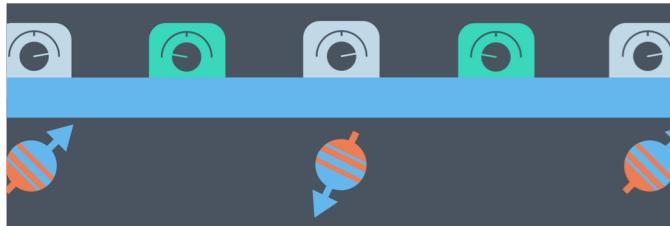
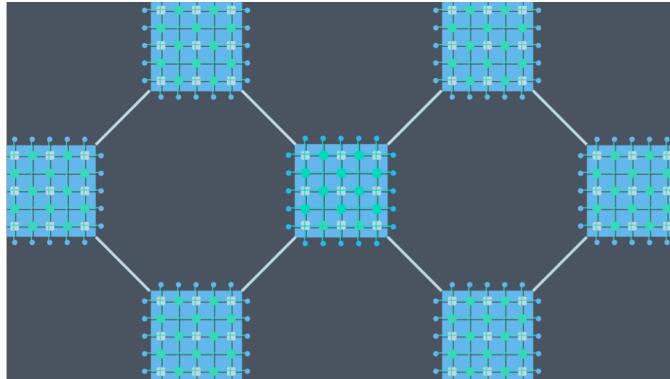


Menno Veldhorst

Operations on spin qubits

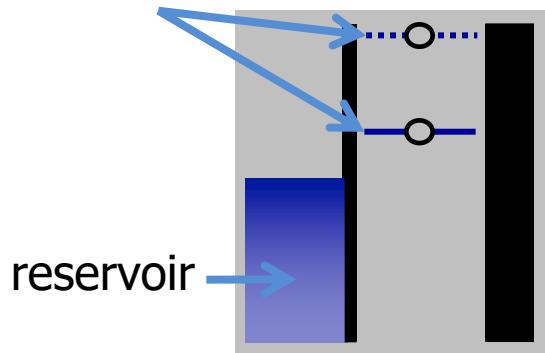


Last time from transistor
To (many) quantum dots

Now quantum dot qubits

Split by
magnetic field

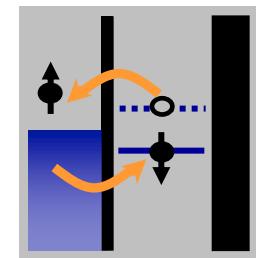
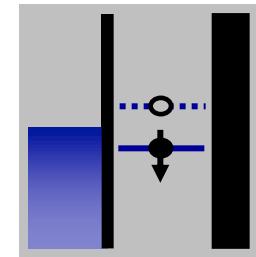
$$H_0 \sim \sum \omega_i \sigma_{zi}$$



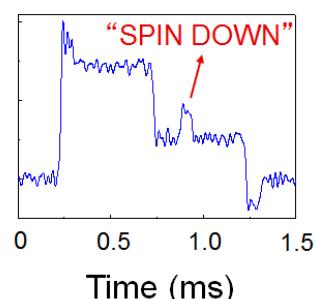
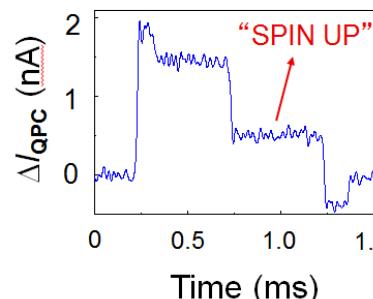
empty dot

