Introduction to Gated Spin Quantum Dot Quantum Computers

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Abstract

Quantum computers have developed to the point where they have started being created, with multiple competing methodologies. Scalable quantum computers are a key goal for further research, and gated spin quantum computers show promise in that regards with their density and capacity to apply manufacturing techniques used for classical computers. This review covers the basics of qubit based quantum computing schemes, and later focuses on gated spin quantum dots and how the issues it faces are dealt with. This literature review is intended to be an introductory text for those new to quantum computing, but have some knowledge of physics.

1 Introduction

Quantum computers are computers which work based on quantum characteristics and were motivated by Richard Feynman[1] as a way to efficiently simulate quantum phenomena. They have gone far in the decades since, and different approaches to them have been explored, with some types already created such as superconductor, ion trap and gated defined quantum dot quantum computers.

Most quantum computer schemes depend on qubits, otherwise known as quantum bits, to carry out calculations, with obvious inspiration taken from classical computers. The main appeal of quantum computers is the possibility of efficiently performing calculations that are hard to carry out classically, such as simulating quantum systems. There's still a long way to go until quantum computers large enough to be useful in this capacity are built, and much of the current research is focused on dealing with practical issues of building scalable quantum computers. To put this issue into scale, it's estimated that $10^6 - 10^8$ physical qubits[2] are needed for quantum chemistry calculations, and Google reported 'quantum supremacy' with 53 qubits[3].

Perhaps it's obvious then to look back at classical semiconductor computers, which regularly accommodate more than a billion transistors, and use semiconductors to build qubits. Semiconductor quantum computing schemes are attractive due to their potential for scalability as a result of their small size and the capacity to apply well developed manufacturing technologies used for classical computers. One such scheme uses gated quantum dots as qubits, and is what this report will focus on.

Quantum dots are semiconductor particles which are nanometres across in all three dimensions and confine either electrons or holes. The spin of electrons or holes confined in quantum dots is used for quantum computing, the idea of which was first proposed in the seminal paper [4] by Daniel Loss and David DiVincenzo. Gated quantum computers use lithographically defined gates on a surface to create quantum dots where electrons or holes are confined as shown in Figure 2 and Figure 5, and carry out calculations while cooled down to less than or equal to 1.5 K as of now[5].

As a popular quantum computing scheme, I believe that gated quantum dots deserve an introductory review paper for those new to quantum computing. This paper will cover the basics of quantum computing in section 2 with subsections covering qubits, gates implemented with qubits, the motivation behind using quantum computers, general criteria for successful quantum computing schemes, and an overview of quantum computing schemes. Gated quantum dots will be explained in section 3, along with current issues and how they are dealt with, and summarise it in section 4.

2 Background in Quantum Computers

2.1 Qubits

Qubits are a quantum analogue of the classical bit, and are used in most implementations of quantum computers. But unlike a classical bit, which can only be represented as a 0 or 1, qubits are better represented as a vector on the Bloch sphere, as shown in Figure 1, beginning on the origin and ending on the sphere's surface. Each state of a qubit is a vector in 2 complex dimensions, and therefore

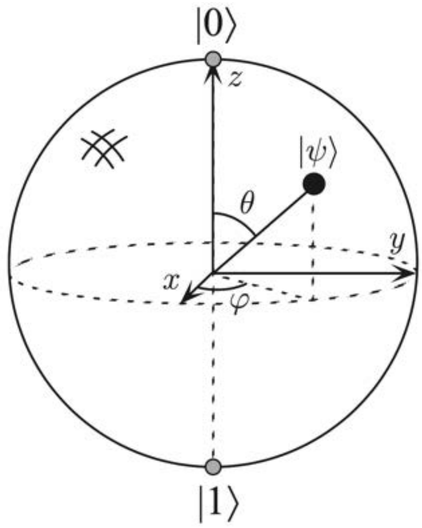

Figure 1: Bloch sphere of a qubit[6]

called a statevector. Two basis states are:

$$|0\rangle = \begin{bmatrix}1\\0\end{bmatrix},\ |1\rangle = \begin{bmatrix}0\\1\end{bmatrix}$$

Which can be interpreted as 0 and 1 respectively for computation. On the Bloch sphere orthogonal states such as $|0\rangle$ and $|1\rangle$ are opposite each other, $|0\rangle$ is along the positive z axis and $|1\rangle$ is along the negative z axis on Figure 1.

An interesting point is that statevectors can be linear sums of $|0\rangle$ and $|1\rangle$, as long as the norm is unity so that the statevector is confined to the Bloch sphere. So for $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ there's a constraint of $|\alpha|^2 + |\beta|^2$, where α and β are complex.

This naturally lends itself to flexibility with regards to basis sets, which can be any two orthogonal statevectors, to use for computation. For example, another popular basis set is $|+\rangle$ and $|-\rangle$, which are along the positive and negative directions of the x axis respectively on Figure 1 and written as

$$|+\rangle = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix} = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle), |-\rangle = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix} = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

Measurement of the qubit state 'collapses' it into a classical value of either $|0\rangle$ or $|1\rangle$. The probability of measuring $|0\rangle$ for $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ is

$$|\langle 0|\psi\rangle|^2 = |\alpha\langle 0|0\rangle + \beta\langle 0|1\rangle|^2 = |\alpha\cdot 1 + \beta\cdot 0|^2 = |\alpha|^2$$

according to Born's rule. Incidentally, α and β in this case are called probability amplitudes of the two computational basis states in such superpositions.

