Recent advances in InAs nanodevices

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NanoSeminar Lecture

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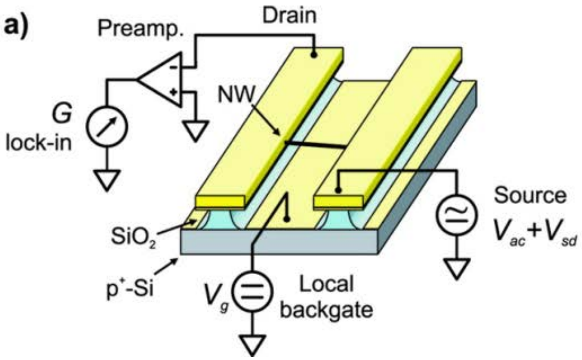
MŰEGYETEM 1782

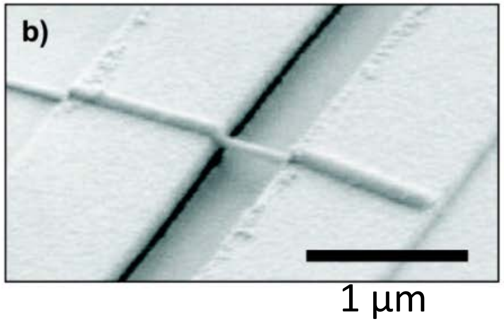
Outline

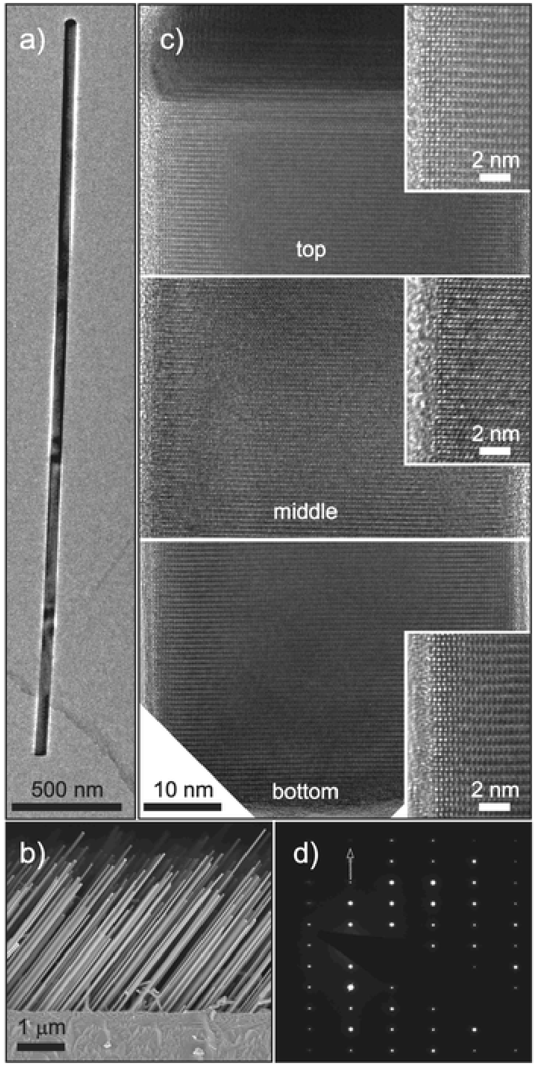
- Fabry-Pérot conductance oscillations
  - Multi-mode Fabry-Pérot conductance oscillations in suspended stacking-faults-free InAs nanowires (Kretinin et al., http://arxiv.org/abs/1005.0229v2)
- The g-factor in InAs nanowires
  - Field Tuning the G-Factor in InAs Nanowire Double Quantum Dots (Schroer et al., http://arxiv.org/abs/1105.1462)
- SOI in InAs quantum dots
  - Electrically tuned spin-orbit interaction in an InAs self-assembled quantum dot (Tarucha et al., 10.1038/nnano.2011.103)
  - Spin-orbit qubit in a semiconductor nanowire (Nadj-Perge et al., 10.1038/nature09682)
- Suspended InAs nanowire resonator
  - High Q electromechanics with InAs nanowire quantum dots (Solanki et al. http://arxiv.org/abs/1108.3255, supplementary material: http://www.tifr.res.in/~nano)

Fabry-Pérot conductance oscillations

- VLS MBE grown InAs NWs
  - diameter: 50-60 nm
  - length: 4-5 µm
  - „stacking-fault-free”, pure wurtzite (bulk InAs: zinc-blende structure)
- Device fabrication
  - chemically etched grooves
  - local backgate evaporation
  - NW deposition, etc.

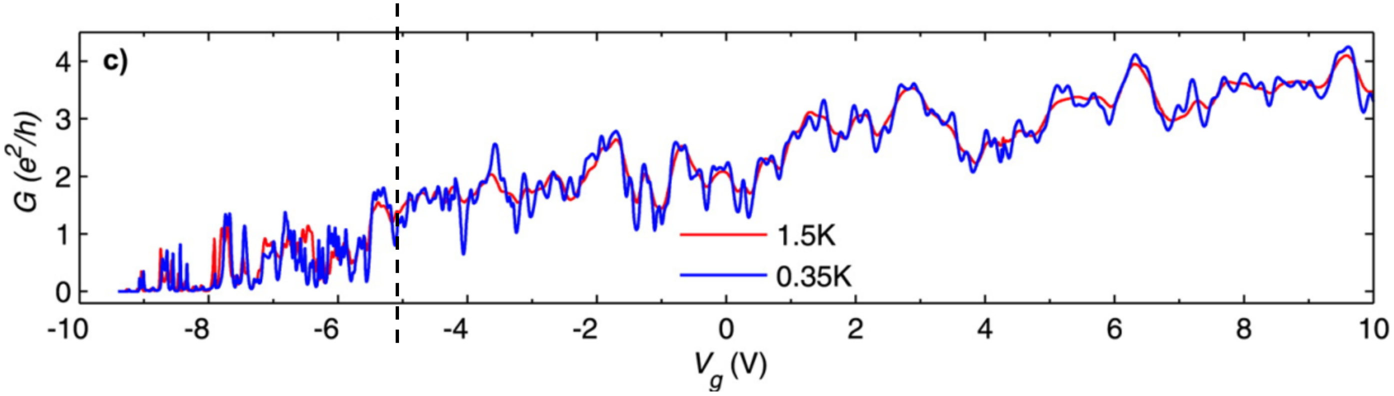




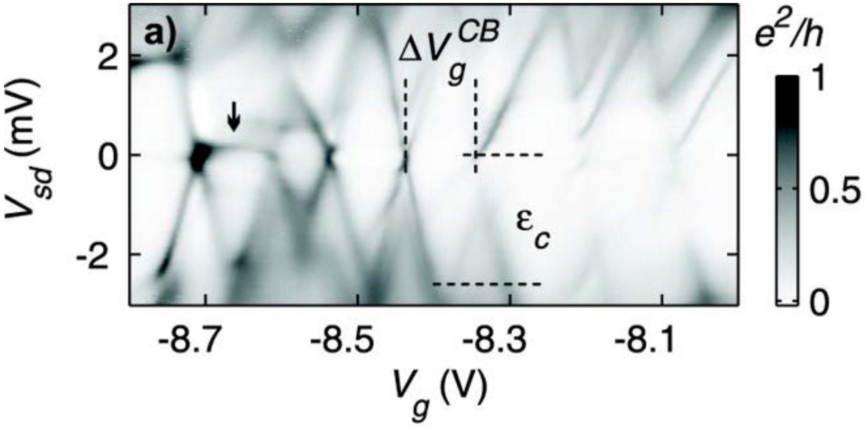


Fabry-Pérot conductance oscillations

- Measurements



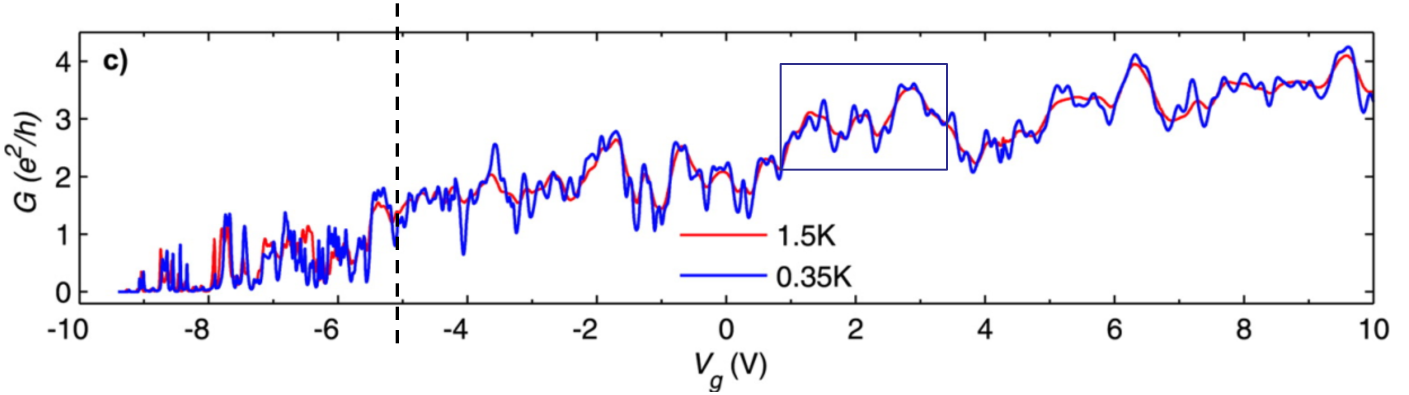
QD behaviour



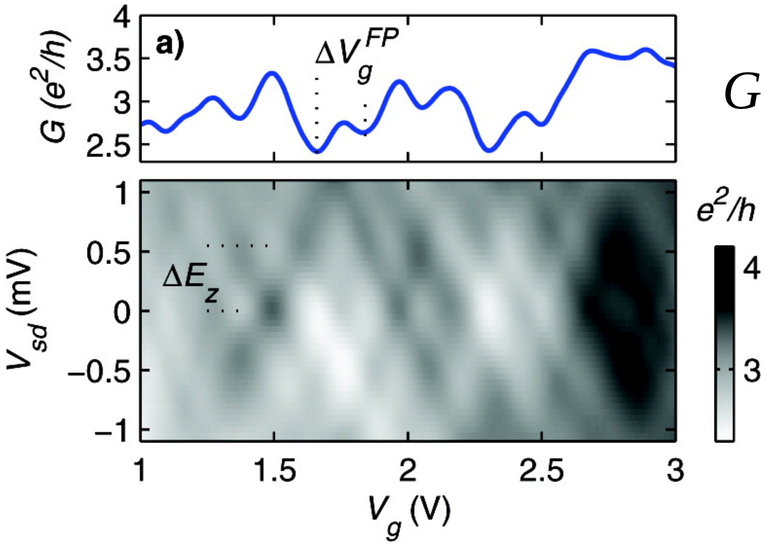
- charging energy: $\varepsilon_c \approx 3$ meV
- gate capacitance: $C_g = e/\Delta V_g^{CB} \approx 1.6$ aF
- Kondo effect (at $V_g \approx -8.6$ V)
  - strong coupling
- NW length: 470 nm

Fabry-Pérot conductance oscillations

- Measurements



Fabry-Pérot oscillations



$G > 2e^2/h$

- quasi-periodic oscillations, chessboard pattern → not UCF
- high conductance ($G > G_0$)
  - not Coulomb blockade oscillations (transport through second 1D subband)