filled dot
spin down

Initialize

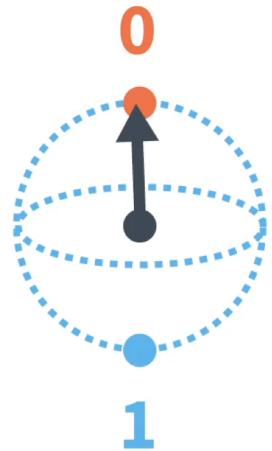


readout

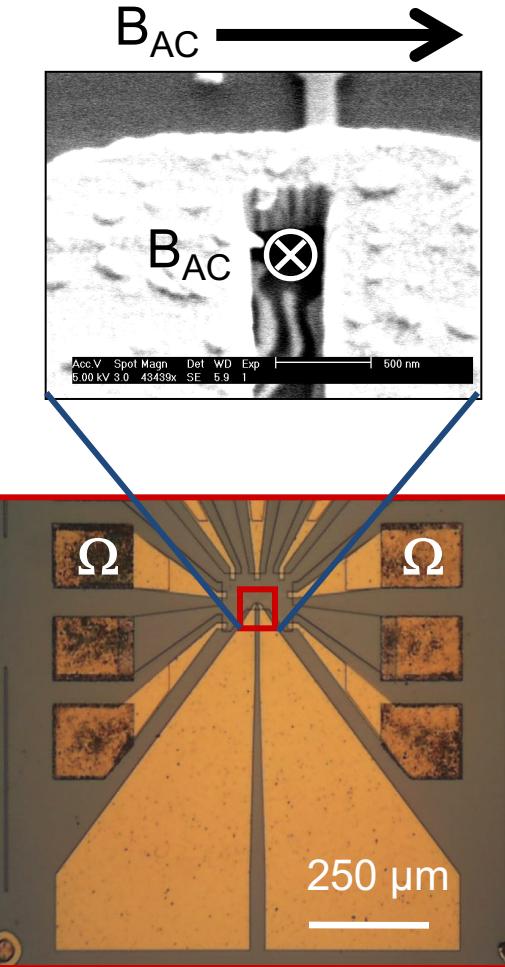


J.M. Elzerman, R. Hanson, L.H. Willems van Beveren, B. Witkamp, L.M.K. Vandersypen, L.P. Kouwenhoven. "Single-shot read-out of an individual electron spin in a quantum dot." *Nature* 430, 431-435 (2004).

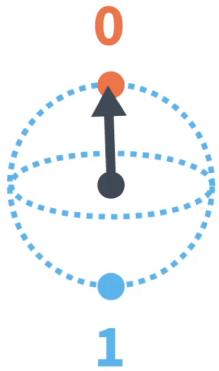
and control



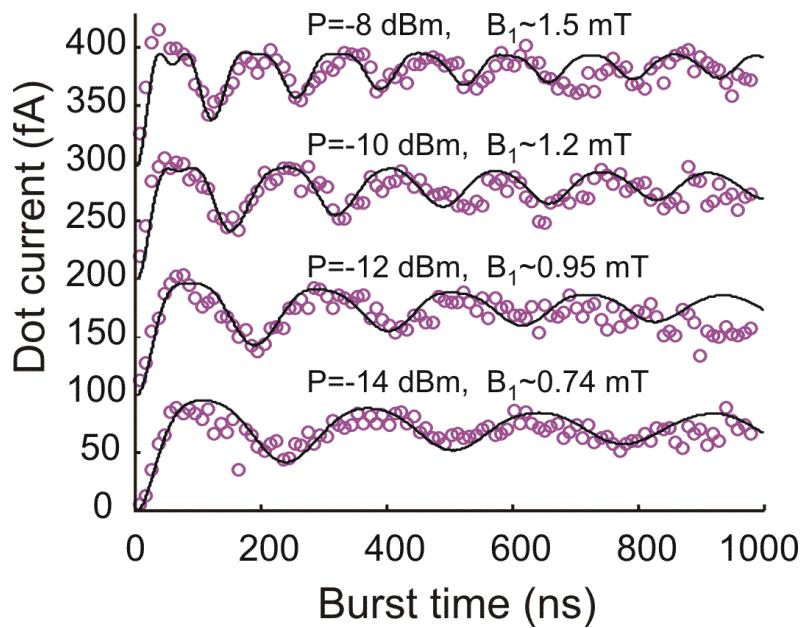
$$H_{RF} \sim \sum A_i(t) \cos(\omega_i t) \sigma_{xi}$$



