Toward a QDQC: Single spin readout and initialization in a quantum dot

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IWQDQC'03 – Notre Dame

ARDA

Artificial atomic physicists are people too

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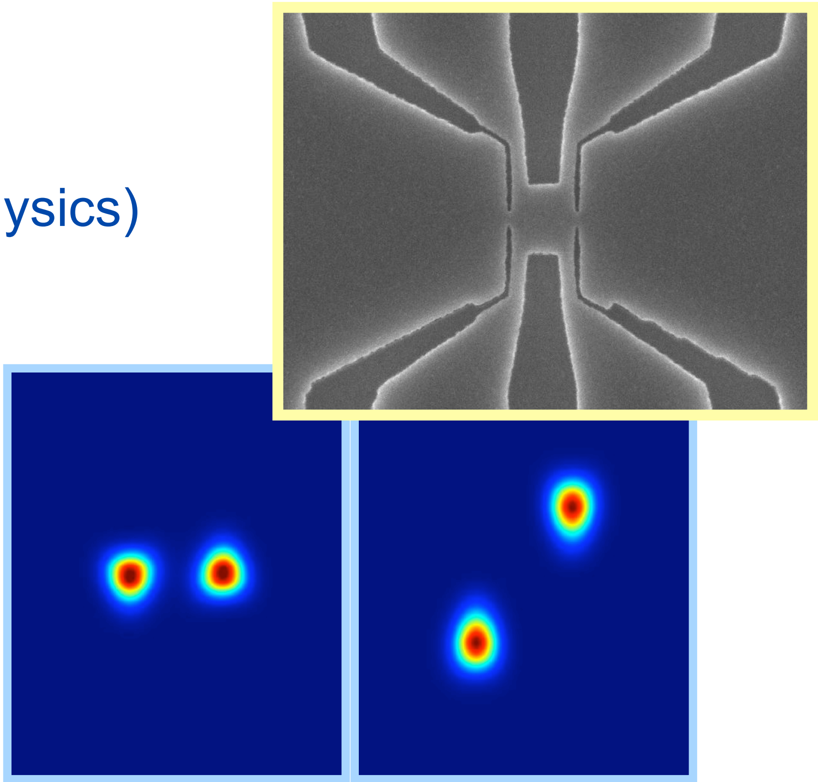
Atomic Seminar, Madison WI

October 2, 2003

Charles Tahan

UW-Madison Solid-State Quantum Computing Team

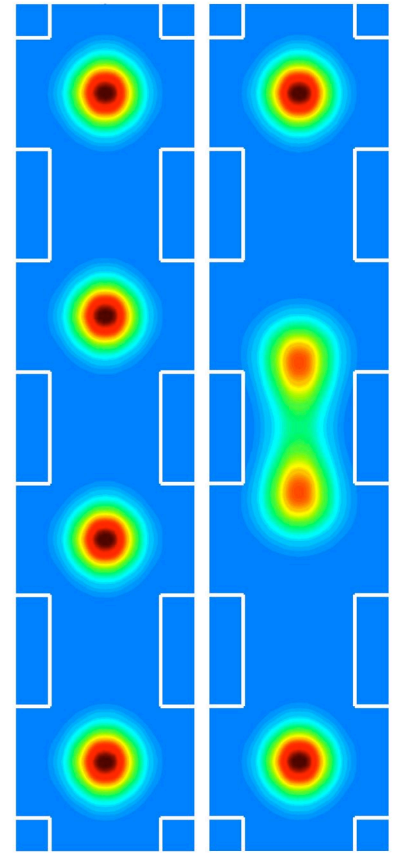
Mark Eriksson (Physics)
Robert Blick (ECE) New!
Sue Coppersmith (Physics)
Robert Joynt (Physics)
Max Lagally (Materials Science)
Dan van der Weide (ECE)
Mark Friesen (Materials Science and Physics)
Don Savage (Materials Science)
Levente Klein (Physics)
Shaolin Liao (Materials Science)
Keith Slinker (Physics)
Charles Tahan (Physics)
Jim Truitt (ECE)
Kristin Morgenstern (Physics)



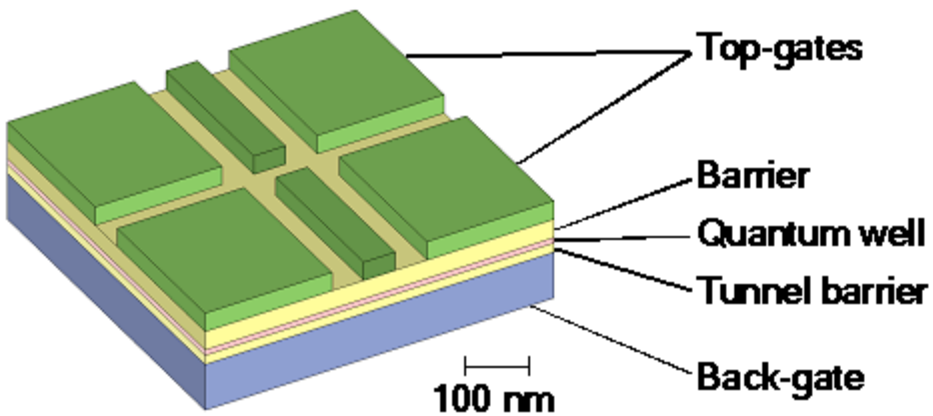
QC Dream Team

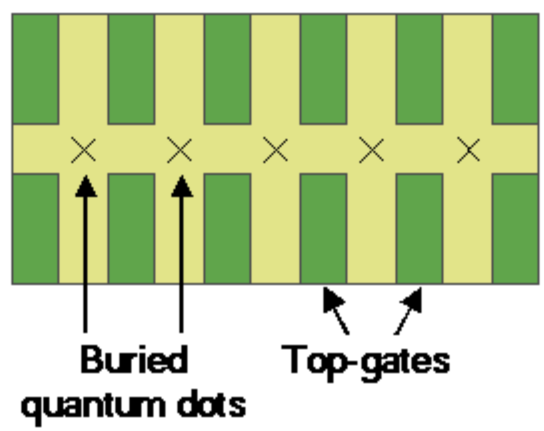
Wisconsin QDQC design

1. **Gated Quantum Dot QC** (Loss & DiVincenzo)
   - 1 electron spin = 1 qubit
   - Self aligning to gates (no need to align to donors)
   - Fast operations through *Heisenberg exchange*
   - Scalable (hopefully)
2. **Silicon**
   - Long decoherence times (T_2 ~ milliseconds for P:^{28}Si)
   - Low spin-orbit coupling
   - Spin-zero nuclei ^{28}Si
3. **Back-gate**
   - Size-independent loading and well-screened manipulation of dots



[Freisen, *et.al.*, APL]
[Freisen, *et.al.*, PRB]

