Tunnelling through vertically coupled InAs quantum dots

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Abstract. We present results on single-electron tunnelling through vertically coupled double InAs quantum dots embedded in a GaAs-AlAs-GaAs tunnelling structure. For strongly coupled dots we observe steps in the current-voltage characteristics for both bias directions. We attribute them to the single-electron tunnelling through an InAs quantum dot molecule. When the vertical coupling between the dots is reduced pronounced peaks in the current-voltage characteristics appear for reverse bias voltages. They can be related to the resonance between two zero-dimensional ground states of individual quantum dot pairs. In a magnetic field the peaks split up into double peaks reflecting the Zeeman splitting in both dots.

1. Introduction

Over the last years several groups succeeded in performing single-electron tunnelling experiments through self-assembled InAs quantum dots (QDs) [1, 2, 3, 4]. These measurements opened a new "spectroscopic" access to the energy level structure of such highly quantised QD systems.

In this paper we will present the first experiments of single-electron tunnelling through individual quantum dot molecules consisting of two vertically coupled InAs QDs.

2. Samples

We have grown three different wafers containing two layers of self-assembled InAs QDs embedded in an AlAs barrier between two highly doped GaAs electrodes. The electrodes consist of n-doped GaAs with graded doping and a 15 nm undoped GaAs spacer layer before the AlAs barrier. The doping profile results into three-dimensional electrodes extending up to the barrier with a Fermi energy $E_F \approx 12$ meV.

Following the growth of the bottom electrode a first layer of InAs is grown on a 5 nm thick AlAs barrier. The lattice mismatch between InAs on AlAs leads to the formation of self-assembled InAs quantum dots. For the three different wafers A, B, and C the dots are then covered by another layer of AlAs with thickness $d_m = 3, 5,$ and 7 nm, respectively, and a second layer of InAs is grown on top. The QDs forming in this top layer are, due to the remaining strain, vertically aligned to the dots in the bottom layer [6]. The size of the upper dots is slightly larger compared to the corresponding lower dots resulting into a lower ground state energy. Finally, the dots are overgrown by a 5 nm thick AlAs barrier and a top n-doped GaAs electrode.

A transmission electron micrograph (TEM) of a sample with $d_m = 5$ nm is shown in Fig. 1. Indeed, the formation of vertically aligned InAs quantum dots can be seen in the Figure.

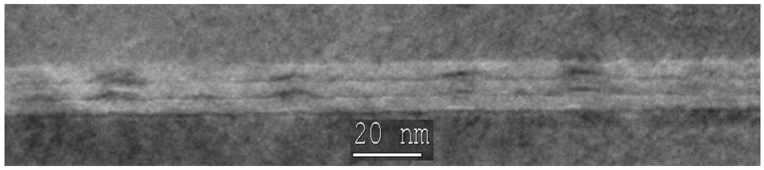

Figure 1. TEM image of a GaAs-AlAs-GaAs tunnelling structure with two layers of embedded InAs quantum dots.

Electric contacts to the quantum dots are realised by annealing AuGeNi into the electrodes. The metallic top contacts also serve as an etch mask for the structuring of macroscopic tunnelling diodes with an edge length of 40 μm and 50 μm containing typically a few million QDs.

3. Resonant Tunnelling: Experiment and Interpretation

In Fig. 2 we show systematic current-voltage (I-V) curves of several samples from the three different wafers A, B, and C for two bias directions. From top to bottom the thickness d_m of the AlAs coupling layer between the InAs QD layers is increased from 3 nm (wafer A) via 5 nm (wafer B) to 7 nm (wafer C). Due to the final height of the dots the effective barrier width d_m of the middle barrier and the nominally 5 nm thick top barrier are reduced by about 2-3 nm (see Fig. 1).

The I-V curves for the samples with the strongest interdot coupling ($d_m = 3$ nm, top panels of Fig. 2) are quite comparable to those of similar devices containing only one layer of InAs QDs [5]. Steps in the I-V curves appear for both bias directions. Each step can be attributed to resonant tunnelling from a three dimensional emitter through a single quantised state, probably the ground state, of a vertically coupled individual InAs quantum-dot molecule.