GaAs

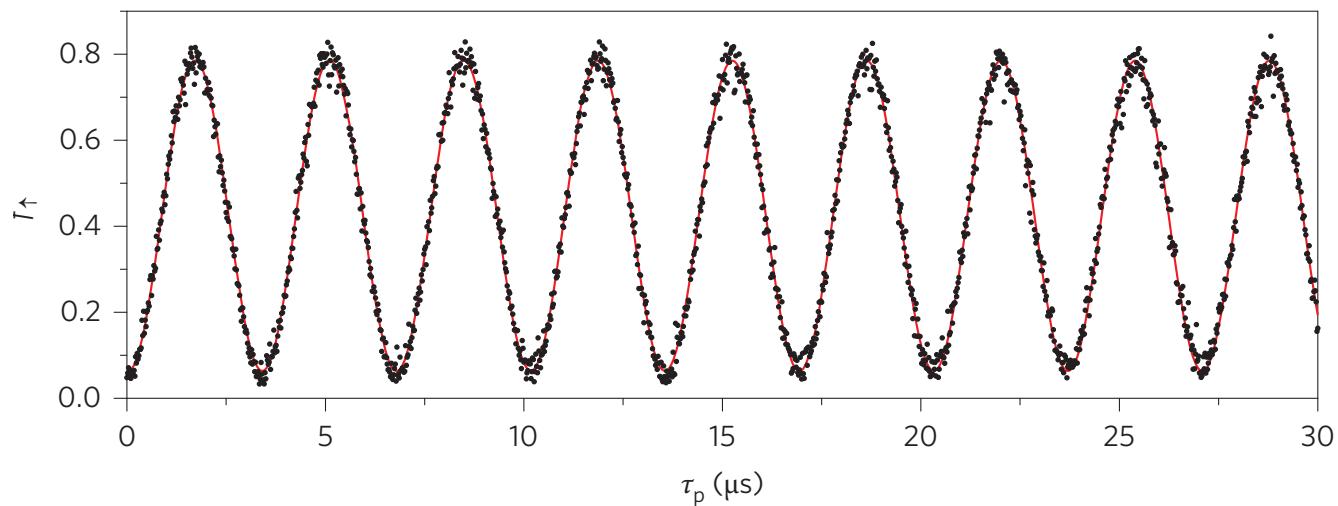
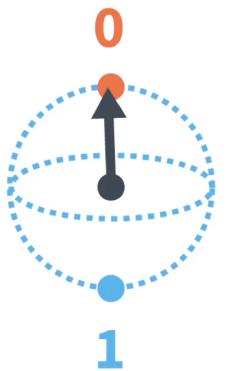


