Amazing feats with artificial atoms: single spin readout and fast initialization

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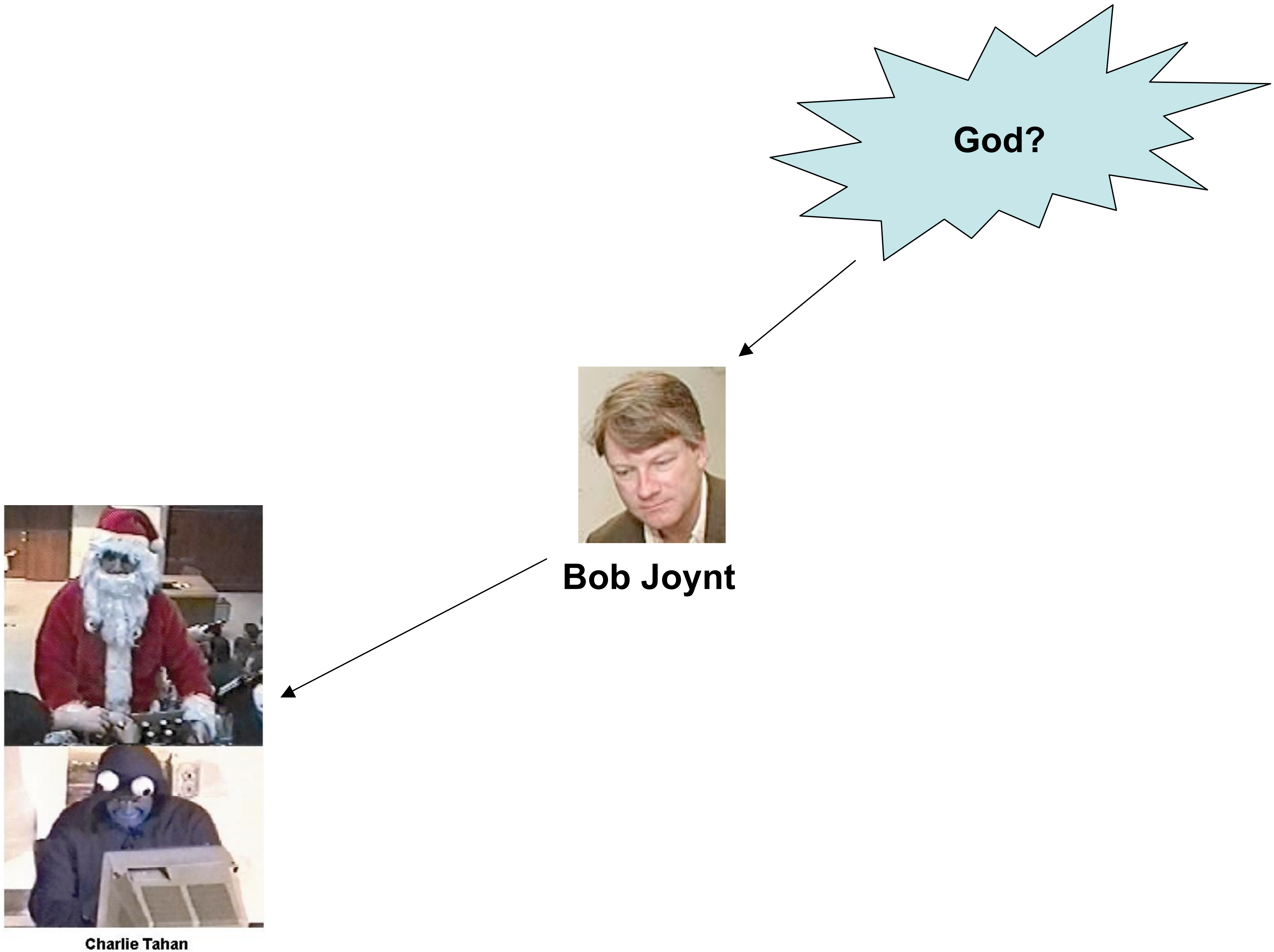
Charles Tahan

Physics Dept., University of Wisconsin-Madison

UW-Madison Atomic Seminar,
12:05pm, Sept. 30, 2003

ARDA


God?
Bob Joynt
Charlie Tahan

UW-Madison Solid-State Quantum Computing

Mark Friesen (Materials Science and Physics)
Mark Eriksson (Physics)
Robert Joynt (Physics)

Robert Blick (ECE)
Sue Coppersmith (Physics)
Max Lagally (Materials Science)
Dan van der Weide (ECE)
Don Savage (Materials Science)
Levente Klein (Physics)
Shaolin Liao (Materials Science)
Keith Slinker (Physics)
Charles Tahan (Physics)
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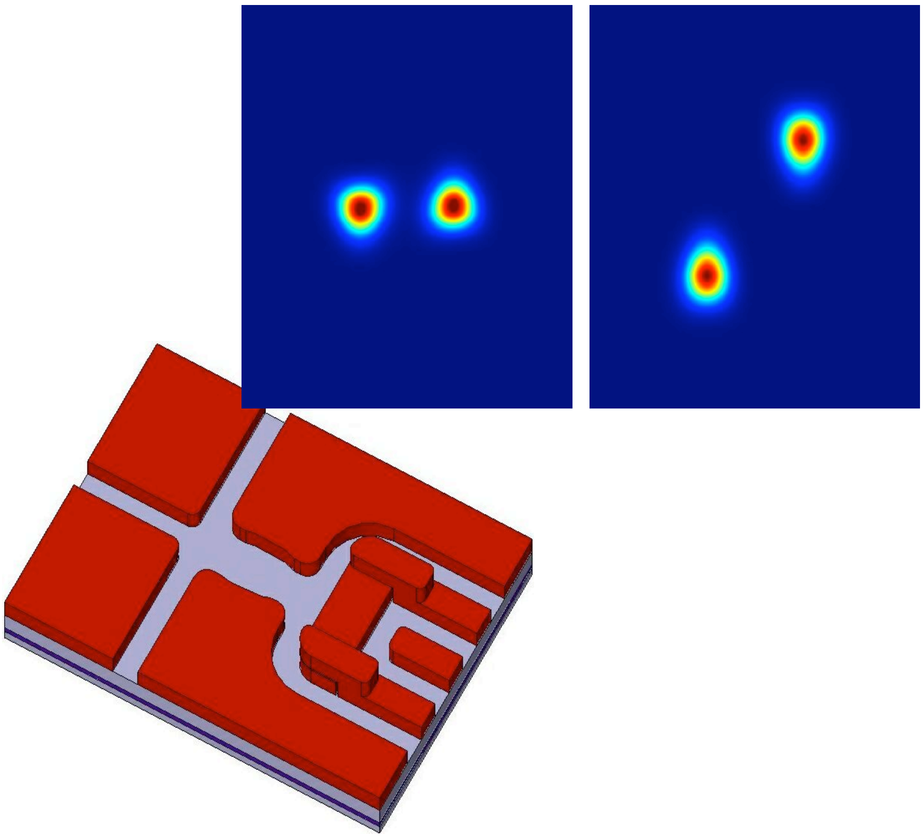
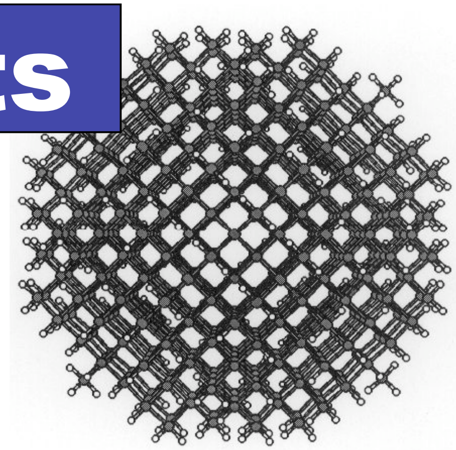
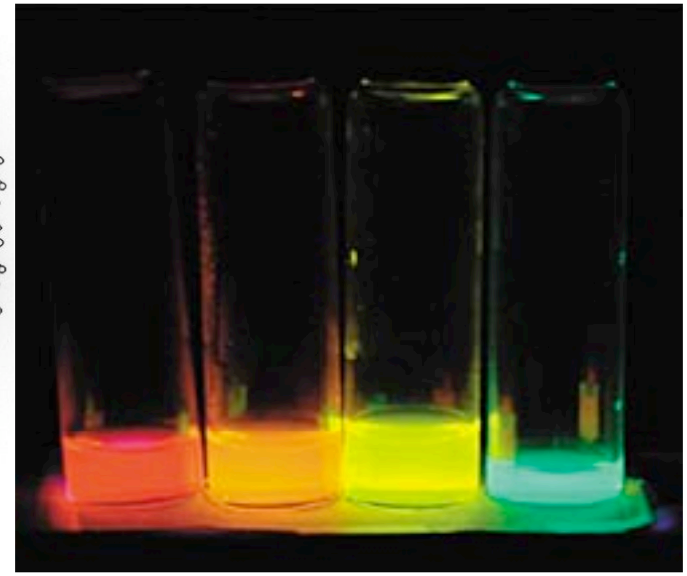
Kristin Morgenstern (Physics)



