

SYSTEMS AND METHODS FOR OPTIMIZING SPIN QUBIT READOUT**TECHNICAL FIELD**

[0001] Aspects of the present disclosure are related to advanced processing systems and in particular to methods for optimizing readout in advanced processing systems.

BACKGROUND

[0002] The developments described in this section are known to the inventors. However, unless otherwise indicated, it should not be assumed that any of the developments described in this section qualify as prior art merely by virtue of their inclusion in this section, or that those developments are known to a person of ordinary skill in the art.

[0003] Large-scale quantum processing systems hold the promise of a technological revolution, with the prospect of solving problems, which are out of reach with classical machines. To date, a number of different structures, materials, and architectures have been proposed to implement quantum-processing systems and to fabricate their basic information units (quantum bits or qubits). Qubits may be understood as a two-level quantum system, where non-degenerate spin states represent the two levels.

[0004] Qubit readout – i.e., determining or measuring the state or encoded information in a qubit – is a fundamental quantum operation in quantum computing. To yield reliable readout results, it is important to measure qubit states with reasonable fidelities (usually above 99% fidelity) and to perform the readout at a speed that is faster than the spin relaxation time of the qubit. Although there are several current readout techniques, they are often prone to errors and may not yield reliable results, especially at higher temperatures.

[0005] Accordingly, improved techniques for measuring qubit states in quantum processing systems are desirable.

SUMMARY

[0006] According to a first aspect of the present disclosure, there is provided a method for optimizing Pauli's Spin Blockade based spin readout in a quantum device comprising at least one double quantum dot system comprising first and second quantum dots and a charge sensor, the method comprising: increasing an asymmetry of tunneling rates between the first and second quantum dots and the charge sensor from a first asymmetry value to a second asymmetry value.

[0007] In some embodiments, the asymmetry of the tunneling rates between the first and second quantum dots and the charge sensor is increased by varying at least one parameter of: physical distances between the first and second quantum dots and the charge sensor, a number of donor atoms in the first and/or second quantum dots, a number of electrons in the first and/or second quantum dots, and/or a configuration of the first and/or second quantum dots. Further, varying the at least one parameter comprises precision engineering of the quantum device using scanning tunneling microscopy.

[0008] The first and second quantum dots are silicon-based quantum dots. Further, the type of Pauli's Spin Blockade (PSB) based spin readout is a latched spin readout. In some embodiments, the latched spin readout is optimized by varying the distance between the first and second quantum dots and the charge sensor. In particular, the distance between the first quantum dot and the charge sensor may be approximately 25nm and the distance between the second quantum dot and the charge sensor may be approximately 15nm.

[0009] According to a second aspect of the present disclosure there is provided a method for optimizing electron spin resonance (ESR) based spin readout in a quantum device comprising at least one quantum dot and a charge sensor, the method comprising: adjusting a tunneling rates between the quantum dot and the charge sensor.

[0010] In some embodiments, the tunneling rate between the quantum dot and the charge sensor is adjusted by varying at least one parameter of: a physical distance between the quantum dot and the charge sensor, a number of donor atoms in the quantum dot, a number of electrons in the quantum dot, and/or a configuration of the quantum dot. Further, varying the at least one parameter comprises precision engineering the quantum device using scanning tunneling microscopy.

[0011] According to a third aspect of the present disclosure, there is provided an engineered quantum processing element comprising: at least one quantum dot in a

semiconductor substrate; a sensor in the semiconductor substrate positioned at a distance from the quantum dot for initialising and/or measuring a qubit associated with the quantum dot; wherein a predetermined tunneling rate between the quantum dot and the sensor is designed by precision fabrication of the quantum processing element for enabling the initialization and/or measurement of the qubit associated with the quantum dot.

[0012] According to a fourth aspect of the present disclosure, there is provided an engineered quantum processing element comprising: at least one double quantum dot system in a semiconductor substrate, the at least one double quantum dot comprising first and second quantum dots and a charge sensor; a sensor in the semiconductor substrate positioned at a distance from the double quantum dot for initialising and/or measuring a qubit associated with the double quantum dot; wherein an asymmetry of tunneling rates between the first and second quantum dots and the sensor is increased from a first asymmetrical tunneling rate to a second asymmetrical tunneling rate by precision fabrication of the quantum processing element for enabling the initialization and/or measurement of the qubit associated with the double quantum dot.

BRIEF DESCRIPTION OF DRAWINGS

[0013] While the invention is amenable to various modifications and alternative forms, specific embodiments are shown by way of example in the drawings and are described in detail. It should be understood, however, that the drawings and detailed description are not intended to limit the invention to the particular form disclosed. The intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the present invention as defined by the appended claims.

[0014] Fig. 1A shows an embodiment of a multi-donor quantum dot device.

[0015] Fig. 1B shows a further embodiment of a multi-donor quantum dot device with an in-plane gate.

[0016] Fig. 2 shows a schematic of a scanning tunneling microscope (STM) image of an example quantum processor device.

[0017] Figs. 3A and 3B show the principle of spin-to-charge conversion.

[0018] Fig. 3C is a chart showing charge sensed by a charge sensor when an electron remains in a quantum dot and does not tunnel to a reservoir.

[0019] Fig. 3D is a chart showing charge sensed by a charge sensor when an electron tunnels from a quantum dot to a reservoir.

[0020] Fig. 3E illustrates the voltage pulses used during the three stages of energy selective measurement (ESM) to align the electrochemical potentials of the electron spins relative to the Fermi-level of the reservoir EF.

[0021] Fig. 3F is a schematic illustrating the electrochemical potential for ESM during the three stages of ESM.

[0022] Fig. 3G is a chart showing signal detected from a nearby charge sensor during

[0023] ESM.

[0024] Fig. 4A is a flowchart illustrating an example ramped spin measurement (RSM) method for measuring spin.

[0025] Fig. 4B shows the voltage pulses used during the RSM method.

[0026] Fig. 4C is a chart illustrating signal detected from a nearby charge sensor during RSM.

[0027] Fig. 5 shows a schematic quantum processing system of two donor quantum dots according to aspects of the present disclosure.

[0028] Fig. 6 is a schematic of a charge stability diagram showing a Pauli spin blockade readout (PSBR) process.

[0029] Fig. 7A is a schematic of a charge stability diagram showing shelving and latching readout processes.

[0030] Fig. 7B is a schematic of the shelving readout procedure, with relevant state ladders and transitions indicated by arrows with numbers corresponding to those shown in Fig. 7A.

[0031] Fig. 7C is a schematic of the latching readout procedure, with relevant state ladders and transitions indicated by arrows with numbers corresponding to those shown in Fig. 7A.

[0032] Fig. 8A is a schematic of a STM image of an optimized quantum device according to aspects of the present disclosure connected to a measurement circuit.

[0033] Fig. 8B is a zoomed in view of a portion of the STM image of Fig. 8A showing a double quantum dot system and a charge sensor.

[0034] Fig. 8C is a chart showing a 2D map of a reflected RF-signal (in mV) as left and right gate voltages are varied.

[0035] Fig. 8D is a chart showing a first discontinuity data for a normalised SET signal as a function of gate voltage.

[0036] Fig. 8E is a chart showing a second discontinuity data for a normalised SET signal as a function of gate voltage.

[0037] Fig. 9A is a schematic charge stability diagram showing the three step pulse sequence used to perform latched spin readout (LSR).

[0038] Fig. 9B shows electron spin states for the (1,1), (2,0) and (2,1) charge configurations.

[0039] Fig. 9C is a plot of example SET charge sensor traces showing a signal for odd parity and even parity states where a readout position is biased to a top of Coulomb peak in the (2,1) region.

[0040] Fig. 10A shows an SET signal as a function of gate voltage while a bath temperature of a dilution refrigerator was varied from 0.1 K to 3.7 K.

[0041] Fig. 10B is a plot of the measured spin readout (1 – Fidelity) as a function of integration time of the SET signal.

[0042] Fig. 10C is a plot showing signal to noise ratio (SNR) as a function of integration time of the SET signal.

[0043] Fig. 10D is a plot showing signal histograms for detecting odd and even states for an integration time of 175 ns at 0.2 K.

[0044] Fig. 10E is a plot showing fidelity and (1 - visibility) of each odd parity and even parity states as a function of a threshold value of an integrated signal.

[0045] Fig. 10F is a plot showing signal histograms for detecting odd and even states for an integration time of 1.5 μ s at 3.7 K

[0046] Fig. 10G is a plot showing fidelity and (1 - visibility) of each odd parity and even parity states as a function of a threshold value of an integrated signal at 3.7 K operation temperature.

DETAILED DESCRIPTION

[0047] As described above, it is important to optimize readout methods for reading out the state of qubits in large-scale quantum processors.

[0048] A number of different techniques exist to fabricate the basic information units (quantum bits or qubits) of quantum processing systems or quantum computers. One way of fabricating qubits, for example, is to use the nuclear spin of a phosphorus donor atom in silicon or the spin of an electron confined to said phosphorus donor atom such that the nuclear/electron spin can act as a qubit. Spin qubits based on phosphorus donor atoms in silicon have demonstrated excellent coherence and relaxation times. These long coherence times, together with the mature fabrication technology based on scanning tunneling microscopy, makes silicon-phosphorus systems a promising semiconductor platform for quantum information processing.