Phase is another factor to keep in mind, and comes in two forms, both of which are a consequence of the complex nature of statevectors. One is global phase, which can be likened to multiplying the statevector by a complex exponent $\exp i\phi$ which has an absolute value of unity. For example a global phase of $\phi = \frac{\pi}{2}$, leads to $\exp i\phi * |\psi\rangle = i * (\alpha |0\rangle + \beta |1\rangle) = i\alpha |0\rangle + i\beta |1\rangle$. The statistics of measurement associated with $|\psi\rangle$ are the same regardless of the global phase, so global phase is not observable and has no real physical meaning. Relative phase on the other hand is useful, and comes in the form of $\exp i\phi$ within a statevector

$$cos(\frac{\theta}{2}) |0\rangle + \exp i\phi sin(\frac{\theta}{2}) |1\rangle \tag{1}$$

corresponding to Figure 1, where ϕ is the angle around the z axis. For example to get $|+\rangle$ and $|-\rangle$ from Equation 1 we use $\theta = \frac{1}{2}$ for both, $\phi = 0$ for the first and $\phi = \pi$ for the latter. Relative phase is useful for computation since states with different relative phases are distinguishable, as shown in subsection 2.2 with the Hadamard gate which can transform between the $\{|0\rangle, |1\rangle\}$ and $\{|+\rangle, |-\rangle\}$ basis sets so that $|+\rangle$ and $|-\rangle$ can be distinguished by measurements in the computational basis. Relative phases can also be transferred between qubits by a process called phase kickback, and can be introduced by phase gates such as Z which are mentioned in subsection 2.2.

An example of a physical implementation of qubits are spin quantum dots, where the spin of confined electrons or holes are used to encode qubits. For example you could directly use the single spins up $|\uparrow\rangle$ and down $|\downarrow\rangle$ to use as the computational basis set like mentioned in [4]. You could also use a quantum superposition of the spin from two quantum dots, like a singlet-triplet [7] approach where the ground singlet state is $|S\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$ is chosen to act as $|0\rangle$ and a triplet state is chosen to $|1\rangle$ out of $|T_+\rangle = |\uparrow\uparrow\rangle$, $|T_+\rangle = |\downarrow\downarrow\rangle$, or $|T_0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$. A hybrid qubit [8] is a hybrid of a single spin qubit and a singlet-triplet qubit, consequently has 3 electrons, and has the two levels $|0\rangle = |S\rangle |\downarrow\rangle$ and $|1\rangle = \sqrt{\frac{1}{3}} |T_0\rangle + \sqrt{\frac{2}{3}} |T_0\rangle$.

Two qualities that are uniquely quantum are the capacity to be in superpositions and entanglement. We have already covered superpositions of the computational basis set for solitary qubits earlier in this subsection. But this also extends to multiple qubit arrangements. For examples with 2 qubits there will be 4 basis states, $|00\rangle$, $|01\rangle$, $|10\rangle$ and $|11\rangle$, each with a corresponding complex amplitude $\alpha_{00}, \alpha_{01}, \alpha_{10}, \alpha_{11}$, which together are normalised to produce 1.

$$\alpha_{00}^2 + \alpha_{01}^2 + \alpha_{10}^2 + \alpha_{11}^2 = 1$$

Naturally this extends so that there will be 2^N different amplitudes for N qubits, and handling this exponential scaling of information proves a powerful tool. There is a fundamental constraint on this though, that only one of these configurations can be read out at end, because measurement of the result collapses this superposition so that only one amplitude becomes 1. The capacity for the state of the system to be presented as a sum of contributions from possible states is called 'coherence', due to the capacity for states to interfere with each other like wavefronts.

Entanglement is a dependence of different qubit states on each other, an ideal example of which are the Bell states, one of which is shown in Equation 2. Entanglement can be created if two qubits interact with each other, even with the use of an intermediary such as photons between two stationary qubits. For example with a Bell plus state:

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \tag{2}$$

In $|\Phi^+\rangle$ if the first qubit is measured to be $|0\rangle$ then the second qubit also becomes $|0\rangle$, and the same also occurs for $|1\rangle$. If you were to separate both qubits after they entangle into such a state, then that means this correlation can be maintained over a distance and information can be transferred from one qubit to the other. Indeed this is a key idea behind quantum cryptography, allowing information to be securely transmitted across a distance. Entanglement could just as well would be useful for the scaling of quantum computers to larger scales.

2.2 Gates

Gates in quantum computers are much like classical gates for computing, in that they take in qubit states, and depending on the input they create output states on the qubits involved. A difference from classical gates are that they deal with superpositions of states on qubits and can create entanglement between qubits in the case of the CNOT gate.

Gates can be represented as matrices acting on the statevectors of individual qubits. All quantum gates are unitary, and thus Hermitian, to conserve the norm of statevectors they act on. Hence gate operations can be seen as rotations on the Bloch sphere in Figure 1.

A major requirement for quantum computers are a universal set of gates. This means a set of gates which can perform any set of calculations. This is also one of the DiVincenzo criteria[9] which serve as requirements for viable quantum computers, and will be covered in subsection 2.4.

A common universal set is the Clifford + T gate set which includes a two qubit gate, CNOT, and three single qubit gates, the Hadamard, S and T gates. S and T are phase gates, which introduce relative phase.

$$H = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1 \\ 1 & -1\end{bmatrix}, S = \begin{bmatrix}1 & 0 \\ 0 & i\end{bmatrix}, T = \begin{bmatrix}1 & 0 \\ 0 & \exp i\frac{\pi}{4}\end{bmatrix}, CNOT = \begin{bmatrix}1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0\end{bmatrix}$$

,

The Hadamard gate as mentioned before in subsection 2.1 converts between the computational and $\{|+\rangle,|-\rangle\}$ basis set. More specifically

$$H\,|0\rangle = |+\rangle\,, H\,|+\rangle = |0\rangle\,, H\,|1\rangle = |-\rangle\,, H\,|-\rangle = |1\rangle$$

The CNOT gate applies an X gate on the second qubit if the first qubit is $|1\rangle$, and does nothing to the second qubit if the first qubit is $|0\rangle$

$$X = \begin{bmatrix}0 & 1 \\ 1 & 0\end{bmatrix}, X(\alpha\,|0\rangle + \beta\,|1\rangle) = \beta\,|0\rangle + \alpha\,|1\rangle$$

Due to the superposition of states $|0\rangle$ and $|1\rangle$ on the first qubit, there is a superposition of whether or not an X gate is applied on the second qubit. In doing so, the CNOT gate entangles the two qubits together. To illustrate this, let's look at an example where the first qubit is $|\psi_1\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$, and the second qubit is $|\psi_2\rangle = |0\rangle$

$$CNOT\,|\psi_1\psi_2\rangle = CNOT(\alpha\,|00\rangle + \beta\,|10\rangle) = \alpha\,|00\rangle + \beta\,|11\rangle$$

As you can see, if $\alpha = \beta = \frac{1}{\sqrt{2}}$ then this is a way to prepare the $|\Phi^+\rangle$ state shown in Equation 2

Another common gate is the Z gate, which applies a $\exp i\pi = -1$ phase.

$$Z = \begin{bmatrix}1 & 0 \\ 0 & -1\end{bmatrix}$$

This paper will not cover further mathematical details on quantum gates and the handling of quantum information. To learn in further detail, a definitive standard resource is [6].