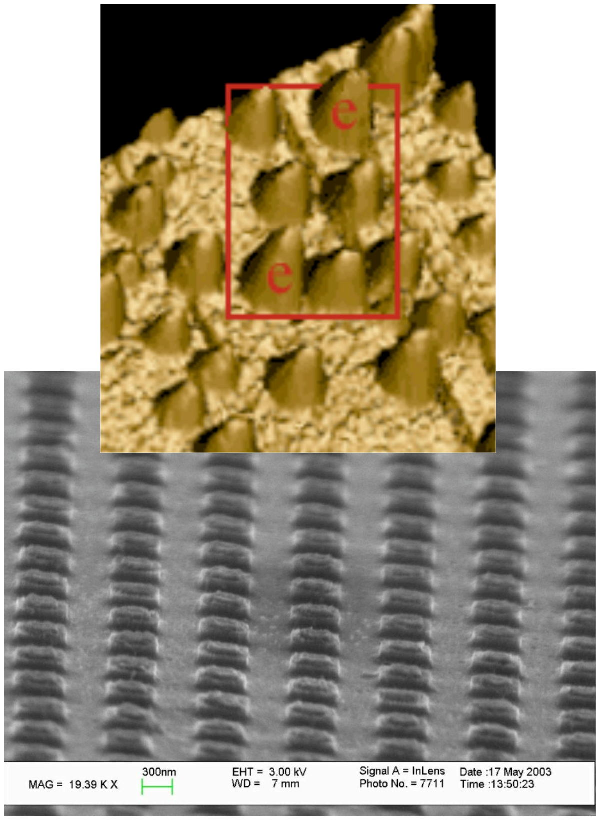
Quantum dots



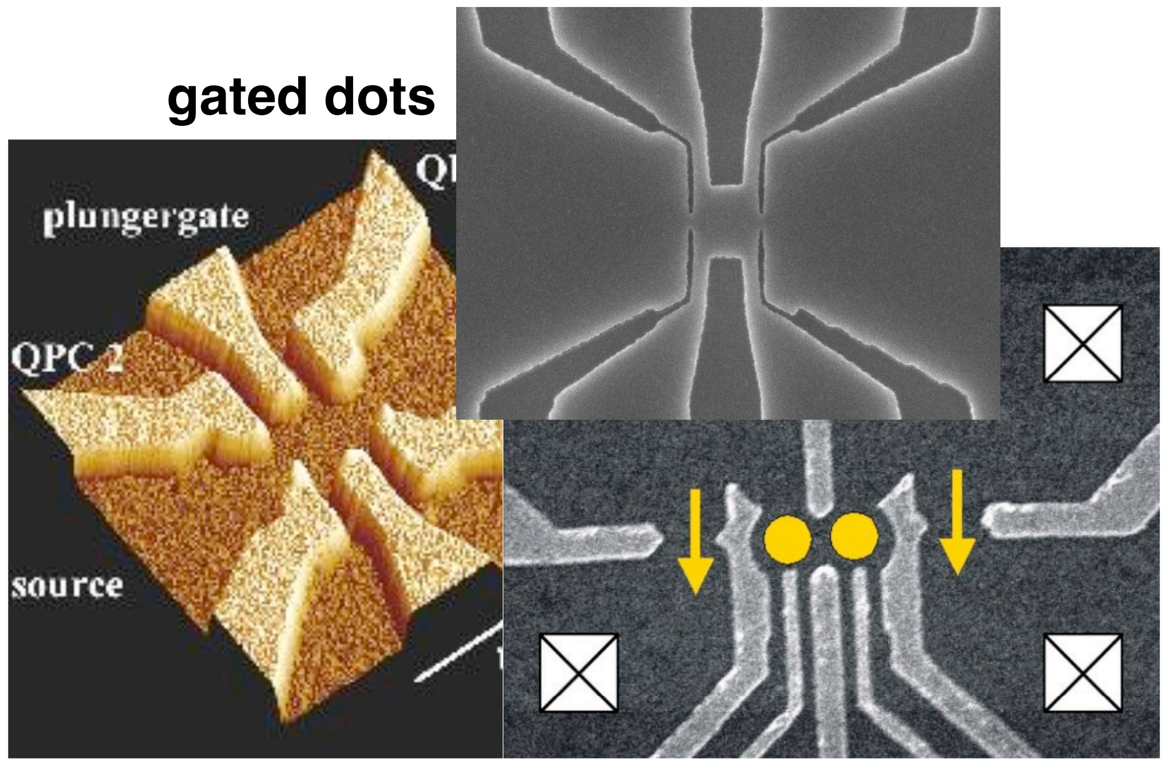
nanocrystals



structural dots



gated dots



Motivation

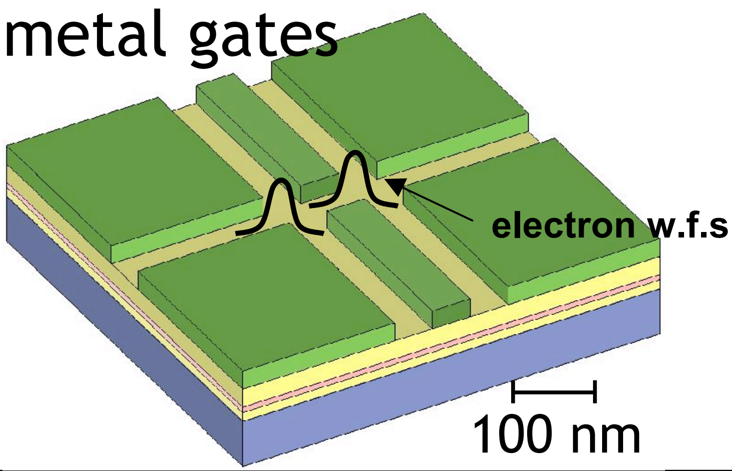
Goal: Measure the state of a single electron spin

Applications: Quantum dot quantum computing, spintronics, fundamentals of Q.M. (decoherence, quantum measurement), and
because it's there

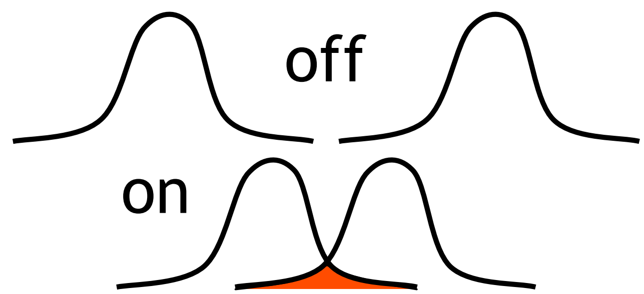
$$\mathbf{m}_e = 9.3\times 10^{-24}\ \mathrm{J/T}$$
$$\mathbf{m}_{refrig} = 0.1\ \mathrm{J/T}$$

Wisconsin-QDQC

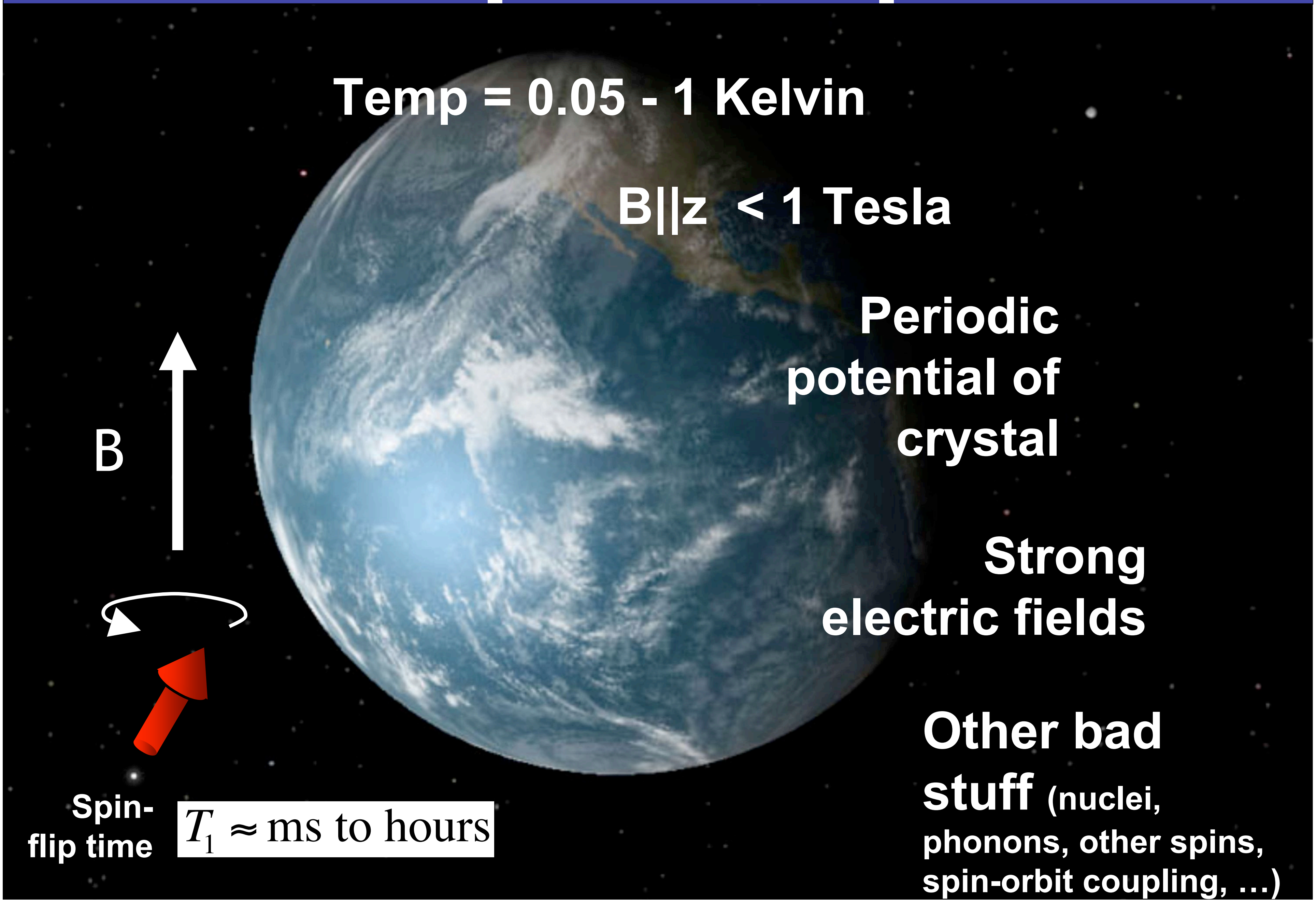
Trap and manipulate electrons via charged metal gates



Overlap wavefunctions to entangle qubits

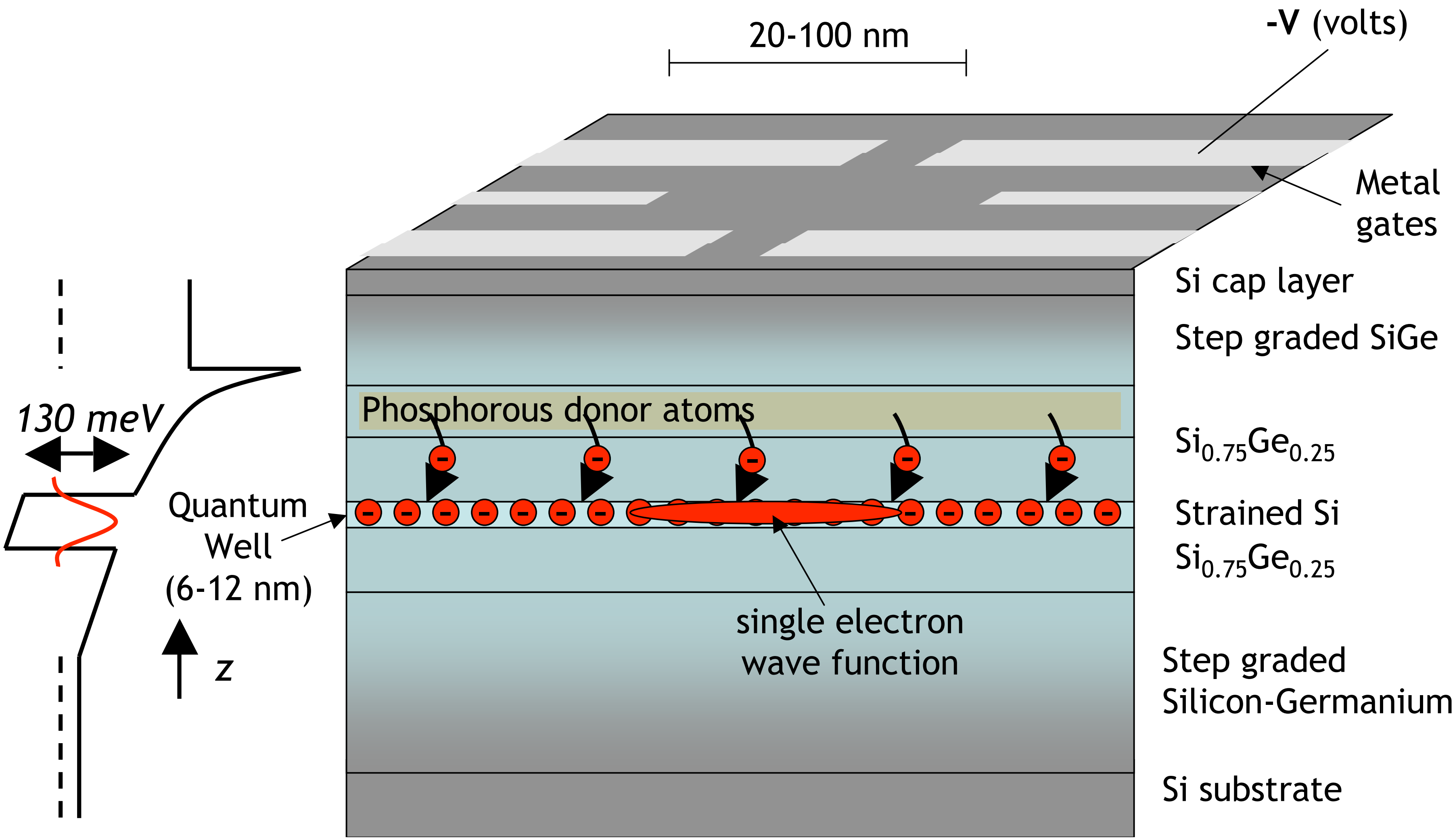


World of a quantum spin-device



A quantum well quantum dot

Goal: **a single electron tunably confined vertically and horizontally in a semiconductor nanostructure**



