Some Extra Reading on Topological Quantum Computation

Review Articles:

- Nayak, Chetan; Simon, Steven H.; Stern, Ady; et al., Non-Abelian anyons and topological quantum computation, *REVIEWS OF MODERN PHYSICS* **80**, 1083-1159 (2008)
- Alicea, Jason, New directions in the pursuit of Majorana fermions in solid state systems, REPORTS ON PROGRESS IN PHYSICS **75**, 076501 (2012)
- Ananda Roy, David P. DiVincenzo, Topological Quantum Computing, arXiv:1701.05052 (2017)

Original Research:

- Sau, Jay D.; Lutchyn, Roman M.; Tewari, Sumanta; et al., Generic New Platform for Topological Quantum Computation Using Semiconductor Heterostructures, PHYSICAL REVIEW LETTERS **104**, 040502 (2010)
- Jason Alicea et al., Non-Abelian statistics and topological quantum information processing in 1D wire networks, *Nature Physics* **7**, 412–417 (2011)
- Mourik, V.; Zuo, K.; Frolov, S. M.; et al., Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices, SCIENCE **336** 6084, 1003 (2012)

Lecture 9, April 26, 2018

This week:

- Semiconductor quantum dots for QIP
  - Introduction to QDs
  - Single spins for qubits
    - Initialization
    - Read-Out
    - Single qubit gates

Please take a seat
in the front center part of the lecture hall
if you do not mind.

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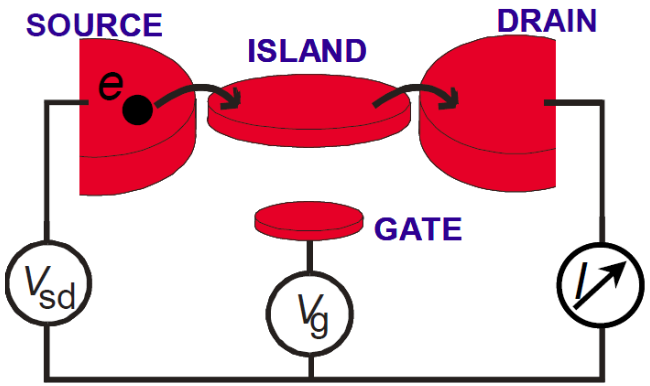
- R. Hanson, L. P. Kouwenhoven, J. R. Petta et al., Spins in few-electron quantum dots, *Reviews of Modern Physics* **79**, 1217 (2007)
- R. Hanson, & D. D. Awschalom, Coherent manipulation of single spins in semiconductors, *Nature* **453**, 1043 (2008)

Electrically Controlled and Measured Quantum Dots

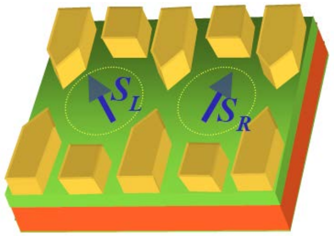
A small semiconducting (or metallic) island where electrons are confined, giving a discrete level spectrum



- Coupled via tunnel barriers to source and drain reservoirs
- Coupled capacitively to gate electrode, to control # of electrons

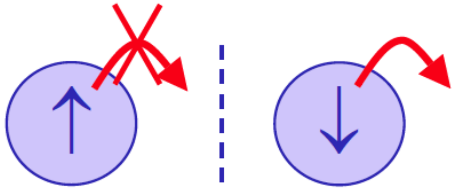
Slides and material courtesy of Lieven Vandersypen, TU Delft

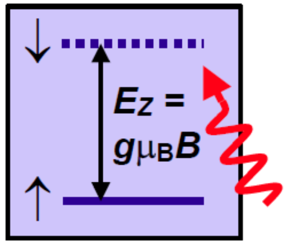
Spin Qubits in Quantum Dots

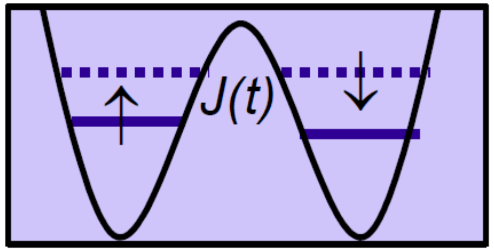


Loss & DiVincenzo,
PRA **57**, 120 (1998)
Vandersypen *et al.*,
Proc. MQC02 (quant-ph/0207059)

Initialization	1-electron, low T, high B_0 $H_0 \sim \Sigma\, \omega_i\, \sigma_{zi}$
Read-out	convert spin to charge then measure charge
ESR	pulsed microwave magnetic field $H_{RF} \sim \Sigma\, A_i(t) \cos(\omega_i t)\; \sigma_{xi}$
SWAP	exchange interaction $H_J \sim \Sigma\, J_{ij}(t)\; \sigma_i \cdot \sigma_j$
Coherence	long relaxation time T_1 long coherence time T_2







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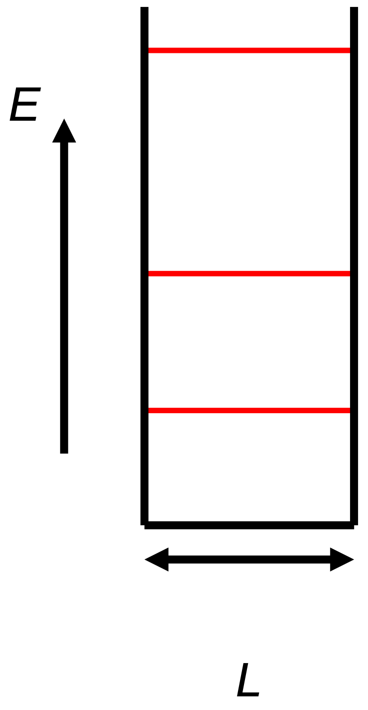
Electrons in Atoms, Quantum Dots

Schrödinger:
electrons in confined systems occupy quantized energy levels



Particle in a box:

$$E_n = \frac{\hbar^2}{2m}\left(\frac{\pi n}{L}\right)^2, \quad n = 1, 2, 3\ldots$$

QDs: 0.1 meV
Atoms: 10 eV

1 meV ~ 250 GHz

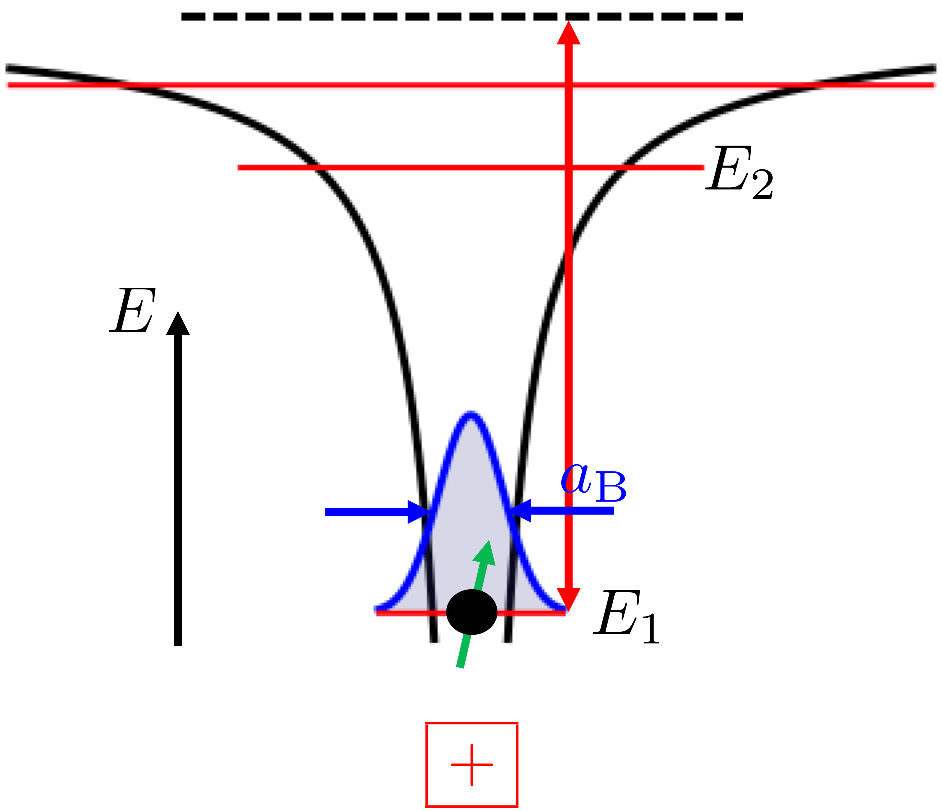
Pauli:
each level can be occupied with one spin-up electron and one spin-down electron

The Hydrogen Atom

Quantized energy levels in the hydrogen atom

$$E_n = -\frac{E_{\mathrm{Ry}}}{n^2}, \quad n = 1, 2, 3 \ldots$$

Single-particle level spectrum



$$E_{\mathrm{Ry}} = \frac{2m}{\hbar^2}\left(\frac{e^2}{8\pi\epsilon_0}\right)^2$$

Atoms: 13.6 eV
GaAs: 6 meV

$$a_{\mathrm{B}} = \frac{\hbar^2}{2m}\left(\frac{8\pi\epsilon_0}{e^2}\right)$$

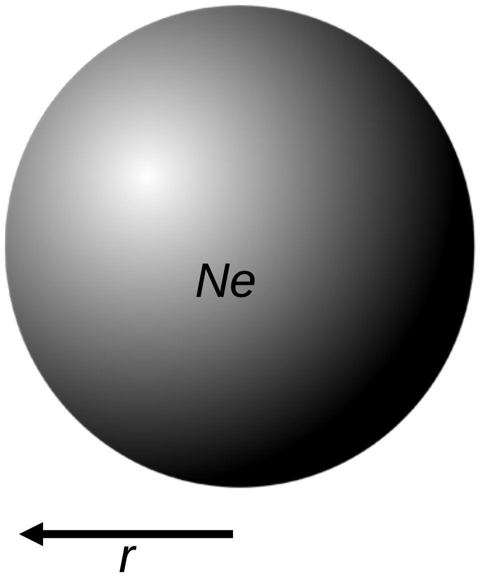
Atoms: 0.53 Å
GaAs: 10 nm

Pauli:
each level can be occupied with one spin-up electron and one spin-down electron

E. Schrödinger, Phys. Rev. **28**, 1049 (1926).

Electrons in Atoms, Quantum Dots

electrons in confined systems interact via Coulomb repulsion



Electrostatic/charging energy

$$E_C = \frac{Q^2}{2C} = \frac{e^2 N^2}{2C}, \quad N \text{ (large) integer}$$

QDs: 1 meV
Atoms: 10 eV

$$C = 4\pi\varepsilon\varepsilon_0 r \quad \text{(Sphere)}$$

$$\Rightarrow E_C = \frac{e^2 N^2}{8\pi\epsilon\epsilon_0 r}, \quad N \text{ (large) integer}$$

Slides and material courtesy of Thomas Ihn, ETH Zurich

Atoms vs. Quantum Dots

	Atom	Quantum dot
Confinement	r^{-1},strong, rigid, hard to tune	r^2, soft, parabolic, tunable
Symmetry	perfect, given by nature	never perfect, hard to achieve
Electrical addressing	hard to achieve	well suitable tunable coupling
Optical addressing	well suitable	well suitable
Coupling to	thermal photons, ...	photons, phonons, other electrons

Both systems give access to single electron/spin manipulation

Slides and material courtesy of Thomas Ihn, ETH Zurich

Lecture 10, May 3, 2018

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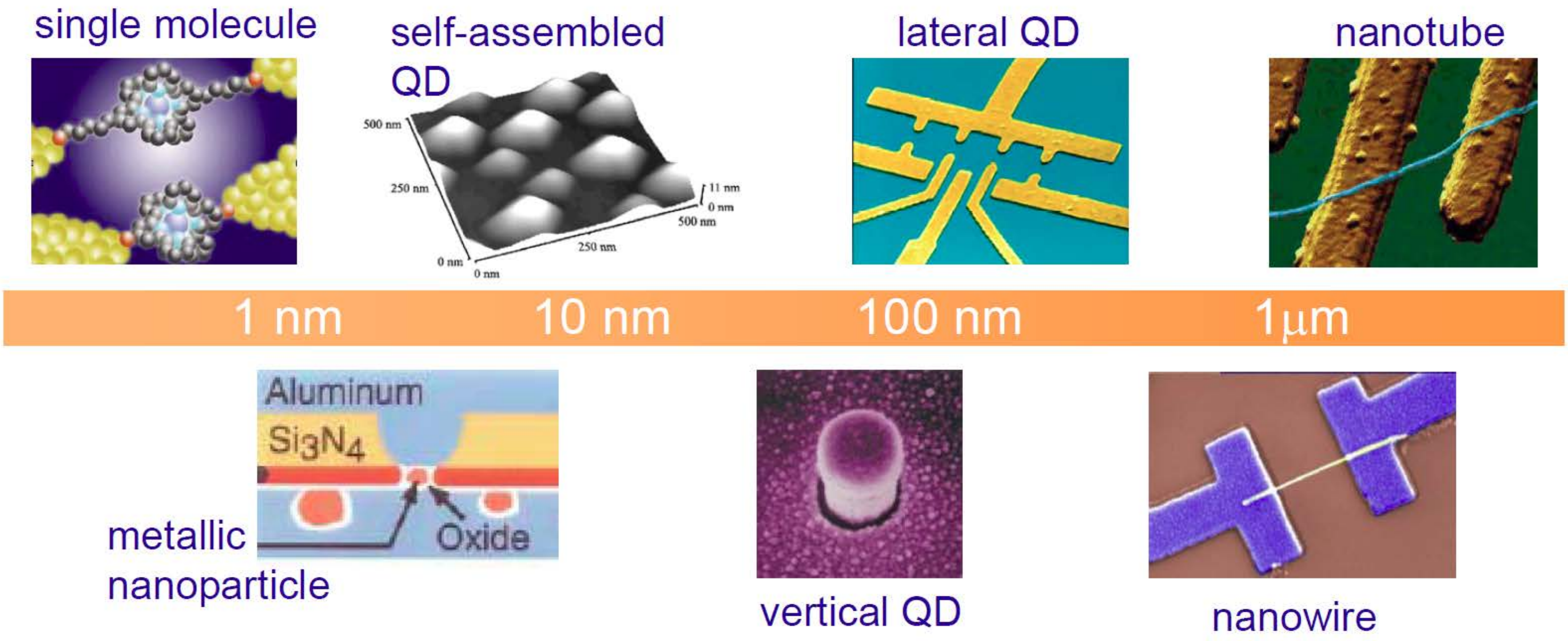
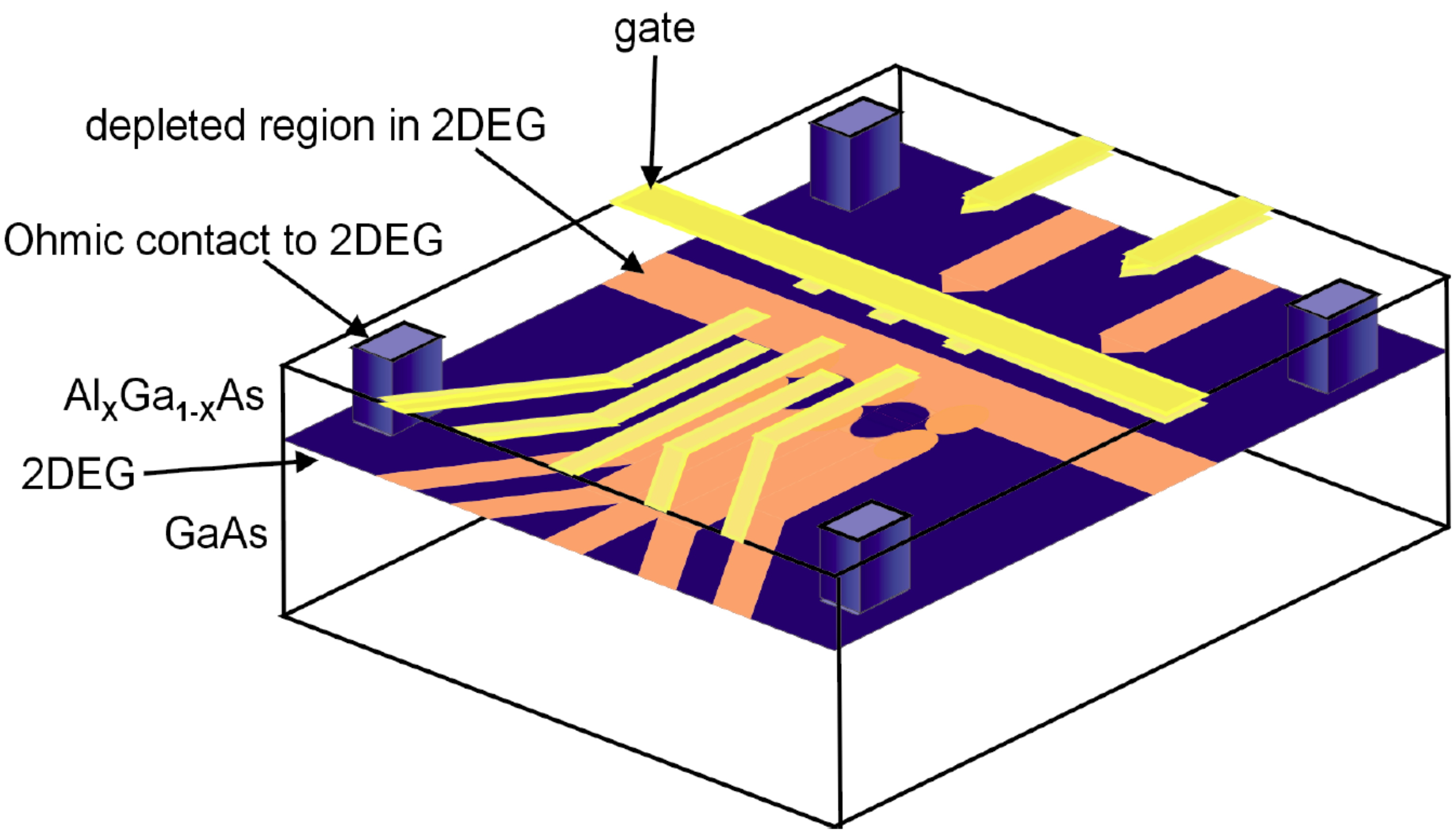
- R. Hanson, & D. D. Awschalom, Coherent manipulation of single spins in semiconductors, *Nature* **453**, 1043 (2008)

Examples of Quantum Dots

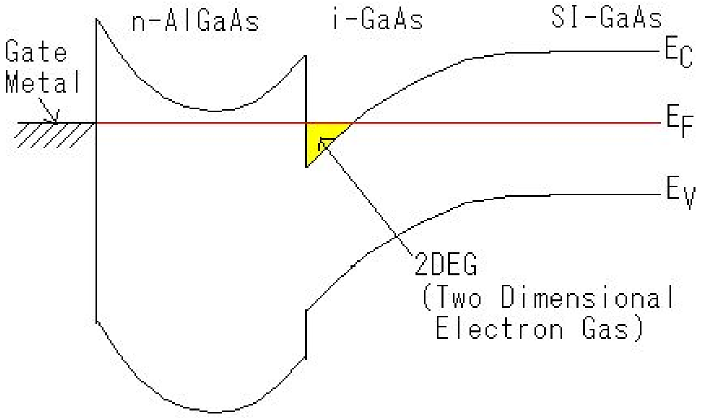


Slides and material courtesy of Lieven Vandersypen, TU Delft

Electrostatically Defined Quantum Dots

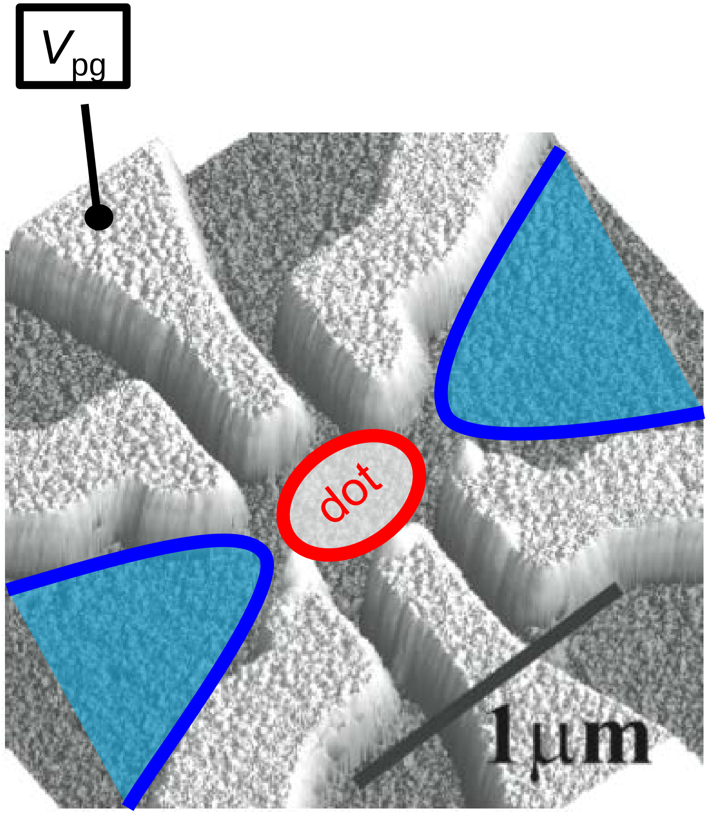


- Electrically measured (contact to 2DEG)
- Electrically controlled number of electrons
- Electrically controlled tunnel barriers



