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Towards long coherence time spin control for quantum information: Characterization of silicon quantum dots and micro-magnets integration

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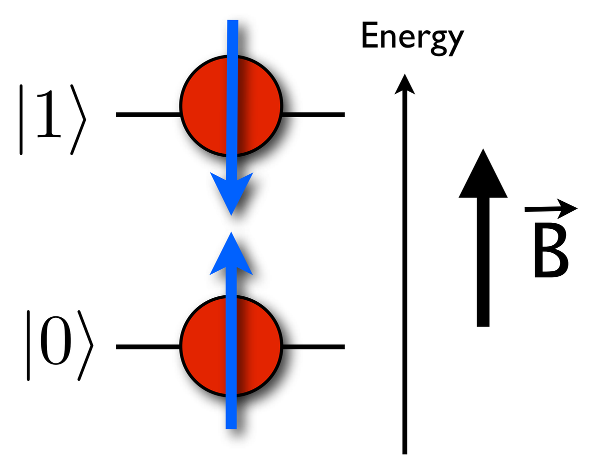
Motivation

Spins are a promising avenue for the implementation of a quantum computer. Information is encoded in the electron spin, which is confined electrostatically by a quantum dot in a semi-conductor substrate, and manipulated by micro-magnets **[1]**. To reduce information loss in this type of quantum bit, it is essential to minimize decoherence. One of the largest contributor to this phenomenon being the hyperfine interaction of the nuclear magnetic field with the electron spin, we can exploit the properties of silicon (Si), containing only 5 % on non-zero magnetic nuclei (close to 0% if isotopically purified), to act as a substrate with long coherence time for our qubit. Here we describe the design of a Si metal-oxide-semiconductor field-effect-transistor based double quantum dot (Si MOSFET DQD) **[2]**, and present preliminary results of device characterization.

Basics of double quantum dots

Electron spin in a magnetic field : ideal **two-level system**.

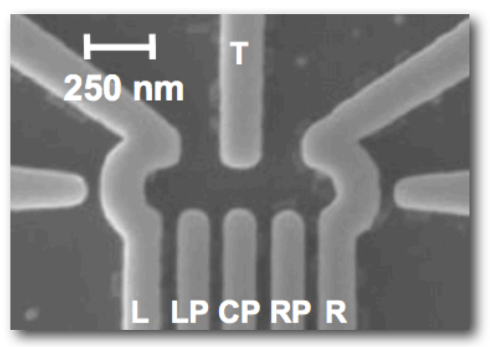


Spin up and spin down: fondamental unit of quantum information.

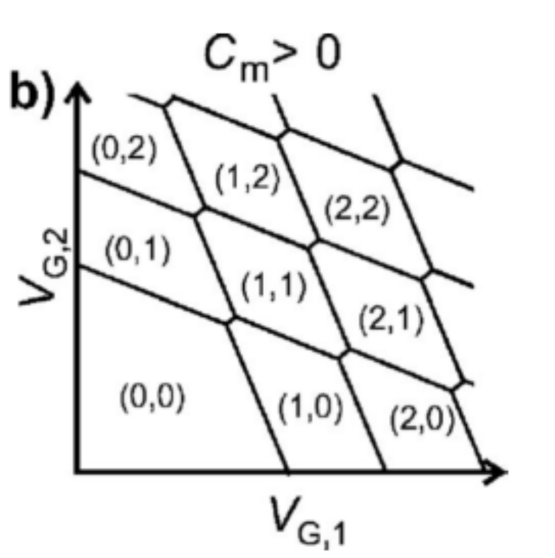
We can confine the electron spin using a **quantum dot**[3].

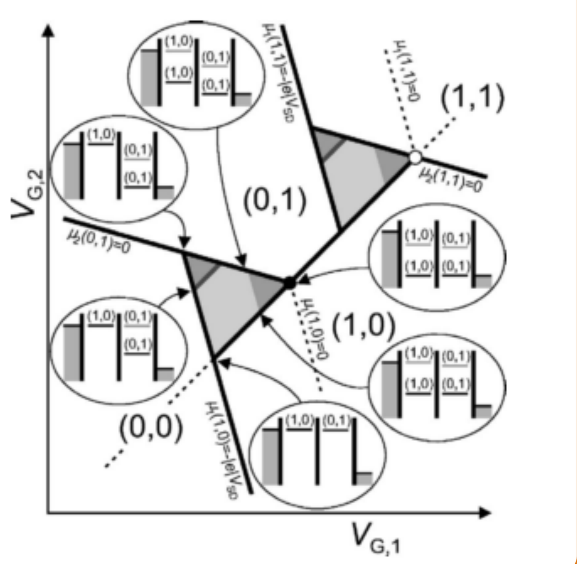
The energy levels for spin up and spin down must be well separated.