2.3 Motivations behind using quantum computers

So, here comes the question: what's the point of building and using quantum computers rather than just sticking to well developed classical computers?

As mentioned before in section 1, one reason is to efficiently simulate quantum systems[1]. Since qubit amplitudes scale as 2^N with qubit number, it takes exponential time to simulate a quantum computer classically. Similarly other many particle quantum systems take exponential time to simulate as particle number rises, assuming approximations aren't taken such as with Quantum Monte Carlo. On the other hand, qubits with their exponentially scaling amplitudes can simulate other quantum systems. This is naturally useful for various fields such as condensed matter and chemistry. In fact condensed matter simulations of the Fermi-Hubbard model[10] and Nagoaka ferromagnetism[11] have already been carried out using gated spin quantum dots, which serve as proofs of concepts for the viability of using this scheme for quantum system simulations.

Interest in quantum computing was first garnered by Shor's algorithm[12] which allows efficient factoring of large numbers into its prime factors, which would make quantum computers powerful at cracking the RSA encryption used for the internet. This showed an immediate impact and use of quantum computing and is still the prime example of such, even after 'post-quantum' cryptography schemes started being developed to be secure to quantum computers.

Another more general use algorithm is the Grover's algorithm[13] which allows a quadratic speed up of searches through unstructured databases, which proves another use of quantum computing. Further quantum algorithms are still being searched for.

It's expected that much like the internet and classical computers, further unthought of applications will reveal themselves.

2.4 General Criteria and Issues for Quantum Computer schemes

The DiVincenzo criteria are well known requirements for viable quantum computer schemes proposed in the defining paper [9], and are:

1. Scalable system with well characterised qubits
2. Can initialise qubits into a fiducial state, eg $|000...\rangle$

3. Decoherence times long enough to carry out calculations
4. Universal set of gates
5. Can measure a single qubit without effecting the state of the rest

The fourth requirement, universal set of gates, has already been covered in subsection 2.2. The second and fifth requirements are pretty self explanatory, and so will be glossed over. To cover the other criteria some explanation is needed.

For the first requirement 'well characterised' means multiple things, and scalability is necessary to build quantum computers large enough to be worth using for calculations instead of using a classical computer. To be well characterised the physical characteristics of the qubit must be well known, so that it can be manipulated as a qubit, and there needs to be two levels which the system prefers to stay in. The possibility of going into higher levels, if they exist, must be small so that the qubit can be used as a quantum bit. Scalability is part of this requirement because only large enough quantum computers are useful, as mentioned in section 1.

Decoherence times are measures of the time over which a qubit state is reliable and coherent, before it is made unreliable due to interactions with the environment. As mentioned in subsection 2.1 when a set of qubits are coherent, the state can be represented as a linear sum of complex coefficients multiplied by different configurations. So decoherence can be seen as an interaction where this quantum superposition of states breaks down. Decoherence times are split into relaxation time T_1, decoherence time T_2, and the dephasing time T_2^*[14]. T_1 is the time taken for a qubit to relax from the higher level to the lower level. T_2 is how long a superposition takes to decay, such as $|+\rangle$ turning into $\{|0\rangle, |1\rangle\}$. T_2^* is basically T_2 averaged over an ensemble. For spin qubits in quantum dots it's usually the case that $T_2^* < T_2$, and $T_2 << T_1$[14]. The time taken for calculations depends on gate latency, the time taken to perform a single operation. In other words, the fifth requirement is the capacity to perform many operations while the quantum state of a qubit is coherent. A measure of the ratio of decoherence time against gate latency is Quality factor.

There is a trade-off between decoherence times and gate latency called the coherence-controllability trade-off. This is because a qubit isolated from the environment doesn't interact as much with it, increasing decoherence times, but it's also harder to interact with and perform operations on such qubits, thereby increasing gate latency.

Another issue to consider is gate fidelity, which is how well a gate works without introducing error, or in other words how close gates are to being the idealised unitary operations that they are intended to be.

To deal with errors which crop up in quantum computers, Quantum Error Correction(QEC) is used. As a brief explanation, duplicates of a qubit, called data qubits, can be used together so that if errors occur in a few qubits then they can be detected and dealt with. Direct measurement can't be used, or else there will be a collapse of the wavefunction so other qubits, called ancilla qubits, are coupled to the data qubits and then they are measured to check for their reaction to errors. This set of multiple data and ancilla qubits is called a logical qubit and acts as one low-error qubit. How the physical qubits are arranged into a logical qubit is called an error code. This means that QEC can make quantum computers fault tolerant, that is for error rates in gate operations below a threshold operations can occur normally[6]. A powerful type of error code called surface code has an error threshold of 1% for operations, or a gate fidelity of 99%[15]. These fidelities are achieved on current quantum computers, and indeed quantum computers implementing surface code have been built as a proof of concept. Unfortunately an issue with QEC is that many physical qubits are needed for a single logical qubit in current implementations. This overhead can be decreased if the gate fidelities increase, so high gate fidelities and potential for scaling to handle the overhead are sought after features.