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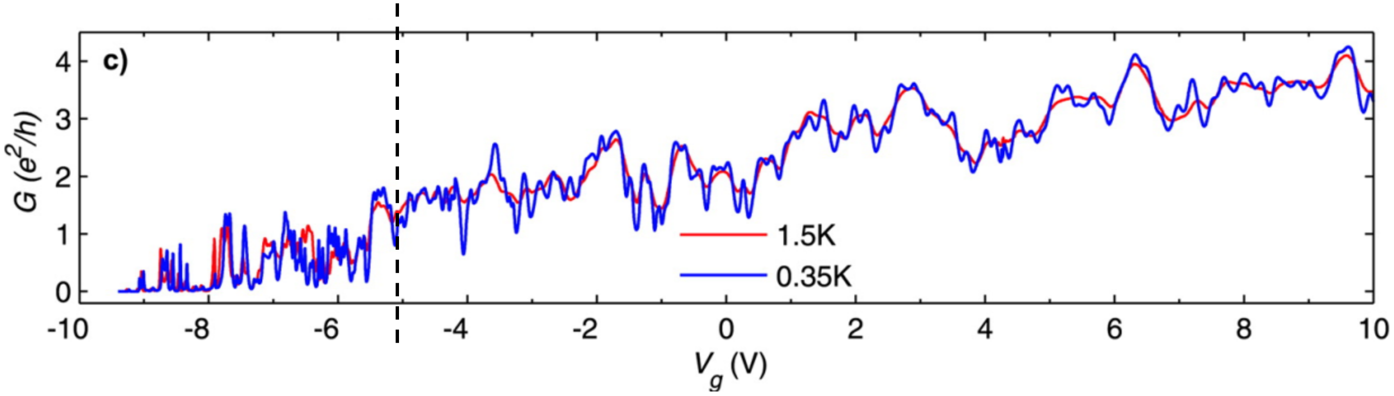
Fabry-Pérot oscillations

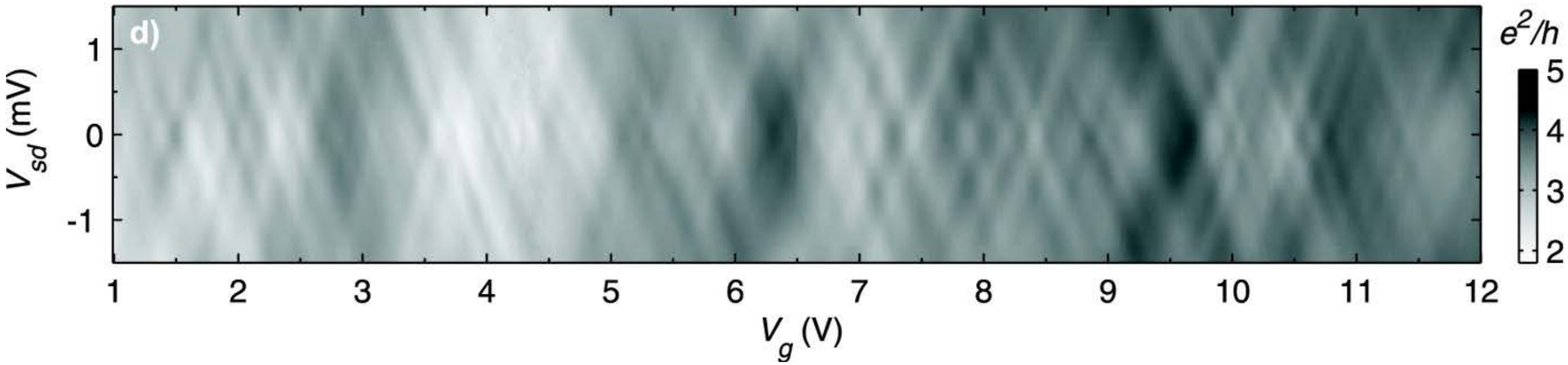
- explanation: electrons are reflected only from the precontact areas

Fabry-Pérot conductance oscillations

- Measurements

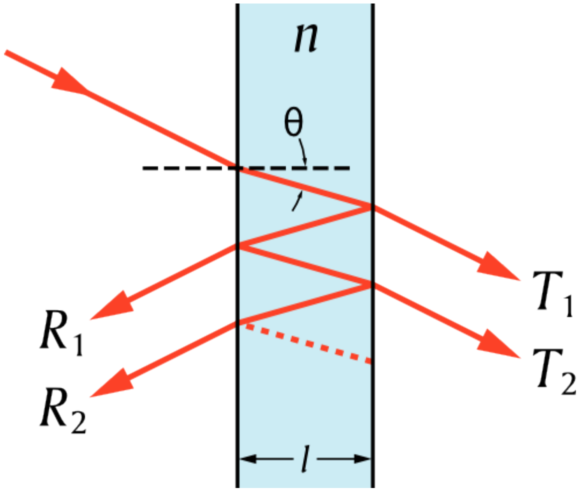


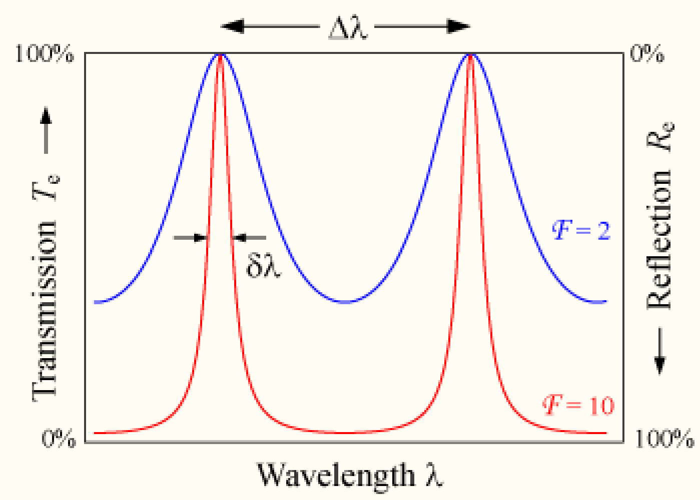
Fabry-Pérot oscillations



Fabry-Pérot conductance oscillations

- Analogy in optics: Fabry-Pérot interferometer
  - transparent plate
  - multiple reflections at the boundaries
  - sharp peaks in the transmission spectrum

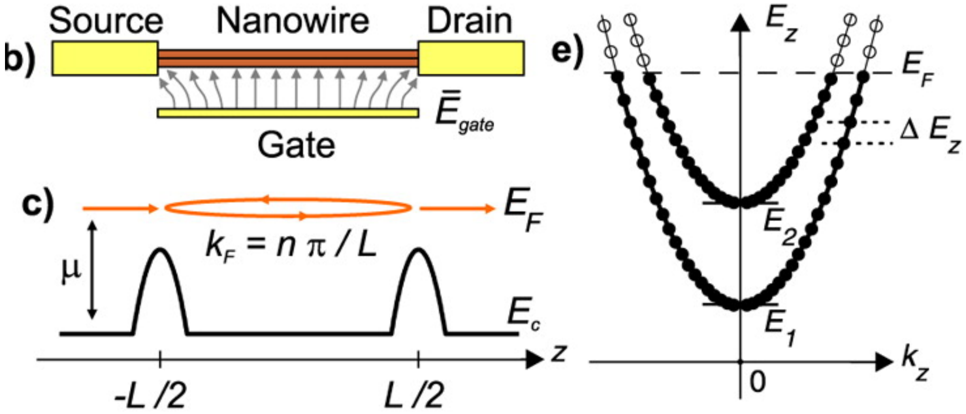




http://en.wikipedia.org/wiki/Fabry-Perot_interferometer

Fabry-Pérot conductance oscillations

- Fabry-Pérot interference



  - Single channel: constructive interference for

$$k_F 2L = 2\pi n \quad \Rightarrow \quad \mu = E_F - E_i = \frac{\hbar^2 k_F^2}{2m^*} = \frac{\hbar^2 \pi^2 n^2}{2m^* L^2}$$

  - tuning: $\mu \propto \alpha V_g$
  - check:

$$\left.\begin{aligned} \delta k_F &= \pi / L \\ \delta n_{1D} &= 2\delta k_F / \pi = C_g^{(L)} \Delta V_g^{FP} / e \end{aligned}\right\} \; L = \frac{2e}{C_g^{(L)} \Delta V_g^{FP}} \quad \Rightarrow$$

L ≈ 400 nm
(SEM: L ≈ 470 nm)

Fabry-Pérot conductance oscillations

- Fabry-Pérot interference
  - Simple model of a multi-mode 1D transport

Barrier shape:

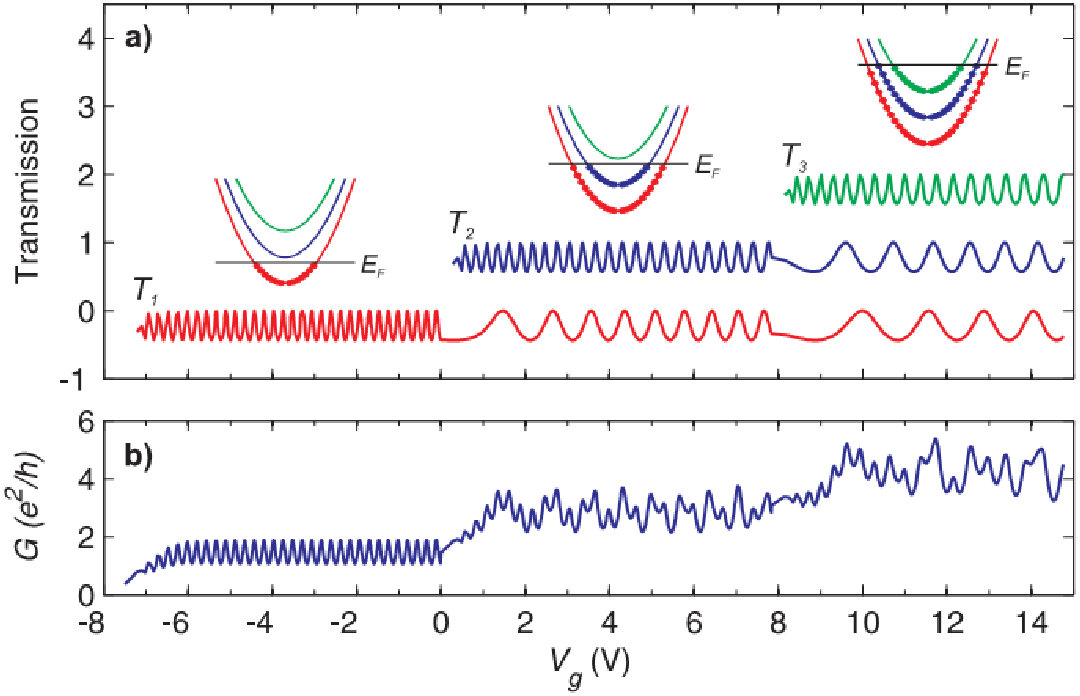
$$V_{L,R} = V_0 - \frac{m^*\omega^2(z \mp L/2)^2}{2}$$

Carrier density:

$$N_{1D} = C_g^L(V_g - V_{th})/e = \frac{2\sqrt{2m^*}}{\pi\hbar}\sum_i \sqrt{\mu}$$

