# Quantum Dots and Spin Based Quantum Computing

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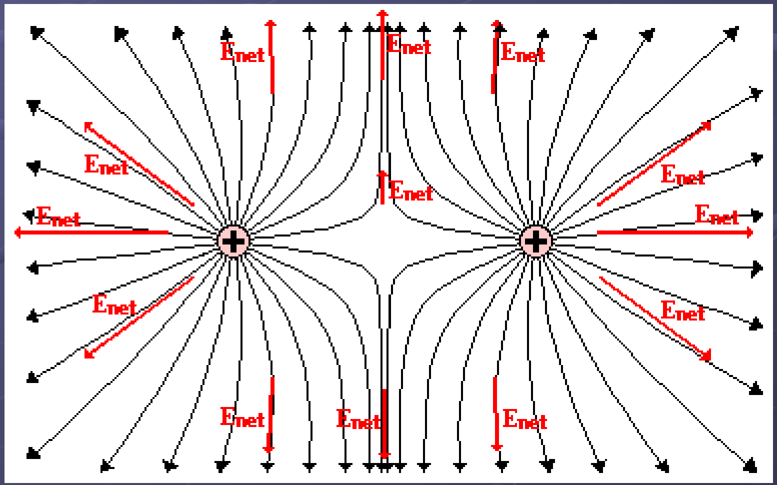
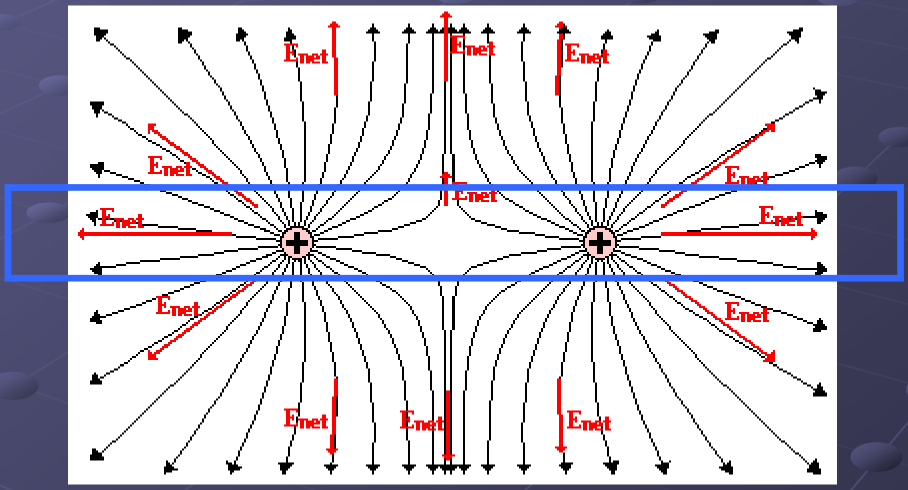
# Electrostatic Traps

- Say we want to trap an electron
- Everyone knows you can't make an electrostatic trap. Laplace's equation prevents it