1/f noise

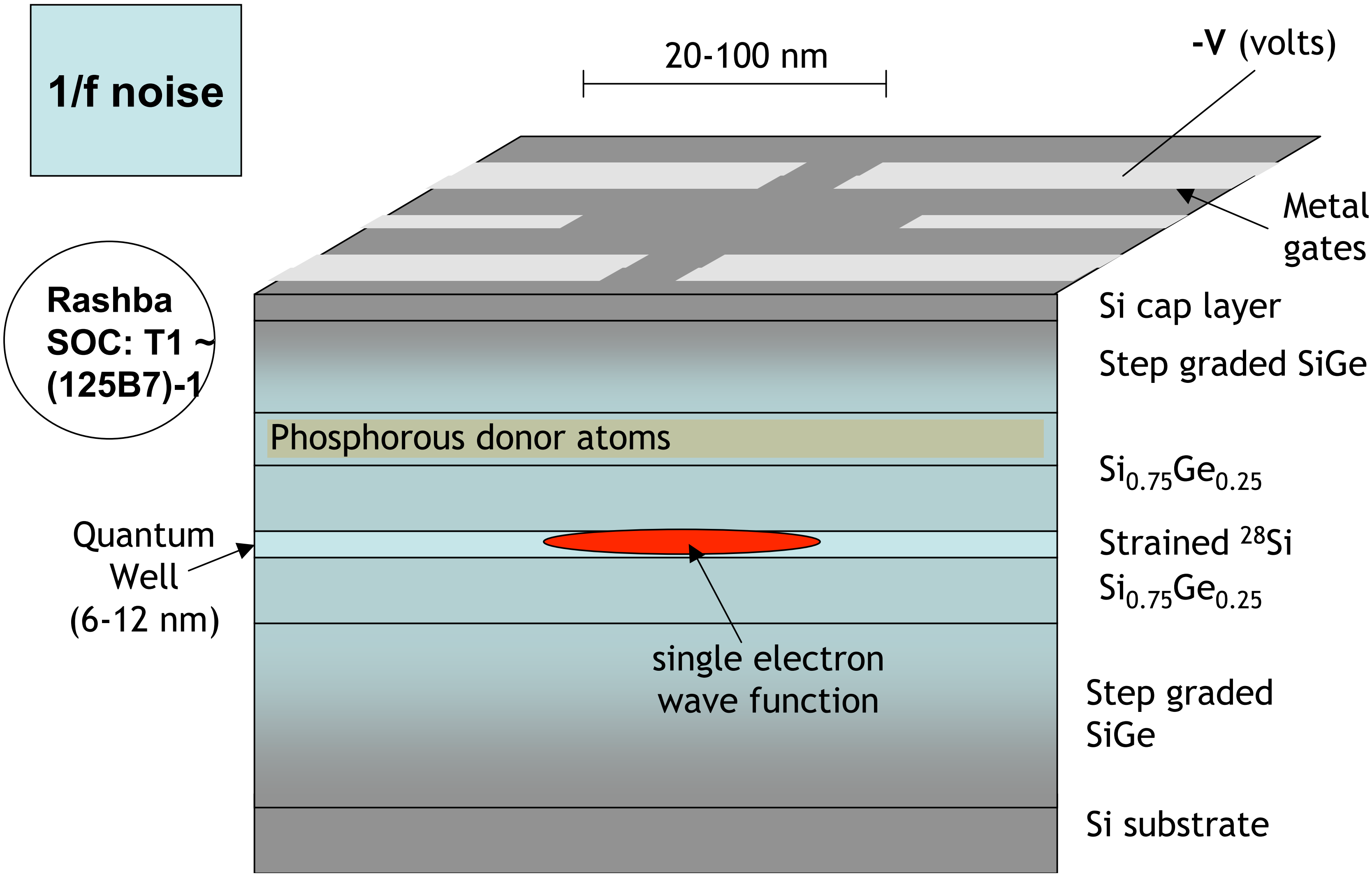
Nuclear spin impurities in Ge

Donor free zone

Qubit-qubit magnetic dipole coupling

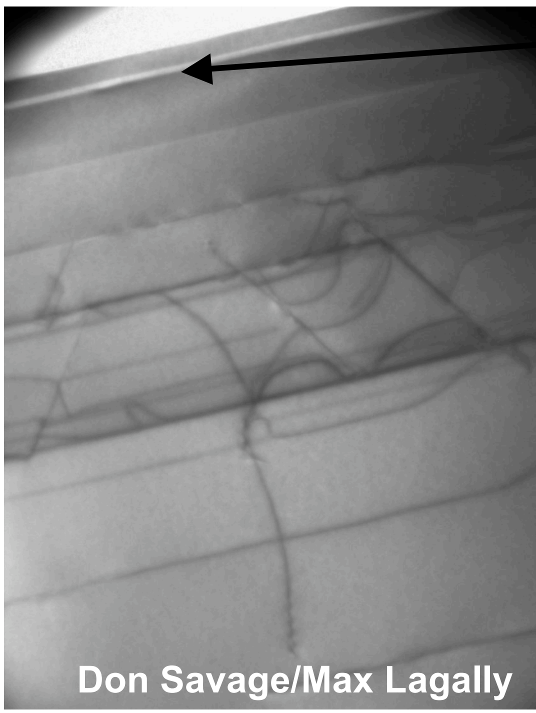
Nuclear ^{29}Si spectral diffusion

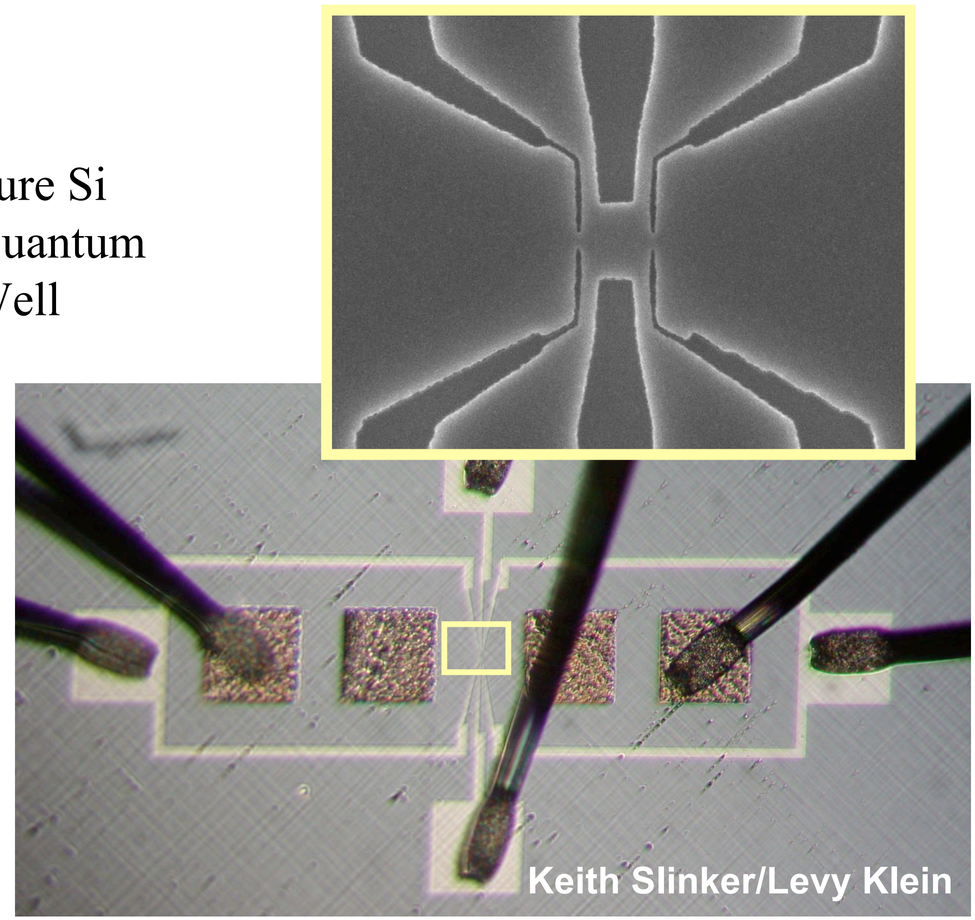
Gate paramagnetism



...in reality

Heterostructure growth and lithography at Wisconsin.

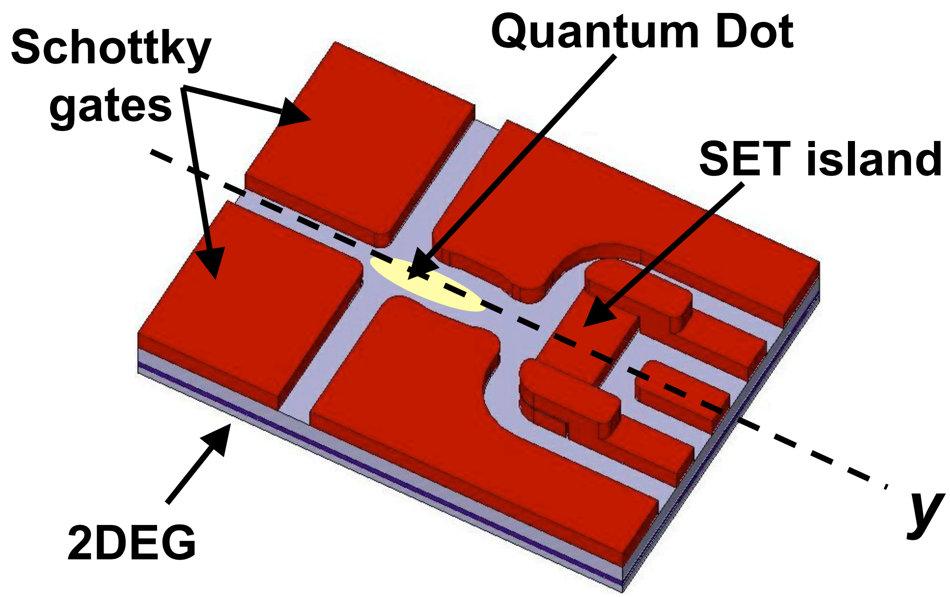




Device design for QD readout

"Motional spin-charge transduction"

- Spin-dependent charge motion
- via Microwave pumping
- with SET detection
- Automatic spin polarization

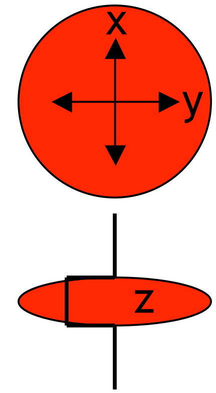


History…spin-charge transduction Loss/Divincenzo, Kane, …

Fast readout and initialization is important for quantum error correction

Electron QD wave functions

single electron
wave function



No B-field: ***SHO***

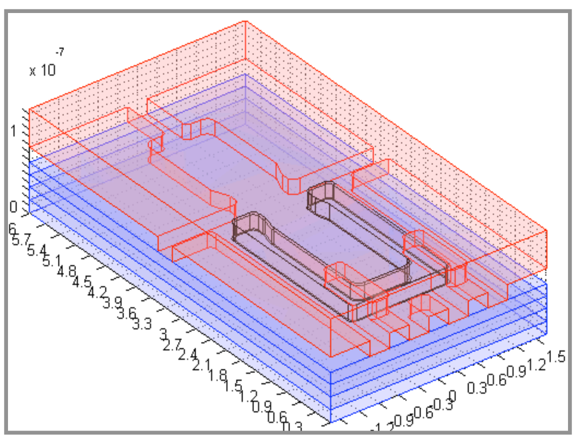
$$E_n(x,y) = \left(n + \frac{1}{2}\right)\hbar\omega_{(x,y)}$$

