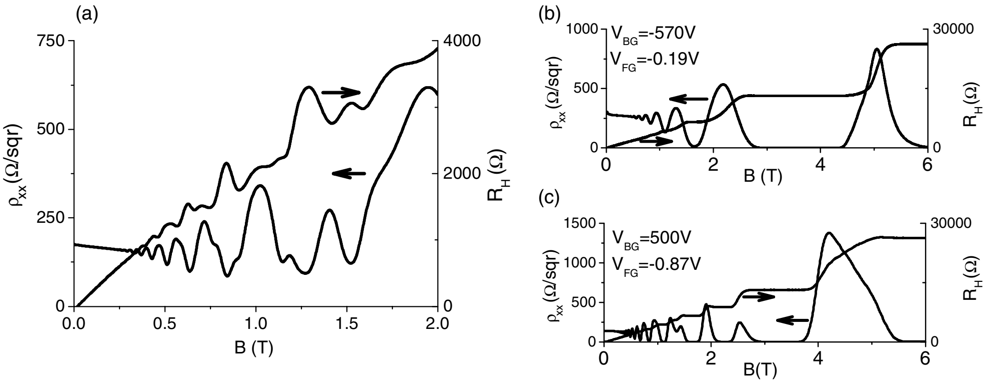


**Figure 2.** Magnetotransport measurements at 1.5 K of device A. (a) No gate bias applied, resulting in parallel conduction through the two quantum wells, (b) gate bias limits conduction to InGaAs 2DEG, (c) gate bias limits conduction to GaAs 2DEG.

The gating configuration of device A is shown in figure 1, and magnetotransport measurements are shown in figure 2. Figure 2(a) shows measurements of an ungated sample and demonstrates that the wafer is parallel conducting with a 2DEG formed in both quantum wells. The fast Fourier transform (FFT) of the Shubnikov–de Haas oscillations is used to measure the carrier densities of the two quantum wells. The carrier densities of the two 2DEGs are measured to be $1.6 \times 10^{11}$ cm$^{-2}$ for the GaAs and $2.3 \times 10^{11}$ cm$^{-2}$ for the $In_{0.05}Ga_{0.95}As$ quantum wells, respectively. Figures 1(b) and (c) show the evolution of the carrier densities of the two quantum wells with applied electric field from either the front gate or back gate, with the remaining gate set to 0 V. By applying a negative front gate voltage the peak frequency of the FFT signal is observed to decrease for the upper ($In_{0.05}Ga_{0.95}As$) well until it is fully depleted, leaving just the remaining GaAs 2DEG (magnetotransport data in figure 2(c)). Similarly, by applying a large negative voltage to the back gate it is possible to deplete the GaAs 2DEG, leaving only the remaining InGaAs 2DEG (figure 2(b)). It can be seen that when two 2DEGs are present, the one further from the gate is shielded from the applied electric field by the closer one. Once the front or back gate has been used to isolate a single 2DEG the remaining gate can be used to tune the carrier density of the remaining channel. In the data shown in figures 2(b) and (c) the 2DEGs have been tuned to have a carrier densities of $1.6 \times 10^{11}$ cm$^{-2}$. At this carrier density the measured mobilities of the independent channels are $2.8 \times 10^5$ cm$^2$ V$^{-1}$ s$^{-1}$ for the GaAs and $1.3 \times 10^5$ cm$^2$ V$^{-1}$ s$^{-1}$ for the $In_{0.05}Ga_{0.95}As$ quantum well. Transport through the two quantum wells is limited by different scattering mechanisms. The GaAs quantum well is limited by scattering from the remote ionized donors and the InGaAs quantum well is limited by alloy scattering [9]. The mobility of the GaAs quantum well is also reduced compared to standard HEMTs due to interface scattering at the bottom GaAs/AlGaAs interface.