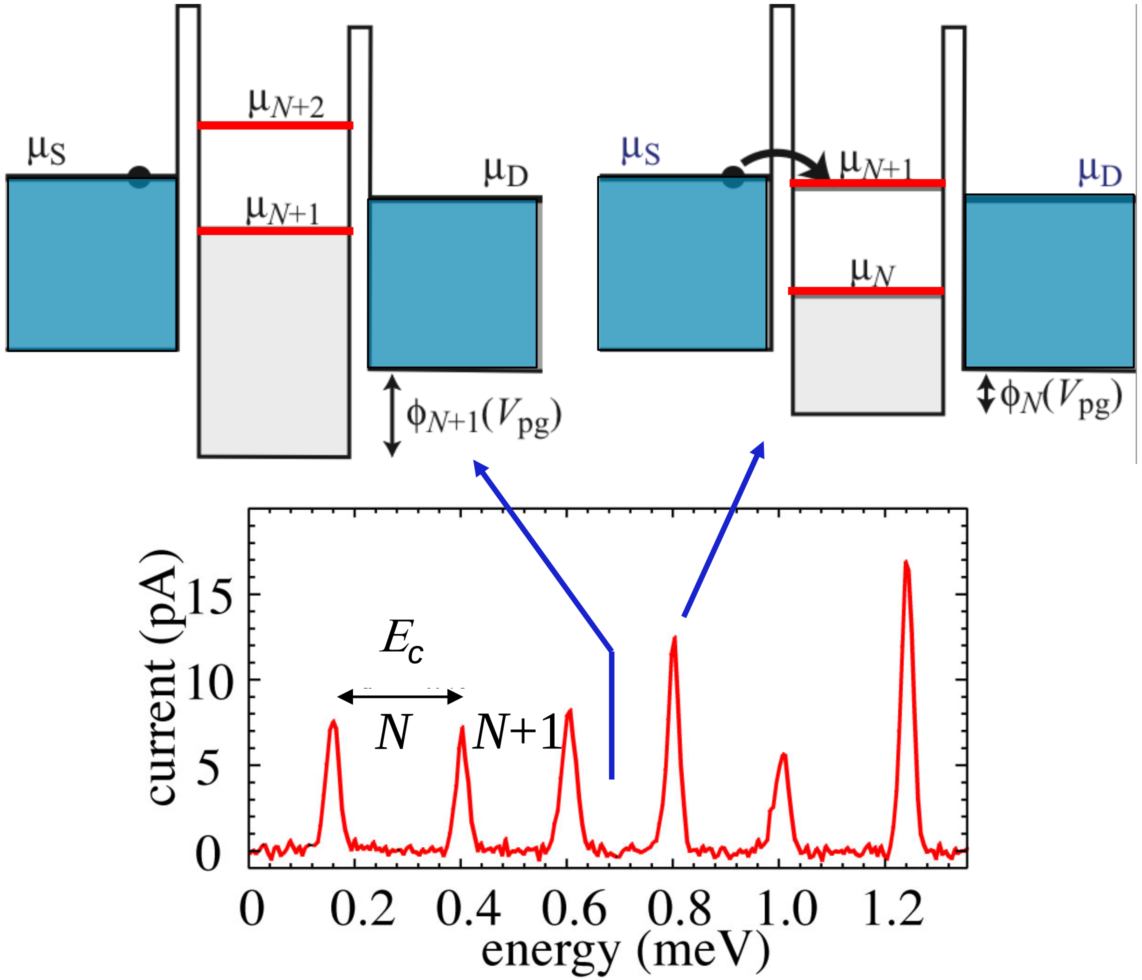
Slides and material courtesy of Lieven Vandersypen, TU Delft
http://vandersypenlab.tudelft.nl/

Coulomb Blockade



Coulomb blockade

Resonant transport

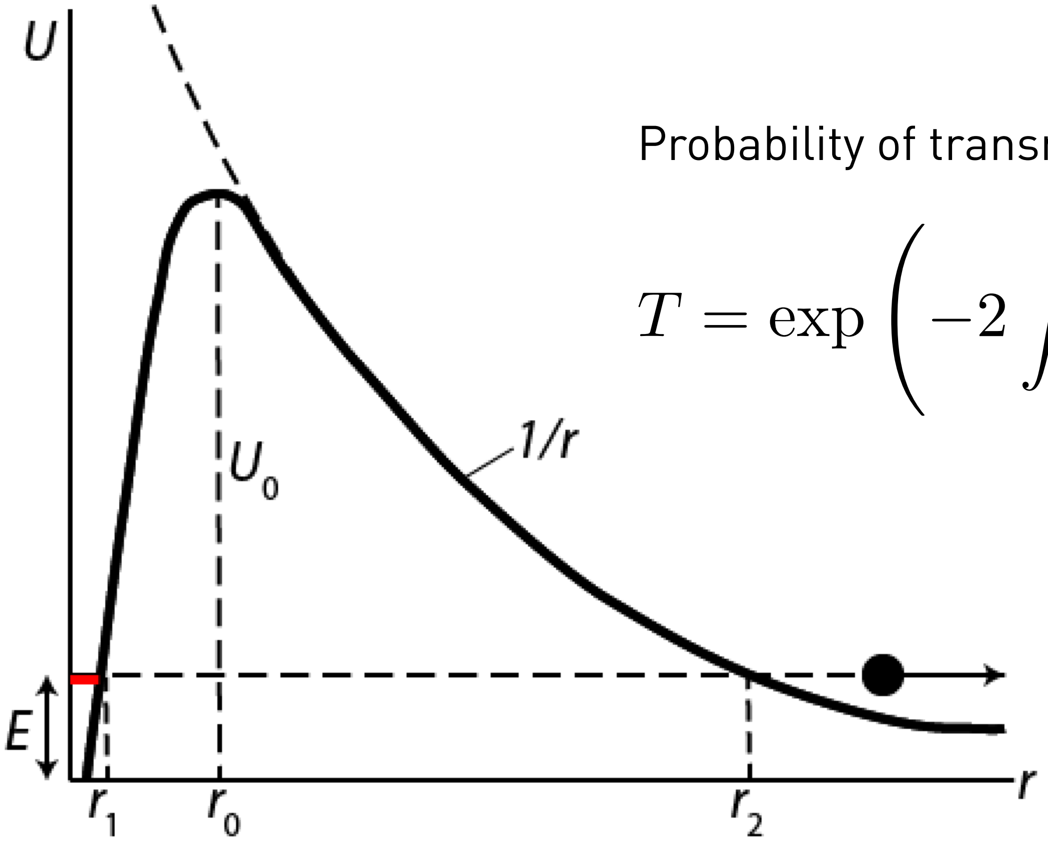


Quantum effects become visible at temperatures < 4.2 K

Slides and material courtesy of Thomas Ihn, ETH Zurich

Tunneling from Discrete Levels

α-decay described by tunneling from quantized levels:



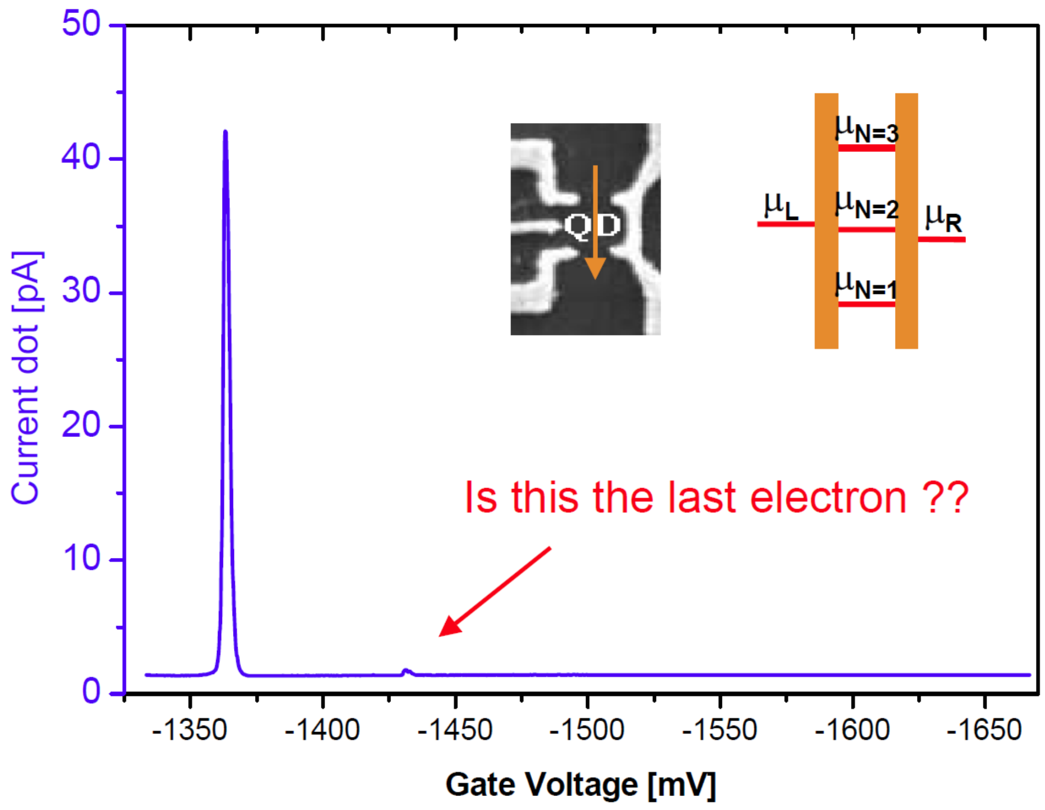
Probability of transmission through barrier (WKB approx.):

$$T = \exp\left(-2\int_{x_1}^{x_2}\sqrt{\frac{2m[U(x)-E]}{\hbar^2}}dx\right)$$

G. Gamov, Z. Phys. **51**, 204 (1928).

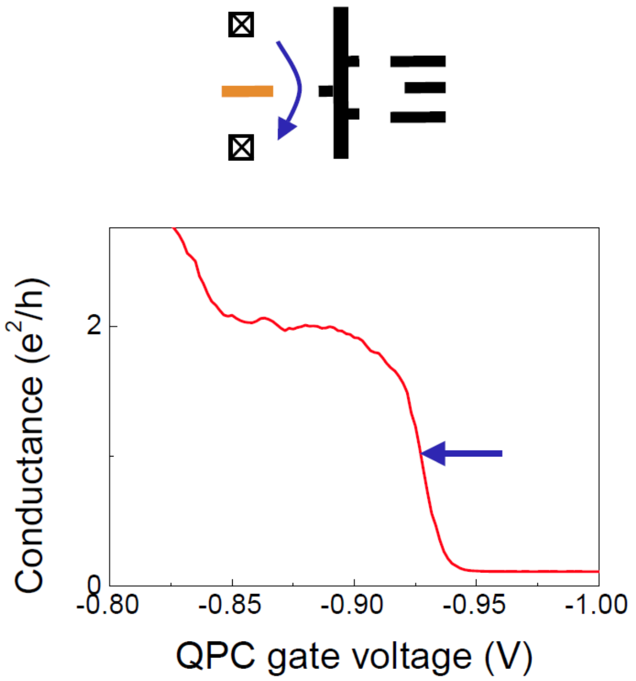
Slides and material courtesy of Thomas Ihn, ETH Zurich

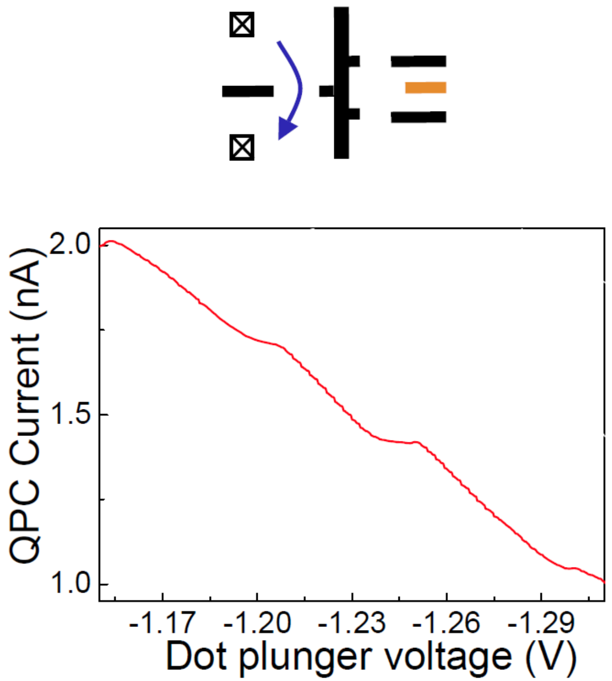
Transport Through Quantum Dot - Coulomb Blockade



Slides and material courtesy of Lieven Vandersypen, TU Delft

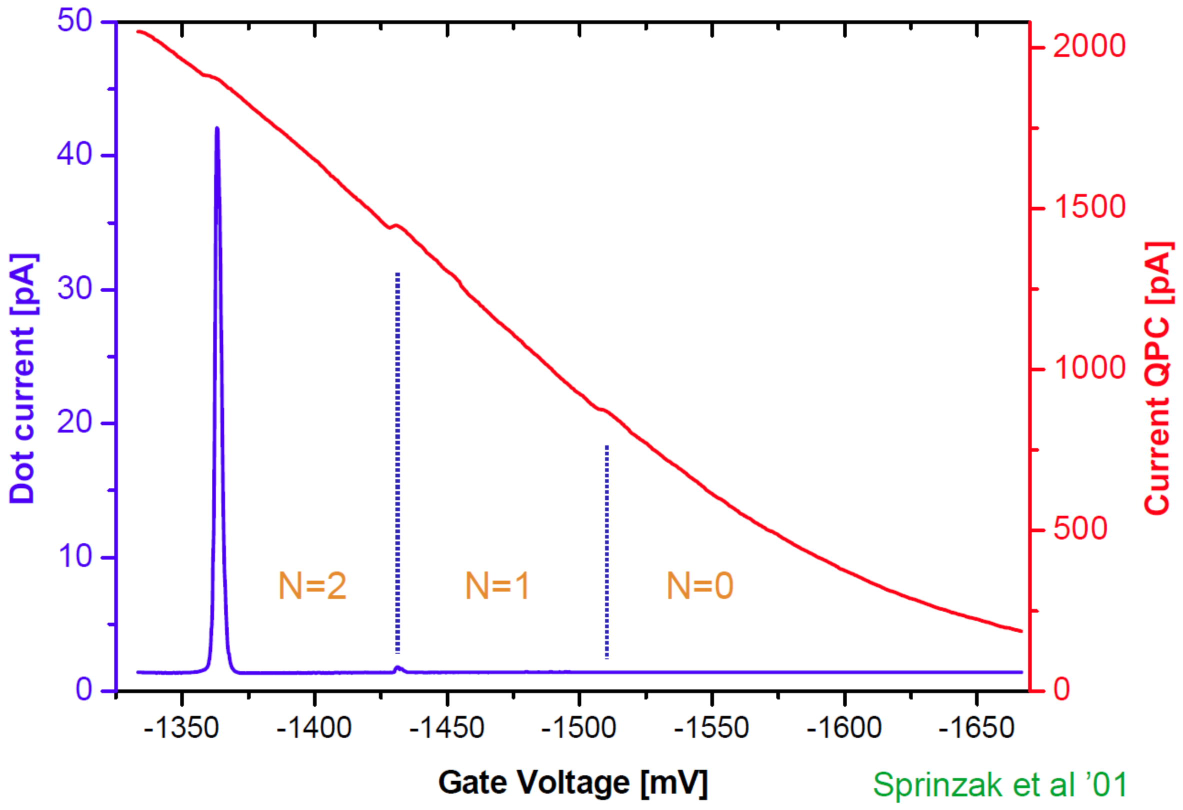
A Quantum Point Contact (QPC) as a Charge Detector





Field *et al*, *Phys. Rev. Lett.* **70, 1311** (1993)
Slides and material courtesy of Lieven Vandersypen, TU Delft

The Last Electron



Field *et al*, *Phys. Rev. Lett.* **70, 1311** (1993)
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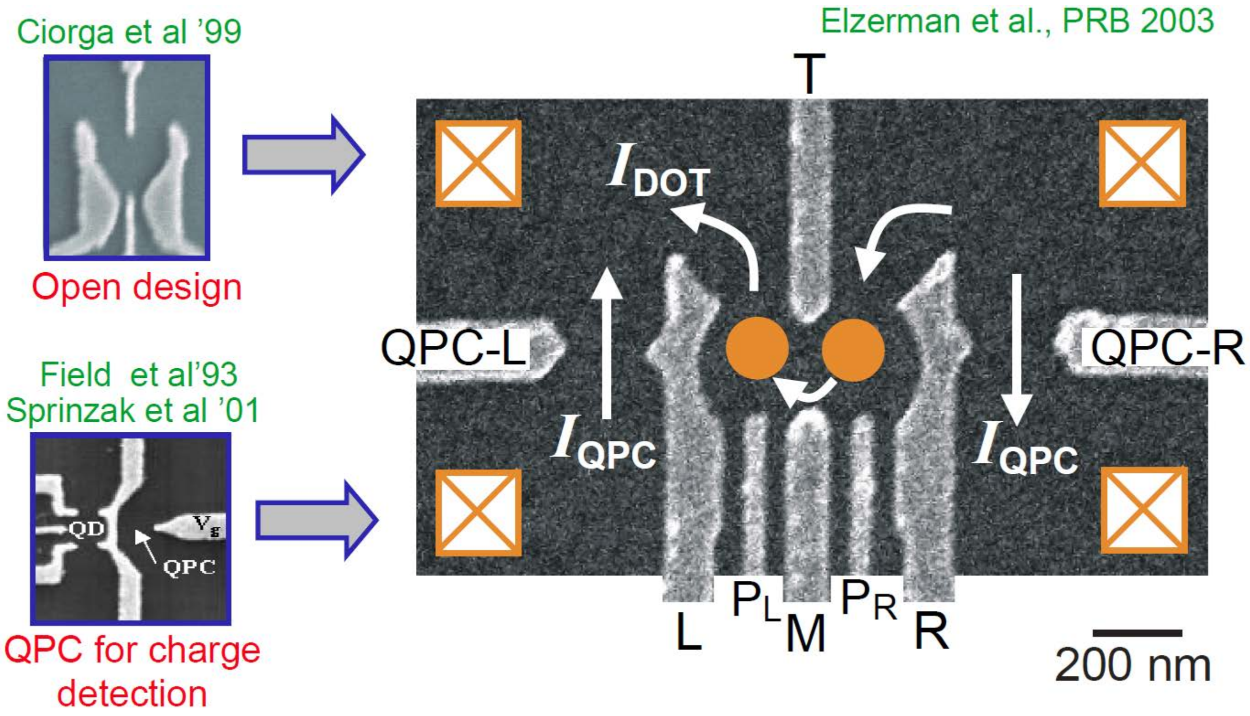
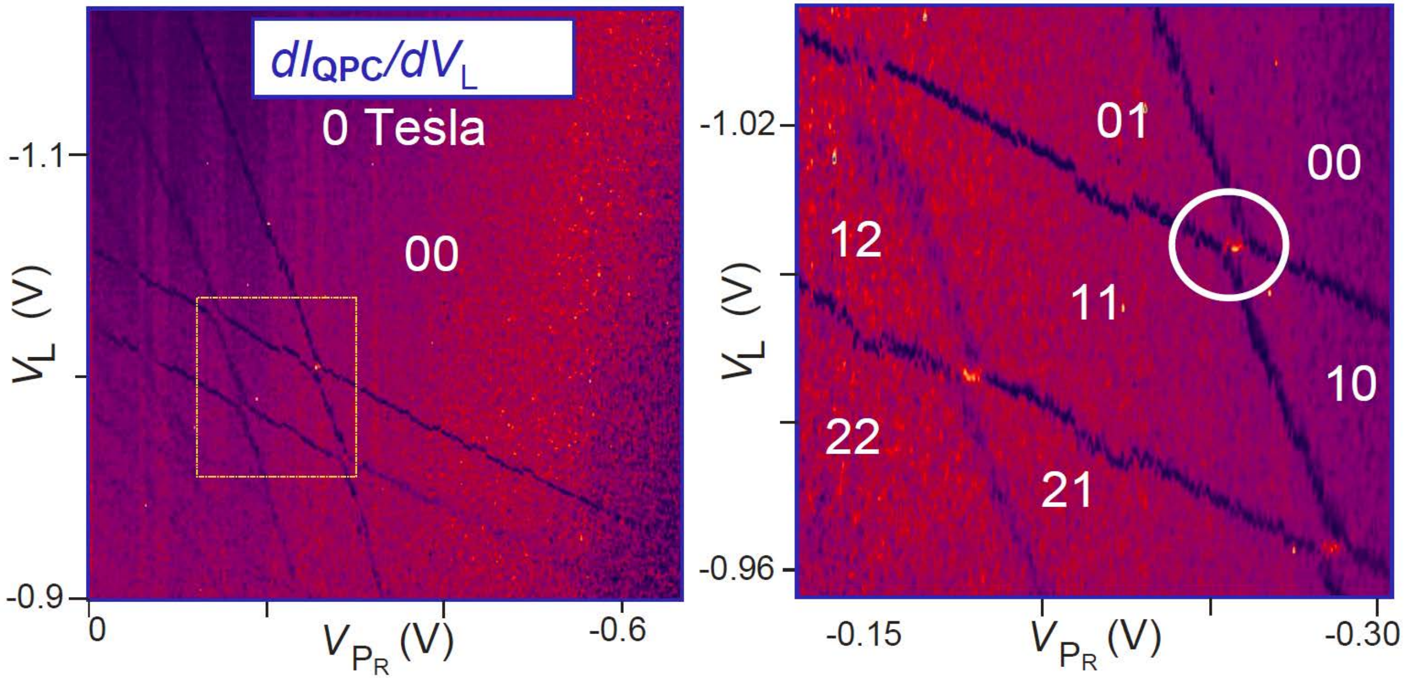
Few-Electron Double Dot Design

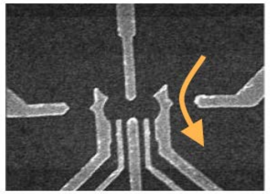


GaAs/AlGaAs wafers:
- NTT (T. Saku, Y. Hirayama)
- Sumitomo Electric
- Universität Regensburg (W. Wegscheider)

Elzerman *et al., Phys. Rev. B* **67,** 161308(R) (2003)
Ciorga *et al., Phys. Rev. B* **61**, R16315(R) (2000)
Field *et al*, *Phys. Rev. Lett.* **70,** 1311 (1993)
Sprinzak *et al Phys. Rev. Lett.* **88,** 176805 (2002)
Slides and material courtesy of Lieven Vandersypen, TU Delft