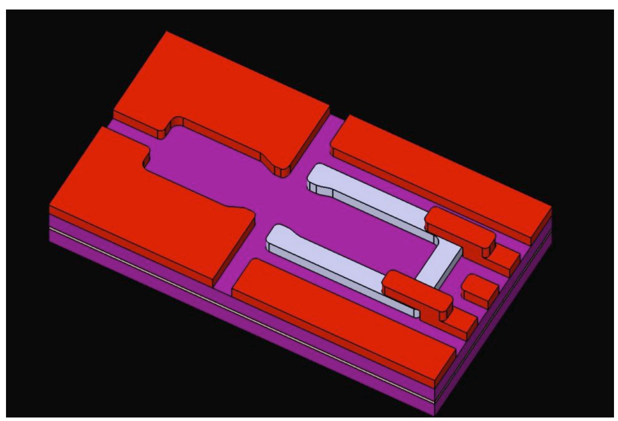
$$F_n(x) = \left(\frac{m\omega}{\pi\hbar}\right)^{1/4} \frac{(-i)^n}{\sqrt{n!(\hbar\omega)^n}} (a_+)^n e^{-\frac{m\omega}{2\hbar}x^2} \qquad a_\pm = \frac{1}{\sqrt{2m}}\left(\frac{\hbar}{i}\frac{d}{dx} \pm im\omega x\right)$$

B || z and circular dots: ***Fock-Darwin***

$$H = \frac{1}{2m}(\mathbf{p} - e\mathbf{A})^2 + \frac{1}{2}m\omega_0{}^2 r^2 \qquad E_{n,l} = \hbar\sqrt{\omega_0{}^2 + \frac{\omega_c{}^2}{4}}(n+1) - \frac{1}{2}\hbar\omega_c l \qquad \omega_c = \frac{eB}{mc}$$

Modeling: ***Poisson ⟷ Schrodinger***





Energy scales

ground to first excited state splitting:

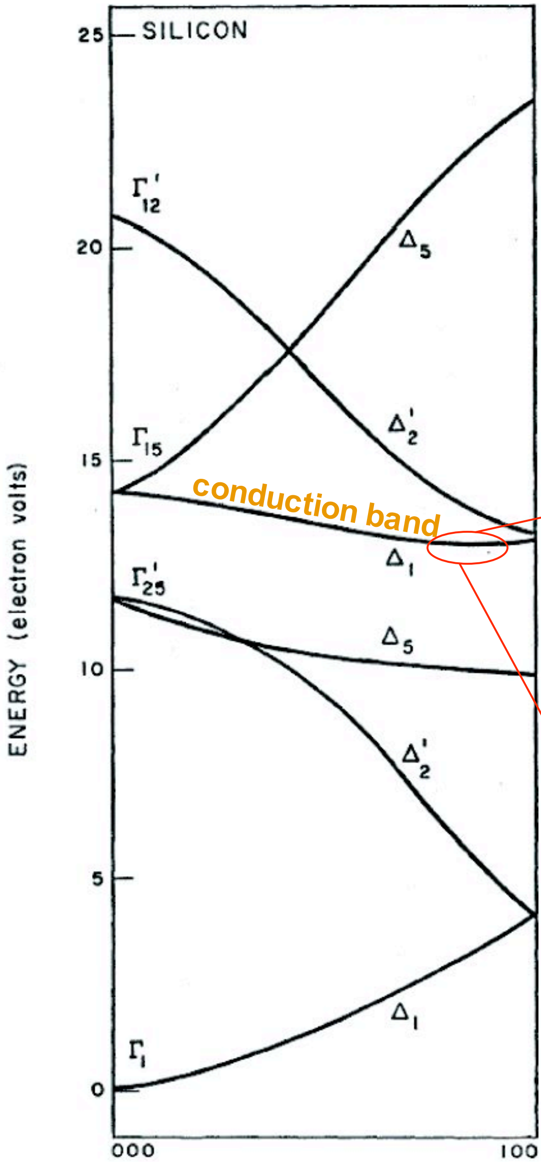
meV ~ microwaves

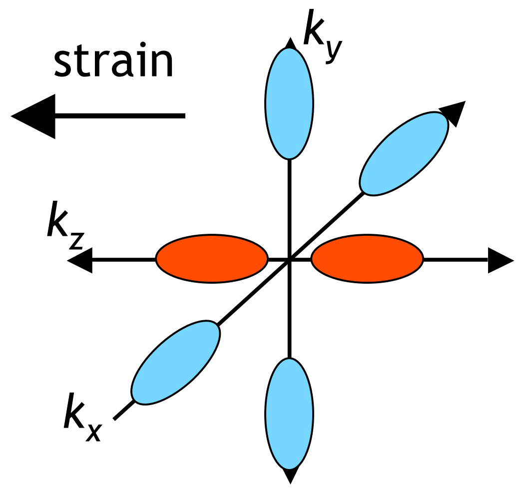
Zeeman splitting

guB = 0.12 meV*B

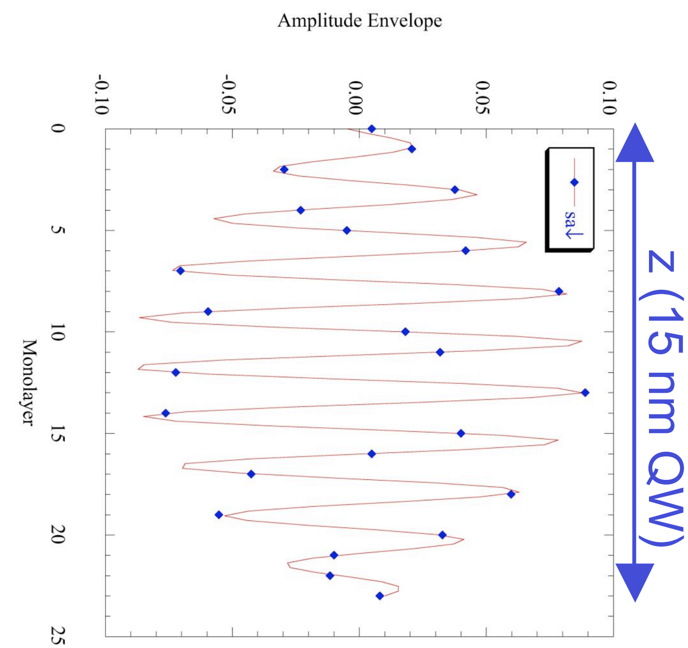
Details...

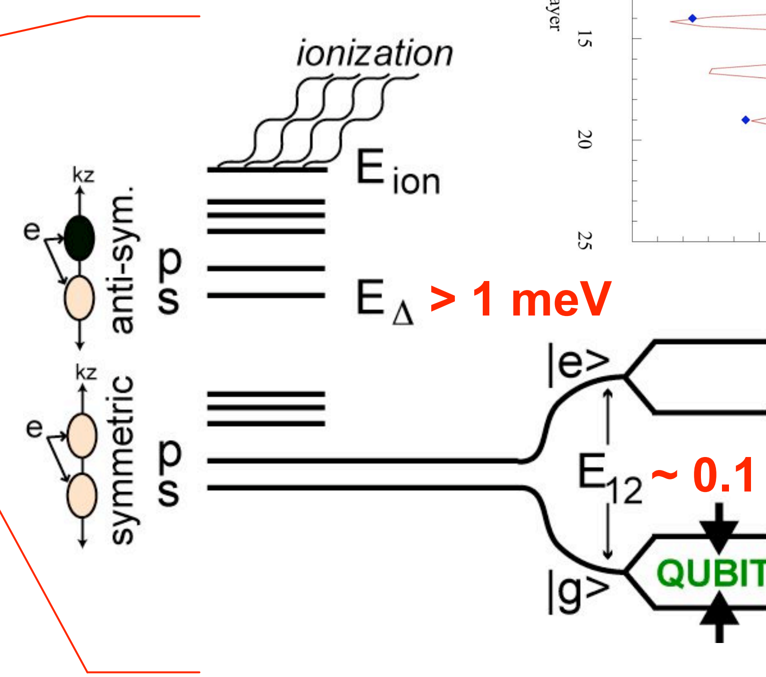
$$|\Psi\rangle = \text{Envelope} \times \text{Bloch}$$