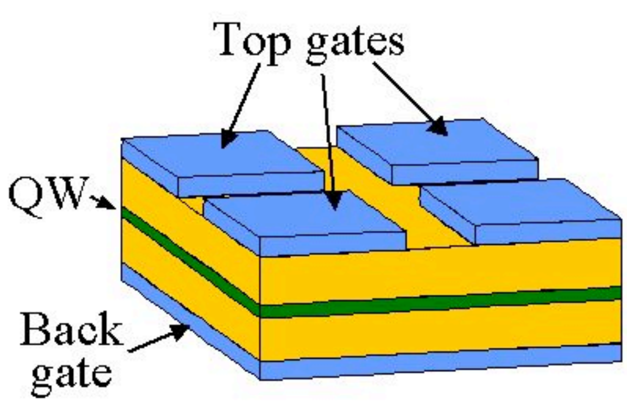


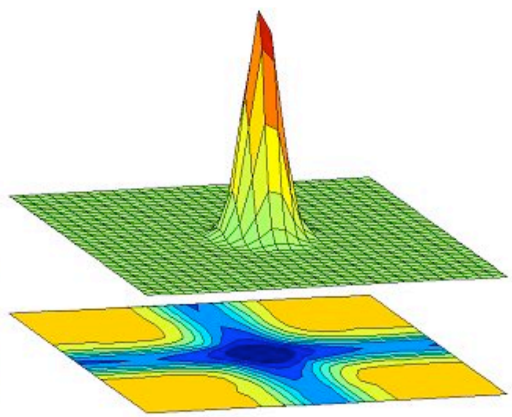


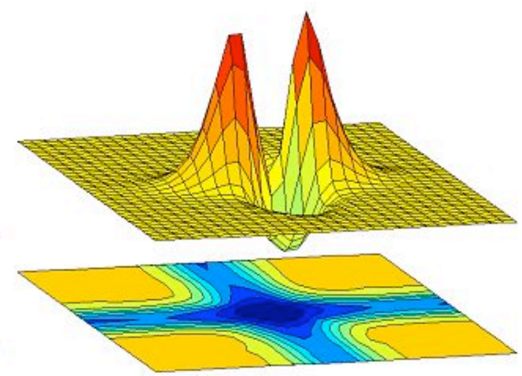
Challenges of Si QDs…and Progress

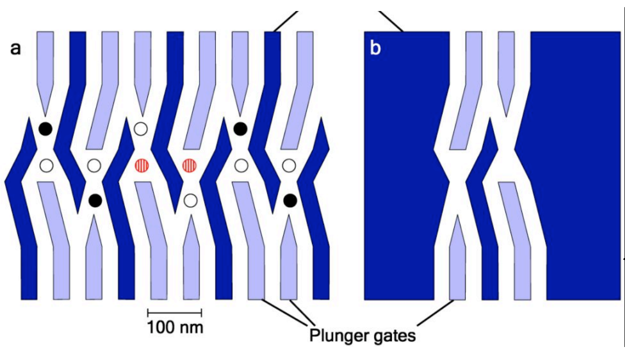
1. Need to work with relaxed SiGe heterostructures
2. Harder to make a good Schottky gate
3. Larger m_{eff} means smaller devices
4. Decoherence
5. Extreme characterization of silicon
6. Need fast readout and initialization of single spin

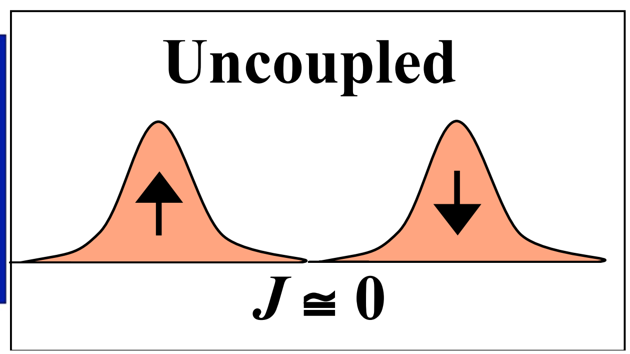
the short short list

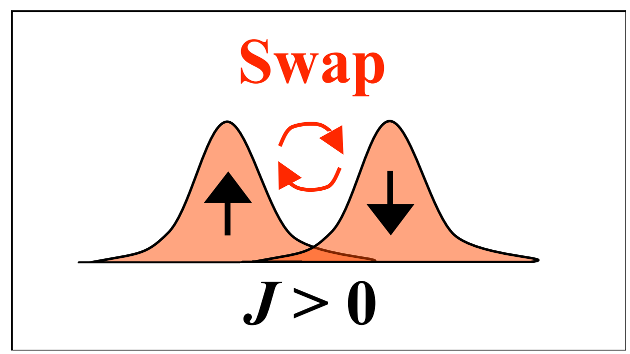






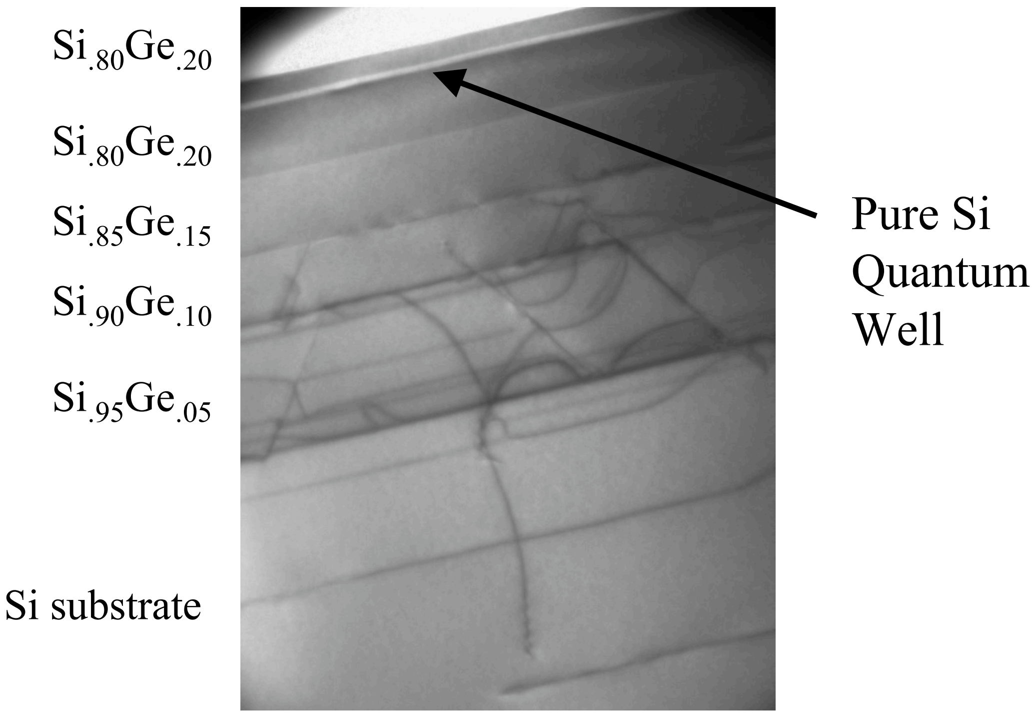






Challenges of Si QDs…and Progress

1. **Need to work with relaxed SiGe heterostructures** close…
2. Harder to make a good Schottky gate
3. Larger m_{eff} means smaller devices
4. Decoherence
5. Extreme characterization of silicon
6. Need fast readout and initialization of single spin ★

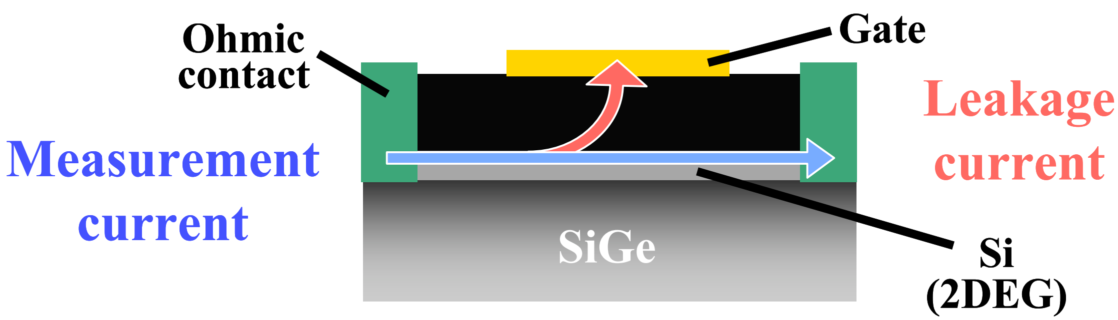


Collaboration – IBM
Pat Mooney *et. al.*
(higher mobility, smoother interface)

Savage/Lagally – Wisc
^{28}Si 2DEGs
(low mobility samples at the moment)

Challenges of Si QDs…and Progress

1. Need to work with relaxed SiGe heterostructures
2. **Harder to make a good Schottky gate** Need to do better!
3. Larger m_{eff} means smaller devices
4. Decoherence
5. Extreme characterization of silicon
6. Need fast readout and initialization of single spin