Few-Electron Double Dot Measured via QPC

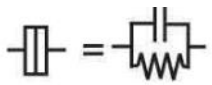


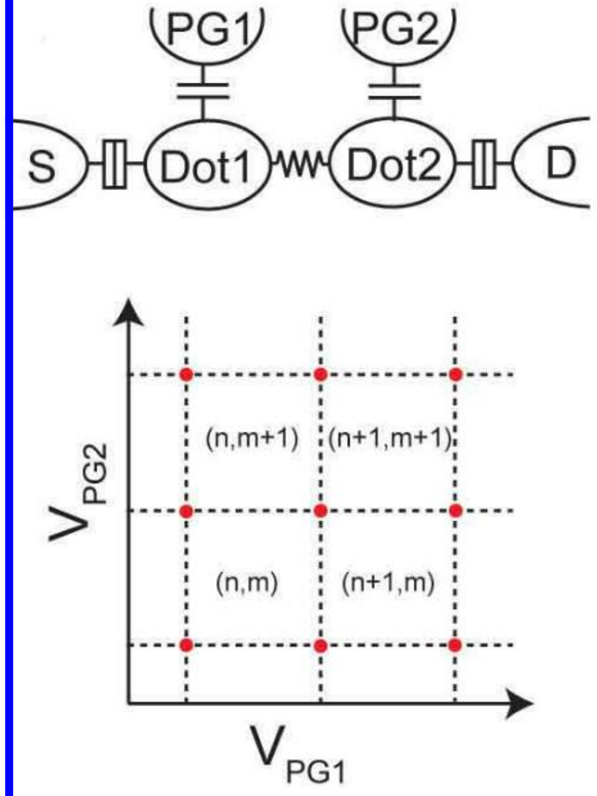


- Double dot can be emptied
- QPC can detect all charge transitions

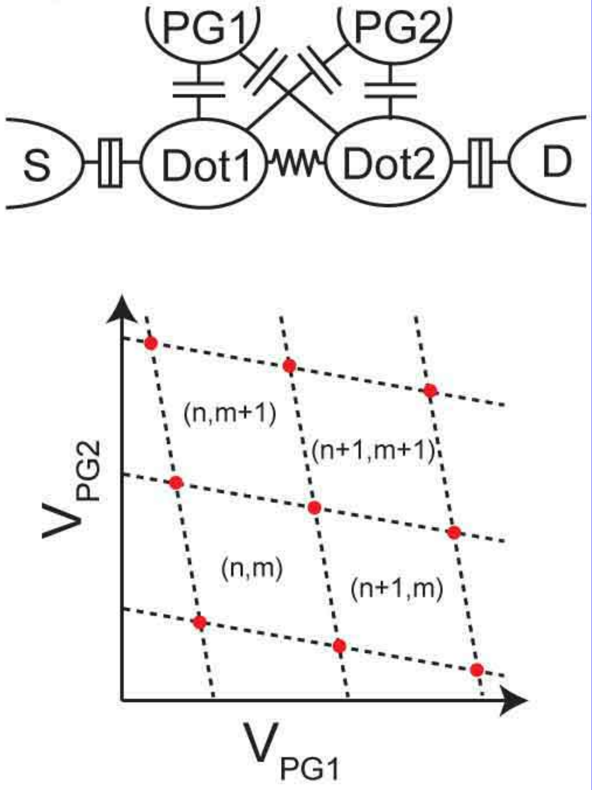
J.M. Elzerman *et al., Phys. Rev. B* **67**, R161308 (2003)
Slides and material courtesy of Lieven Vandersypen, TU Delft

Double Dot Charge Stability Diagram

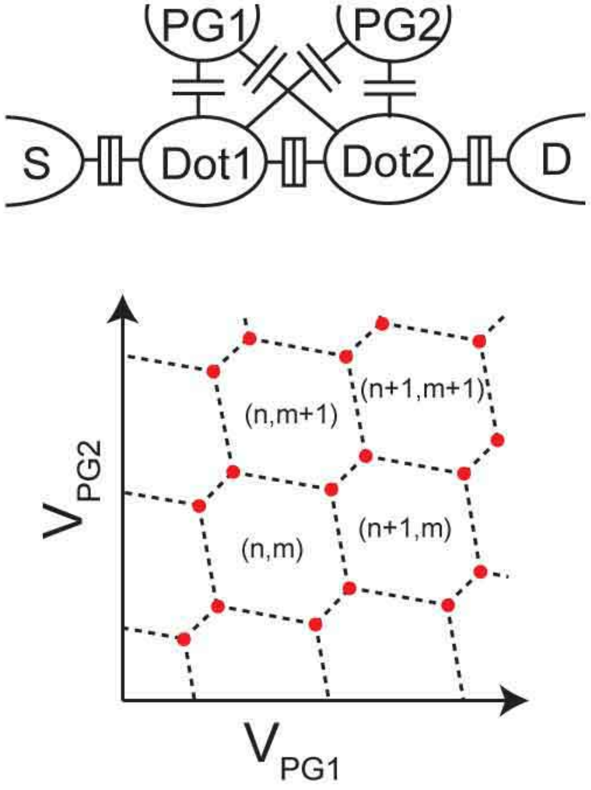




each dot coupled
only to its gate



each dot coupled
to **both gates**



both dots coupled to
each other

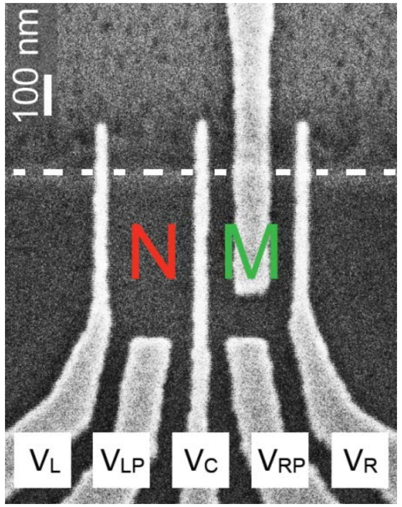
Double Dot Current

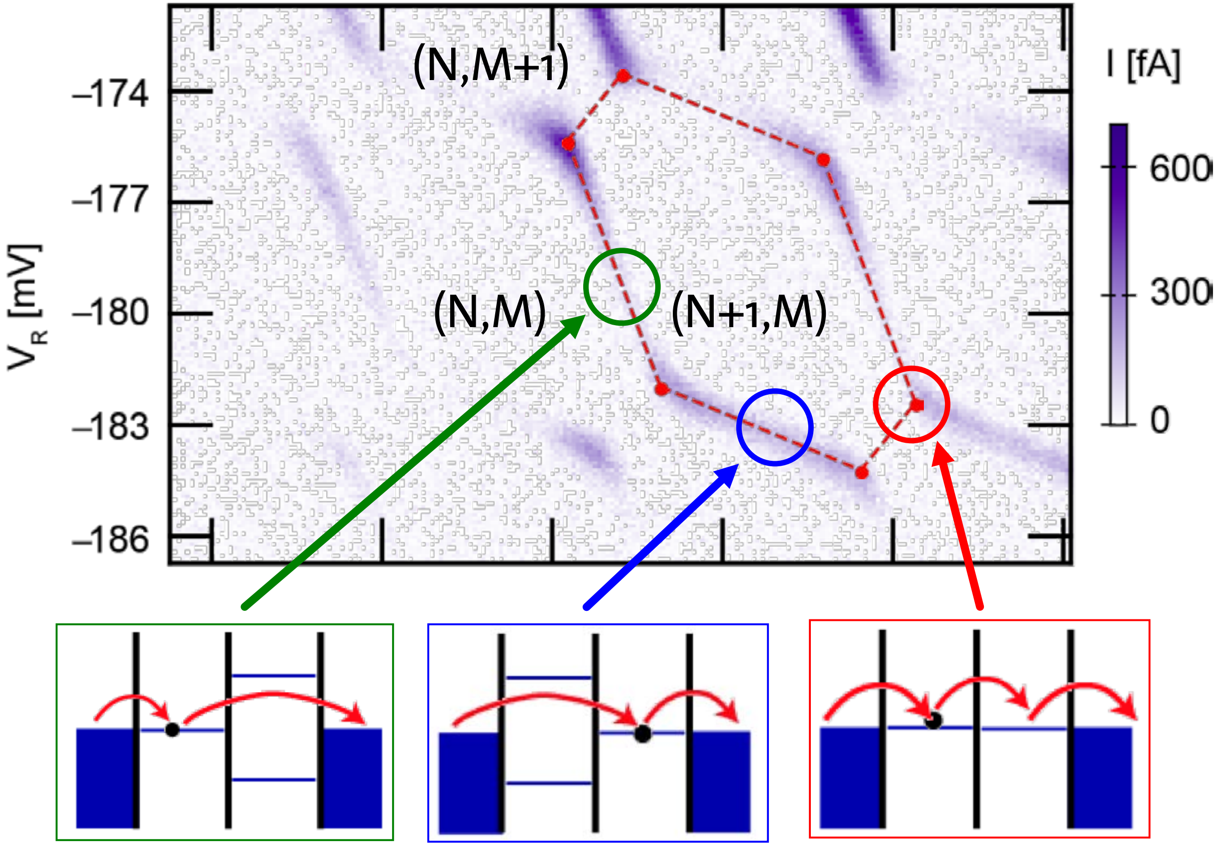
Transport measurements:

- Charging diagrams

dot properties:

- many electron regime
- large charging energy
- consider two-level approx.





co-tunneling

sequential tunneling

T. Frey *et al.*, *PRL* **108**, 046807 (2012)

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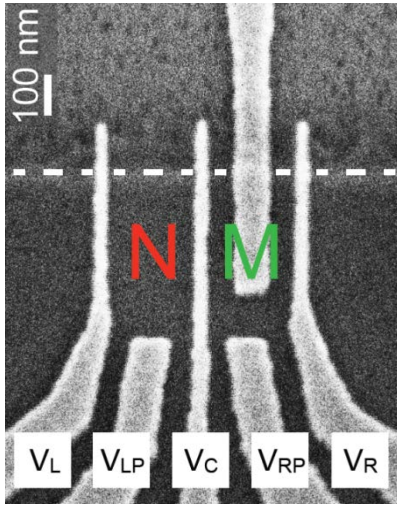

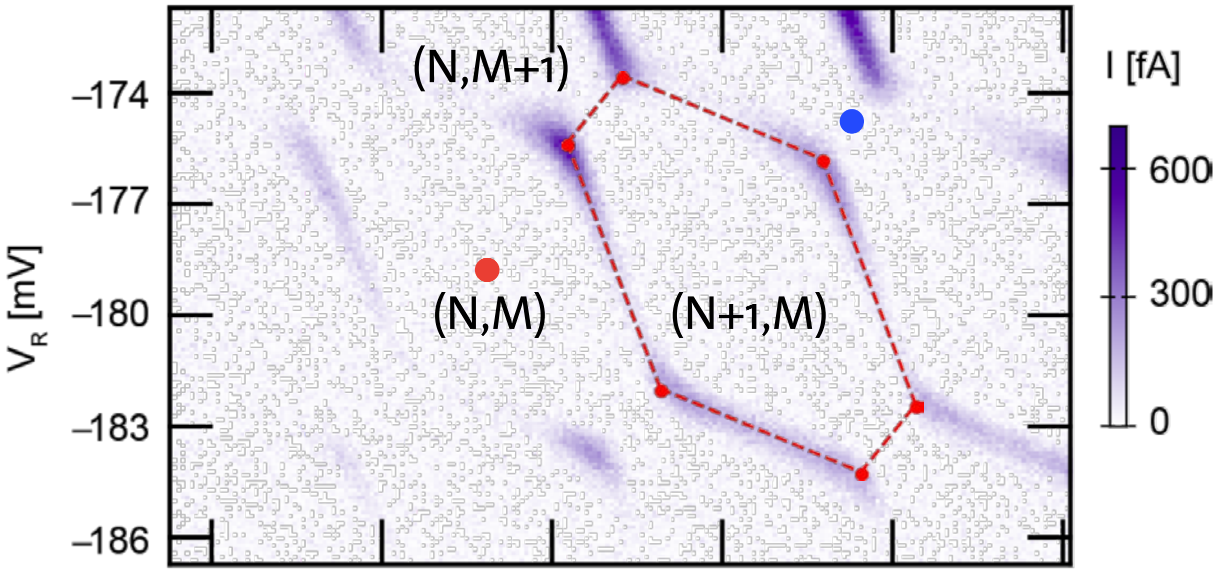

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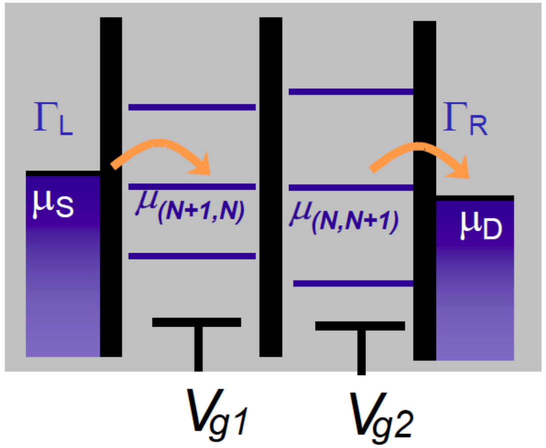
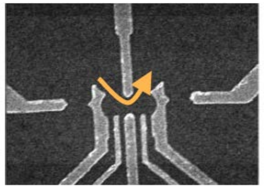
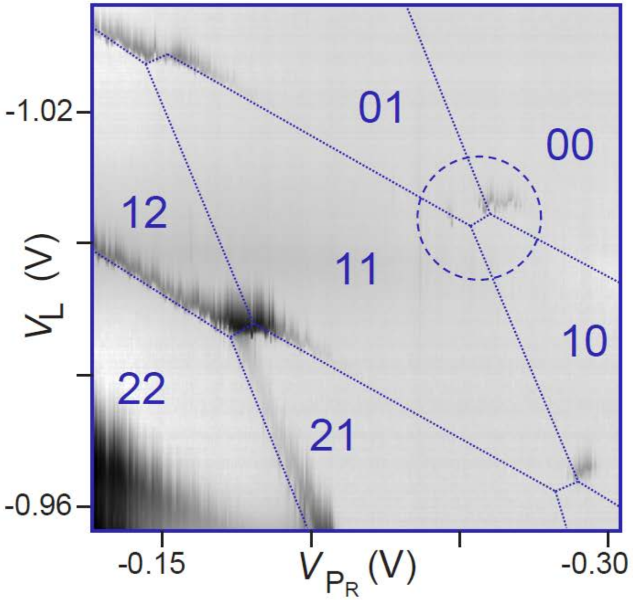
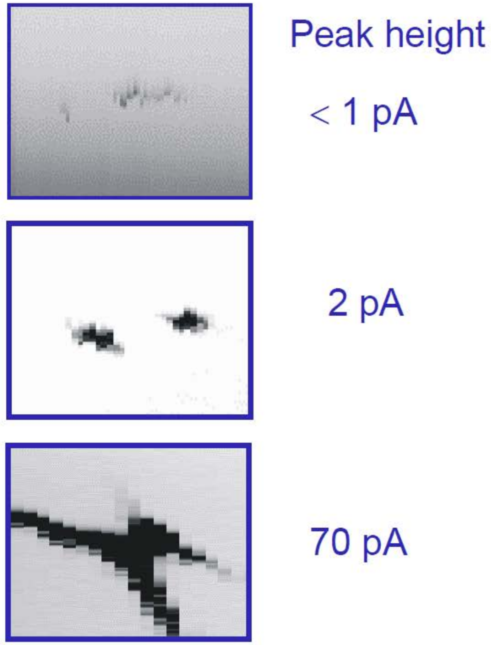
Single Electron Tunneling Through Two Dots in Series



Few-electron double dot:
Transport current through dots







J. Elzerman *et al., Phys. Rev. B* **67**, 161308(R) (2003)
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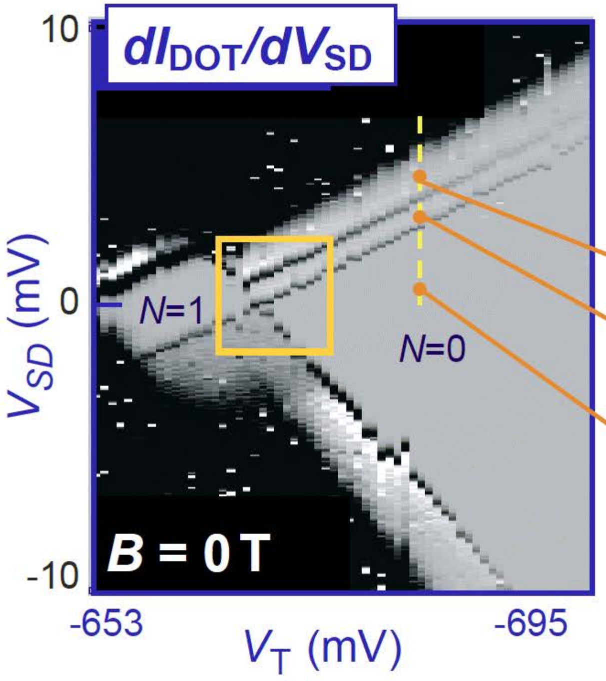
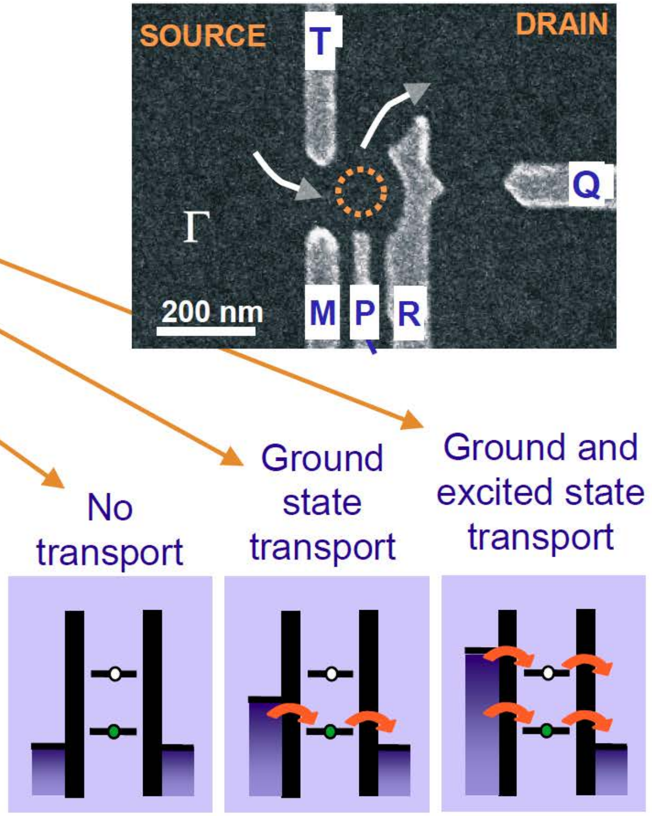
Energy Level Spectroscopy at $B = 0$





- $\Delta E \sim 1.1$meV
- $E_C \sim 2.5$meV

J. Elzerman *et al., Phys. Rev. B* **67**, 161308(R) (2003)
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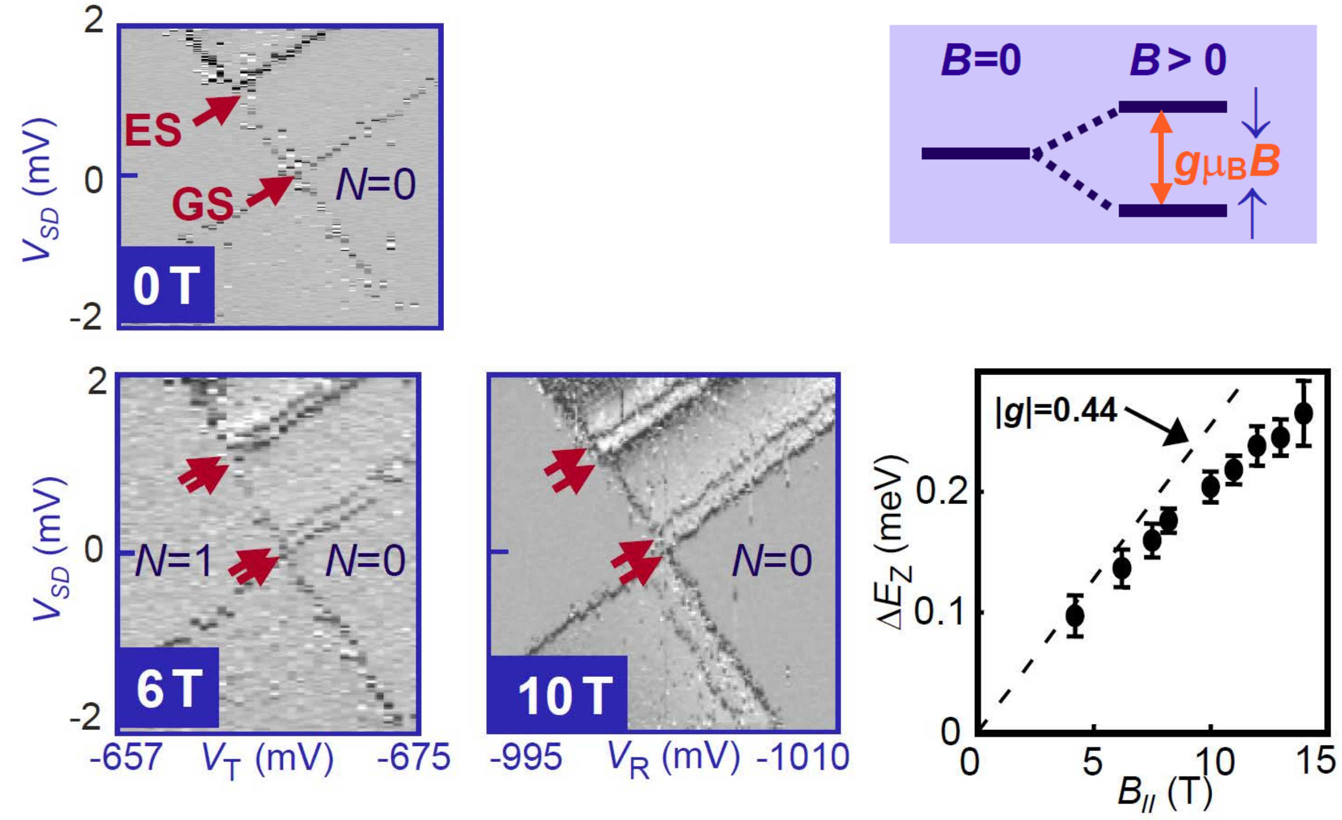
Single Electron Zeeman Splitting in $B_{//}$



