Gate-defined clean nanodevices coupled to impedance matching circuits at GHz frequencies (+ new results on S-dot-N)

V. Ranjan, T. Hasler, M. Jung, J. Gramich, J. Schindele, S. d'Holosy, L. Hofstetter, A. Baumgartner, C. Schönenberger, *Univ. of Basel*

G. Puebla-Hellmann, M. Muoth, C. Hierold, A. Wallraff, *ETHZ*

G. Fülöp, S. Csonka, *Budapest Univ. of Technology and Economics*

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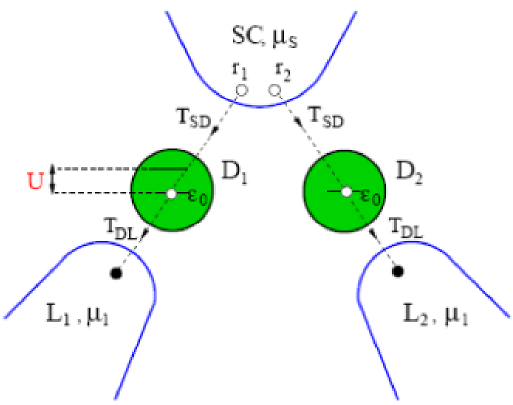
Motivation

PHYSICAL REVIEW B, VOLUME 63, 165314 (2001)

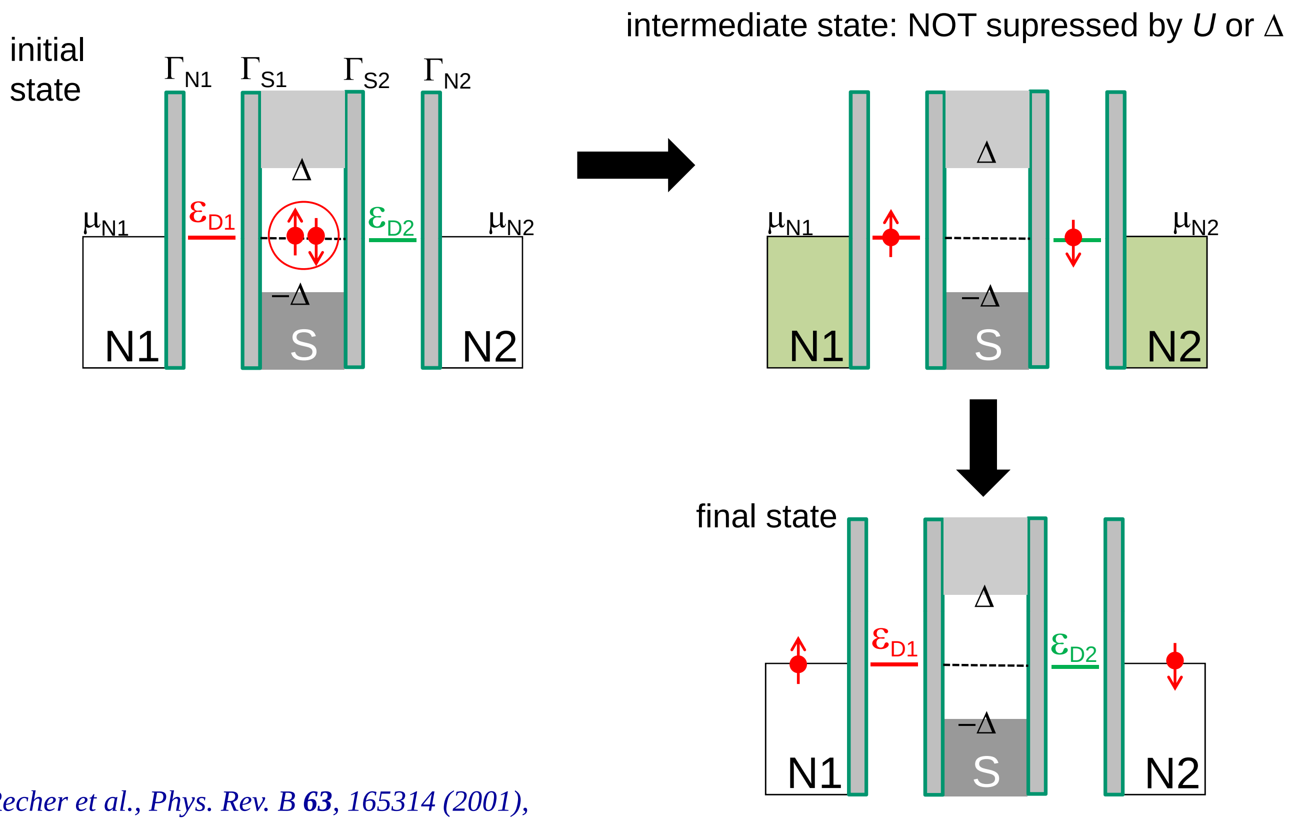
Andreev tunneling, Coulomb blockade, and resonant transport of nonlocal spin-entangled electrons