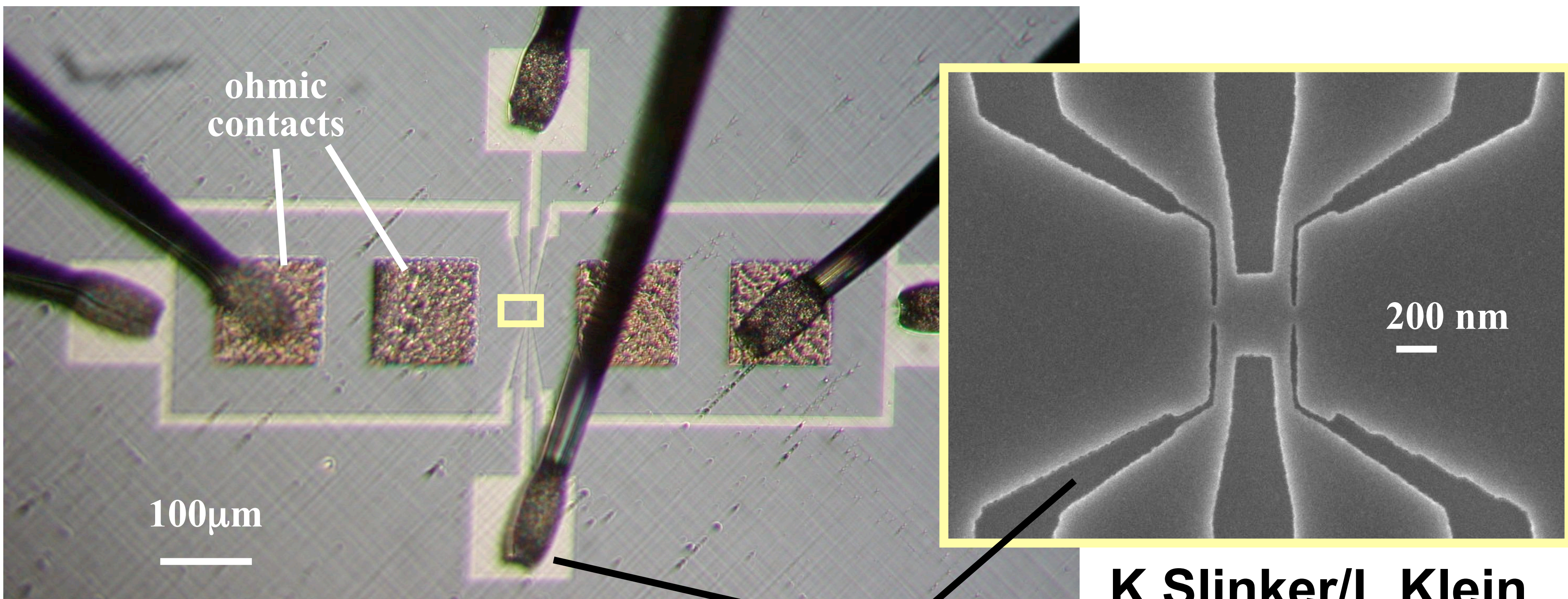


K.Slinker/L.Klein & *wisc.et.al.*

Current structures: few *nanoamps* (gate bias = 1V, temperature = 2K)

Challenges of Si QDs…and Progress

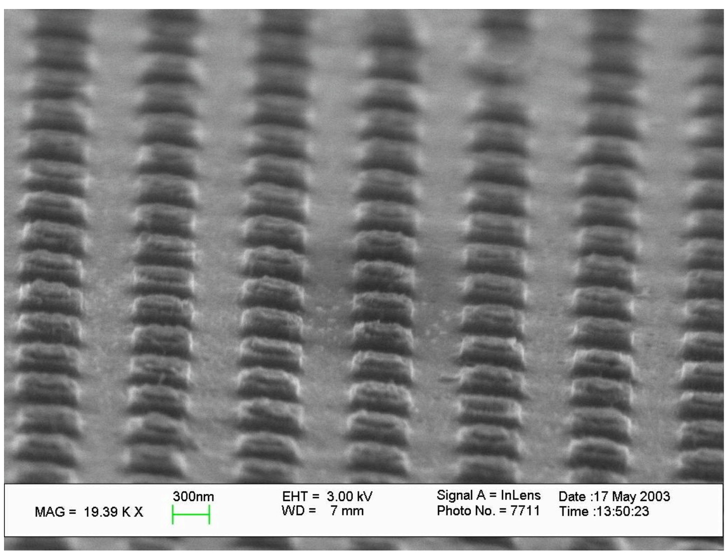
1. Need to work with relaxed SiGe heterostructures
2. Harder to make a good Schottky gate
3. **Larger m_{eff} means smaller devices** ✓ E-Beam Lithography
4. Decoherence
5. Extreme characterization of silicon
6. Need fast readout and initialization of single spin ★



K.Slinker/L.Klein

Challenges of Si QDs…and Progress

1. Need to work with relaxed SiGe heterostructures
2. Harder to make a good Schottky gate
3. Larger m_{eff} means smaller devices
4. **Decoherence** — seeking proof
5. Extreme characterization of silicon
6. Need fast readout and initialization of single spin



J.Truitt & *wisc.et.al.* <> Lyon *et. al.*

ESR measurements of arrays of etched Si quantum dots

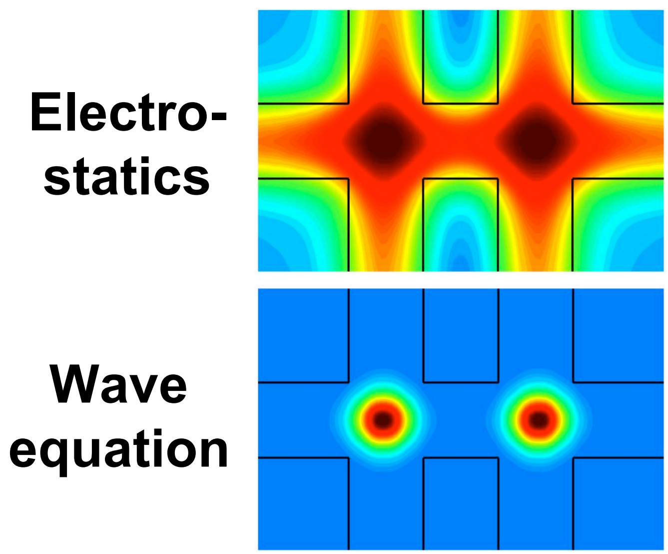
Theory

[Tahan, *et.al.*, PRB, *Strained Si*]
[S.Liao, *et.al.*, TBP, *Impurities*]
[Tahan, *et.al.*, TBP, *Anisotropic SO in Si*]