Hanson et al, *Phys. Rev. Lett.* **91**, 196802 (2003)
Also: Potok et al, *Phys. Rev. Lett.* **91**, 016802 (2003)
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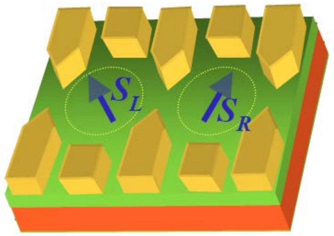
Spin Qubits in Quantum Dots



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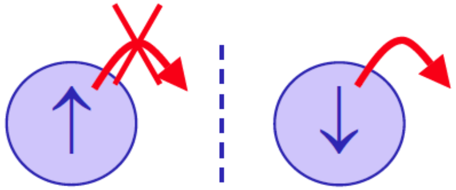

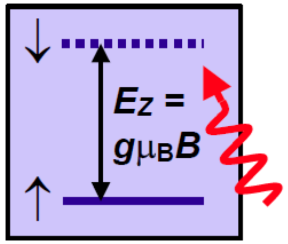

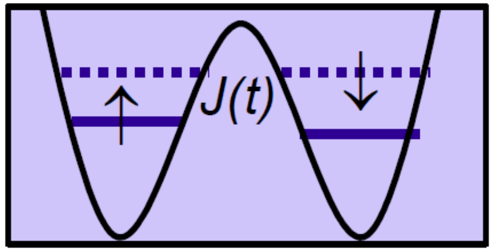

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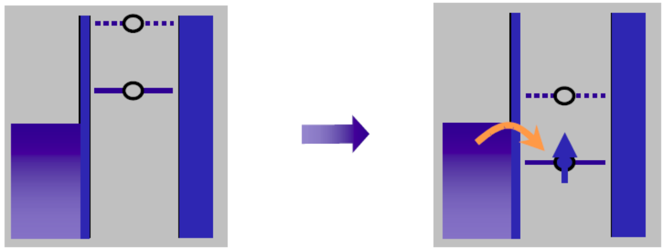
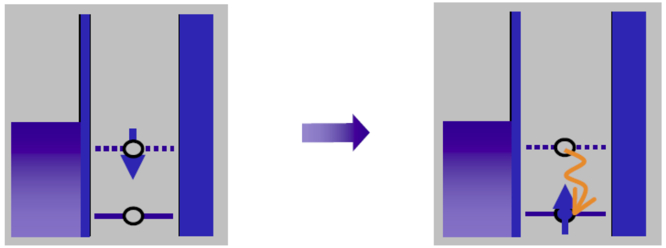
Initialization of a Single Electron Spin

Method 1:
spin-selective tunneling



Method 2:
relaxation to ground state



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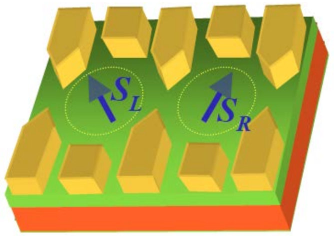

Loss & DiVincenzo, *PRA* 1998
Vandersypen et al., *Proc. MQC02* (quant-ph/0207059)

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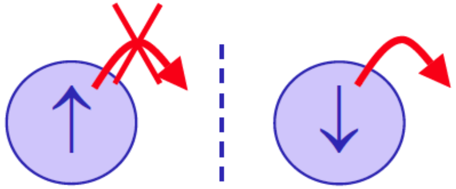
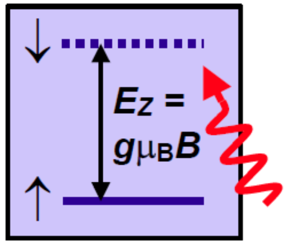
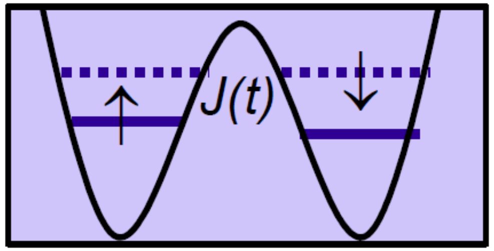
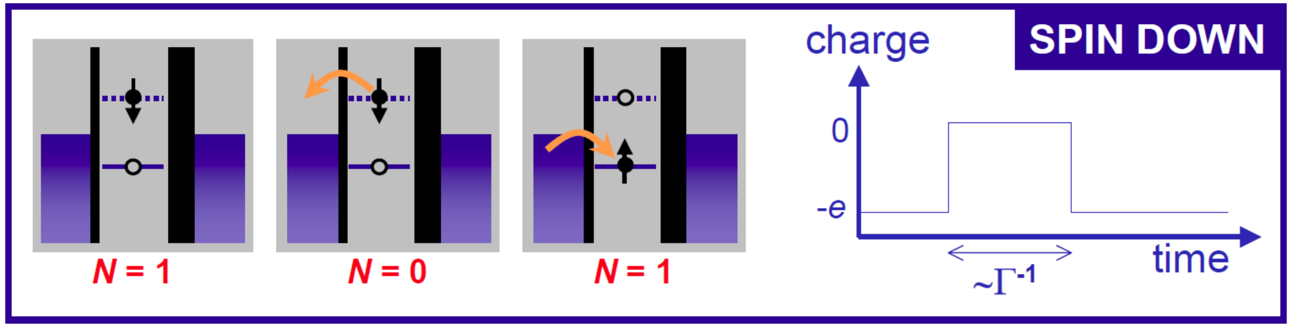






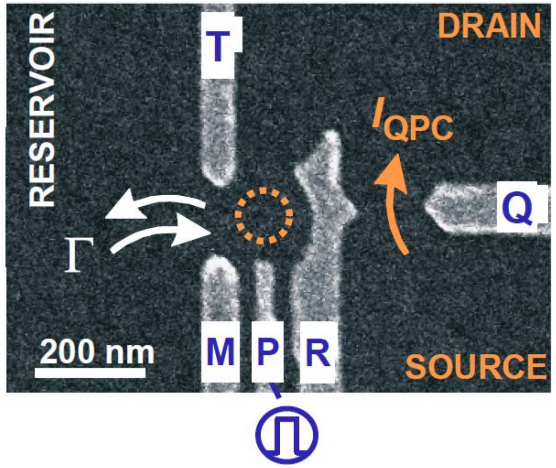
Slides and material courtesy of Lieven Vandersypen, TU Delft

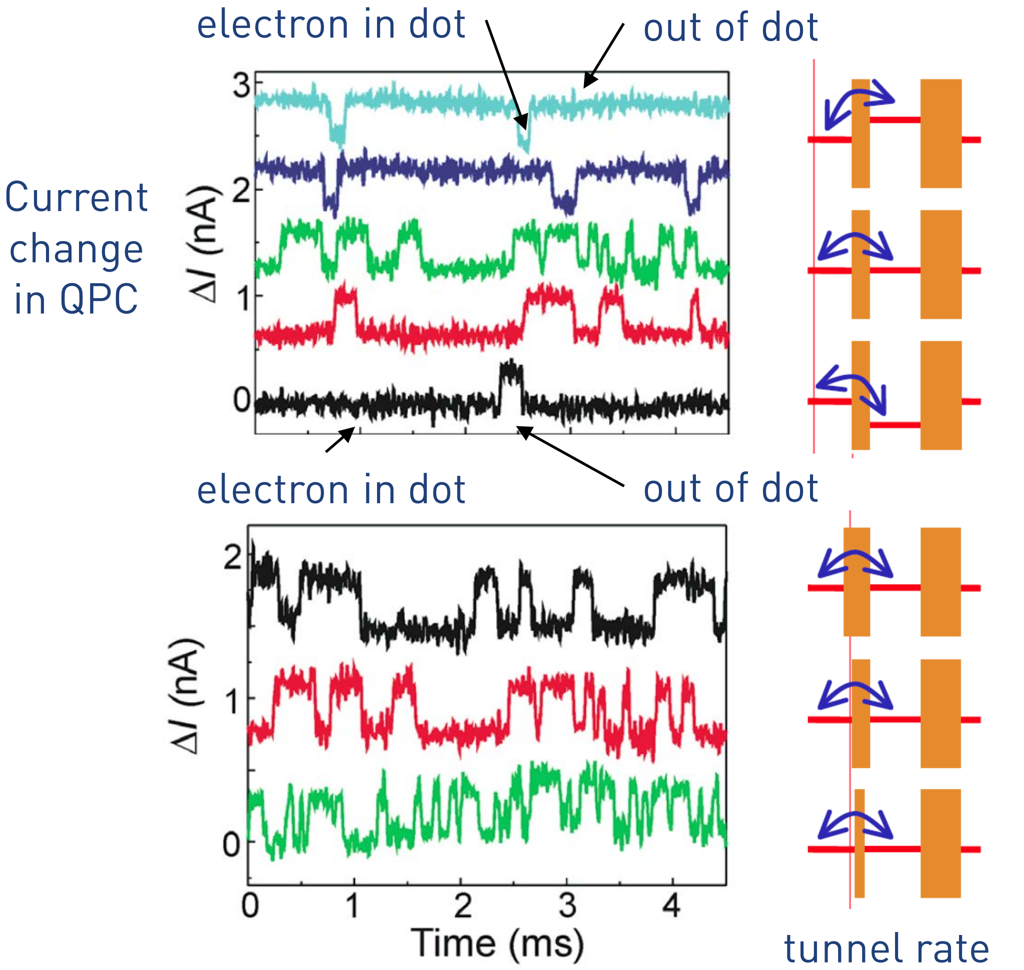
Spin Read-Out Principle: Convert Spin to Charge



Slides and material courtesy of Lieven Vandersypen, TU Delft

Observation of individual tunnel events



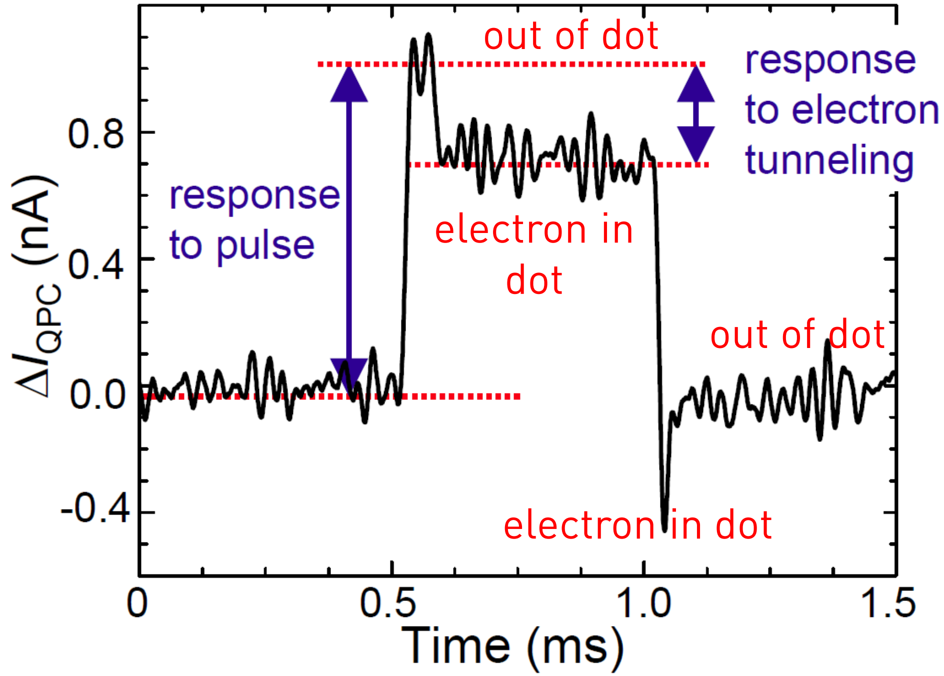


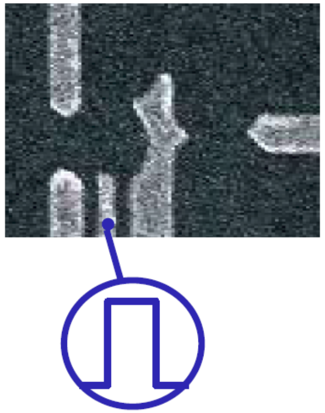
tunnel rate increases with reduced barrier width

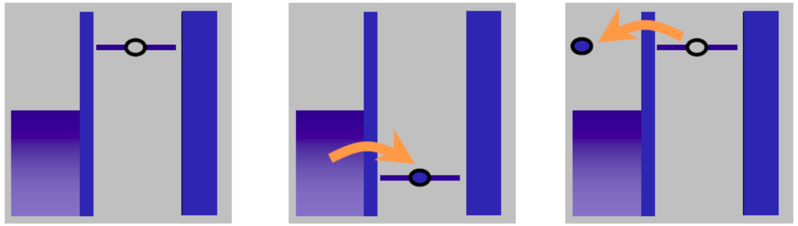
- V_{SD} = 1 mV
- I_{QPC} ~ 30 nA
- ΔI_{QPC} ~ 0.3 nA
- Shortest steps ~ 8 µs

Vandersypen *et al.*, *App. Phys. Lett.* **85**, 4394 (2004)
Schlesser*et al.*, (2004)
Slides and material courtesy of Lieven Vandersypen, TU Delft

Pulse-Induced Tunneling

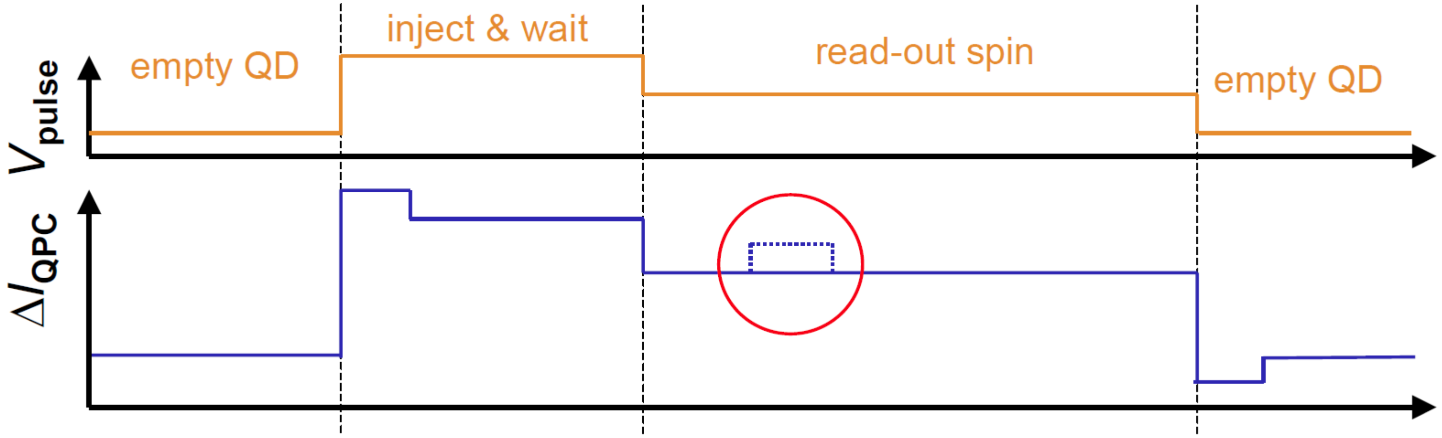


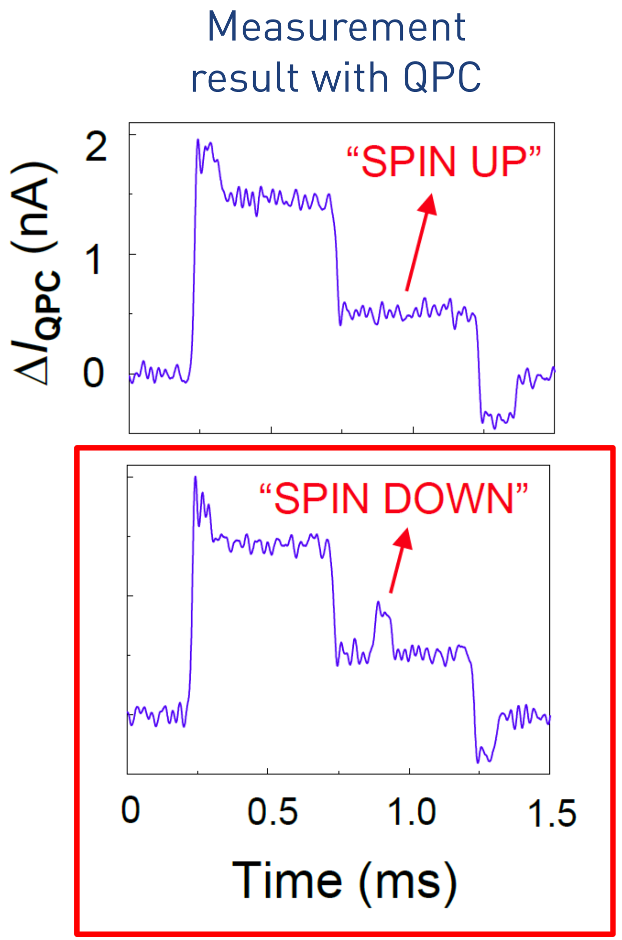


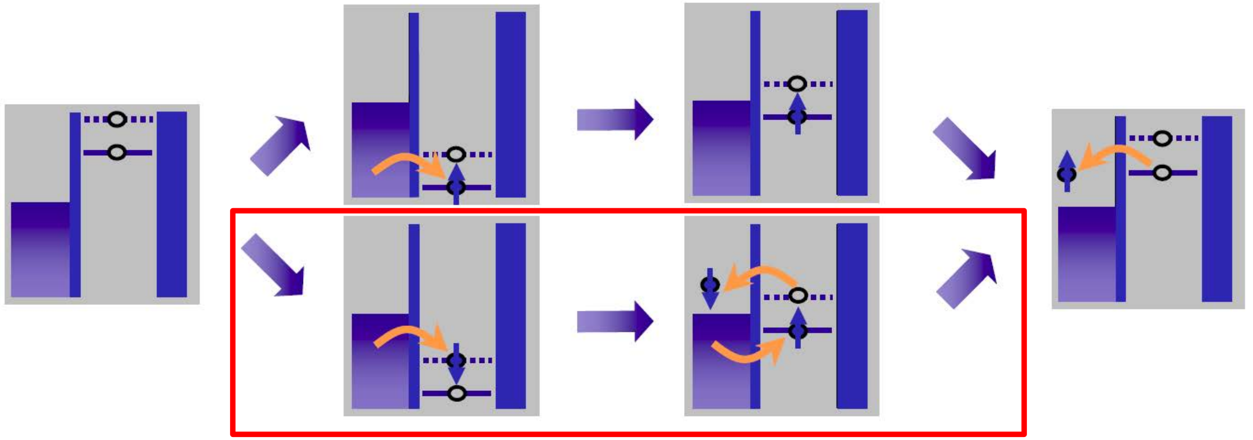


Slides and material courtesy of Lieven Vandersypen, TU Delft

Spin Read-Out Procedure & Measurement Result

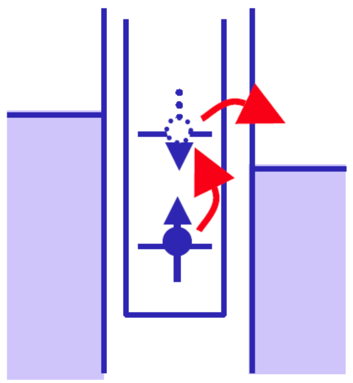






Inspiration: Fujisawa *et al.*, *Nature* **419**, 279 (2002)
Elzerman *et al.*, *Nature* **430**, 431 (2004)
Slides and material courtesy of Lieven Vandersypen, TU Delft

Electron Spin Resonance (ESR) Detection in a Single Dot

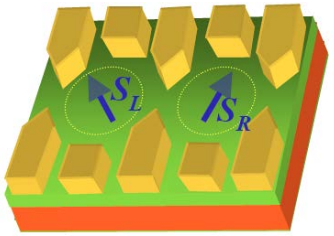


ESR lifts Coulomb blockade

Microwave induced spin flip raises (Zeeman) energy of electron and allows it to tunnel out to the right (drain) and new electron to tunnel in from the left (source) creating current.