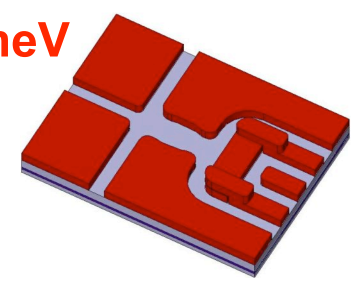




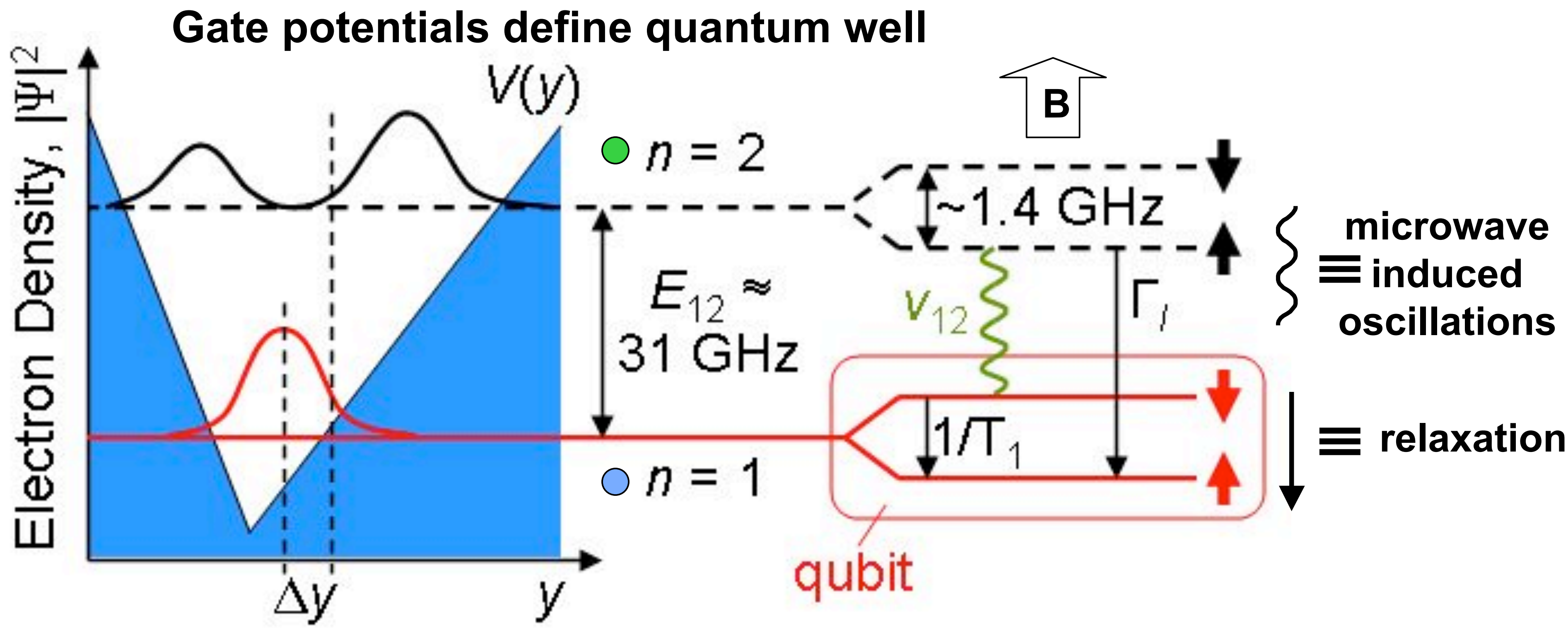
Bloch functions

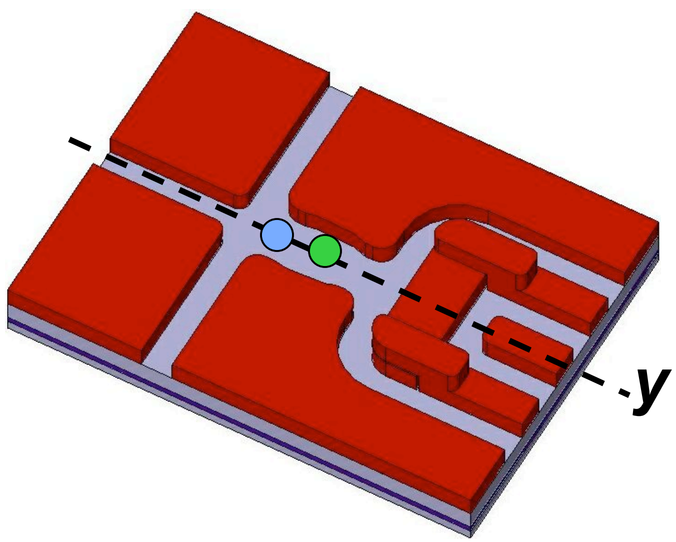






Charge movement in asymmetric well





• spin info to charge info via spin-dependent excitation

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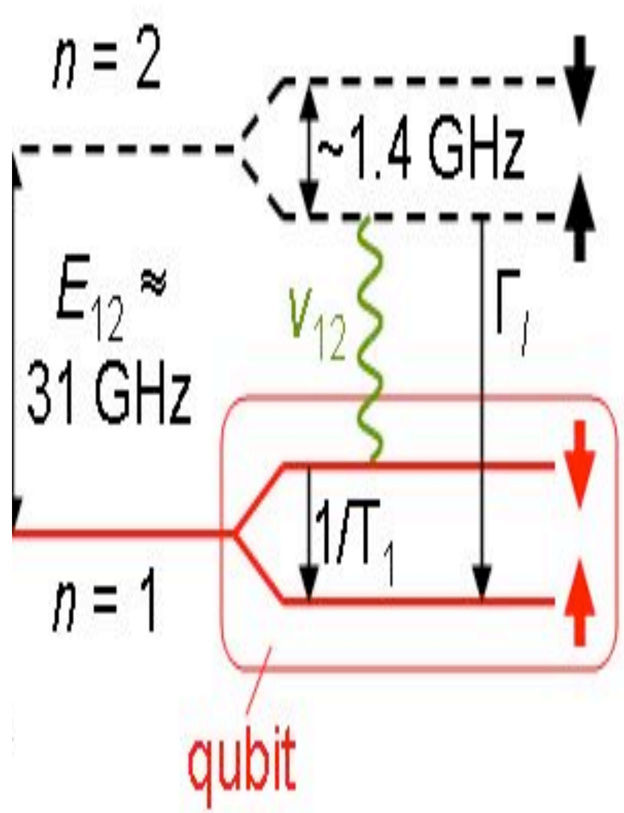
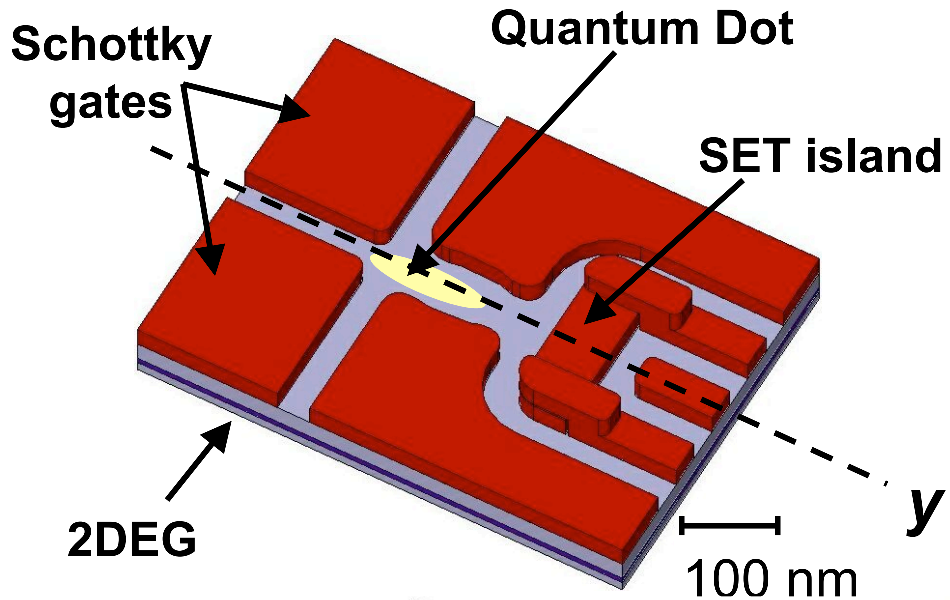
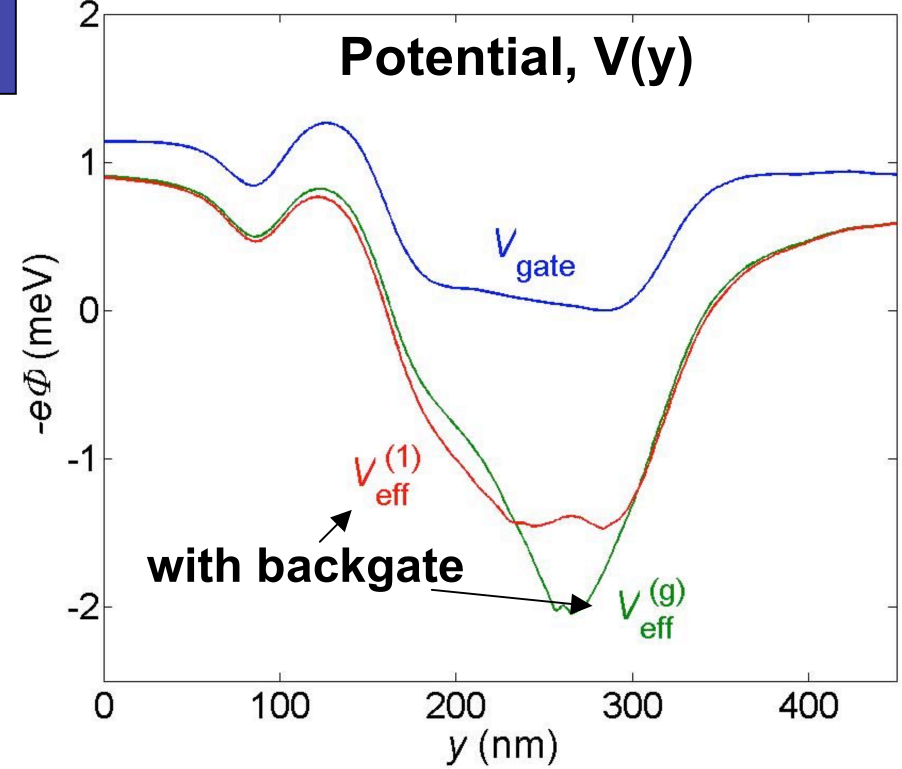
Will it work?
We need to calculate...

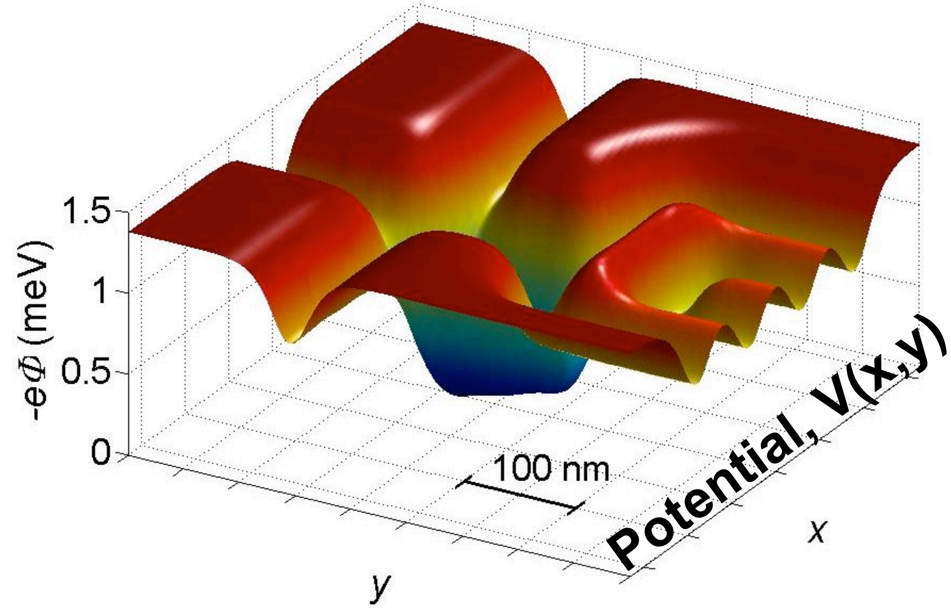
- Transition rates
  (is readout faster than initialization?)
- Wavefunctions
  (for the rates)
- Charge induced on SET
  (is the change detectable?)
- Quantum dynamics
  (complexities?)