A second method of electrical control of the 2DEG composition has been investigated using surface gates only, whilst the back gate remains grounded at all times. Previous studies have shown that electron-beam defined surface gates can control the position of the electron wavefunction in double quantum well systems [8]. The gate pattern studied here is shown in the insets of figure 3 and contains a pair of split-gates with a midline between them. The split-gates have a width of 1.2 $\mu$m and a length of 400 nm. The midline is deposited in the middle of the split-gate and has a width of 400 nm. Previous work has shown that a negative split-gate voltage $V_{SG}$ defines narrow conducting channels in both the upper and lower quantum wells. However, as $V_{SG}$ becomes more negative, the subbands in the lower channel are depopulated

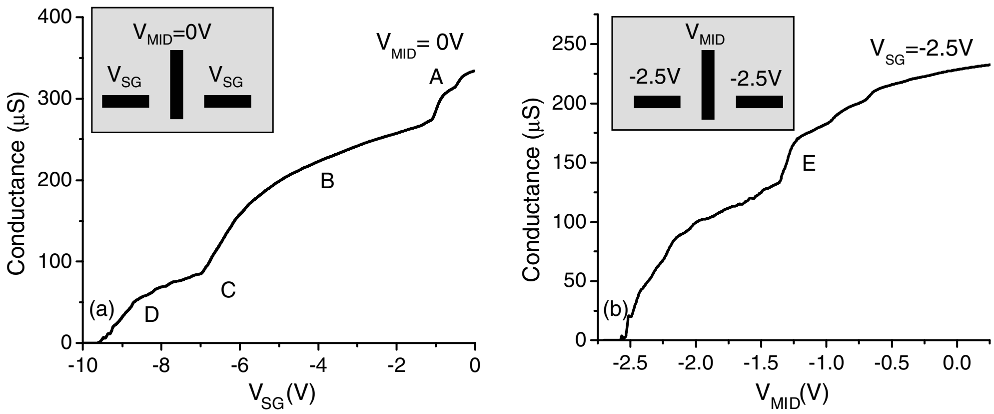


**Figure 3.** Conduction through the split-gate midline device as a function of either (a) split-gate voltage $V_{SG}$, or (b) midline voltage $V_{MID}$. Regions A–E are explained in detail in the text.

first, and then the upper channel depopulates. The midline voltage $V_{MID}$ has the opposite effect; as it is made more negative, the upper channel is depopulated first. Therefore, by varying $V_{SG}$ and $V_{MID}$, the fraction of the current passing through the upper and lower channels can be tuned. Figure 3 shows the two-terminal conductance ($G = I/V$) of the sample as a function of applied gate voltage. In figure 3(a) the split-gate voltage is swept at constant midline voltage, $V_{MID} = 0$ V, as $G(V_{SG})$ is measured, and in figure 3(b) the midline voltage is swept at constant split-gate voltage, $V_{SG} = -2$ V, as $G(V_{MID})$ is measured. We can identify the following different transport characteristics, labelled A–E. Region A shows the definition of narrow, non-ballistic quasi-one-dimensional conduction channels in the two quantum wells, similar to the definition usually seen in one-dimensional split-gate devices [10]. During region B conduction is allowed through both quantum wells, and the channel in the GaAs quantum well is slowly depleted. This depletion is finally achieved at point C ($V_{SG} = -6.8$ V), where there is a sharp change in gradient of the conductance trace. This lesser gradient is due to the higher sheet resistance of the $In_{0.05}Ga_{0.95}As$ quantum well. Finally, region D shows the depletion of the $In_{0.05}Ga_{0.95}As$ quantum well. The low mobility of the sample means that the mean free path of the electrons is less than the length of the channel, and so ballistic effects such as quantized conductance are not observed. Quantized conductance has been observed in an InGaAs quantum well (as shown in [9]), and the resonances observed in region D are associated with the disorder of the $In_{0.05}Ga_{0.95}As$ lattice and the roughness of the $In_{0.05}Ga_{0.95}As$ interfaces [9] and are seen throughout the $In_{0.05}Ga_{0.95}As$ conduction region. These resonances are reproducible between sweeps and after thermally cycling the device. Thus using the split-gates alone allows conduction to be limited to the InGaAs well only.

