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GaAs/AlGaAs/InGaAs Vertical Triple Barrier Single Electron Transistors

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A gated vertical sub-micron triple barrier structure with undoped $Al_{0.22}Ga_{0.78}As$ barriers and $In_{0.05}Ga_{0.95}As$ wells is used to study the properties of two weakly coupled quantum dots containing just a few electrons. We find that the conductance peaks becomes sparse as the excitation voltage is decreased due to a mismatch between the dots of the ladders of energy levels, and a pairing of the conductance peaks in a magnetic-field due to spin-degeneracy.

1. INTRODUCTION

To date, single electron phenomena in crystalline semiconductors have been studied widely in a planar geometry[1]. However, planar single electron transistors (SET's) have a number of drawbacks. The barriers are not well defined, and are strongly affected by the voltage applied to the gates, so it is not possible, in practice, to realize the condition that the number of electrons trapped in the system, N, approaches zero, and the zero dimensional quantisation energy is much smaller than the "classical" charging energy, and thus the so-called Coulomb blockade oscillations are usually very periodic, i.e. the device is operating in the "classical" Coulomb blockade regime.

These drawbacks can be overcome by using **vertical** SET's. Relatively few groups have tried gating a double barrier structure (DBS), and there have been no reports of attempts to do likewise with a triple barrier structure (TBS). The well defined heterostrucure barriers are fixed at growth, and the tunneling barrier potential is only weakly affected by the gate voltage. Consequently, it is possible to probe the regime where there are only a few electrons in the system ($N \rightarrow 0$), and the "classical" charging energy and lateral quantisation energy become comparable.

We have investigated the linear conductance characteristics ("Coulomb blockade oscillations") of a single quantum dot formed in a small DBS, and found a "shell" structure at zero magnetic field, and an intricate magnetic field dependence, both of which can be regarded as attributes of an *artificial semiconductor atom*[2]. The next step up in complexity is an *artificial semiconductor diatomic molecule* which can be realised in the vertical geometry with a sub-micron TBS. A gated TBS can be employed to study electron charging of, and resonant tunneling through, a two dot system containing just a few electrons. For a central barrier thickness of 76 Å, the coupling between the two "controllable" quantum dots in the slightly asymmetric TBS's investigated is **weak**. We describe the electrical properties of the structure and compare them with those of a DBS.

2. EXPERIMENT

Devices with a geometry shown schematically in fig. 1, and a top contact diameter, D, are fabricated by a technique involving electron-beam lithography, a combined dry and wet etch to a point just *below* the TBS, and deposition of a Schottky gate on the mesa side wall. Processing is similar to that previously employed for sub-μm gated DBS's[3]. The drain current, I_d, is measured as a function of the drain voltage, V_d, and gate voltage, V_g. By making the gate more negatively biased the depletion region associated with the gate spreads inwards "squeezing" the conducting channel. This channel has a diameter which can be much less than D. The presence of impurities can influence fine structure in the electrical characteristics, so instead of delta-doping the barriers to populate the quantum wells with electrons at zero bias[4], we use $In_{0.05}Ga_{0.95}As$ quantum wells to ensure that the threshold bias of the lowest "normal" resonance is zero. The resulting conduction band profile at zero bias is shown pictorially in fig. 2, along with the TBS material parameters.

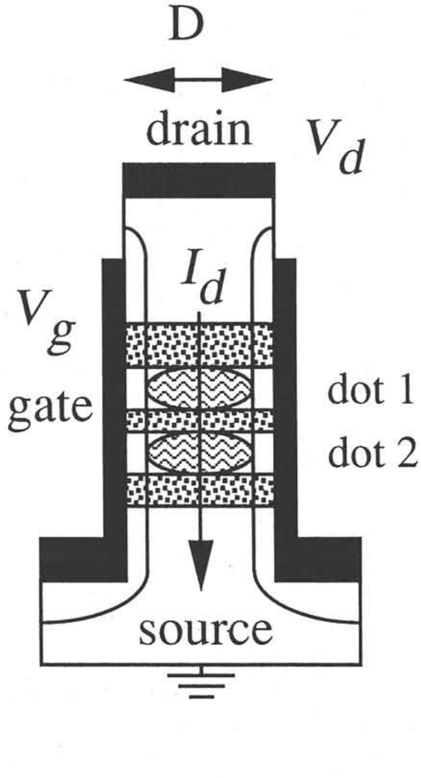

Fig. 1. Schematic diagram of the sub-μm vertical SET.