$$H_{RF} \sim \sum A_i(t) \cos(\omega_i t) \sigma_{xi}$$



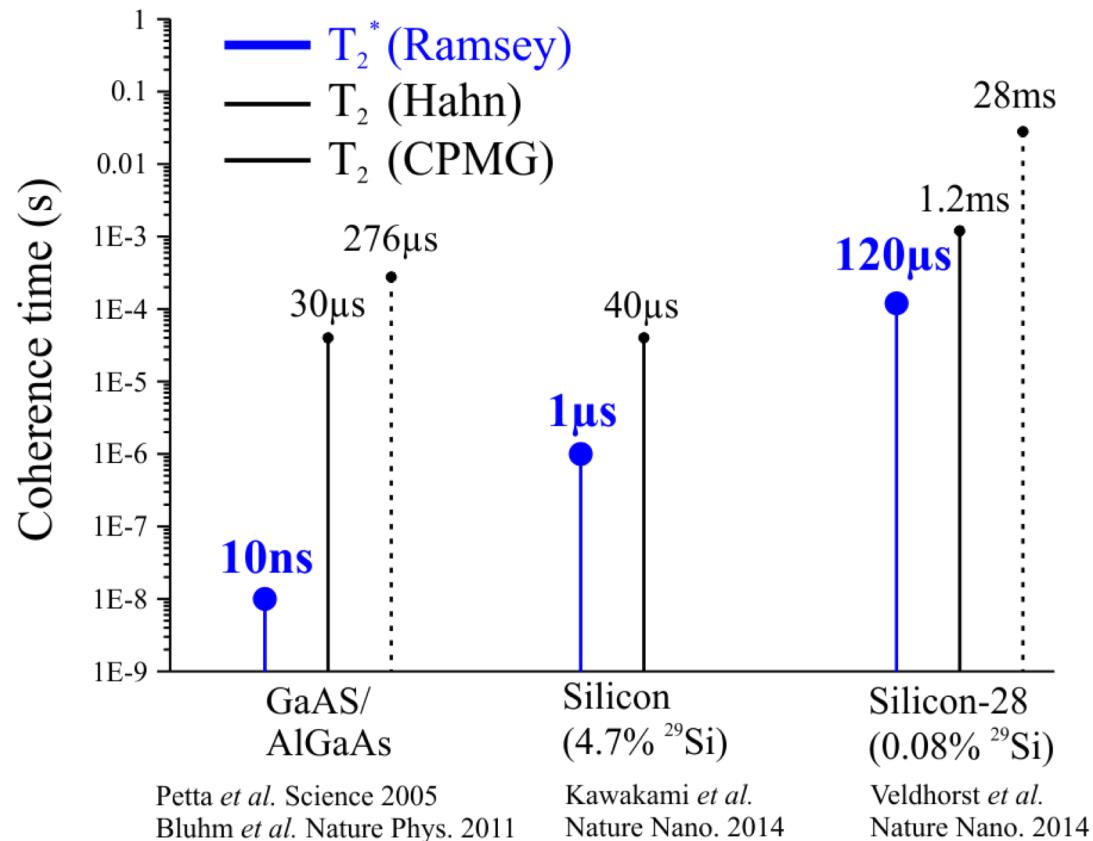
F.H. Koppens, C. Buizert, K.J. Tielrooij, I.T. Vink, K.C. Nowack, T. Meunier, L.P. Kouwenhoven, L.M.K. Vandersypen. "Driven coherent oscillations of a single electron spin in a quantum dot." *Nature* 17, 766-771 (2006).

Silicon (^{28}Si)



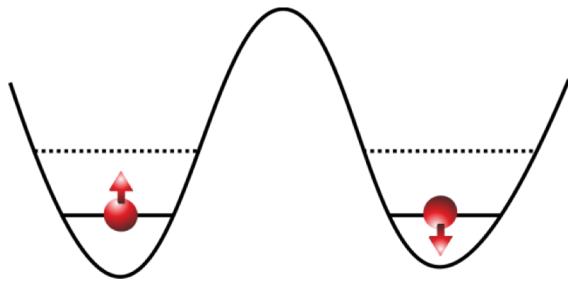
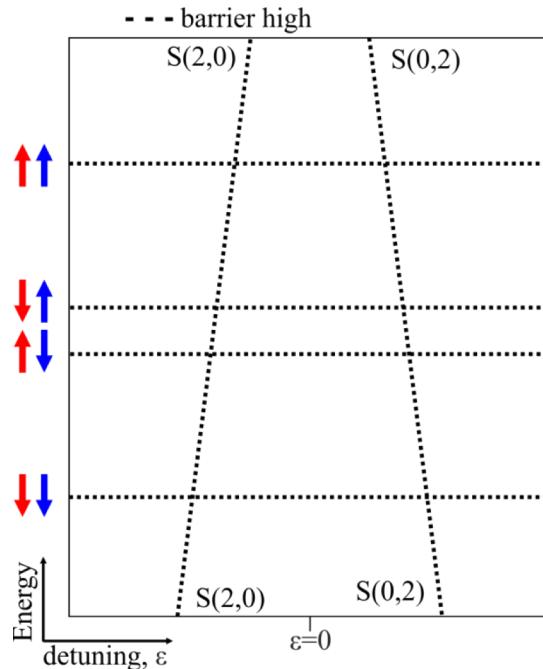
$$H_{RF} \sim \sum A_i(t) \cos(\omega_i t) \sigma_{xi}$$

M. Veldhorst, J.C.C. Hwang, C.H. Yang, A.W. Leenstra, B. de Ronde, J.P. Dehollain, J.T. Muhonen, F.E. Hudson, K.M. Itoh, A. Morello, A.S. Dzurak. "An addressable quantum dot qubit with fault-tolerant control-fidelity." Nature Nanotechnology 9, 981-985 (2014).



