Using electron spins for implementing qubits

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REGINNA 4.0 First Summer School - 7 July 2023

Overview

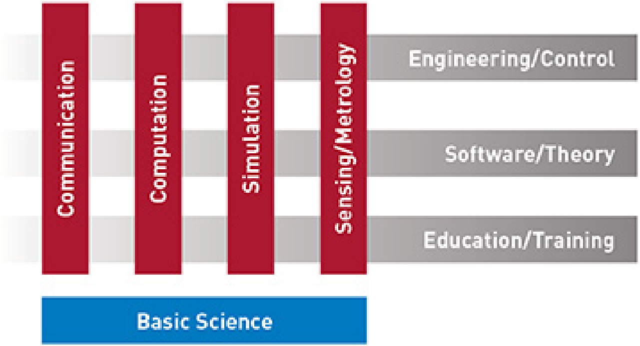
1. Generalities on quantum computing

2. Quantum dots as qubits

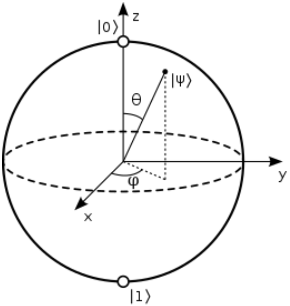
3. Existing quantum computers

Generalities on quantum computing

The quantum technologies



The qubit



$$|\psi\rangle = \cos(\theta/2)|0\rangle + e^{i\varphi}\sin(\theta/2)|1\rangle$$

Linear superpositions

The physical implementation of quantum computation

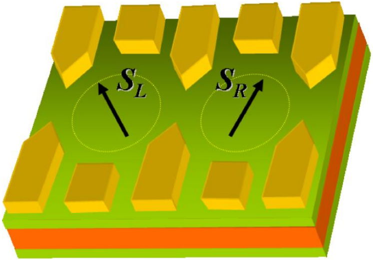
The DiVincenzo criteria

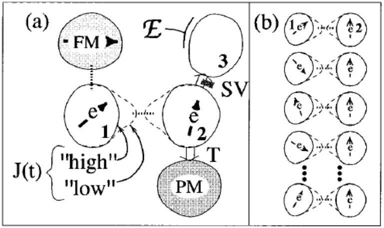
1. A scalable physical system with well characterized qubits
2. The ability to initialize the state of the qubits to a simple fiducial state
3. Long relevant decoherence times
4. A “universal” set of quantum gates
5. A qubit-specific measurement capability

See: D. P. DiVincenzo, Fortschritte der Physik. 48, 771 (2000)

Quantum dots as qubits

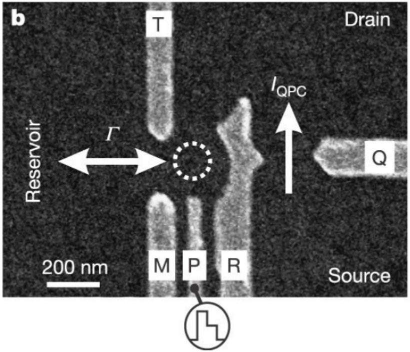
“Quantum computation with quantum dots”



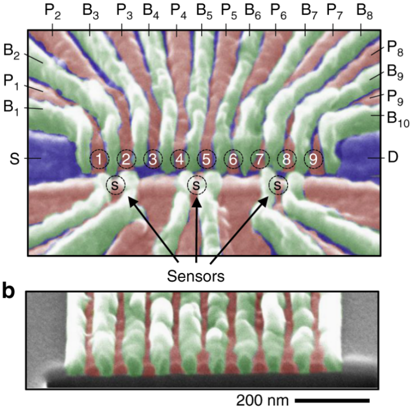


Loss and DiVincenzo, Phys. Rev. A 57, 120 (1998)

"Quantum computation with quantum dots"



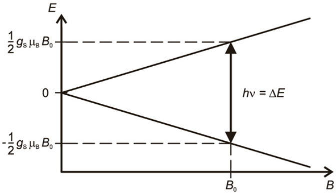
Elzerman *et al.*, 2004



Mills *et al.*, 2019

Single-qubit gates

Pulsed magnetic fields



- The rotations are implemented by applying a transverse and oscillating magnetic field $B_1(t) = A_b \cos(2\pi\nu_L t)$
- Relevant physical parameters: $\nu_L = g\mu_B B_0/h$ (Larmor frequency) $\nu_R = g\mu_B A_b/h$ (Rabi frequency)