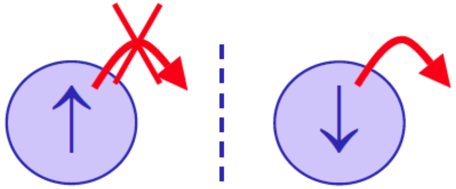
Engel & Loss, *Phys. Rev. Lett.* **86**, 4648 (2001)
Slides and material courtesy of Lieven Vandersypen, TU Delft

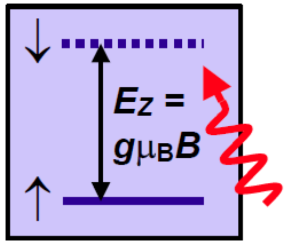
Spin Qubits in Quantum Dots

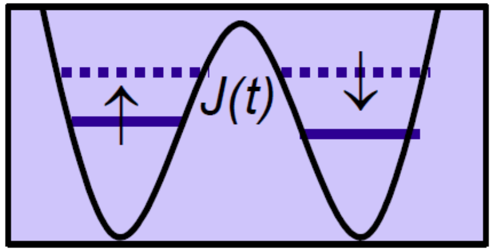


Loss & DiVincenzo, *PRA* 1998
Vandersypen et al., *Proc. MQC02* (quant-ph/0207059)

Initialization	1-electron, low T, high B_0 $H_0 \sim \Sigma\, \omega_i\, \sigma_{zi}$
Read-out	convert spin to charge then measure charge
ESR	pulsed microwave magnetic field $H_{RF} \sim \Sigma\, A_i(t) \cos(\omega_i t)\ \sigma_{xi}$
SWAP	exchange interaction $H_J \sim \Sigma\, J_{ij}(t)\ \sigma_i \cdot \sigma_j$
Coherence	long relaxation time T_1 long coherence time T_2



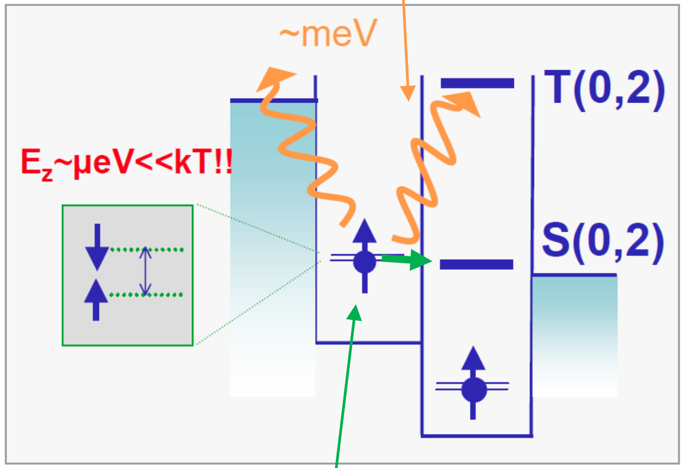




Slides and material courtesy of Lieven Vandersypen, TU Delft

Double Dot in Spin Blockade for ESR Detection

Tunneling of spin up from left to right is blockaded as it can only form triplet state (both spins up, S=1).



T: Triplet state
S: Singlet state

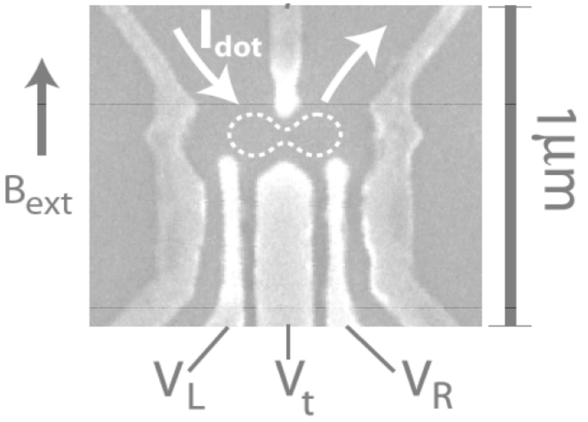
Advantage: inter-dot transition instead of dot-lead transition

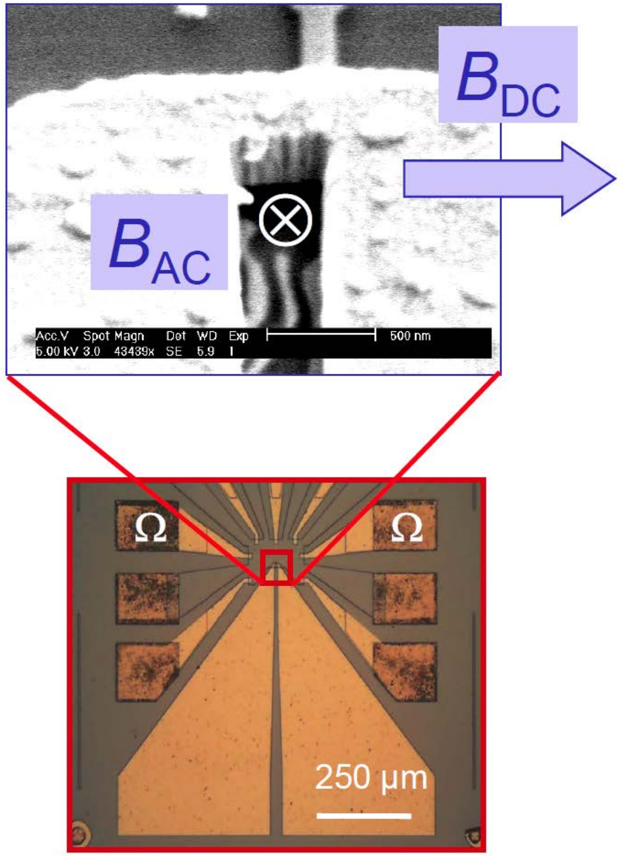
- Insensitive to temperature
  ⇒ can use $B < 100$ mT, $f < 500$ MHz
- Insensitive to electric fields

ESR spin flip (to down) allows for formation of lower energy singlet state (up and down S=0), lifts spin blockade and allows for tunneling from left to right creating current

Combine ESR detection: Engel & Loss, *Phys. Rev. Lett.* **86**, 4648 (2001)
with spin blockade: Ono & Tarucha, *Science* **297**, 1313 (2002)
Slides and material courtesy of Lieven Vandersypen, TU Delft

ESR Device Design





- Gates ~ 30 nm thick gold
- Dielectric ~ 100 nm calixerene
- Stripline ~ 400 nm thick gold

- Expected AC current ~ 1 mA
- Expected AC field ~ 1 mT
- Maximize B_1, minimize E_1

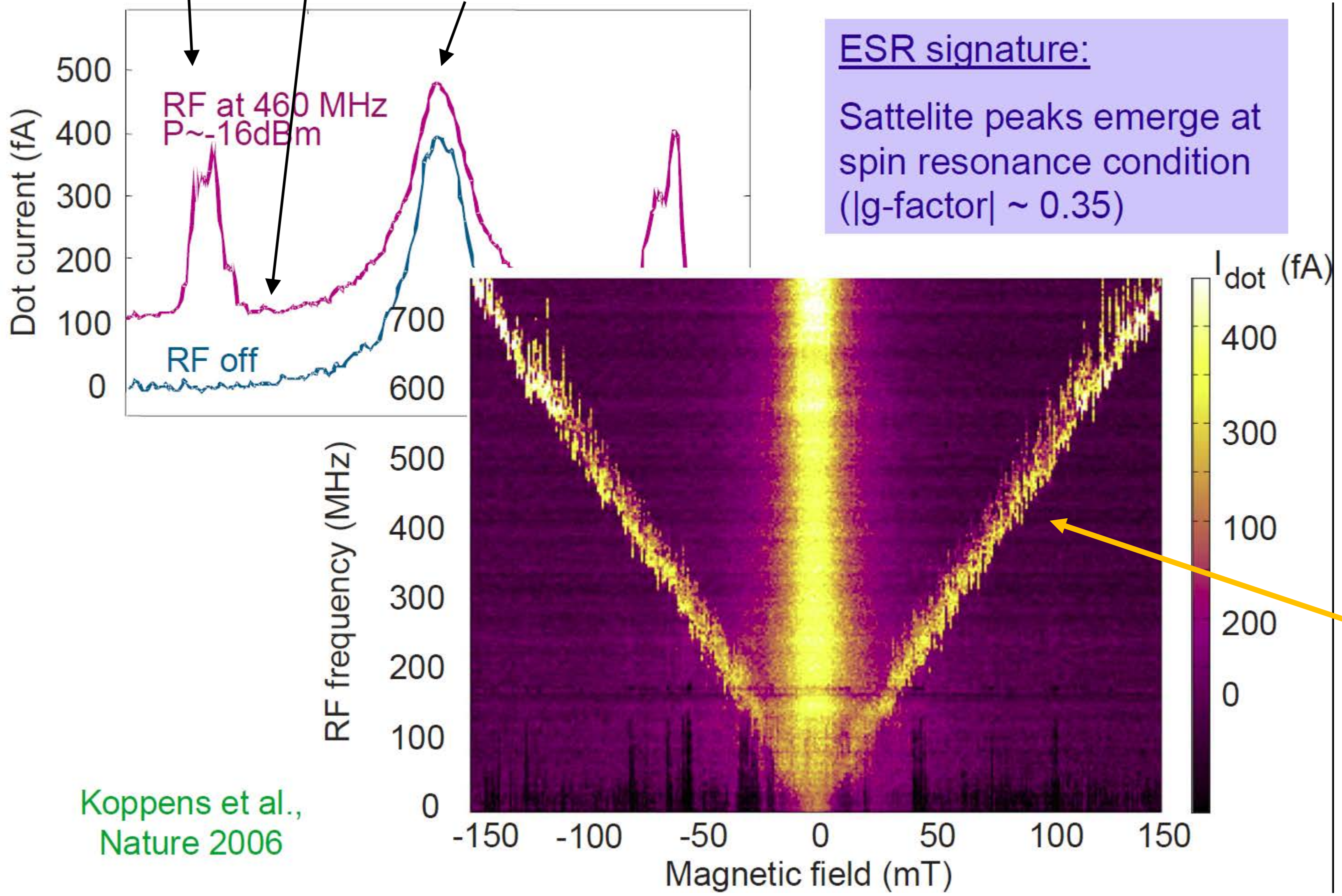
Slides and material courtesy of Lieven Vandersypen, TU Delft

ESR Spin State Spectroscopy

Spin blockade at B lifted by ESR spin flip -> current

Spin blockade at B -> no current

No spin blockade at B = 0 -> current



ESR signature:

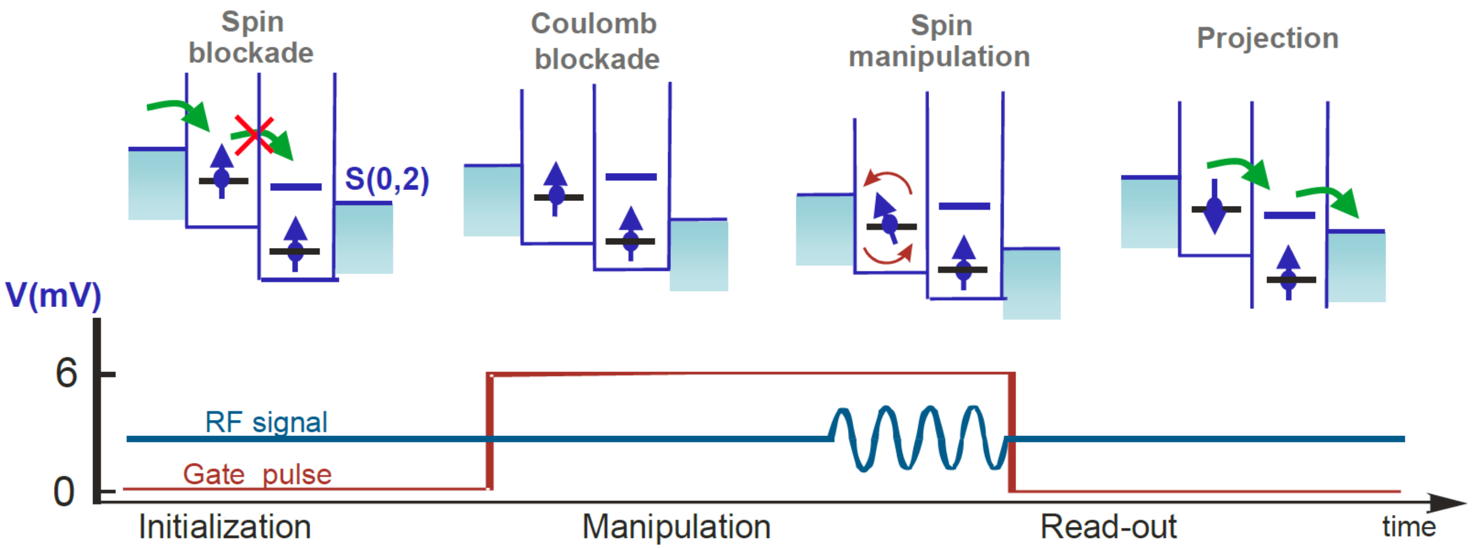
Sattelite peaks emerge at spin resonance condition (|g-factor| ~ 0.35)

Linear scaling with B: Zeeman effect

Koppens *et al., Nature* **442**, 766 (2006)

Slides and material courtesy of Lieven Vandersypen, TU Delft

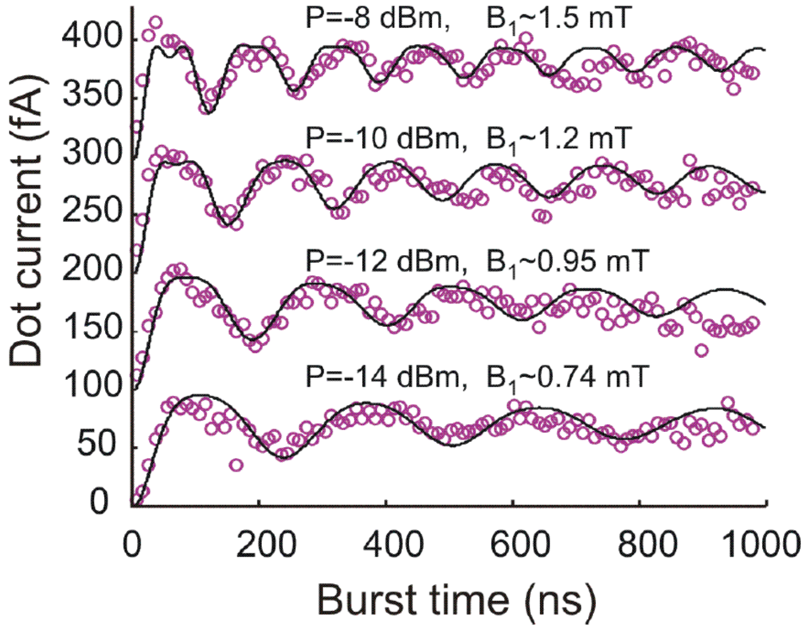
Coherent Manipulation: Pulse Scheme

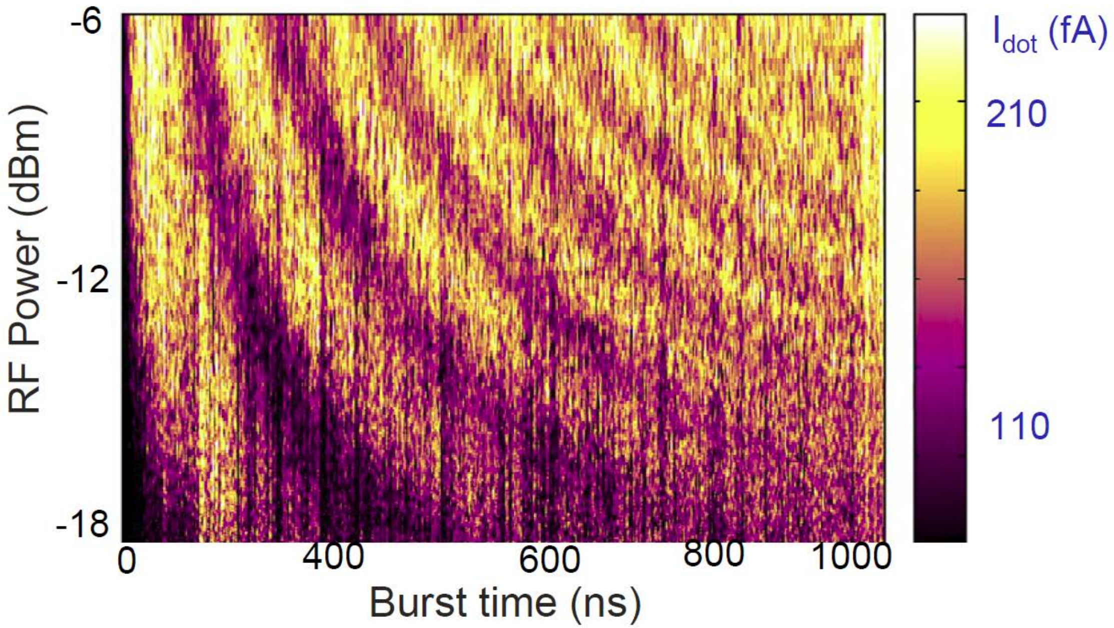


- Initialization in mixture of ↑↑and ↓↓
- Measurement switched off (by pulsing to Coulomb blockade) during manipulation
- Read-out: projection on {↑↑,↓↓} vs. {↑↓,↓↑} basis

Koppens *et al.*, *Nature* **442**, 766 (2006)
Slides and material courtesy of Lieven Vandersypen, TU Delft

Coherent Rotations of Single Electron Spin



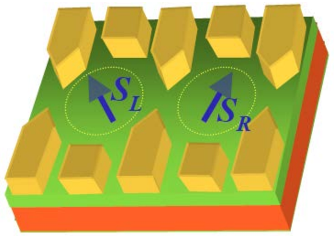


- Oscillations visible up to 1 μs
- Decay non exponential
  - slow nuclear dynamics (non-Markovian bath)
- Agreement with simple Hamiltonian
- Taking into account different resonance conditions both dots

- Oscillation frequency ~ B_{AC}
  - clear signature of Rabi oscillations
- π/2 pulse in 25 ns
- max B_1=B_{AC} /2 = 1.9 mT
- $B_{N,z}$= 1.3 mT
  - estimated fidelity ~73%

Koppens *et al., Nature* **442**, 766 (2006)
Slides and material courtesy of Lieven Vandersypen, TU Delft

Spin Qubits in Quantum Dots



Loss & DiVincenzo, *PRA* 1998
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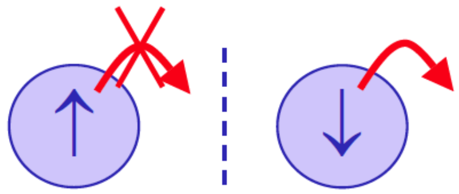
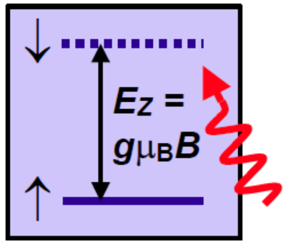
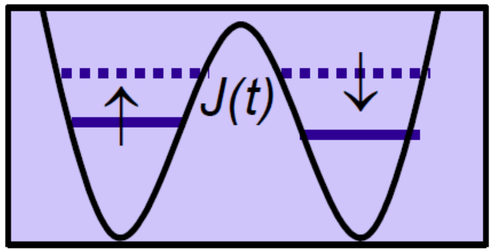
Coherence	long relaxation time T_1 long coherence time T_2

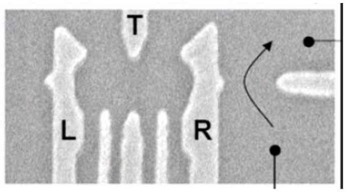


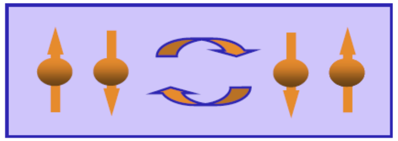


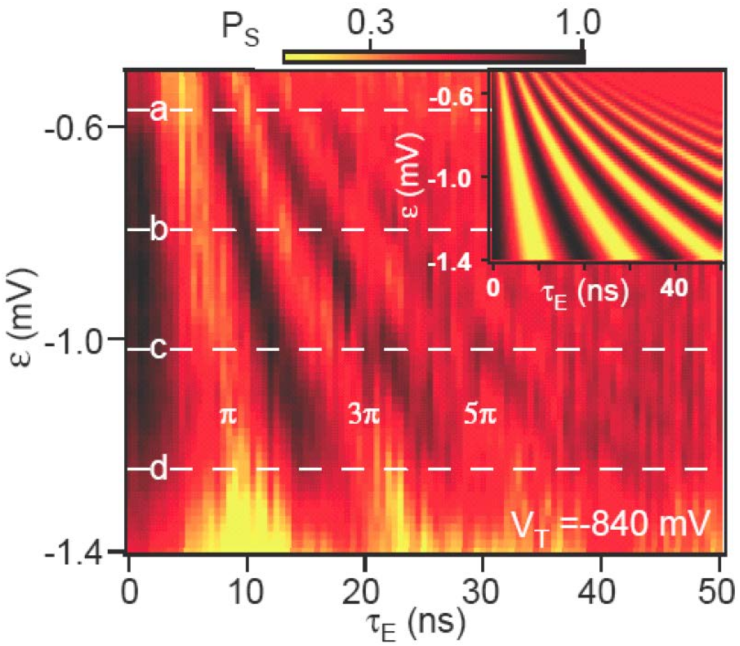


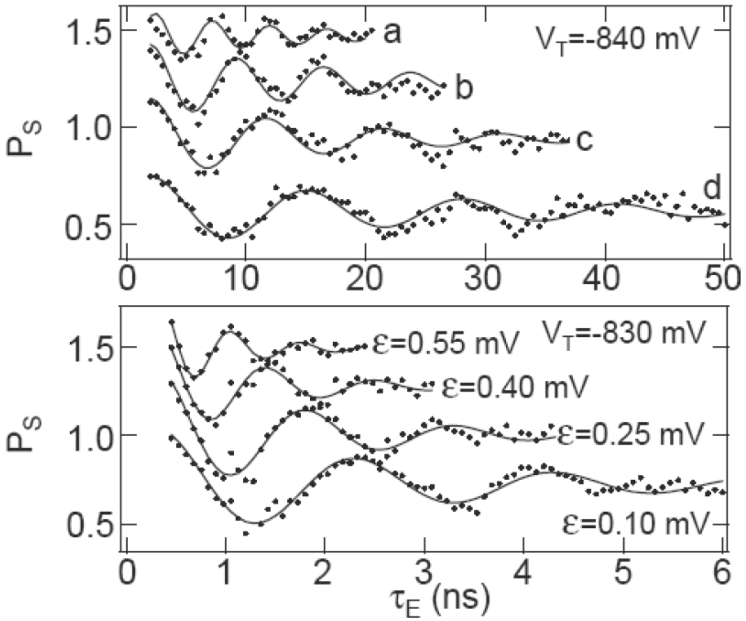
Slides and material courtesy of Lieven Vandersypen, TU Delft

