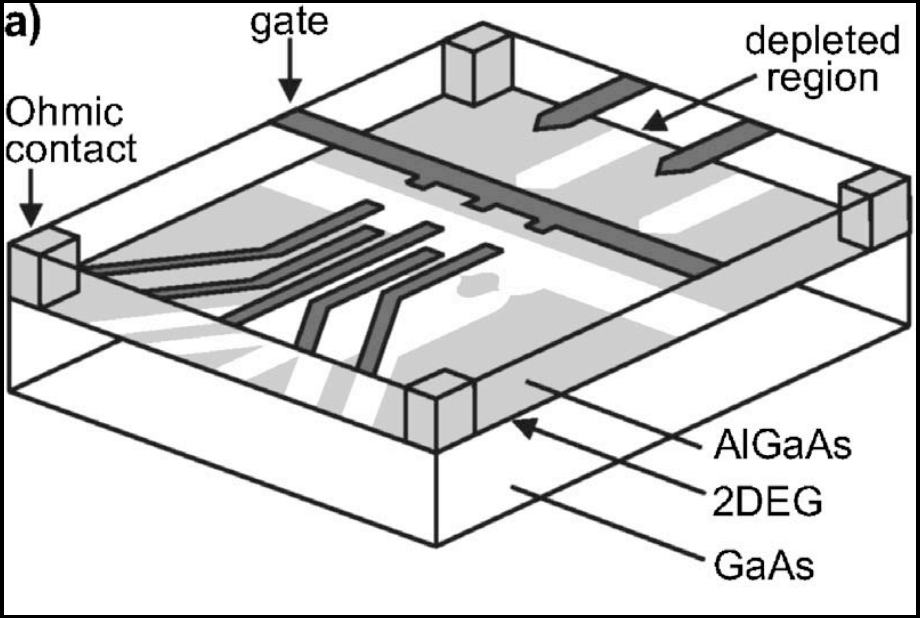
Laterally confined Semiconductor Quantum dots

Martin Ebner and Christoph Faigle

Semiconductor Quantum Dots

1. Material Composition & Fabrication
2. Biasing
3. Energy diagram
4. Coulomb blockade
5. Spin blockade
6. QPC
7. Readout
8. Rabi oscillations
9. Summary

Materials and Fabrication



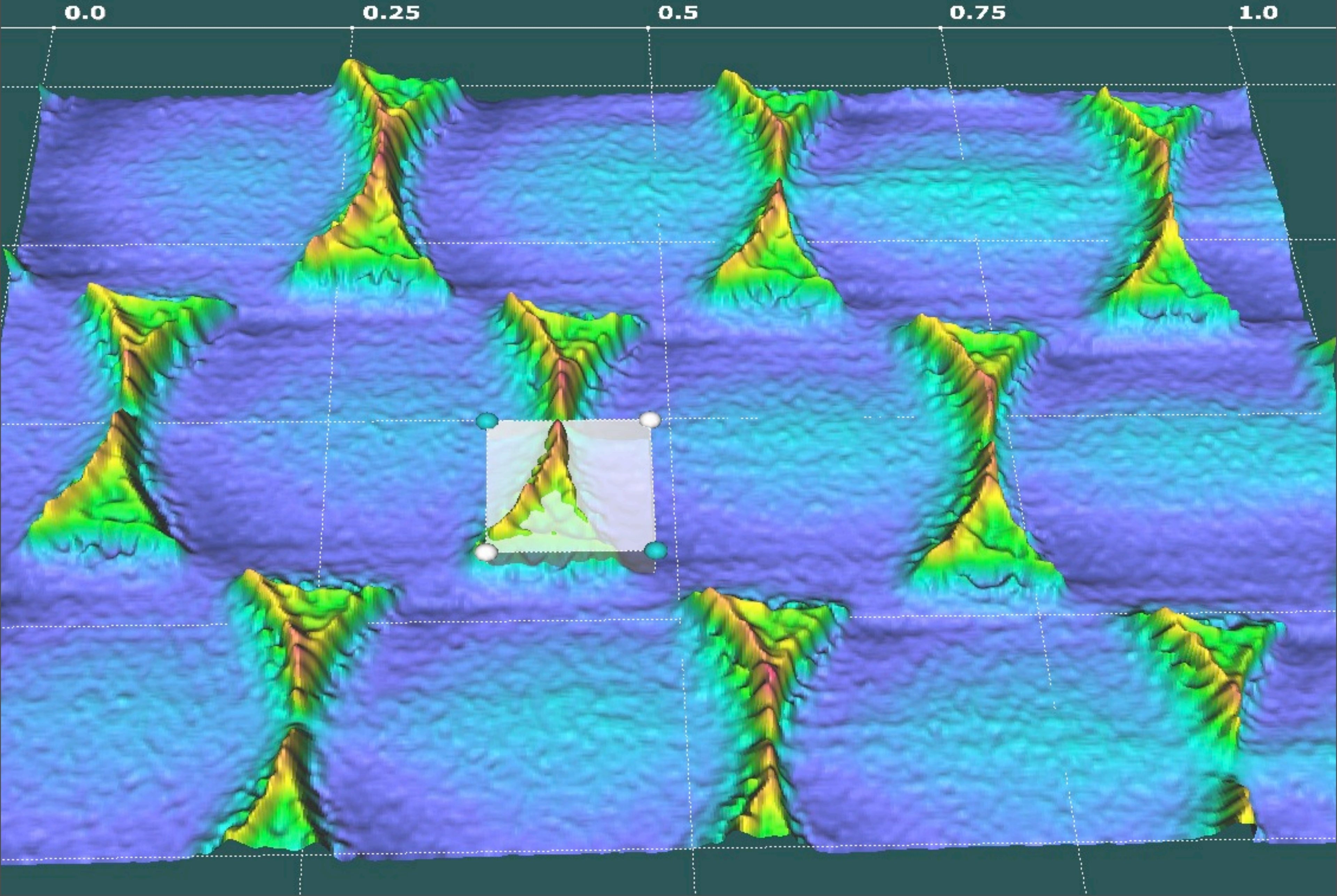
AlGaAs layer doped with Si introduces free electrons which accumulate at the AlGaAs/GaAs interface

creation of 2D electron gas (height ca. 10 nm) at interface.

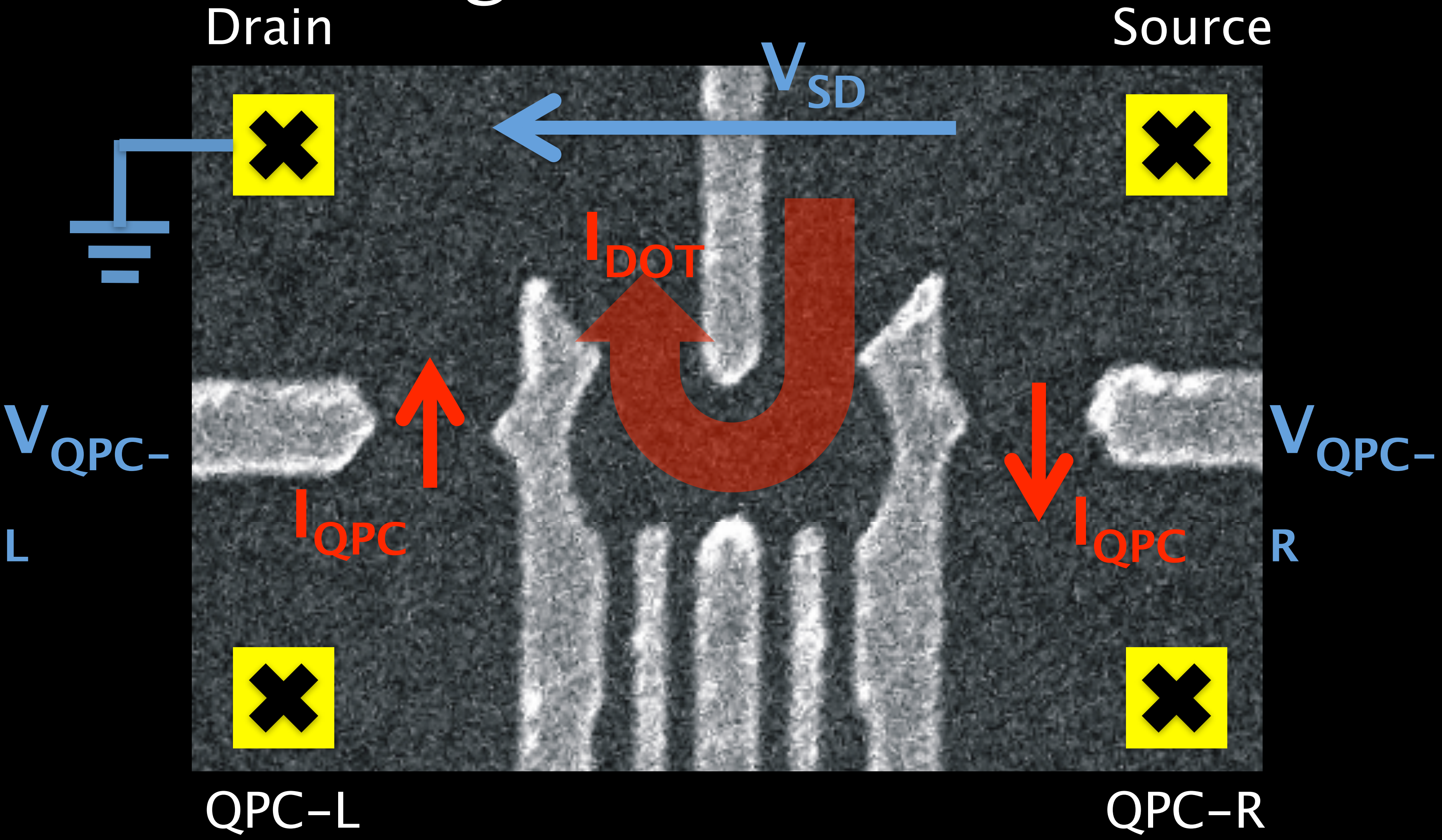
Through molecular beam epitaxy, electrodes are created (~10 nm). Through choice of structure, depleted areas can be isolated from the rest of the electrons -> QDs

By applying voltages to metal electrodes on top of AlGaAs layer, local depletion areas in the 2DEG are created