Physical constraints

- Initialization: $B_0 \gg k_B T/g\mu_B$
- Relaxation (phonons): $1/T_1 \propto B_0^7$
- Dephasing (nuclei): $\nu_R \gg 1/T_2$

Two-qubit gates

Supplementary material (II): Heisenberg interaction $H_{12} = J\mathbf{S}_1 \cdot \mathbf{S}_2$

Initial factorized state:

$$|\Psi(t=0)\rangle = |01\rangle = \frac{1}{\sqrt{2}}(|T\rangle + |S\rangle) \tag{1}$$

Time evolution induced by a finite singlet-triplet splitting J:

$$\begin{aligned} |\Psi(t>0)\rangle = e^{-iHt/\hbar}|\Psi(0)\rangle &\propto \frac{1}{\sqrt{2}}(e^{-iJt/\hbar}|T\rangle + |S\rangle) &(2)\\ &= \frac{e^{-iJt/2\hbar}}{\sqrt{2}}(e^{-iJt/2\hbar}|T\rangle + e^{+iJt/2\hbar}|S\rangle) &(3)\\ &\propto \cos(Jt/\hbar)|01\rangle - i\sin(Jt/\hbar)|10\rangle &(4) \end{aligned}$$

Factorized of entangled final states:

$$\begin{aligned} |\Psi(t=\pi\hbar/2J)\rangle &\propto |10\rangle \ (\text{SWAP}) &(5)\\ |\Psi(t=\pi\hbar/4J)\rangle &\propto \frac{1}{\sqrt{2}}(|01\rangle - i|10\rangle) \ (\sqrt{\text{SWAP}}) &(6) \end{aligned}$$

All-electrical spin manipulation: spin-orbit interaction

- Exploiting a built-in property of the material in order to have an effective, momentum-dependent B-field or a tunable, inhomogeneous g tensor
- Inducing a synthetic SOI through a magnetic-field gradient

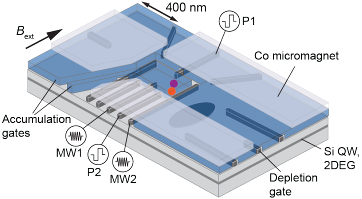
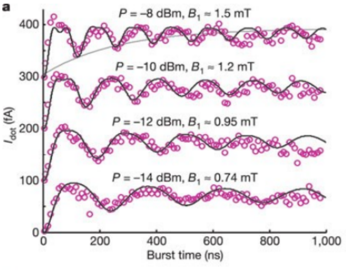


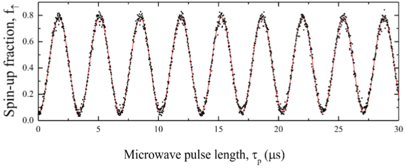
Figure: Vandersypen Lab (QuTech)

- Passing from the conduction to the valence band (from electrons to holes)

The material matters: group IV SCs are better than III-V



Koppens *et al.*, 2006
(GaAs, $T_2^* = 27\,\text{ns}$)

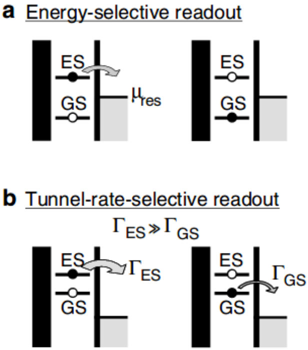


Veldhorst *et al.*, 2014
(isotopically purified Si, $T_2^* = 120\,\mu$s)

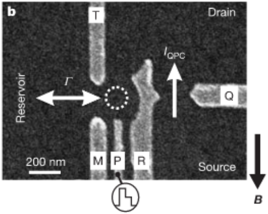
Readout of a single electron spin

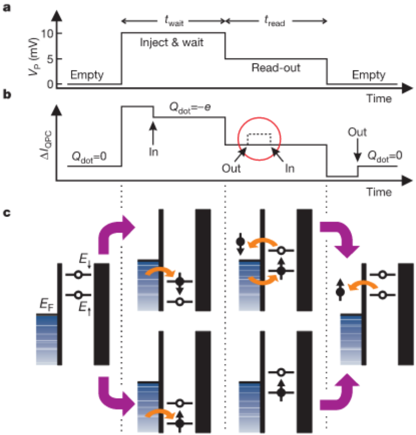
Spin readout in semiconductor QDs:

1. Correlating spin and charge state through spin-dependent electron tunneling
2. Detecting the charge state through the capacitive coupling to a QPC/SET



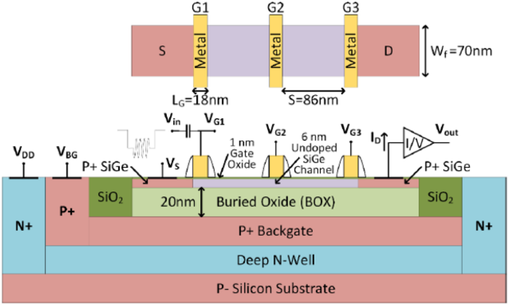
Readout of a single electron spin





Elzerman *et al.*, Nature 430, 431 (2004)

Hole-spin qubits in fabricated pMOS



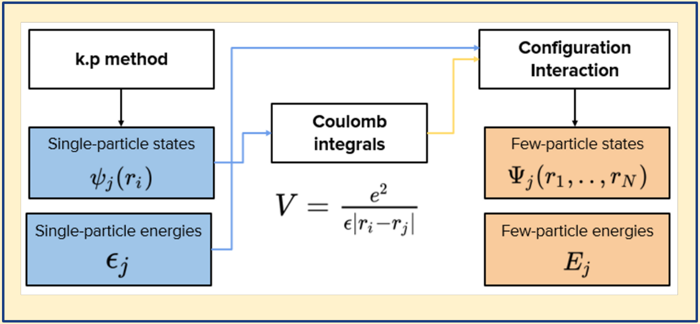
Si p-MOSFET double quantum dot structure in the 22nm FDSOI process

Multiscale approach to the qubit simulation

Fabricated MOSFET $\Longrightarrow$

Down-scaled device $\Longrightarrow$

TCAD simulation $\Longrightarrow$


k.p method

Single-particle states $\psi_j(r_i)$

Single-particle energies ϵ_j

Coulomb integrals

$$V = \frac{e^2}{\epsilon |r_i - r_j|}$$

Configuration Interaction

Few-particle states $\Psi_j(r_1, .., r_N)$

Few-particle energies E_j

$\Longrightarrow$ Effective qubit Hamiltonian, compact models

The device & the quantum dot formation

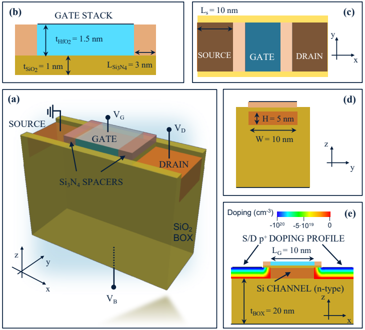


Figure: Down-scaled version of a fabricated pMOSFET (Global Foundries 22nm FDSOI process)

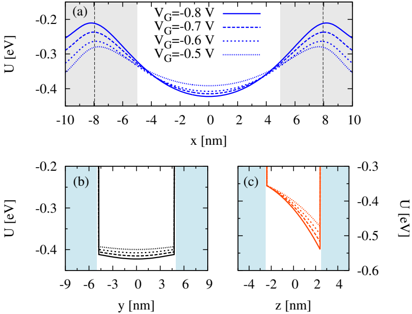


Figure: Simulated confining potential along the symmetry axes of the Si channel for $T = 2$K

The device & the quantum dot formation

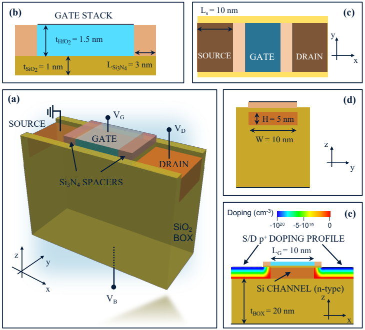


Figure: Down-scaled version of a fabricated pMOSFET (Global Foundries 22nm FDSOI process)

The GS doublet is characterized by:

- Localization in the Si channel
- Predominant hh character
- Quasi mirror symmetries
- Energy gap $\Delta/k_B = 76 - 80\,\mathrm{K}$

V_G [V]	$p(\mathcal{R}_{SD})$[%]	$p(\mathcal{R}_{NS})$ [%]	$p(\mathcal{R}^y_{Ox})$ [%]	$p(\mathcal{R}^z_{Ox})$ [%]
-0.8	0.91	0.77	0.01	0.19
-0.6	1.42	1.23	0.01	0.18
V_G [V]	$p^{hh}_{1,\xi}$ [%]	$p^{lh}_{1,\xi}$ [%]	$p^{so}_{1,\xi}$ [%]	
-0.8	86.44	11.57	1.99	
-0.6	83.14	14.56	2.30	
V_G [V]	$\langle\sigma_{yz}\rangle$	$\langle\sigma_{zx}\rangle$	$\langle\sigma_{xy}\rangle$	$\langle\sigma_r\rangle$
-0.8	0.9655	0.9670	0.8548	0.8870
-0.6	0.9550	0.9692	0.8894	0.9289

Can the spin be rotated electrically, and how fast?

Rabi frequencies for rotations around the X and Z axes of the Bloch sphere:

$$f_R^X = \frac{1}{h} \left| \langle 1, \Uparrow | \delta U | 1, \Downarrow \rangle \right|$$

$$f_R^Z = \frac{1}{2h} \left| \langle 1, \Uparrow | \delta U | 1, \Uparrow \rangle - \langle 1, \Downarrow | \delta U | 1, \Downarrow \rangle \right|$$

and for a sequence of the two:

$$f_R^{XZ} = \left(\frac{1}{f_R^X} + \frac{1}{f_R^Z} \right)^{-1} = \frac{f_R^X f_R^Z}{f_R^X + f_R^Z}$$

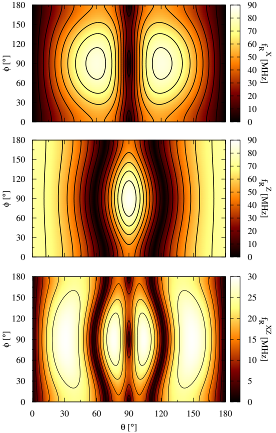
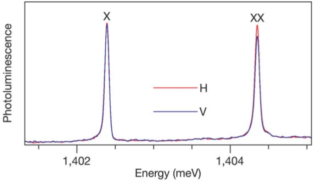
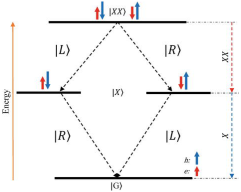
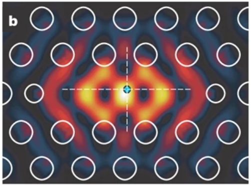


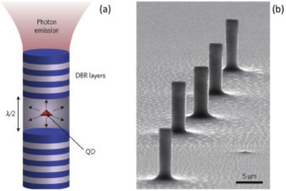
Figure: Dependence on the orientation of $\mathbf{B} = B(\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$

Quantum dots as sources of entangled photons



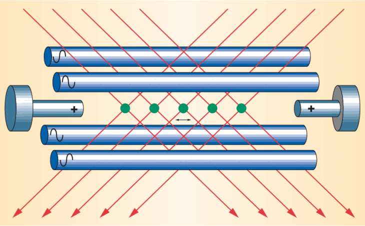


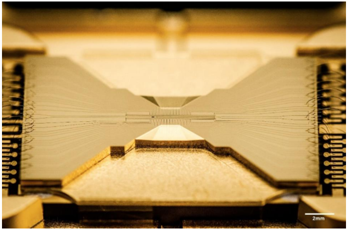




Existing quantum computers

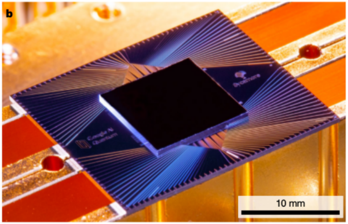
Trapped ions

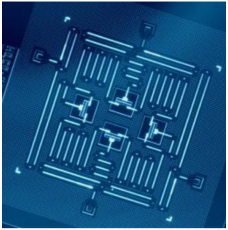




- Qubit encoding in the hyperfine levels of the ions
- Initialization of the nuclear and vibrational states by optical pumping
- Quantum gates by laser pulses, qubit-qubit coupling by vibrational modes
- Optical qubit measurement (fluorescence)