In double quantum dots, electrons circulate from source to dot 1 to dot 2 to drain.



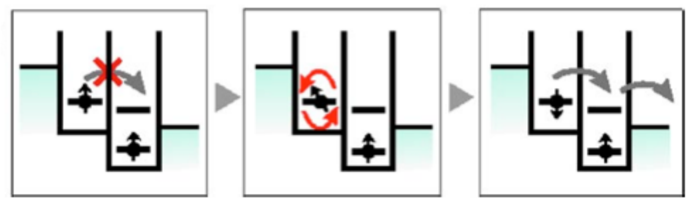
Standard stability diagramm and bias triangles in DQDs:





Spin manipulation in DQD

By applying a **magnetic pulse** with a frequence corresponding to the Zeeman splitting between the spin up and down level, it is possible to induce a **spin rotation**. This is a technique called **electron spin resonance (ESR)**[4].



$$h\nu_r = g\mu_B B$$

- This spin rotation is detected by measuring the electrical transport in the dot.
- In a double dot, Pauli exclusion principle forbids transport when the spins in the two dots are identical. This is the **spin blockade**[3].

Silicon quantum dots

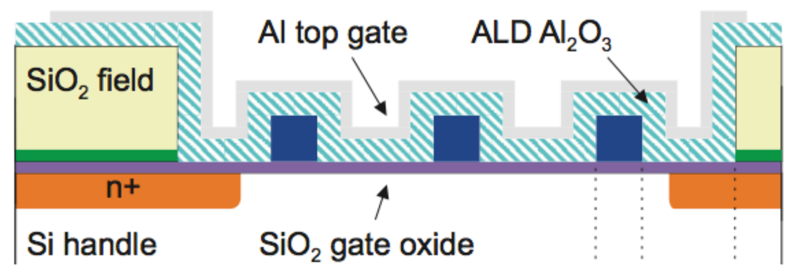
ESR was mostly developed in GaAs quantum dots. Unfortunately, the decoherence time is limited in GaAs by the hyperfine interaction caused by the magnetic nuclear spins[3].

Isotope	Natural abondance (%)	Nuclear spin (I)
^{28}Si	92	0
^{29}Si	5	1/2
^{30}Si	3	0
^{69}Ga	60	3/2
^{71}Ga	40	3/2
^{75}As	100	3/2

≈95% nonmagnetic nuclei

0% nonmagnetic nuclei

- If we could develop a quantum dot in a material without this problem, such as **silicon**, we would potentially reduce greatly the decoherence.
- Carroll's group from Sandia developed an enhancement-mode silicon MOS structure with a lateral geometry, which can form a double quantum dot[5].
- A 2-dimensional electron gas is formed by applying a positive voltage on the top-gate. Electrons are confined by applying negative voltage on depletion gates.