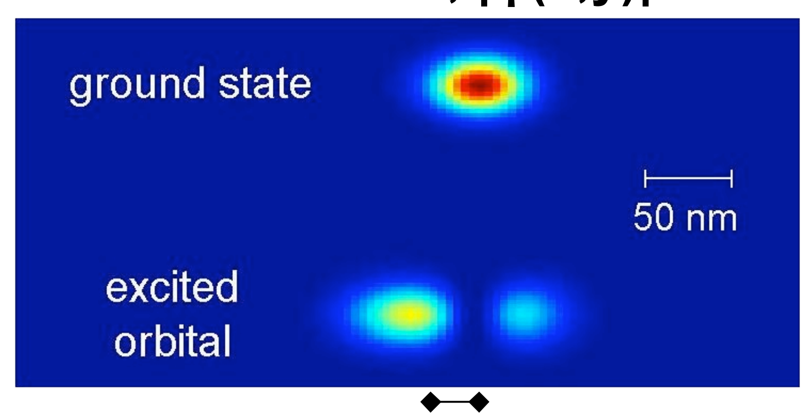
Device Simulation





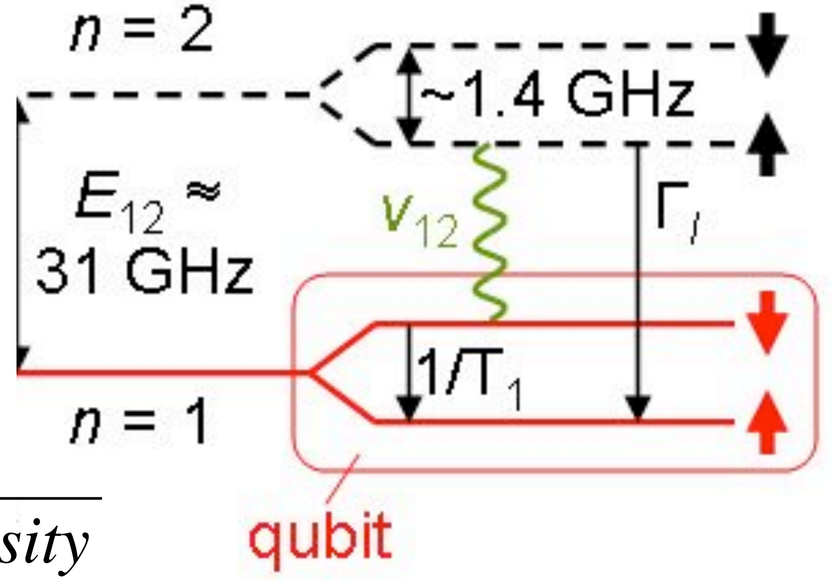


Wavefunction, |ψ(x,y)|^2



Charge movement ~ 10 nm

Optical transitions



$$|h\nu| = |\langle g\downarrow|V_{light}|e\uparrow\rangle|$$

electric dipole approx.

$$V_{light} = -\frac{e}{m}\frac{E_0}{\omega_{light}}\hat{\varepsilon}\cdot\mathbf{p} \qquad E_0 = \sqrt{\frac{2Intensity}{c\varepsilon_0\sqrt{\varepsilon_{Si}}}}$$

$$\nu_R \approx M\frac{e}{m(E_{eg}-g\mu_B B)}\sqrt{\frac{2}{c\varepsilon_0\sqrt{\varepsilon_{Si}}}}|\langle g\uparrow|\hat{\varepsilon}\cdot\mathbf{p}|e\uparrow\rangle|\sqrt{Intensity}$$

Spin-orbit mixing: $M = \frac{|\langle g\downarrow|\hat{\varepsilon}\cdot\mathbf{p}|e\uparrow\rangle|}{|\langle g\uparrow|\hat{\varepsilon}\cdot\mathbf{p}|e\uparrow\rangle|} < 1$

Spin-orbit coupling

$$M = \frac{\left|\langle g\downarrow|\hat{\varepsilon}\cdot\mathbf{p}|e\uparrow\rangle\right|}{\left|\langle g\uparrow|\hat{\varepsilon}\cdot\mathbf{p}|e\uparrow\rangle\right|} < 1$$

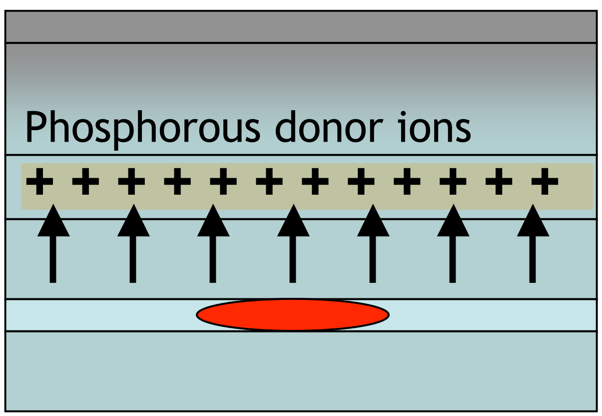
$$H_{SO} \propto \nabla V \cdot (\sigma \times \mathbf{p})_{\mathbf{z}}$$

$$H_{SO} \propto \frac{1}{r}\frac{dV}{dr}\mathbf{L}\bullet\mathbf{S}$$

$$|e\uparrow\rangle_{SO} = |e\uparrow\rangle + \sum_r \frac{\langle e\uparrow|H_{SO}|r\rangle}{E_{re}}|e\downarrow\rangle$$

$$V = V_{crystal} + V_{gates} + V_{Ez}$$

$$\Delta g = g_{Si} - g_0 = 1.998 - 2.0023 = -0.004$$

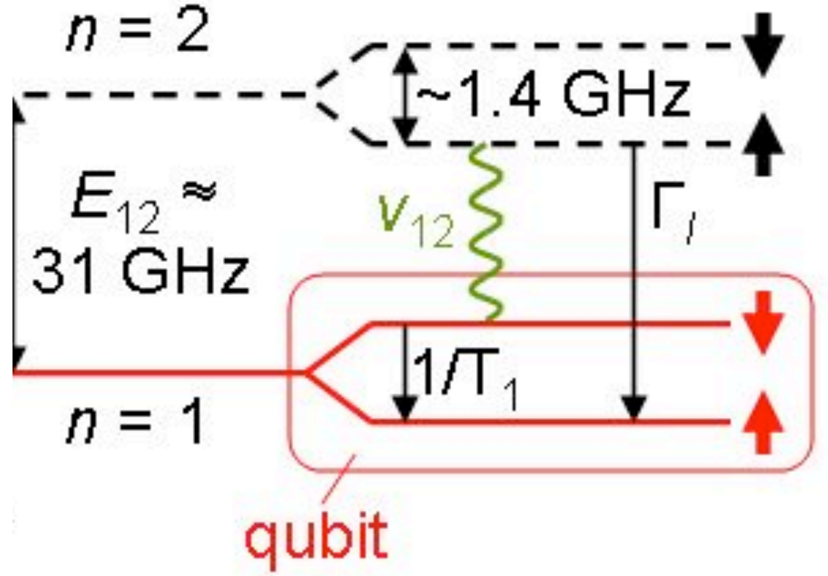


$\mathbf{E_z \sim 10^6\ V/m}$ → $H_{SO} \sim \alpha\left(p_x\sigma_y - p_y\sigma_x\right)$

$$\Rightarrow M \approx 0.003$$

Relaxation

$$\Gamma_I >> \Gamma_R > 1/T_1$$



$$H_{electron-phonon} = \sum_{ij} U_{ij} \Xi_{ij}$$

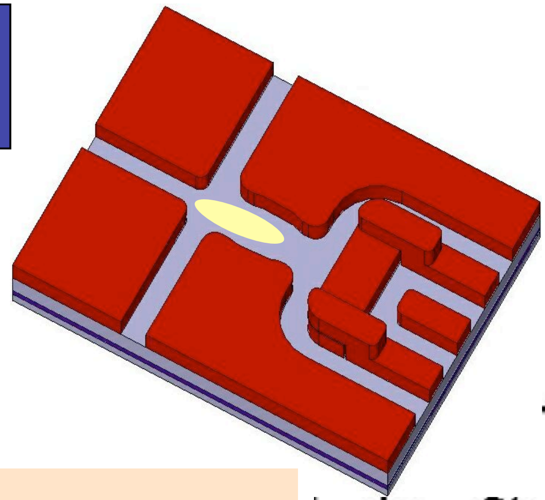
strain (U_{ij})

deformation energy (Ξ_{ij})

$$\Gamma_I^{\uparrow\uparrow} = \frac{2\pi}{\hbar} \left| \langle g \uparrow | H_{e-p} | e \uparrow \rangle \right|^2 \delta\left(\hbar\omega_{\mathbf{q},t} - E_{eg}\right)$$

$$\Gamma_I^{\uparrow\uparrow} = \frac{E_{eg}{}^5}{\pi\hbar^6\rho}\left(\left|\langle g|x|e\rangle\right|^2 + \left|\langle g|y|e\rangle\right|^2\right)\left\{\frac{35\Xi_d{}^2 + 14\Xi_d\Xi_u + 3\Xi_u{}^2}{210 v_l{}^7} + \frac{2\Xi_u{}^2}{105 v_t{}^7}\right\}$$

Operation speed

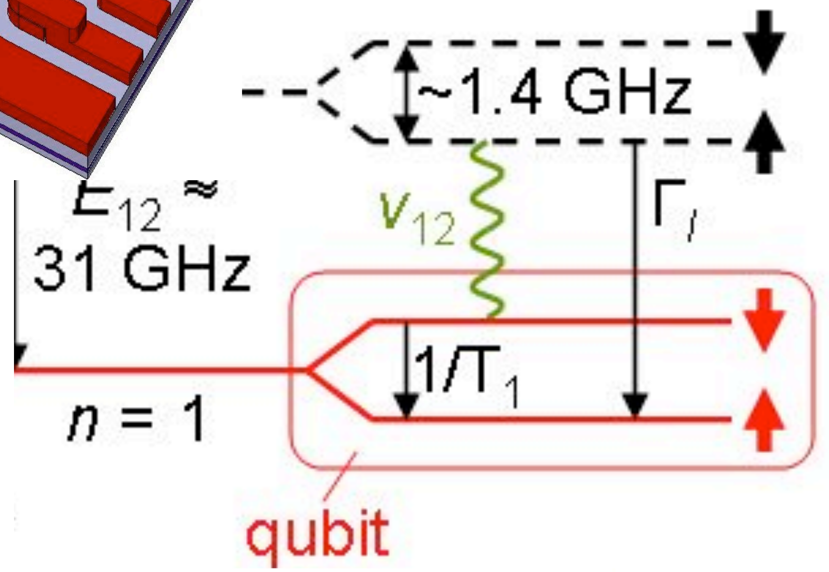


T < 100mK

Bz = 0.05 T

Some rough numbers…

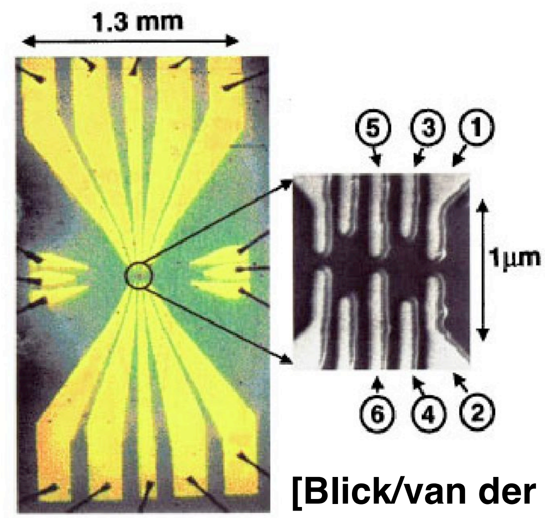
for $E_e - E_g \approx 0.1\,\mathrm{meV}$



Silicon	GaAs
Initialization (relaxation) time:	
nanoseconds	**nanoseconds**
Readout frequency (w/ spin-flip):	
$\upsilon_R = 0.6\sqrt{I}\ \mathrm{MHz}$	$\upsilon_R = 60\sqrt{I}\ \mathrm{MHz}$

