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Quantum dot (QD) circuits have demonstrated to be particularly good systems for studying electronic transport and for implementing solid state qubits. They notably offer the possibility to control the spin of confined single electrons to realize spin qubits. These are especially attracting for quantum information processing because of their robustness to decoherence which should allow to implement a full electron-spin based quantum computation scheme. Among the various materials in which such QDs based spin qubits have been demonstrated, semiconductor heterostructures are considered candidates of choice because of the high tunability and readout techniques they offer. Lately, several experiments demonstrated the manipulation of two spin-1/2 qubits implemented in double QD (DQD) circuits as well as the realization of universal quantum one- and two-qubits gate operations. An additional key feature of these semiconductor QD circuits is their potential for scalability.

Realization of a scalable architecture of semiconductor spin qubits is one of the remaining challenge that has to be overcome for implementing more complex algorithms. Steps toward this direction have been taken by experimentally realizing triple QD (TQD) circuits or quadruple QD (QQD) circuits formed by two capacitively coupled DQDs. In these systems however, the number of implemented qubits is still limited to one or two. A square-like configuration of tunnel coupled series-QQD device has been demonstrated, in still limited to one or two. A square-like configuration of tunnel coupled series-QQD device has been demonstrated,13 in particularly good systems for studying electronic transport and for implementing solid state qubits. They notably offer the possibility to control the spin of confined single electrons to realize spin qubits. These are especially attracting for quantum information processing because of their robustness to decoherence which should allow to implement a full electron-spin based quantum computation scheme. Among the various materials in which such QDs based spin qubits have been demonstrated, semiconductor heterostructures are considered candidates of choice because of the high tunability and readout techniques they offer. Lately, several experiments demonstrated the manipulation of two spin-1/2 qubits implemented in double QD (DQD) circuits as well as the realization of universal quantum one- and two-qubits gate operations. An additional key feature of these semiconductor QD circuits is their potential for scalability.

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for forming and manipulating spin qubits.\(^7\) Two sets of three gates, visible on top of gate C, allow for forming QDs in multiple electrons regime for charge sensing purpose. Each of these charge sensors can be used as radio frequency (rf) charge sensor.\(^{15-17}\) Throughout this paper, we use the rf-sensor on the left, whose resonant circuit frequency is \(f = 203.9\) MHz. All the measurements are performed at the base temperature of around 10 mK.

The voltage applied to gate C is \(V_C = -450\) mV, below the pinch off voltage of the 2DEG (\(V_{\text{pinch-off}} = -350\) mV). We can form the four QDs as indicated by white circles in Fig. 1(a) by applying negative voltages to the other gates. Fig. 1(b) shows the stability diagram obtained by modulating \(V_{P1}\) and \(V_{P4}\), the voltages, respectively, applied to plunger gates \(P_1\) and \(P_4\). The measured signal is the derivative of the rf demodulated signal amplitude with respect to \(V_{P1}\), so as to display the charge transition lines of each QD. Four different slopes are identifiable, corresponding to the four different QDs. The stability diagram is in accordance with the device geometry as the slopes of each QD are directly related to the QD distance to the modulating plunger gates. Therefore, we can assign the charge state \((N_1,N_2,N_3,N_4)\), with \(N_i\) the number of electrons in QD\(_i\). We find that the single electron regime is already demonstrated in this stability diagram, as the charge state \((0,0,0,0)\) is observed for \(V_{P1} \leq -50\) mV and \(V_{P4} \leq -170\) mV.

We model our QQD device as shown in Fig. 2(a). This purely classical model is an extension of the capacitive DQD model\(^{18}\) to four QDs. We consider each QD to be capacitively coupled to its plunger gate via \(C_{gi}\), to the nearest neighbor plunger gate via \(C_{i\pm1}\), and to the nearest QD via the mutual capacitance \(C_{mi}\). QD1 and QD4 are also coupled to the left and right leads via \(C_L\) and \(C_R\), respectively. We therefore have 15 parameters to adjust in this model. However, thanks to the symmetry of the device pattern and the slopes of the transition lines measured in the stability diagram, we can reproduce with good agreement the transition lines around the \((1,1,1,1)\) region as shown in Figs. 2(b) and 2(c) with \(C_{p1} = C_{p2} = C_{p3} = 10\) aF and \(C_{i\pm1,i} = 1\) aF for \(i = 1, 2, 3, 4\). Note that we chose to only consider first neighbor plunger gate cross-capacitive coupling. This model already gives good qualitative and quantitative agreements with our data and as such is a good trade-off with more complete models requiring additional parameters.

We then need to consider the realization of spin readout. This mandatory feature for any purpose of quantum information manipulation is usually performed by Pauli spin blockade technique (PSB). It can be performed by DC measurements of the current in the biased regime\(^{19}\) or by pulse measurement techniques at high frequencies.\(^1\) In both of these schemes, it is necessary that two neighboring QDs have for adjacent charge states \((2,0)\) (or \((0,2)\)) and \((1,1)\).