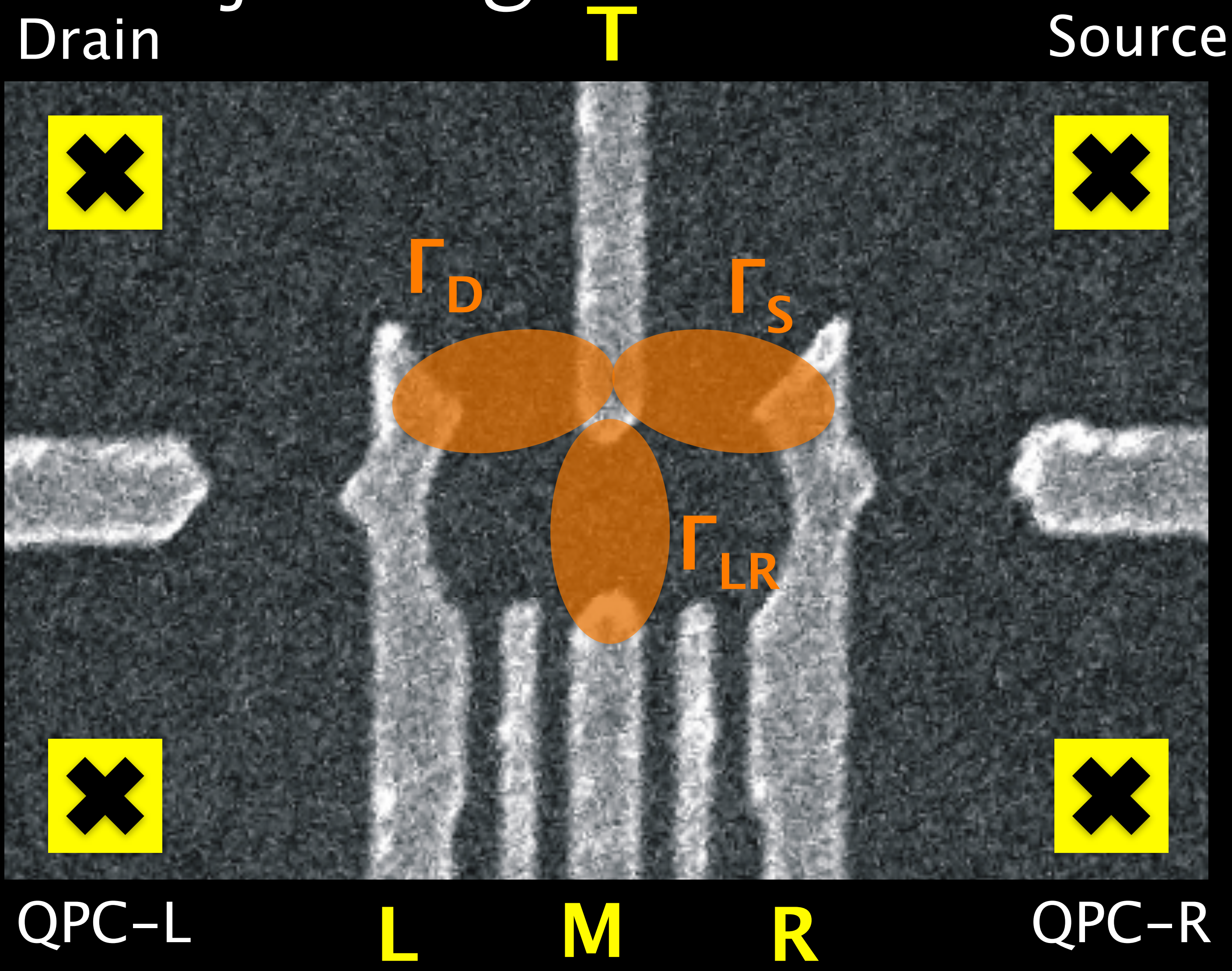
To be able to measure the quantum effects, the device is cooled to 20mK.