[0049] Fig. 1A shows a multi-donor quantum dot device 100. As shown in the figure, the quantum dot 101 is formed in a structure comprising a semiconductor substrate 102 and a barrier material/dielectric 104. In this example, the substrate is isotopically purified silicon (Silicon-28) and the dielectric is silicon dioxide. In other examples, the substrate may be silicon (Si). Where the substrate 102 and the dielectric 104 meet an interface 106 is formed. In this example, it is a Si/SiO₂ interface. In this example, there are two donor atoms 108A and 108B located within the quantum dot 101 in the semiconductor substrate 104. In some examples the donor atoms 108A, 108B are phosphorus atoms. In this example, quantum dot 101 includes two donor atoms 108, which herein is generally referred to as a 2P quantum dot.

[0050] Further, a gate 110 and an antenna 112 may be located on the dielectric 104 in a region substantially above the multi-donor quantum dot 101. Voltages may be applied to gate 110 to confine an electron 114 in the quantum dot 101. Electron 114 may be shared by the two donor atoms 108A and 108B. It will be appreciated that device 100 may comprise additional gates. In some examples, more than one electron is confined in the quantum dot 101.

[0051] Fig. 1B shows another example multi-donor quantum dot device 150. This is similar to the device shown in Fig. 1A. The difference being the placement of the gates. In Fig. 1A, the gates are displayed as being placed on top of the dielectric 104. In this example, the gates are located within the semiconductor substrate 102. In some embodiments, gate 110 is placed within the substrate in the same plane as the quantum dot 101. The in-plane gate 110 may be connected to the surface of the substrate via metal vias (not shown). Voltages may be applied to gate electrode 110, located within the semiconductor substrate, to confine one or more electrons 114 in the quantum dot 101.

[0052] It will be appreciated that device 150 may comprise additional gates located within the semiconductor substrate 102. In some embodiments, multi-donor quantum dot device may include a combination of one or more gates located on the dielectric 104 and one or more gates located within the semiconductor substrate 102.

[0053] In the 2P quantum dot with one electron, there are a total of three spins (the two nuclear spins from the donors and the spin of the electron). As such, each of the three spins may be considered a qubit.

[0054] In some embodiments, there may be one donor atom 108. This donor atom may be a phosphorus atom and in such an example, the quantum dot may be called a 1P quantum dot. In some embodiments, there may be three donor atoms 108. These three donor atoms may be phosphorus atoms and in such examples are collectively called a 3P quantum dot.

[0055] In other examples, there may be m donor atoms – where m is an integer. In the case where there are m donor atoms that are phosphorus atoms the multi-donor quantum dot may be called an m P quantum dot. In a general quantum dot system with m donors and one electron, there are $m+1$ total nuclear and electron spins and therefore $m+1$ possible qubits.

[0056] Gates 110 and 112 may be used to tune the electron filing on the quantum dot 101. For example, an electron 114 may be loaded onto the quantum dot 101 by a gate electrode, e.g., 110. The physical state of the electron 114 is described by a wave function – which is defined as the probability amplitude of finding an electron in a certain position. Donor quantum dots in silicon rely on using the potential well naturally formed by the one or more donor atom nucleus to confine the electron spin. In some embodiments, there may be more than one electron 114 loaded onto the quantum dot 101. In examples with more than one electron on the quantum dot, it may be preferable to have an odd number of electrons.

[0057] Single-shot spin readout is an important requirement for error-corrected quantum computing in semiconductor spin qubits. Spin qubit devices rely on spin-to-charge conversion and detection of the charge for qubit readout. There are two main methods for performing single-shot spin readout, these include – reservoir readout (where an electron from a quantum dot tunnels into and out of a reservoir during the readout process) and Pauli's spin blockade (PSB) based readout. There are two main types of reservoir-based spin readout techniques – energy-selective measurement (ESM) and ramped readout. Further there are two main types of PSB based readout techniques – shelved and latched readout. These readout methods will be described in the following section.

[0058] Fig. 2 shows a schematic of a scanning tunneling microscope (STM) image of an example device 200 including a quantum dot 202 and an electron 204 that may be tunneled into the quantum dot under specific conditions.

[0059] The whole device 200 may be epitaxial – i.e., the donor dot 202 may be fabricated within a substrate (such as a p-type Si substrate (1–10 Ω cm)). Positioning the donor dot 202 epitaxially can significantly reduce impact of noise on the qubit. In some examples, the quantum dot 202 is formed about 20-50nm from the surface.

[0060] The device 200 includes a charge sensor quantum dot 206 (such as a single-electron transistor (SET)), a source 208, and a drain 210. The quantum dot 202 may be tunnel coupled to the charge sensor quantum dot 206 (e.g., an SET) and/or an electron reservoir such as 212 to load the one or more electrons 204 onto the donor dot 202. Further, the qubit thus formed (in this example, the electron spin) may be controlled by one or more gates 212. Fig. 2 illustrates three gates – left gate 212A, middle gate 212B, and right gate 212C, which can be used to control the electrochemical potentials of the donor dot 202. An SET gate 214 is predominately used to control the electrochemical potential of the SET 206. In one implementation, the gates 212 may be metal contacts on the surface. In another implementation, the gates 212 may be phosphorus-doped silicon (SiP) gates fabricated epitaxially within the semiconductor substrate. In either case, the gates allow full electrostatic control of the qubit.

[0061] In reservoir readout methods, a quantum dot is tunnel coupled to a reservoir, e.g., reservoir 208 or SET 206. For example, a multi-donor quantum dot is tunnel coupled to an SET 206.

[0062] One example type of reservoir-based spin readout technique is referred to as energy-selective measurement (ESM). Fig. 3 schematically shows this measurement technique. In particular, Figs. 3A and 3B depict a single electron spin 302 confined in a quantum dot 202. In Fig. 3A, the electron 302 is in the spin-up ($|\uparrow\rangle$) state and in Fig. 3B the electron 302 is in the spin-down ($|\downarrow\rangle$) state. In ESM, a static magnetic field (B_0 – not shown) is applied to split the spin-up and spin-down states by the Zeeman energy. The quantum dot potential is then tuned such that if the electron is spin-down (as seen in Fig. 3B), the electron 302 leaves the quantum dot 202 and returns to a reservoir (e.g., 206 or 210), whereas it will stay on the quantum dot 202 if it is spin-up (as seen in Fig. 3A).

[0063] Figs. 3C and 3D are charts showing the charge state of the quantum dot 202 as a function of time as detected by a nearby charge sensor (e.g., SET 206). If the electron remains in the quantum dot 202 after the quantum dot potential has been tuned (see Fig. 3A), the charge of the quantum dot 202 remains the same over a period of time (as shown in Fig. 3C). Alternatively, if the electron tunnels to the reservoir 206 or 210 after the quantum dot potential has been tuned (see Fig. 3B), the change is detected in the charge of the quantum dot 202. This change in charge of the quantum dot 202 can be seen in Fig. 3D where the charge increases after a period of time. In this manner, the electron spin state is correlated with its charge state. Thus, measurement of the charge on the quantum dot reveals the original electron spin state.

[0064] The above description of the ESM technique is described with reference to a system where the spin-up electron has lower energy than the spin-down electron. For example, the measurement technique may be performed in a GaAs (Gallium arsenide) material. In this case, the lower-energy spin-up electron cannot tunnel to the reservoir. In other examples, the spin-up state may have higher energy compared to the spin-down state. For example, in a silicon material. In these examples, the lower-energy spin-down state cannot tunnel to the reservoir.

[0065] In some cases, to measure the spin of an electron spin qubit using ESM a three stage process is used. Fig. 3E is a schematic showing the electrochemical potential (y-axis) for ESM. The three-stage process commences with an empty quantum dot 202. The first stage 310 (Load stage) loads an electron 204 with an unknown (random) spin onto the quantum dot 202. During the second stage 320 (read stage), the electron spin state is measured (using a nearby charge sensor). In this example, only the spin-up electron can tunnel to the reservoir 206 or 210. A subsequent spin-down electron will then be loaded onto the quantum dot 202. Finally, at the third stage 330 (empty stage) the quantum dot 202 is emptied by moving the energy levels above the Fermi level (or Fermi energy) E_F .

[0066] The different stages are typically controlled by a three-level voltage pulse on a nearby gate (see Fig. 3F) – for example on one or more of gates 212A-212C. The voltage pulse shifts the energy levels of the quantum dot 202 around the Fermi level, E_F , (represented by the dashed line in Fig. 3E) of the tunnel-coupled reservoir 206/210. For example, in the first stage 310, the energy levels 312 of the electron qubit are below the Fermi level. In the second stage 320, the energy levels 312 of the electron qubit are around the Fermi level. In the third stage 330, the energy levels 312 of electron qubit 304 are above the Fermi level.