Interaction off

2 Qubits



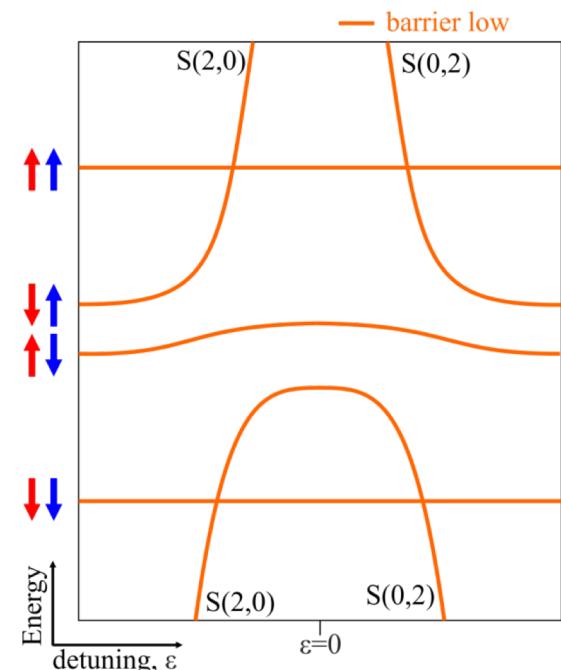
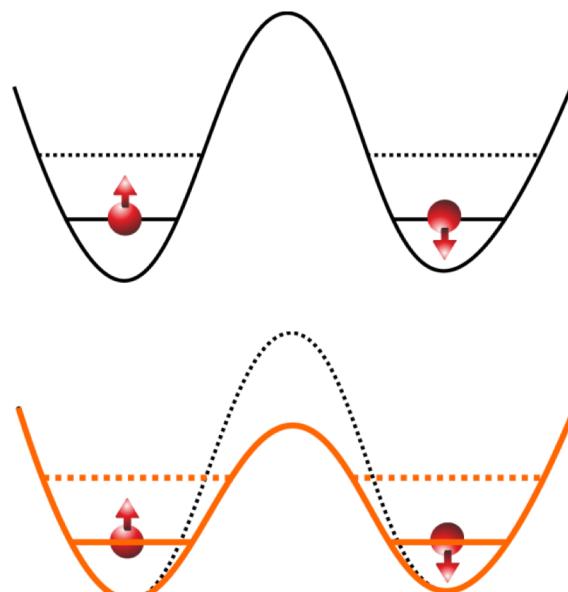
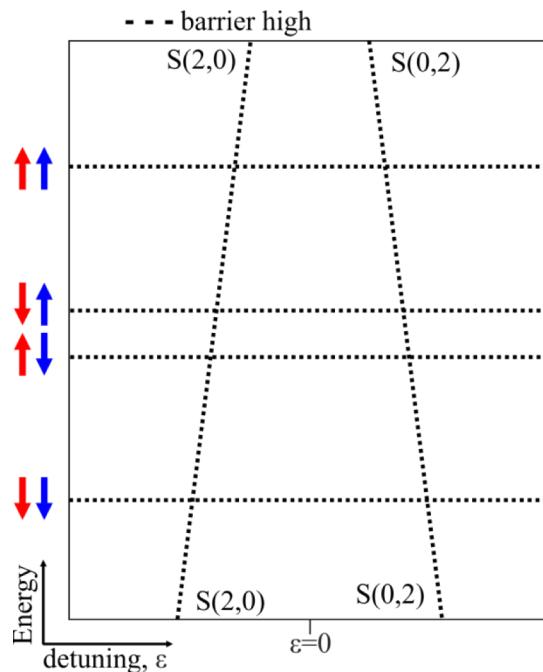
$$H_J \sim \sum J_{ij}(t) \sigma_i \cdot \sigma_j$$

