Quantum computing with semiconductor spins
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This paper describes the experimental development of semiconductor quantum-dot spin qubits. The fundamental unit for quantum computing is a qubit, a gate-defined quantum dot. The paper discusses specific criteria (also known as DiVincenzo criteria) that need to be followed for functionalizing qubits. First, the qubits could be initialized in their respective ground state. Second, the final state of the qubit should be measurable with high probability. Third, the qubit's state could be manipulated via a single qubit gate (changing the state of a single qubit) and a two-qubit gate (changing the state of an entangled qubit). Fourth, the system's state should not decohere until the readout is done. Five, the qubits should be scalable i.e. for performing higher computational problems, more qubits are required, so we should be able to connect the qubits in arrays. Any system which follows these five DiVincenzo criteria can behave as a quantum computer.

Quantum gates are analogous to classical transistors, where the transistor gate voltage controls the flow of electrons in the semiconductor, whereas a quantum gate controls the system's state (up spin or down spin). Gate Defined Quantum Dots were created to overcome the problem of single electron transistors (SET). Multiple gate electrodes are used in this method to control the potential landscape of the semiconductor material and create consecutive potential barriers and wells, thus creating QDs. For a system of two QDs, a negative voltage is applied through the gate electrodes (those that control potential wells) to empty the QD. Slowly increasing the voltage lets electrons fill the first QD and then the second QD; it is confirmed by checking the charge stability diagram (current readings). Now, once the electron has entered QDs, we can change the tunnelling barrier between them and make both QDs interact with each other.

Any arbitrary spin state of an electron can be represented on the surface of a Bloch Sphere. In the Bloch Sphere, the θ part gives the probability, and the ϕ part gives the phase of the state vector. The perturbation in a two-level system can be understood via Rabi oscillations. Applying a magnetic field to the system causes Zeeman-splitting creating a difference in the energy levels of the spins. A spin state of a qubit can be read out by adjusting the Fermi level of the reservoir between the two spin states, such that the up spin (high energy) electrons can tunnel through to the reservoir and a down spin enters the QD. The system can be tuned to an on or off-state by tuning the tunnelling barrier. For performing quantum gate operations, it is necessary to preserve the entangled state. Generally, there are two ways a state can lose its information. First, relaxation from a high energy state to a lower energy state (the time scale is denoted by T1 and for GaAs, it can go up to 1 second). Secondly, by interacting with the surrounding environment, such as hyperfine interaction, phonon interaction, spin-spin coupling, etc. This timescale is denoted by T2, and for GaAs, it is in the range of nanoseconds. Silicon isotopes (Si^{28}) show timescales of microseconds which is much better than GaAs. Also, the CNOT gates operate by adjusting the rabi frequency of the target qubit based on the control qubit's state.

The paper discusses two types of gate-defined quantum dots made using silicon. First is the SiGe quantum dots; here, Silicon is sandwiched between layers of SiGe. The Si is present in a 2D electron gas (a region where the quantum dot will be formed). Second is the MOS (metal oxide semiconductor) quantum dot it has a Si-SiO_2 interface. However, Si-SiO_2 is more similar to the commercially available transistors and is hence easier to make. The paper briefly discusses Grover's algorithm, which is a search algorithm and has a time complexity of $\sqrt{n}$.

Scaling up is the biggest issue which needs to be addressed in future. For device fabrication of a quantum chip in silicon, an all-optical technique is used.

Machine learning algorithms have been implemented on a controlled two-qubit gate with eight gates to bypass errors caused by charge impurities by learning and adjusting the gates accordingly.

The wiring issues that arise by incorporating multi-qubit manipulation, here quantum multiplexing schemes can help us to draw analogy closely to the classical multiplexing systems observed in electronic chips.

Questions raised during presentation

Q1. Why does GaAs have a nuclear spin and 28 Si isotope does not?
Ans. Subatomic particles (electrons, protons, and neutrons) have an intrinsic property known as spin, which gives rise to spin angular momentum. The nucleus also has energy states given by the nuclear shell model, which follows Pauli's exclusion principle. In the case of half-filled energy levels, we will have net nuclear spin corresponding to unpaired nucleons. GaAs have nuclear spin (I=3/2), I=1+ for Ga and I=5/2- for As, Si28 has no nuclear spin due to an equal number of protons and neutrons.

Q2: How did optical photolithography get to be as precise as 20nm?

Ans: There is an industrial method for creating photolithography patterns up to 15 nm precision called Extreme UltraViolet (EUV) lithography. It involves using Sn plasma as light source and performs lithography in a vacuum. They use defect-free Mo/Si multilayers as the photomask and use multiple reflection interferences using mirror arrangements to give out a highly resolved interference pattern.

Q3: How are you controlling or distinguishing the degenerate states of quantum qubits?
Ans: It is possible to have degenerate states for quantum information, but it is possible to distinguish them. For example, in a 3-qubit system with one down spin, 011, 101 and 110 are the possible degenerate states, but each qubit can be read out individually. So, the qubit information remains distinguished even in the presence of large degeneracy.

Q4: Why GaAs was chosen for QC?
Ans: It has high mobility and hence a larger relaxation time as more time Is required to come to the ground state. Due to higher crystalline behaviour, the electrons maintain their high state before relaxing to the ground state. It is analogous to behaviour of Time-resolved Pl spectra.

Q5: How QD obtained, and what location?
Ans: 3 direction confinement 1. 2DEG 2. Potential via gates to avoid tunnelling 3. The gate electrodes (TC, BC, TL, TR, BR, BL).

Q6: What type of photoresist (+ or -)?
Ans: Positive.

Q7: How is an oxide formed in this MOSFET and location?
Ans: Native oxide no need for insulating layer location all around the area between Gates and QD.