State-conditional coherent charge qubit oscillations in a Si/SiGe quadruple quantum dot

Daniel R Ward1,2,5, Dohun Kim1,3,5, Donald E Savage4, Max G Lagally4, Ryan H Foote1, Mark Friesen1, Susan N Coppersmith1 and Mark A Eriksson1

Universal quantum computation requires high-fidelity single-qubit rotations and controlled two-qubit gates. Along with high-fidelity single-qubit gates, strong efforts have been made in developing robust two-qubit logic gates in electrically gated quantum dot systems to realise a compact and nanofabrication-compatible architecture. Here we perform measurements of state-conditional coherent oscillations of a charge qubit. Using a quadruple quantum dot formed in a Si/SiGe heterostructure, we show the first demonstration of coherent two-axis control of a double quantum dot charge qubit in undoped Si/SiGe, performing Larmor and Ramsey oscillation measurements. We extract the strength of the capacitive coupling between a pair of double quantum dots by measuring the detuning energy shift (=75 μeV) of one double dot depending on the excess charge configuration of the other double dot. We further demonstrate that the strong capacitive coupling allows fast, state-conditional Landau–Zener–Stückelberg oscillations with a conditional π phase flip time of about 80 ps, showing a promising pathway towards multi-qubit entanglement and control in semiconductor quantum dots.

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RESULTS

We study a linear quadruple quantum dot formed in an undoped Si/SiGe heterostructure, as shown in Figure 1a. The dots are formed under the gates D3 through D4, approximately under the dashed line shown in Figure 1a, and for the experiments we report here, it is useful to describe the quadruple quantum dot as a pair of double quantum dots. The right double dot (RDD), formed under the gates D3 and D4, forms a charge qubit that will be manipulated coherently based on the charge state of the left SiGe quantum dot qubits, require a blanketing array of metal electrodes that partially screen the capacitive coupling, making this issue all the more urgent.12,17,30,40–43

Here we present measurements of a quadruple quantum dot formed in an undoped Si/SiGe heterostructure and demonstrate fast and charge-state-conditional coherent manipulation of two strongly coupled double quantum dots. Non-adiabatic pulsed gate techniques allow fast two-axis control of the double dot charge qubit formed. We show that the strong capacitive coupling (>18 GHz) between two sets of double quantum dots enables charge-state-conditional coherent Landau–Zener–Stückelberg (LZS) interference with a conditional π phase flip time of approximately 80 ps, demonstrating progress towards realizing high-fidelity two-qubit control. Although we focus here on conditional coherent operations of a charge qubit, the measurement strategy and strong inter-qubit coupling deduced from the present study can also be directly applied to singlet–triplet25 or hybrid quantum dot qubits,18,20 where strong capacitive coupling will have an essential role in the realisation of fast two-qubit gates.
double dot (LDD), which is formed under gates $D_1$ and $D_2$. Charge sensing is performed by two charge-sensing quantum dots adjacent to the left (LSD) and right (RSD) hand sides of the quadrupole dot array. The location of sensor LSD is close to the position that would naively be expected by examination of Figure 1a; to improve its charge sensitivity, sensor LSD is shifted to a position very close to the quadruple dot by careful tuning of the large number of gate voltages available on that side of the device. We monitor changes in the conductances $g_L$ and $g_R$ of sensor dots LSD and RSD, respectively, to monitor the electron occupations of double dots LDD and RDD. Figure 1c,d shows charge stability diagrams for the LDD (Figure 1c) and RDD (Figure 1d), respectively, demonstrating control of the four dot occupations as a function of the four gate voltages $V_{D1}, V_{D2}, V_{D3}$ and $V_{D4}$. As we show in Supplementary Figure S1e, the tunnel coupling and the capacitive coupling between the LDD and RDD both are reduced when the LDD has lower electron occupation. Thus, we perform here coherent manipulation in the regime for which the LDD has a total electron occupation larger than $(10,10)$.