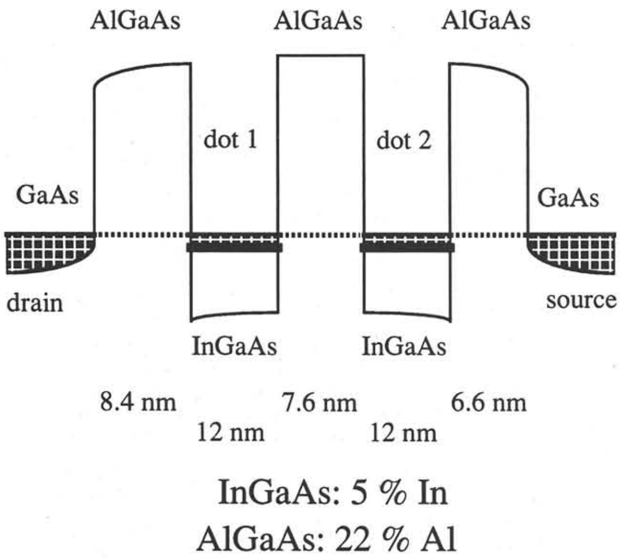

Fig. 2. Pictorial profile of the conduction band for the TBS at zero bias. The TBS material parameters are also given.

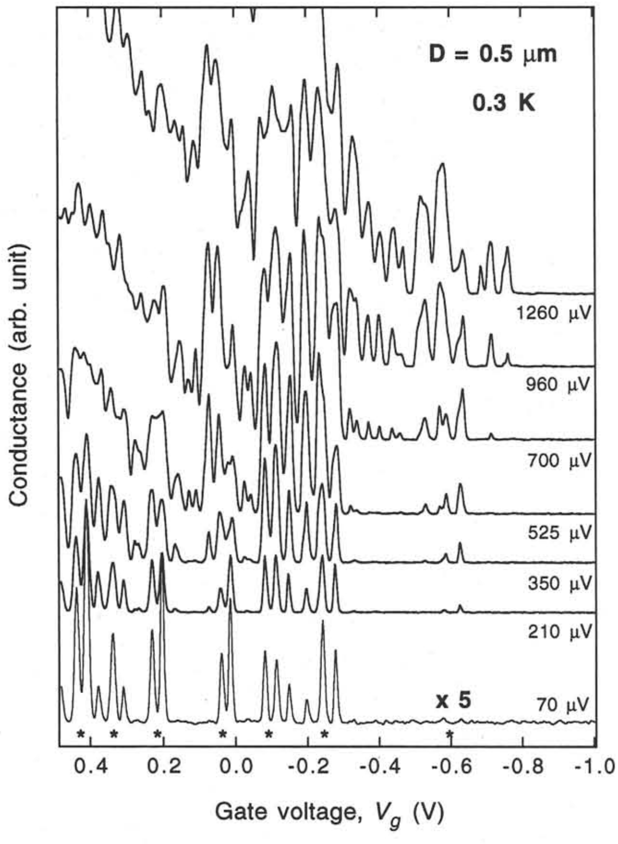

Fig. 3. Conductance - V_g characteristic as a function of excitation voltage to the drain for a D = 0.5 μm TBS. Curves are offset vertically for clarity. The bottom curve has been magnified by a factor of 5.

3. DISCUSSION

The peak current of the main resonances seen in the I_d - V_d characteristic is strongly reduced as V_g is made negative. This demonstrates effective "squeezing" of the conducting channel. The device yield is such that the performance of a "large" number of devices can be analyzed. Clear trends in the peak current of the main resonances, and the "pinch-off" gate voltage as D is reduced below 1 μm are found.