Quantum computing is inherently probabilistic, and the goal of algorithms is to make the correct output the most likely one. This means that, even if noise is dealt with, the answer is still not certain. This can be easily solved by repeating the algorithm a multiple times and choosing the most frequent output. This also means that repetition of code can also be used to deal with errors. Of course, this increases the operation times.

2.5 Overview of Qubit schemes

This subsection is a very brief overview of different quantum computing schemes which make use of qubits. A more in depth comparison comparison can be found here [16]. Note that this overview is in no way comprehensive, and there are other qubit schemes being researched.

The gated spin quantum dots scheme's main advantage is its potential scalability, thanks to the small size of quantum dots and the possibility of integrating CMOS manufacturing techniques used for classical computers[17]. Another key advantage is the capacity to control qubits purely through electrical means. Two major drawbacks are the need to cool to a low temperature to carry out operations, as of now at most 1.5K[5], and charge noise which leads to decoherence[19]. The first means that dilution refrigerators are needed and classical control and read out equipment need to work at low temperatures, and the latter is a challenge limiting the fidelity of two qubit gates that needs to be resolved to allow fault tolerant computation.

Self-assembled quantum dots are worth mentioning due to being the other main scheme making use of electron spin in quantum dots[14]. Self assembled ones occur due to the random growth process of a semiconductor, and unlike gate defined ones are controlled using photons and operate up to 4K. Their random nature is a major disadvantage because their optical properties rely on their size and shape. While the higher operating temperatures means less cooling power is needed, the random formation means that it's difficult to produce scalable quantum computers. Self-assembled quantum dots on the other hand have potential in quantum networks due to the coupling between photons and the confined electron or hole spin.

Dopant or donor atoms, like phosphorus, in silicon couple to electrons. Similar to gated quantum dots these electrons can be used for computation, but use of nuclear spins has also been achieved. These have long decoherence times compared to other semiconductor qubits[18], and also have the potential to integrate CMOS manufacturing techniques for scalability. The nuclear spins have much longer coherence times, but due to the coherence-controllability trade-off mentioned in subsection 2.4 the operations correspondingly take longer to operate on. The main disadvantage is the high precision manufacturing requirements for placing the donor atoms.

Another impurity based spin qubit scheme is to use optically active defects, with particular focus placed on nitrogen vacancy(NV) centres placed in diamond. A nitrogen donor atom couples to a vacancy in the carbon lattice, and has optically controllable electron and nuclear spins. The advantages and disadvantages of donor atoms mentioned above apply, in addition to the advantage of an optical interface which provides potential in quantum networks over a distance[18].

Photonic quantum computers use photons as qubits with qubit states such as $|0\rangle$ and $|1\rangle$ distinguished by properties like polarisation, orbital angular momentum, time (of arrival), and number of photons[20]. There are two approaches to implementing gates, one is through a combination of single photon operations and measurements, and the other is to use optically active defects and quantum dots. The advantages are that photons have long decoherence times due to not reacting much with the environment, it can be built in CMOS compatible silicon which increases scalability, and the high speed of light makes it ideal for quantum networks.

Trapped ions are a line of ions trapped by electric potentials in a vacuum, with operations performed using photon pulses. The main advantages are long decoherence times[21] and that this technology has been well developed, with high fidelities for both single and two qubit gates below the error threshold. A disadvantage is long gate times.

Neutral atom computers[22] are similar in concept to trapped ion computers, but instead involve trapping neutral atoms in an array with lasers and exciting them from the ground to become Rydberg atoms with photons, to use this excited state and the ground state for qubit levels. This scheme has the advantage of qubits being identical and that qubits do not experience much cross-talk, which is a type of interference from densely packed qubits that is a problem for other qubit schemes including gated quantum dots. The principal disadvantage of this scheme is that neutral atoms are vulnerable to collisions with residual gas atoms that can knock them out of their traps.

Superconducting qubits[23] are essentially nonlinear LC circuits which exhibit quantised energy levels when cooled to milli-Kelvin temperatures. This has high compatibility with existing manufacturing techniques, since it basically involves circuity, and allows electrical control. Due to their large sizes and coupling to their environment, superconducting qubits have lower decoherence times than other schemes like gate based quantum dots and impurities. Another issue is that huge amounts of cooling power is needed to cool the qubits to such a low temperature, leading to large energy costs. This is a highly popular scheme that is being pushed forward by multiple players, most prominently Google and IBM.

Topological computers[24] use quasi-particles which are neither fermions nor bosons called anyons for computation. These are intrinsically non-local, and so are protected topologically from local perturbations, essentially protecting the qubits from error. This has the massive advantage of being able to forego QEC and the qubit overhead associated with each logical qubit. Unfortunately, the technology handling this is not yet well developed and faces engineering challenges.

It's still unknown which, if any, quantum computing scheme will emerge dominant in the future and unclear how things will develop.

3 Gated spin quantum dots

3.1 Overview of spin quantum dots in quantum computing

The gated spin quantum dot scheme, along with the idea of using spin states confined in quantum dots for quantum information processing, was first proposed in the seminal paper [4]. It explained how to implement an electrically gated quantum computer, with a universal set of one and two qubit gates, where qubits were spin states of single electron quantum dots. Two qubit gates could be realised through

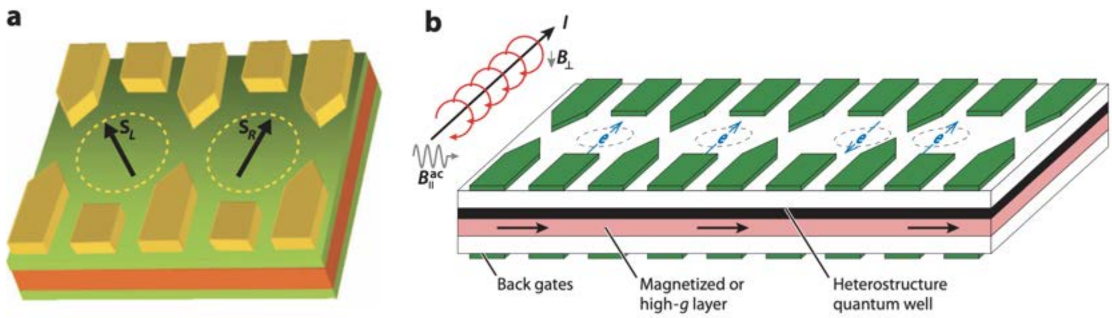

Figure 2: Diagram of a lateral quantum dot. Part a shows two neighbouring electrically gated single spin quantum dots, and part b shows an array based on part a [14]

voltage controlled tunnelling barriers between neighbouring qubits, and one qubit gates could be implemented through pulses of magnetic fields or with coupling to an auxiliary with a similarly controlled tunnelling barrier in between.