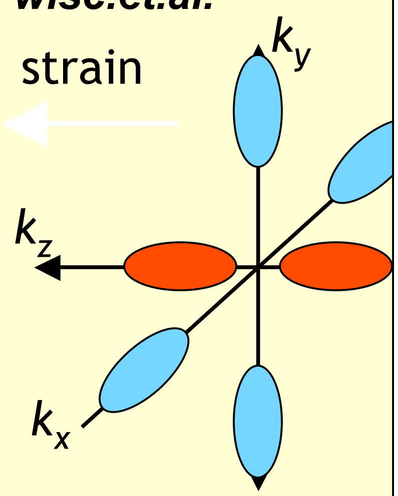
Challenges of Si QDs…and Progress

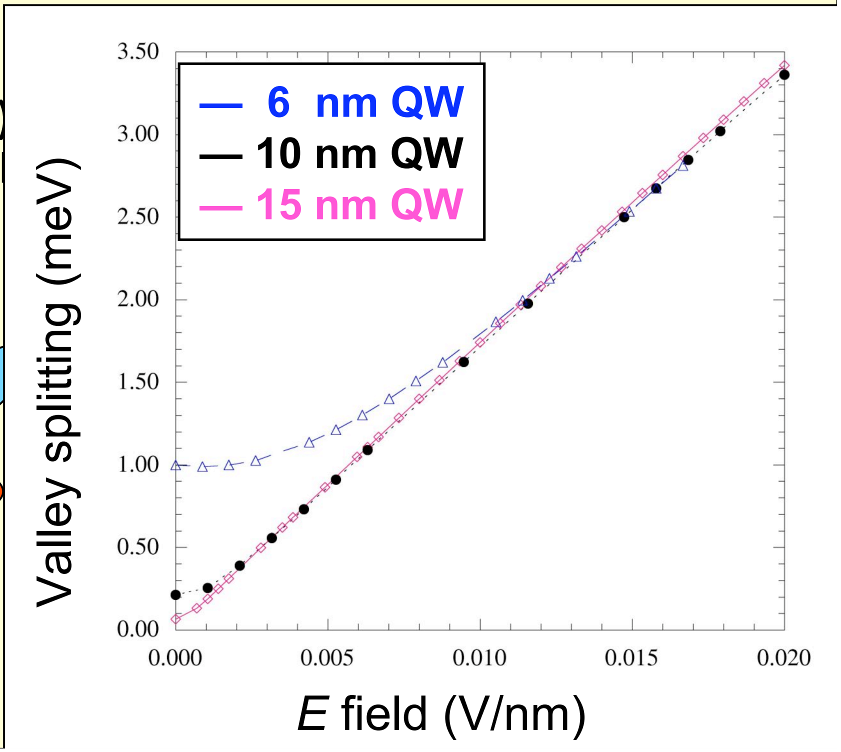
1. Need to work with relaxed SiGe heterostructures
2. Harder to make a good Schottky gate
3. Larger m_{eff} means smaller devices
4. Decoherence
5. **Extreme characterization of silicon** lot's of progress
6. Need fast readout and initialization of single spin ★

*Electrostatic QM Simulations (**M.Freisen et.al.)***



Valley splitting
G.Klimeck(JPL), T.Boykin(Alabama), S.Coppersmith, M.… *wisc.et.al.*

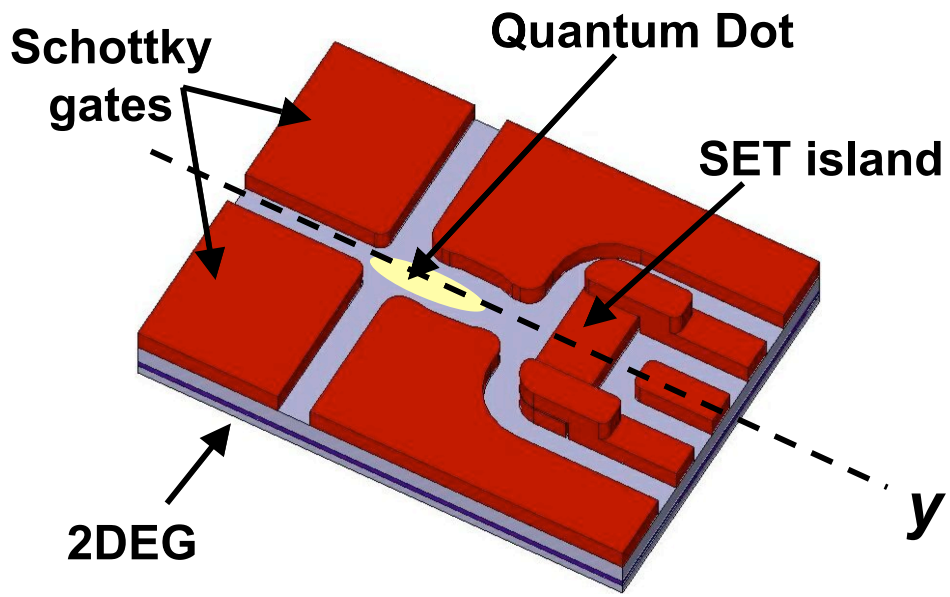




Device design for QD readout

[Friesen, Tahan, Joynt, Eriksson, *condmat*]

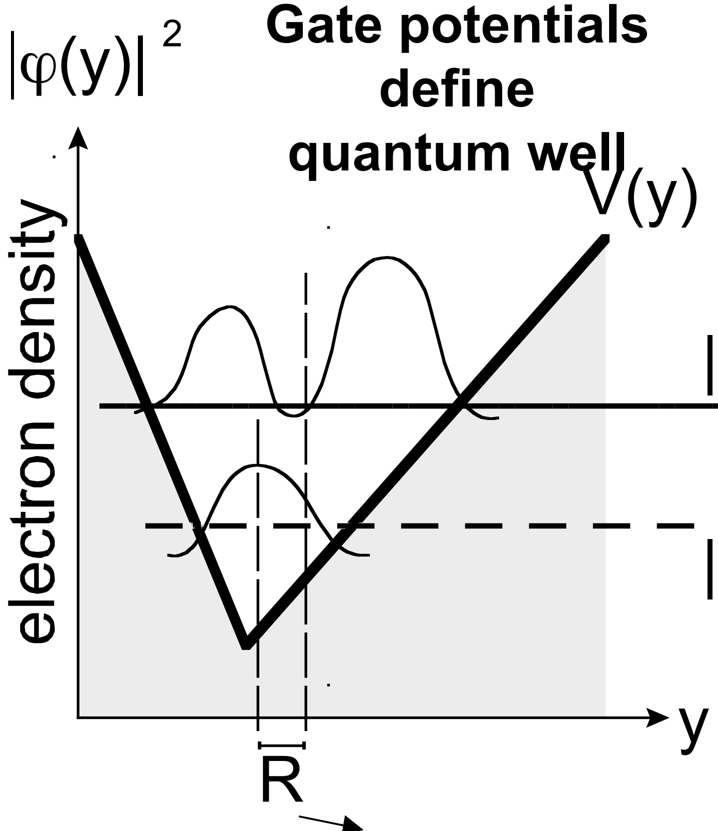
- Spin-dependent charge motion
- SET detection
- Microwave pumping



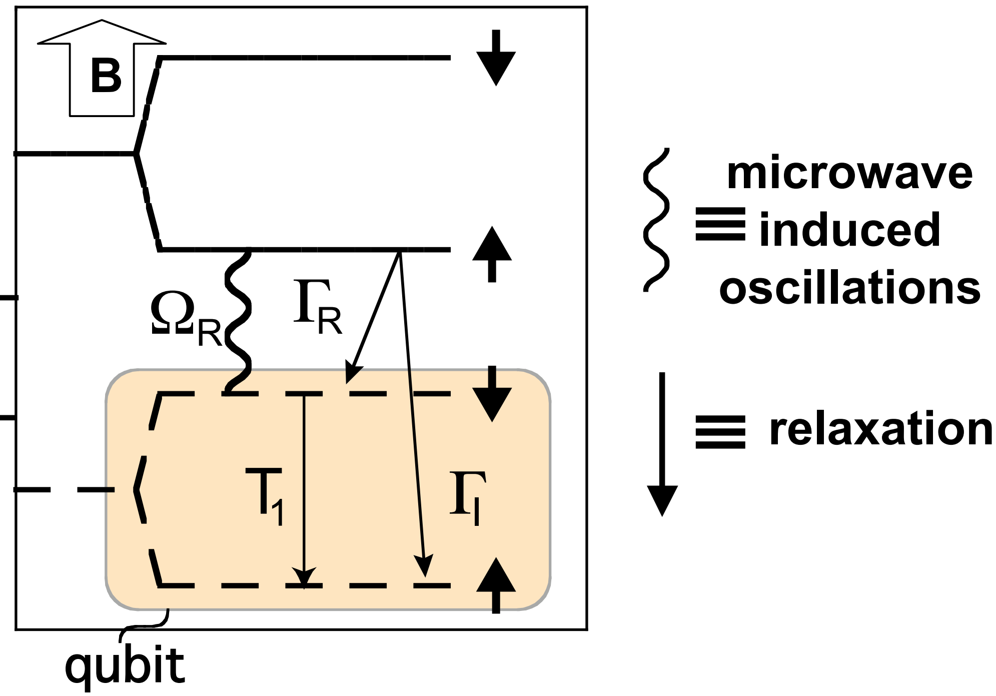
Fast readout and initialization is important for error correction