We first show coherent two-axis control of an undoped Si/SiGe double dot charge qubit formed in the RDD. For this demonstration, the LDD energy detuning $\epsilon_L$ is kept $>300$ μeV so that the LDD charge occupation is not affected by the RDD manipulation pulses. The charge states are defined as $|0\rangle_L = |-\rangle$ (excess charge is on the left dot) and $|1\rangle_L = |+\rangle$ (excess charge is on the right dot). The initial qubit state $|0\rangle_R$ is prepared at negative RDD energy detuning $\epsilon_R$. As shown schematically in Figure 2a–c, non-adiabatic control of the charge qubit is performed using abrupt changes in detuning energy with precise control of the pulse duration time as well as the amplitude. The pulses, generated using a Tektronix AWG70002A arbitrary waveform generator (AWG) with a risetime of 40 ps, are applied to gate $D_3$ through a commercial bias tee (Picosecond PulseLabs 5542–219). X-rotations on the Bloch sphere, shown in Figure 2a, correspond to oscillations between the qubit states $|0\rangle_R$ and $|1\rangle_R$. Changing the peak detuning ($\epsilon_P$) abruptly to $\epsilon_P = 0$, as shown by the green pulse in Figure 2b, yields in the ideal case an X-rotation on the Bloch sphere. At $\epsilon = 0$ the Hamiltonian is $H = \Delta g_0 \sigma_x$, where $\Delta g_0$ is the tunnel coupling between $D_3$ and $D_0$ so the state evolves periodically in time at the Larmor frequency $2\Delta g_0/h$, where $h$ is Planck’s constant. In the experiment, there is a finite rise time for the pulse at the sample, and the axis of rotation on the Bloch sphere will depend on the exact detuning value reached at each stage of the pulse, so that the schematic drawings in Figure 2a,c are simpler than the case realized in the experiment. After a time $t = \Delta g_0/h$, the final state is measured by abruptly changing the detuning back to negative $\epsilon_P$. We use the difference of the conductance of the RDD between $|0\rangle_R$ and $|1\rangle_R$ to determine a time-averaged signal proportional to the probability $P_1$ of the state being in $|1\rangle_R$.

Figure 2d,e shows coherent oscillations of $P_1$, resulting from the non-adiabatic Larmor pulse sequences described above. In Figure 2d, we plot $P_1$ as a function of $t_p$ and the gate voltage $V_{D3}$, the latter of which determines the base level of $\epsilon_P$. In order to overcome a sampling time limitation of our AWG, we modified the pulse generation scheme to allow sub-picosecond timing resolution (see Supplementary Figure S2). In Figure 2d, the path of the pulse maximum level detuning $\epsilon_P = 0$ is curved (see the white dashed curve following the maxima in Figure 2d, which is drawn by running a smooth curve through the oscillation peaks), most likely because of the finite rise time of the pulse and frequency-dependent attenuation in the microwave coaxial cable.32 Figure 2e shows a line cut through this path corresponding approximately to $\epsilon_P = 0$, revealing periodic oscillations in $P_1$ at a frequency of order 10 GHz, corresponding to $\Delta g_0/h \approx 5$ GHz. We typically observe beating of the oscillations after $t_p \approx 300$ ps. This likely arises because of the superposition of a reflected part of the pulse with the original pulse, modifying the detuning amplitude.18,32

The high-frequency oscillations of $P_1$ in Figure 2d for $V_{D3} < 222$ meV arise from coherent LZS interference patterns.44,45 As $V_{D3}$ becomes less positive in Figure 2d, the pulse maximum level detuning enters the regime $\epsilon_P > 0$, where the interdot tunnel coupling acts as a beam splitter.46,47 Here the splitting ratio between the upper and lower branches of the charge qubit dispersion is determined by the detuning ramp rate in comparison with the tunnel coupling. On the return edge of the pulse, the two different trajectories returning through the beamsplitter at $\epsilon_P = 0$ can coherently interfere.