Coherent Exchange of Two Spins







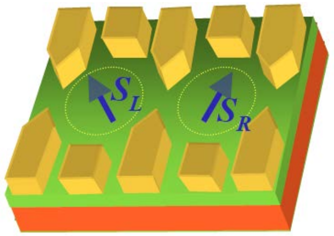


Spin exchange as in NMR

- free evolution under exchange Hamiltonian
- swap$^{1/2}$ in as little as 180 ps
- three oscillations visible, independent of J

Petta *et al.*, *Science* **309**, 2180 (2005)
Slides and material courtesy of Lieven Vandersypen, TU Delft

Spin Qubits in Quantum Dots



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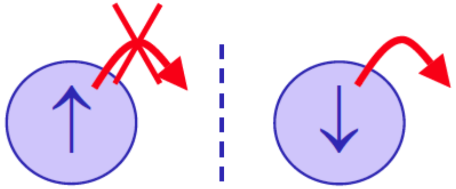
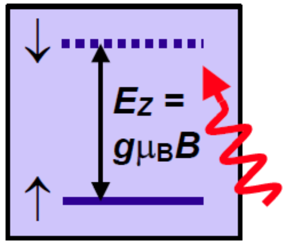
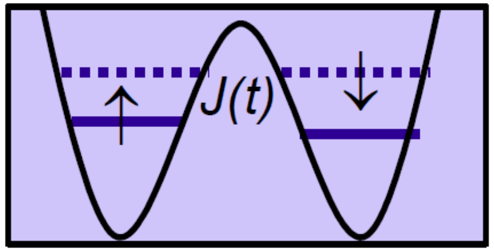






Slides and material courtesy of Lieven Vandersypen, TU Delft

Summary Gate-Defined Quantum Dots

Semiconductor quantum dots for QIP

- Fulfill all DiVincenzo Criteria

Challenges

- Use materials with long spin lifetimes (Si, graphene) and low charge noise
- Scaling to larger number of qubits

Current promising developments

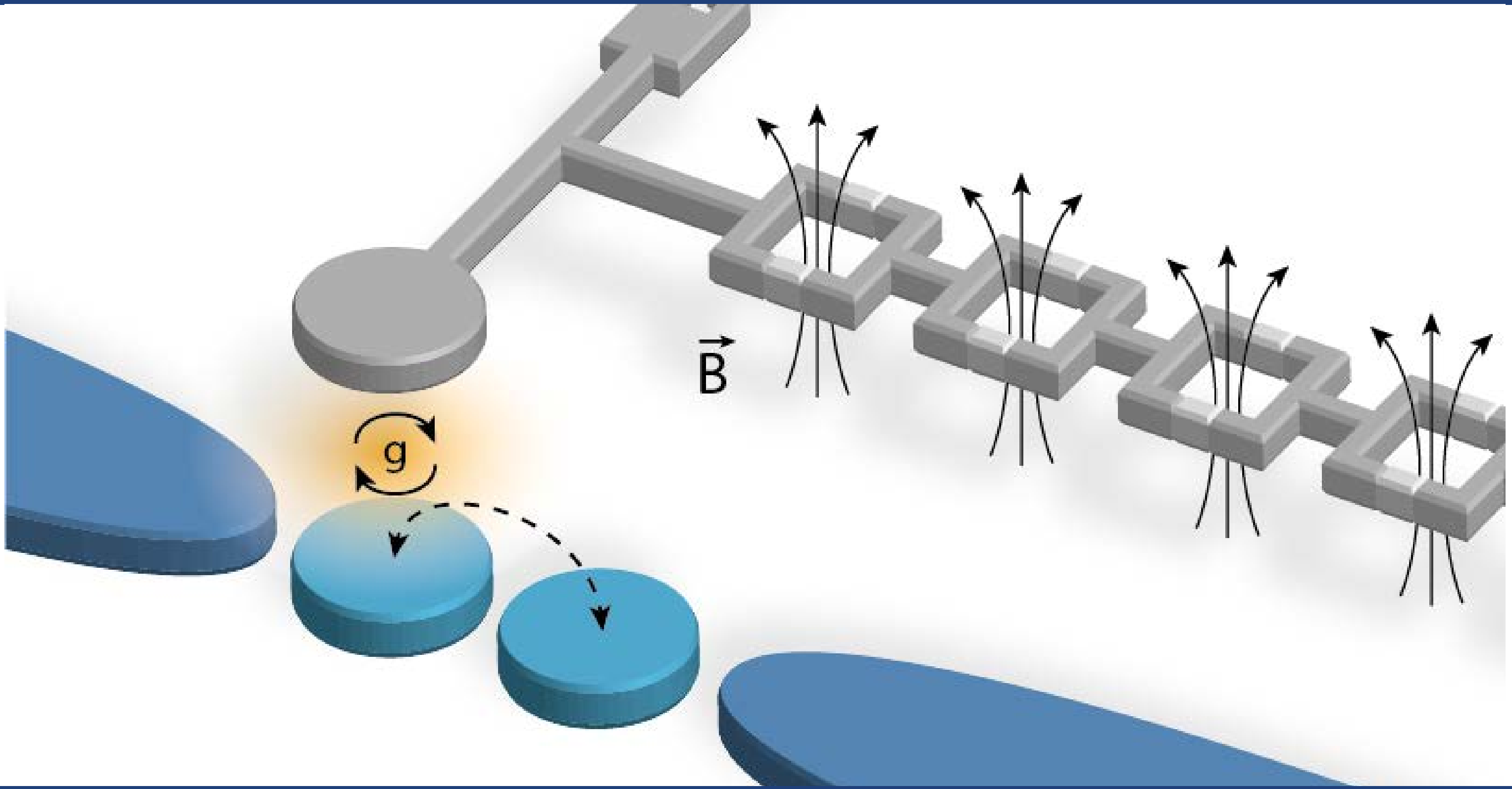
- Circuit QED for quantum dots (see additional slides)

Book on basics:

- Thomas Ihn, Semiconductor Nanostructures: Quantum States and Electronic Transport, ISBN 978-0-19-953442-5, Oxford University Press, Oxford, 2010.

Introductory Review Articles:

- R. Hanson, L. P. Kouwenhoven, J. R. Petta et al., Spins in few-electron quantum dots, *Reviews of Modern Physics* **79**, 1217 (2007)
- R. Hanson, & D. D. Awschalom, Coherent manipulation of single spins in semiconductors, *Nature* **453**, 1043 (2008)



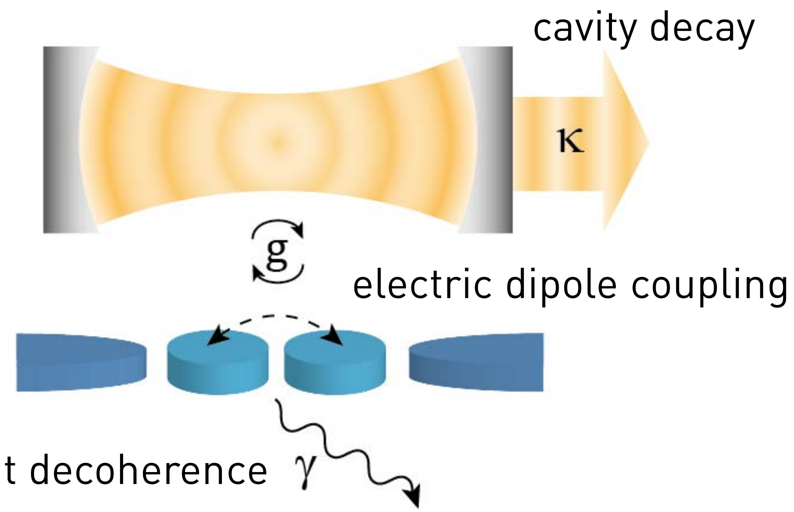
Strong Coupling Cavity QED with Semiconductor Quantum Dots Enabled by High Impedance SQUID Array Resonators

A. Stockklauser, P. Scarlino, J. V. Koski, S.Gasparinetti, C. K. Andersen, C. Reichl, W. Wegscheider, T. Ihn, K. Ensslin, A. Wallraff (ETH Zurich)

Development of Circuit QED for Semiconductor Quantum Dots

Microwave cavities

Semiconductor quantum dots

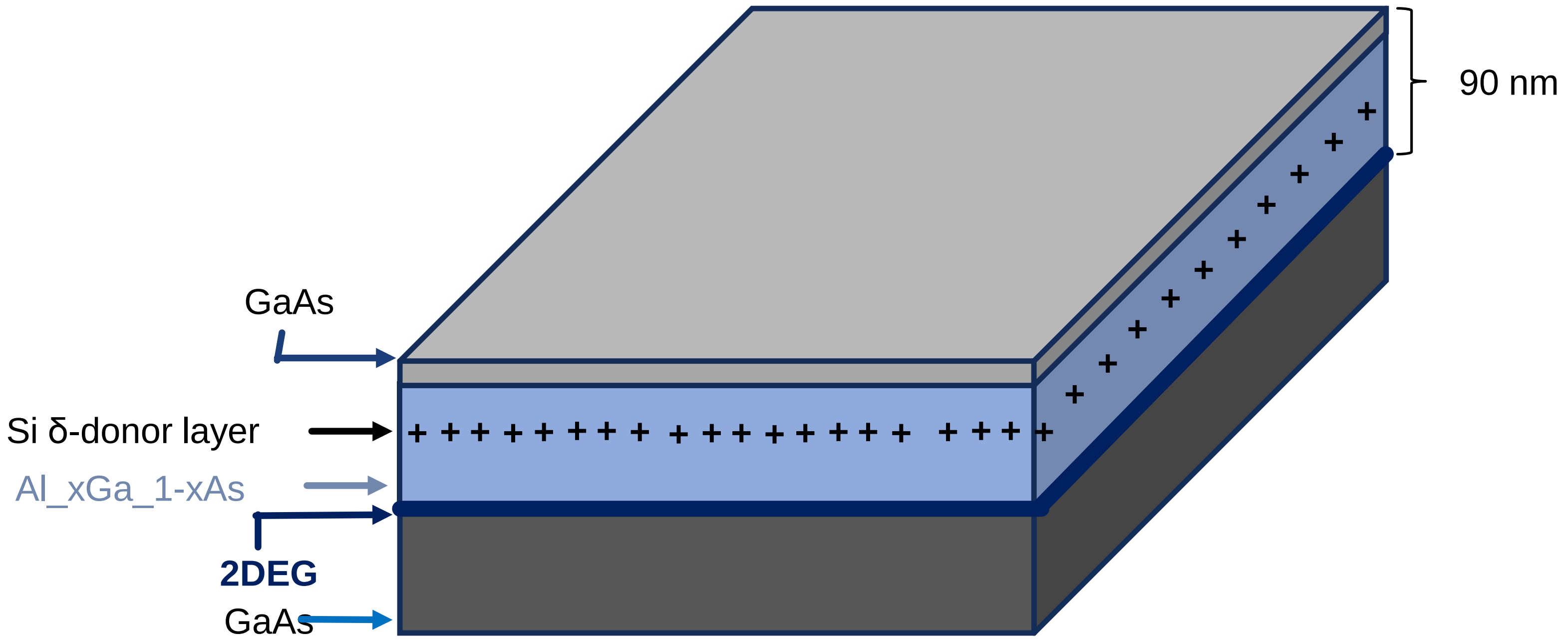


strong coupling regime
$(g \gg \kappa, \gamma)$

	$\gamma/2\pi$	$g/2\pi$
▪ GaAs DQDs Frey *et al.*, *PRL* **108**, 046807 (2012) Toida *et al.*, *PRL* **110,** 066802 (2013)	300 MHz	30-50 MHz
▪ InAs nanowire DQDs Petersson *et al.*, *Nature* **490**, 380-383 (2012)	1 GHz	20-50 MHz
▪ Carbon nanotube DQDs Delbecq *et al.*, *PRL* **107**, 256804 (2011)		
▪ Graphene DQDs Deng *et al.*, *PRL* **115**, 126804 (2015)		

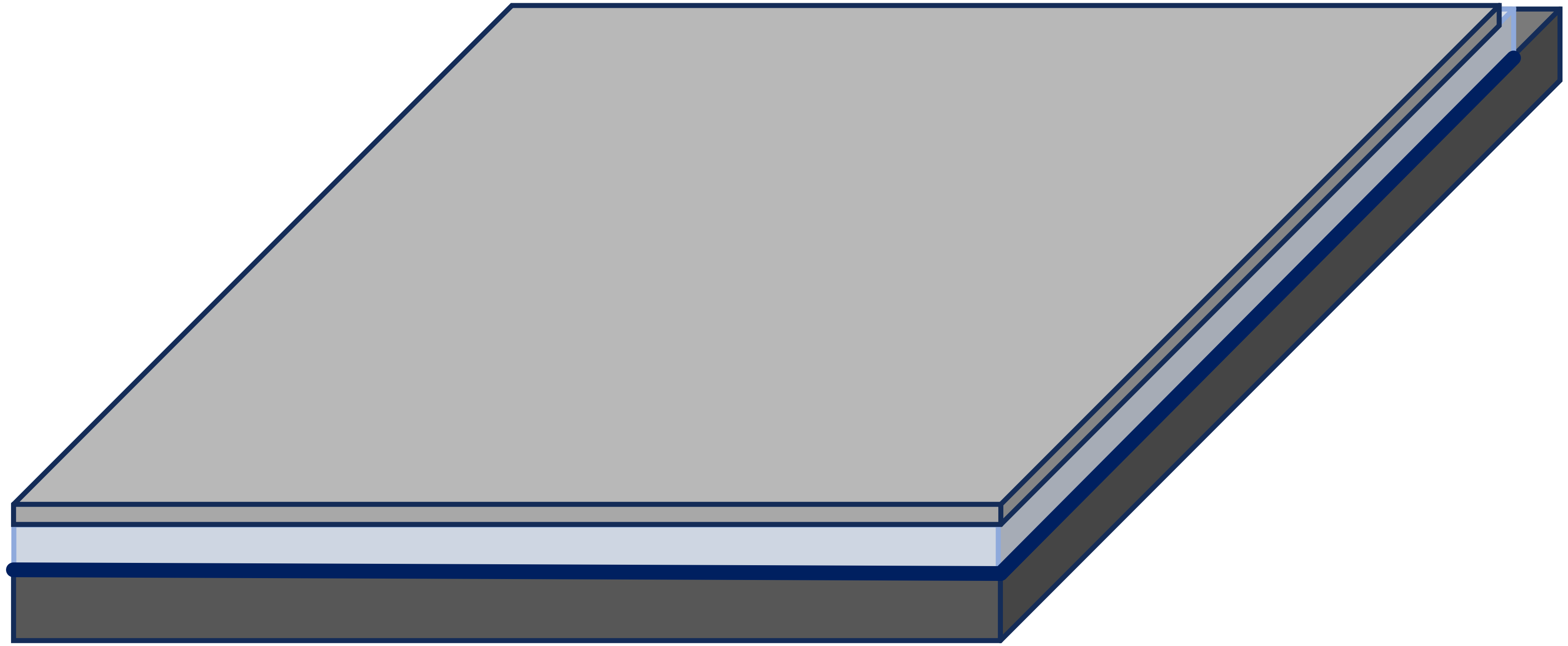
not in the strong coupling regime
$(g \ll \gamma)$