0.0
0.25
0.5
0.75
1.0

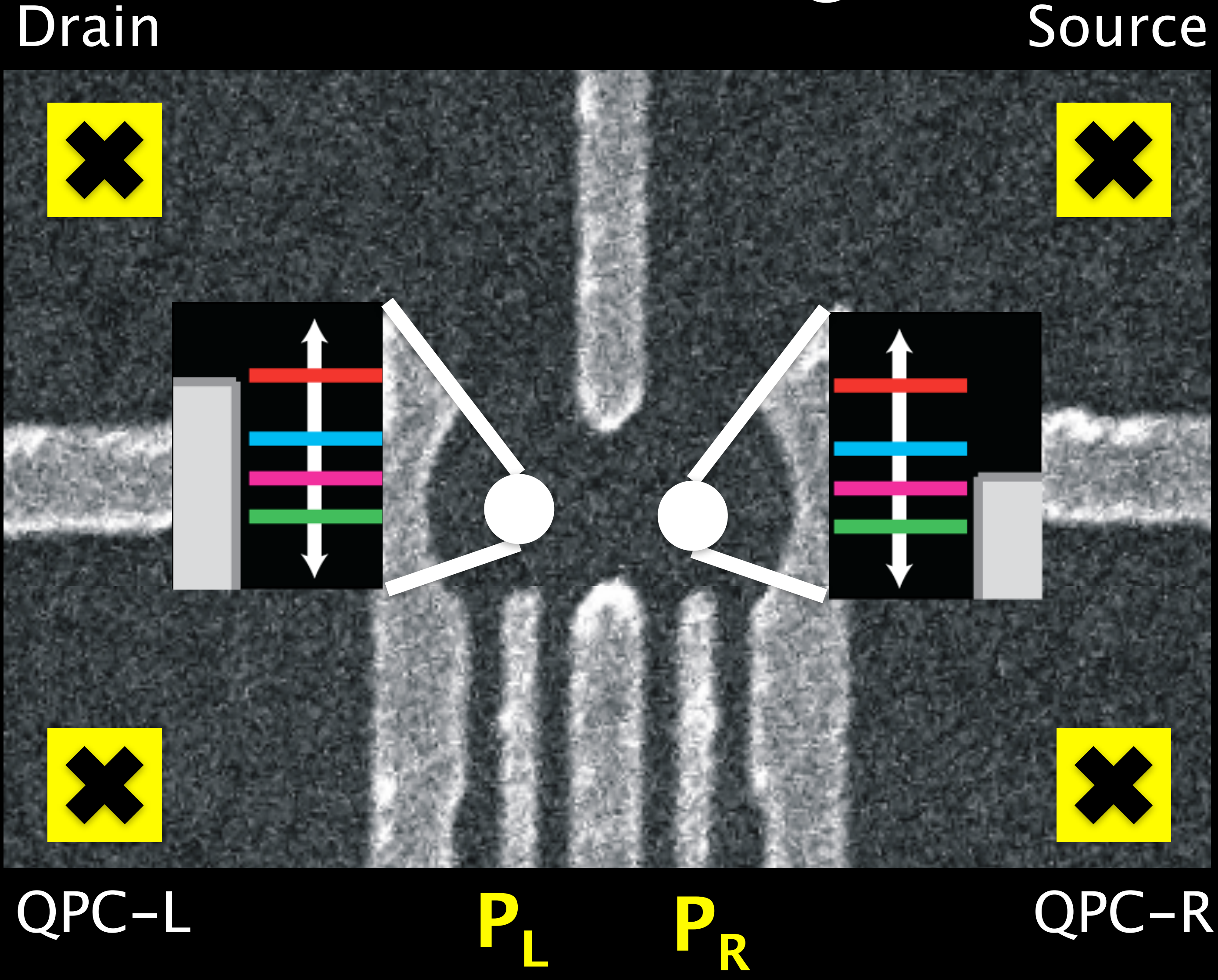
Biasing the Quantum Dot

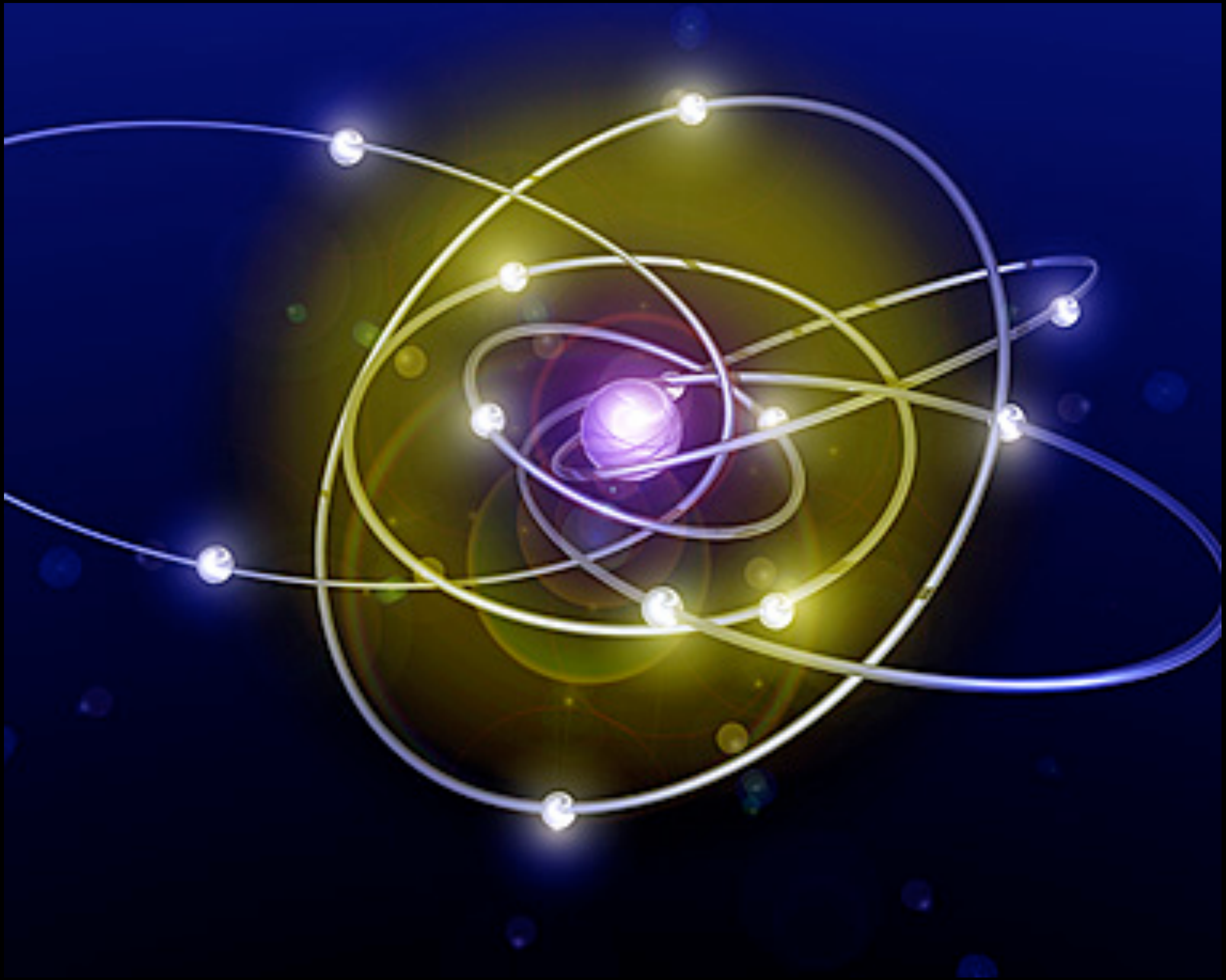


adjusting tunnel rates

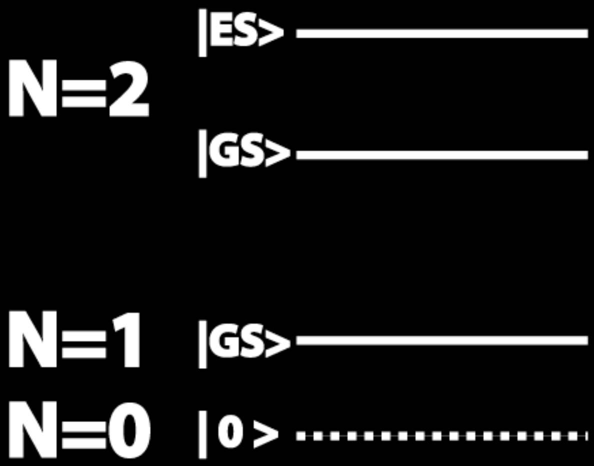


Gate voltages





Energy diagrams

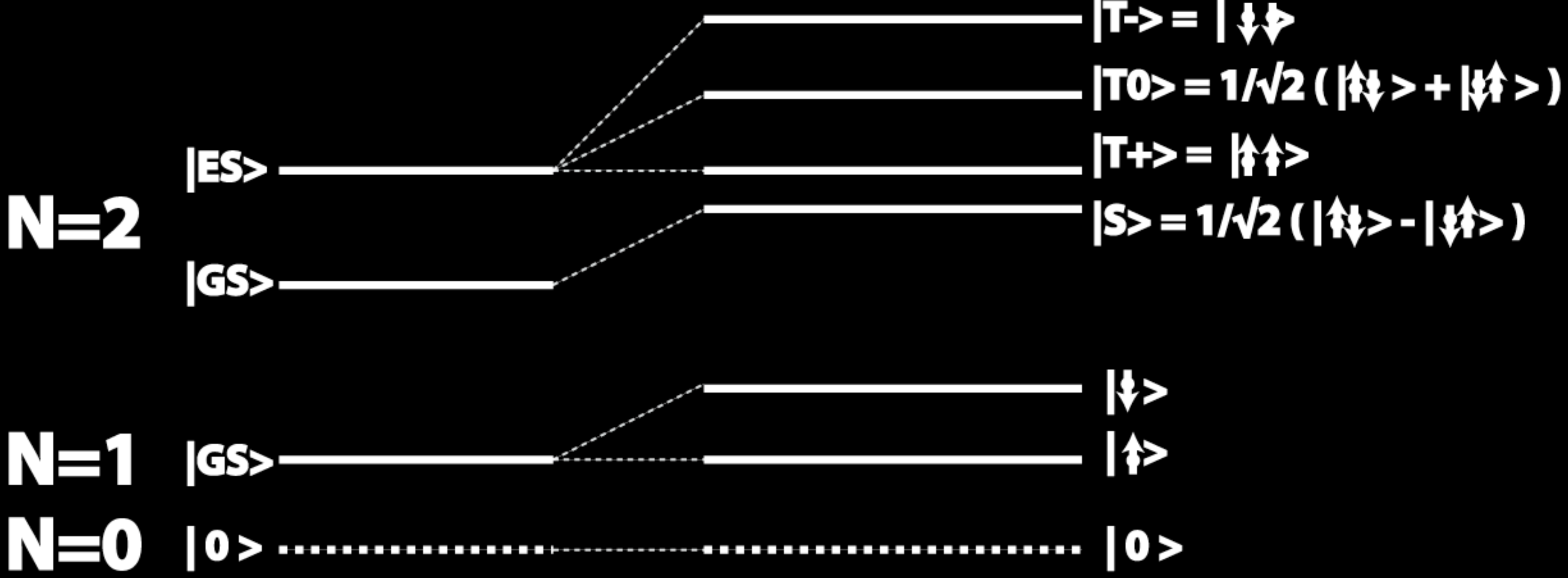


N=2
|ES>
|GS>

N=1
|GS>

N=0
|0 >

Zeeman splitting

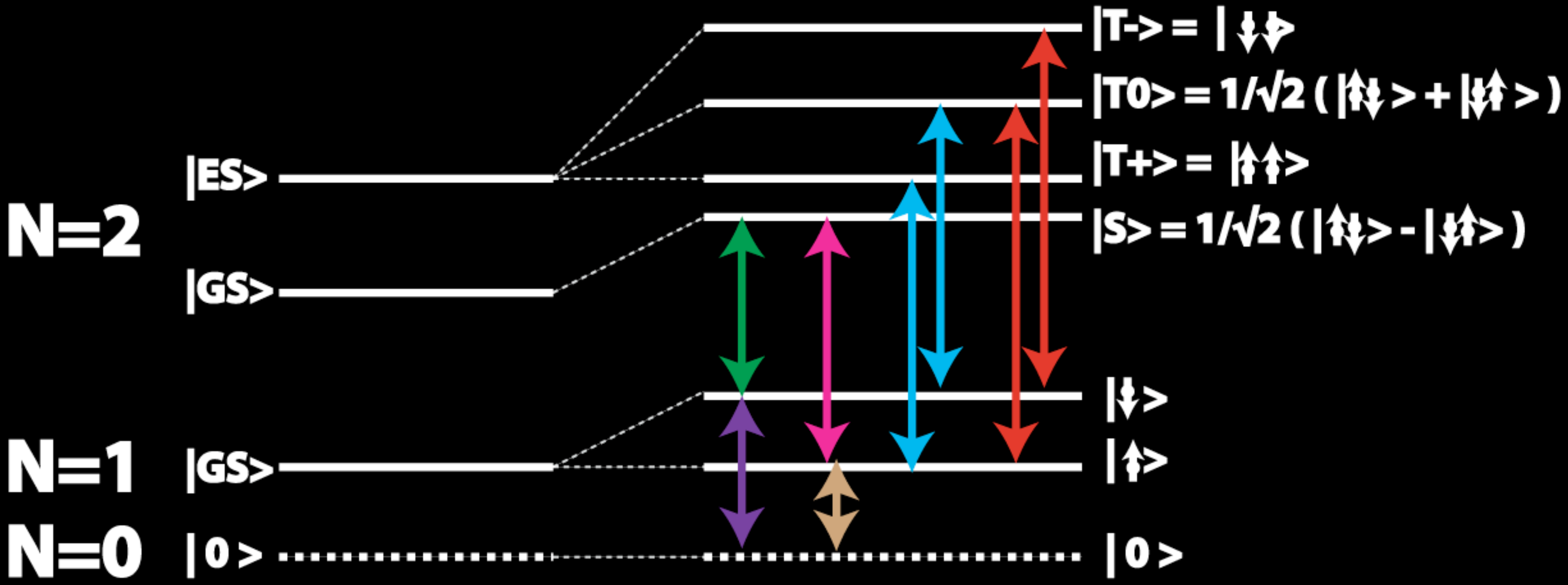


by application of a magnetic field -> Zeeman splitting