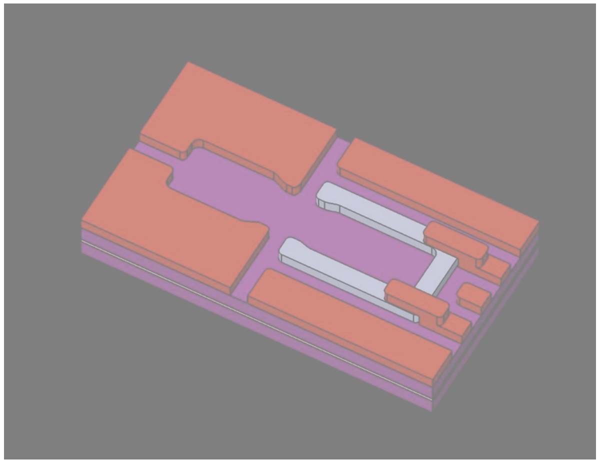
Intensity: $0.1 - ?\ Watts/m^2$

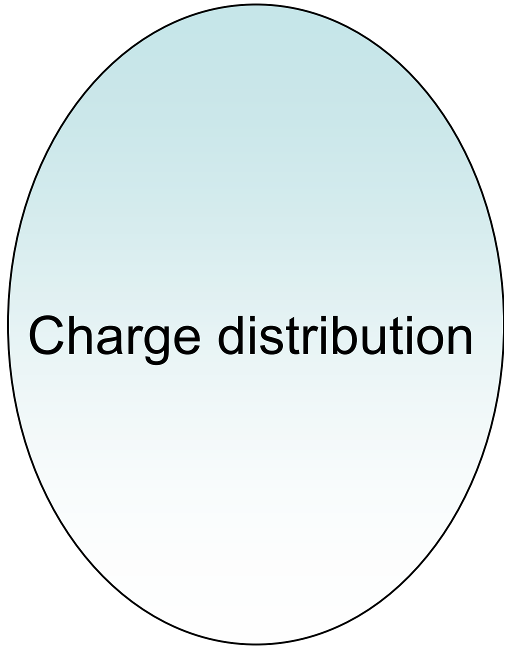
…on chip focusing or direct gate modulation…



[Blick/van der Weide, APL]

A Single Electron Transistor (SET)





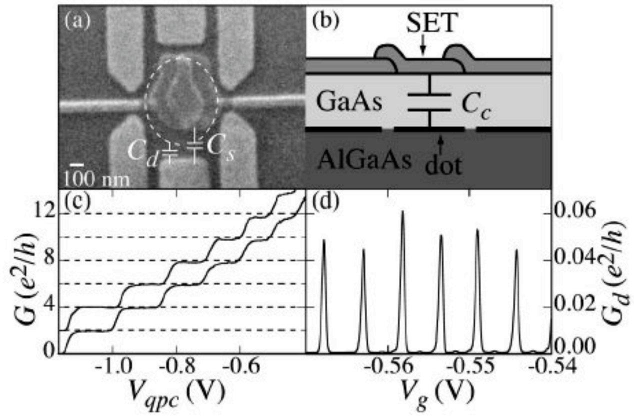
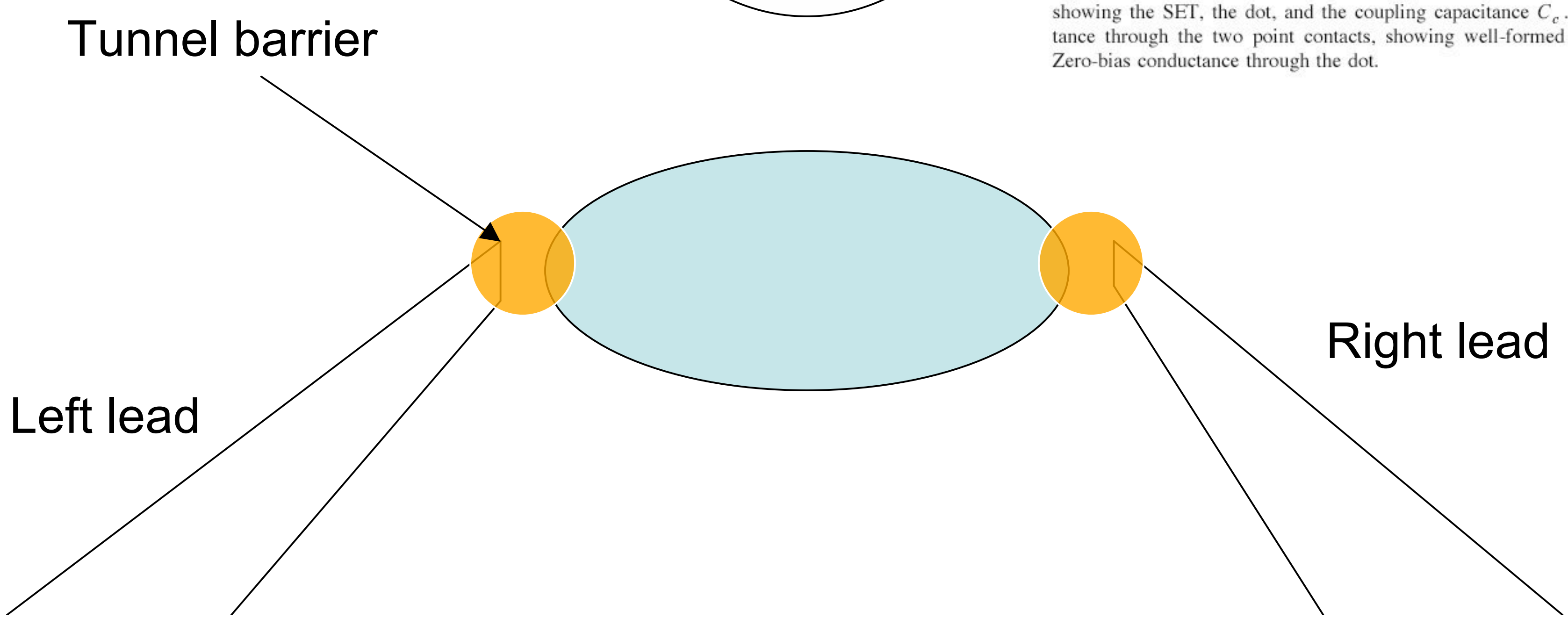
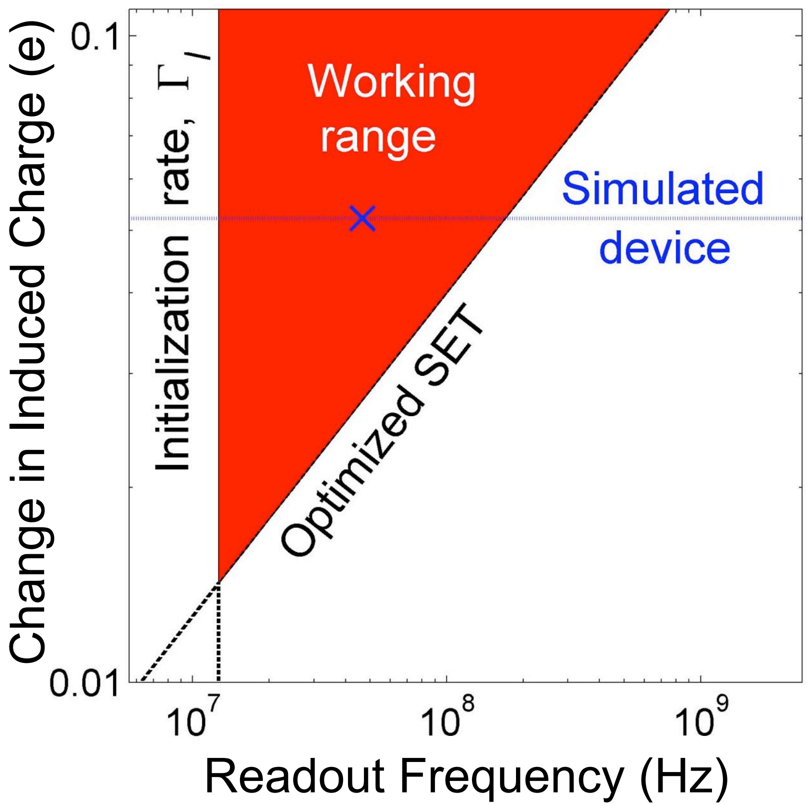


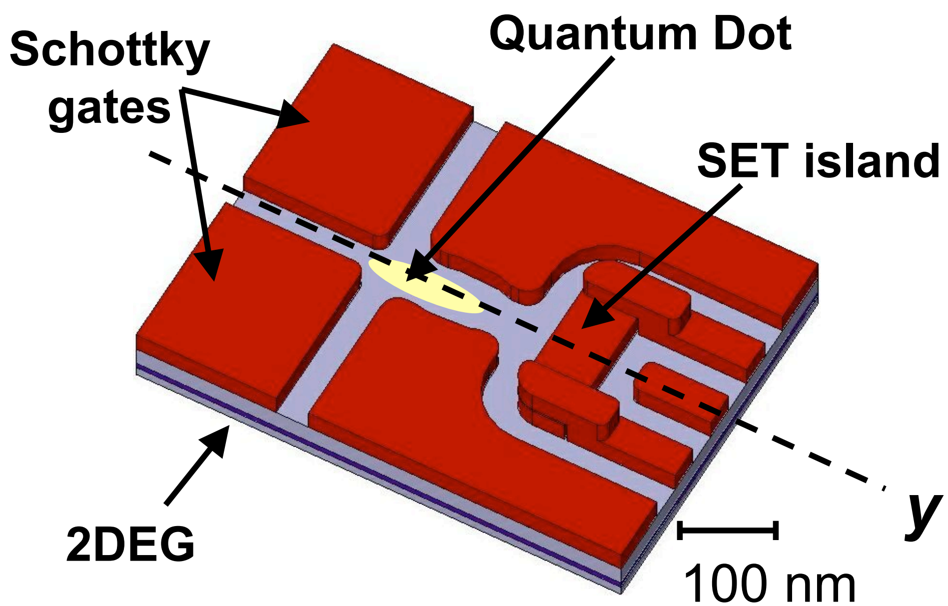
FIG. 1. (a) Scanning electron micrograph of a typical sample. The approximate location of the dot is illustrated by the dashed line. The capacitances C_s and C_d described are also indicated. (b) Schematic cross-sectional view showing the SET, the dot, and the coupling capacitance C_c. (c) Conductance through the two point contacts, showing well-formed plateaus. (d) Zero-bias conductance through the dot.



Charge detection

Induced electronic charge on SET island: $\Delta Q = 0.052\ e$





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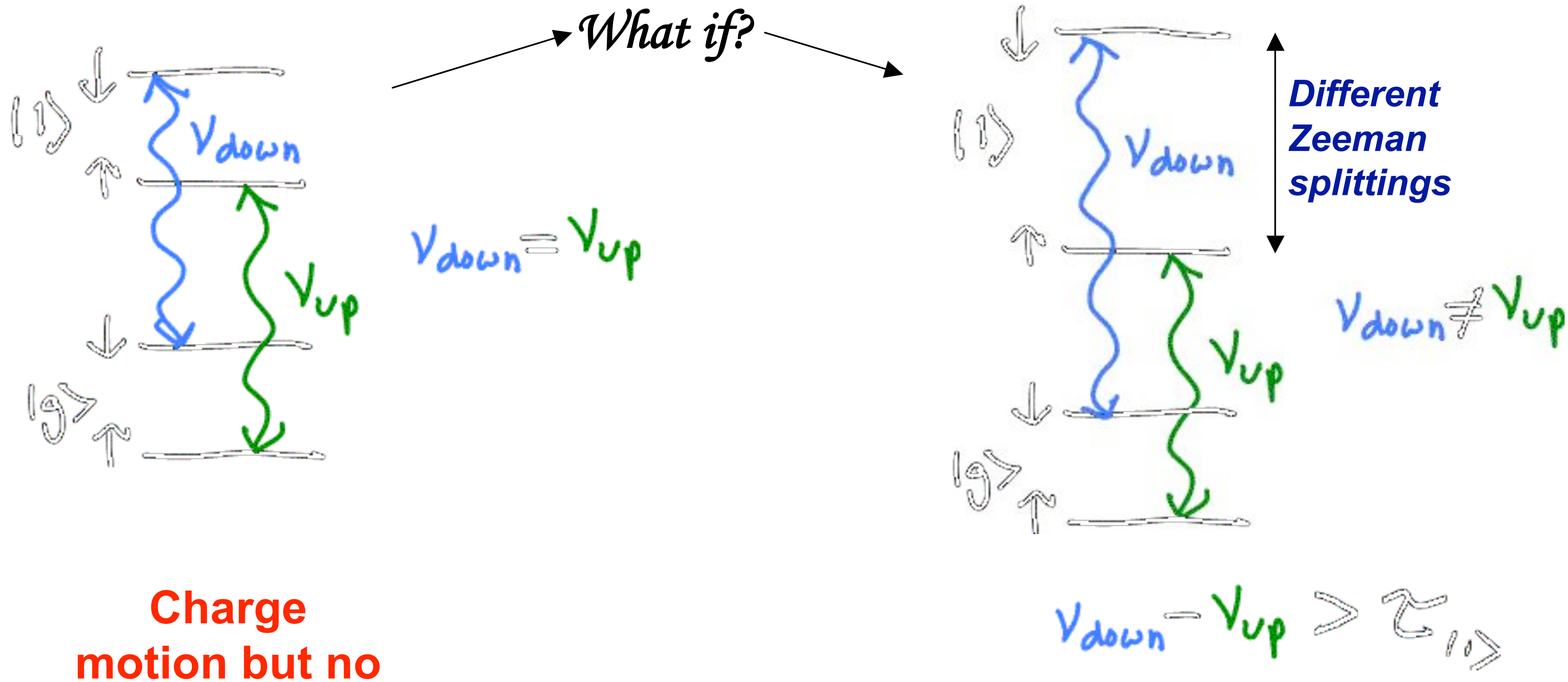
Open questions