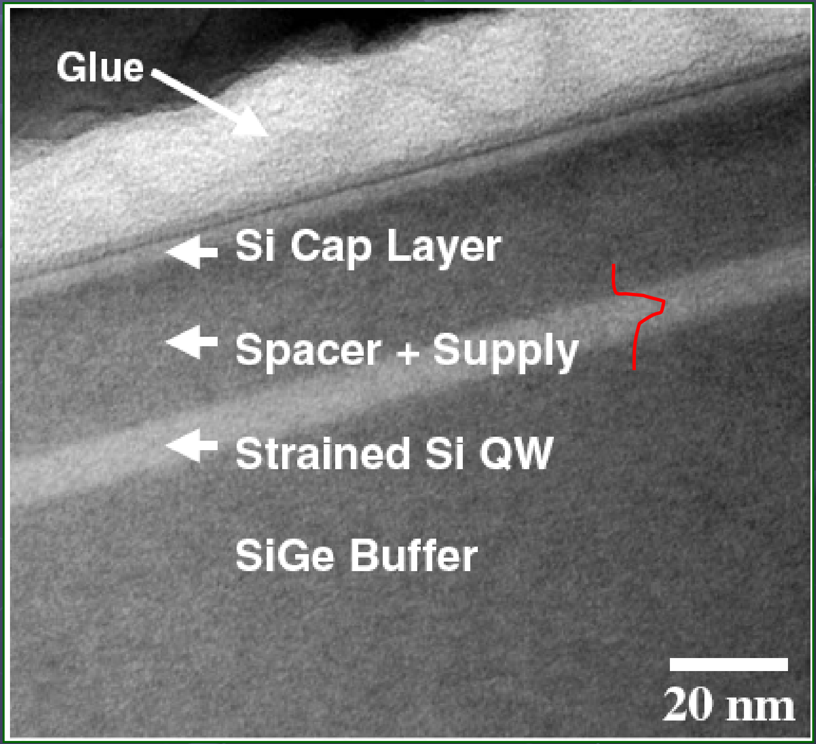
# Solutions

- First involves oscillating sign of charges
- Or else… just restrict electron to 2D!
- Surely there is no such structure in nature



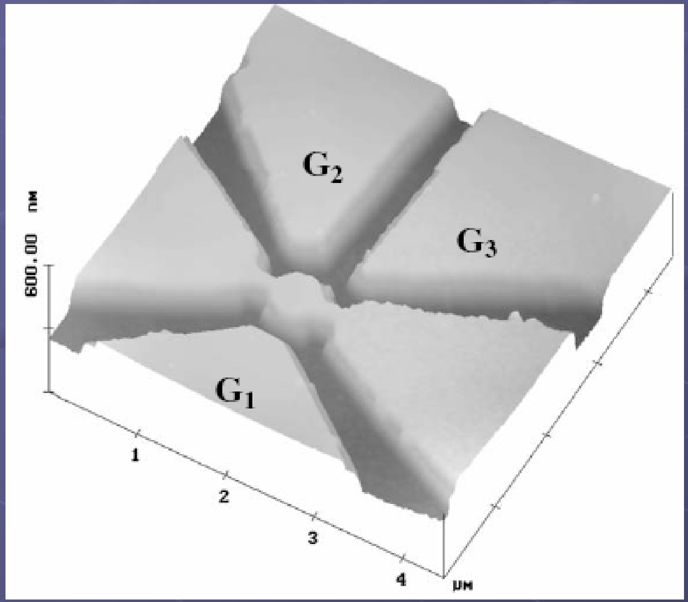
# 2DEG

- 2 Dimensional Electron Gas (2DEG)
  - By growing a thin Si layer on top of a SiGe substrate, one can make a 2D quantum well
  - The Ge strains the lattice, destroying the usual 6 fold degeneracy, so that vertical states have lower energy than horizontal ones.