D. Loss and D.P. DiVincenzo
"Quantum computation with quantum dots."
Phys. Rev. A 57, 120 (1998).

Interaction off

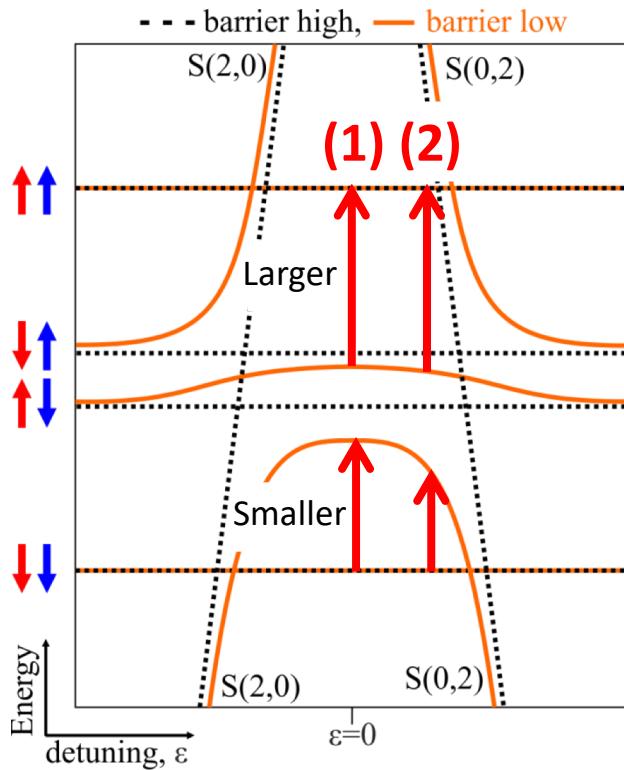
2 Qubits

Interaction on

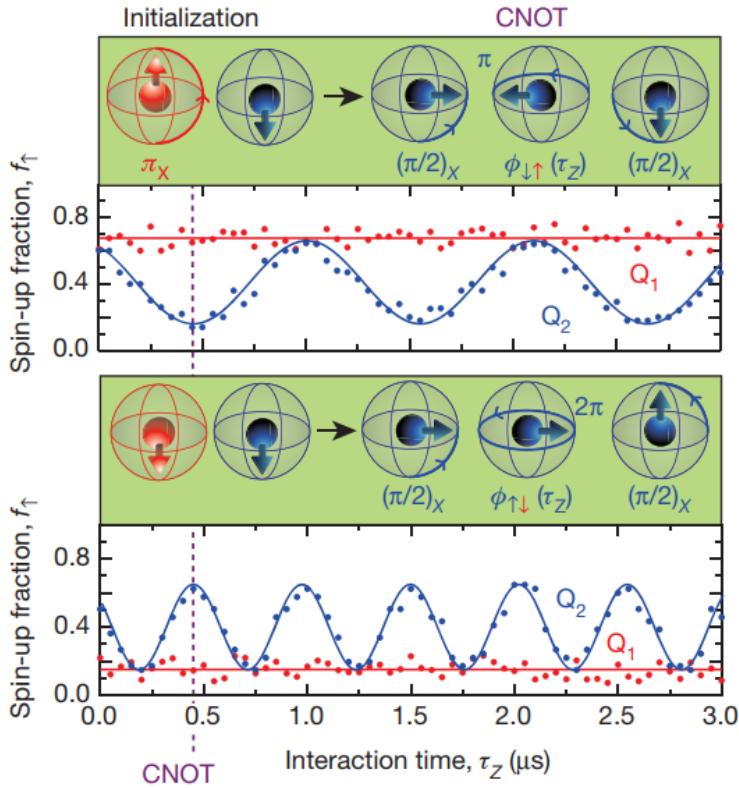
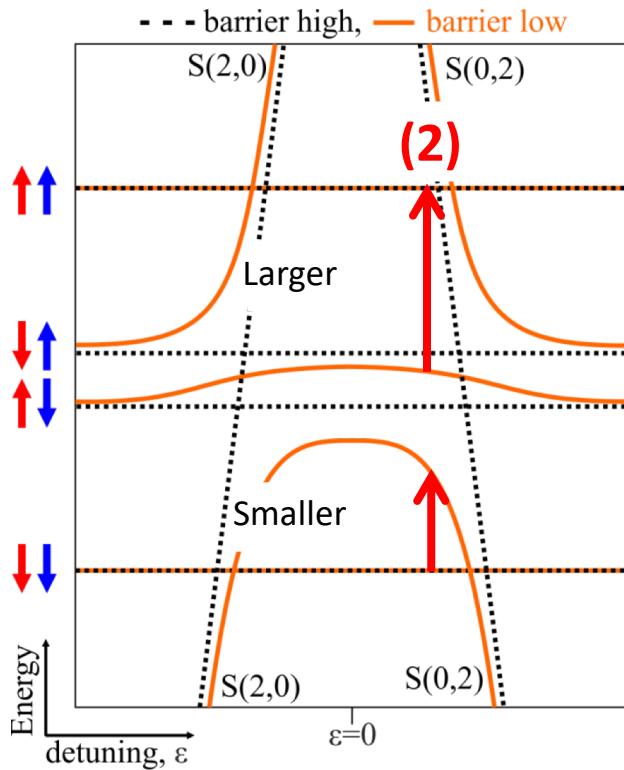