[0067] Fig. 3F shows the shape of the voltage pulses applied to a gate (e.g., gate 212A-212C) to perform the three stages 310, 320 and 330. Before a pulse is applied, the quantum dot 202 is empty and both the spin-up and spin-down energy levels are above the Fermi energy E_F of a nearby reservoir. Then at stage 310, a voltage pulse (called the load phase) is applied for time t_{wait} . This pulse pulls the energy levels of both spin states below E_F . An electron 302 can now energetically tunnel into the quantum dot 202 from the reservoir. The particular electron can either be in the spin-up or spin-down state. During this stage 310, the electron 302 is trapped on the quantum dot 202 and Coulomb blockade prevents a second electron from being added to the quantum dot 202. After t_{wait} , the voltage pulse is reduced and maintained for a duration t_{read} , in order to position the energy levels of the spin-up and spin-down states in a read-out configuration. In this example, a readout configuration means that the energy levels 312 of the electron qubit are around the Fermi level (see stage 320 of Fig. 3E). If the electron spin is $|\downarrow\rangle$, its electrochemical potential, $\mu_{0\leftrightarrow\downarrow}$ is below E_F , so the electron remains on the quantum dot 202. If the spin is $|\uparrow\rangle$, its electrochemical potential, $\mu_{0\leftrightarrow\uparrow}$ is above E_F , so the electron tunnels to the reservoir. Now the Coulomb blockade is lifted and an electron with spin-up can tunnel onto the dot 202. After t_{read} , the pulse ends and the dot 202 is emptied again (stage 330). In the read phase 320, the voltage pulse quickly moves the electrochemical potentials $\mu_{0\leftrightarrow\downarrow}$ and $\mu_{0\leftrightarrow\uparrow}$ such that E_F is situated between them. In this position a spin-up electron is more likely to tunnel out of the quantum dot 304 and to the reservoir 306 compared to a spin-down electron. If a spin-up electron tunnels to the reservoir 306 then a spin-down electron can tunnel onto the quantum dot 304 from the reservoir 306 at this stage.

[0068] This two-step tunneling process creates a ‘blip’ in the nearby charge sensor 206 response, which is a signature that spin-to-charge conversion of the electron spin state has been performed. Fig. 3G shows the signal from the nearby sensor 206 during ESM. The x-axis represents time and the y-axis represent the charge signal. The signal for the electron spin-up state is shown in solid lines 324 and the signal for the electron spin-down state is shown in dashed lines 326. The signal is shown for the load stage 310, the read stage 320 and the empty stage 330. During the read phase 320, the spin-up state is detected as a characteristic ‘blip’ 322 in the charge sensor signal 324.

[0069] Typically, readout in spin qubits has been performed using ESM with extremely high fidelities up to 99.95% at milli-Kelvin temperatures. However, despite achieving record

fidelities at low temperatures, the readout time remains approximately 1 μ s to 100 μ s and comparable to the electron spin coherence time.

[0070] Further, the protocol relies on the precise alignment of both the spin-up and spin-down energy levels $\mu_{0\leftrightarrow\downarrow}$ and $\mu_{0\leftrightarrow\uparrow}$ about E_F . The alignment procedure is usually performed by measuring a so-called ‘spin-tail’ by varying the read level from below E_F to above E_F and then determining the optimal read level by analysing the measurement fidelity. In a large-scale quantum computing architecture such precise alignment may not be feasible for every qubit on a timescale that is allowed by charge noise.

[0071] Additionally, ESM requires that the ratio of qubit tunnel rates to be ~ 800 corresponding to $E_Z > 13k_B T_e$ when $\mu_{0\leftrightarrow\downarrow} = -\mu_{0\leftrightarrow\uparrow}$ for high-fidelity readout. However, recent proposals and experiments are investigating the possibility of operating spin qubits at temperatures above 1K to increase cooling power for cryogenic electronics. Therefore, it would be beneficial to have a spin readout technique that can still be used when $E_Z \sim k_B T_e$.

[0072] Another example type of reservoir-based spin readout technique is referred to as ramped spin readout (RSR). Fig. 4A illustrates an example method 400 for measuring spin qubits based on the ramped spin readout method. Like the ESM method, the RSR method 400 includes three steps. At step 402, the quantum dot 202 is emptied. At step 404, one electron 204 with an unknown spin is injected in the quantum dot 202 by applying a voltage pulse for a time t_{LOAD} . At step 406, the spin state of the electron 204 is measured by applying ramped detuning for a time t_{READ} . These steps of the RSR method 400 are controlled by applying a voltage on one or more nearby gates 212, which shifts the energy levels of the quantum dot 202 around the Fermi level, E_F , of the tunnel coupled reservoir 208.

[0073] Fig. 4B shows the shape of the voltage pulses applied to one or more gates 210 during method 400. Again, there are three stages: the load stage 410, the read stage 420 and the empty stage 430. As seen in Fig. 4B, the voltage pulses 412 and 432 are similar to the voltage pulses applied in the ESM method during the load and empty stages, respectively – see Fig. 3F. However, during the read phase 420 (i.e., at step 406), instead of pulsing the voltage to a single detuning value and waiting a time t_{read} for the electron spin-up state to tunnel out to the reservoir 208, in the present method 400, the detuning is ramped 422 from below the Fermi energy E_F to above the Fermi energy E_F during the read stage.

[0074] Further, the load stage 410 and empty stage 430 are equivalent to the load stage 310 and empty stage 330 of the ESM method. However, the read phase now involves

determining when a blip occurs during the read phase rather than if a blip is detected. Fig. 4C shows a corresponding signal from the charge sensor 206 during RSM. The x-axis represents time and the y-axis represents the charge signal. The signal for the electron spin-up state is shown in solid lines 440 and the signal for the electron spin-down state is shown in dashed lines 442. The signal is shown for the load stage 410, the read stage 420 and the empty stage 430. During the read phase 420, the spin-up state is detected as a characteristic 'blip' 444 in the charge sensor signal 440.

[0075] A blip 444 in the charge electron spin-up sensor signal 440 before a certain threshold time indicates the presence of a spin-up electron 204. A blip in the charge sensor signal 442 after the threshold time indicates the presence of a spin-down electron 204. Further, the charge sensor signals 440, 442 reach their maximum value before the empty phase 430 as the spin-down electron also tunnels out to the reservoir 208 during the read phase.

[0076] The ramping 422 during the read stage 420 of the detuning fundamentally changes the way in which the spin-to-charge conversion process operates in RSR.

[0077] Firstly, the tunnel rates of the electron $|\downarrow\rangle$ and $|\uparrow\rangle$ states, $\Gamma_{\text{in/out } \downarrow}$ and $\Gamma_{\text{in/out } \uparrow}$ respectively, become time dependent. Specifically, the 'tunnel out' rates are slow at the beginning of the ramp 422 (generally on the order of a few Hz) and then increase over the duration of the ramp while the 'tunnel in' rates are fast at the start of the ramp 422 (generally less than a MHz) and then decrease over time. These time-dependent tunnel rates are the reason that RSR can outperform ESM.

[0078] Secondly, in the RSR technique, the time threshold is redefined. For ESM, the time threshold is equivalent to the readout time (t_{read}) and is chosen to determine if a blip 322 is detected. If a blip is detected the qubit state is assigned to be in the spin-up state $|\uparrow\rangle$, whereas if no blip is detected before the time threshold then the spin state is assigned to be in the spin-down state $|\downarrow\rangle$. However, for RSR the time threshold is used to threshold when a blip occurs. If a blip 444 is detected before the time threshold then the spin state is assigned to be $|\uparrow\rangle$ and if the blip 444 occurs after the time threshold then the spin state is assigned as $|\downarrow\rangle$.

[0079] Since the electrochemical potentials of both spin states are above E_F at the end of the ramp 422, a blip 444 or step is always detected in the charge sensor signal during the read phase 420; that is, the electron spin has to be in either $|\uparrow\rangle$ or $|\downarrow\rangle$.

[0080] Such a ramp pulse 422 in the read phase 420 may be advantageous for a number of reasons. For high temperature or low magnetic field conditions the optimal energy position occurs where both $\mu_{0\leftrightarrow\downarrow}$ and $\mu_{0\leftrightarrow\uparrow}$ are below E_F and the tunnel rates to the electron reservoir 208 are slow. The slow tunnel rates mean that the readout time becomes impractical. Ramped spin readout mitigates this long readout time that would otherwise be required by attempting readout at every detuning position for a short amount of time. Therefore, in such situations, the spin readout can achieve high-fidelity while keeping the readout time short.

[0081] Additionally, the alignment of the RSR method 400 is comparatively simple and fast over the traditional 'spin-tail' measurement and involves performing the same pulse sequence as for the actual readout protocol.

[0082] Finally, the use of ramp pulses 422 significantly reduces the bandwidth requirements for fast pulsing which could possibly lead to lower electron temperatures since additional filtering can be implemented (where electron temperature refers to the temperature associated with the energy distribution of the electrons in the system).

[0083] A second example method for single-shot readout is the Pauli spin blockade readout (PSBR) method. The PSBR in a double quantum dot system is used as a method for reading out the electron charge in order to determine the spin of the electron. The PSBR occurs when the transport of electronic charge is blocked due the spin properties of the system.

[0084] Fig. 5 is a top view schematic of a two-donor quantum dot (singlet-triplet qubit) system 500 that may be used for PSBR. In some examples, a two-donor quantum dot system may be called a 'double dot' system. In this example, there are three gates 502, 504, 506. There are two quantum dots (donor dots) 508, 510 each tunnel-coupled to a single electron transistor (SET) 512. In this example, the double quantum dot system is a 1P-2P system, with three nuclear spins 514, 516, 518 shown by the small double arrows. There are two electrons and thus two electron spins 520, 522 in the system shown by the large arrows. The gates and/or SET may be fabricated on top of the dielectric or within the silicon substrate 102. In some examples, the gates and/or SET may be fabricated substantially in-plane with the double-donor quantum dots.