Conductance:

$$G = \frac{2e^2}{h}\sum_i T_i$$



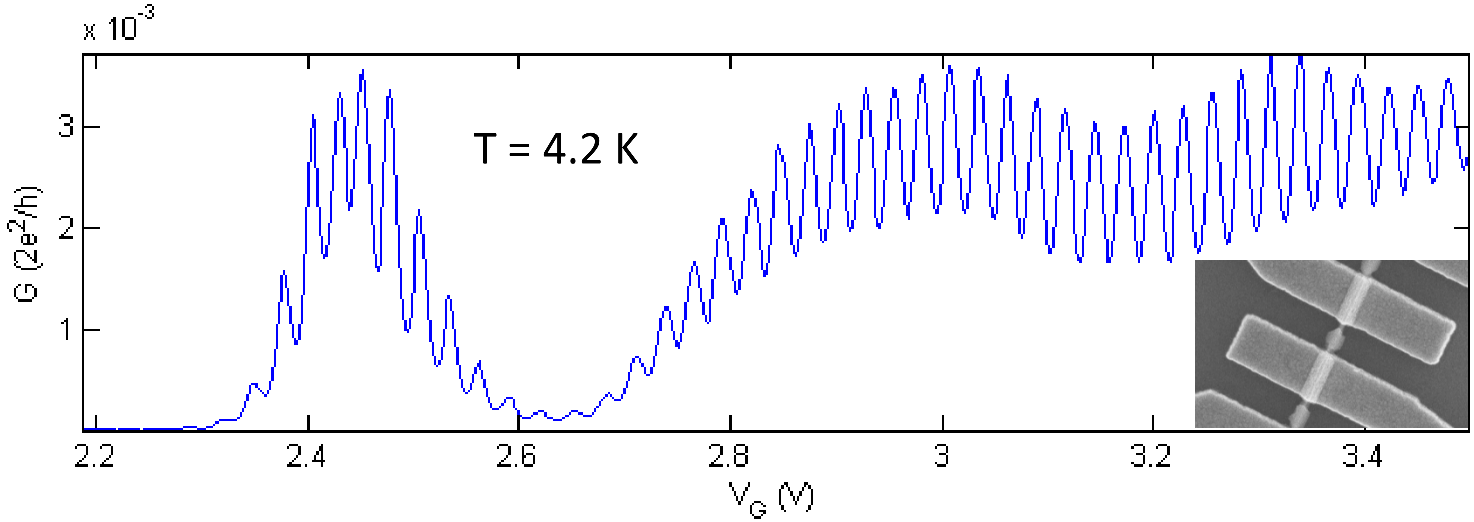
$$T_i = \left[P^2(\varepsilon_L,\varepsilon_R) + Q^2(\varepsilon_L,\varepsilon_R) + 2P(\varepsilon_L,\varepsilon_R)Q(\varepsilon_L,\varepsilon_R)cos\left(2k_iL + \phi_L + \phi_R\right)\right]^{-1}$$

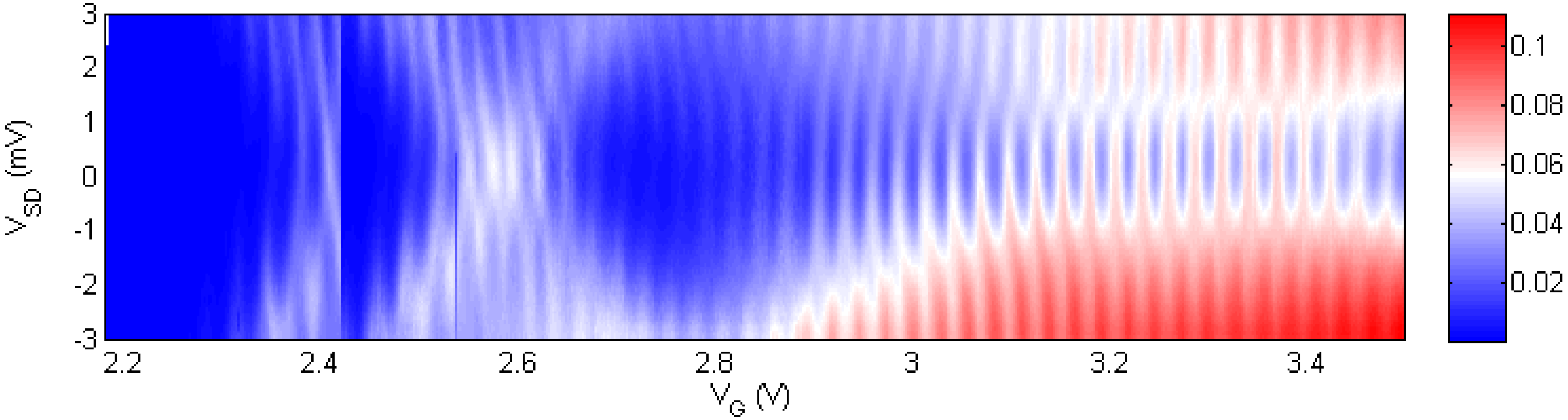
$$P(\varepsilon_L,\varepsilon_R) = \sqrt{(1+exp[-2\pi\varepsilon_L])(1+exp[-2\pi\varepsilon_R])}$$

$$Q(\varepsilon_L,\varepsilon_R) = exp[-\pi(\varepsilon_L+\varepsilon_R)] \qquad \varepsilon_{L,R} = (E_F - V_0)/\hbar\omega$$

Fabry-Pérot conductance oscillations

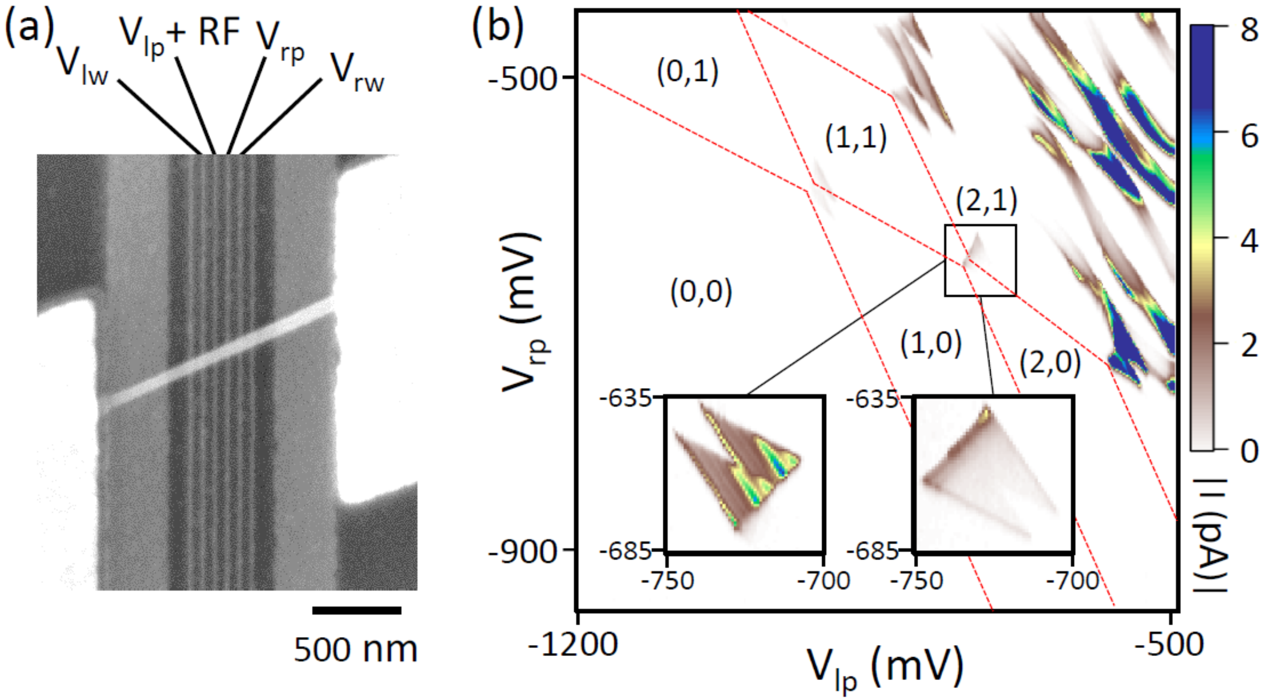
- S. d’Hollosy, G. Fülöp, Sz. Csonka (unpublished)


T = 4.2 K



Field tuning the g-factor

- Device
  - double QD in InAs NW with bottom gate structure
  - InAs: strong SOI → fast spin rotations
  - Pauli spin blockade: (1,1) triplet state; (2,0) is blocked
    - leakage current: spin-flip, cotunneling



Field tuning the g-factor

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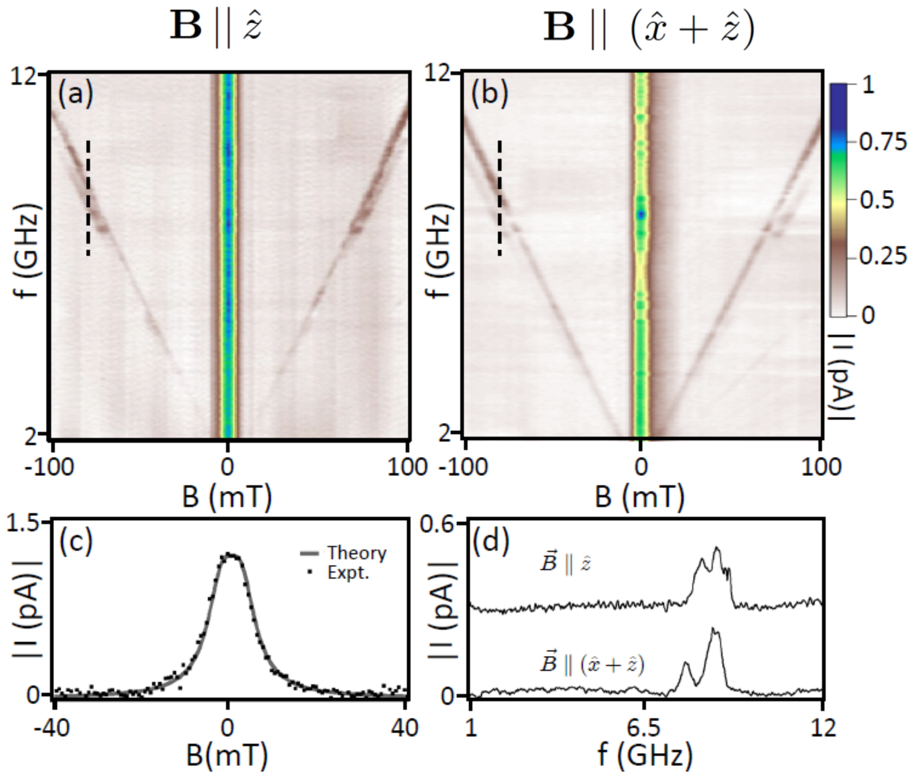


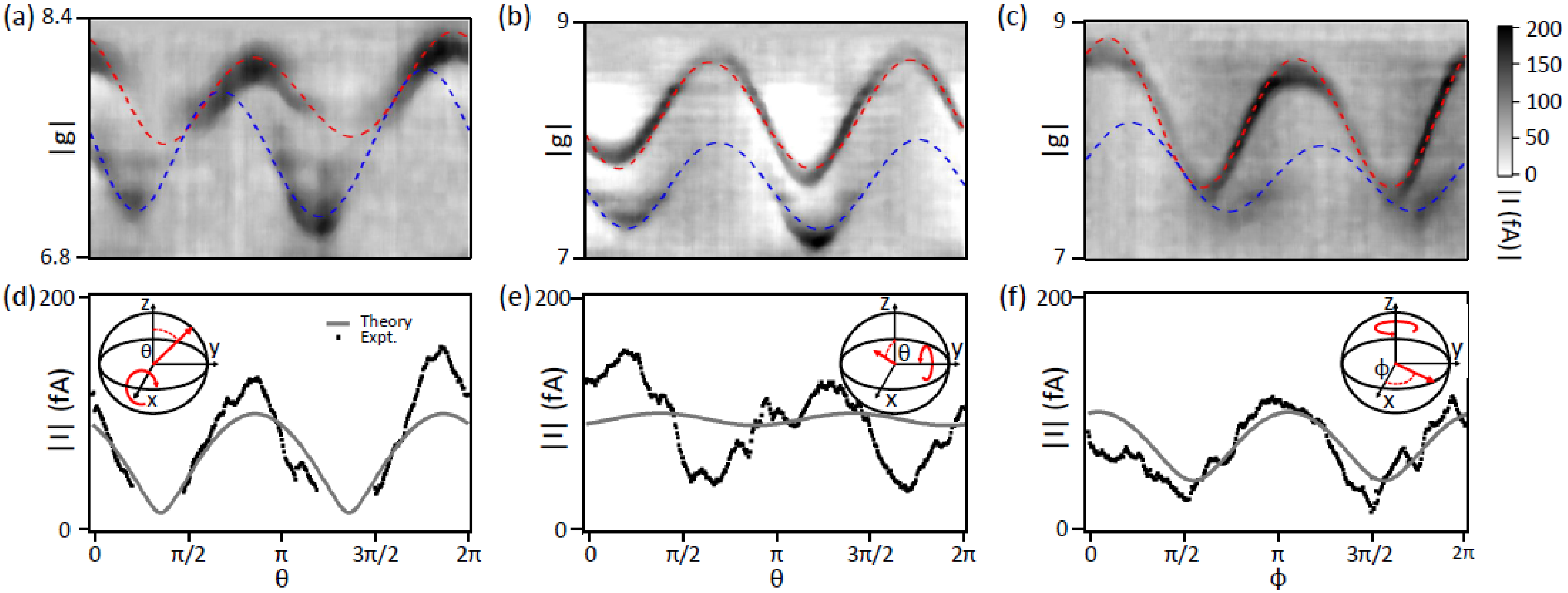
Resonance condition:

$$hf = g\mu_B|\mathbf{B}|$$

Hyperfine field → zero field peak ($B_N \approx 3.3$ mT)