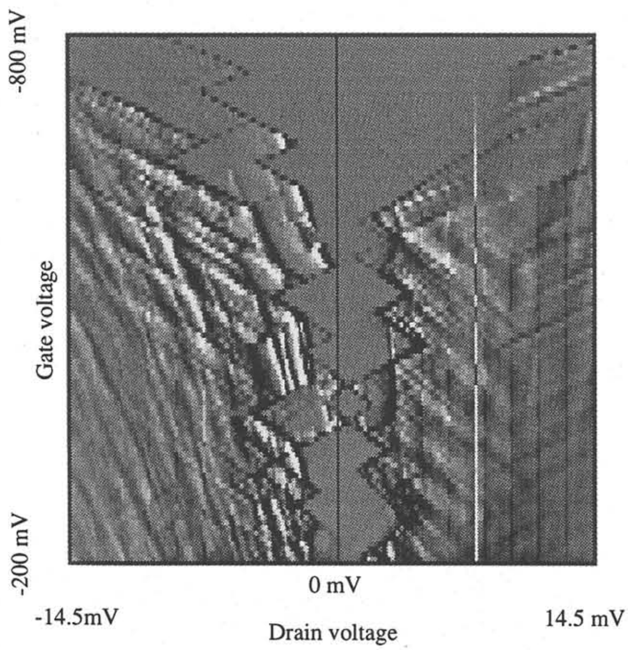

Fig. 4. Grey scale plot of dI_d/dV_d as a function of V_d and V_g for the D = 0.5 μm TBS at 0.3 K.

The conductance - V_g characteristic as a function of excitation voltage to the drain is shown in fig. 3 for a D = 0.5 μm TBS at 0.3 K. A conductance peak occurs when there is simultaneous transport through both of the quantum dots. The total number of electrons in the two coupled dots on one side of a peak differs from that on the other side by two. Starting from V_d = 700 μV, some conductance peaks ("Coulomb oscillations") are more strongly suppressed than others as V_d is reduced, and are absent at V_d = 70 μV, i.e. only a few peaks survive when $V_d \rightarrow 0$ V (indicated by "*" in fig. 3). This can be clearly seen in the grey scale representation of dI_d/dV_d against V_d in fig. 4 for the same device. The diamond shaped areas in the vicinity of V_d = 0 V represent the regions of Coulomb blockade. However, over a wide gate voltage range, and particularly close to "pinch-off", these diamonds are usually not well formed, i.e. the vertices are not connected at V_d = 0 V, so the diamonds are "open". In contrast, for a single quantum dot, even close to "pinch-off", there is no decrease in the number of conductance peaks with excitation voltage, so the diamond shaped regions of Coulomb blockade are well defined and are connected to each other at V_d = 0 V, as illustrated by the grey scale plot for a D = 0.6 μm DBS in fig. 5. The behaviour of two dots connected in series has been investigated theoretically by

Ruzin *et al.*[5]. They coined the expression "Stochastic Coulomb Blockade" to refer to the observation depicted in fig. 3, i.e. the conductance peaks become sparse as $V_d \to 0$ V. For a conductance peak to survive at a vanishingly small excitation voltage in the TBS, an energy level in dot 1 must be perfectly aligned with an energy level in dot 2. Such stringent conditions are rarely meet for two weakly coupled dots when the TBS is controlled by a single gate, because even a "slight" mismatch between the ladders of energy levels in the two non-identical dots can be greater than the resonant tunneling width through the central barrier.