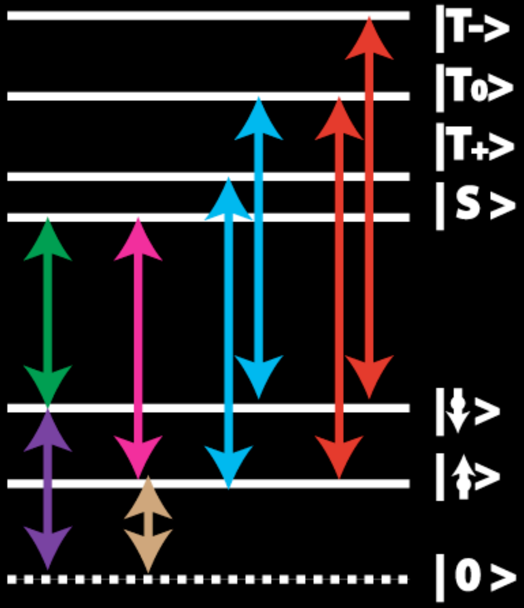
Zeeman splitting

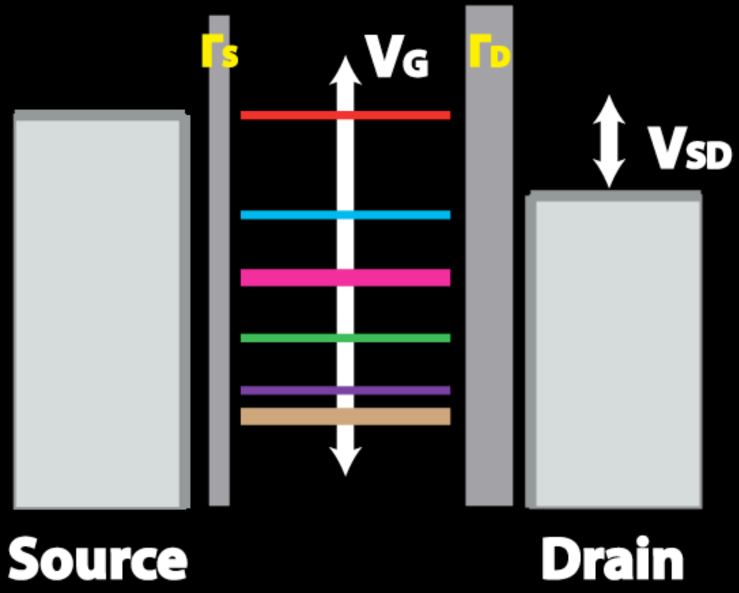
$$\Delta E = g \cdot \mu_B \cdot B$$

State transition energies

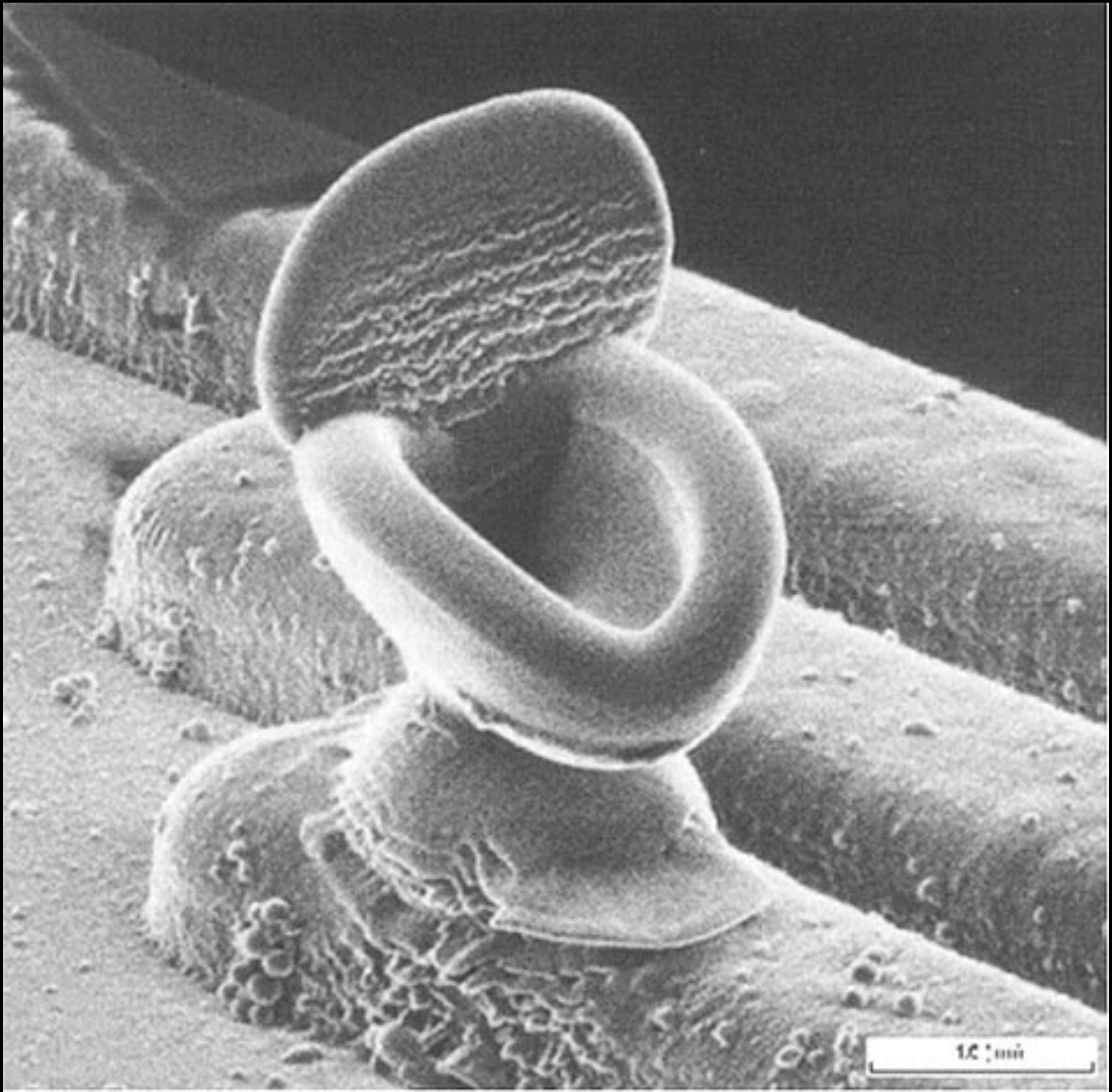


Transition energies and potentials



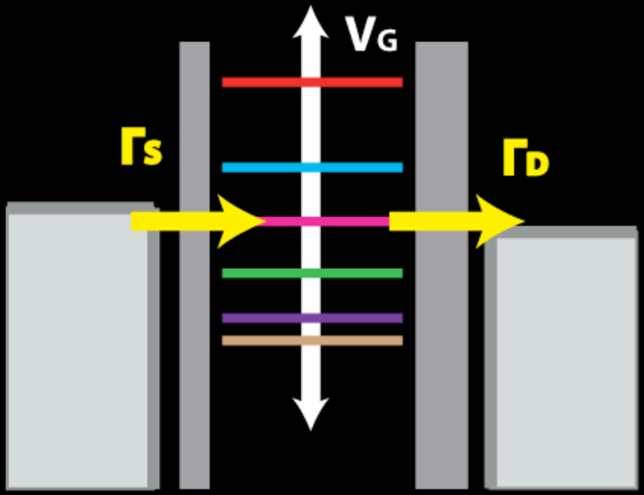


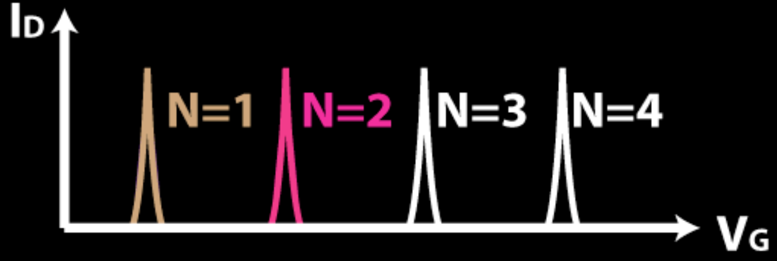
State Preparation: align source potential and transition energy
by tuning V_G