$$H_J \sim \sum J_{ij}(t) \sigma_i \cdot \sigma_j$$

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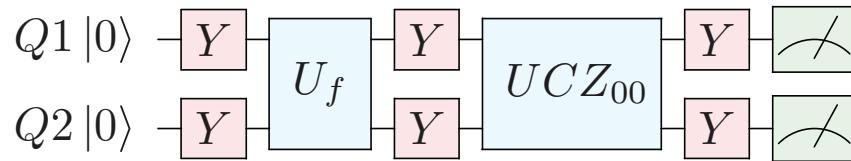


- (1) Tune tunnel coupling
(2) Control detuning ϵ

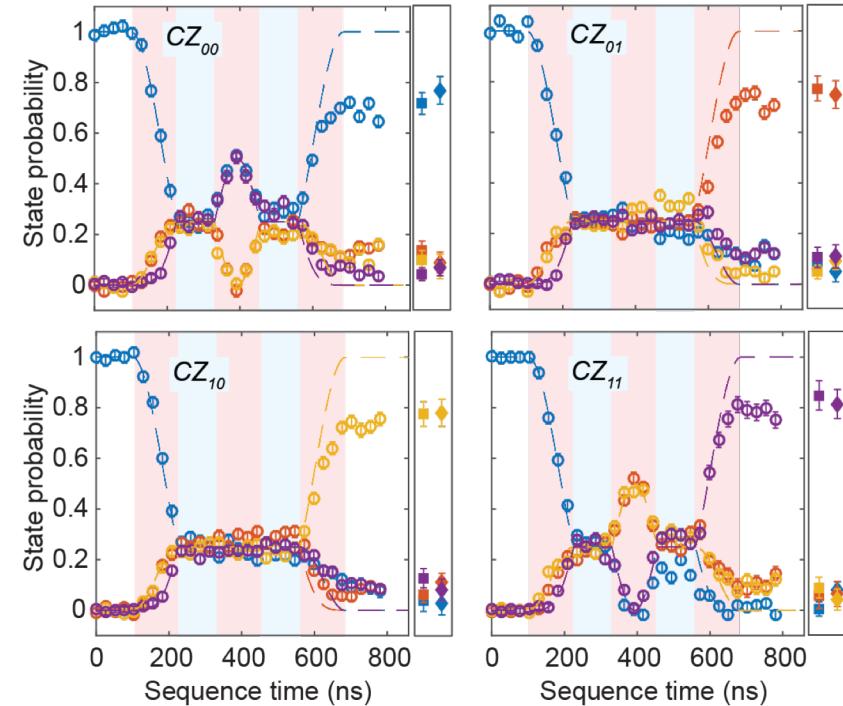


M. Veldhorst, C.H. Yang, J.C.C. Hwang, W. Huang, J.P. Dehollain, J.T. Muhonen, S. Simmons, A. Laucht, F.E. Hudson, K.M. Itoh, A. Morello, A.S. Dzurak. "A two-qubit logic gate in silicon." *Nature* 526, 410-414 (2015).