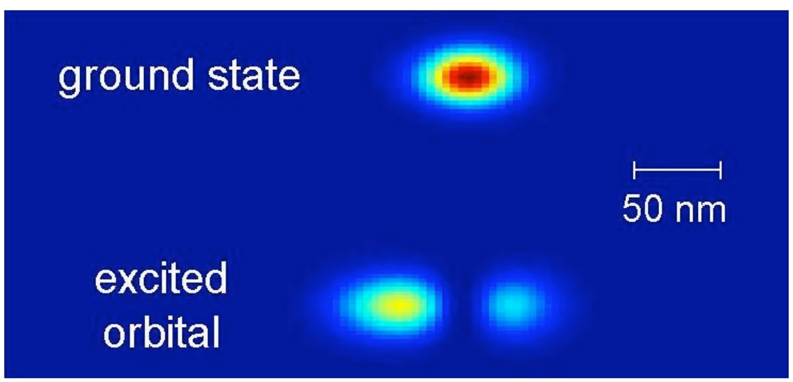
History…spin-charge transduction Loss/Divincenzo, Kane, …

Charge movement in asymmetric well



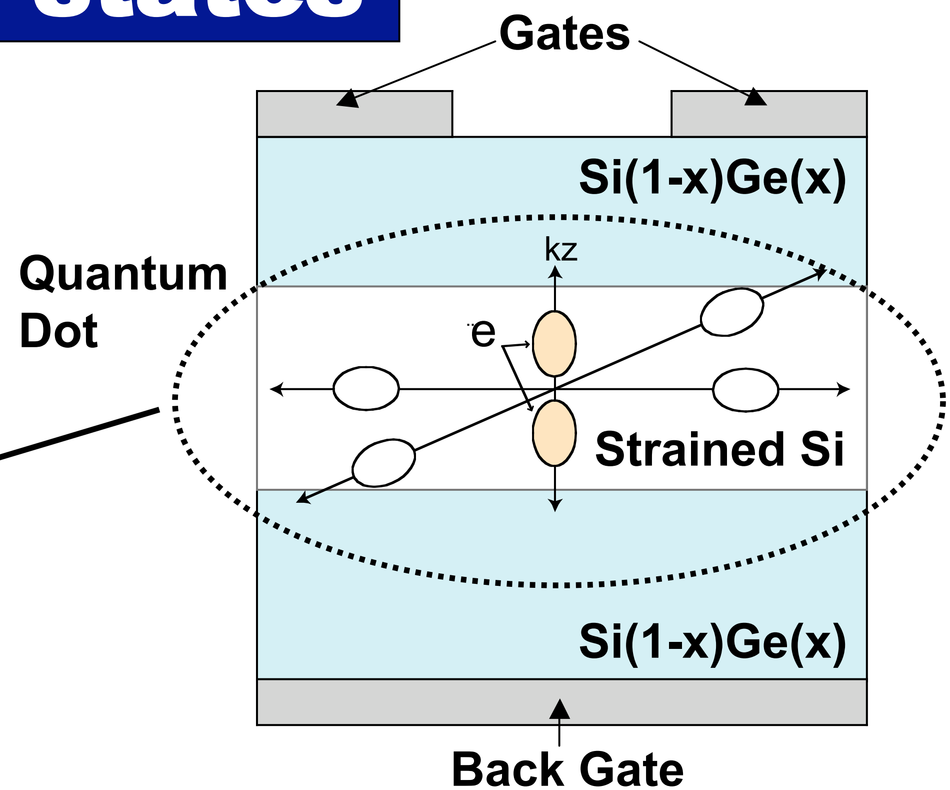
Center of charge movement

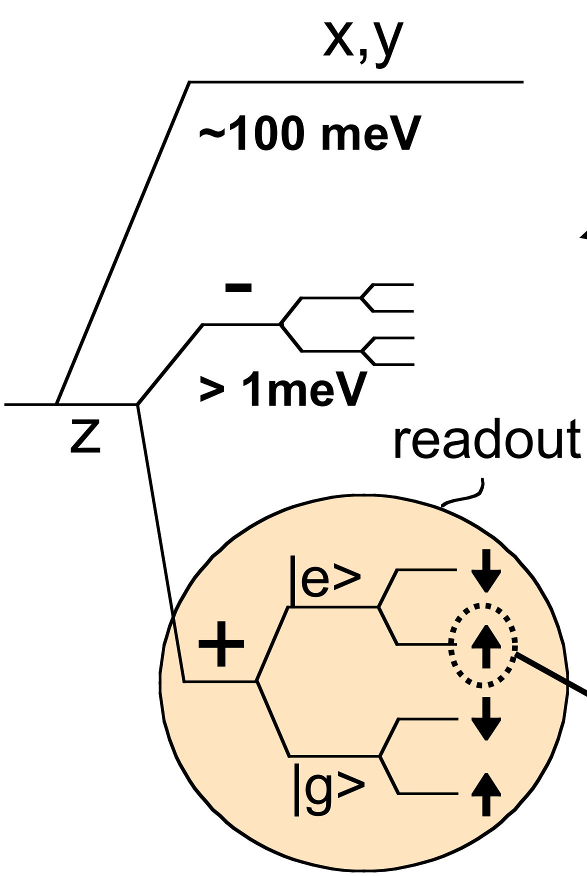




- spin info to charge info via spin-dependent excitation

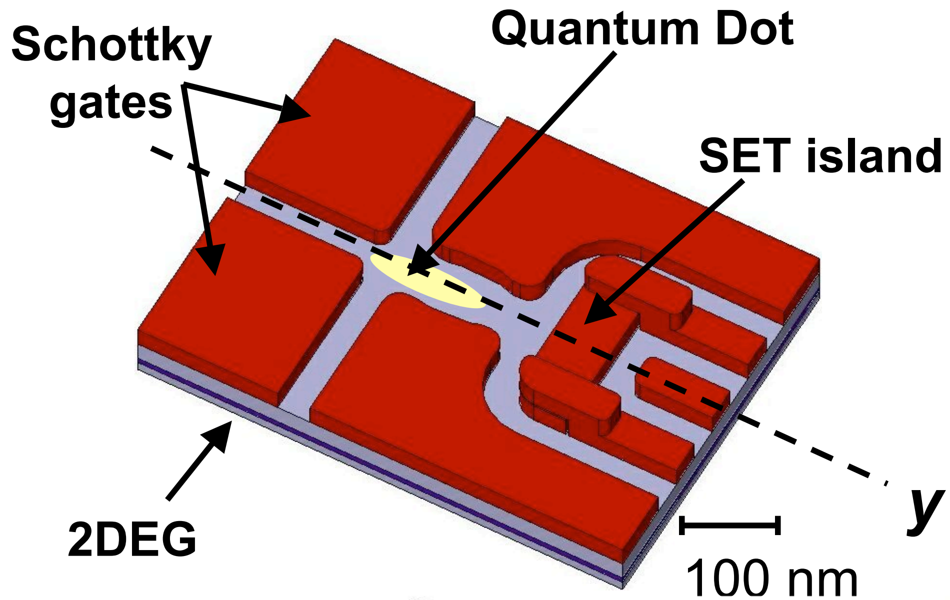