Double Quantum Dots Created in GaAs Heterostructure

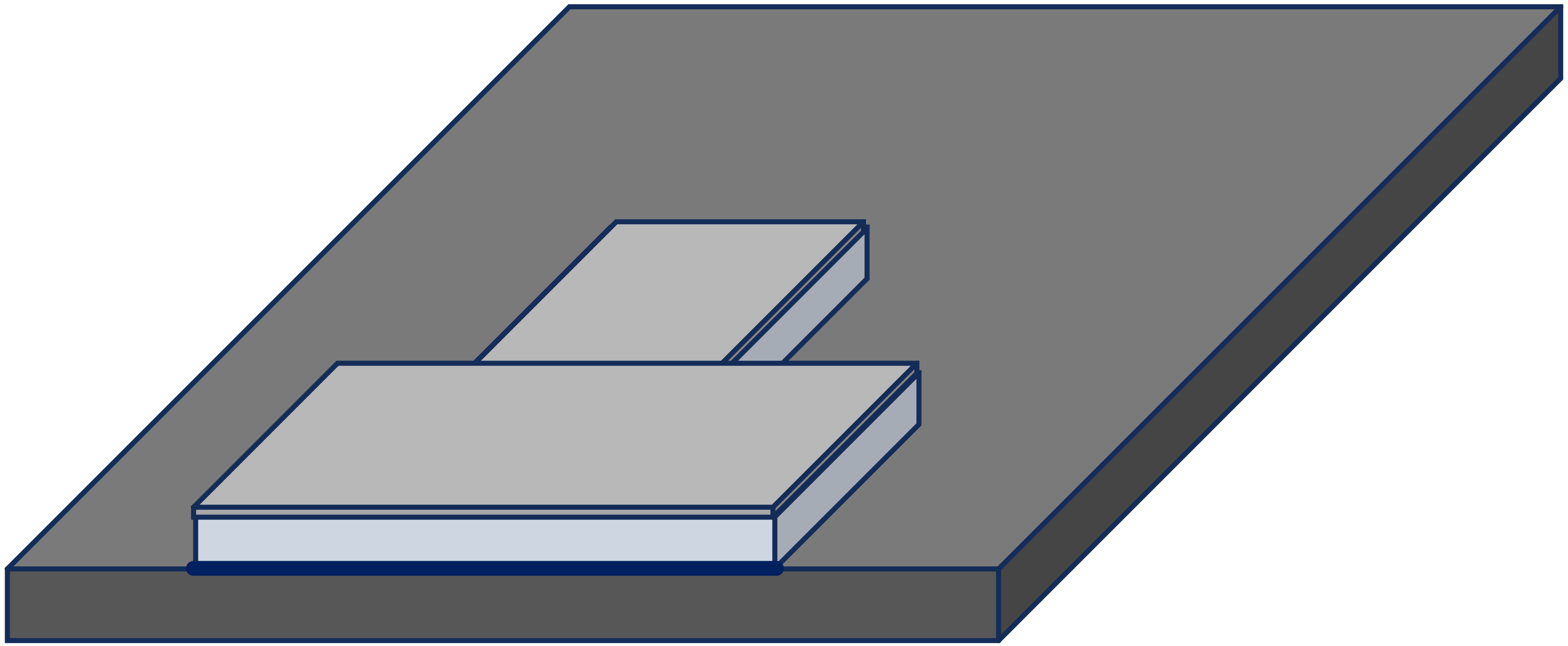


Wafer : C. Reichl, W. Wegscheider

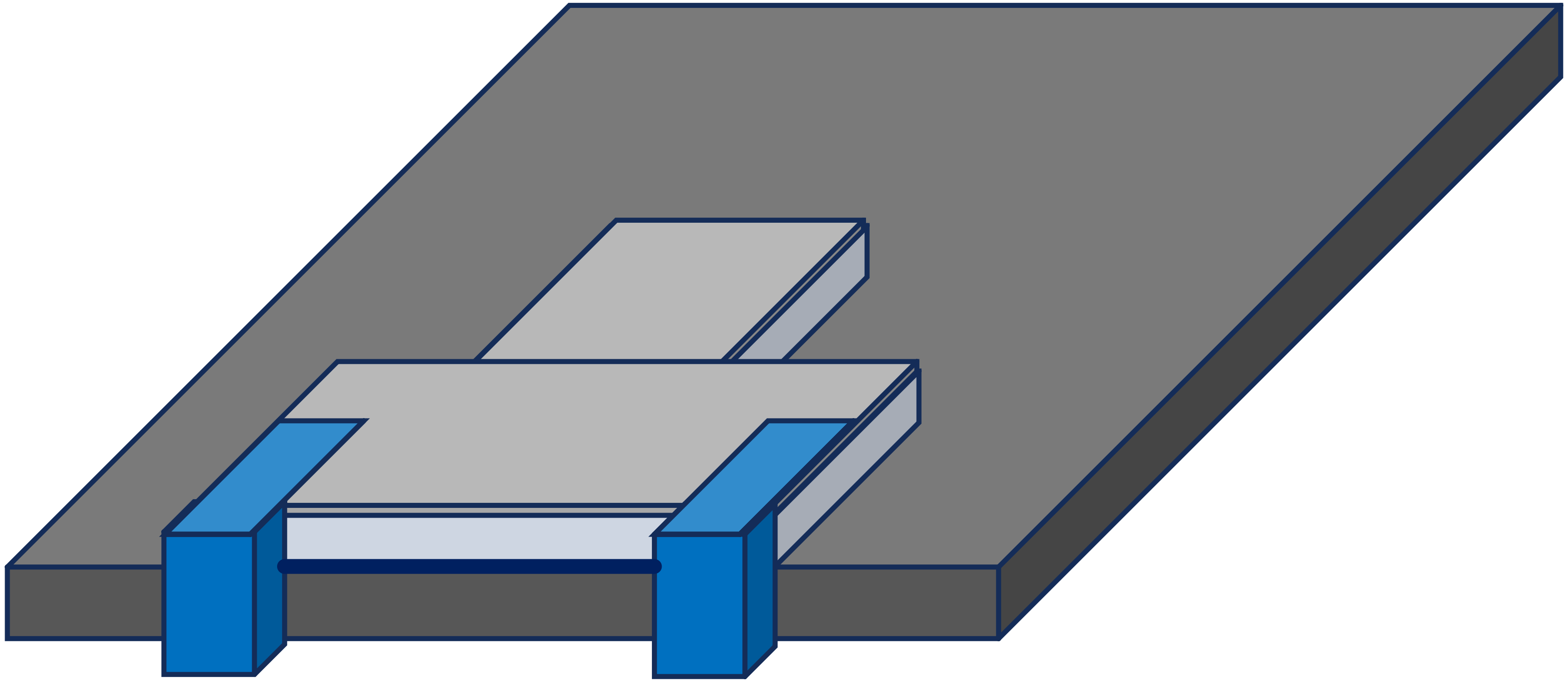
GaAs/AlGaAs Heterostructure



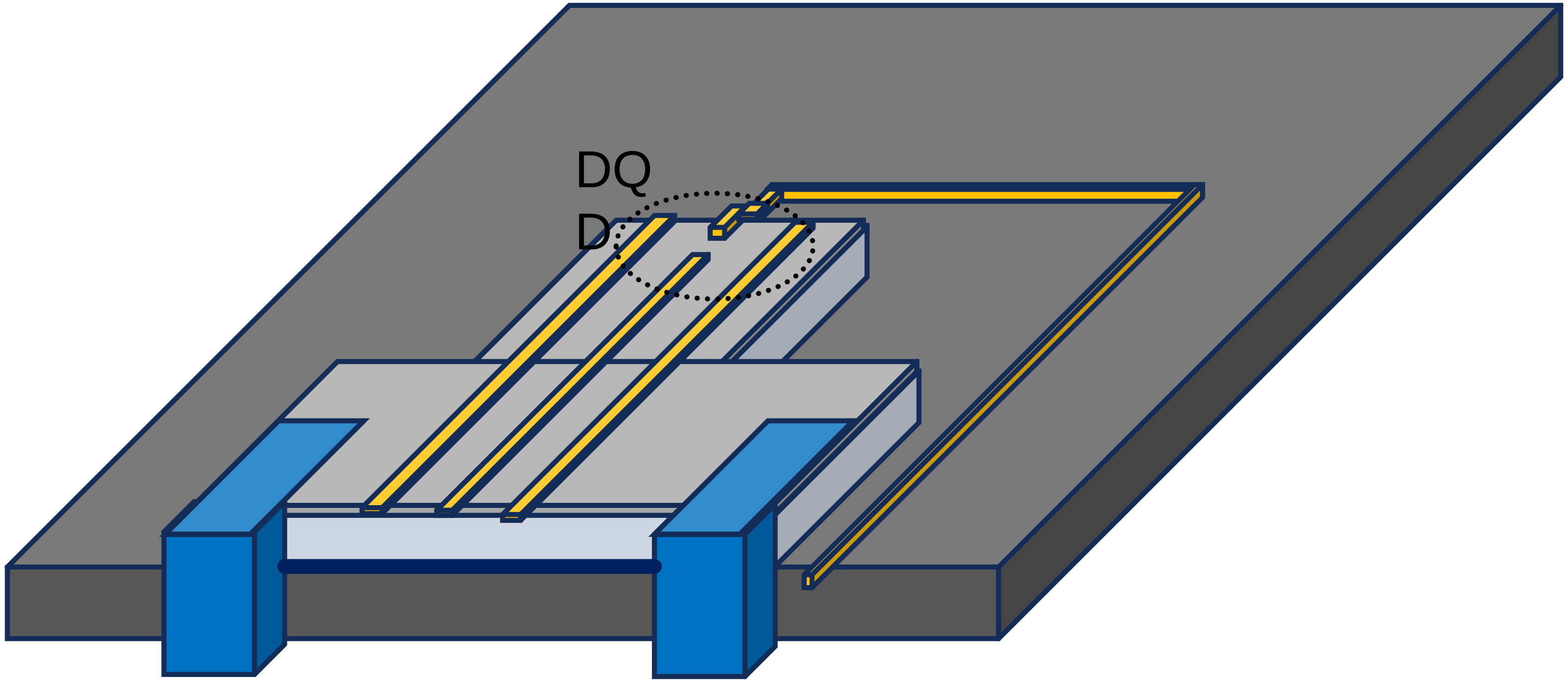
MESA Etching



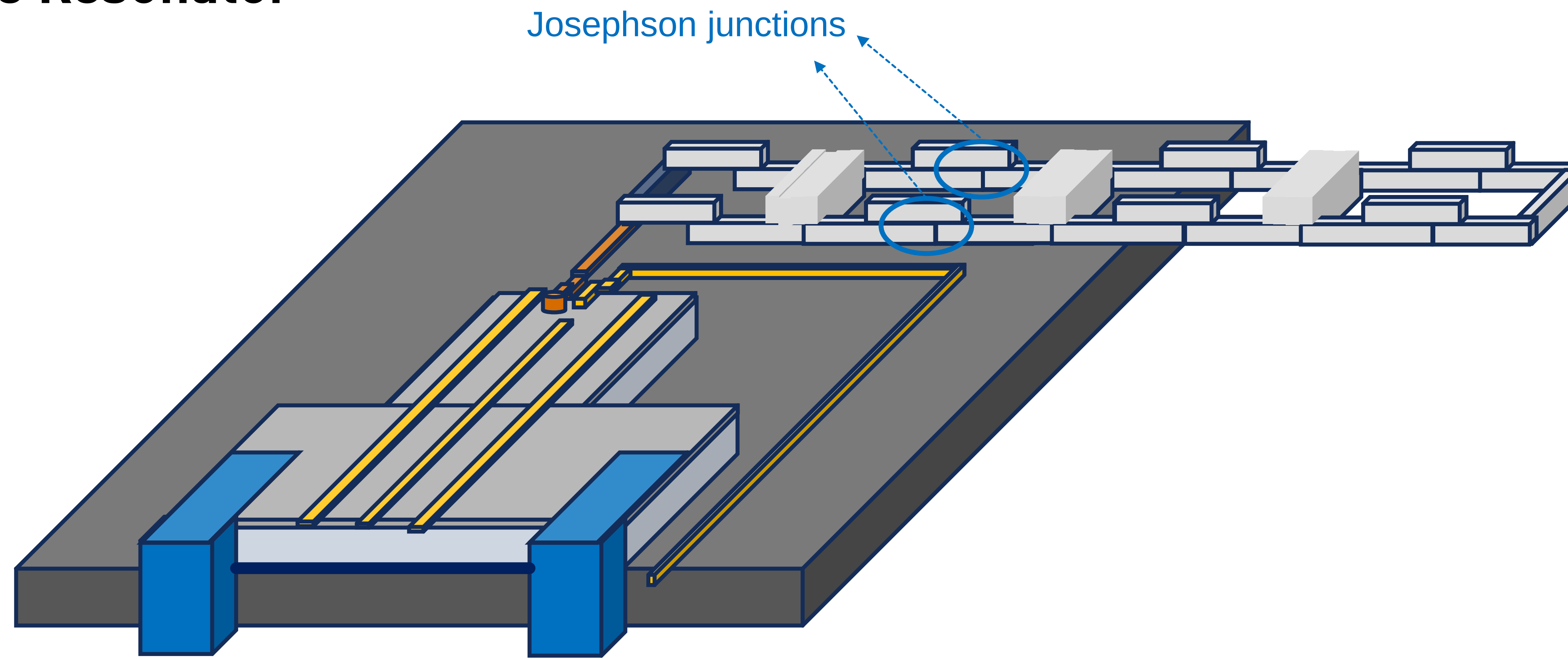
Ohmic Contacts



Depletion Gates



Microwave Resonator



High Impedance SQUID Array Resonator

- Increase dipole coupling

$$g \propto d \cdot V_0^{\mathrm{rms}} \propto \omega_r \sqrt{Z_r}$$

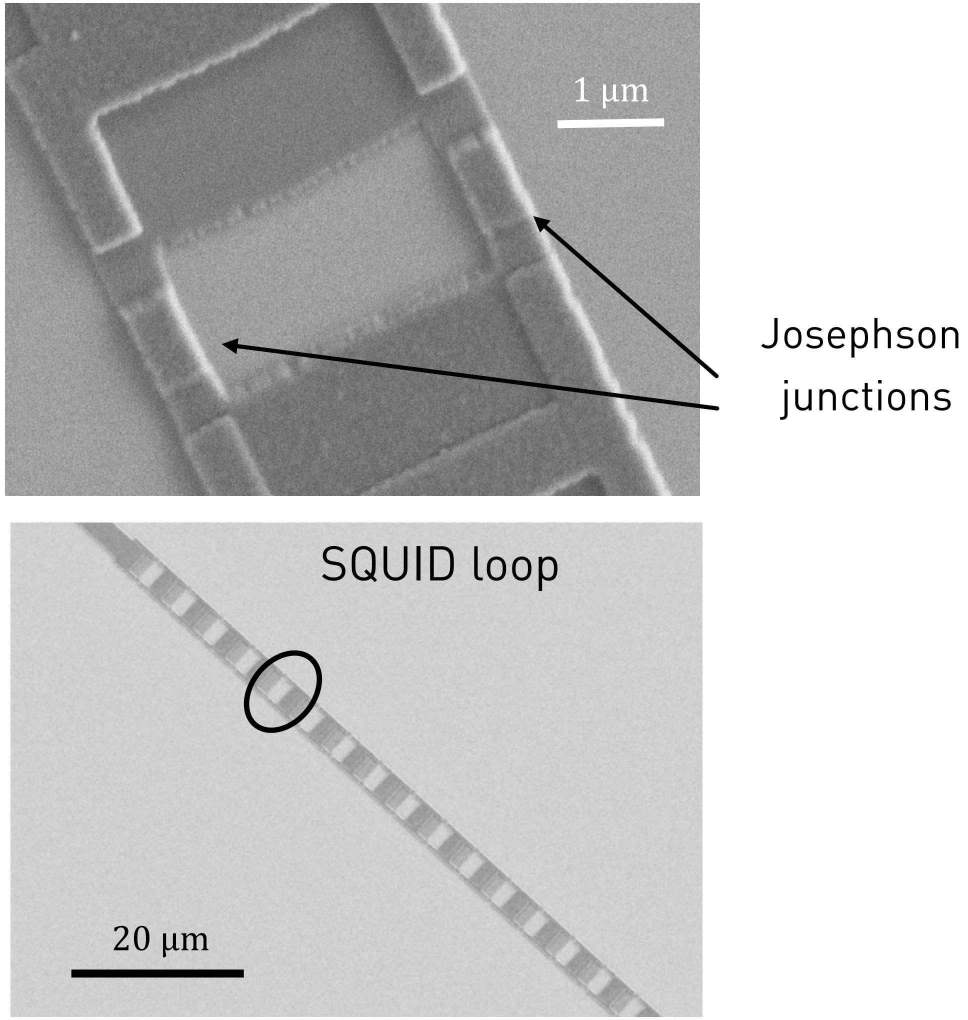
- Maximize impedance $Z_r = \sqrt{L_r/C_r}$

- Josephson junction as high impedance circuit elements

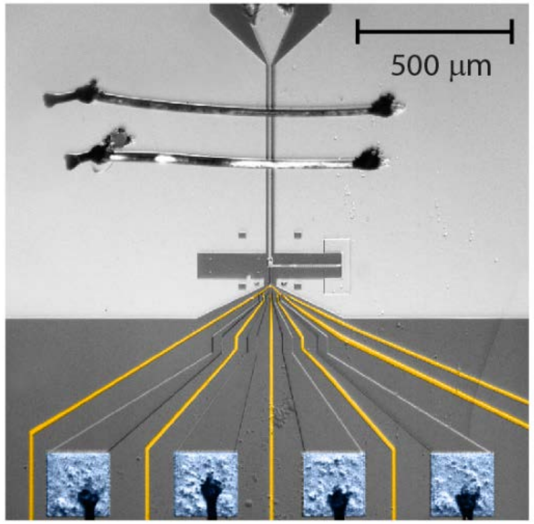
$$L_J = \frac{\Phi_0}{2\pi I_c \cos \varphi_0}$$

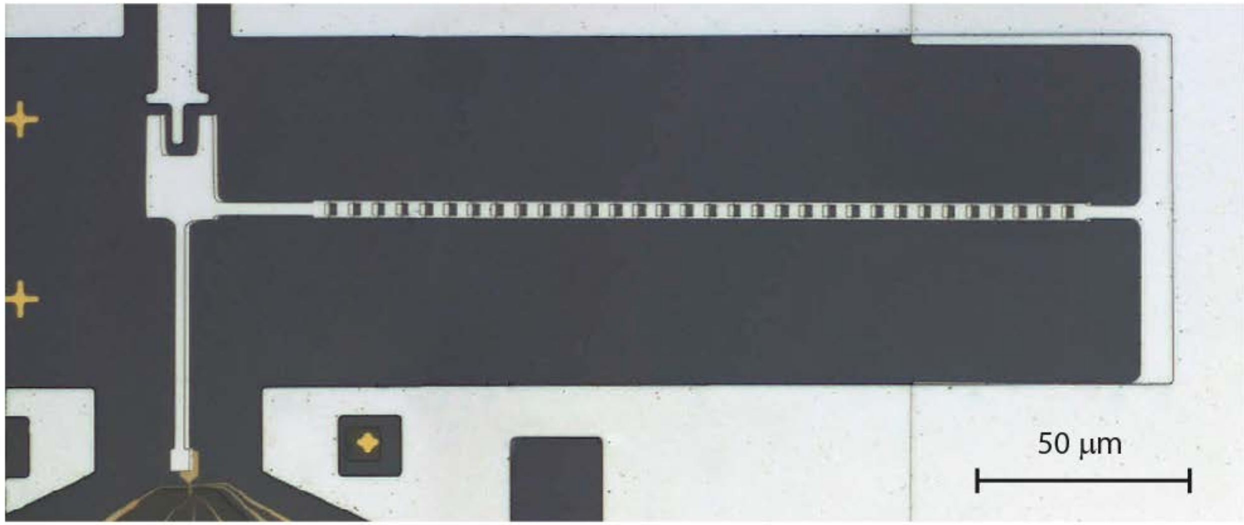
→ Resonator design based on SQUID array

Altimiras et al., APL **103**, 212601 (2013).
Masluk et al., PRL **109**, 137002 (2012).
Castellanos-Beltran, Lehnert, APL **91**, 083509 (2007).

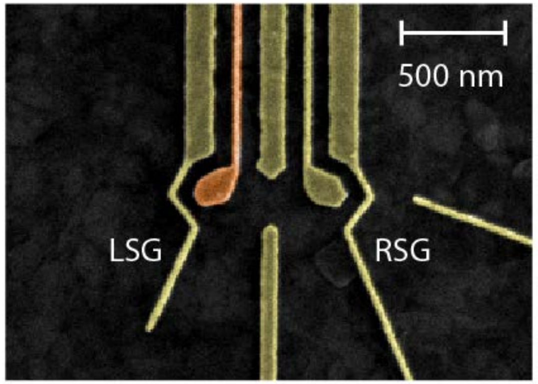


Integrated GaAs DQD with SQUID Array Resonator in Hybrid Device

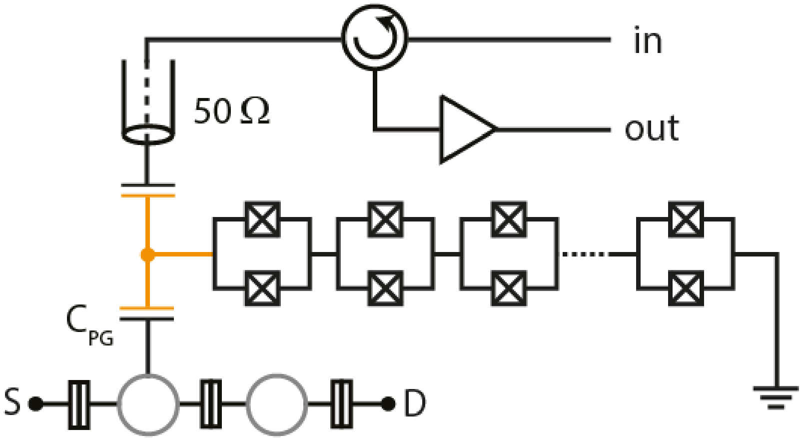




32 SQUID array resonator
- 200 μm long
- Al based
- Dolan bridge technique



Gate defined GaAs DQD
- On small mesa
- Resonator coupling gate not DC biased



Microwave reflectometry measurement
- Josephson parametric amplifier
- Custom FPGA electronics

Stockklauser, Scarlino *et al.*, *PRX* **7**, 011030 (2017)

Characteristics of SQUID Array Resonator

- SQUID inductance

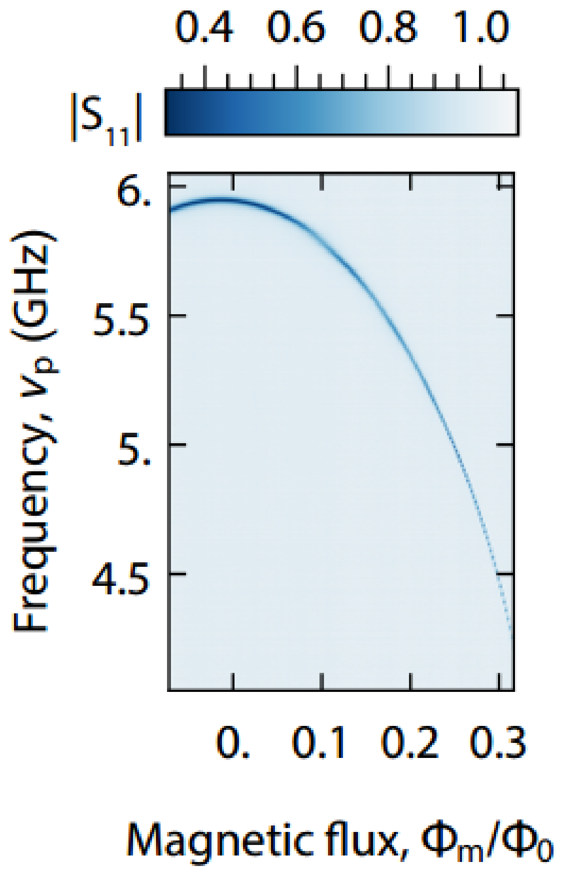
$$L_J^S(\Phi_m) \propto |\cos\left(\frac{\pi\Phi_m}{\Phi_0}\right)|^{-1}$$

→ Flux-tunable inductance, impedance and resonance frequency

- $\nu_r = 4 - 6\ \text{GHz}$
- $Z_r = 1.3 - 1.8\ \text{k}\Omega$

  ➔ $\sqrt{Z_r/\ 50\ \Omega} \sim 6$

- $(\kappa_{int}, \kappa_{ext}, \kappa)/2\pi\ = (10.0, 2.3, 12.3)\ \ \text{MHz}$

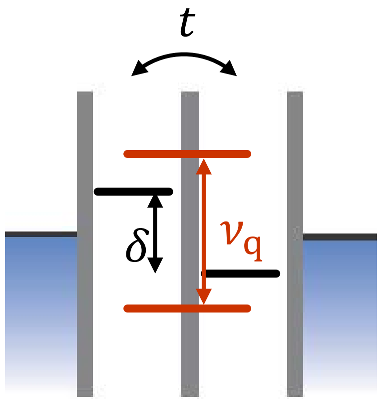


Stockklauser, Scarlino *et al., PRX* **7**, 011030 (2017)

Dispersive Interaction

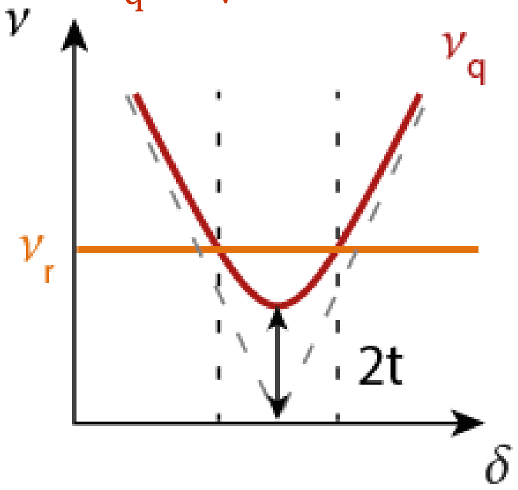
energy detuning δ

tunnel coupling t

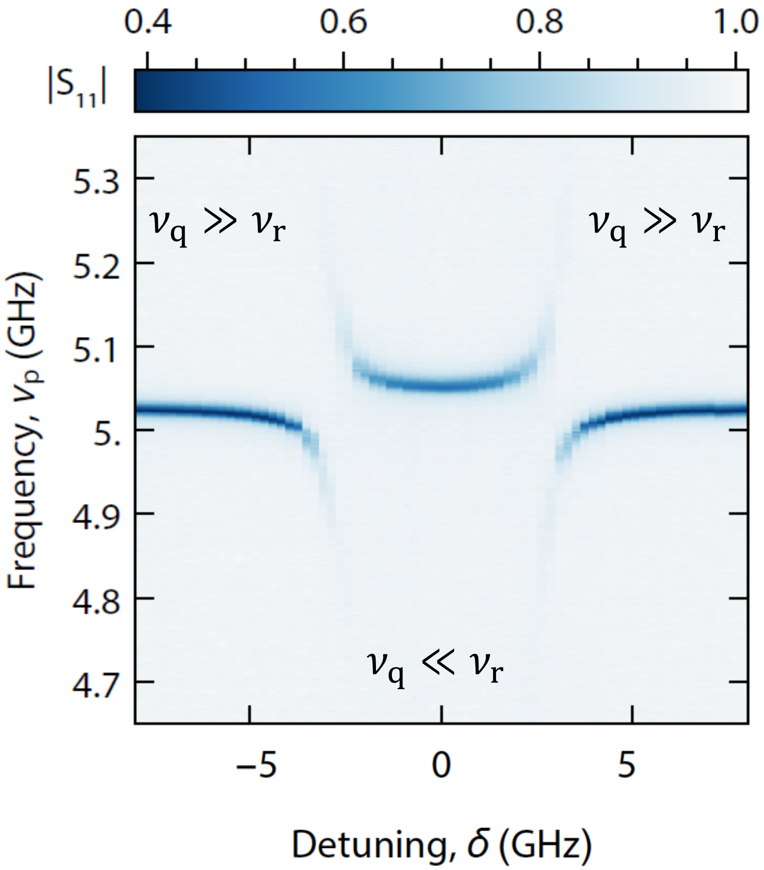


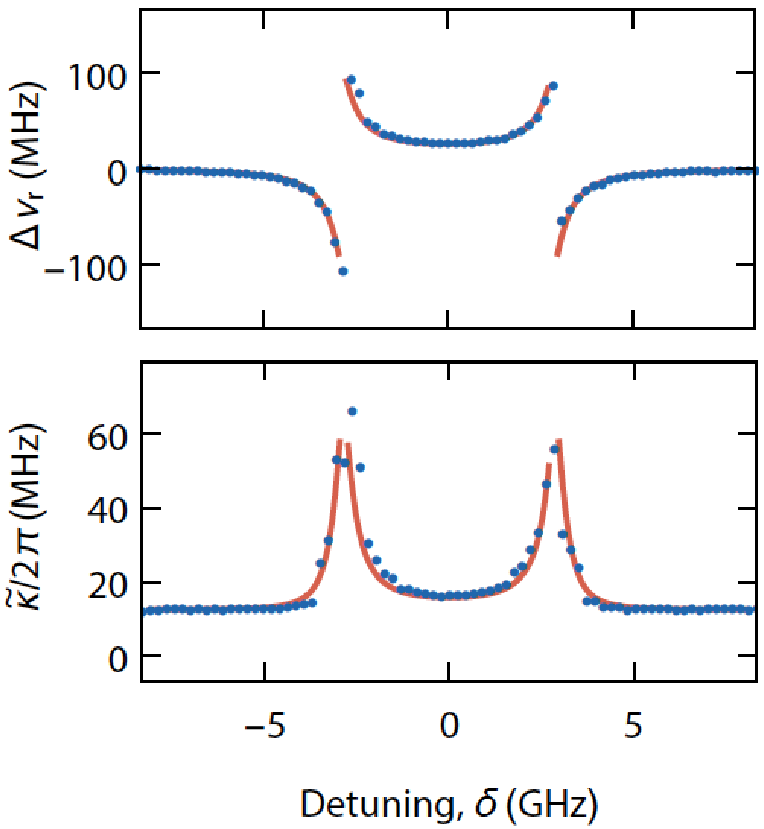
qubit frequency

$\nu_q = \sqrt{4t^2 + \delta^2}$



$2t = 4.13$ GHz
$\nu_r = 5.03$ GHz
$2t < \nu_r$





Dispersive indication of strong coupling: $(g, \gamma_1, \gamma_\varphi, \kappa)/(2\pi) = (145, 60, 38, 12)$ MHz