Patrik Recher, Eugene V. Sukhorukov, and Daniel Loss



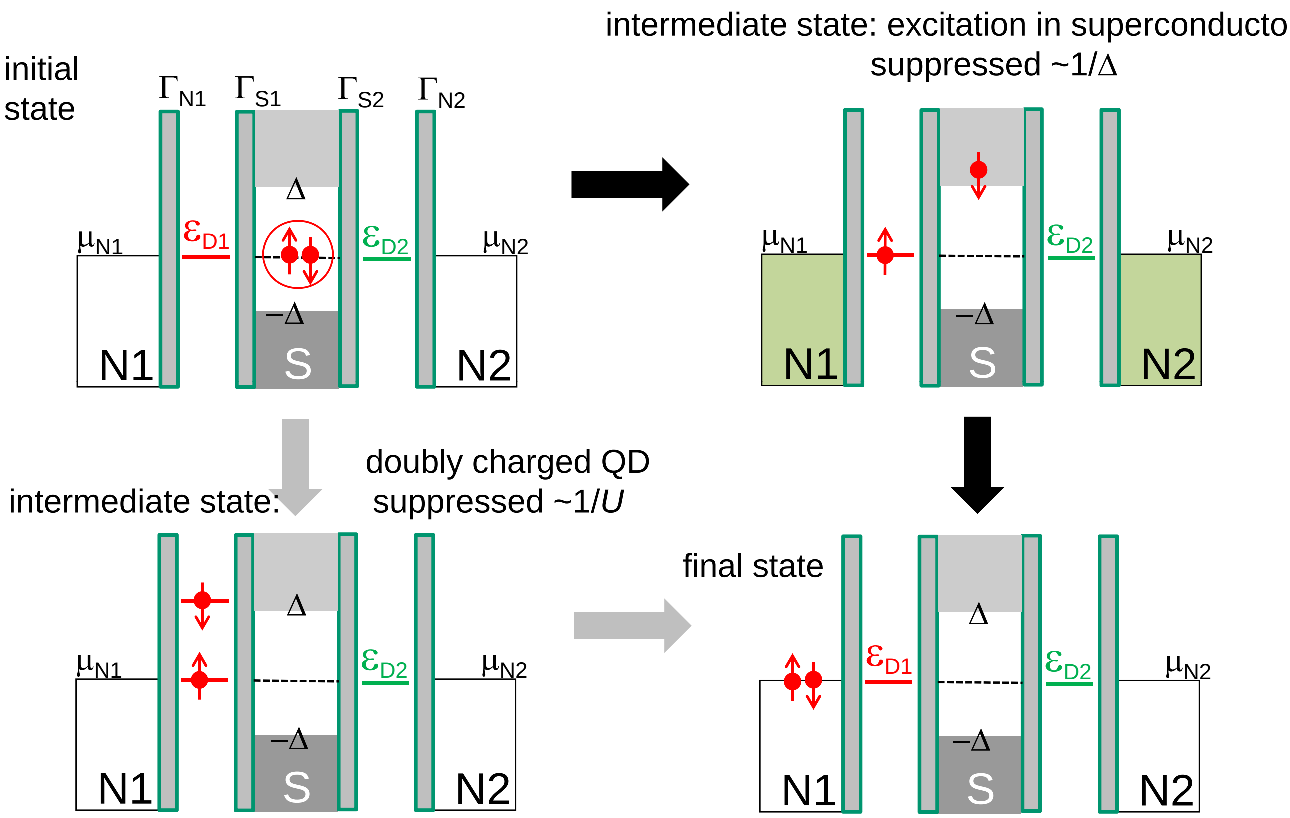
Cooper-pair splitter device

Cooper-pair splitting: how it works



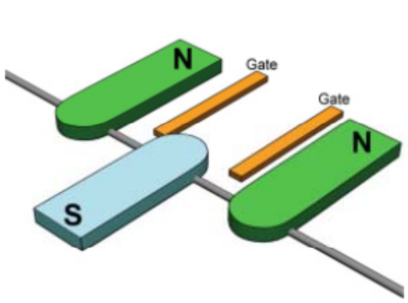
Recher et al., Phys. Rev. B ***63****, 165314 (2001),*
D. Feinberg et al., Eur. Phys. J. B ***36****, 419 (2003)*

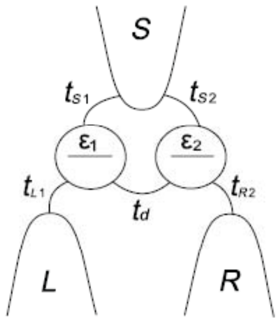
but...there are other processes