2DEG QD energy states

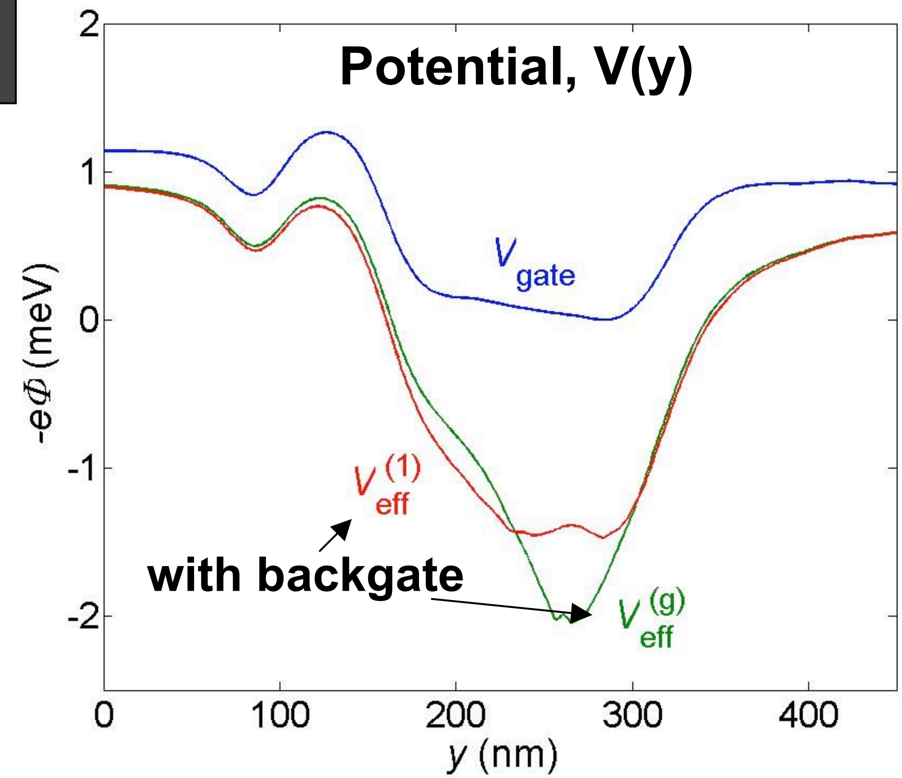


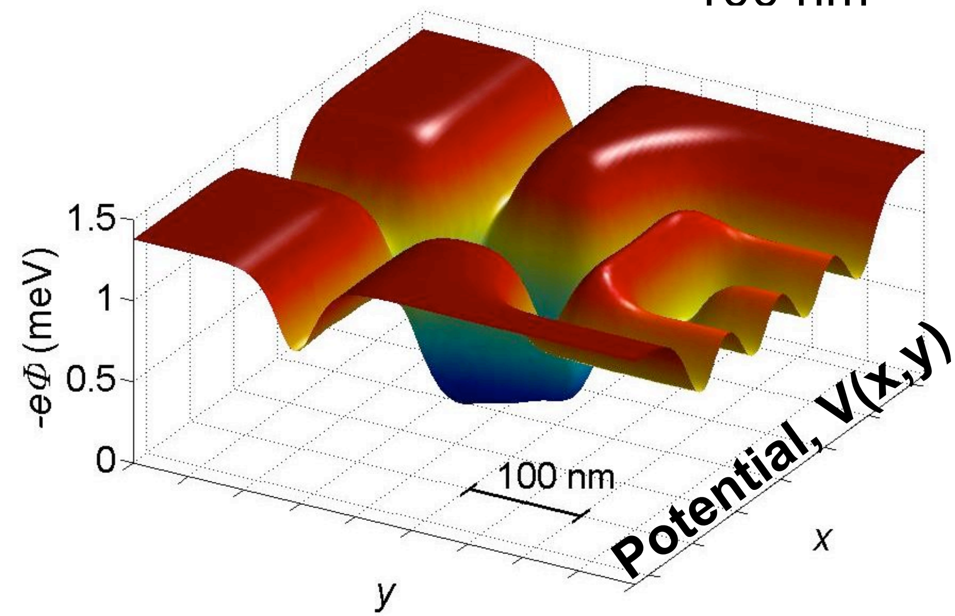


$$\left|e,\uparrow\right\rangle = \text{Envelope} \times \text{Bloch}$$

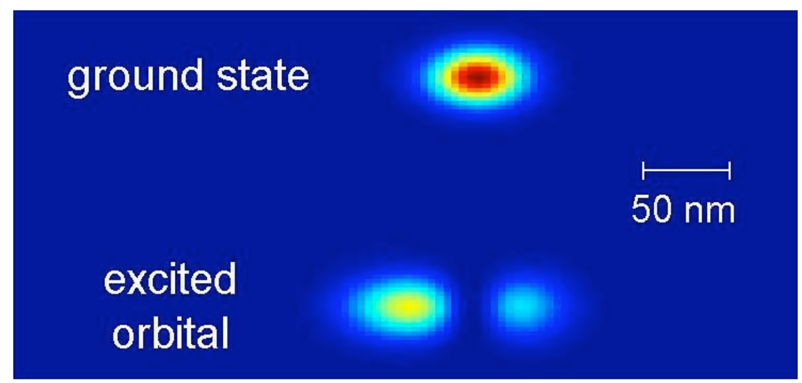
Device Simulation





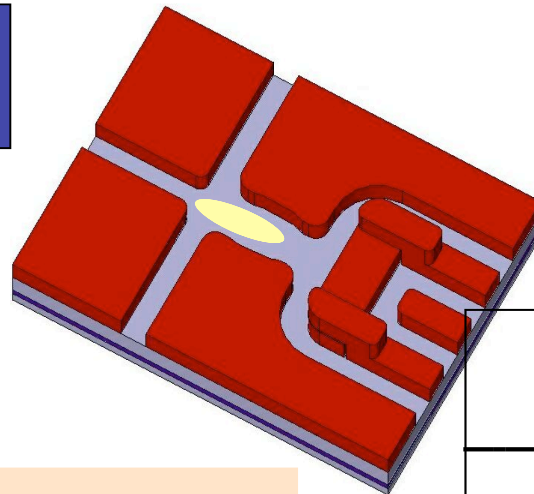


Wavefunction, $|\psi(x,y)|^2$



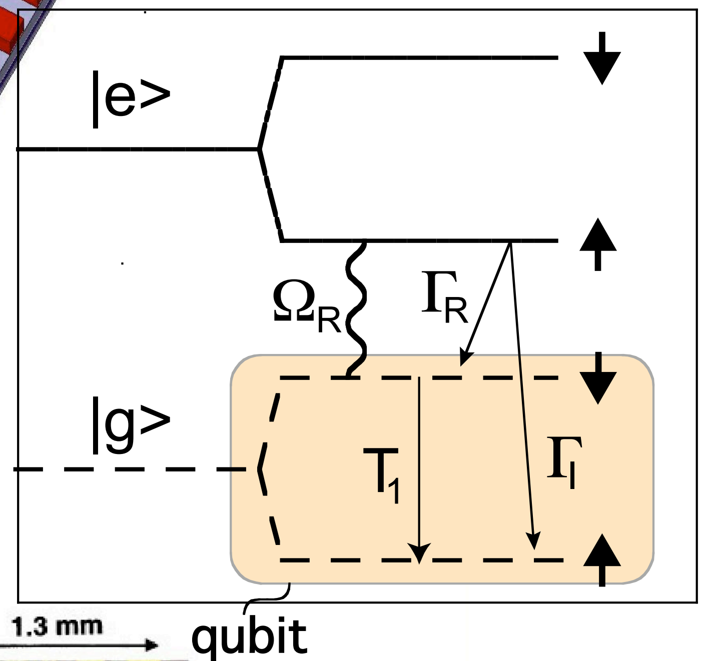