This scheme can in principle be extended to larger number of series QDs, by applying the pulsed PSB scheme to successive DQDs of the array. In the case of a TQD circuit, the PSB measurement would be done on the left QDQ, \((2,0,1) \leftrightarrow (1,1,1)\), and right QDQ \((1,0,2) \leftrightarrow (1,1,1)\), with the center QD being common.\(^{10}\) For QQDs, we are similarly looking for PSB conditions on the left QDQ, \((2,0,1,1) \leftrightarrow (1,1,1,1)\), and right QDQ, \((1,1,0,2) \leftrightarrow (1,1,1,1)\). The boundaries of the charge state \((1,1,1,1)\) is defined by a transition line of each QD. However, to meet the conditions of PSB for one QDQ, we need to have the transition lines of the corresponding two QDs to cross and form one corner of the \((1,1,1,1)\) region. Figs. 2(b) and 2(c) show that none of the required conditions for PSB are met as neither the \((2,0,1,1)\) nor the \((1,1,0,2)\) charge states are adjacent to the \((1,1,1,1)\) region. In this diagram, in order to achieve the PSB condition on the left QDQ, one has to push the transition line of QD2 towards more positive \(V_{P1}\) so that it crosses the second transition line of QD1 above the transition line of QD3 along \(V_{P4}\). Similarly, to obtain the PSB condition on the right QDQ, one has to push the transition line of QD3 towards more positive \(V_{P4}\) so that it crosses the second transition line of QD4 above the transition line of QD2 along \(V_{P1}\). Following this procedure, and with the help of the QQD capacitive model, we find that there exists no configuration in which the left and right DQDs PSB conditions can be met on a single stability diagram defined by two plunger gates. This fact sets a clear gap with TQD devices in the search of a scalable architecture, as both PSB conditions can be found on the same stability diagram for TQD. It implies that more complex manipulations of the QQD system are necessary to fully operate and measure the spin state of each QDs.

Up to now, we only considered the stability diagram of the QQD in the \((V_{P1}, V_{P4})\) plane. However we have a set of four available plunger gates to explore the complete manifold of the QQD charge states. Within this picture, each charge state region is 4-dimensional and can be explored along the axes \(V_{P1}, V_{P2}, V_{P3}\), and \(V_{P4}\). Our simple capacitive model then reveals especially useful to explore the charge states space along any combination of these axes.
FIG. 3. Suitable regions for spin blockade measurements. (a) Calculated stability diagram in the plane defined by plunger gates \( P_1 \) and \( P_2 \), allowing for PSB condition in the left DQD. (b) Calculated stability diagram in the plane defined by plunger gates \( P_3 \) and \( P_4 \), allowing for PSB condition in the right DQD. (c) Charge stability diagram in the plane defined by plunger gates \( P_1 \) and \( P_2 \), with \( V_{P1} = -60 \) mV and \( V_{P2} = -10 \) mV. The two regions \((1,1,1,1)\) and \((2,0,1,1)\) between which the spin blockade measurements on the left DQD can be performed are shown by white arrows. (d) Charge stability diagram in the plane defined by plunger gates \( P_3 \) and \( P_4 \), with \( V_{P3} = -335 \) mV and \( V_{P4} = -190 \) mV. The two regions \((1,1,1,1)\) and \((1,1,0,2)\) between which the spin blockade measurements on the right DQD can be performed are shown by white arrows. The color code of the transition lines in (a) and (b) corresponds to the one of Fig. 2(b).

Figs. 3(a) and 3(b) show the calculation of the stability diagrams (where the first two electrons of each QDs are considered) in the planes \((V_{P1}, V_{P2})\) and \((V_{P3}, V_{P4})\), respectively. The PSB conditions for each DQD is naturally found in each respective plane. The corresponding stability diagrams measurements are shown in Figs. 3(c) and 3(d). Fig. 3(a) (Fig. 3(b)) shows that we should expect the transition lines of QDs 2, 3, and 4 (1, 2, and 3) to have similar slopes, little influenced by \( V_{P1} \) (\( V_{P2} \)). The transition line spacing \( \Delta V_i \) between two consecutive charge states of each QD, is also directly related to the distance of each QD to the driving plunger gates, respectively, giving \( \Delta V_2 \leq \Delta V_3 \leq \Delta V_4 \). These features are well observed in Figs. 3(c) and 3(d), confirming the agreement of the capacitive model of Fig. 2(a) with our device. The comparison between theory and experiment allows us to clearly identify each DQD transition line and find out the PSB conditions \((2,0,1,1) \rightarrow (1,1,1,1)\) in the plane \((V_{P1}, V_{P2})\) and \((1,1,0,2) \rightarrow (1,1,1,1)\) in the plane \((V_{P3}, V_{P4})\) as depicted by the white arrows.

An additional advantage of this scheme is that the transition lines of the two QDs where the PSB condition is met form a standard DQD honeycomb pattern in the corresponding plunger gate voltage plane. It provides better clarity for manipulating the left and right DQDs and allows for direct implementation of the standard DQD PSB schemes. This should particularly help limiting the modulation of gates potential and tunnel coupling of the two other QDs, which could give rise to spurious effects such as states mixing.

Ideally, one can first find the \((1,1,1,1)\) region in the \((V_{P1}, V_{P2})\) plane. Then, from that charge state, the charge stability diagram is explored in the other planes. One would then readily find the PSB conditions for each DQD with the minimum number of gate operations.

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20. Note1, \( \Delta \psi \) includes both the charging energy \( E_C \) and the orbital spacing \( \Delta \) of each dot QD, adjusted by the lever-arm of the driving plunger gates. Hence, similar charging energies and orbital spacing lead to different transition lines separations, depending on the plane they are displayed in.