For a single quantum dot, we have recently observed a "shell" structure in the electrochemical potential, i.e. the energy need to add one extra electron to an N-electron quantum dot [2]. When a low magnetic field is applied parallel to the tunneling current, conductance peaks evolve in pairs as a result of the filling of spin degenerate states. This pair-like behaviour is likewise seen for the two weakly coupled dots as shown in fig. 6 for a D = 0.6 μm TBS at an excitation voltage of 540 μV, and is also associated with spin-degeneracy. It is interesting to note that the height of the conductance peaks in each pair are strongly correlated. In particular, some of the pairs disappear or appear as the B-field is increased. This may be related to a magnetic field induced change in the mismatch of energy levels between the dots.

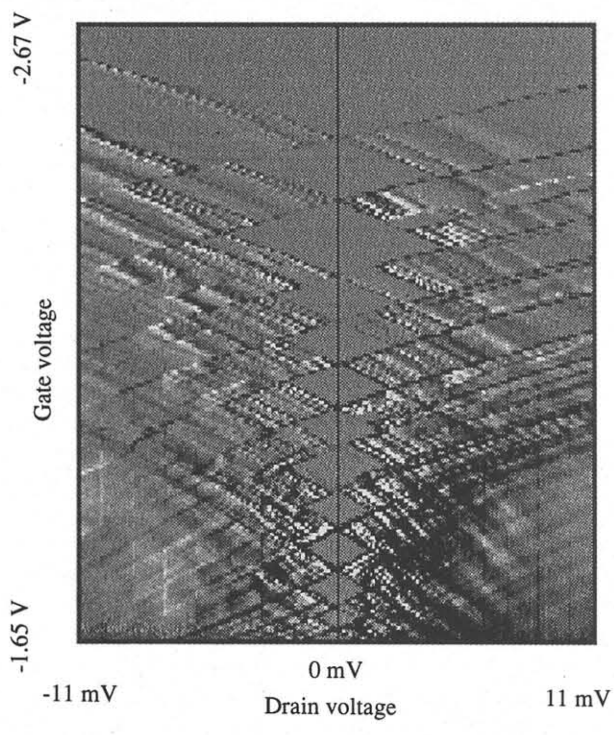

Fig. 5. Grey scale plot of dI_d/dV_d as a function of V_d and V_g for a D = 0.6 μm DBS at 0.3 K.

4. CONCLUSION

Well defined vertical triple barrier single electron transistors are ideal for looking at the properties *of artificial semiconductor diatomic molecules* containing just a few electrons. For suitably optimised starting material, both the linear and non-linear transport characteristics provide a new insight in to the behaviour of two weakly coupled quantum dots. We observe a decrease in the number of conductance oscillations as the excitation voltage is reduced due to the stringent conditions for simultaneous transport through both of the dots. The pairing of the conductance peaks in a magnetic-field is related to spin-degeneracy.

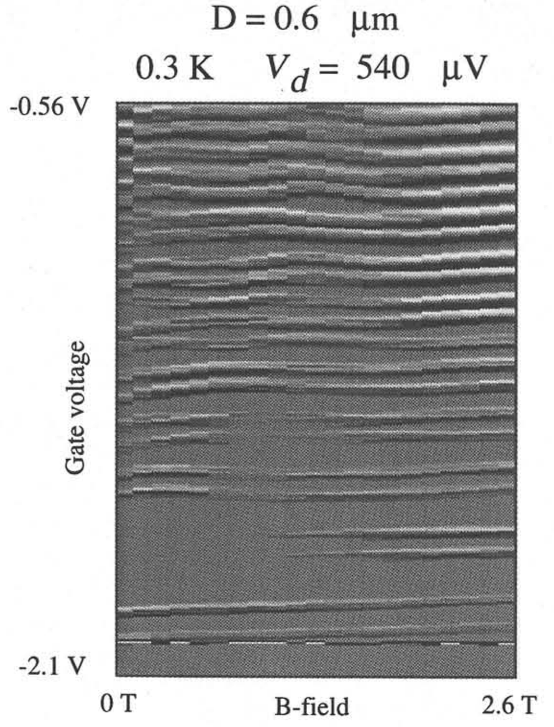

Fig.6. Grey scale plot of dI_d/dV_d as a function of V_g and B-field for a D = 0.6 μm TBS.

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