Charge movement ~ 10 nm

Operation speed



T < 100mK

Bz = 0.05 T



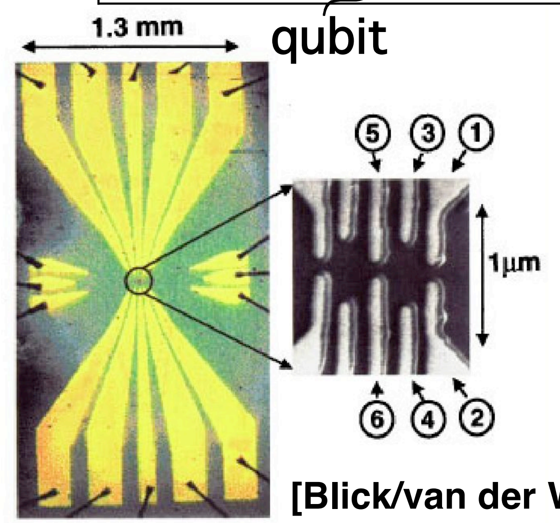
Some rough numbers…

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

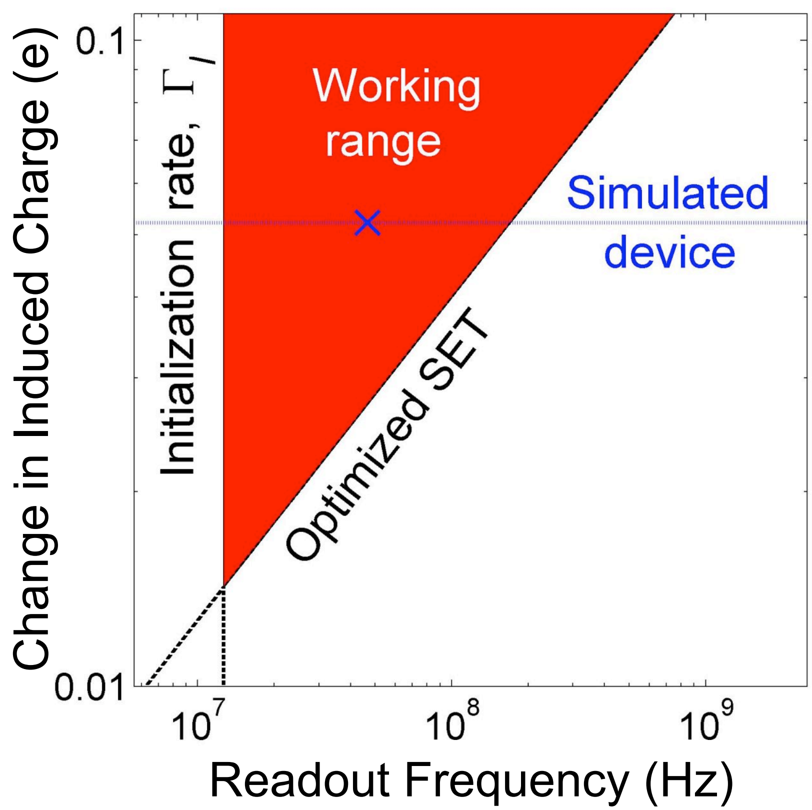
…on chip focusing or direct gate modulation…

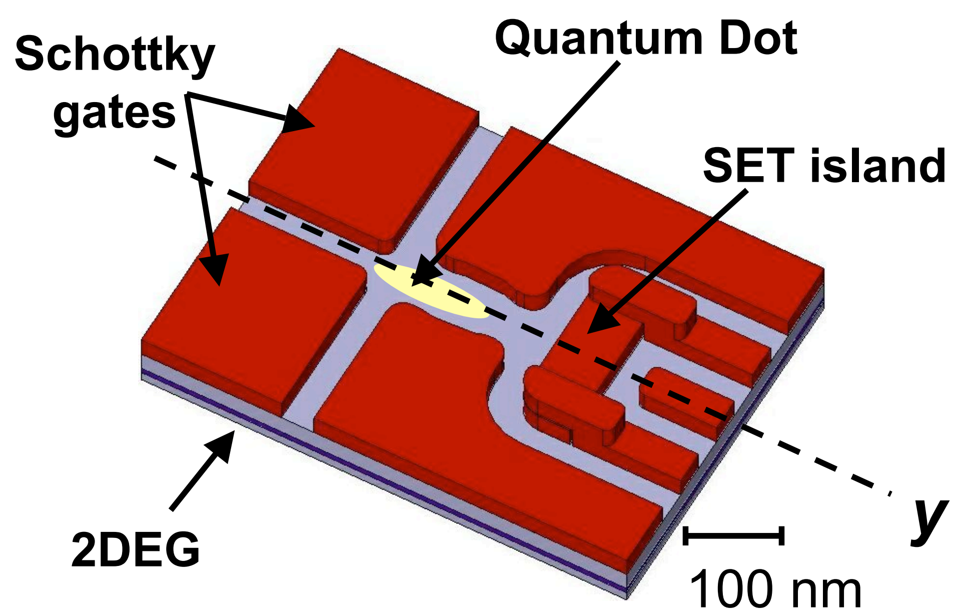


[Blick/van der Weide, APL]