Quantum computing @Google





- Superconducting (transmon) qubits
- General purpose quantum computing, demonstrated the quantum supremacy
- A 53-qubits quantum processor (Sycamore)

See: https://quantumai.google/

A symbolic but important achievement

nature

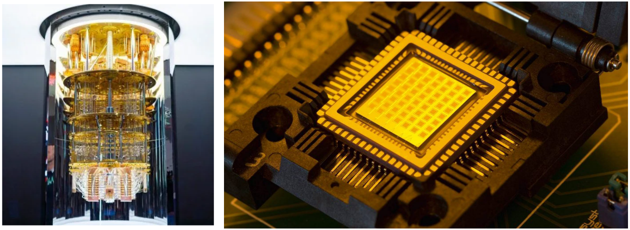
QUANTUM SUPREMACY

Classical supercomputer outperformed by quantum chip for the first time

"Our Sycamore processor takes about 200 seconds to sample one instance of a quantum circuit a million times—our benchmarks currently indicate that the equivalent task for a state-of-the-art classical supercomputer would take approximately 10,000 years."

F. Arute *et al.*, Nature 574, 505 (2019)

Quantum computing @IBM



- Superconducting qubits
- General purpose quantum computing
- IBM Q System One (20 qubits), IBM Q System (53), Eagle (127 qubits)

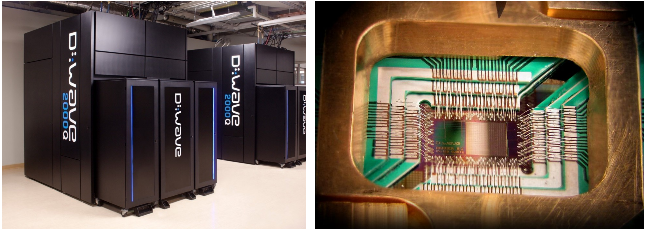
See: https://www.ibm.com/quantum-computing/

The Noisy Intermediate Scale Quantum (NISQ) era

- The implementation of useful quantum algorithms requires $\sim 10^3$ logical qubits, which might correspond to $\sim 10^6$ physical qubits, considering the overhead due to error protection and correction.
- However, the limit of $n = 50$ qubits has now been hit, where brute force simulations of the quantum device become unfeasible.
- We have entered the NISQ era, characterized by values of n between 50 and a few hundreds, a number of gates of the order of 10^3, imperfect control on the qubits, and no error correction.

J. Preskill, arXiv:1801.00862v3 (2018)

Quantum annealing @D-Wave



- A different approach to quantum computing
- Applications in combinatorial optimization (NP-hard) problems
- D-Wave One (128 qubits), D-Wave Two (512), D-Wave 2X (1024), D-Wave 2000Q (2048), Pegasus (5640)

See: https://www.dwavesys.com/

Closing remarks

- Quantum computers hold the promise of solving problems that are otherwise intractable. However, in order to fully maintain the promise, orders of magnitude improvements are needed in the circuit volume.
- Current quantum quantum computers are complex enough to challenge “classical computers” on specific tasks.
- Near term quantum computers can find interesting applications, for example in optimization problems or within hybrid (quantum-classical) approaches.

Entanglement in a nutshell

- Entanglement is a property of the quantum state of a composite system (unlike interaction, which is a property of the system). It results from the application of the superposition principle to composite systems.
- The state of a bipartite (AB) system is entangled if it cannot be written in a factorized form: $|\Psi\rangle \neq |\psi_A\rangle \otimes |\psi_B\rangle$.
  For example: $|01\rangle$ and $|00\rangle + |10\rangle = (|0\rangle + |1\rangle) \otimes |0\rangle$ are factorized states, $|00\rangle + |11\rangle$ is an entangled state.
- The definition can be generalized to mixed states and to multipartite systems.
- If A and B are entangled, the maximum amount of knowledge on the state of AB can correspond to a complete lack of knowledge on the state of A and B, taken individually. On the other hand, the correlations between A and B can violate "classical" bounds.
- If A and B are entangled, a measurement performed on A affects the state of B, and the effect propagates faster than light (action at a distance).