Field tuning the g-factor

- Measurements: anisotropy
  - one large and two smaller, equal axes
  - the large axis is different for each dots and not aligned with the NW



$$hf = g\mu_B|\mathbf{B}|$$

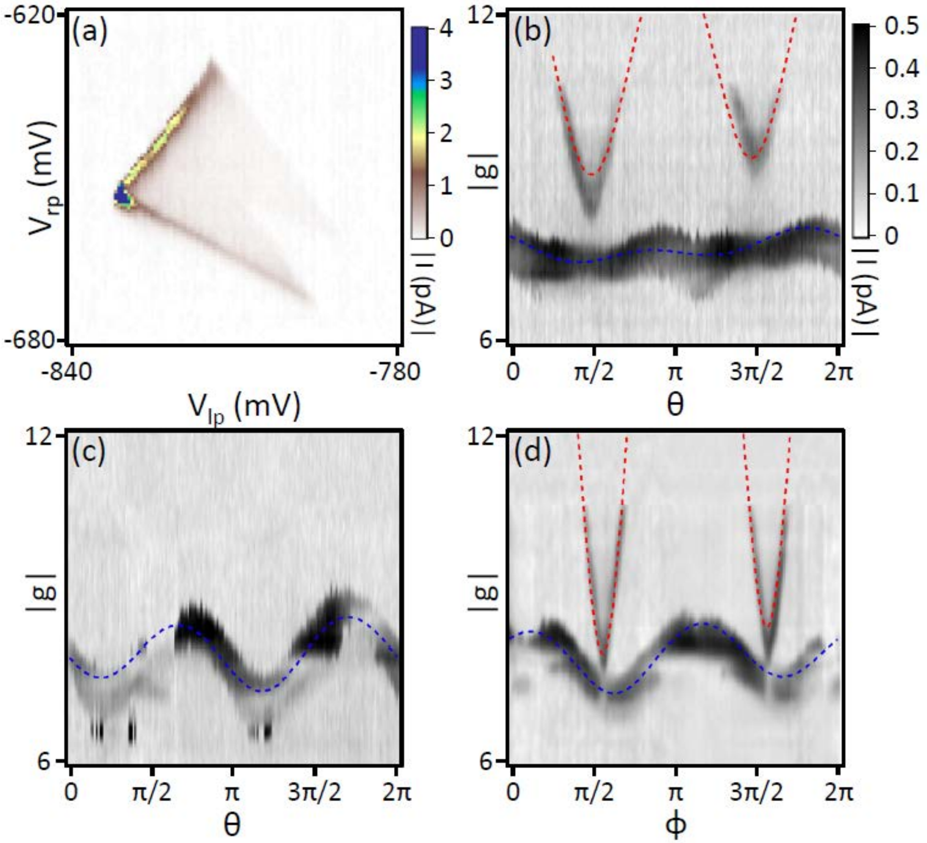
$$g(\mathbf{B}) = \frac{\sqrt{g_1^2B_1^2 + g_2^2B_2^2 + g_3^2B_3^2}}{|\mathbf{B}|}$$

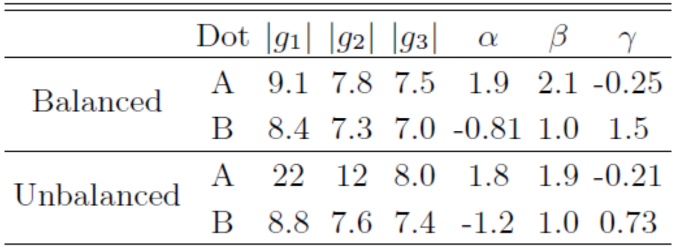
	Dot	$\|g_1\|$	$\|g_2\|$	$\|g_3\|$	α	β	γ
Balanced	A	9.1	7.8	7.5	1.9	2.1	-0.25
	B	8.4	7.3	7.0	-0.81	1.0	1.5

$$\mathbf{B}_{so}(t) = 2\mathbf{B} \times \mathbf{\Omega}(t) \qquad I \sim f_R \sim B_{SO}$$

Field tuning the g-factor

- Measurements: field tuning
  - different (unbalanced) confinement potential

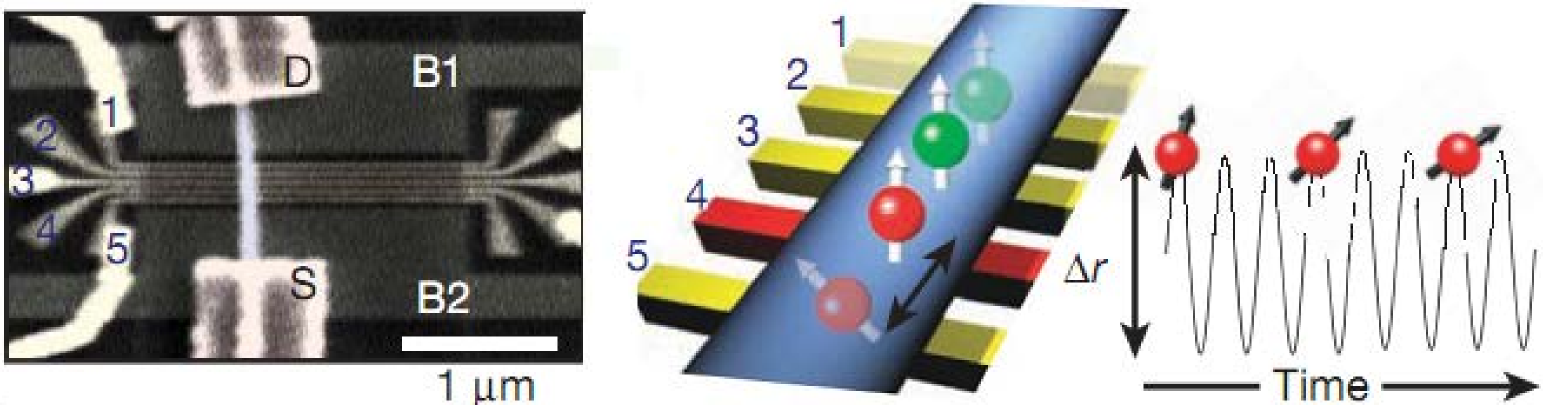


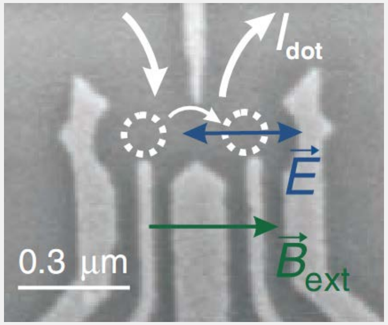


	Dot	$\lvert g_1\rvert$	$\lvert g_2\rvert$	$\lvert g_3\rvert$	α	β	γ
Balanced	A	9.1	7.8	7.5	1.9	2.1	-0.25
	B	8.4	7.3	7.0	-0.81	1.0	1.5
Unbalanced	A	22	12	8.0	1.8	1.9	-0.21
	B	8.8	7.6	7.4	-1.2	1.0	0.73

SOI in InAs quantum dots

- Spin-orbit qubit in an InAs nanowire
  - bottom gate structure
  - Pauli spin blockade
  - microwave frequency driven EDSR (electric-dipole spin resonance)

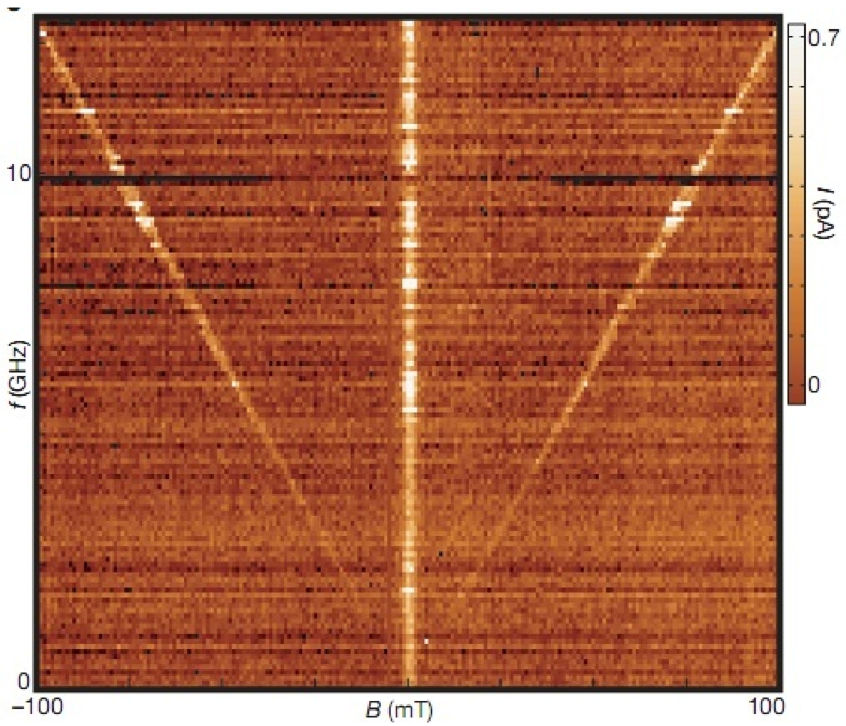




Nowack et al., Science 318, 1430 (2007)

