From transistor to qubits: Write-up

In this term paper, we have extensively studied quantum dots in semiconductors as a potential candidate for making a quantum computer.

We had given a motivation as to why we need a quantum computer and discussed what sorts of problems pose exponential memory limitations on classical computers that a quantum computer can handle. We connected it with the two superpowers a quantum computer has. Then we introduced the DiVincenzo criteria for realizing a quantum computer out of an experimental system. We also addressed how our gate-defined quantum dot system addresses initialization, readout, single-qubit and two-qubit gate manipulation, decoherence, and scalability

We introduced quantum dots (QD) by describing a SET we studied in class and showed how we could control electron occupation in the SET islands using the gate voltage. Then to achieve complete control over the interaction between electrons along with the electron occupation, we switched to gate-defined QD. We then looked at the device structure of such a QD, the charge stability diagram, and how we experimentally got it to calibrate the QD gates.

Since the paper introduced GaAs as the first semiconductor where scientists realized a quantum dot, we have shown a fabrication of a QD made from GaAs/AlGaAs heterostructure (MBE produces that) such that the conduction band potential confines the Fermi level. Starting material was a 2D electron gas, confining the electrons from the other two transverse directions leads to a QD. We also discussed the fabrication procedure of sequential photolithography and e-beam lithography to achieve the desired QD structure.

To understand the arbitrary single-qubit manipulation, we explained the theory of the Bloch sphere and showed how it corresponds to the representation of any arbitrary two-level system. We then described Rabi oscillations and showed how it follows from a time-dependent perturbation theory with an electromagnetic light in the RF range as the perturbation. By adjusting the duration of this RF pulse, we can move to any point on our Bloch sphere and thus make a single qubit gate.

Then we realized the electron spin inside the QD as our qubit and removed their degeneracy by adding a magnetic field and causing Zeeman splitting. Then by adjusting the electron reservoir, we also showed how we could make an electron come out of the QD and get read by the SET as a current signal if it is in the higher energy state. Then using the same argument, we could also create an initialization to the lower energy of spin with the same reservoir configuration. Then moving on to a two-qubit gate, we showed how a CNOT gate is applied by controlling the interaction between two quantum dots and adjusting the RF such that the rabi oscillation is twice for a down spin than that of an up spin, thus only flipping the target when the control is up.

To look into the fourth DiVincenzo criterion, we looked at the lifetime of our qubit. We showed how they affect our qubit coherence by introducing two timescales, T_1(relaxation time) and T_2 (decoherence time). We saw that T_2 plays a more crucial role in decohering qubit state, and for GaAs, it was in the range of nanoseconds. We could do better than nanoseconds using silicon isotopes (Si^{28}). Unlike the GaAs, which had nuclear spin ($I = \frac{3}{2}$), $I = 1^+$ for Ga, $I = 5/2$- for As, Si^{28} has no nuclear spin due to an equal number of protons and neutrons. Thus, we can have T_2 up to 250 µs.

We continued to the two types of Si-based QD: Si-Ge QD and MOS QD. After their brief description, we also argued why Si-Ge is a better alternative due to lesser surface defects. We showed a quantum algorithm, namely Grover's search algorithm, that changes the sign of that qubit configuration we wish to find. We could sort the result quickly by implementing Hadamard gates and amplification, though the output had some experimental errors.

Finally, we addressed the scalability of our system. We looked at an all-optical device fabrication of a quantum chip in silicon. The flexible architecture allowed simultaneous qubit manipulation of around 10,000 per array, and VLSI technology had studied the precise fabrication technique extensively. To reduce readout errors due to charge traps and impurities, we have looked at machine learning algorithm schemes implemented on an eight-gate controlled two-qubit gate to bypass the defect errors by learning and adjusting the gates accordingly.

Thirdly, to reduce the wiring issues we might get by incorporating multi-qubit manipulation, we looked at quantum multiplexing schemes that draw an analogy close to the classical multiplexing systems we see in our electronic chips. To complete the discussion of quantum multiplexers, we showed photonics as a plausible qudit (d-dimensional qubit) to entangle our d-qubits and transfer quantum information via photonic chips and optical cables. We also saw how we could do readouts for a qudit using single photon detectors.

Q&A during the 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 provided 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. Spins of GaAs and Si isotopes are given in the relaxation and decoherence paragraph.

Q2: How did optical lithography get as precise as 20nm?

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

Q3: How are you controlling or distinguishing the degenerate states of quantum qubits?

Ans: We indeed have large degeneracy in a quantum system, 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. Still, we can read out each qubit individually ($|011\rangle = 0 \otimes 1 \otimes 1$, and each qubit lives in its own Hilbert space). So, the qubit information remains distinguishable even in the presence of large degeneracy.

Q4: Why was GaAs chosen for QC?

Ans: It has high mobility and, hence, more relaxation time as more time is required to reach the ground state. Due to higher crystalline behavior, the electrons maintain their excited state before relaxing to the ground state. It is analogous to the conduct of Time-resolved Pl spectra.

Q5: How is an oxide formed in this MOSFET and location?

Ans: Native oxide for Al exists, and it doesn't ask for an insulating layer since oxide exists at the location all around the area between Gates and QD.

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

Ans: Positive

Q7: How oxide formed in this MOSFET and location?

Ans: Native oxide no need of insulating layer location all around the area between Gates and QD