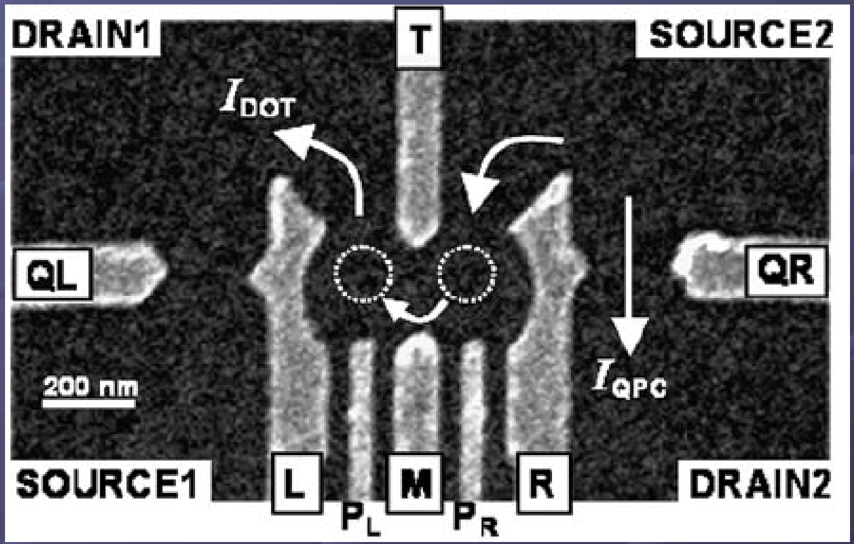


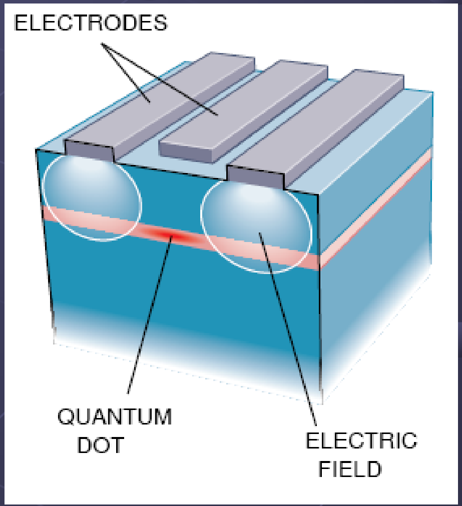
# Making a Quantum Dot

Etching




Top-gates



# Quantum Dots and Spin

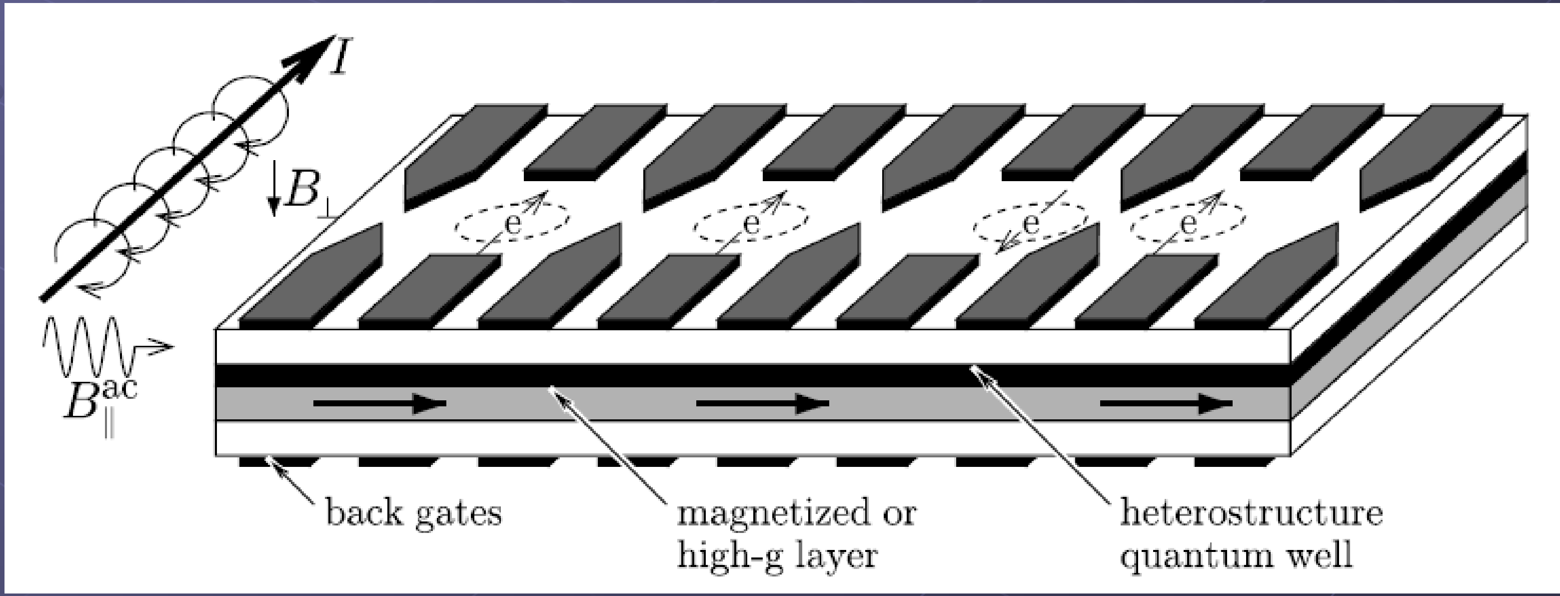
- Because individual quantum states are accessible in a quantum dot, we can trap individual elections
- The number of electrons can be controlled with bias electrodes
- The spin of each electron is available to us
- Spin is hard to measure – measure charge instead

# Two Proposals

- The classic proposal by Loss and DiVincenzo involves using individual electron spins.
- Another proposal by Levy calls on using a two spin system. The |01>_p state is |0>_L, and |10>_p is |1>_L.