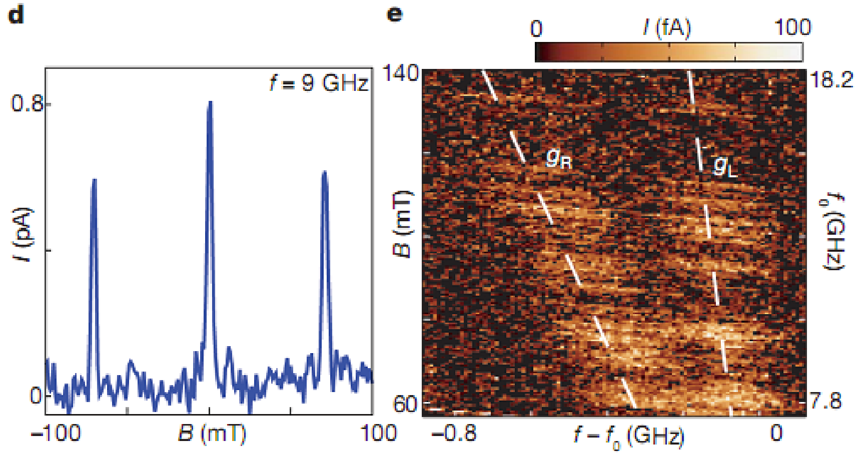
SOI in InAs quantum dots

- Spin-orbit qubit in an InAs nanowire: EDSR



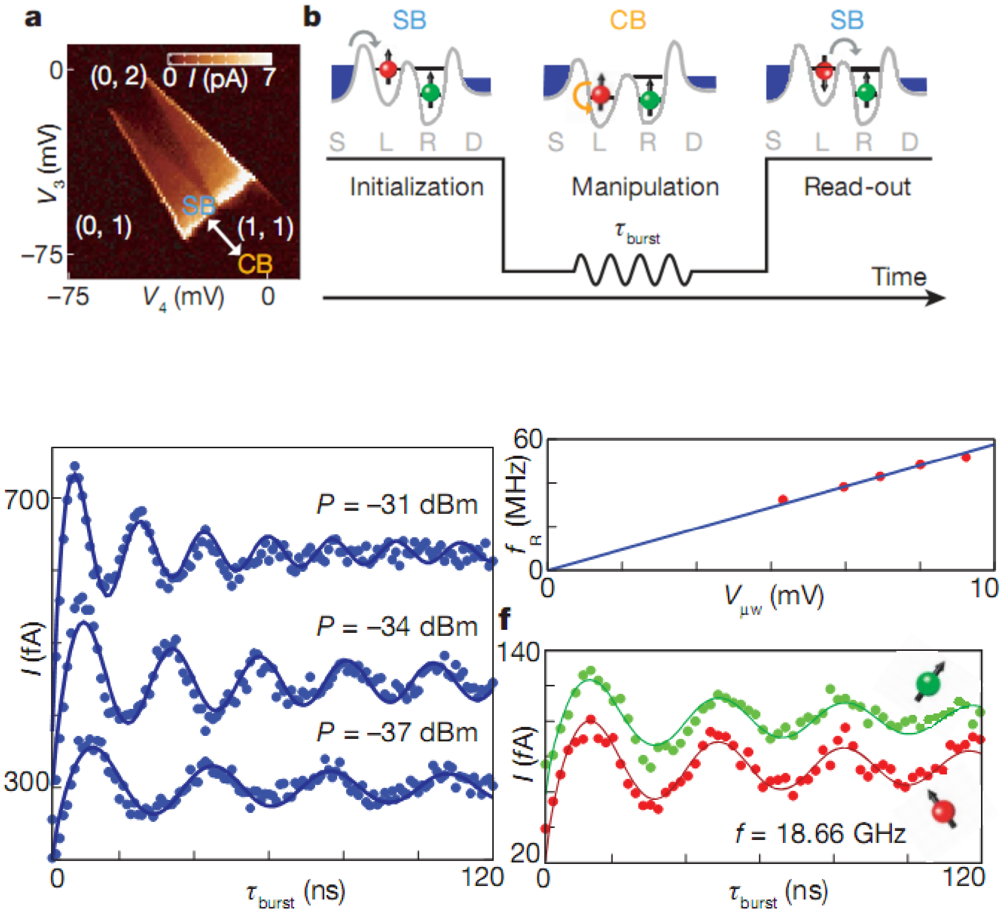
- Energy splitting: $E_Z = g\mu_B B$
- Resonance: $f_0 = g\mu_B B/h$
- Hyperfine field: $B_N = 0.66 \pm 0.1\ \mathrm{mT}$
- g-factors: $|g_L| = 9.2 \pm 0.1$
  $|g_R| = 8.9 \pm 0.1$

→ separated addressing



SOI in InAs quantum dots

- Spin-orbit qubit in an InAs nanowire: Rabi oscillations
  - coherent control over spin-orbit qubit states



- f = 13 GHz, B = 102 mT
- fitting function:

$$a\cos(f_R\tau_{\mathrm{burst}}+\varphi)/\tau^d+b$$

- highest Raby frequency: f_R = 58 MHz
  qubit flip: ≈110 microwave period

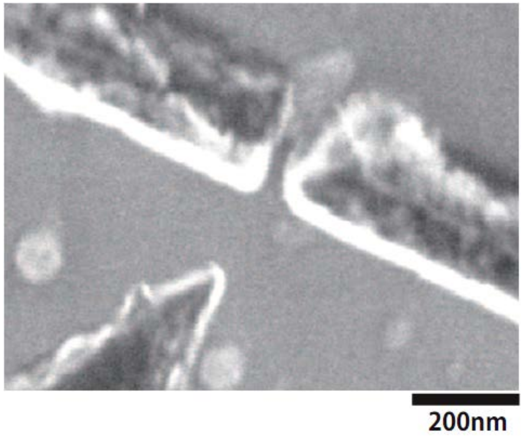
$$f_R \propto \sqrt{P}$$

- separated addressing
- T_1 >> 1 µs
- T_2 = 8 ± 1 ns

Earlier: highest $f_R \approx$ 4.7 MHz
(f_{ac} = 15.2 GHz, B ≈ 3 T)

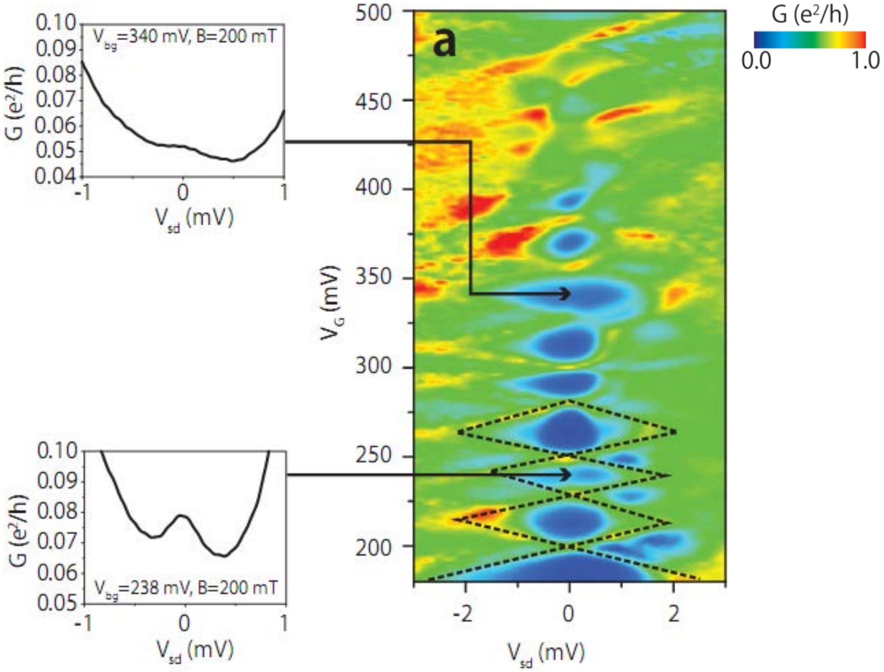
SOI in InAs quantum dots

- Electrically tuned spin-orbit interaction
  - self-assembled InAs quantum dot



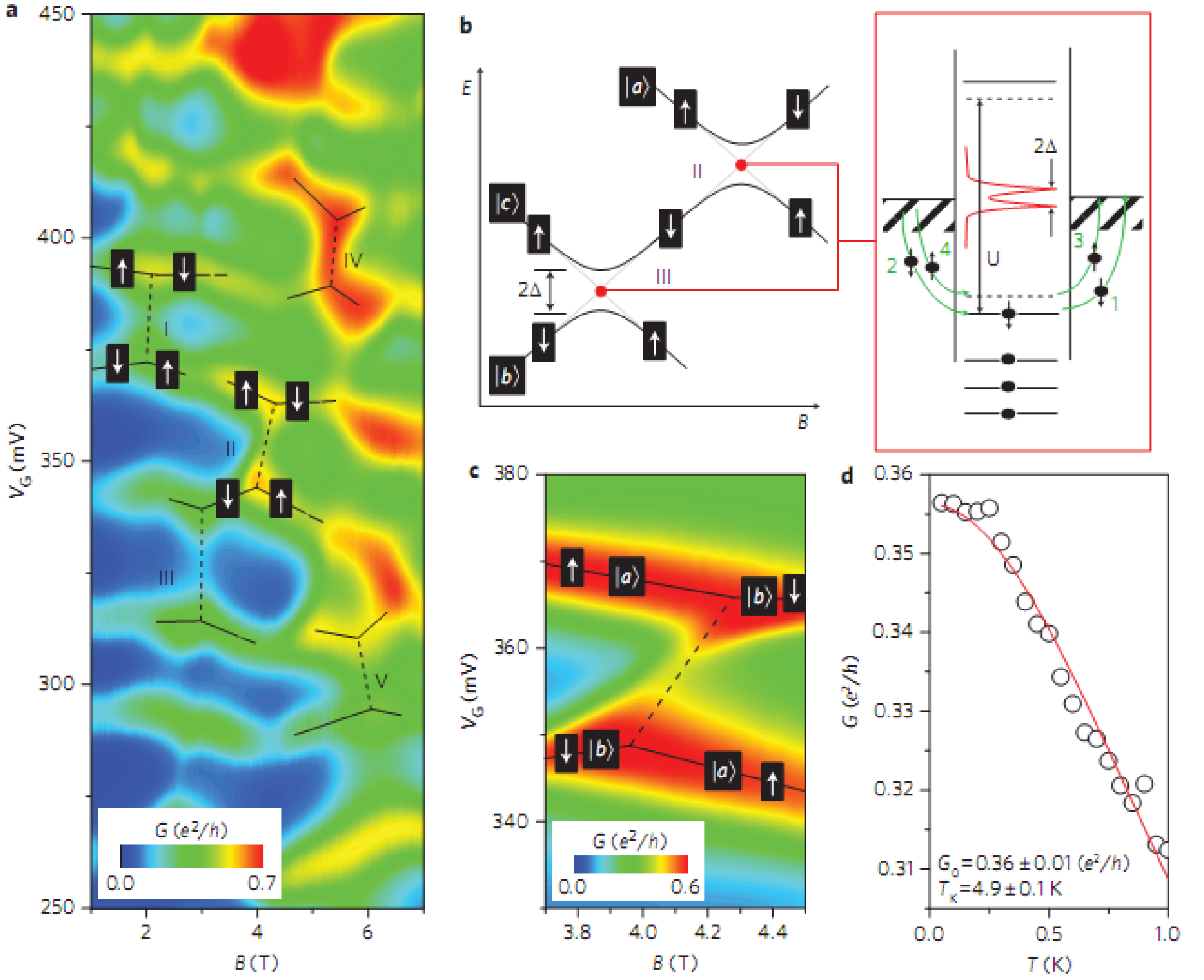
- Ti/Al (5/100 nm)
- charging energy: U ≈ 1.4 - 2.7 meV
- level spacing: $\varepsilon_d \approx 0.3$ - 0.7 meV

- spin-1/2 Kondo effect



SOI in InAs quantum dots

- Electrically tuned spin-orbit interaction
  - evaluation of SOI energy: splitting of the Kondo peak