[0085] The left and right quantum dots 508, 510 can each tunnel to the SET 512 via the left tunnel coupling (t_L) and the right tunnel coupling (t_R), respectively. The two quantum

dots 508, 510 are also tunnel coupled to each other via t_0 allowing the electrons 520, 522 to form singlet and triplet states across both quantum dots. In general, each dot 508, 510 can be occupied by an odd number of electrons. In such cases, only the behaviour of one unpaired, highest energy electron in each dot contributes to the singlet-triplet qubit formation. In this example, the SET 512 serves as an electron reservoir for the donor dots 508, 510 and is used as a charge sensor. The surrounding gates 502, 504, 506 control the electrostatic environment of the quantum dots 508 and 510.

[0086] In some examples, each quantum dot 508, 510 may have a single donor atom and the donor atom may be a phosphorous (P) atom such that the system is a 1P-1P system. In other embodiments, the system may be an nP-mP system and the donor dots 508, 510 may have any number of phosphorous donor atoms, where $n = m$ or $n \neq m$ and n and m are both positive integers.

[0087] Each electron has two possible spin states, spin-down and spin-up, denoted $|\downarrow\rangle$ and $|\uparrow\rangle$, respectively. Combining the two spin states of each electron 520, 522 yields four new states – that is, there are four possible combined spin states. There is one singlet state with total spin angular momentum 0. This state is denoted:

$$|S\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

[0088] Where the first arrow and second arrow in each ket indicates the spin direction of the first and second electron, respectively. The remaining three states are triplet states, each with total spin angular momentum 1. These triplet states are denoted:

$$|T_+\rangle = |\uparrow\uparrow\rangle$$

$$|T_0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

$$|T_-\rangle = |\downarrow\downarrow\rangle.$$

[0089] Here, the $|T_+\rangle$ and the $|T_-\rangle$ triplet states correspond to both electrons being in the spin-up state and spin-down state, respectively.

[0090] Of the four possible relative spin states of the electrons (S, T_0, T_+, T_-), information is generally stored in the S (singlet state) and T_0 (a triplet state) states (the so-called ‘logical subspace’). This choice is generally motivated by two advantages. First, the two qubit states remain unaffected by changes in magnetic field (with magnetic quantum number, $m=0$), which

further decouples them from the environment. Second, due to the Pauli Exclusion Principle, in the S and T_0 states, each electron has an orbital wavefunction hybridised between the two donor dots 508, 510, and in the $|T_+\rangle$ and $|T_-\rangle$ triplet states both electrons are confined to separate donor dots. Therefore, by tuning the relative electrochemical potentials of the two dots 508, 510, the charge distribution of electrons can be tuned.

[0091] The singlet-triplet states of the two electron system describes the system in the spin basis. Alternatively, the two electron system may be represented in the charge basis, denoted by ordered pairs: $(1,1)$, $(0,2)$ and $(2,0)$. Where (n_L, n_R) corresponds to n_L electrons in the left dot and n_R in right dot.

[0092] As mentioned above the PSB can be used in a double dot system to readout electron spin. For example, the ground charge state for a double quantum dot with two electrons is the $(0,2)$ charge state. In this example the double quantum dot includes a left and right quantum dot. When the system is in the charge configuration $(1,1)$ an electron may tunnel from the left dot to the right dot in order for the system to be in the ground state $(0,2)$. This electron tunneling is energetically favourable. Electron tunneling generally conserves the spin of the system. The ground charge state $(0,2)$ is a spin singlet therefore the $(1,1)$ singlet state can transition to the $(0,2)$ singlet state by tunneling of an electron. However, the $(1,1)$ triplet state is not allowed to transition into the $(0,2)$ singlet state. Combined with a charge sensor the PSB can be used to readout the spin state of the spin qubit.

[0093] To realise purely electrical control of the singlet-triplet qubit, the two quantum dots 508, 510 need to be characterised by a different spin Zeeman splitting. Zeeman splitting is typically caused by the interaction between an external magnetic field and the electron's magnetic dipole moment. The Zeeman energy difference, ΔE_z , allows coupling between the singlet and triplet states and therefore the ability to perform qubit rotations.

[0094] In electrostatically-defined quantum dots, ΔE_z can be produced by a nuclear spin bath, an external magnetic field (e.g., B_0), micro-magnets, spin-orbit interaction, or a difference of g-factors between the two quantum dots. However, in donor-based devices the same coupling can be achieved using hyperfine interaction between electron and nuclear spins inherently present in the system.

[0095] For example, each of the phosphorous donor atoms has a nuclear spin 514, 516, 518 that interacts with the two electron spins 520, 522. The electron-nuclear hyperfine interaction can be described as an effective magnetic field experienced by the electrons. The

magnetic field can be treated as homogeneous if the hyperfine interaction is the same at both dots 508, 510. Alternatively, if the interaction differs between the dots then it is the magnetic field gradient that causes a difference in the Zeeman splitting, ΔE_z .

[0096] Although ΔE_z is desirable as it is necessary for fast singlet-triplet qubit operation, it is also a source of triplet relaxation. That is, it provides an energy pathway for the $|T_0\rangle$ triplet state to relax to another state, i.e., singlet $|S\rangle$. The fast relaxation is most prominent in the context of the singlet-triplet qubit readout, significantly limiting the visibility of the standard PSBR. Additionally, in donor-based devices, ΔE_z can change in time together with nuclear spin polarization of the donors, as nuclear spins can undergo uncontrolled flips. As such, these processes need to be accounted for when designing and interpreting readout outcomes for singlet-triplet qubits in donor-based devices.

[0097] PSBR gives relatively small contrast between the singlet and triplet states since it relies on measuring the charge distribution within the double quantum dot. The PSBR method also suffers from fast triplet relaxation when singlet-triplet state mixing is present in the system.

[0098] Fig. 6 schematically illustrates the PSBR method. In particular, it shows a charge stability diagram 600 with detuning between quantum dots (ϵ) on the y-axis and the parameter γ (indicating the potentials applied on one or more of the gate electrodes) controlling the total number of electrons in the system on the x-axis. There are three areas of the diagram – namely the charge configurations (1,1), (0,2) and (1,2). The charge configuration (1,2) indicates the addition of an electron to the system, so there are three electrons in total – one on the left dot and two on the right dot.

[0099] The dotted arrow 602 represents the PSBR method. The method includes changing the detuning adiabatically from the (1,1) charge configuration to the Pauli-blocked (0,2) charge configuration. During the transition, the singlet qubit state $|S\rangle$ is mapped to the (0,2) charge configuration while for the $|T_0\rangle$ triplet state the tunneling between the dots is blocked so $|T_0\rangle$ stays in (1,1) charge configuration. For high fidelity readout the charge configurations need to be measured faster than a relaxation rate between $|T_0\rangle$ to $S(0,2)$. This may be difficult due to the fast relaxation caused by the magnetic field gradient.

[0100] While PSBR is one of the most standard and widely used singlet-triplet readout techniques, the method is not without issues. First, the PSBR method has relatively small contrast between singlet and triplet states. Second, the PSBR method may suffer from fast triplet relaxation when singlet-triplet mixing is present in the system.

[0101] In order to address one or more of the shortcomings of PSBR method other techniques have been developed. In particular, there are two main types of PSBR based readout techniques – shelved and latched readout – which are discussed below.

[0102] Shelving readout is a modified PSBR based method that overcomes some of the limitations of PSBR. Shelving readout has been demonstrated to be efficient for gate-defined quantum dot devices which may also offer advantages for donor quantum dot systems as well. In particular, the shelving readout method for donor-based devices has improved readout fidelity in comparison to the standard PSBR. Moreover, shelving readout is well-suited for singlet-triplet qubits subject to large magnetic field gradients, typically of the order of a few mT (ten-hundredths of MHz) of ΔE_z , where ΔE_z changes in time, which is a characteristic very specific to the donor-based system (in gate-defined quantum dots, ΔE_z is either constant in time due to use of micro-magnets or the changes in ΔE_z are not widely discussed).

[0103] Shelving readout operates in the charge occupation subspace comprising the (1,1), (0,2) and (1,2) configurations. The electron distribution between the dots is controlled with detuning ϵ while loading of additional electrons from the SET 512 is determined with a parameter γ , which represents the global energy shift of both quantum dots 508 and 510. Both ϵ and γ can be controlled by the gates surrounding the double-dot system. In some examples gates 502, 504, and 506 can be used to control these parameters.

[0104] Figs. 7A and 7B schematically show the shelving readout method in the charge subspace and spin subspaces, respectively.

[0105] In particular, Fig. 7A shows a charge stability diagram 700 with detuning between the two quantum dots 508, 510, ϵ , on the y-axis and the parameter γ (indicating the potentials applied on one or more of the gate electrodes) controlling the total number of electrons in the system on the x-axis. There are three areas of the diagram – namely the charge configurations (1,1), (0,2) and (1,2). The arrows labelled 1a, 2a and 3a in the schematic represent the shelving readout protocol, with the circled numbers indicating the order of the readout steps. Fig. 7B shows a schematic 710 of the shelving process with relevant states organized in order of increasing energy (lower energy at the bottom increasing to higher energy at the top) and transitions indicated by arrows with the numbers corresponding to Fig. 7A.