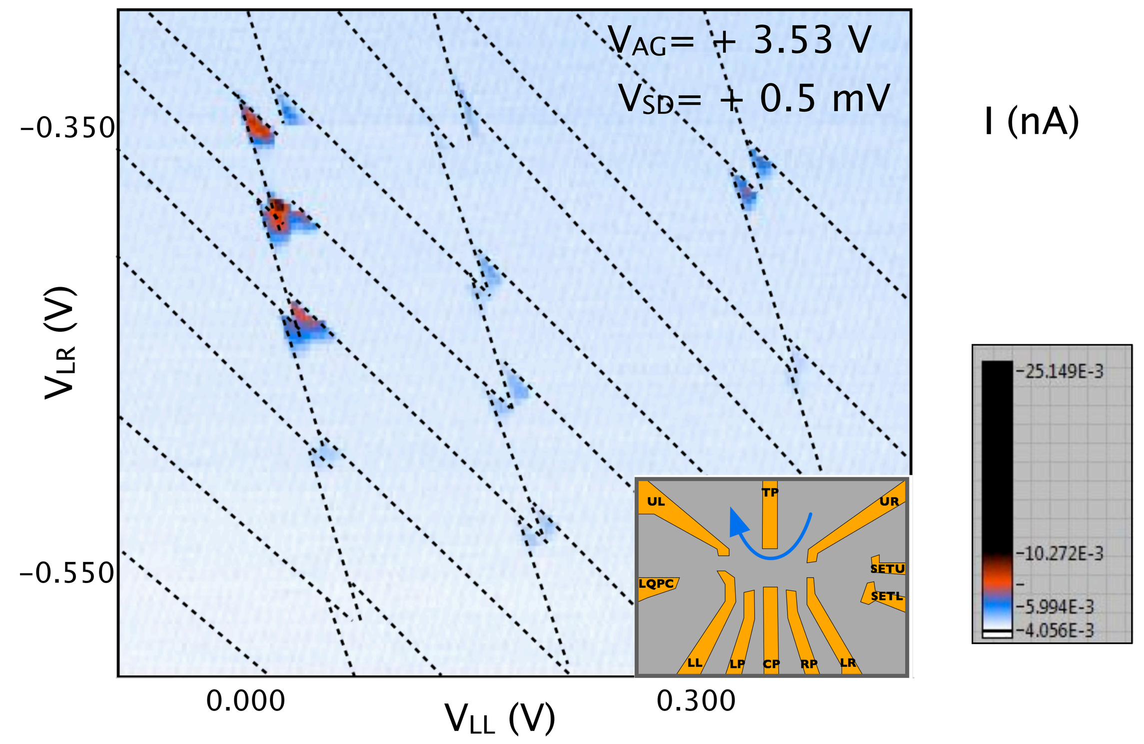


- This type of device would provide less decoherence and a simpler integration with standard classical CMOS electronics, since it's basically a MOSFET.