- Degenerate points: Kondo effect

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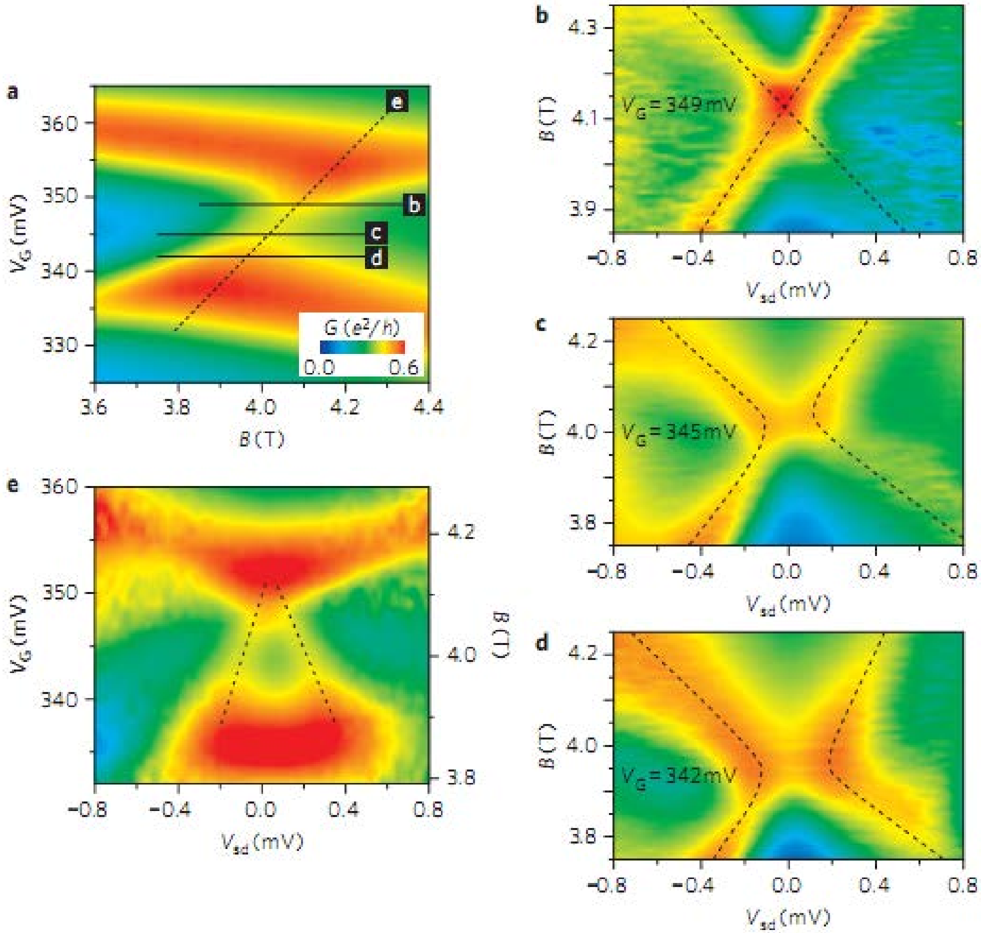
enhanced conductivity (dashed line)

SOI in InAs quantum dots

- Electrically tuned spin-orbit interaction
  - electrical tunability of the SOI energy



- non-equilibrium transport measurements: two peaks in the energy spectrum at

$$eV_{sd} = \pm 2\Delta$$

SOI in InAs quantum dots

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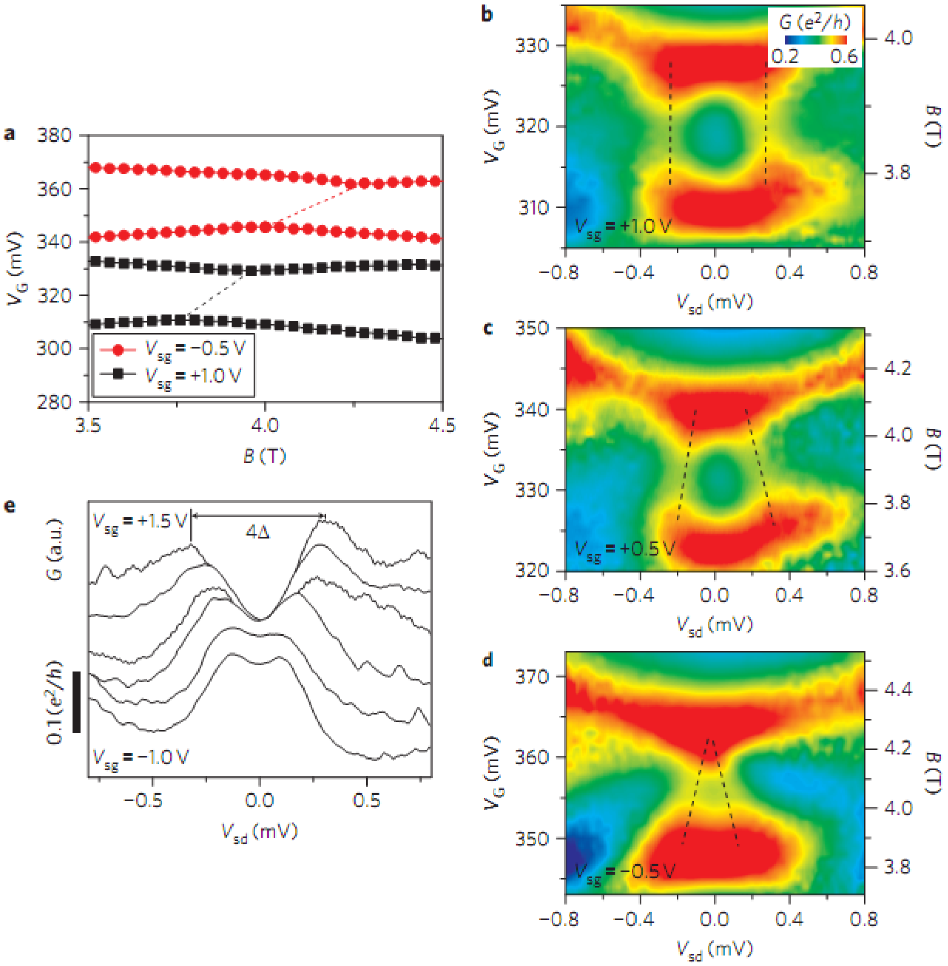

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SOI in InAs quantum dots

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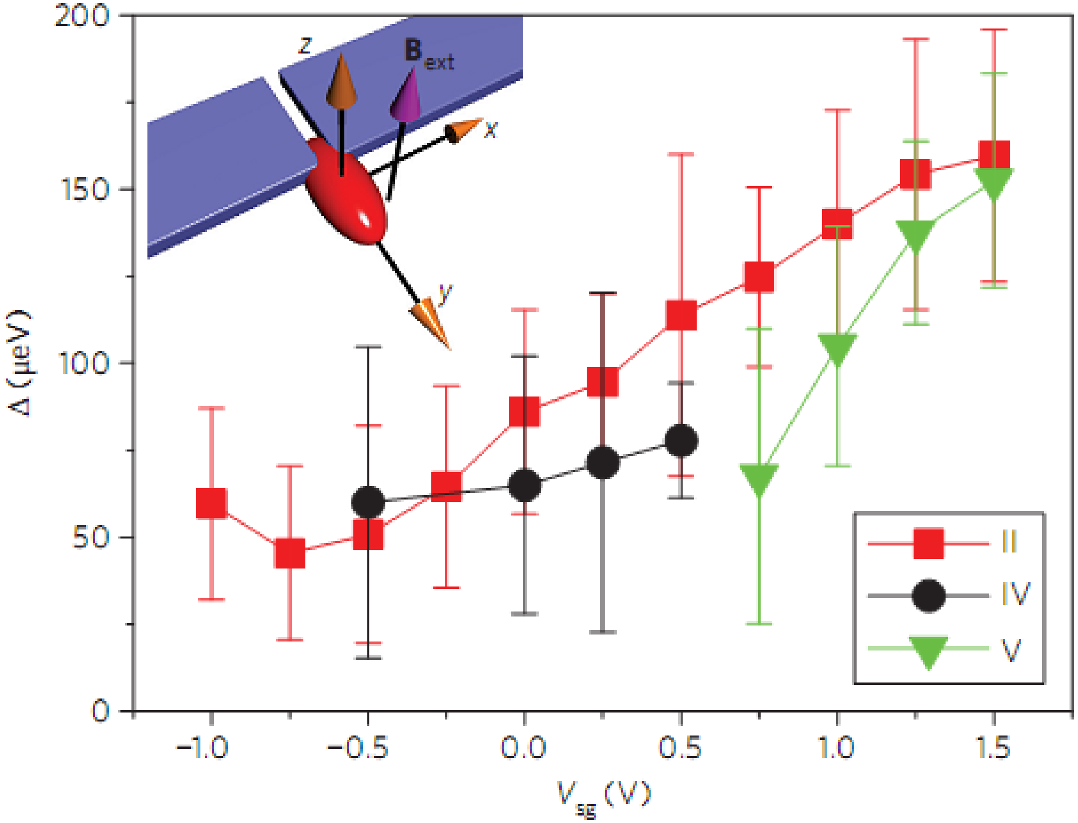
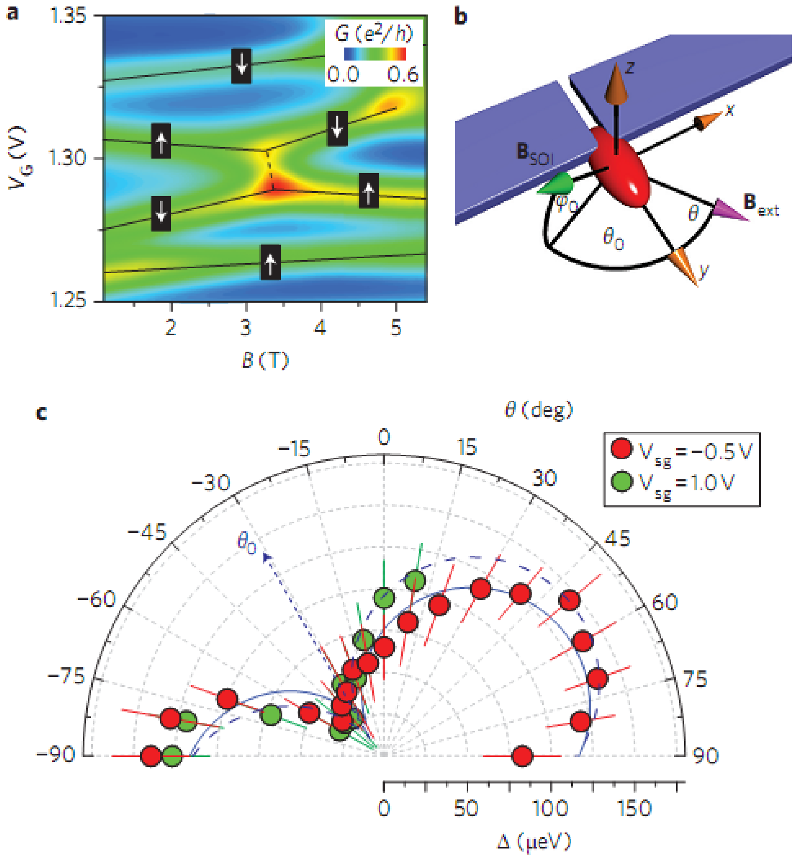


- effect of V_G (and V_{sg}) varies with the orbital states
- $\Delta \approx 50..150$ μeV

SOI in InAs quantum dots

- Electrically tuned spin-orbit interaction
  - in-plane anisotropy of the SOI energy

$$\Delta = |\langle a\uparrow|\mathcal{H}_{\mathrm{SOI}}|b\downarrow\rangle| = |\langle a\uparrow|\lambda\mathbf{E}\cdot(\mathbf{p}\times\boldsymbol{\sigma})|b\downarrow\rangle|$$



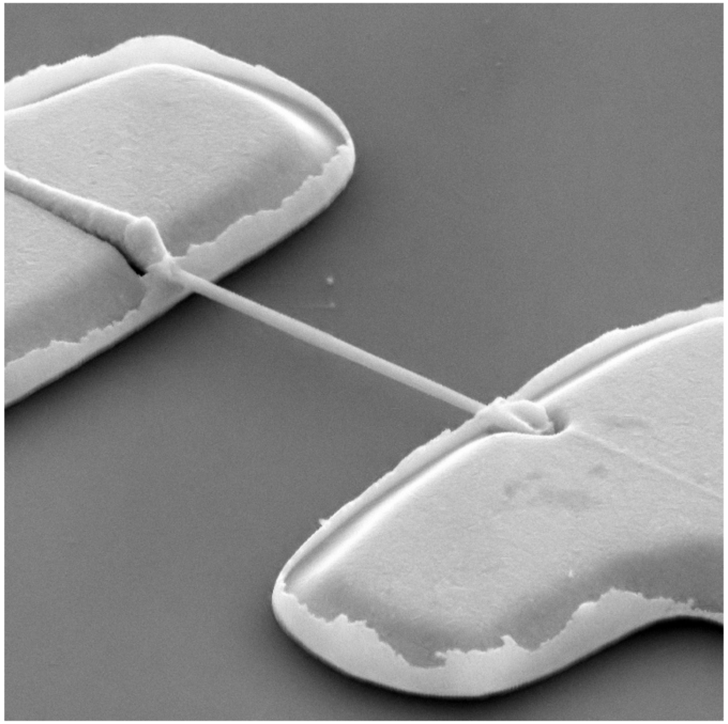
- 2D: quenching of Δ at a 'magic angle': B_{ext} || B_{SOI}/i
- lack of quenching → 3D quantum dot