Figure 3(b) shows a sweep of the midline gate when the pair of split-gates are held at $V_{SG} = -2.5$ V after the definition of the narrow conducting channels. As $V_{MID}$ is made more negative the InGaAs quantum well is depleted first. Then at point E the upper well is fully depleted, leaving conduction through the lower well only, which is slowly depleted until at $V_{MID} = -2.6$ V where the conduction falls to zero. Thus the application of $V_{MID}$ allows conduction to be limited to the GaAs quantum well.

The gate characteristics of device B can be mapped in a two-dimensional parameter space ($V_{SG}$, $V_{MID}$) by plotting the transconductance, $dG/dV_{SG}$ as shown in figure 4, obtained by measuring $G(V_{SG})$ at various constant values of $V_{MID}$. Transconductance is plotted to demonstrate the combined effect of the split-gate midline design, and to visualize the regions

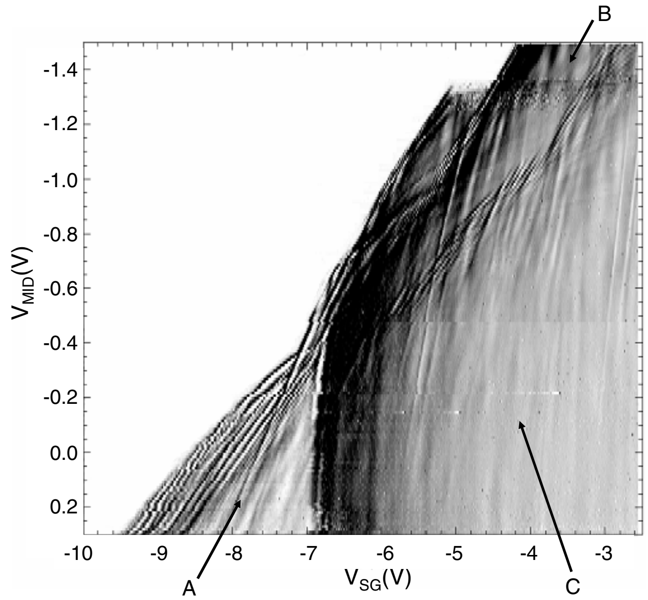


**Figure 4.** Transconductance $dG/dV_{SG}$, presented as a greyscale, of the split-gate midline device as a function of split-gate voltage $V_{SG}$ and midline voltage $V_{MID}$.

of large changes in conductance as these are associated with the regions of interest. Dark areas represent transconductance maxima. In figure 4 it is possible to identify the three transport regimes available in the device, labelled A–C. Region A shows the characteristic resonances of conduction through InGaAs as this is the only conducting quantum well, whilst region B shows conduction through GaAs only. Finally, region C shows a large gate range where conduction is allowed through both quantum wells. Thus through a choice of appropriate values for $V_{SG}$ and $V_{MID}$ conduction can be limited to either GaAs, InGaAs or allowed through both layers and switched between them.

In conclusion, we have demonstrated two gating schemes for selecting the material composition of the electron wavefunction in a GaAs/InGaAs double quantum well. Large-area front and back gates allow the isolation of a two dimensional electron gas in either well, whilst through the use of a split-gate midline device it is possible to select the conduction pathway through a GaAs/InGaAs double quantum well device with quasi-one-dimensional channels using surface gates only. The application of a GaAs/InGaAs DQW structure is a stepping-stone towards a successful spin qubit, due to the difference in Landé $g$-factor between the GaAs and InGaAs [7], where a single electron is moved between the two materials. The high dependence of the $g$-factor on the InGaAs composition make the GaAs/InGaAs material system ideally suited for such an application. Such a DQW system may also be used to investigate the effect of the local $g$-factor and spin–orbit coupling on various low-dimensional spin-related phenomena, such as the $0.7(2e^2/h)$ conductance structure in quantum wires [11] and the Kondo effect in quantum dots [12].

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