Stockklauser, Scarlino *et al.*, *PRX* **7**, 011030 (2017)

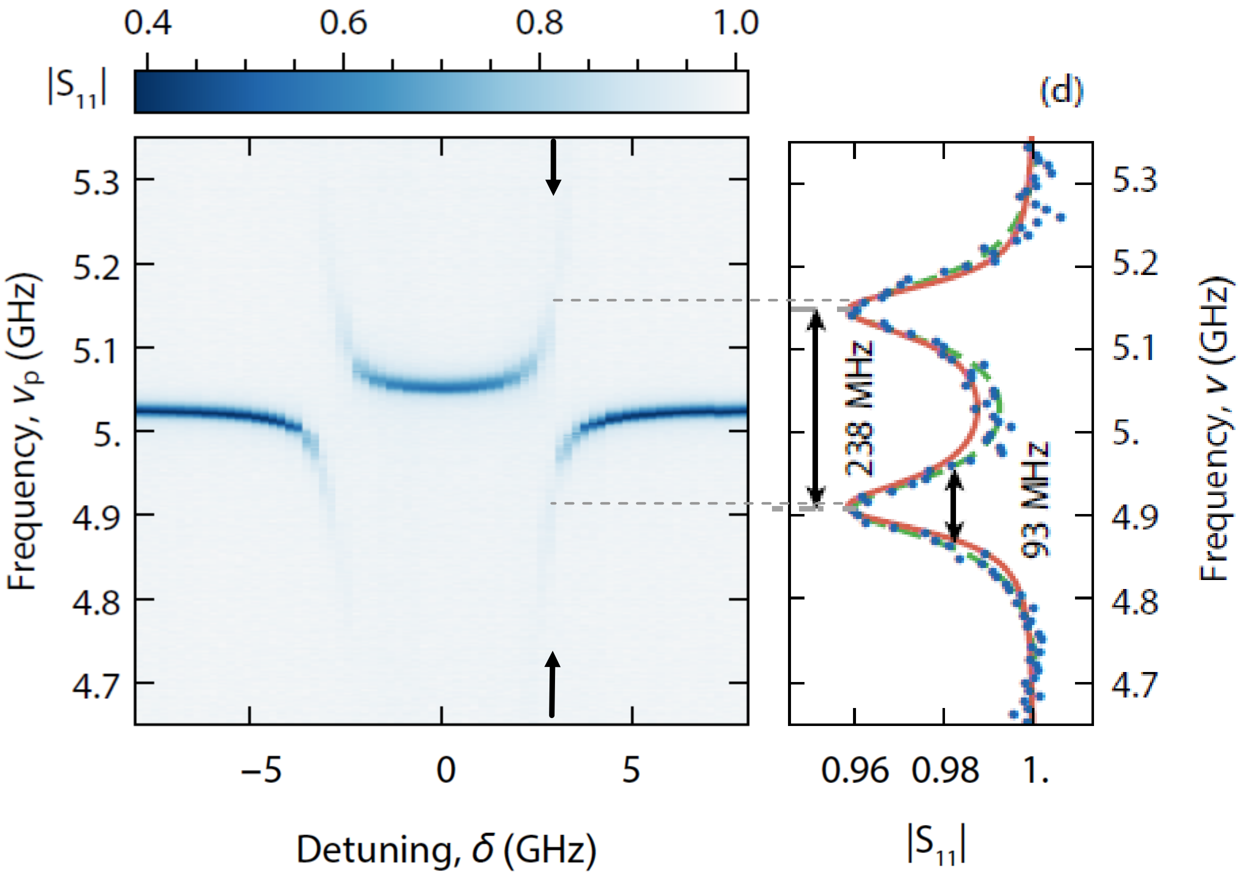
Strong Resonant Interaction

First (joint with Petta at Princeton) observation of **strong coupling cavity QED** $(g > \kappa, \gamma)$ in **gate defined semiconductor QDs:**

$$(g, \gamma_1, \gamma_\varphi, \kappa)/(2\pi) = (145, 60, 38, 12)\ \mathrm{MHz}$$

Enables:

- QND qubit readout
- Non-local qubit/qubit coupling
- Charge qubit to photon conversion
- Potentially spin qubit to photon conversion
- Essential for quantum information processing with semiconductors



- Makes many/all features of circuit QED accessible to research and development on semiconductor nano-structures

Stockklauser, Scarlino *et al.*, *PRX* 7, 011030 (2017)
Mi *et al.*, *Science* **355**, 156 (2017)

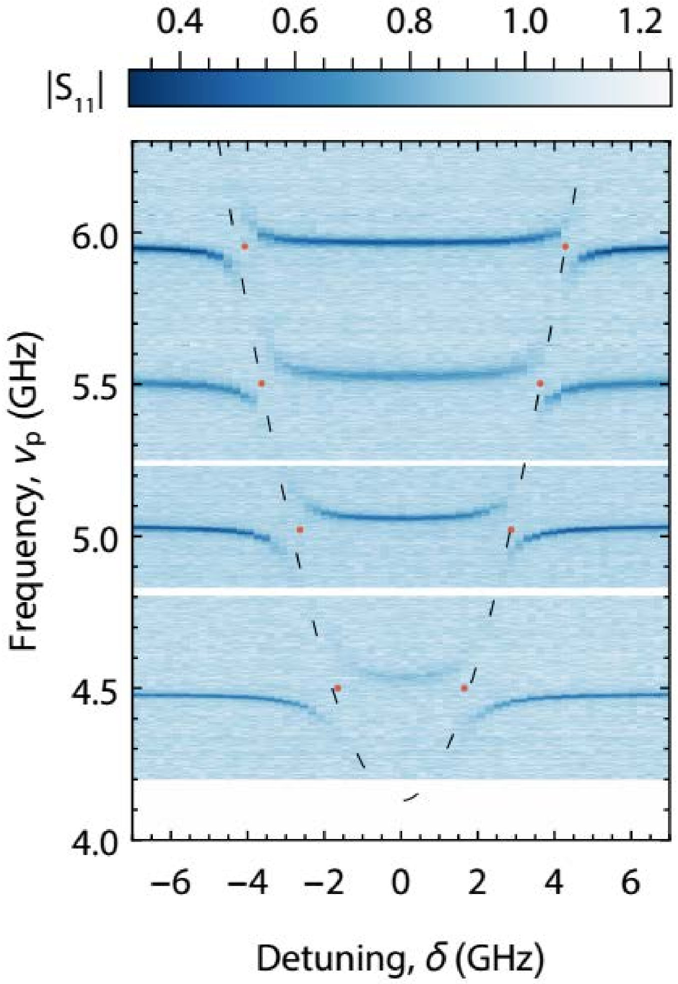
Two Approaches to Qubit Spectroscopy

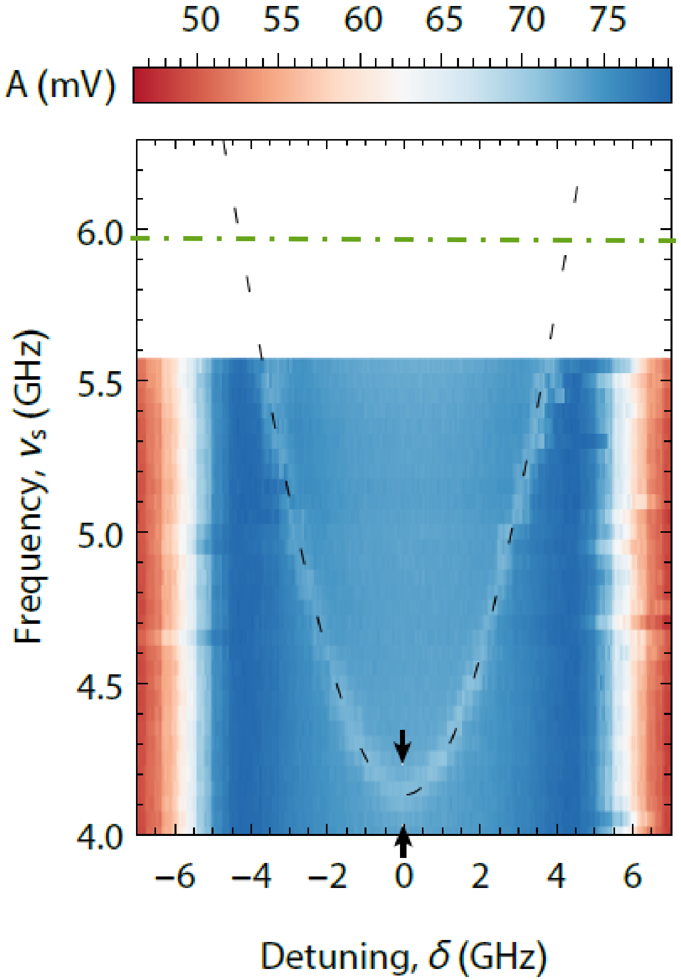
Tunable resonator spectroscopy

Fixed tunnel coupling
$2t = 4.13$ GHz

$\nu_r(\Phi_m) = \nu_q$
(●)

$\nu_q(\delta) = \sqrt{4t^2 + \delta^2}$
(−)





Two-tone spectroscopy

Fixed probe frequency
$\nu_p = \nu_r = 5.947$ GHz

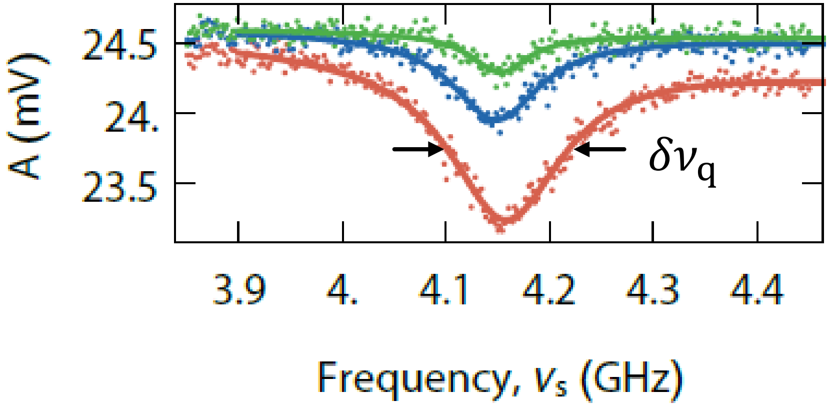
Spectroscopy frequency
ν_s

$\nu_q(\delta) = \sqrt{4t^2 + \delta^2}$

Stockklauser, Scarlino
Inspired by: Schuster *et al.* PRL **94**, 123602 (2005).

Drive Strength Dependence of Qubit Line-Shape

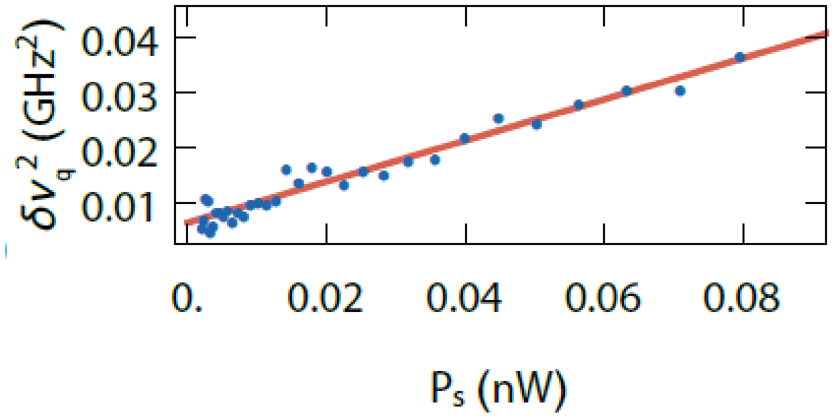
Two-tone spectroscopy measurement



- Power broadening and saturation with spectroscopy drive strength P_s
- Low power limit reveals coherence

Stockklauser, Scarlino *et al., PRX* **7**, 011030 (2017).
Inspired by: Schuster *et al. PRL* **94**, 123602 (2005).

Qubit line width $\delta\nu_q^2$ vs. drive strength P_s



- For $P_s \to 0$

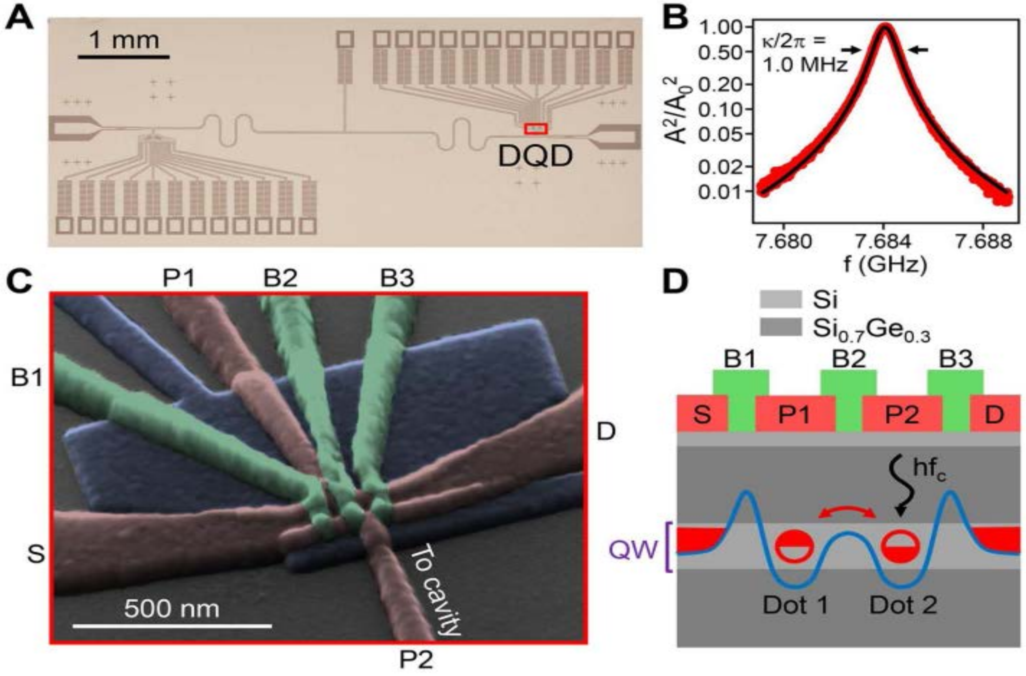
$$\frac{1}{T_2} = \pi\delta\nu_q$$

$$\gamma_2/2\pi = 40\ \mathrm{MHz}$$

- Surprisingly small linewidth for charge states in piezoelectric GaAs
- Even better coherence observed in subsequent experiments

Recent Companion Experiments on Strong Coupling

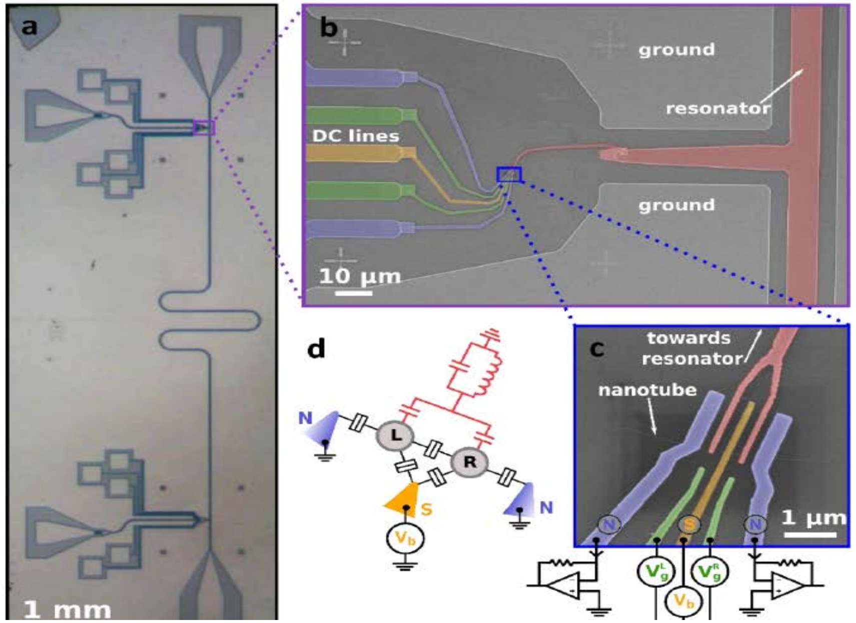
Si\SiGe DQD (dipolar coupling)
X. Mi et al., Science **355**, 156-158 (2017)



- $Z_0 = 50\ \Omega$
- $g/2\pi \approx 6.7$ MHz
- $(\kappa, \gamma)/2\pi \approx (1, 2.6)$ MHz

strong coupling regime
$(g > \kappa, \gamma)$

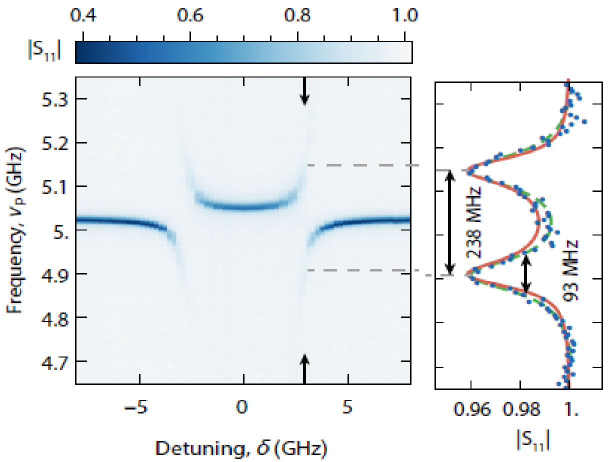
Carbon Nanotube DQD with superconducting leads
L. E. Bruhat et al., arXiv:1612.05214



- $Z_0 = 50\ \Omega$
- $g/2\pi \approx 10$ MHz
- $(\kappa, \gamma)/2\pi \approx (1, 4)$ MHz

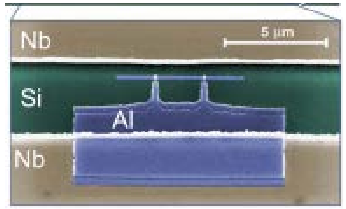
Conclusion and Perspectives

Strong coupling in semiconductor QDs



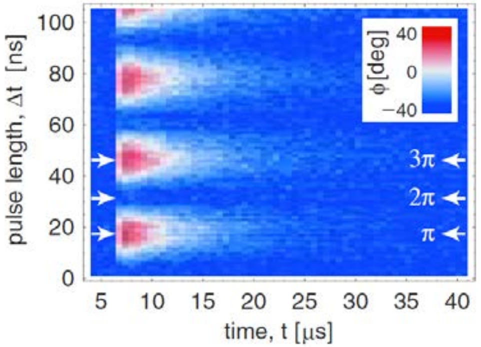
Stockklauser, Scarlino *et al.*, *PRX* **7**, 011030 (2017).
Mi *et al.*, *Science* **355**, 156 (2017)

- coherent coupling to other types of qubits



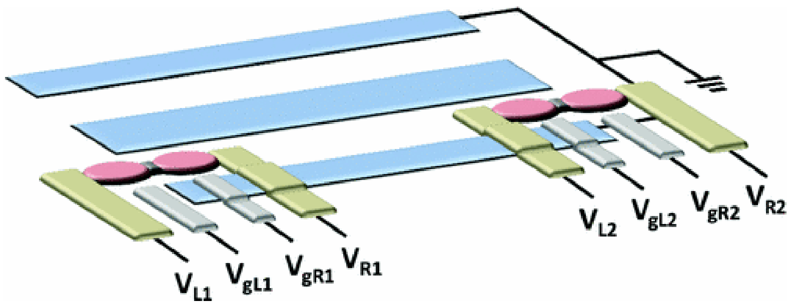
Nature **431**, 162 (2004)

- Time-resolved measurements with dispersive readout



PRL **95**, 060501 (2005)

- Non-local coherent coupling of multiple DQDs



Bergenfeldt *et al.*, *PRB* **87**, 195427 (2013)
Delbecq *et al.*, *Nat. Comm.* **4**, 1400 (2013)