1.0 μm

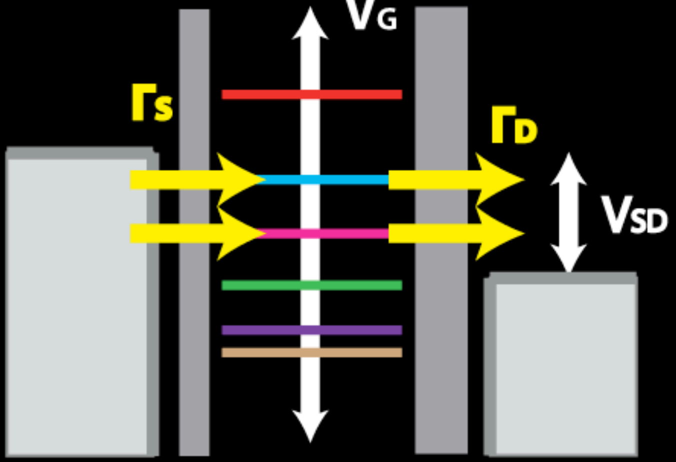
Coulomb blockade

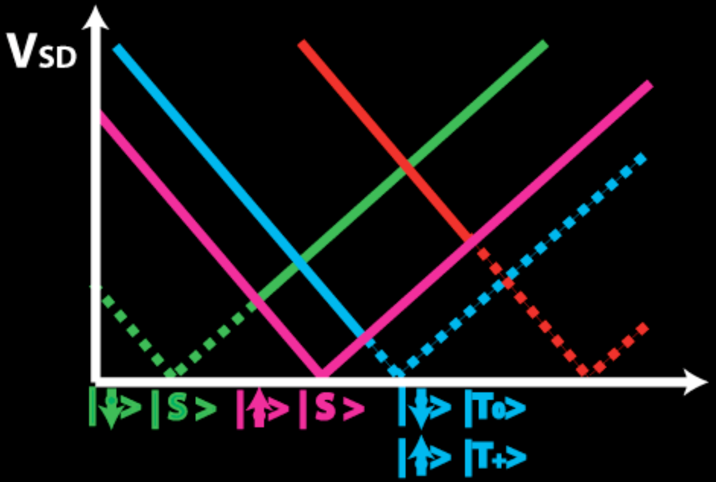
Low-bias regime $V_{SD} < \Delta E_Z$



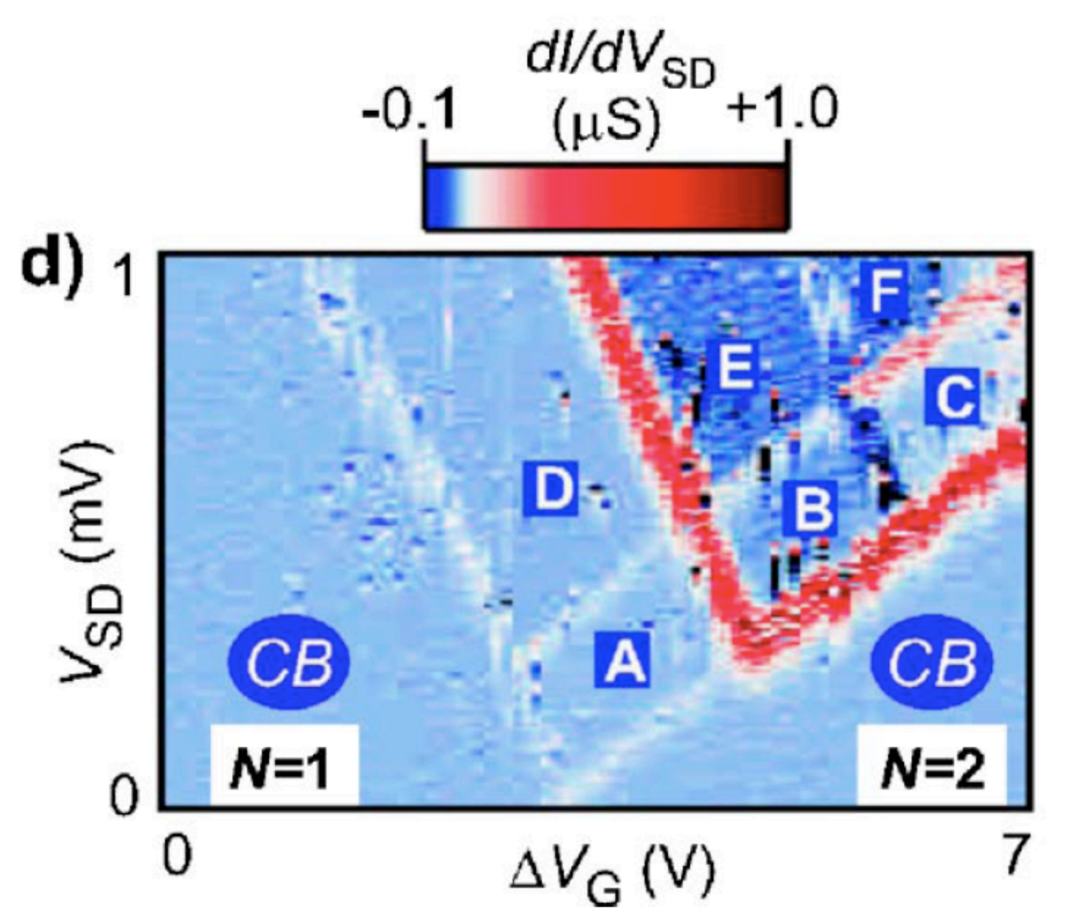


High-bias regime $V_{SD} > \Delta E_Z$





Hanson, Vandersypen *et* al. 2004: Coulomb diamonds

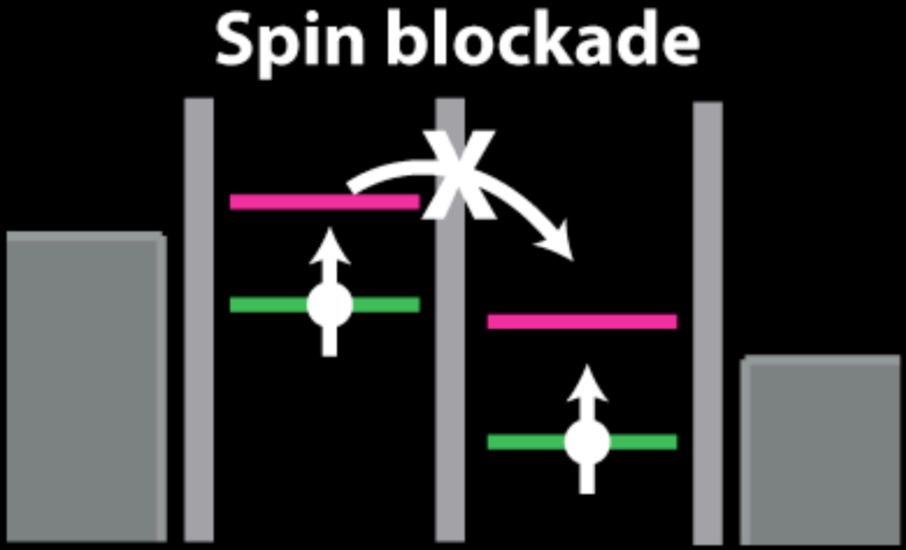


Transition potentials and tunneling

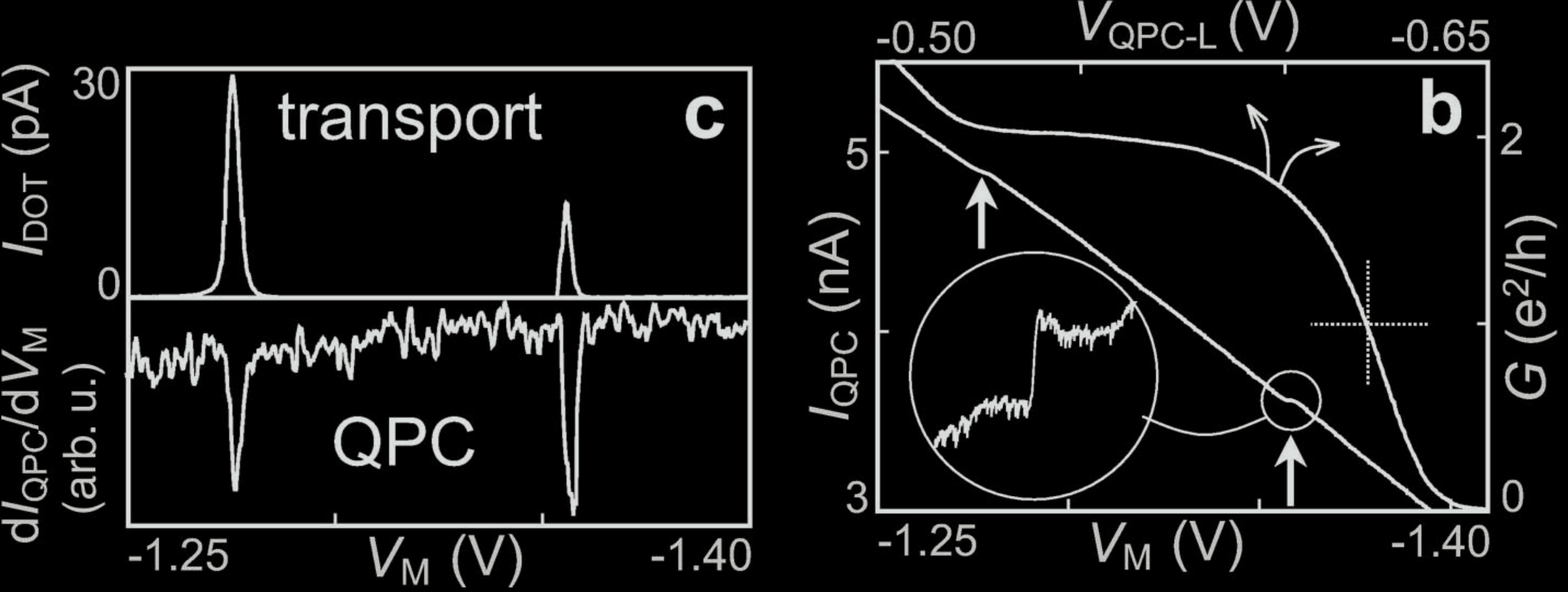
1. Source-drain potential differences lead to single-electron tunneling, depending on the potential of the gate
2. Tunneling works only when **ground to ground-state transition levels** are tuned into the bias window. Once initial current flows excited state transitions can contribute to the tunneling → two-path tunneling
3. If the next ground state also falls into the potential window, there can be two-electron tunneling
4. Allowed regions are mapped by the coulomb diagram, in Coulomb blockade regions, there is no tunneling and thus no current flow

Spin blockade

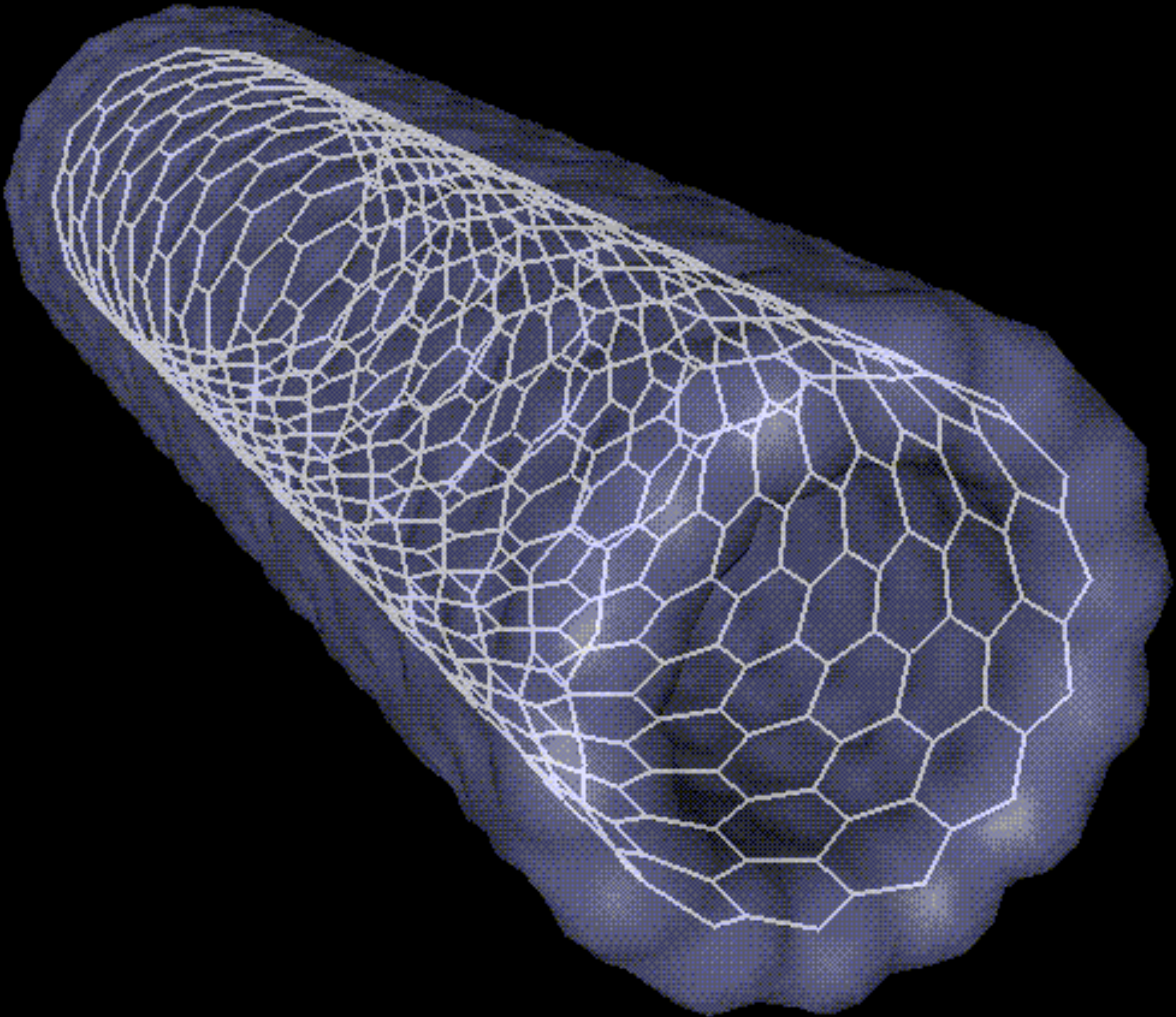
1. According to the Pauli principle, no two electrons with the same spin are allowed on one orbital



QPC



V_{QPC} has to be tuned to regime of maximum sensitivity → steepest

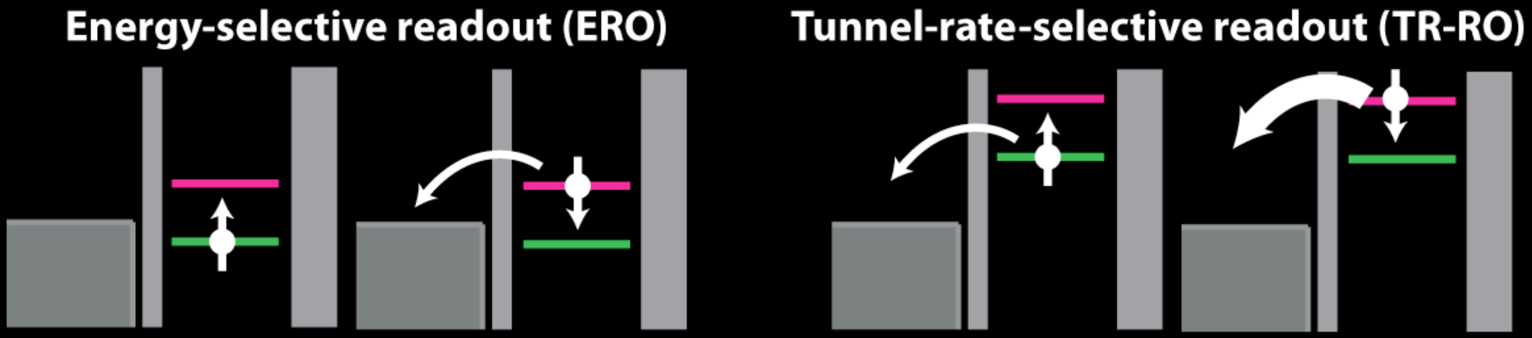


Charge sensing

1. determine number of electrons on dot
2. non-invasive (no current flow)
3. only one reservoir needed
4. conductance of QPC electrometer depends on electrostatic environment
5. failure for long tunnel times and high tunnel barriers
6. measurement time about 10us

