

Series Coupled Vertical Triple Quantum Dot Structures

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1. Introduction

Multiple quantum dot (QD) systems offer highly attractive spin and charge properties. The electronic properties of double QDs arranged in series, the simplest system with more than one quantum dot, have been widely reported [1]. These include molecular properties [2,3], and current rectification by Pauli spin blockade in the weak coupling regime [4,5]. The latter has played an important role in revealing hyperfine coupling [5,6], and has applications for spintronics including spin state initialization and detection of electron spin manipulation relevant for quantum computation [7,8]. Concerning more complex quantum dot systems, triple QD structures have been theoretically investigated [9-13]. However, because of the difficulty in fabrication, it is only comparatively recently that experimental works on laterally-coupled triple QD structures [14-23] have been reported, and only some of these for the few-electron regime [17,18,21-23].

We introduce here the basic electronic properties of two types of vertical triple QD structure. The key benefit of using the vertical QDs as building-blocks is that we can keep the number of necessary gate electrodes (and hence processing complexity) to a minimum, i.e., the gate electrodes are principally required to modulate the electro-chemical potentials of the QDs but are not necessary to form the QDs. In one structure, we have three vertical QDs coupled laterally in series with the current flowing vertically and in parallel through the QDs (pvTQD). In the other structure, we have three vertical QDs coupled vertically in series with the current flowing vertically and in series through the QDs (svTQD). Note the series (collinear) arrangement of dots contrast with the triangular arrangement we have recently investigated [23].

Each structure has attractive features. For the pvTQD, gate control is more extensive (flexible) allowing for easier assignment of charge states, and orbital and spin configurations. Also the current is easier to measure even when not all QDs are on resonance because of the parallel flow of current through the QDs. On the other hand, the QDs are laterally less well defined, so the effective position of the three QDs is not “rigid”, and the lateral QD coupling strength is limited by processing constraints. For the

svTQD, gate control is (currently) more limited and so identification of states and configurations may be harder in practice. None the less, the QDs are very well defined in all directions, and so the three-QD-molecule is less “floppy”, and the vertical QD coupling strength may be engineered to be large as it is fixed at growth by choice of material parameters. The “rigid” svTQD system is attractive to investigate spin blockade and nuclear spin effects.

2. Vertical triple quantum dots in parallel

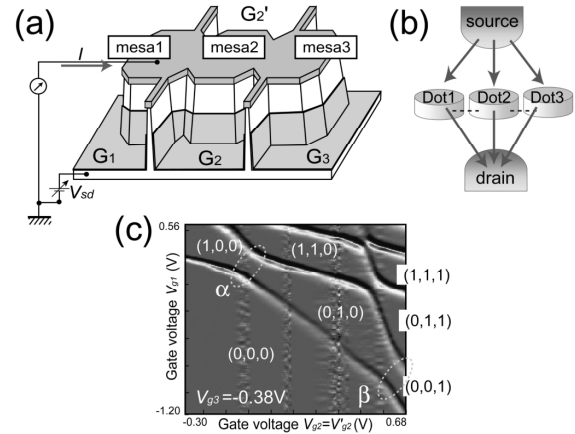


Fig. 1 (a) Schematic of pvTQD device. (b) Cartoon of current flow in this triple QD device. (c) Measured transconductance dI/dV_{g1} as a function of $(V_{g1}, V_{g2}=V_{g2}')$ for constant $V_{g3}=-0.38V$ at $\sim 100mK$.

Figure 1 (a) shows a schematic diagram of our pvTQD device. Three QDs (Dot1, Dot2 and Dot3) are formed inside of three touching mesas (mesa1, mesa2 and mesa3). We measure the DC current I flowing from the source, through the three QDs in parallel, to the drain electrode as illustrated in Fig. 1(b). The three mesas are sufficiently close to induce tunnel coupling between adjacent QDs. Gate electrodes (G_1 , G_2 (G_2'), G_3), attached to the mesas can modulate the QD electro-chemical potentials inside the pvTQD device. The electronic states of the pvTQD may thus be altered by adjusting the gate voltages on electrodes G_1 , G_2 (G_2') and G_3 , namely V_{g1} , V_{g2} ($=V_{g2}'$), V_{g3} . Fig. 1 (c)