The measurement of qubit state rotations about the $Z$-axis on the Bloch sphere, shown schematically in Figure 2c, can be performed using two $X_{\text{mid}}$ pulses. The qubit state is first prepared in the state $|+\rangle_R = \sqrt{1/2}(|0\rangle_R-|1\rangle_R)$, by initialising to state $|0\rangle_R$ and by performing an $X_{\text{mid}}$ rotation. The qubit state then acquires a relative phase $\phi = e^{-i\Delta \epsilon R \Delta t_{\text{mid}}/h}$, where $t_{\text{mid}}$ is the time spent between the two $X$ rotations at the base value of the detuning and the qubit energy splitting $\epsilon_{R,|0\rangle} = \sqrt{\epsilon_P^2 + (2\Delta g_0)^2}$. This phase evolution corresponds to a rotation of the qubit state around the Z-axis of the Bloch sphere. Figure 2f,g shows the resulting quantum oscillations of the qubit state around the Z-axis of the Bloch sphere. In Figure 2g, the line cut is taken at $V_{D3} = -222.7$ mV in Figure 2f, corresponding to $\epsilon_P = 0$, and a smooth third-order polynomial background oscillation was removed from the raw data for clarity.33,35 (Supplementary Figure S3). By fitting the data to an exponentially damped sinusoidal oscillation, we extract the Ramsey fringe oscillation frequency $f_{\text{Ramsey}} \approx 56$ GHz and a coherence time $T_2 \approx 51$ ps.
Bloch vector during a non-adiabatic DC-pulsed gate (Larmor oscillation). An abrupt change in the detuning \( \varepsilon_R \) is the eigenstate of the Hamiltonian, to \( \varepsilon_L = 0 \) induces a rotation of the state around the \( X \)-axis of the Bloch sphere. (a) Time evolution of the Bloch vector during a Ramsey fringe measurement pulse sequence. An \( X_{3/2} \) pulse is applied to initialise the state on the \( X \)-axis plane of the Bloch sphere, and the state then evolves freely around the \( Z \)-axis for evolution time \( t_e \) with the rotation frequency \( \omega_{01,R} \), \( \hbar \) determined by the right qubit energy splitting \( E_{01,R} = \sqrt{\varepsilon_R^2 + (2\Delta_R)^2} \), where \( \Delta_R \) and \( \alpha_{\varepsilon} \) are defined in the energy level diagram. A second \( X_{3/2} \) pulse maps the \( Y \)-axis to the \( (Z) \)-axis, and the average charge occupation is measured via the conductance change of the RSD (Figure 1a). (b) Demonstration of Z-axis control performed with a Ramsey fringe experiment (corresponding to the orange pulse sequence shown in b): uncalibrated \( P_t \) as a function of \( V_{D3} \) \( \Delta \) gate D3 on gate \( D_3 \). As these LZS oscillations are measured in the regime, where the pulse maximum level detuning \( \varepsilon_L > \Delta_R \) the red solid line shows a linear fit to \( \Delta H_{LZS} \approx \alpha_{\varepsilon} \Delta t_{D3} \) with best fit parameter of gate \( D_3 \) lever arm \( \alpha_{\varepsilon} \approx 32.5 \text{ GHz/mV} \approx 135 \mu\text{eV/mV} \).

The gate voltage dependence of both the LZS interference and the Ramsey fringe frequencies provides accurate measures of the detuning lever arm. Figure 2h shows the LZS oscillation frequency \( f_{LZS} \) as a function of \( V_{D3} \). As these LZS oscillations are measured in the limit \( \varepsilon_R > \Delta_R \) we use an approximate form of the charge qubit energy level, \( E_{01,R} = \sqrt{\varepsilon_R^2 + (2\Delta_R)^2} \approx \varepsilon_R = h\Delta_{LZS} \), and fit the data to the form \( \Delta H_{LZS} = \alpha_{\varepsilon} \Delta t_{D3} \) to determine the gate lever arm \( \alpha_{\varepsilon} \approx 32.5 \text{ GHz/mV} = 135 \mu\text{eV/mV} \).

We now discuss the measurement of the capacitive coupling between the double quantum dots. With the detuning lever arm calibrated as described above, the coupling strength can be measured by sweeping \( \varepsilon_L \) and \( \varepsilon_R \) through the LDD and RDD charge degeneracy points. Figure 3 shows the LDD and RDD polarisation lines, characterised by measuring the differential conductance of the left and right sensors, LSD (Figure 3a) and RSD (Figure 3b), as functions of the two critical variables, the detuning parameters for the LDD and RDD. \( \varepsilon_L \) and \( \varepsilon_R \) by controlling the voltages on \( V_{D1}, V_{D2} \) and \( V_{D3}, V_{D4} \), respectively. The positions of the excess charges (the electrons in each double dot that are free to move) are shown schematically as insets to Figure 3b. The coupled charge stability diagram reveals the four possible ground-state charge configurations for an extra electron in each of the two double dots. The grey dashed lines in Figure 3b.
show the RDD detuning energy shift ($\Delta \varepsilon_R$) arising from the movement of a single electron from left to right in the LDD. The shift in this line is a direct measure of the energy shift in the RDD resulting from the capacitive coupling between the two double dots. From the energy calibrations reported above, we extract $\Delta \varepsilon_R=75 \mu \text{eV}=18.3 \text{GHz}$. This energy shift is the available detuning modulation for the performance of two-qubit gates in quantum dots of a size and separation similar to those studied here.