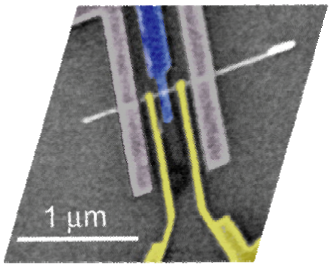
eRecher et al. Phys. Rev. B ***63****, 165314 (2001)*

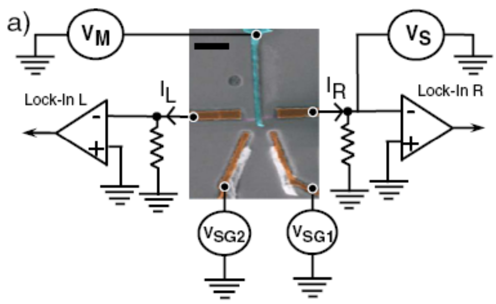
How do samples look like ?





note the **different tunneling coupling** parameters !



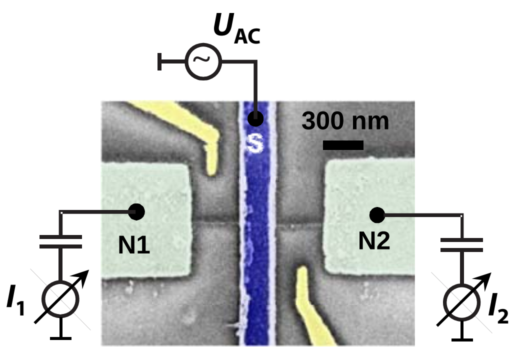


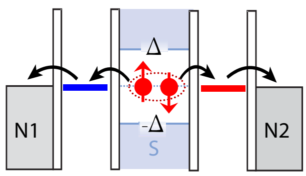
*L. Hofstetter, et al., Nature **461**, 960-963 (2009)*