[0106] The shelving readout method maps the two-electron spin states $|\uparrow\downarrow\rangle$ and $|\downarrow\uparrow\rangle$ to different charge configurations, namely (0,2) and (1,1), respectively. In particular, the shelving protocol starts in the (1,1) charge configuration region. Further, the shelving protocol

starts at high detuning ϵ where the exchange coupling J is negligible and ΔE_z sets the eigenstates to approximately:

$$|G\rangle = |\uparrow\downarrow\rangle$$

$$|E\rangle = |\downarrow\uparrow\rangle.$$

[0107] In this context, a high detuning refers to a detuning value where exchange J gets much smaller than the Zeeman energy difference ΔE_z (as exchange depends on detuning while Zeeman energy difference is constant). The exact value of detuning depends on the specific values of Zeeman energy difference and how the exchange J depends on detuning and that the exchange detuning dependency is mainly impacted by tunneling between the quantum dots T_0 . Typically, if ΔE_z is hundreds of MHz and T_0 is of the order of 1 GHz, detuning would be tens-hundreds GHz.

[0108] The first step, step 1a, is to ramp non-adiabatically along the γ -axis in a set time period, t_{in} , to γ_{max} to the (1,2) charge configuration region and stay there for a second time period t_{wait} . The potentials created by control gates (e.g., gates 502, 504 and 506) are changing so that γ is effectively ramped (from some initial γ in the (1,1) region to γ_{max} in the (1,2) region).

[0109] If γ_{max} is set such that the energy level of the $|\downarrow S\rangle$ lies between the $|\downarrow\uparrow\rangle$ and the $|\downarrow\downarrow\rangle$ states (see Fig. 7B), then the subsequent transition $|\downarrow\uparrow\rangle \rightarrow |\downarrow S\rangle \rightarrow |\downarrow\downarrow\rangle$ (indicated by the arrows denoted 2a in Fig. 7B) becomes available. Consequently, the $|\downarrow\uparrow\rangle$ state is mapped to the metastable triplet state $|T_- \rangle = |\downarrow\downarrow\rangle$.

[0110] The transition takes place due to the spin-down electron $|\downarrow\rangle$ tunnelling from the SET 512 to the right quantum dot 510 (charge state (1,2)) and the spin-up electron $|\uparrow\rangle$ tunnelling back to the SET 512. At the same time, the $|\uparrow\downarrow\rangle$ energy level does not undergo any transition as the $|\uparrow S\rangle$ state is energetically inaccessible and no electron can tunnel from the SET 512 to the right dot 510.

[0111] At step 2a, the system is brought back to the (1,1) charge configuration region. Then by adiabatic change of detuning ϵ , the system is moved to the Pauli-blocked region in the (0,2) charge configuration region at step 3a. The potentials created by control gates (e.g., gates 502, 504 and 506) are changed such that γ is effectively ramped from γ_{max} in (1,2) region to some γ in (1,1) region.

[0112] This is the Pauli-blocked region and is a part of (0,2) region between $\epsilon = 0$ line and the dashed line 702 below it in Fig. 7A. In that region the singlet (0,2) is below the energy levels of (1,1) states, while the triplet (0,2) is above those states. As such, $S(1,1)$ state can tunnel to $S(0,2)$ and triplets cannot tunnel to any (0,2) charge configuration state. If the dashed line 702 is crossed (moving towards negative ϵ) the triplet (0,2) energy level goes below all the (1,1) energy levels. Then the Pauli spin blockade doesn't work anymore, as triplets (including $|T_- \rangle$ and $|T_+ \rangle$) can tunnel to (0,2) and cannot be distinguished from the singlet anymore.

[0113] In the absence of a magnetic field gradient, $\Delta E_z = 0$, the states $|G \rangle$ and $|E \rangle$ are split by the exchange interaction J and form singlet $S(1,1)$ and triplet $T_0(1,1)$ states, respectively. The energy difference ΔE_z mixes singlet and triplet states and in the limit of $\Delta E_z \gg J$ sets $|G \rangle = |\uparrow\downarrow \rangle$ and $|E \rangle = |\downarrow\uparrow \rangle$. Otherwise, the opposite states are set for $|G \rangle$ and $|E \rangle$ for $\Delta E_z < 0$.

[0114] In an intermediate regime, where J and ΔE_z are comparable, the mixing of $|S \rangle$ and $|T_0 \rangle$ (or $|\uparrow\downarrow \rangle$ and $|\downarrow\uparrow \rangle$) strongly depends on the relative amplitudes of exchange J and ΔE_z . As the exchange J is controllable with the detuning ϵ between the $S(1,1)$ and $S(0,2)$ states, the singlet-triplet mixing can be modulated by the detuning ϵ .

[0115] The shelving process causes $|\uparrow\downarrow \rangle$ to be mapped to the singlet (0,2) state – see Fig. 7B. While the $|\downarrow\uparrow \rangle$ state is mapped to the blocked triplet state $|T_- \rangle$ – of charge configuration (1,1).

[0116] Latched spin readout (LSR) is another modified PSBR based method that overcomes some of the limitations of PSBR. The LSR method may greatly increase the signal contrast between singlet and triplet states in comparison to conventional PSBR and shelving methods as the final charge states to be measured, namely (0,2) and (1,2), differ by one electron.

[0117] This may yield a larger charge signal for a charge sensor to detect in comparison to what can be achieved for the (1,1)-(0,2) dipole. Moreover, latching is insensitive to the sign of the magnetic field gradient as it always maps the ground, singlet state to the (0,2) charge state and the excited, triplet-like state to the (1,2) charge configuration.

[0118] While LSR provides an improved signal contrast, its efficiency can be compromised by the triplet relaxation process. The excited triplet-like state $|E \rangle$ is subject both to the standard $|T_0 \rangle$ to $|S \rangle$ relaxation as well as fast charge relaxation via $S(1,1)$ to $S(0,2)$, as ΔE_z introduces an admixture of the singlet in $|E \rangle$. Therefore, LSR is more efficient for small

magnetic field gradients. Further, LSR also requires a large differential tunnelling between the quantum dots and the reservoir, so that the electron tunnelling to and from the SET for one of quantum dots is enabled and for the other is suppressed.

[0119] Figs. 7A and 7C schematically show the LSR method in the charge subspace and spin subspaces, respectively. Fig. 7C shows a schematic 720 of the latching process with relevant states organized in order of increasing energy (lower energy at the bottom increasing to higher energy at the top) and transitions indicated by arrows with the numbers corresponding to Fig. 7A.

[0120] At step 1b, the system is detuned from the (1,1) charge configuration to the Pauli blocked (0,2) region. This transition needs to be adiabatic to allow the ground state $|G\rangle$ to tunnel to $S(0,2)$ fast enough to avoid triplet relaxation, that is $t_{ramp} < T_{relax}$.

[0121] At step 2b, γ is very quickly increased to point 704 in the (1,2) region. The system is then kept there for a time period t_{wait} where the charge state of the quantum dots is measured. At point 704 the excited state $|E\rangle$ maps to the (1,2) charge configuration due to electron tunneling from the SET 512 to the right dot 510. In order to preserve the contrast between the (1,2) and the (0,2) charge configurations electrons tunneling from the SET 512 to the left dot 508 need to be suppressed. This means that the time period t_{wait} needs to be much larger than $1/\Gamma_R$ but smaller than $1/\Gamma_L$.

[0122] Electron spin qubits controlled via AC electric or magnetic fields have shown tremendous progress in recent years. Single and two-qubit gate fidelities exceeding 99% have been demonstrated, along with greater than 99% fidelities in initialisation and measurement. With these milestones achieved, the field is now attempting to scale up qubit numbers while maintaining high-fidelity quantum operation. A critical challenge for scale up is the cryogenic cooling power needed to operate a large number of qubits. One of the significant advantages of semiconductor spin qubits is their robustness to high temperature operation with single-qubit gates demonstrated above 1 K with a control fidelity of above 99%. However, at these high temperatures the readout fidelity is reduced to approximately 60-95%. The reduction in the readout fidelity was attributed to the reduced sensitivity of the SET charge sensor at high-temperatures (>1 K) used in the experiments due to thermal broadening. Despite this lower measurement fidelity, the promise of high-temperature operation opens the possibility of adding classical control electronics alongside the quantum processor, thereby significantly decreasing the demands of cryogenic cooling.

[0123] Phosphors-doped silicon quantum dots are ideally suited for high-temperature operation due to the strong confinement potential of the one or more phosphorus donors. This strong confinement provides three main advantages. First, smaller qubits such as donor atoms or small quantum dots have larger orbital energy spacings as the excited states are far from the operable ground basis states (~ 5 meV). This may significantly increase the operating temperature range for qubit control and readout. Second, the strong confinement results in large on-site energies (U) of the charge sensors ($U \sim 5$ meV) allowing for the electron occupation to remain well-defined to high temperatures. Third, precision lithography allows for the strongly confined quantum dots to be placed very close to the charge sensor (~ 10 nm), resulting in a large capacitive coupling, such that the ‘strong-response’ regime of the SET charge sensor can be reached for maximum signal contrast.

[0124] To address one or more of the issues identified above, aspects of the present disclosure provide mechanisms to optimize qubit readout using any of the readout techniques described above. To do so, aspects of the present disclosure control the tunneling rate between the qubit being measured and the SET. In particular, if PSB based readout is desirable for a quantum processing system, aspects of the present disclosure increase the asymmetry of the tunneling rates between the two quantum dots tunnel-coupled to the SET. This can be done by precision engineering of the quantum dots at the time of fabrication or during operation. For example, the two quantum dots can be precision engineered such that their physical distances from the SET can be varied. Similarly, the two quantum dots can be precision engineered or configured during operation such that their donor numbers are varied and/or their electron numbers are varied, and/or the configuration of each quantum dot is varied to control the asymmetry of the tunnel rates.