We now show that the capacitive coupling demonstrated above enables fast charge-state-conditional-phase evolution of a quantum dot charge qubit. We study LZS oscillations in the RDD in the presence of a slowly varying perturbation from the excess charge in the LDD. Figure 4a illustrates schematically in green the pulse applied to the RDD for this experiment. The pulse is applied at a series of different values of $\varepsilon_L$ (the vertical axis in Figure 4b–f). The pulse minimum detuning is controlled using $V_{D3}$, and the pulse amplitude is held fixed at 210 $\mu \text{eV}$. In Figure 4b–f, we vary $V_{D3}$ from 221.7 to 222.5 in steps of 0.2 $\mu \text{eV}$. The effect of these steps is to change the energy in detuning of the maximum of the fast pulse, thus changing the frequency of the LZS oscillations. For example, the oscillations in Figure 4a are much faster than those visible in Figure 4f. The physical origin of this variation is the energy difference between the two charge qubit states: in Figure 4a, the maximum of the pulse sits at large detunings, corresponding to a large energy difference between the states. In contrast, in Figure 4f, the pulse maximum sits at detunings much closer to the charge qubit anticoercing, so that the energy difference between the charge qubit states is significantly smaller.

For each of these LZS oscillation measurements, $\varepsilon_L$ is slowly swept from $+180$ to $-320 \mu \text{eV}$ (see the vertical axis in the top panels of Figure 4b–f). This variation in $\varepsilon_L$ has two effects. First, the cross-talk between $\varepsilon_L$ and the RDD results in a continuous shift in the detuning of the RDD, causing the LZS oscillations be tilted in each of the top panels of Figure 4b–f. Second (and this is the main result of Figure 4), at $\varepsilon_L=0$, the excess charge occupation of the RDD changes from (0, $L$) to (1, $L$) — this change occurs quite abruptly at zero detuning of the LDD, as can be observed in Figure 4b–f. This change in the charge configuration of the RDD produces a sudden decrease in frequency in Figures 4b–f at $\varepsilon_L=0$. This decrease in frequency reflects the decreased detuning $\varepsilon_R$ that the LZS pulse maximum reaches because of the effective change in the pulse minimum detuning energy.

The bottom panels of Figure 4b–f show line cuts of the LZS oscillations in the RDD for the (0, $L$), LDD ground state (black arrow on the left in Figures 4b) and (1, $L$) LDD ground state (red arrow on the left in Figure 4f). At any given evolution time $t_p$, a phase change is clearly visible, and this phase change arises from the shift of one electron in the LDD. Using this effect, a charge-state-conditional $\pi$ phase flip can be achieved in a time $t_p$ as short as 80 ps, as indicated by the black arrow in Figure 4e.

Figure 4g shows the difference in $f_{\text{ZS}}$ between the cases when the LDD ground state is (0, 1) (black circles) and when this ground state is (1, 0) (red circles). The frequency differences vary from 7 to 10 GHz, and this plot can be used to infer the speed of a conditional phase (CPHASE) gate if full control over qubits in both the left and right double dots in a device like that shown here is realized in the future. We emphasise that the frequency changes observed here arise from competing effects: $f_{\text{ZS}}$ of the RDD increases as we change a gate voltage to increase $\varepsilon_L$, whereas $f_{\text{ZS}}$ decreases as we cross zero detuning in the LDD, resulting in the motion of a single electron charge. As we take line cuts at $\varepsilon_L=+80 \mu \text{eV}$ to clearly show LZS oscillations in the (0, 1) and (1, 0), ground states, we believe that using an LDD detuning pulse amplitude $<160 \mu \text{eV}$, when LDD coherent manipulation is realized, can lead to a faster conditional phase gate than that estimated here.
DISCUSSION
Here we have demonstrated a strong capacitive coupling of \( \approx 18 \) GHz between two double quantum dots in a linear quadruple dot array geometry, and this coupling enabled the observation of fast charge-state-conditional coherent oscillations with a conditional phase flip time of 80 ps. Coupling of this magnitude demonstrates a key physical interaction necessary for a two-qubit CPHASE gate. Moreover, because we measure single-qubit X (Larmor) and Z (Ramsey) rotations with rotation frequencies also on the order of 10 GHz, one can envision universal quantum logic gates in semiconductor charge qubits that are all fast. Although we use abrupt changes in the baseline detuning here, resonant microwave control is also possible,\(^{26,36}\) in which case a two-qubit controlled not gate (CNOT) could be implemented in analogy with ref. 27. We stress, however, that the full demonstration of two-qubit charge qubit gates remains as a challenge, as in this work coherent control of the LDD could not be achieved. A more compact gate geometry that enables greater tunability in the tunnel coupling, which could potentially be achieved using an overlapped Al/Al\(_2\)O\(_3\) gate structure,\(^{26,43}\) is a promising path towards achieving fully tunable tunnel couplings in both neighbouring double quantum dots. Finally, we note that the strong capacitive coupling observed here is also a valuable resource with the potential to enable two-qubit gates in multi-electron spin qubits, including singlet–triplelet\(^{6,25}\) and hybrid quantum dot qubits.\(^{18,20,48–50}\)