A programmable two-qubit device in silicon

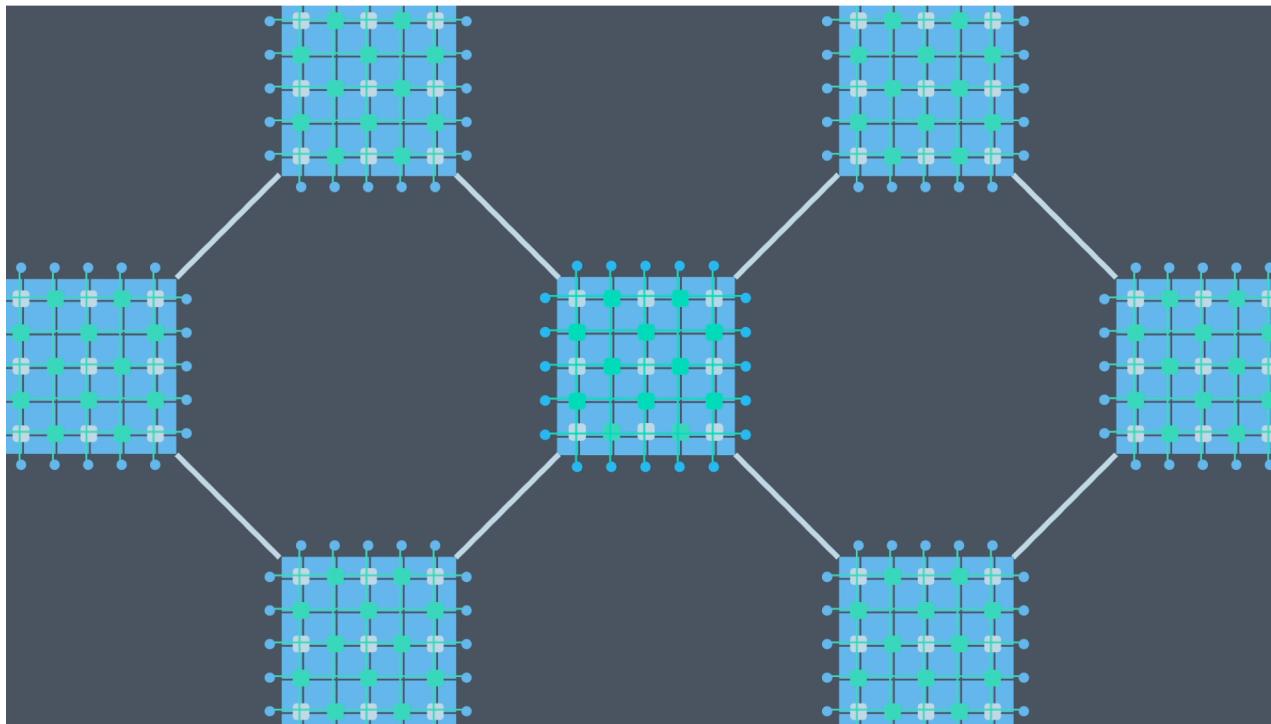


Grover and Deutsch-Jozsa algorithms
successfully implemented



T.F. Watson, S.G.J. Philips, E. Kawakami, D.R. Ward, P. Scarlino, M. Veldhorst, D.E. Savage, M.G. Lagally, M. Friesen, S.N. Coppersmith, M.A. Eriksson, L.M.K. Vandersypen. "A programmable two-qubit quantum processor in silicon." *Nature* 555, 633-637 (2018).

Interfacing spin qubits with quantum dots



L.M.K. Vandersypen, H. Bluhm, J.S. Clarke, A.S. Dzurak, R. Ishihara, A. Morello, D.J. Reilly, L.R. Schreiber, M. Veldhorst. "Interfacing spin qubits in quantum dots and donors – hot dense, and coherent." *npj Quantum Information* 3, 34 (2017).