Single shot spin readout

1. Spin-to-charge conversion



- Energy selective readout

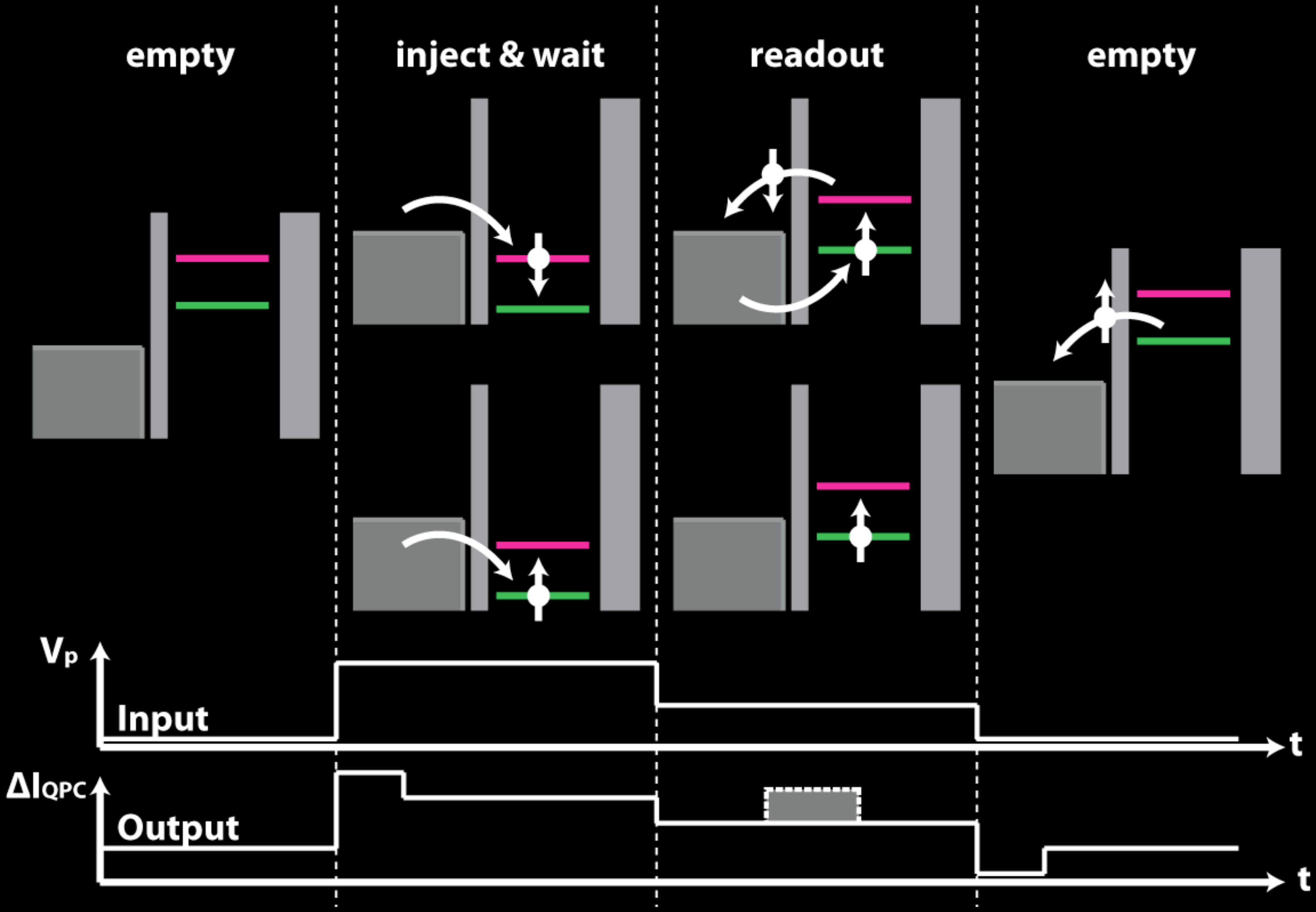
  only excited state can tunnel off quantum dot due to potential

- Tunnel-rate-selective readout

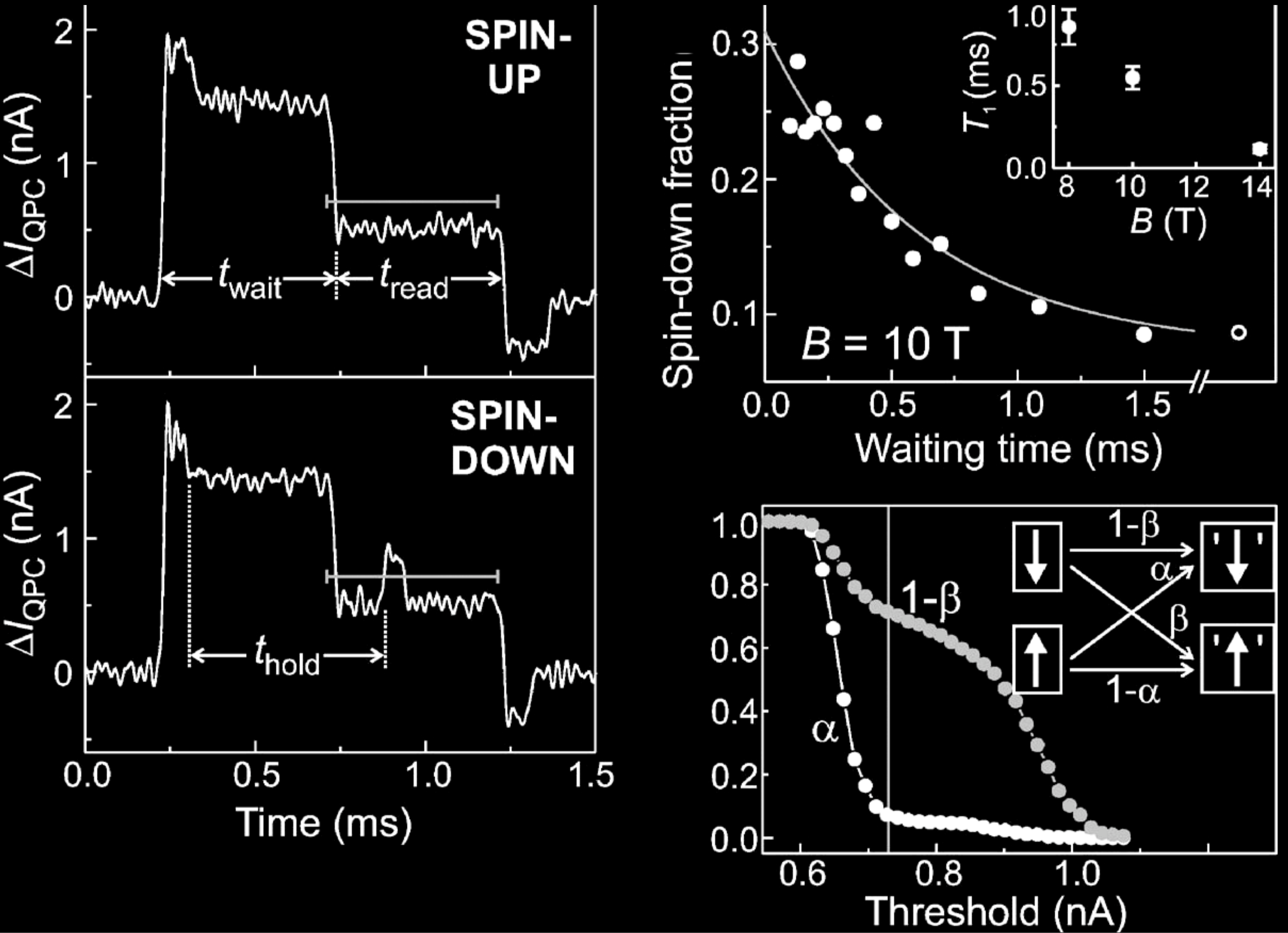
  difference in tunnel rate leads to high probability of one state

  then charge is measured on dot, original state is determined

Energy selective readout

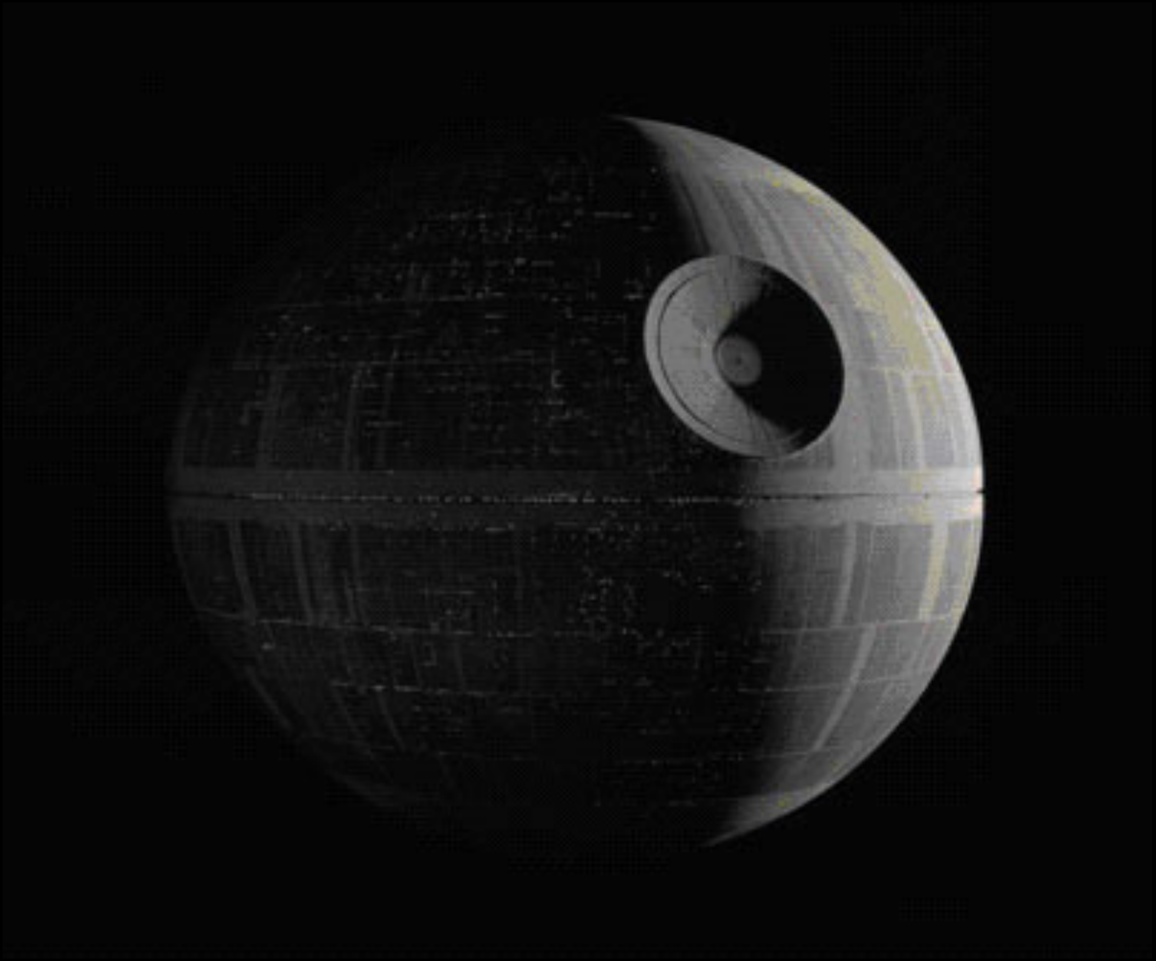


Elzerman *et al.* 2004:
fidelity: 82%, T1: 0.5ms @10 T



EOR Problems

1. requires large Energy splitting: $k_b T \ll \Delta E_Z$
2. sensitive to fluctuations of el.stat. potential
3. photon assisted tunneling from $|\downarrow\rangle$ to reservoir due to high frequency noise ???