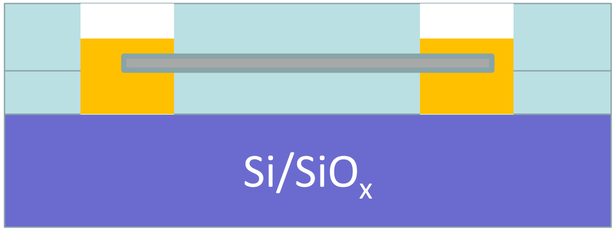
$$\mathbf{B}_{\mathrm{SOI}} = \lambda\mathbf{E}\times\mathbf{Q}$$

$$\mathbf{Q} = \langle a|\mathbf{p}|b\rangle$$

InAs nanowire resonator

- Sample fabrication
  - VLS MOCVD grown NWs; diameter: 80-120 nm, length: ≈8 µm
  - suspending the NWs: sandwiching them between layers of e-beam resist





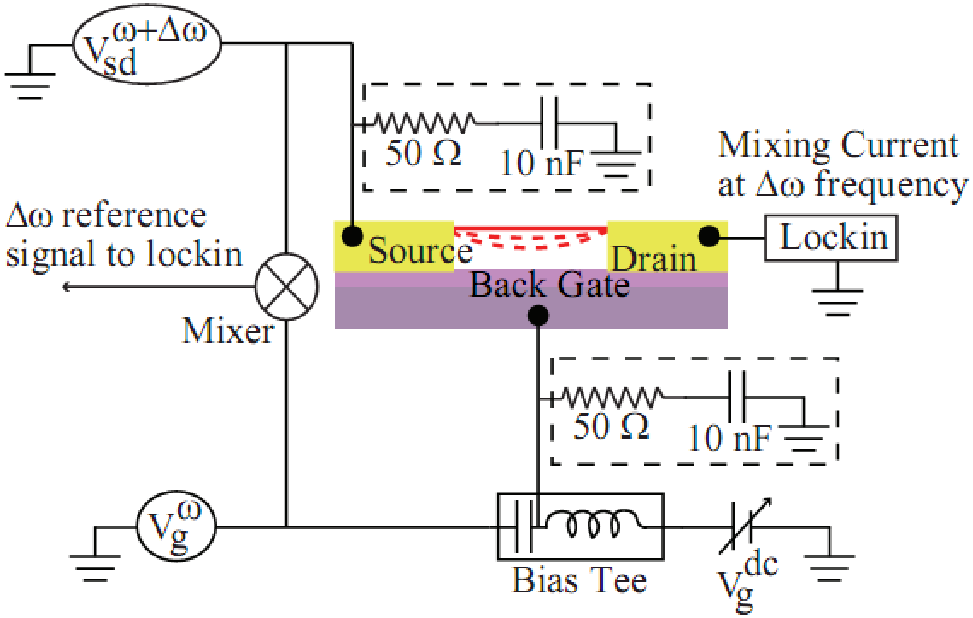
InAs nanowire resonator

- Measurements
  - Heterodyne mixing technique:

    AC voltage on backgate actuating the NW (ω)

    AC voltage on the source for mixing (ω+Δω)

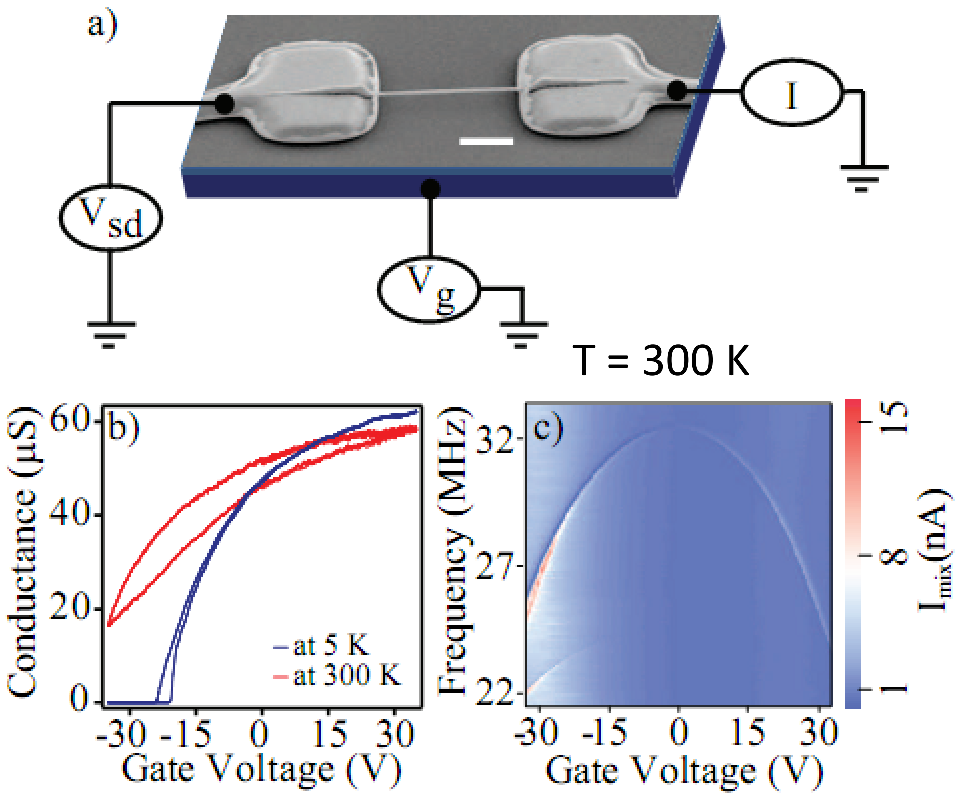
Mixing current: $$I_{mix}^{\Delta\omega} = \frac{1}{2}\frac{dG}{dq}\left(\frac{dC_g}{dz}z(\omega)V_g^{dc} + C_g V_g^{ac}\right)\tilde{V}_{sd}$$



InAs nanowire resonator

- Measurements
  - Heterodyne mixing technique:

Mixing current: $I_{mix} = \frac{dG}{dV_g}(A\xi_f + B)$



T = 300 K

ξ_f : amplitude of oscillation

Gate voltage tunes:

- the tension
- the carrier density

InAs nanowire resonator

- Measurements
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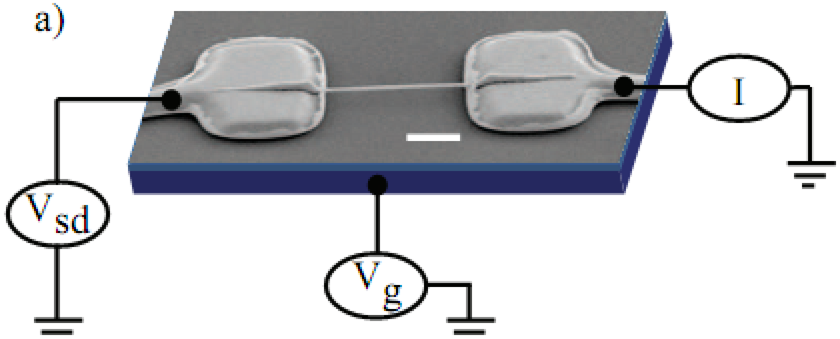
Mixing current: $I_{mix} = \frac{dG}{dV_g}(A\xi_f + B)$



ξ_f : amplitude of oscillation

Gate voltage tunes:

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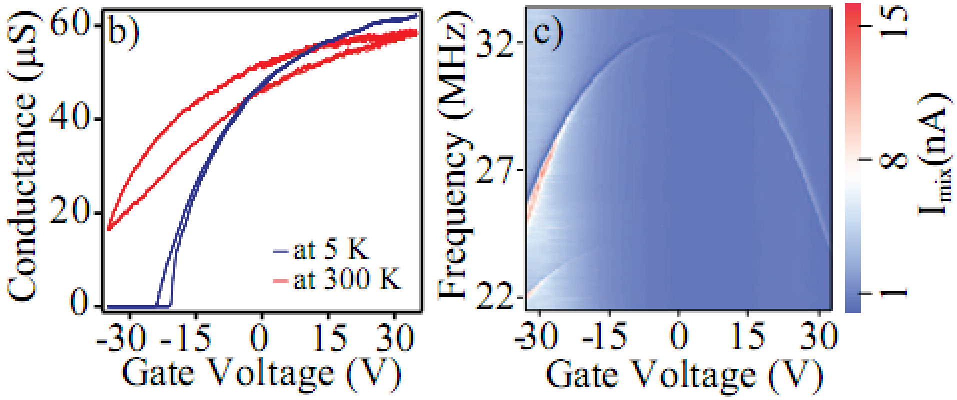
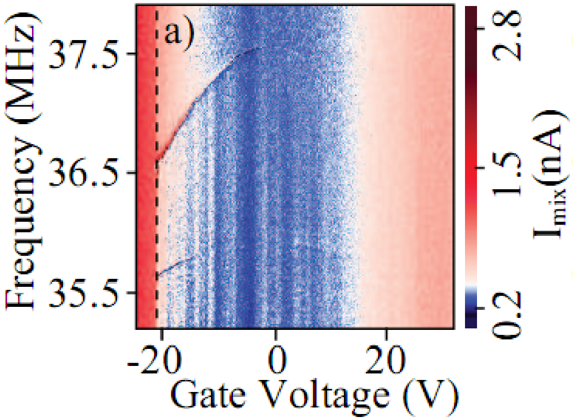
- the carrier density

T = 5 K

- contraction → tension varies

T = 300 K





InAs nanowire resonator

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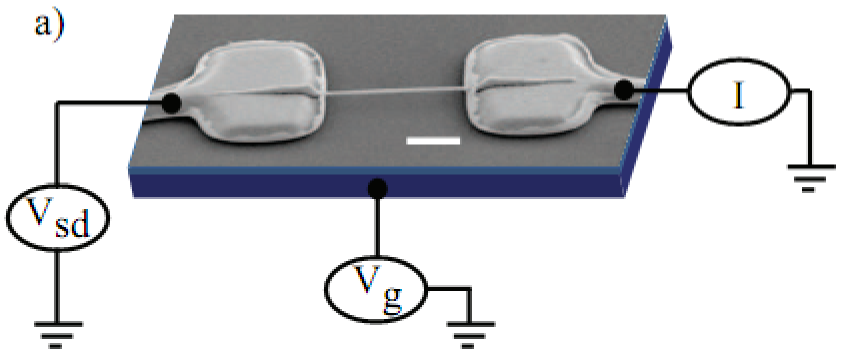