- Can we beat phonon relaxation?
- Efficiency?
- Effect of measuring device?
- Heating?

$$\dot{\rho} = -\frac{i}{\hbar}\left[H, \rho\right]$$

$$H = H_{QD} + H_{SET} + H_{ENV} + H_{LIGHT}$$

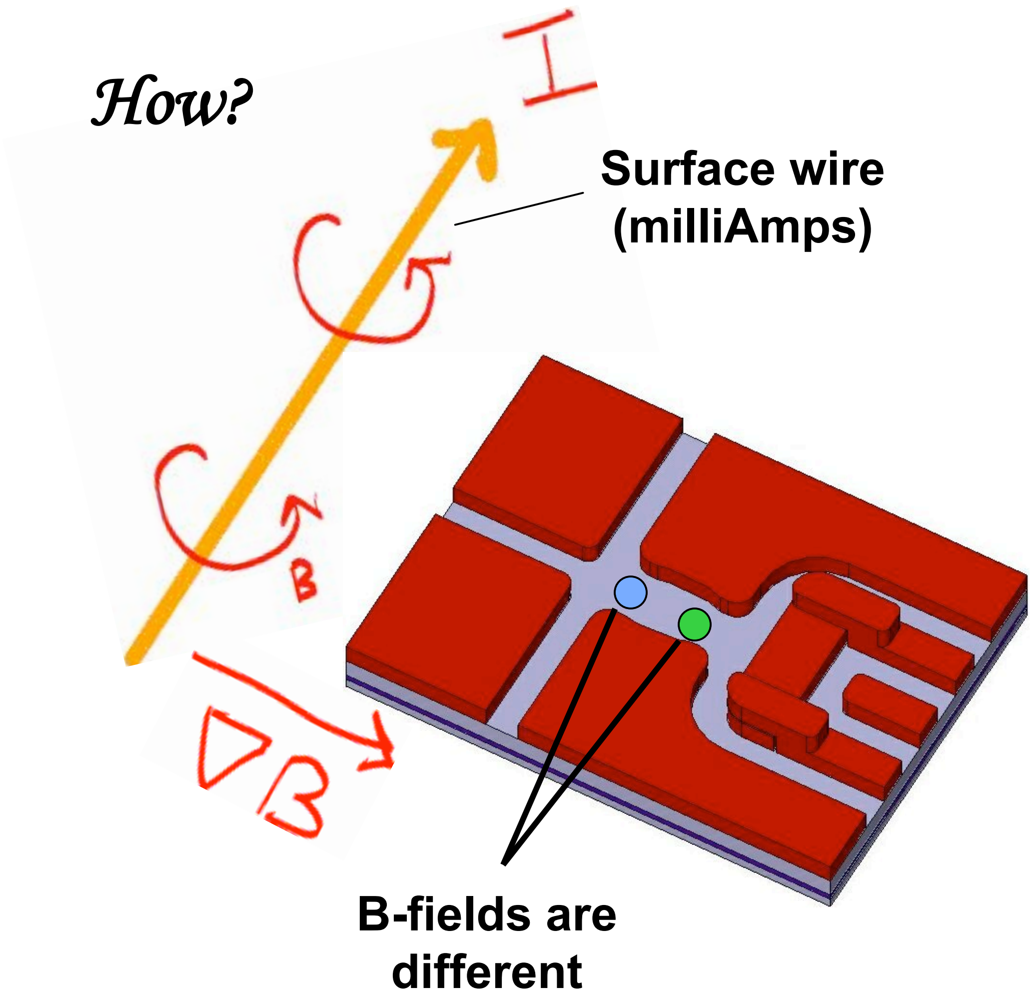
New ideas…

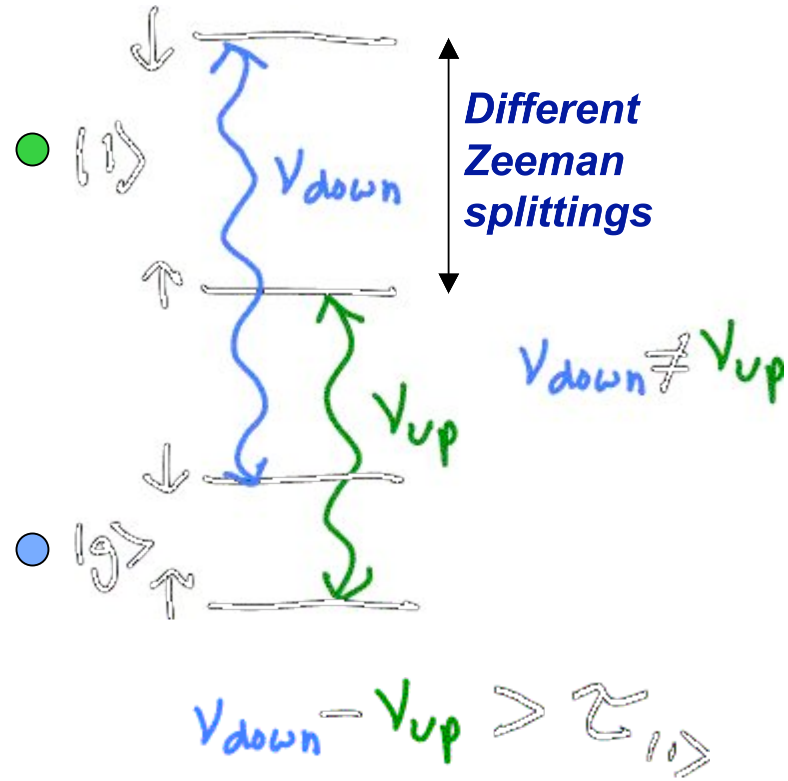


Charge motion but no spin information

Spin-dependent charge motion with no spin-flip needed

New ideas…



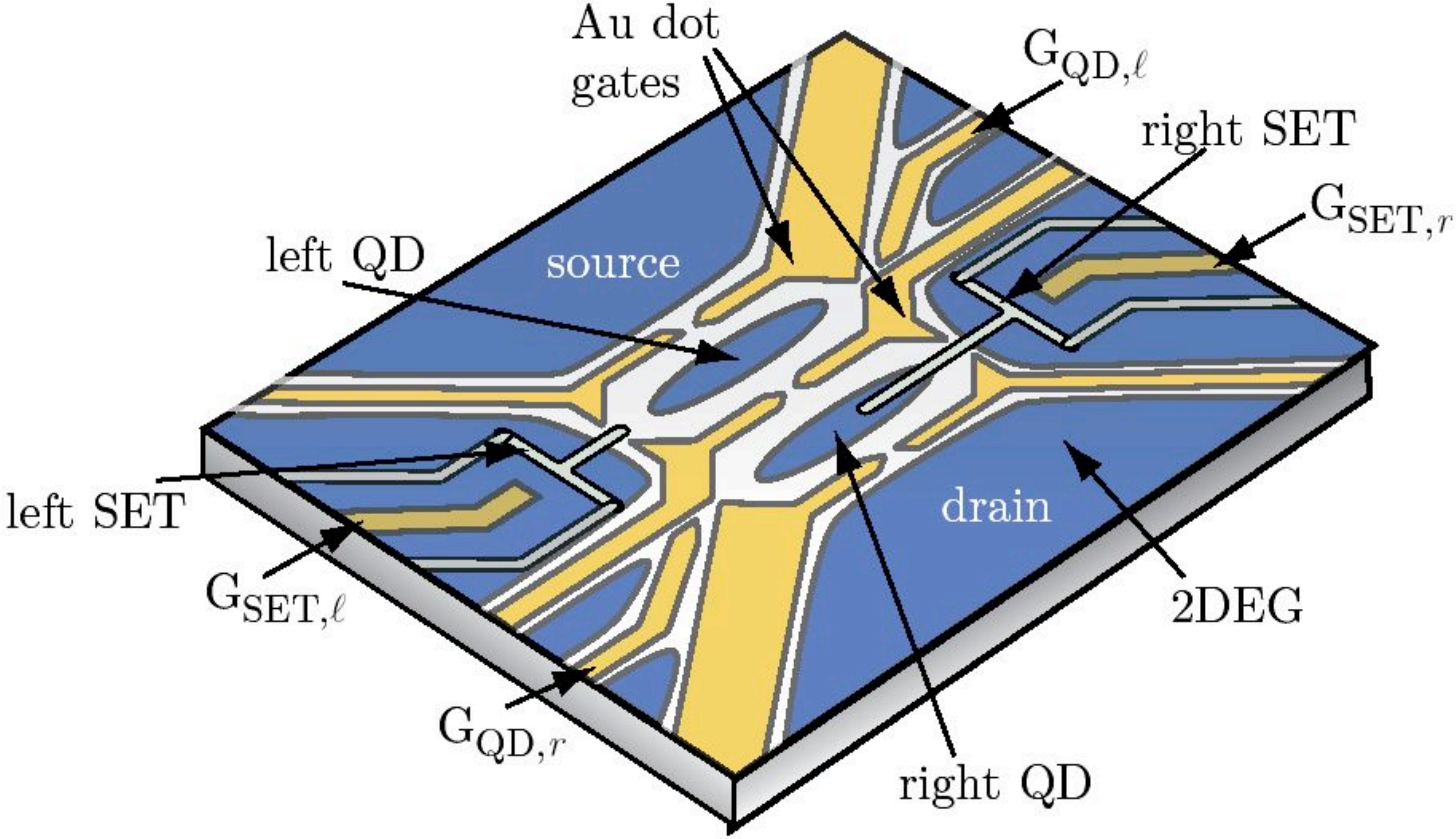


Spin-dependent **charge motion with no spin-flip needed!**

Increases readout speed by over 1000 (for Si)

Implementation

SET fabrication - Implementation in GaAs – Initialization scheme
Collaboration with Alex Rimberg (Rice)



The end

- Microwave enabled spin-charge transduction
- http://qc.physics.wisc.edu/ for more information on this and all Wisconsin QC
- Ad: "*Spin-based Quantum Dot Quantum Computing*"; Thursday **Oct. 9**, **1pm**, Engineering Hall (Blick's class on Quantum Electronics)

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