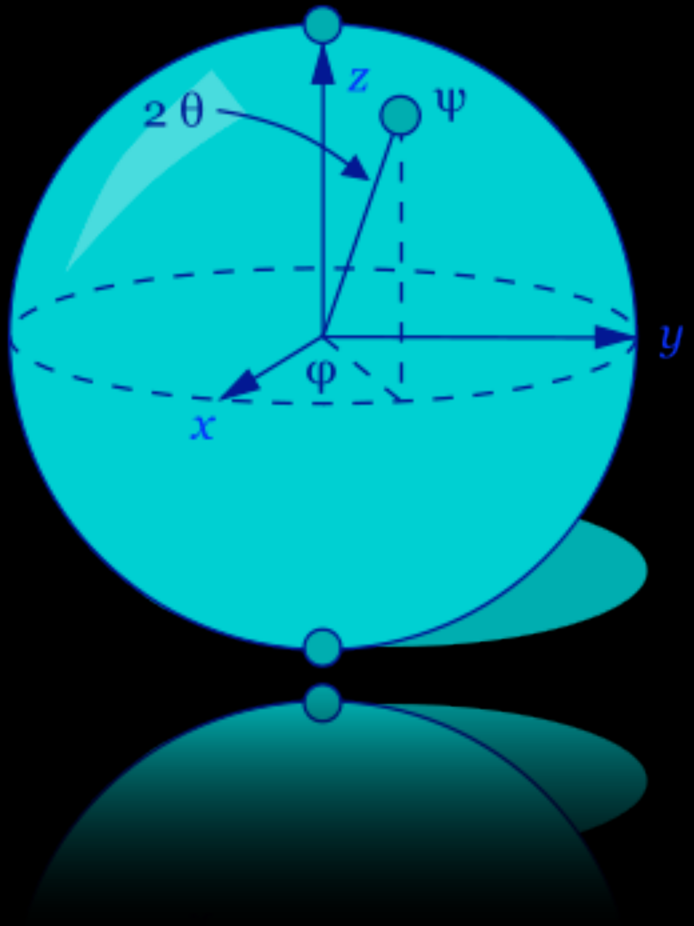


RABI Oscillations

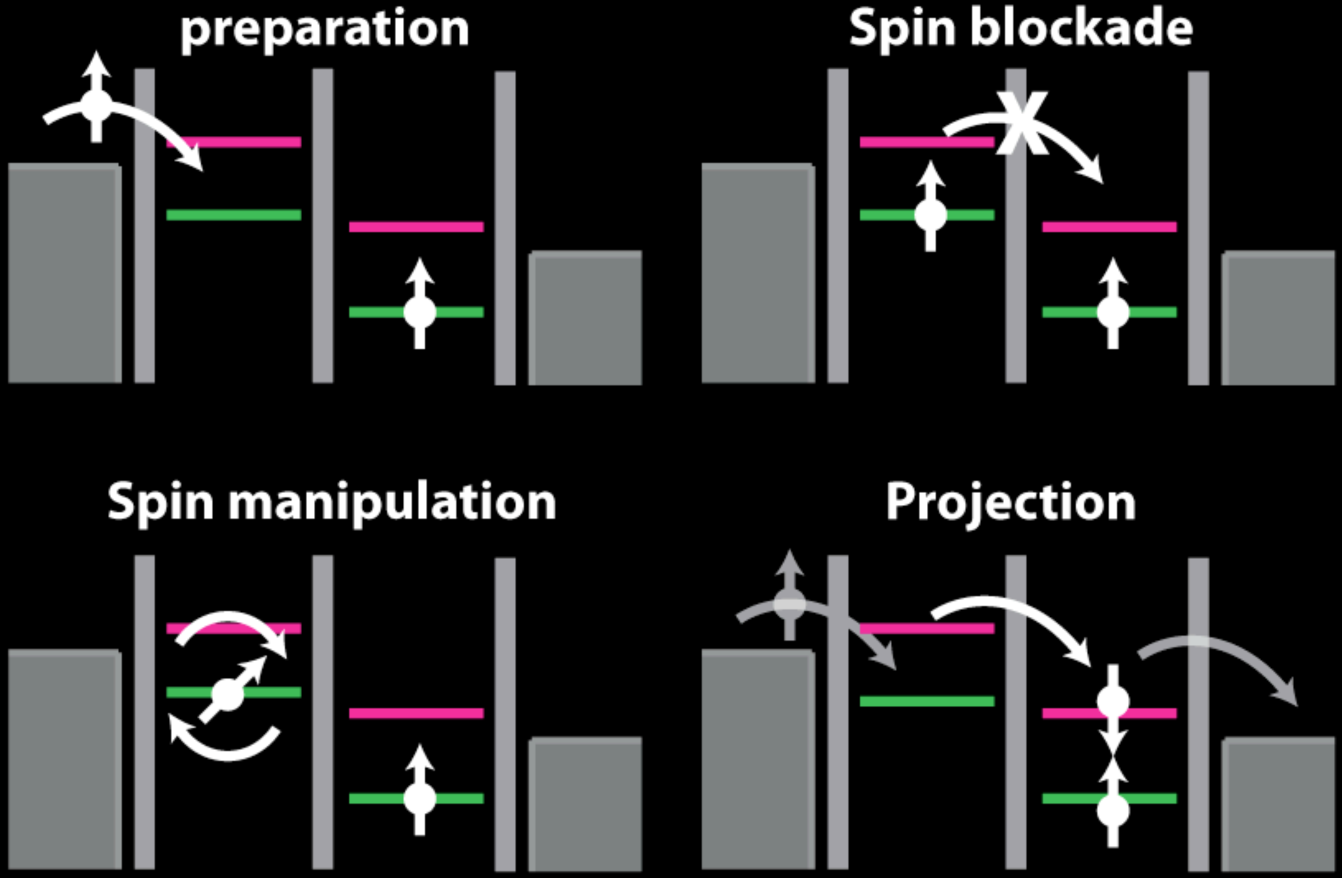
1. ESR: electron spin resonance

2. alternating B_{ac} perpendicular to B_{ext} and resonant to state splitting

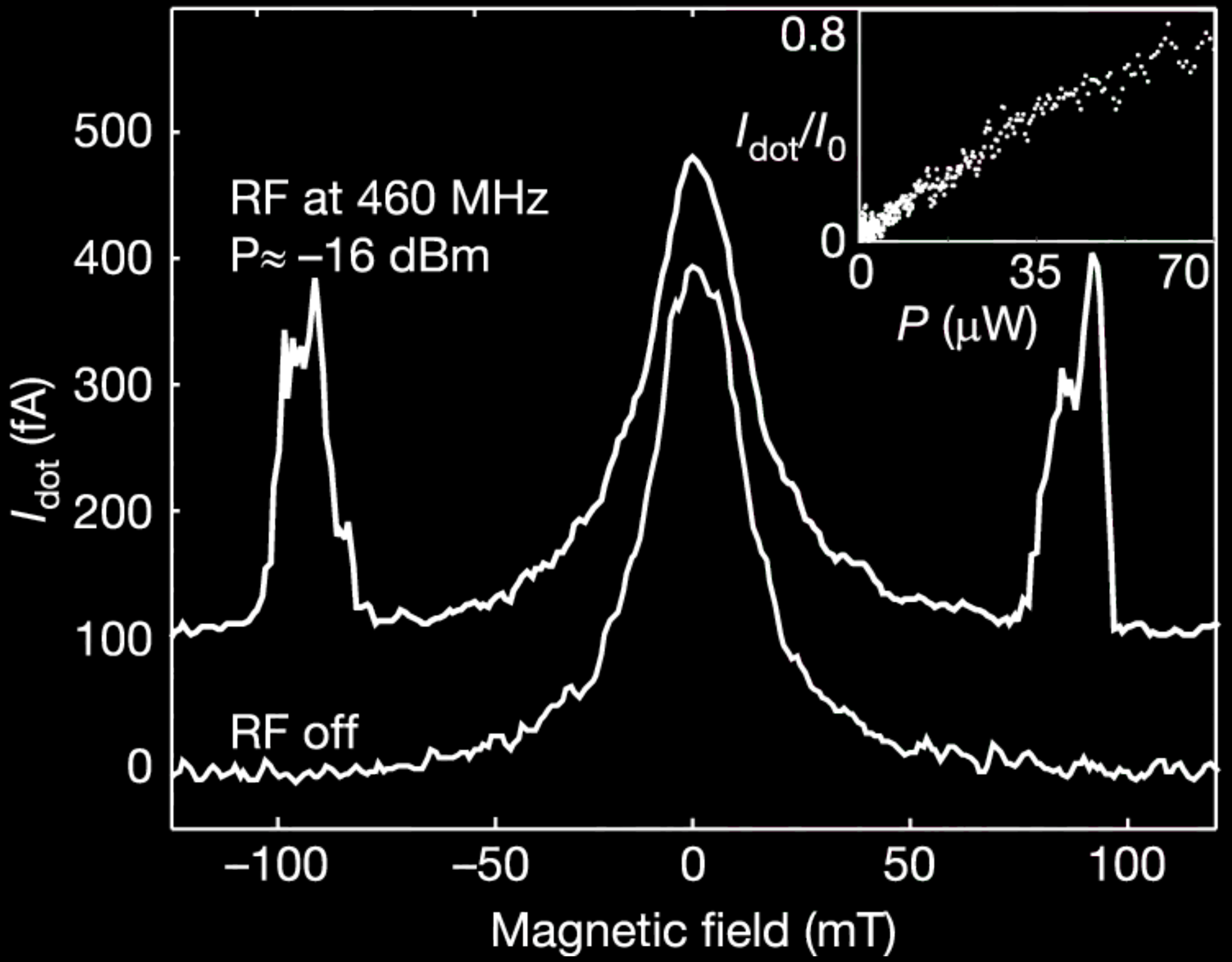
$$h \cdot f_{ac} = g \cdot \mu_B \cdot B_{ext} = \Delta E_Z$$