[0125] The asymmetry in the tunnel rates can be quantified by the ratio of the tunnel rate of the quantum dot that is further from the reservoir Γ_T compared to the tunnel rate of the quantum dot that is closer to the reservoir Γ_B , Γ_T/Γ_B . The fidelity of the readout is increased as $\frac{\Gamma_T}{\Gamma_B} \rightarrow 0$. Generally speaking, the value of Γ_B should be fast compared to the readout time, generally greater than 100 MHz would be a good lower limit. The value of Γ_T should be slow enough to measure the difference in the charge sensor signal. Given that Γ_B would be above 100 MHz, in some examples, then Γ_T should ideally be below 20 kHz in those examples.

[0126] The physical distance between a quantum dot and a charge sensor affect tunneling times. The relationship between the physical distance and the tunneling time is exponential

with the separation between the quantum dot and the electron reservoir (charge sensor). The physical distances between the quantum dots and the reservoir can be optimized by first finding desired tunnel rates of the quantum dots to the reservoir followed by relating those desired tunnel rates to a known expression for the tunnel rates and distance between the quantum dots and the reservoir.

[0127] Further, the number of donors in each quantum dot influence the respective tunnel rates to the charge sensor. The larger the number of donors in a quantum dot the slower the tunnel rate is to the electron reservoir (for the same number of electrons on the quantum dot). For example, the tunnel rate will be slower for a 3P with a single electron compared to a 2P with a single electron at the same distance from the reservoir. This is due to the smaller electronic wavefunction of the electron from a deeper potential from the positive charge of the nuclei. Accordingly, by adjusting the number of donor atoms in the quantum dots, the asymmetry in their tunneling rates can be adjusted.

[0128] Similarly, the number of electrons confined to each quantum dot also influence the respective tunnel rate to the charge sensor. In particular, the more electrons on the quantum dot, the faster the tunnel rate to the electron reservoir (for the same number of nuclei defining the quantum dot). For example, the tunnel rate of a 3P binding 3 electrons will be faster than a 3P quantum dot binding a single electron for the same distance of the 3P quantum dot to the electron reservoir. This is again due to the fact that the higher electron state is less bound to the donors and the electronic wavefunction is larger. Accordingly, by adjusting the number of electrons confined to each quantum dots, the asymmetry in their tunneling rates can be adjusted.

[0129] Further still, the configuration of the donor atoms within a quantum dot changes the tunnel rate of that quantum dot in a non-trivial fashion. Ultimately, if the electron wavefunction of a quantum dot overlaps more with the reservoir wavefunction then the tunnel rate between them will be increased and if the electron wavefunction of a quantum dot overlaps lesser with the reservoir wavefunction then the tunnel rate will be lesser. So, by adjusting the configuration of donor atoms in a quantum dot, its wavefunction and consequently its overlap with the wavefunction of the reservoir can be adjusted to increase the asymmetry between the tunneling rates of the quantum dots to the reservoir.

[0130] As such, any combination of these parameters can be used to increase the asymmetry between the tunnel rates. However, the combination of these parameters for each

device design depends on other factors relevant for the particular quantum device. As an example, if the number of donor atoms in each quantum dot was required to be 3P-3P with 2 electrons (based on other constraints), then the physical distance between the quantum dots and the reservoir and/or the donor positions within the quantum dots can be tuned to achieve the required asymmetry in tunnel rates. More than one parameter can be varied and the effects may be cumulative. That is, if the distance between the quantum dot and the reservoir is increased while changing from a 2P to 5P quantum dot then the tunnel rate for that quantum dot will be slowed due to both effects.

[0131] The asymmetry of the tunnel rate directly contributes to the fidelity of the readout process. Accordingly, in one embodiment, to optimize the device geometry for the highest fidelity, the quantum dots can be positioned in a line pointing away from the charge sensor/reservoir. However, this may reduce the differential lever arm between the quantum dots if gates are used on the left and right (as shown in the figures). Therefore, in such embodiments, a small angle to the orientation of the quantum dots relative to the charge sensor can be introduced to achieve strong tunnel rate asymmetry while maintaining tunability between the quantum dots for qubit operation.

[0132] On the other hand, if reservoir readout is desirable for a quantum processing system, aspects of the present disclosure adjust the tunneling rate between the quantum dot and the SET for improved efficiency of the readout method. This can be done by precision engineering of the quantum dot at the time of fabrication. For example, the quantum dot can be precision engineered such that its physical distance from the SET is set to a precise value. Similarly, the tunneling rate can be controlled by precisely engineering the quantum dot to have a specific number of donor atoms, a specific number of electrons, and/or a specific quantum dot configuration.

[0133] The tunneling rate for PSB based readout or reservoir readout may be predetermined by simulating the particular readout process (e.g., PSB based, or reservoir based) and optimising the tunneling rate over the 4 parameters (depending on which ones can be adjusted and which ones are constrained based on other requirements of the quantum device). If one or more of the parameters are constrained, then the other parameters are swept over to identify the best combination for the quantum device while taking into account the actual desired outcome from the experiments.

[0134] It will be appreciated that large-scale quantum processors can be fabricated such that they are optimized for both types of readout – reservoir based and PSB based readout methods. In such cases, some portions of the large-scale processor may be fabricated such that those portions are optimized for reservoir-based readouts whereas other portions of the large-scale processor may be fabricated such that those portions are optimized for PSB-based readout.

[0135] The example results here show how the use of Coulomb confined phosphorus-doped silicon quantum dots (see Fig. 1) allow for fast, high fidelity single-shot readout using LSR using the techniques described herein. Since LSR, only depends on charge tunnelling, it has less thermal and external magnetic field constraints than traditional energy-selective spin readout. This means that SET charge sensors can be engineered to be strongly capacitively-coupled and can be driven with more power, resulting in high signal-to-noise ratios (SNR). This allows for operation of the device at much higher temperatures (~ 3.7 K), compared to gate-defined quantum dots (~ 1.5 K).

[0136] Further, the results show that by engineering the location of two multi-donor quantum dot qubits with nanoscale precision with respect to a compact charge sensor, qubit readout using LSR of two electrons takes only 175 ns integration time with a fidelity of 99.91% at ~ 0.2 K. Upon comparison of the readout fidelities at 0.2 K and 3.7 K, it is observed that the fidelity is only slightly reduced at the higher temperatures due to the lower SNR of the SET. Through optimisation of the LSR parameters, a single-shot spin parity readout of the electron spins at 3.7 K within 1.5 μ s with a maximum readout fidelity of 98.34% is demonstrated.

[0137] In particular, the following results show that the combination of strong confinement potential present in donor qubits with precision engineering of the tunnel rates allows for the operation of the charge sensors at the highest temperatures recorded so far (3.7 K) using latched spin readout, giving a maximum fidelity of 98.34% in 1.5 μ s (while maintaining greater than 98% fidelity within 1 μ s). These results demonstrate a clear performance improvement of state preparation and measurement using donor systems and offer the real possibility for operation of the surface-code using electron spins in semiconductor qubits.

[0138] These results demonstrate the possibilities for fast response phosphorus doped silicon SET sensors that allow high-temperature, large-scale quantum computing operation.

[0139] Fig. 8A shows a schematic of a STM of an optimised fabricated device 800 in combination with a measurement circuit 810.

[0140] The bright regions of the STM of the optimised device 800 correspond to bare silicon bonds where the atomic hydrogen mask has been removed to define the quantum dots 508 and 510, an SET 512 and control gates 502, 504, and 506. The measurement circuit 810 is a resonant LC tank circuit. The source contact 511 of the optimized device 800 is connected to a RC bias-tee and rf-tank circuit with a resonance frequency of $f_r \sim 225$ Mhz. This circuit 810 probes the reflected input RF signal due to an admittance change of the RF-SET.

[0141] The optimised device 800 is precision engineered such that the left quantum dot 508 and the right quantum dot 510 are asymmetrically tunnel coupled to the SET 512. That is, the device 800 is engineered such that $t_L \neq t_R$.

[0142] In this example device 800, the asymmetric tunnel couplings is achieved by increasing the relative geometric distance between one of the dots (i.e., right quantum dot 510) and the SET 512 reservoir.

[0143] Fig. 8B shows an enlarged view 820 of the two quantum dots 508 and 510 and the top of the SET 512. As can be seen in Fig. 8B the right dot 510 is approximately 25 nm from the SET 512 and the left dot 508 is approximately 15 nm from the SET 512. As such, the right dot 510 is approximately 10 nm further from the SET compared to the left dot 508. The inventors found that this asymmetric in the distance from the SET 512 strongly suppresses electron tunnelling from the SET 512 to the right dot 510. It will be appreciated that naming the dots left and right is arbitrary. The two dots may also be labelled the bottom dot (B) 508 and top dot (T) 510. As described herein, the distance is measured from the centre of the quantum dot to the edge of reservoir. In this device, the bottom quantum dot is estimated to be a 2P quantum dot and the top quantum dot is estimated to be a 1P quantum dot.

[0144] The data from the device 800 shown here corresponds to a single rf-quadrature only, since the resonance frequency operating point is tuned such that the signal is maximised in one quadrature (Q) and minimised in the other (I).