Characterization of a Si DQD

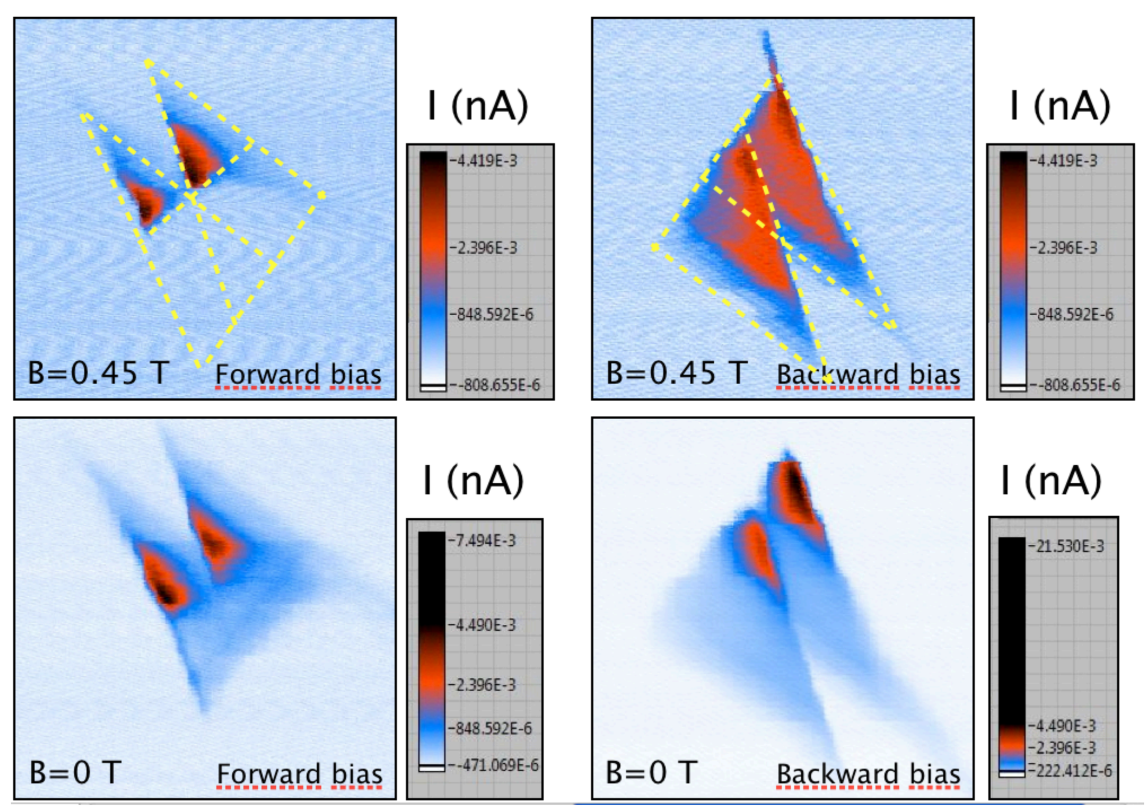
Using a dilution fridge T=8 mK

Formation of a double dot in the many electrons regime



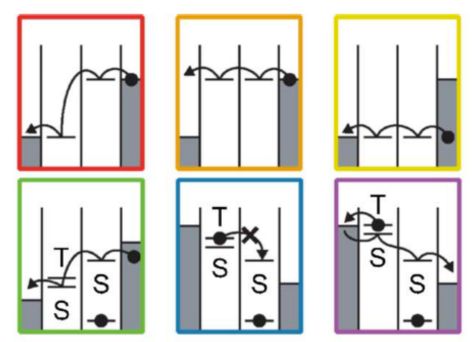
Charging energy estimated to ≈5 meV (for left dot) and ≈2 meV (for the right dot) in the many electrons regime.

Observation of Pauli Spin Blockade (Few electrons regime)



V_{AG}= + 3.85 V
Bias = 1 mV

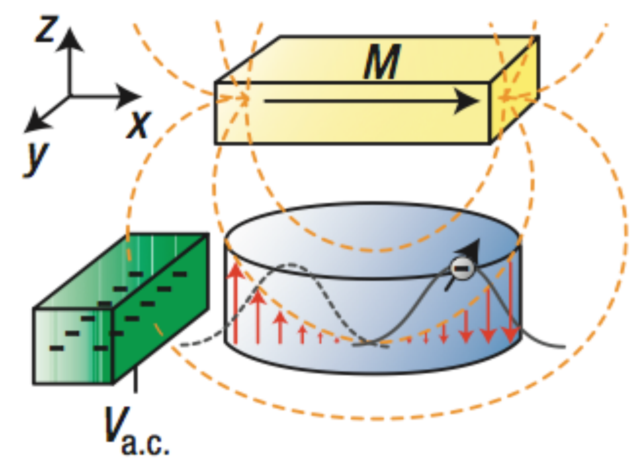
Explications for the different regions of the bias triangles[6].



Micro-magnets for spin control

To implement spin rotations with ESR, we need fast oscillating magnetic field, which is experimentally difficult.

Instead, we use a fast oscillating *electric field* to move the electron inside a strong magnetic field created by a **micro-magnet**. The electron then sees an effective AC magnetic field[1].



$$\tau_\pi = \frac{1}{2}\frac{1}{f_{Rabi}}$$

$$f_{Rabi} = \frac{1}{2}\frac{g^*\mu_B B_{ac}}{h}$$

$$\Delta = \hbar^2/m^*\,{l_{orb}}^2$$

$$B_{ac} = \frac{e\,E_{ac}\,{l_{orb}}^2\,b_{SL}}{\Delta}$$

The goal of this project is to integrate micro-magnets to perform spin rotations in the Si DQD devices developped by Sandia's team. Previous simulations indicate that fast rotations are expected.

Conclusion and future work

A double quantum dot was successfully formed in a MOSFET type silicon double quantum dot device. The observation of Pauli Spin Blockade indicates that this type of device could be suitable for quantum information purposes. Future work includes attaining the single electron regime, which is necessary for the spin manipulation. Also, in parallel with those efforts, we are working on the integration of micro-magnets on the devices, to realize fast spin rotations. Those fast spin rotations, in combination with the expected longer coherence time in silicon, are the essential components for effective quantum information manipulation in quantum dots.

References

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