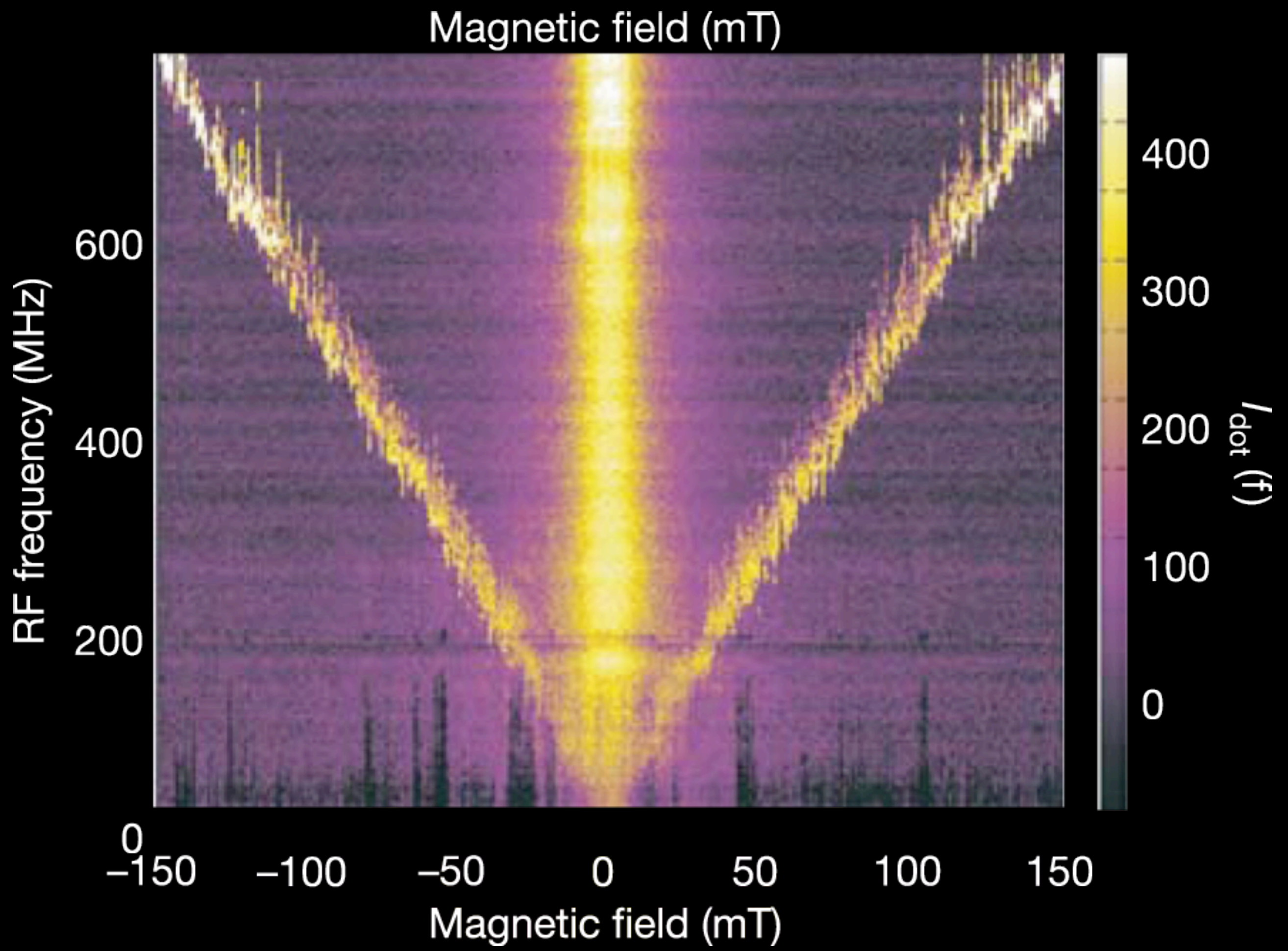
continuous Rabi oscillation detection scheme



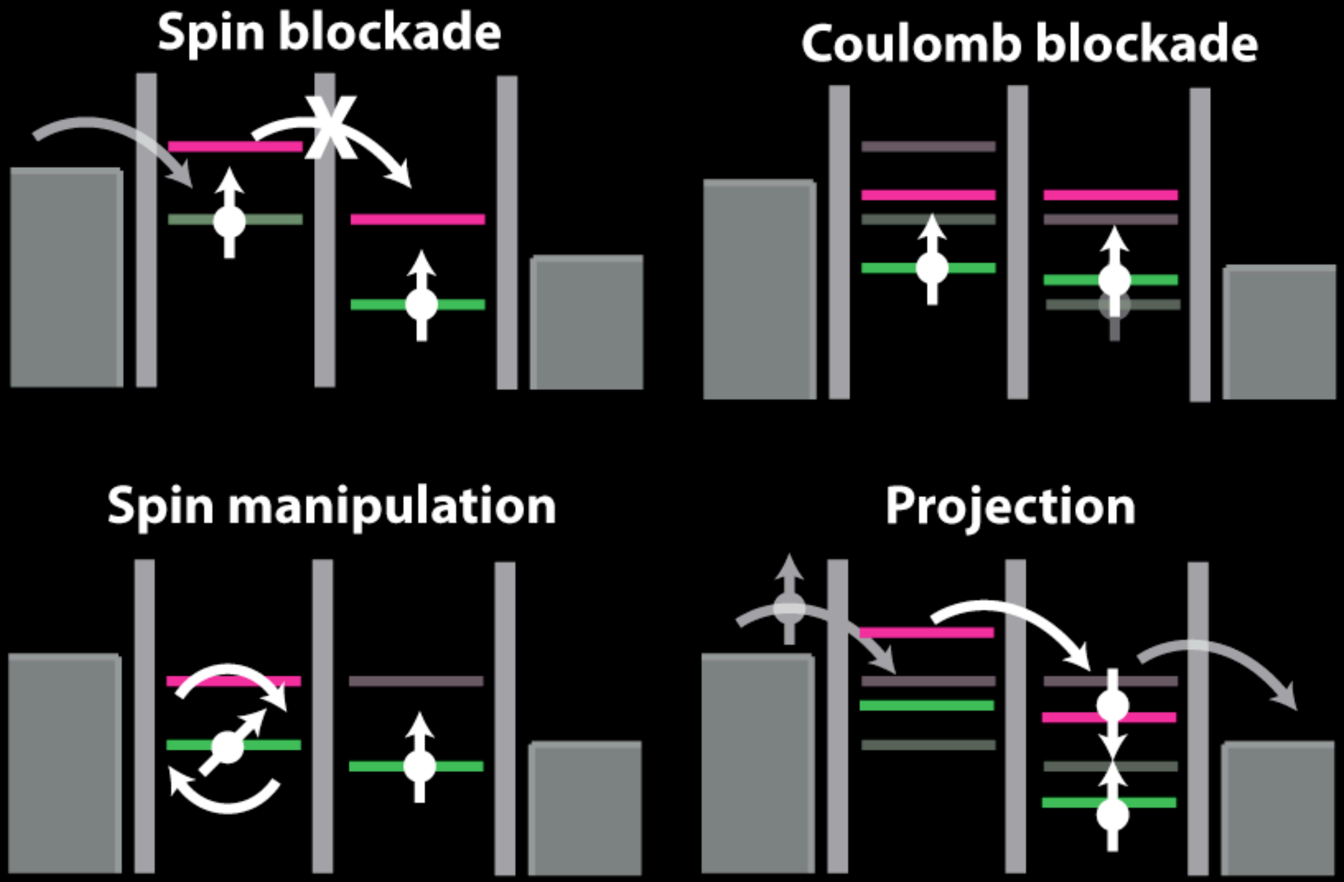
Koppens *et al.*: Tuning B_{ext}



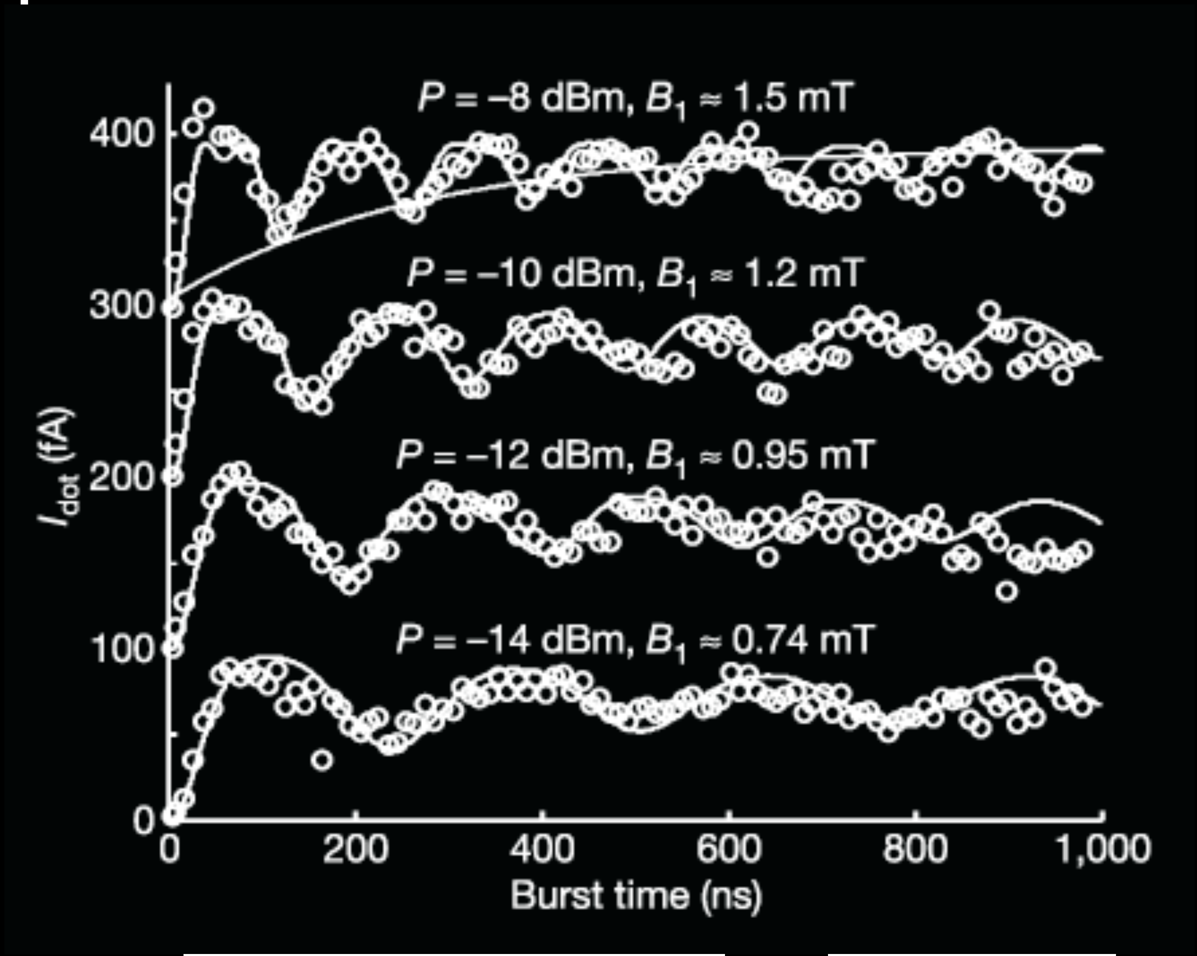
Koppens *et al.*: Tuning B_{ext} and B_{ac}



pulsed Rabi oscillation detection scheme



Koppens *et al.*: Rabi oscillations



$$f_{rabi} = g \cdot \mu_B \cdot \frac{B_1}{h}$$

$$B_1 = \frac{B_{ac}}{2}$$

Rabi performance

1. fidelity: 73% (131° instead of 180°)
   - use stronger B_{ac}
   - application of composite pulses
   - measure and compensate nuclear field fluctuations (nuclear state narrowing)
2. qbit discrimination:
   - B_{ac} or B_{ext} gradient
   - local g-factor engineering
   - use electric field (spin-orbit-interaction)

Summary

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 (relative) decoherence times, much longer than the gate-operation time.? (T1 ≈ 1ms, T_2^* ≈ 10ns, T2 > 1μs [spin echo])
4. A universal set of quantum gates.✖ NO ENTANGLEMENT YET (2005)
5. A qubit-specific measurement capability.✔ ($T_{readout}$ ≈ 10μs)

Thanks for your attention!