If the coupling between the two InAs QD layers is reduced ($d_m = 5$ nm and $d_m = 7$ nm) the steps in the I-V curves disappear and pronounced peaks appear for reverse bias direction, see Fig. 2, middle and bottom panel. For this bias direction the electrons first tunnel into the upper dots and subsequently through the lower ones into the bottom electrode. Then each peak observed can be attributed to sequential tunnelling through two quantum dots in series [7]. A schematic band structure is sketched in the bottom panel of Fig. 3. For zero bias the second (smaller) dot is energetically situated above the first (larger) one (Fig. 3a). When a bias is applied the two QD energy levels move towards the Fermi energy and both levels start to coincide energetically (Fig. 3b). As a consequence, and when they are additionally situated in between the band edge E_C and the Fermi energy E_F of the emitter, a peak appears in the I-V characteristics. For higher bias voltages, the energy level of the smaller dot moves below the larger one and no tunnelling current is observed anymore (Fig. 3c).

In contrast to steps observed in single dot devices the peak widths are not thermally broadened. They are essentially only dependent on the intrinsic width of the two QD levels involved in the tunnelling process determined by the interdot coupling and the tunnelling coupling to the emitter and the collector, respectively.

Under forward bias we still observe very rarely (compared to similar single dot devices) steps in the I-V curve for the weakly coupled double dot devices ($d_m = 5$ nm and $d_m = 7$ nm).

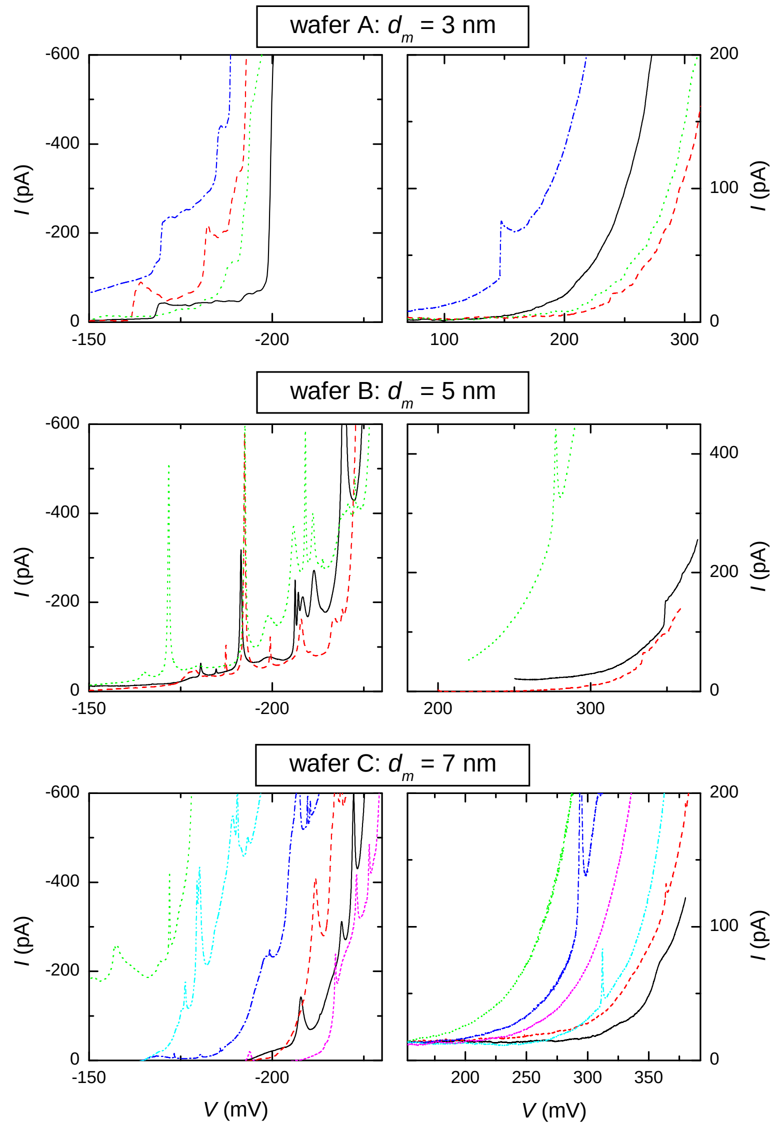

Figure 2. Typical I-V-characteristics for several samples from the three different wafers A, B, and C. From top to bottom the coupling between the two InAs QD layers is decreased by increasing the nominal width of the middle AlAs barrier.

As in single dot devices [5] they show a temperature dependent broadening of the step edge. Therefore, we believe that we can still attribute them to resonant tunnelling from a three-dimensional emitter through a single energy state of a quantum dot molecule.