Gated quantum dots use 2 dimensional electron(2DEG) or hole(2DHG) gases within heterostructures. The lithographically defined gates on the surface are used to confine electrons (or holes)[14] as shown in Figure 2, and these places of confinement are the quantum dots. Another name for the quantum dots in Figure 2 are lateral quantum dots.

Fidelities higher than 99.9% have been achieved for single qubit gates[19], which is within the 1% error threshold[15] of QEC required to carry out fault tolerant computing. However, the same can't be said about two qubit gates, where fidelities are around 95% currently[25].

Gated quantum dots have largely met the DiVincenzo criteria mentioned in subsection 2.4. Initialisation of qubit states can be carried out through approaches such as measurement[6] and spin selective readout[26]. Potential for scalability is a strong point of gated spin quantum dots quantum dots with the capacity to integrate conventional semiconductor technology used for classical computers, such as the crossbar approach and CMOS manufacturing technologies which will be briefly mentioned in subsection 3.3, and their small sizes as seen in Figure 5.

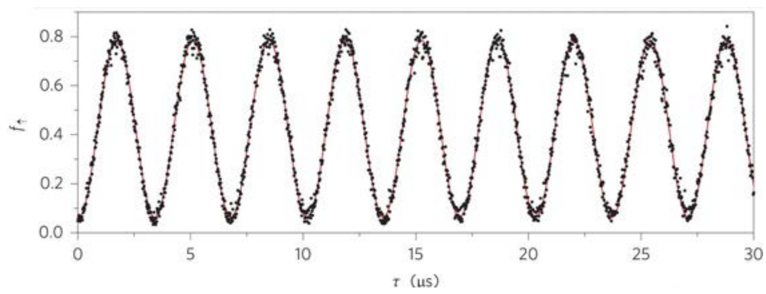

Figure 3: Spin probability $f_\uparrow$ of a quantum dot spin being up over time, during an ESR pulse[28]

3.2 Details of Gated spin quantum dots

The main materials used for the creation of gated quantum dots in research used to be GaAs and AlGaAs, but over time there's been a shift to purified ^{28}Si and Si/SiGe because nuclear spin decoherence can be virtually eliminated[27] by using materials with zero nuclear spin.

A requirement of gated spin quantum dots is low temperature, with at most 1.5K at the moment[5]. This can be achieved by using placing the quantum circuitry in a dilution refrigerator.

Zeeman splitting due to a constant magnetic field perpendicular to the horizontal plane allows the different qubit states to have different energies and therefore be distinguishable. For two electron spins, the singlet is the lower energy state due to antisymmetrisation, and the triplets are higher energy and show Zeeman energy splitting. Micromagnents can be used to apply this magnetic field.

The two main methods to control electron spin, and therefore the qubits, are electron spin resonance(ESR) and electric-dipole induced spin resonance(EDSR)[14].

ESR involves using pulses of alternating magnetic fields at the resonance frequency(RF) of the Zeemam splitting of the qubit along the transverse plane of a lateral quantum dot, while there is still a constant magnetic field. This leads to a rotation of the qubit between the two levels as shown in Figure 3. This type of oscillation of the qubit state is called the Rabi oscillation. ESR can also be done using optical pulses for optically active spin qubits, however electrically gated qubits are optically inactive[14].

The spin orbit interaction, which couples the orbital motion of a charge with its spin, means that an oscillating electric field leads to an effective magnetic field with the same frequency[14]. This RF magnetic field can then be used with the ESR technique to control the qubit state. This is EDSR, and means that a single qubit state can be rotated by purely electric means. Another way of applying EDSR is applying electric fields in a magnetic field gradient to electrically control spin qubits.

The most widely used mechanism for two qubit gates is the exchange interaction as envisaged in the seminal paper [4].

It is difficult to measure spins directly but possible to detect charges on a quantum dot through devices such as a quantum contact point(QPC). So 'spin to charge' conversion techniques are used, where the motion of the charge depends its spin. An example of this is energy selective readout as shown in Figure 4. To explain what's happening, voltage over time as shown in part a controls the energy level of the left quantum dot, part b shows the current response of the QPC which is used to detect an electron on the right quantum dot, and part c shows the motion of the electron depending on its spin. For the first portion of time, the Fermi energy E_F of the left reservoir quantum dot is below above both Zeeman splitting energy levels on the target quantum dot on the right. For the second portion E_F is raised above both levels on the right and the electron naturally tunnels into a lower energy level on the right. If the electron was in an up spin, it will settle into the corresponding upper split energy level, and if down into the lower split energy level. For the third portion, E_F is allowed to drop between the splitting, and motion of the electron depends on its spin. If the electron has an up spin it will tunnel back onto the lower energy reservoir, if not then it will stay on the right quantum dot, and this can be detected. For the last portion the voltage and therefore E_F drops completely, letting the electron tunnel back if it hasn't already.

3.3 Issues and how they are dealt with

A major cause for decoherence is the hyperfine interaction of electron spins with nuclear spins of atoms surrounding the quantum dot. The overall nuclear spin acts as a slowly oscillating magnetic field called the Overhauser field[14] acting on the electron spins. Spin echo techniques deal with the hyperfine interaction[14]. The rationale behind spin echo techniques is that at very short time scales the Overhauser magnetic field can be approximated as a constant magnetic, so by flipping the qubit it will experience the opposite effect from the magnetic field which will balance out the effect from the previous orientation. Nuclear spin noise can be nearly entirely dealt with by using semiconductors without nuclear spins, like purified ^{28}Si[27]. This highly increases coherence times, so nuclear spin decoherence has been largely dealt with.