MATERIALS AND METHODS

Fabrication
The device heterostructure was grown using chemical vapour deposition on commercially available SiGe substrates with a 29% Ge composition. The chemical vapour deposition growth sequence from the starting substrate was deposition of a strain-matched SiGe buffer layer followed by deposition of a 12-nm-thick strained Si well. The well was capped by deposition of 50 nm of SiGe, followed by a few nanometres of sacrificial strained Si to cap the heterostructure.

Devices were fabricated using a combination of electron beam lithography and photolithography. The device nanostructure was fabricated in two layers starting on a 15 nm gate dielectric of Al\(_2\)O\(_3\) deposited by atomic layer deposition. The first layer of control gates was patterned in two electron beam lithography/metallisation steps to improve the gate density, and the metal layers were Ti followed by Au. The second reservoir gate layer (see inset to Figure 1a) is isolated from the first with another 80 nm layer of Al\(_2\)O\(_3\) grown via atomic layer deposition. The second gate layer was also metallised with Ti/Au. A third layer of Al\(_2\)O\(_3\) was deposited over the second gate layer to protect the gates during subsequent fabrication steps. Ohmic contacts were fabricated using annealed P+ ion implants.

Measurement
The charge stability diagrams of the LDD and RDD are characterised by measuring the conductance changes through the left and right sensor dots (LSD and RSD, respectively, see Figure 1a) that are operated at a fixed voltage bias of 50 \( \mu \)V, and the currents are measured with two current preamplifiers (DL Instruments model 1211). Supplementary Figure S1 shows large-scale charge stability diagrams and the positions of charge transitions of the LDD and RDD in the electron occupation regime used in the present experiment. For the manipulation of the RDD charge qubit, fast voltage pulses with repetition rate of 25 kHz are generated using two outputs of a Tektronix AWG70002A arbitrary waveform generator, which are added to the dot-defining dc voltage through a bias tee (Picosecond Pulselabs 5542–219) before being applied to gate D\(_3\). The conductance change through the RSD with and without the manipulation pulses, measured with a lock-in amplifier (EG&G model 7265), is used to determine the average charge occupation. For the measurement of changes in charge occupation, probabilities resulting from fast manipulation pulses, we modulated the manipulation pulses with a low frequency (\( \approx 777 \) Hz) square wave envelope, similar to the technique used in previous studies.\(^{36,48}\) We compare the measured signal level with the corresponding \(|0\rangle\) to \(|1\rangle\) charge transition signal level, calibrated by sweeping gate D\(_3\) and applying a 777 Hz square pulse to gate D\(_3\) with an amplitude same as that of the manipulation pulses.

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CONTRIBUTIONS
DRW fabricated the quantum dot device and developed hardware and software for the measurements. DK performed electrical measurements with RHF and analysed the data with MAE, MF and SNC. DES and MGL prepared the Si/SiGe heterostructure. DRW fabricated the quantum dot device and developed hardware and software for the measurements. DK performed electrical measurements with RHF and analysed the data with MAE, MF and SNC. DES and MGL prepared the Si/SiGe heterostructure.

COMPETING INTERESTS
The authors DRW, MAE, MF, and SNC are co-inventors on a patent application related to some of the nanostructure designs described in this work. The remaining authors declare no conflict of interest.

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