*Herrmann et al., PRL **104**, 026801 (2010)*

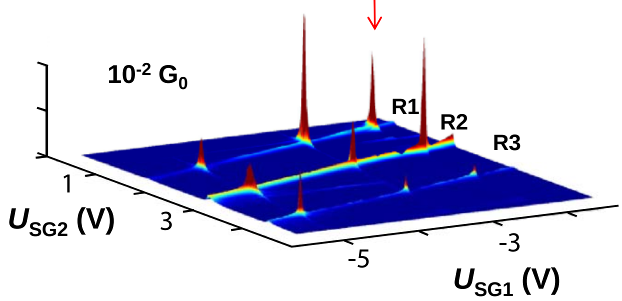
What have we achieved?

splitting efficiency > 90%





G peaks
at resonance
much above
background



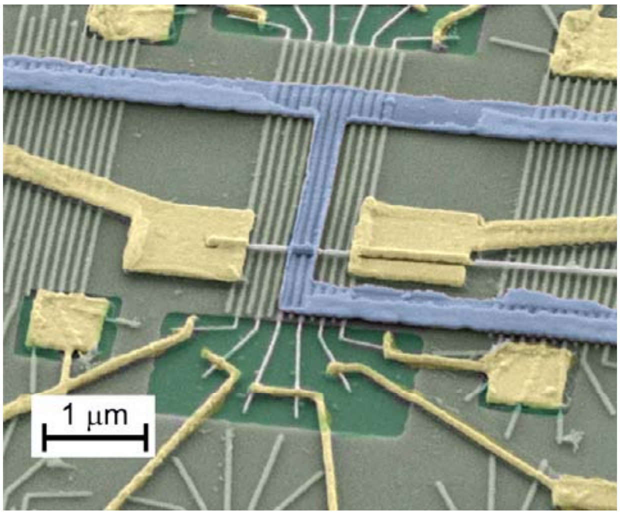
but to engineer the efficiency, need to be able to control (and tune) all relevant tunnel couplings

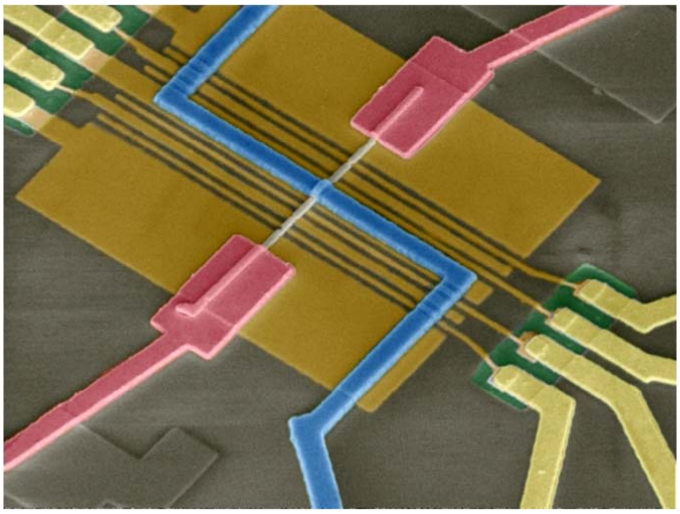
J. Schindle et al. Near-unity Cooper pair splitting, Phys. Rev. Lett. 109, 157002 (2012)