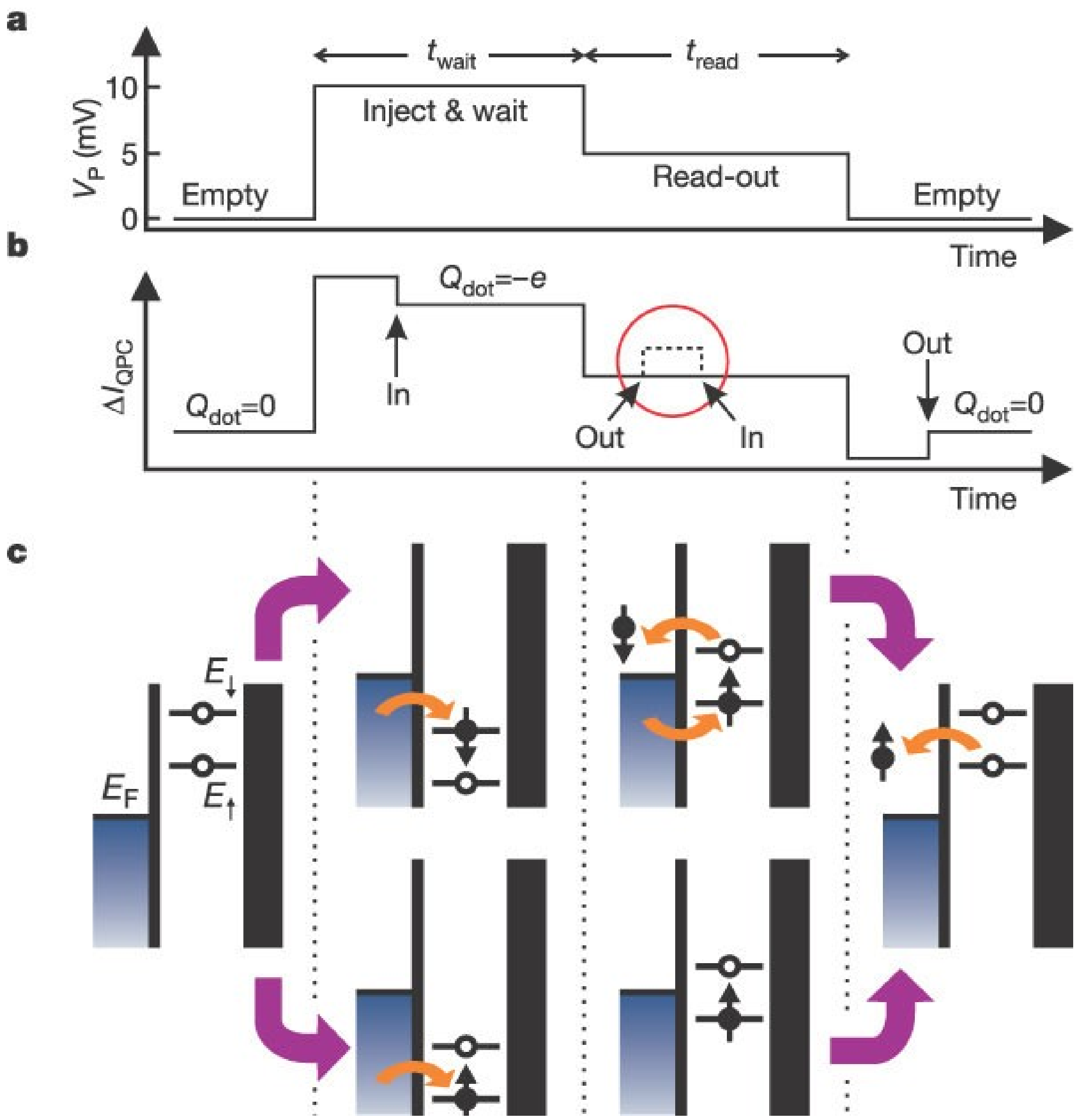

Figure 4: Process of spin dependent read out[26] after a electron has been loaded to the target quantum dot. Part a shows the voltage pulse used to control, part b shows the the current read out from the QPC, and c shows a schematic of the process.

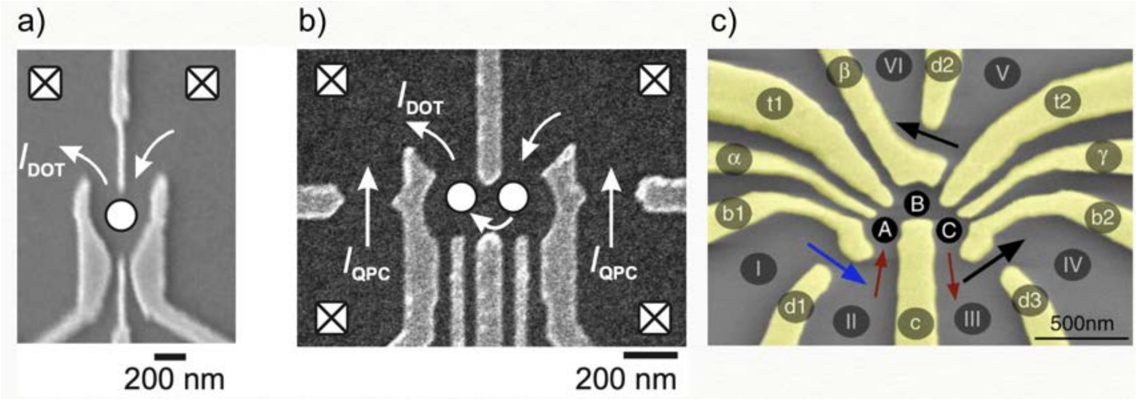

Figure 5: Gated quantum dots. Parts a, b, c respectively show scanning electron microscope micrographs of one, two and three quantum dot arrangements. Parts a and b are from [31], and c is from [32].