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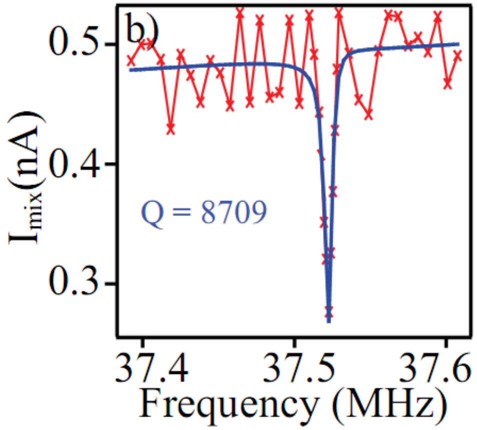
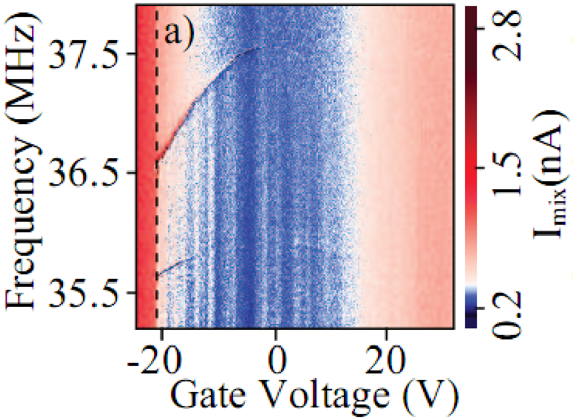
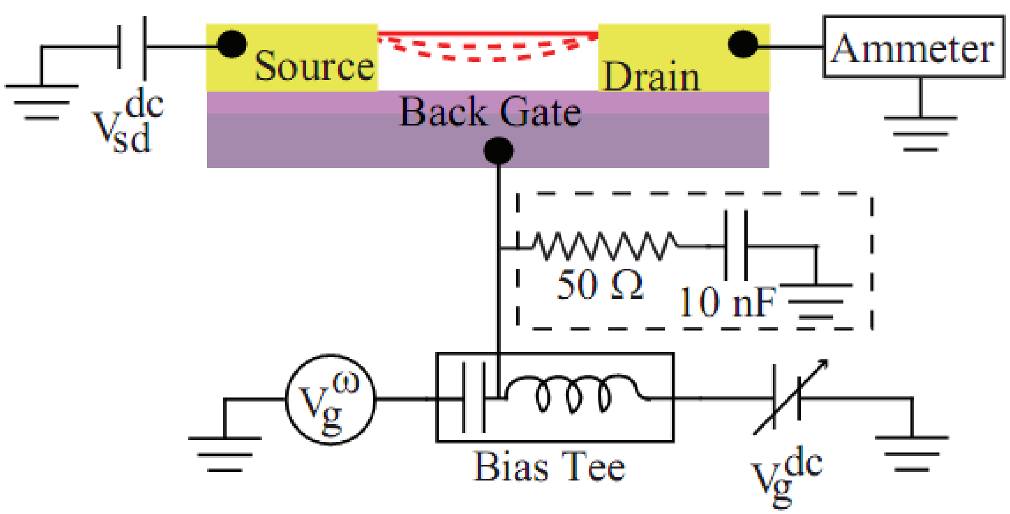


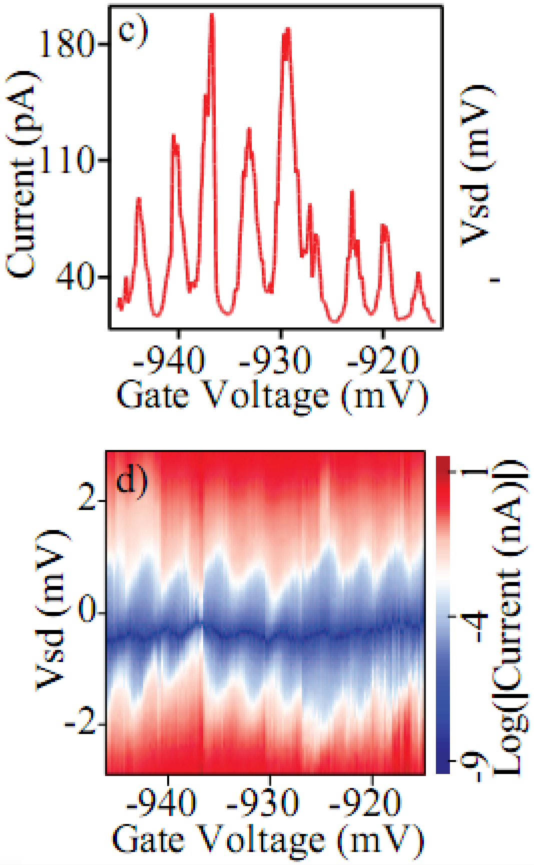
fit → Q ~ 10^4 @ 5K



InAs nanowire resonator

- Measurements
  - Coulomb blockade physics at mechanical resonance
  - Rectification technique:
    - single RF source at back gate

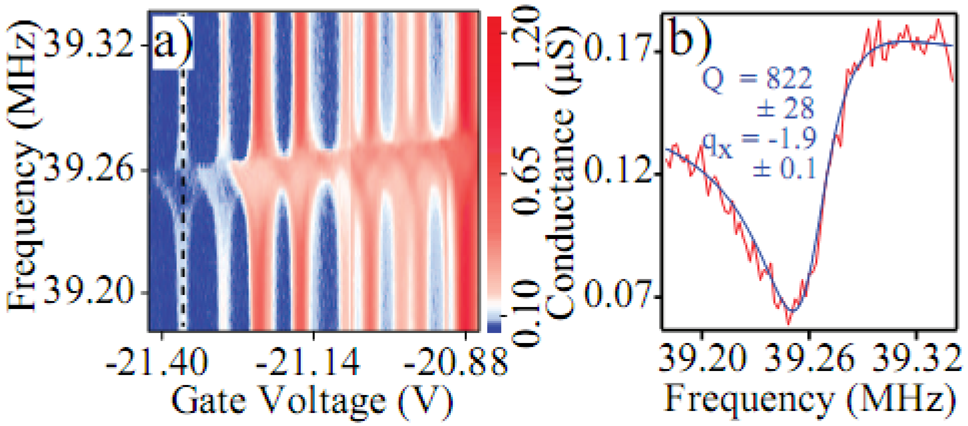




Charging energy: $\varepsilon_c \approx 2$ meV

InAs nanowire resonator

- Measurements
  - Coulomb blockade physics at mechanical resonance



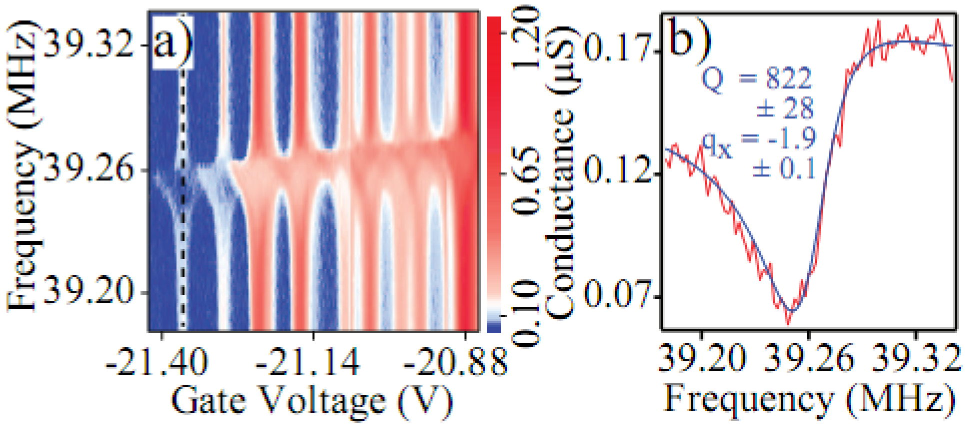
- Coulomb peaks broaden
- Magnitude of CB peaks is altered
  - direct coupling of dot potential to the backgate voltage
  - modification of dot potential due to mechanical motion

Fano resonance

$$\begin{aligned} N(t) &= C_g(t)V_g(t)/e = N_0 + \delta N(t),\\ G_{total} &= G_0 + G_{rect} \simeq G_0 + \frac{1}{2}\frac{d^2G}{dN^2}\overline{(\delta N(t))^2} \end{aligned}$$

InAs nanowire resonator

- Measurements
  - Coulomb blockade physics at mechanical resonance



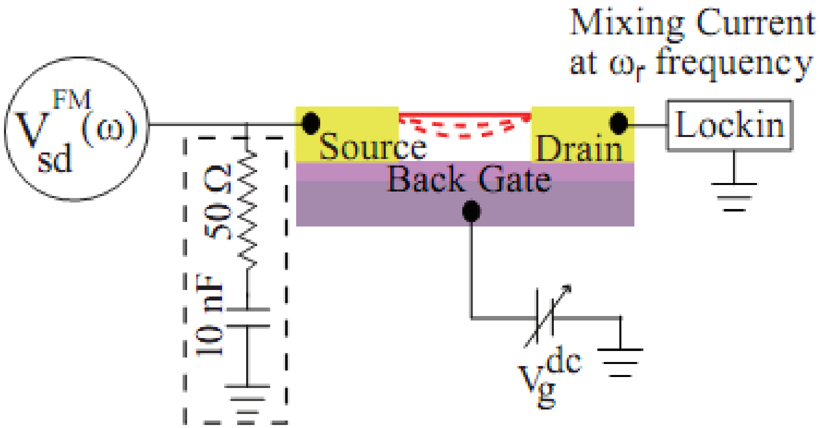
$$G_{rect}(\tilde{\omega}) = G_D \frac{|\,\tilde{\omega} + q_x + i q_y\,|^2}{\tilde{\omega}^2 + 1}$$

$$\begin{aligned} q_x &= -\left(\frac{1}{C_0}\frac{dC}{dz}\right)\left(V_0 \frac{dF}{dV_g}\right)\frac{Q}{k_{osc}} \\ \tilde{\omega} &= \frac{\omega - \omega_0}{\gamma/2} \\ G_D &= \frac{1}{2}\frac{d^2G}{dN^2}\left(\frac{C_0}{e}\right)^2 |V_{ac}|^2 \\ q_y &= 1 \end{aligned}$$

Right at a CB peak Q reduces to 10^3

InAs nanowire resonator

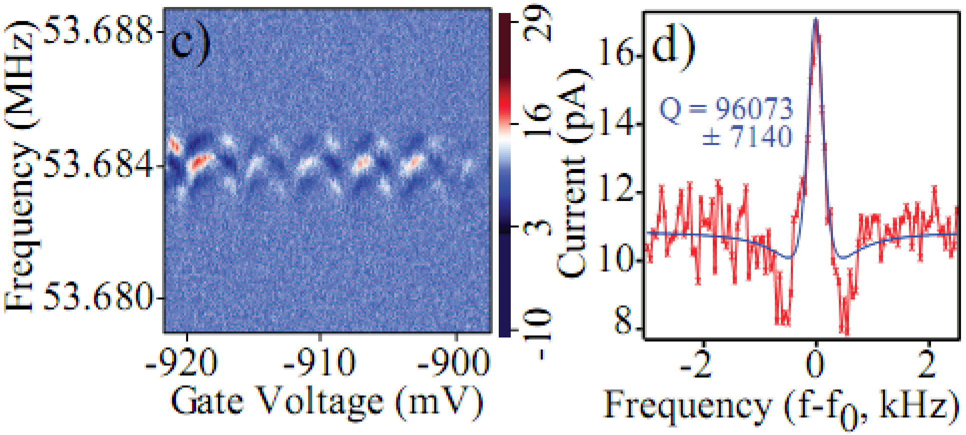
- Measurements
  - Coulomb blockade physics at mechanical resonance
  - FM modulation technique



$$V_{SD}^{FM}(\omega) = V_0 Sin(\omega + \frac{\omega_\Delta}{\omega_r} Sin(\omega_r t))t$$

$$I(\omega) = A + B\frac{2\omega\left((\omega^2-\omega_0^2)-\frac{\omega_0^2}{Q}\right)\left((\omega^2-\omega_0^2)+\frac{\omega_0^2}{Q}\right)}{\left[(\omega^2-\omega_0^2)^2+\left(\frac{\omega\omega_0}{Q}\right)^2\right]^2}$$

Q ≈ 10^5 @ 100 mK



Thank you for your attention!