4. Magneto-tunnelling

When a magnetic field is applied the peaks observed in Fig. 3 split up in two, see Fig. 4. Again, the peak width is essentially not thermally broadened. The splitting of the peaks is linear in magnetic field and can be explained by the Zeeman splitting of two individual dot levels. Since the first (upper) dot is larger its Zeeman splitting is smaller than the one of the second (lower) dot [8, 9]. As a consequence, two different bias voltages are required to align the two different spin levels of the respective QDs, see Fig. 4b and 4c and two peaks

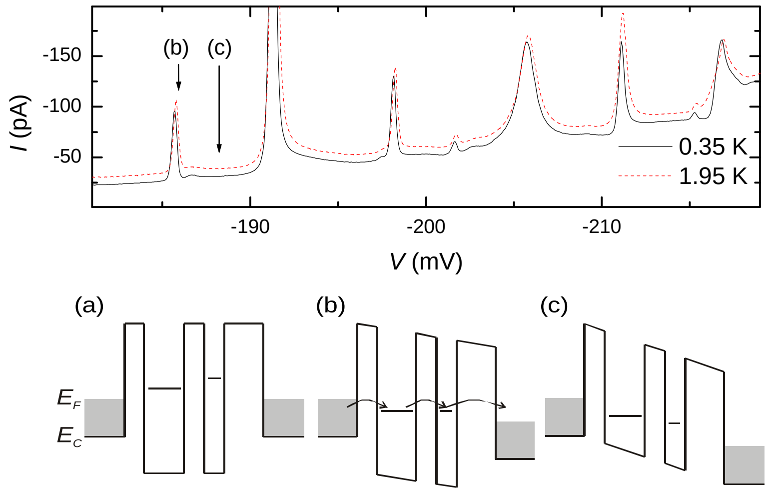

Figure 3. *top:* Reverse bias I-V curve for a diode containing weakly coupled layers of InAs QDs ($d_m = 5$ nm) for two different temperatures.
bottom: Bias voltage dependence of the schematic band structure of an GaAs-AlAs-GaAs tunnelling structure containing two weakly coupled QDs.

appear in the I-V curves. In each of these peaks electrons with one single spin species are transmitted through the dots. The peak splitting $\Delta V = \Delta E_z/\alpha_m e$ reflects the difference in the Zeeman splitting of the two dots $\Delta E_z = (g_2 - g_1)\mu_B B$. Here $g_1 < g_2$ are the Landé-factors of the upper and the lower InAs QDs and the lever factor α_m denotes the voltage drop over the middle barrier compared to the total voltage applied between source and drain. Using a reasonable value $\alpha_m \approx 0.15$ we find that the g-factor differences in the two dot layers are of the order of unity and comparable to g-factor differences of individual InAs QDs of different size [8].

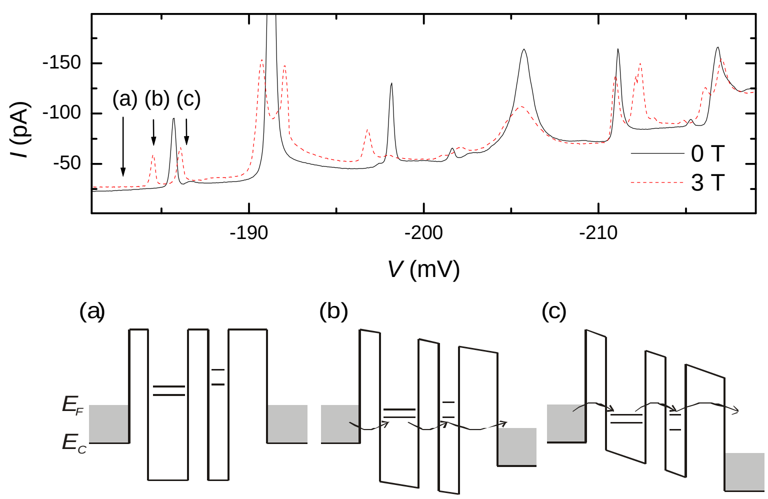

Figure 4. *top:* I-V-characteristics for reverse bias at zero and finite magnetic field and $T = 0.35$ K. Splitting of the current peaks in two is due to Zeeman splitting of both dot levels (dashed line).
bottom: Sketches of the conduction band profile: (a) none of the states are aligned, (b) electrons of one spin species are able tunnel through two states, and (c) at higher bias electrons of the other spin species tunnel through the double QD.

5. Conclusions

In conclusion we have measured resonant single electron tunnelling through vertically coupled InAs QDs. The observed features were assigned to sequential tunnelling through two individual vertically coupled dots of different size.

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