The second main source of decoherence, that is now a main limiting factor, is charge noise[29] caused by electric field fluctuations in semiconductor devices, that results in spin dephasing and scales as $\frac{1}{f}$, where f is the field or qubit resonance frequency. An issue with charge noise is that it's not yet understand what the cause of charge noise is. Currently methods to deal with it include improving materials and interfaces, and dynamic decoupling which basically involves complex sequences similar to spin echo techniques[29]. Charge noise also affects gate fidelities of two qubit gates based on the exchange interaction, as mentioned in subsection 3.2, and a way of dealing with this is to operate the system in a 'symmetry point' where the exchange energy is less sensitive to charge noise[30].

Errors can be dealt with by QEC with surface code as mentioned in subsection 2.2 provided error rates are below 1%[15].

One of the DiVincenzo criteria mentioned in subsection 2.4 is a scalable system of well characterised qubits. While having well characterised qubits isn't so much of a problem, scalability of gated quantum dots still needs to be worked on. Scaling gated quantum dots naturally lends itself to 2D arrays, however a major issue with such a set up is fan-out, the increasing number of control equipment needed. An easy way to visualise this is by looking at Figure 5 where the number of gates increases quite substantially from one to three quantum dots.

Two methods to deal with fan-out are multiplexing and the crossbar approach. Multiplexing involves sending one control signal to control multiple qubits at the same time. This works if different qubits are created to have different resonance frequencies, and means that the control pulse is a composite of pulses to the different

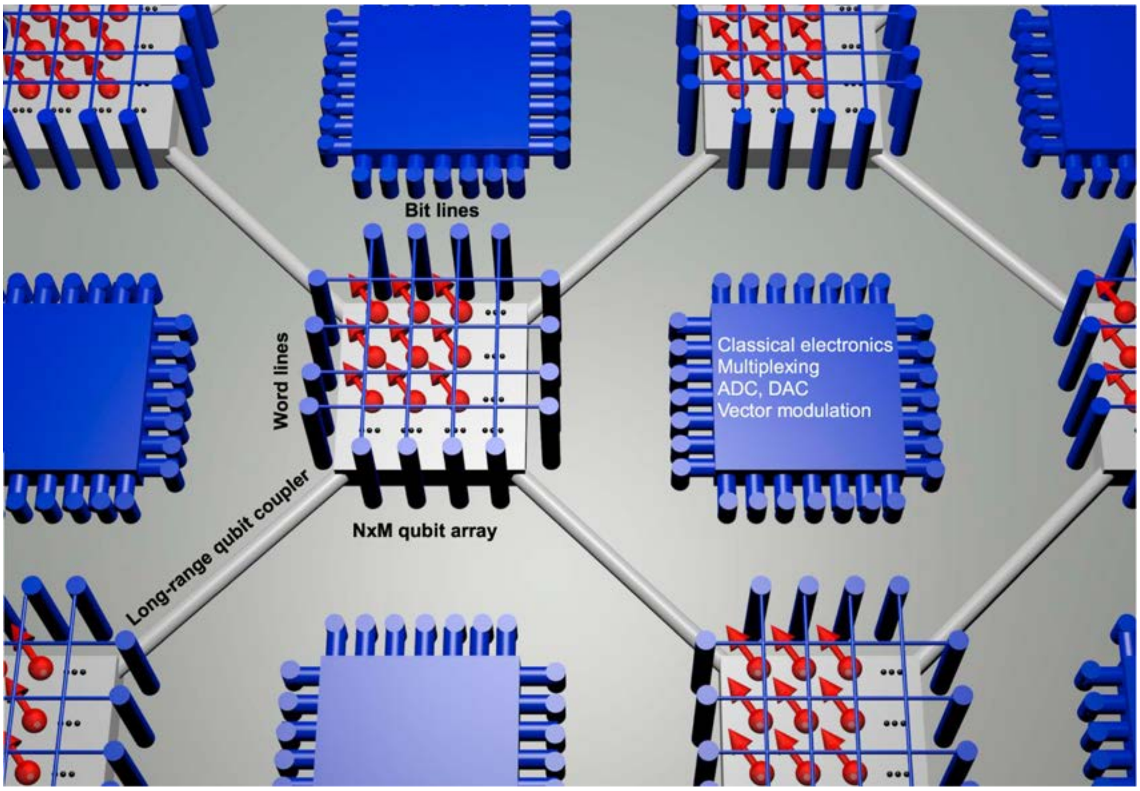

Figure 6: Sketch of a crossbar scheme connecting arrays of qubits with control lines, and leaving space for classical electronics which is shaded blue[34]

qubits being controlled. This naturally reduces the equipment needed to control qubits.

The crossbar approach is a type of arrangement used in classical processors, and research is being done into integrating it with gate quantum dots[33] and other qubit schemes[34]. A schematic example is shown in Figure 6, which involves small sets of arrays connected by row lines and column lines which are used for the read-out and control of these arrays. This can evidently be combined with multiplexing with qubits in an array manufactured so that each qubit has a different resonant frequency. The crossbar scheme means that control lines do not have to directly connect to each qubit, and can be limited to the grid of lines shown in Figure 6 and controls within each array.

Complementary metal–oxide–semiconductor(CMOS) manufacturing technologies are used to build the billions of transistors in classical computer chips CMOS. Leveraging these highly developed technologies would be very helpful for fabricating large scale gated quantum dot computers, and research is currently being carried out regarding this[17]. A CMOS gated quantum dot qubit is shown in Figure 7.

Cross talk is a problem that crops up with dense qubit arrangements, and investigations are being done to suppress cross talk in gated spin quantum dot arrays[35]. The sparse arrangement shown in Figure 6, where small arrays are separated, could be used to reduce crosstalk as well[34].

Another point of consideration is that any electronics used to control and measure the qubits should have power dissipation low enough to be handled by the refrigerator cooling the quantum dots, and not raise the temperature of the quantum dots. The cooling power naturally results in energy costs, so increasing the possible operation temperatures as achieved in [5] could be a way to reduce this energy cost.