# Single Qubit Rotations: L&D

- AC magnetic fields can cause spin flips
- Electrons can be transported to a high-g substrate where the magnetic interaction is stronger



# Entanglement: L&D

- Spin-Spin Exchange Interaction

$$H_S(t) = J(t)\,\mathbf{S}_1 \cdot \mathbf{S}_2$$

Although |11> and |00> are unaffected by this perturbation, |10> and |01> are not eigenstates. These states are rotated. After a time pi*hbar/2*J, we have performed half of a swap operation. This is a known universal quantum gate

$$\left(\frac{1}{2}\begin{pmatrix} 2 & 0 & 0 & 0 \\ 0 & 1+i & 1-i & 0 \\ 0 & 1-i & 1+i & 0 \\ 0 & 0 & 0 & 2 \end{pmatrix}\right)\hat{}\,2 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

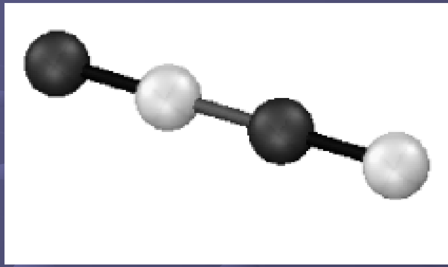
J is increased by decreasing the potential barrier separating the dots

# Single Qubit Rotations: Levy

- The two qubit rotation in L&D becomes a one qubit ‘x’ rotation for Levy!  But |01>_p+|10>_p is not rotated…
- If the two QDs have different values of g, a magnetic field will cause a splitting between the up state of the first QD and the second.  This allows ‘z’ rotations, and so together with the first arbitrary one qubit rotations.

# Entanglement: Levy

- Place two qubits side by side, so that the center two are coupled
- This coupling is sufficient to generate a nAND or cNOT gate



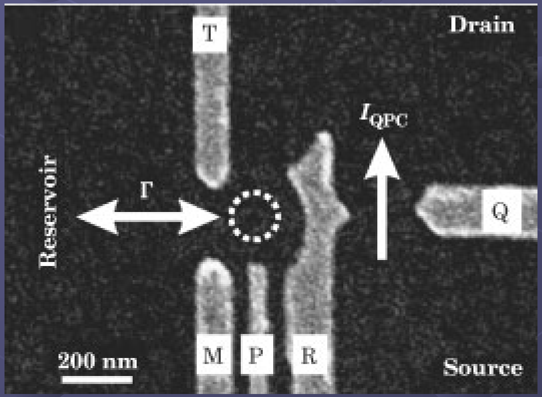
$$\hat{U}_{\text{nAND}} \equiv \hat{U}_0(\pi/2)\hat{e}_{23}(\pi/2)\hat{U}_0(\pi)\hat{e}_{23}(\pi/2).$$

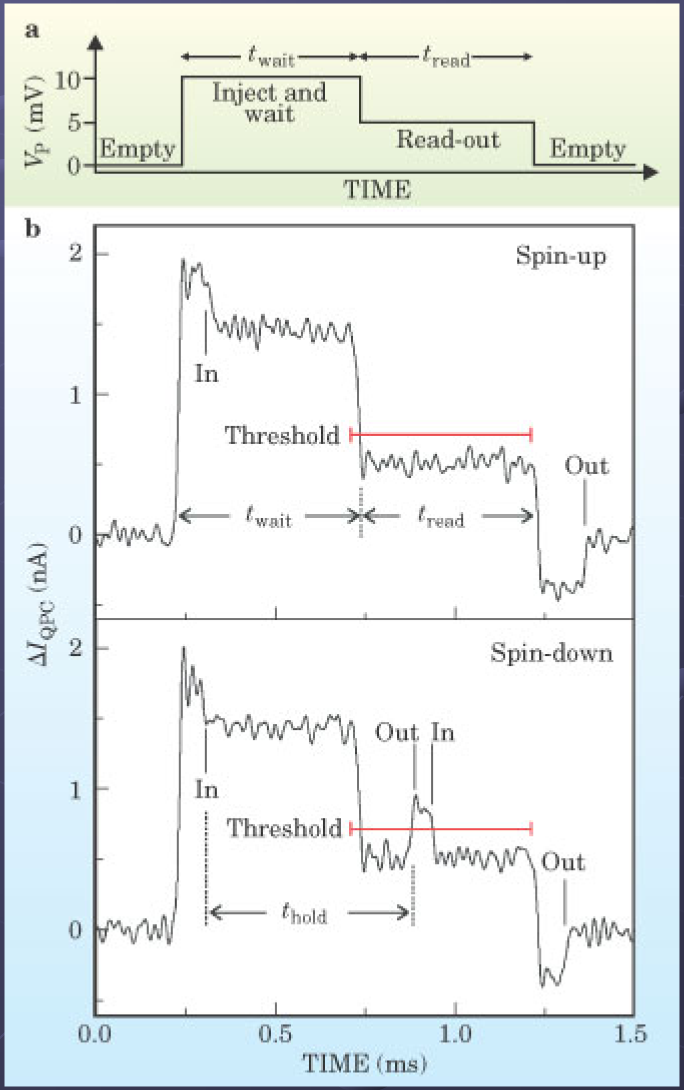
$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$\hat{u}_{\text{cNOT}} = \hat{r}_2^y(-\pi/2)\hat{u}_{\text{nAND}}\hat{r}_2^y(\pi/2)$$