shows the measured transconductance dI/dV_{g1} plotted in the V_{g1} - V_{g2} plane for constant $V_{g3} = -0.38$ V. We can distinguish three different families of Coulomb oscillation lines in Fig. 1 (c) associated with the three QDs formed in the device. We can deduce the number of trapped electrons on Dot1, Dot2 and Dot3 (N_1, N_2, N_3) from Fig. 1(c) and Coulomb diamond measurement (not shown) [22]. The anti-crossing features marked α and β in Fig. 1(c) provide clear evidence that adjacent QDs are coupled quantum mechanically. From examination of the (total electron number) $N=2$ current stripe, the coupling between the two end dots, Dot1 and Dot3, is confirmed to be weaker than that between adjacent dots. By performing excitation spectroscopy, this structure can reveal the rich electronic physics expected for TQDs.

3. Vertical triple quantum dots in series

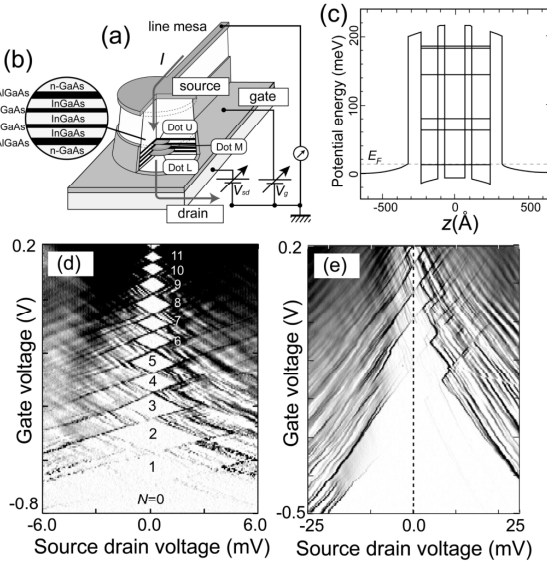


Fig. 2 (a) Schematic of svTQD device. (b) Cross-section through quadruple-barrier triple-quantum-well resonant tunneling structure. (c) Calculated self-consistent one-dimensional conduction band profile (nominally symmetric around $z=0$ Å at zero bias) for this resonant tunneling structure. Measured differential conductance dI/dV_{sd} as a function of (V_{sd}, V_g) at ~ 100 mK for two svTQD devices showing (d) regular and (e) irregular Coulomb blockade diamonds.

Figure 2 (a) shows a schematic diagram of our svTQD device. The three QDs are embedded in a single sub-micron circular mesa surrounded by a single Schottky gate. The device is fabricated from a nominally symmetric quadruple-barrier triple-quantum-well resonant tunneling structure as shown in Fig. 2 (b). We adjusted the total barrier thickness to be approximately the same as that for vertical double QDs [3,4] in order to maintain a measurable tunnel current. The three QDs (DotU, DotM, DotL) are formed “rigidly” in each of the InGaAs quantum well layers. Figure 2 (c) shows the calculated self-consistent one-dimensional conduction band profile for this structure along the (z -) growth direction. Note for the svTQD studied, the energy

splitting between the coupled dot ground states is designed to be small (~ 1 meV) relative to the lateral confinement energy for each constituent dot. The metal on top of the thin line mesa attached to the central circular mesa is connected to a large bonding pad (not shown in Fig. 2(a)). We measure DC current I as a function of source-drain voltage V_{sd} and gate voltage V_g .

Figures 2(d) and 2(e) show the differential conductance dI/dV_{sd} plotted in the V_{sd} - V_g plane for two different svTQD devices. In Fig. 2 (d), regular and closed Coulomb diamonds are observed even in the few-electron regime. In this device, the conduction band profile at zero bias is likely close to symmetric in the z -direction as anticipated from the calculated profile in Fig. 2(c). In contrast, in Fig. 2(e), for the other device, less regular and even open Coulomb diamonds are evident. The appearance of these diamonds is similar to that for weakly coupled double QDs with finite energy offset between adjacent dots at zero bias [4].

3. Conclusions

We investigated three vertical QDs coupled either laterally or vertically in series. In the parallel configuration, from the gate voltage dependence of the Coulomb oscillation lines, we confirmed the formation of three QDs and identified the charge configurations for each Coulomb blockade region. In the series configuration, the measured Coulomb diamonds exhibited regular (irregular) shape, suggesting that the conduction band profile along the z -direction is symmetric (asymmetric) at zero bias. That such device-to-device variation is seen is reasonable in multi-dot structures controlled by a single gate.

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