[0145] Fig. 8C shows a 2D map of the reflected RF-signal (in mV) as the left gate 502 voltage is varied (x-axis) and the right gate 506 voltage is varied (y-axis). The bright lines, running at 45°, correspond to where electrons tunnel through the SET 512 causing a mostly dissipative response of the tank circuit (probing mostly RF-SET conductance) meaning that most of the signal comes from real part of the conductivity (i.e., a change in resistance). The distinct breaks in the RF-signal (dashed white lines – 830), correspond to charge transitions

of electrons between the two quantum dots 508 and 510 and the electron reservoir 512. The charge states (n_L, n_R) corresponding to the number of electrons on the left and right quantum dots in each region are also shown also. The two different tunnelling processes can be detected by the SET 512.

[0146] There are two types of breaks or discontinuities in the stability diagram in Fig. 8C. These two discontinuities are highlighted in the figure by box 832 (for transitions $(1,1) \leftrightarrow (2,0)$ region) and box 834 (for transitions $(2,0) \leftrightarrow (2,1)$ region). For the first discontinuity 832 data for the normalised SET signal (y-axis) as a function of gate voltage (x-axis) is shown in Fig. 8D. In particular, data for the $(1,1)$ region 836, $(2,0)$ region 838 and the readout contrast 840 are shown. For the second discontinuity 834 data for the normalised SET signal (y-axis) as a function of gate voltage (x-axis) is shown in Fig. 8E. In particular, data for the $(2,0)$ region 842, $(2,1)$ region 844 and the readout contrast 846 are shown.

[0147] In addition to the distinct shifts in SET response due to a change in total electron number, there are also small shifts or discontinuities at the $(1,1) \leftrightarrow (2,0)$ region, highlighted by the box 832 in Fig. 8C. A transition between $(1,1)$ and $(2,0)$ charge configurations corresponds to the movement of an electron between the two quantum dots 508 and 510. These shifts are typically not observable in devices with symmetric dot-SET coupling. Since the total number of electrons is conserved across this transition, the capacitive shift of the reflected signal from the SET charge sensor 512 due to this electron movement is small.

[0148] Here the movement of electrons between the quantum dots shifts the conductance peak by less than a full peak width (from 836 to 838) as illustrated in Fig. 8D, resulting in a readout contrast (difference in SET signal) that is < 1 . This is the operating regime for standard PSB readout. To maximise the readout contrast, the strong-response SET regime can be leveraged by performing LSR in the $(2,1)$ charge region instead, where the total electron number of the system changes by 1. The addition and removal of a whole electron results in a much larger capacitive shift of the conductance signal during readout by a full peak width (842 to 844), as illustrated in Fig. 8E. In this case, there is maximum readout contrast of 1.

[0149] Fig. 9A shows a schematic charge stability diagram showing the three step pulse sequence used to perform LSR. Here the charge configurations are shown as a function of detuning of a first gate (G_1) on the x-axis and detuning of a second gate (G_2) on the y-axis. Fig. 9B shows the electron spin states for the $(1,1)$, $(2,0)$ and $(2,1)$ charge configurations in order of increasing energy (low energy states at the bottom and high energy states at the top).

[0150] The first step of the LSR method is to randomly initialize the system into one of the four two-electron spin states ($|\uparrow\uparrow\rangle, |\uparrow\downarrow\rangle, |\downarrow\uparrow\rangle$ or $|\downarrow\downarrow\rangle$) at point A, in the (1,1) charge region.

[0151] Next, the system is pulsed to point B in the (2,0) charge region where the even parity states ($|\uparrow\uparrow\rangle, |\downarrow\downarrow\rangle$) remain in the (1,1) charge configuration due to PSB. Meanwhile the odd parity spin states form the singlet-triplet T_0 states ($|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle$) in the (2,0) region. The pulse from A $\rightarrow$ B passes through the $S - T_-$ anti-crossing, hence the finite rise time (~ 1 ns) of the arbitrary waveform generator used to generate the pulse results in a small adiabatic loss (0.07%), as calculated by the Landau-Zener formula. The time spent at point B is short (e.g., < 5 ns), such that the even parity states do not have enough time to relax to the (2,0) charge ground state, but long enough that the singlet-triplet (T_0) states mix together due to the strong hyperfine coupling present in donor devices. Pauli spin blockade is lifted for the odd states, allowing these states to occupy the (2,0) charge configuration.

[0152] Lastly, latched readout is performed by pulsing from point B to point C in the (2,1) charge region and waiting for a settling time of 250 ns before integrating the SET signal. Here, as shown in section C of the energy level diagram in Fig. 9B, an even parity state maps directly to the (2,1) charge configuration while an odd parity state is initially “latched” to the (2,0) charge state, due to the slow tunnel rate between the charge states $(2,0) \leftrightarrow (2,1)$ that has been engineered by moving quantum dot 510 further away from the SET sensor as illustrated in Fig. 8B.

[0153] Fig. 9C is a plot of example SET charge sensor traces showing the signal for odd parity 902 and even parity 904 states where the readout position is biased to the top of Coulomb peak in the (2,1) region. The inset 910 shows the signal at times $< 1 \mu\text{s}$ and where the shaded regions of 50 ns and 175 ns correspond to the integration windows used for the fidelity analysis.

[0154] By biasing the readout position to the top of a conductance peak in the (2,1) region, it is observed that the SET charge sensor trace produced by the even state 904 remains high throughout the measurement period. While the odd state 902 starts with a low trace that becomes high as it relaxes to the ground state (see the dashed arrow in Fig. 9B). Parity-based readout can also be used for readout of an individual spin qubit (top/right quantum dot 510) via coupling to the ancilla (bottom/left quantum dot 508 loaded deterministically with an electron in the spin-down state). The high signal contrast observed

arises due to the addition of a whole electron with associated large capacitive shift of the charge sensor, allowing for high fidelity readout.

[0155] In some cases, LSR offers two main advantages: high temperature operation and non-stochastic tunnel events. The lower thermal constraints on LSR also mean more power can be applied to the readout sensor, further increasing the readout signal. For LSR, the SET signal begins in the desired measurable state, either ‘even’ or ‘odd’ (see Fig. 9C), hence the measurement window can be applied straight away, reducing the integration time needed (i.e., how long the charge sensor signal is averaged. The longer the integration time, the more of the signal is averaged over). Finally, since LSR directly measures the two-spin states, this may be used to characterise the tunnel coupling t_0 between quantum dots via a ‘spin-funnel’ measurement. This is done by plotting the detuning position of the $S - T_-$ anti-crossing. For this device 800, the inter-dot coupling is $t_0 = 3$ GHz at 0.2 K with an estimated gradient magnetic field of ~ 50 MHz.

[0156] Ultimately, the fidelity of LSR strongly depends on the tunnelling transport characteristics of the SET and how it varies with temperature. Fig. 10A shows the SET signal as a function of gate voltage while the bath temperature of the dilution refrigerator was varied from 0.1 K to 3.7 K. Data 1000 shows the conductance peak for bath temperature 0.2K and data 1001 shows the conductance peak for bath temperature 3.7K. The SET signal peak height does not vary considerably even up to 3.7 K. Here, the tank circuit is being driven at high RF-power, already effectively power-broadening the SET response. This power-broadening only weakly affects the LSR fidelity (due to the strong capacitive coupling of the quantum dot to the SET which shifts the signal by a full peak width) and hence the device can be operated in the power-broadened regime for all temperatures.

[0157] Now that the performance of the SET as a function of temperature is established, LSR at 0.2 K and 3.7 K is used to investigate the low-temperature and high-temperature single-shot spin readout fidelity.

[0158] Fig. 10B is a plot of the measured spin readout ($1 - \text{Fidelity}$) on the y-axis as a function of integration time of the SET signal on the x-axis. The measured spin readout is plotted for 0.2K 1002 and for 3.7 K 1004. For short integration times the fidelity is limited by the SNR of the SET since the cold High-electron mobility transistor preamplifier noise (from circuit 810) dominates the signal. For longer integration times the relaxation rate of the (2,0) odd parity states into the (2,1) charge state begins to dominate the fidelity and leads to an exponential increase in readout error seen in Fig. 10B.

[0159] The optimal integration time is therefore a trade-off between these two effects: SNR and relaxation. The fidelity is significantly better at 0.2 K than at 3.7 K for short integration times due to the lower SET signal at higher temperatures. For integration times longer than 1 μ s, the fidelities at both temperatures begin to approach each other. This is due to the fact that in this regime, relaxation errors dominate, and the measured relaxation time of the singlet at 3.7 K (~ 45 μ s) is the same as the relaxation time at 0.2 K. Therefore, the main difference in the readout fidelities at the two temperatures is simply due to the SNR of the SET.

[0160] The SNR of the SET is plotted as a function of integration time at 0.2 K and 3.7 K in Fig. 10C. The data for 0.2K is shown by 1006 and the data for 3.7K is shown by 1008. From this plot it can be observed that the SNR values of the SET is significantly larger at 0.2 K compared to 3.7 K for any given integration time as expected.