# Readout

- With Zeeman splitting and P bias, Kouwenhoven at Delft can make only the spin up state have E>E_f



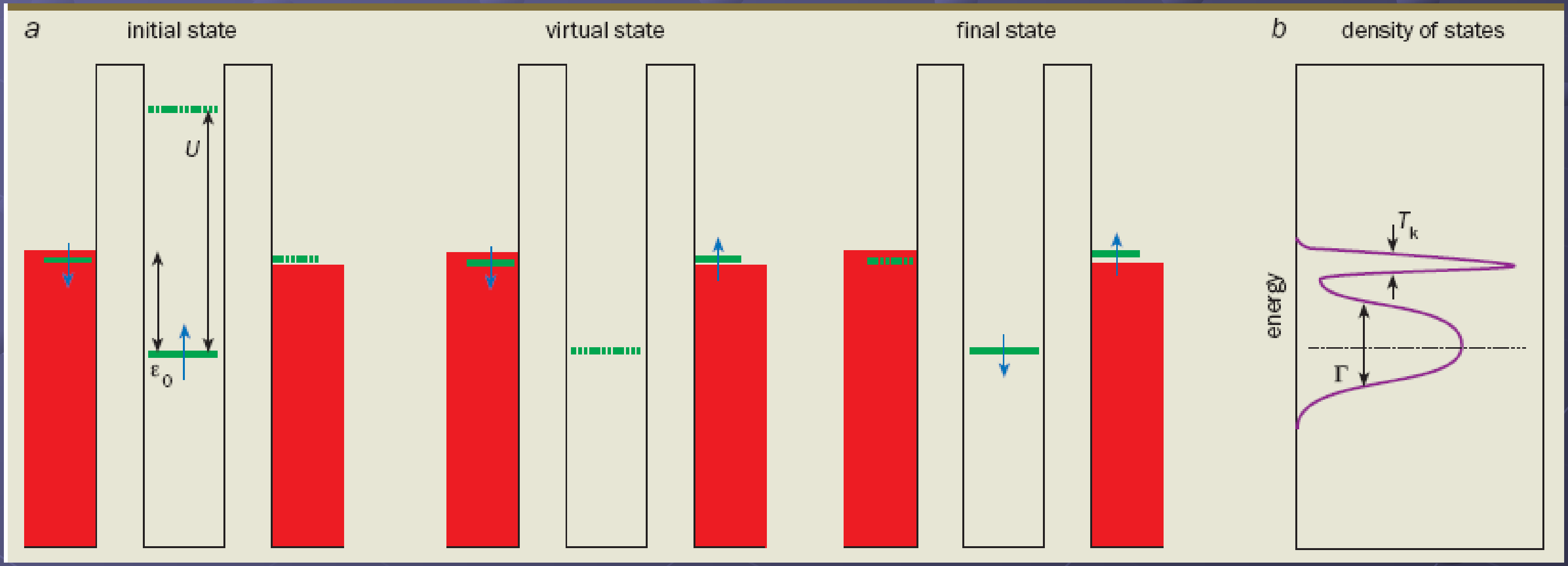



# Decoherence

- T_1 is the relaxation time: time scale it takes an up spin to swap to a down spin due to interaction to nuclear magnetic moments. >1ms
- T_2 is the coherence time: time scale a quantum superposition survives. T_2<<T_1 frequently. .1-1ms in Si, because the dominant Si isotope has spin 0

# Scalability

- Its easy to build many quantum dots
- Characterizing each
- How do you entangle distant QDs? Kondo effect and RKKY?



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