4 Conclusion

This literature review introduced and explained the basics of qubit based quantum computing before quickly going over the gate controlled quantum dot scheme and the challenges it faces. It serves as an introductory text accessible to those new to quantum computing.

Quantum computers were first thought of as a way to simulate quantum systems to by using a computer based on quantum phenomena, and indeed have carried out such simulations, and developed to the point where they are being fabricated. Qubits are a quantum analogue of classical bits which allows a coherent superposition of both energy levels, and its coherency and entanglement are what makes quantum computers attractive. Currently, there are not enough qubits to perform useful calculations so a key motivations is to produce scalable quantum computers. Gates in quantum computing work much like classical computing, except that they can handle superpositions of states, and can introduce entanglement. The DiVincenzo criteria define what is expected of viable quantum computing schemes. Errors pop up in quantum computing, which can be dealt with by QEC as long as they are below a threshold of 1%. Multiple quantum computing schemes are being explored, each with their own advantages and issues, and it's still early days so it's not clear which if any will end up dominant.

Gated spin quantum dots are a scheme which uses lithographically defined gates on the surface of a plane heterostructure to form quantum dots, nanometre scale semiconductor particles which confine electrons or holes, and uses the spins of the confined electrons or holes as qubits while cooled to at most 1.5K. The two main methods to control gated spin quantum dots are ESR and ESDR. Nuclear spin de-

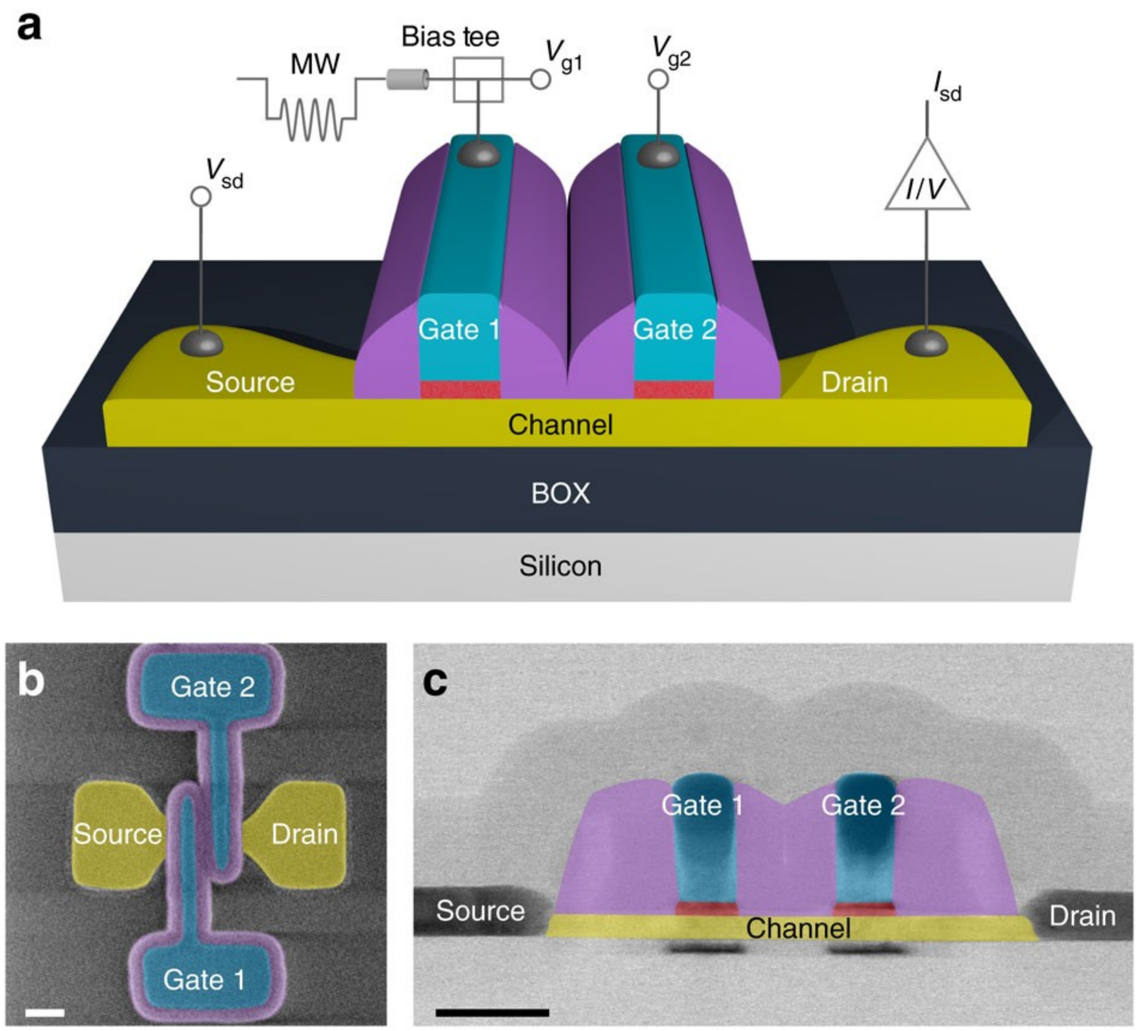

Figure 7: Part a shows a schematic of a silicon gated quantum dot CMOS. Parts b and c show colourised electron microscopy micrographs, with b taken through microscopy scanning and c taken through microscopy transmission.[17]

coherence used to be a source of noise, but it's largely been dealt with, and the current main cause of error is charge noise which has an unknown origin. Charge noise is an issue because it means that two qubit gates have errors above the 1% threshold provided by QEC. Gated spin qubits are attractive because of their potential scalability as a result of their small size and the capacity to integrate CMOS manufacturing techniques, and lends itself to scaling up as a 2D array. Two issues to scalability are cross-talk and fan-out, and are being currently being dealt with.

Quantum computing, including gated spin quantum dots, is a young and flourishing field with an assortment of research and challenges for the taking now that it has moved to efforts of creating scalable quantum computers.

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