[0161] From extrapolating the SNR values (solid lines in the Fig. 10C) versus integration time for both temperatures, the measurement time τ_m of the sensor can be estimated. Where the measurement time is defined as the integration time required to achieve a SNR of 2. Separate to the integration time, the measurement time is a metric that accounts for the noise and bandwidth of the charge sensor, giving an indication of the quality, and should be as short as possible for high-fidelity readout. Here, the measurement time was found to be $\tau_m = 6 \pm 1.5$ ns for 0.2 K and $\tau_m = 104 \pm 12$ ns for 3.7 K. At elevated temperatures of 3.7 K, the phosphorus-doped silicon SET still acts as a high contrast, fast charge sensor. The plateau in the SNR observed around 5 μ s at both 0.2 K and 3.7 K is most likely due to the relaxation of an odd parity state into the (2,1) charge state, such that the signal becomes comparable to that of the even parity state.

[0162] The maximum fidelity at 0.2 K was calculated to be 99.91% with an integration time of 175 ns. The signal histogram 1010 is shown in Fig. 10D, where random states were loaded at the start of the latched readout sequence (point A in Fig. 9A), resulting in two equal sized probability peaks corresponding to the odd and even states. Further, just an odd state may be deterministically loaded onto the system (by waiting longer at point B in Fig. 9A), which results in a single peak, as illustrated by the signal histogram 1012 overlayed. As seen in these results, the readout errors at 0.2 K (0.09%) are an order of magnitude lower than the 1% fault-tolerant threshold and three orders of magnitude faster than the longest reported dephasing time (270 μ s) for an electron spin qubit using phosphorus-doped silicon. These readout metrics are comparable to the fastest recorded superconducting qubit readout times

and faster than the highest reported times for spin qubits (99% at 1.6 μ s) while demonstrating one of the highest fidelities to date.

[0163] Fig. 10E is a plot of the fidelity as a function of the signal threshold (mV) used to distinguish between the singlet and triplet peaks in the histogram at 0.2 K (see Fig. 10D). There is a large plateau where the fidelity remains above 99% indicating the resilience of the readout to fluctuations in the absolute level of the SET signal. This large plateau corresponds to the large separation (> 0.3 mV) between the histogram peaks observed at 0.2 K (see Fig. 10D). High fidelity readout was maintained while decreasing the integration times further, with 99.15% achieved at the minimum measured integration time of 50 ns.

[0164] At 3.7 K, the maximum readout fidelity obtained was 98.34% in 1.5 μ s. At this high operating temperature, readout fidelities greater than 98% can be maintained with integration times less than 1 μ s. Fig. 10F shows the optimal measured signal histogram for randomly loaded states 1014 for LSP where the asymmetry in the peaks is due to the relaxation of the singlet-state. Also shown in Fig. 10F is the histogram for deterministically loaded odd states 1016 where only one peak is visible, as expected.

[0165] Fig. 10F shows a plot of the signal histogram when random states 1014 were loaded at the start of the LSR sequence (point A in Fig. 9A), resulting in two probability peaks corresponding to the odd and even states. Also shown in Fig. 10E is the signal histogram for when an odd state is loaded onto the system – see data 1016.

[0166] Fig. 10G is a plot of the individual state fidelities as a function of the threshold voltage used to distinguish the two histograms. Compared to 0.2 K, a reduction of only less than 2% fidelity is found when operating the device 800 at 3.7 K. This fidelity is currently limited by the SNR of the charge sensor which can be increased further by better amplification of the SET signal and/or additional optimisation of the SET design. The readout fidelity obtained at 3.7 K also implies that at temperatures above 1 K (where the use of a dilution unit is not required) should be readily achievable for qubit readout above 99% allowing for high temperature qubit operation

[0167] These results represent a significant improvement over previous spin readout experiments. In particular, the use of LSR in qubit systems has generally increased spin readout fidelities over non-latched methods, reaching and exceeding the 99% threshold required for fault tolerant quantum computation. Also due to the greater signal contrast, LSR has shortened the integration time necessary to obtain high fidelity readout. Hence, by combining a strongly coupled SET with asymmetric engineering of dot-to-reservoir tunnel rates to enable LSR (by variation in the geometric location of the quantum dots during device

fabrication), a sub-microsecond readout with a fidelity of over 99.9% has been achieved in PSB based readout.

[0168] Although the quantum processing systems described herein have been shown with gate electrodes for controlling corresponding qubits, these may not always be necessary. In other embodiments and examples other control means may be utilized without departing from the scope of the present disclosure.

[0169] The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive.

[0170] As used herein, except where the context requires otherwise, the term "comprise" and variations of the term, such as "comprising", "comprises" and "comprised", are not intended to exclude further additives, components, integers or steps.

CLAIMS

1. A method for optimizing Pauli's spin blockade based spin readout in a quantum processing device, the quantum processing device comprising:
at least one double quantum dot system comprising first and second quantum dots, and
a charge sensor,
the method comprising: increasing an asymmetry of tunneling rates between the first and second quantum dots and the charge sensor from a first asymmetry value to a second asymmetry value.
2. The method of claim 1, wherein the asymmetry of the tunneling rates between the first and second quantum dots and the charge sensor is increased from the first asymmetry value to the second asymmetry value by varying at least one parameter of:
physical distances between the first and second quantum dots and the charge sensor,
a number of donor atoms in the first and/or second quantum dots,
a number of electrons in the first and/or second quantum dots, and/or
a configuration of the first and/or second quantum dots.
3. The method of claim 2, wherein varying the at least one parameter comprises precision engineering the quantum processing device using scanning tunneling microscopy during a fabrication process of the quantum processing device.
4. The method of any one of claims 1-2 wherein the first and second quantum dots are silicon-based quantum dots.
5. The method of any one of claims 1-4, wherein the type of Pauli's spin blockade based spin readout is a latched spin readout.

6. The method of claim 5, wherein the latched spin readout is optimized by varying the physical distance between the first and second quantum dots and the charge sensor.

7. The method of claim 6, wherein the distance between the first quantum dot and the charge sensor is approximately 25nm and the distance between the second quantum dot and the charge sensor is approximately 15nm.

8. A method for optimizing electron spin resonance based spin readout in a quantum processing device, the quantum processing device comprising at least one quantum dot and a charge sensor, wherein the at least one quantum dot is coupled to the charge sensor, the method comprising: adjusting a tunneling rate between the at least one quantum dot and the charge sensor.

9. The method of claim 8, wherein the tunneling rate between the at least one quantum dot and the charge sensor is adjusted by varying at least one parameter of:

- a physical distance between the at least one quantum dot and the charge sensor,
- a number of donor atoms in the at least one quantum dot,
- a number of electrons in the at least one quantum dot, and/or
- a configuration of the at least one quantum dot.

10. The method of claim 9, wherein varying the at least one parameter comprises precision engineering the quantum processing device using scanning tunneling microscopy during a fabrication process of the quantum processing device.

11. An engineered quantum processing element comprising:
at least one quantum dot in a semiconductor substrate;
a sensor positioned at a distance from the at least one quantum dot for initialising and/or measuring a qubit associated with the at least one quantum dot;

wherein a predetermined tunneling rate between the quantum dot and the sensor is designed by precision fabrication of the quantum processing element for enabling the initialization and/or measurement of the qubit associated with the quantum dot.

12. The engineered quantum processing element of claim 11, wherein the tunneling rate between the quantum dot and the sensor is designed by varying at least one parameter of:

- a physical distance between the quantum dot and the sensor,
- a number of donor atoms in the quantum dot,
- a number of electrons in the quantum dot, and/or
- a configuration of the quantum dot.

13. The engineered quantum processing element of claim 12, wherein varying the at least one parameter comprises precision engineering the quantum processing element using scanning tunneling microscopy during a fabrication process of the engineered quantum processing element.

14. An engineered quantum processing element comprising:

at least one double quantum dot system in a semiconductor substrate, the at least one double quantum dot comprising first and second quantum dots;

a charge sensor positioned at a distance from the double quantum dot for initialising and/or measuring a qubit associated with the double quantum dot;

wherein an asymmetry of tunneling rates between the first and second quantum dots and the charge sensor is increased from a first asymmetrical tunneling rate to a second asymmetrical tunneling rate by precision fabrication of the quantum processing element for enabling the initialization and/or measurement of the qubit associated with the double quantum dot.

15. The engineered quantum processing element of claim 14, wherein the asymmetry of the tunneling rates between the first and second quantum dots and the charge sensor is

increased from the first asymmetrical tunneling rate to the second asymmetrical tunneling rate by varying at least one parameter of:

physical distances between the first and second quantum dots and the charge sensor,

a number of donor atoms in the first and/or second quantum dots,

a number of electrons in the first and/or second quantum dots, and/or

a configuration of the first and/or second quantum dots.

16. The engineered quantum processing element claim 15, wherein varying the at least one parameter comprises precision fabrication of the quantum processing element using scanning tunneling microscopy during a fabrication process of the engineered quantum processing element.

17. The engineered quantum processing element of any one of claims 14-16 wherein the first and second quantum dots are silicon-based quantum dots.

18. The engineered quantum processing element of any one of claims 14-17, wherein the charge sensor is configured to initialize and/or measure the qubit using Pauli's Spin Based Readout.

19. The engineered quantum processing element of any one of claims 14-17, wherein the charge sensor is configured to initialize and/or measure the qubit using latched Spin Readout.

20. The engineered quantum processing element of claim 19, wherein the latched spin readout is optimized by precisely fabricating a distance between the first and second quantum dots and the charge sensor.

21. The engineered quantum processing element of claim 20, wherein the distance between the first quantum dot and the charge sensor is approximately 25nm and the distance between the second quantum dot and the charge sensor is approximately 15nm.