Charge detection

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





Submitted to PRL, cond-mat/0304422

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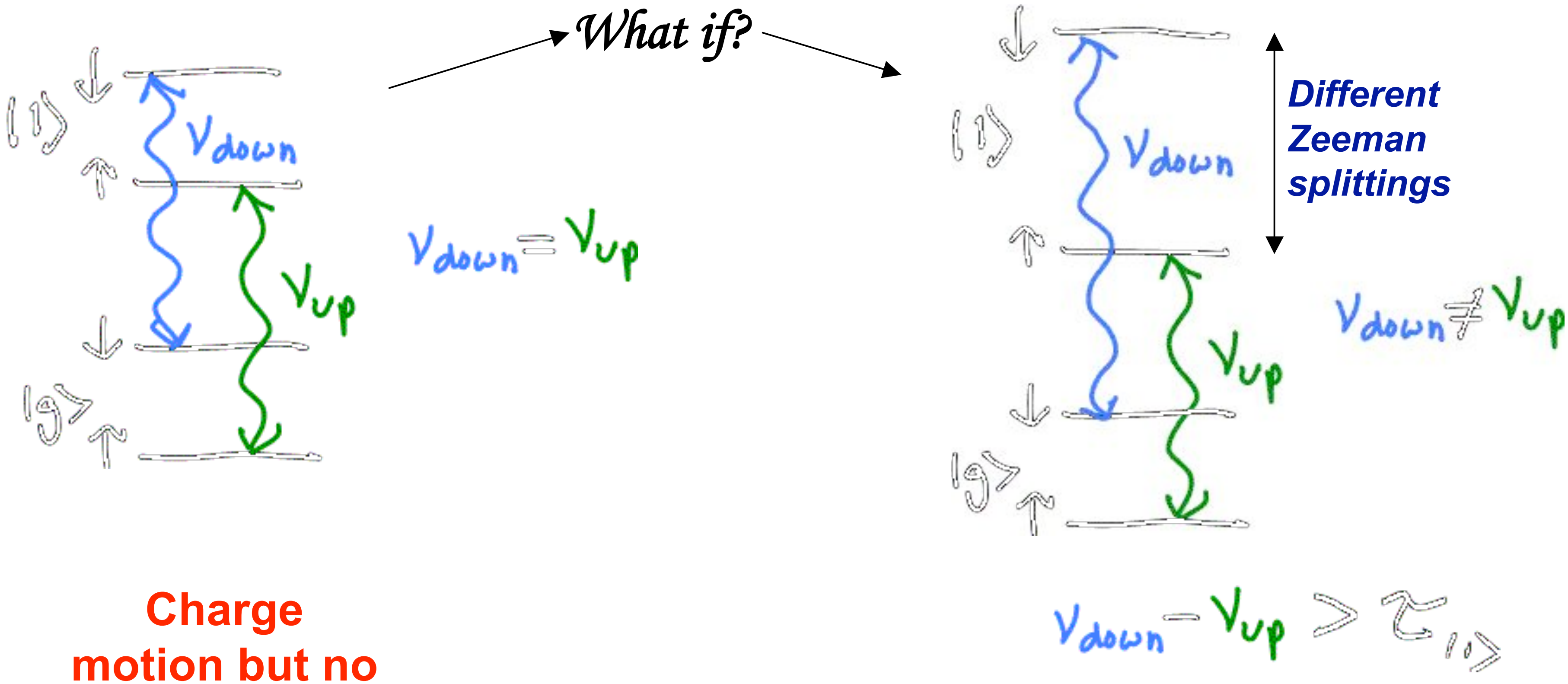
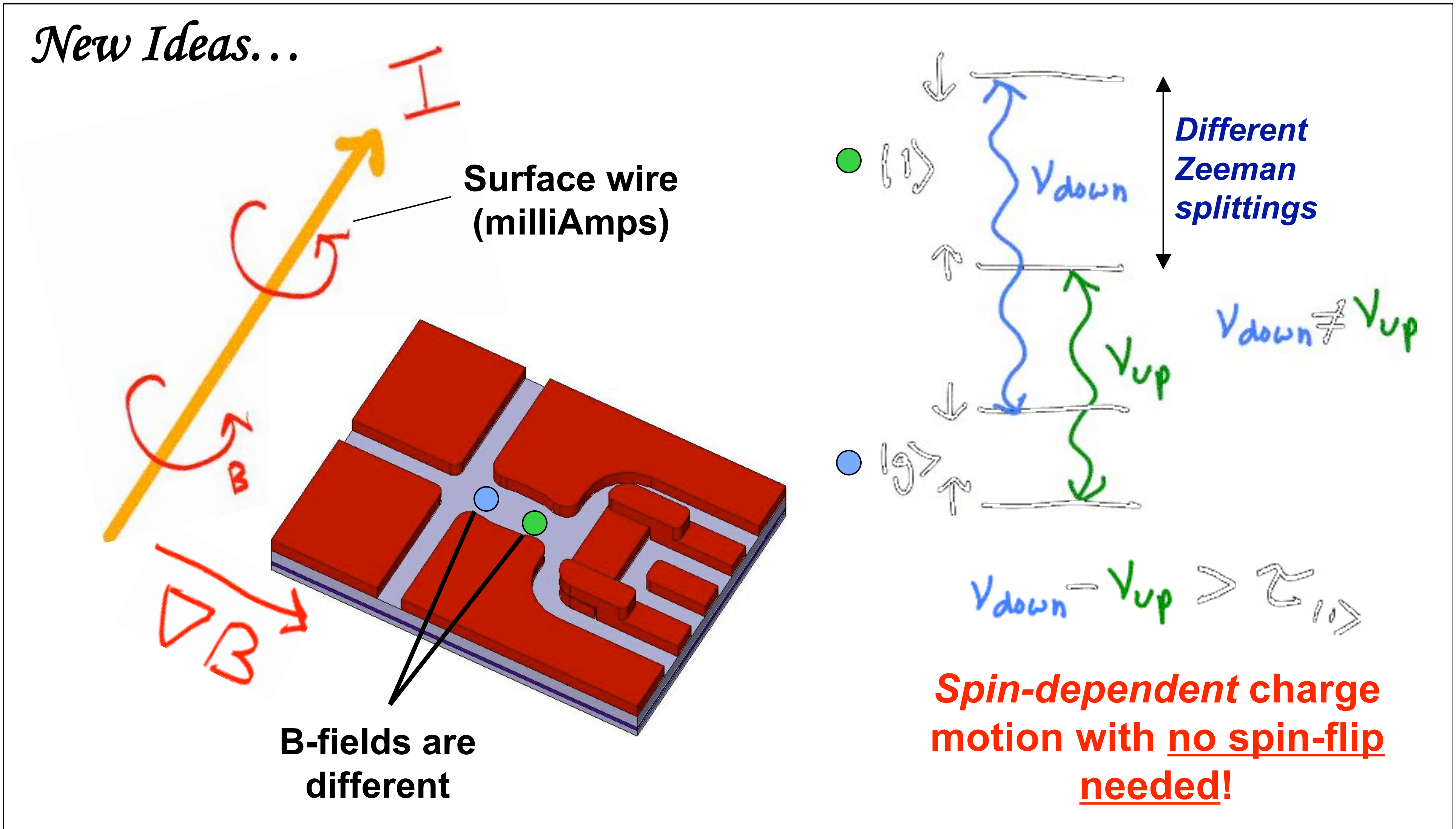
New ideas…



Charge motion but no spin information

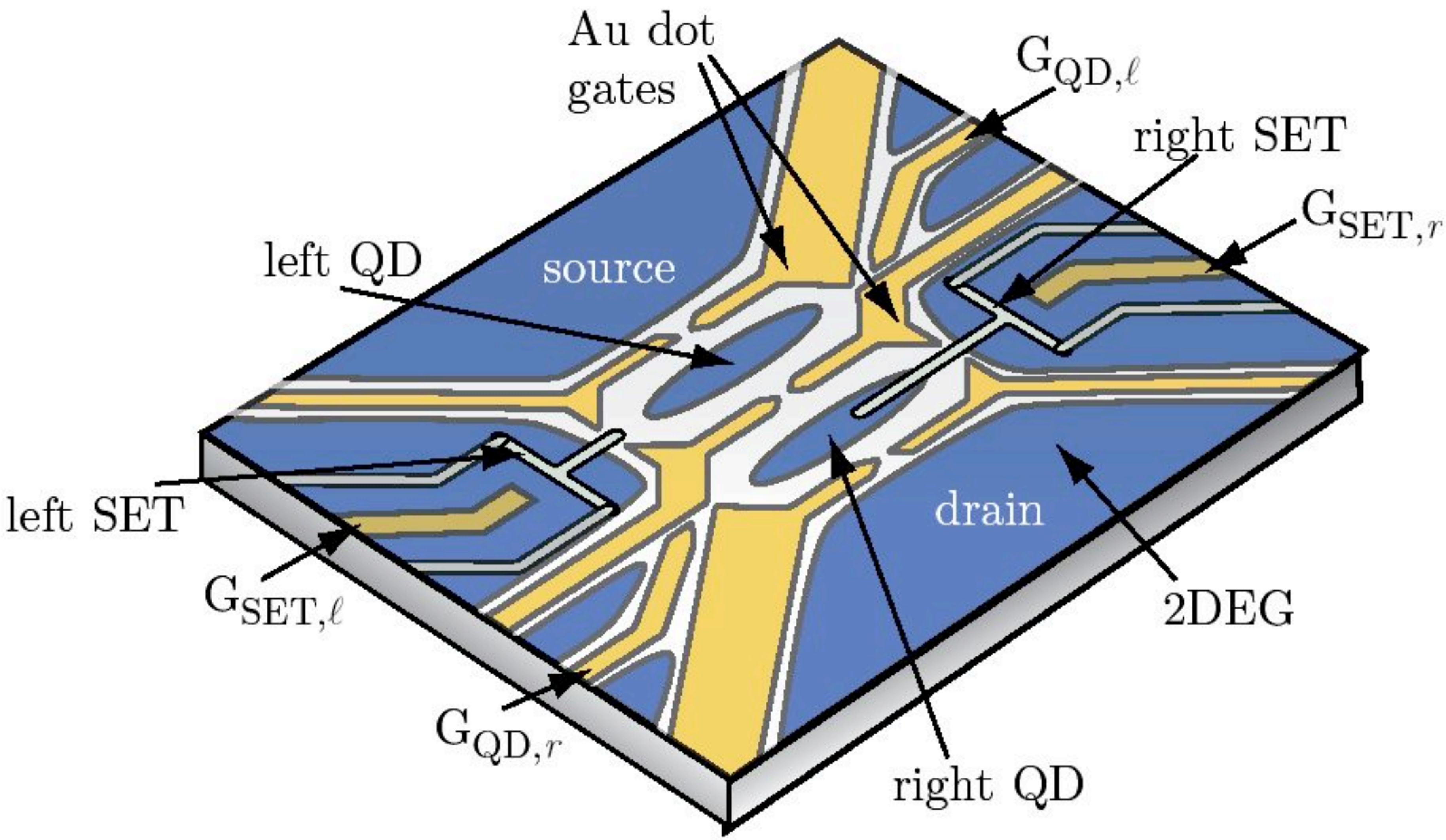
Spin-dependent **charge motion with no spin-flip needed**

New ideas…



➡ **Increases readout speed by over 1000 (for Si)**

Implementation in GaAs – 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

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