Control of Γ in NW-based devices

Nb contact

Al contact



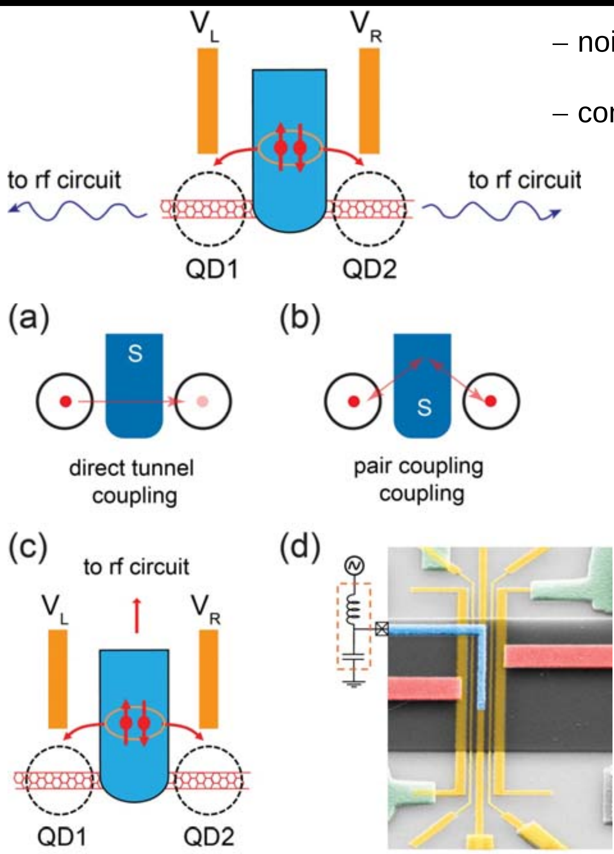


larger gates closer to drain contacts

Budapest – Basel – Copenhagen collaboration (Gergö Fülöp and Samuel d'Hollosy)

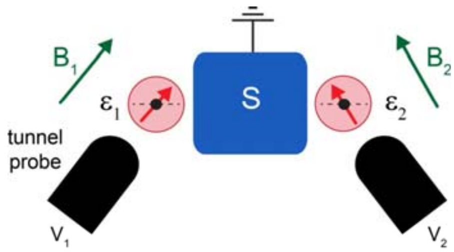
theory: A. Baumgartner et al. (2014) and A. Levy-Yeyati et al. (2015)

Goal (on the longer run)

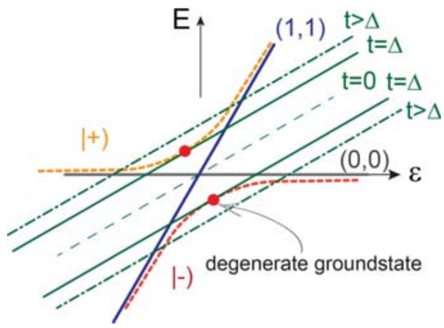


– noise correlations at fast time-scales

– compare with non-local conductances



– p wave superconductivity
– spin-blockade

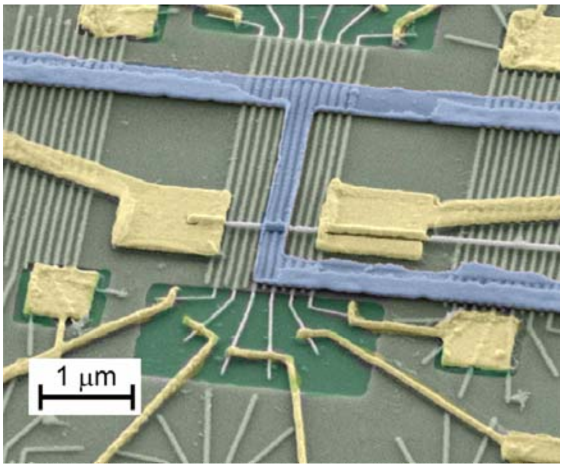


A. Cottet and T. Kontos et al.

J. König et al. and C. Flensberg et al.

Conclusion so far

experimental observations



- splitting efficiency in "right" regime can reach very large values → 100%
- conductance changes in the two dots are intriguing. We find: ++ and +-
- if tunneling coupling between dots is large, level anti-crossing expected but until now not well present in data
- it is not so straightforward to change the different coupling parameters

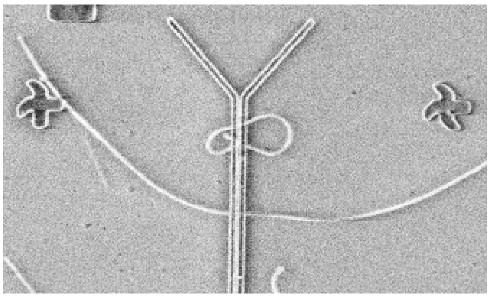
Ultraclean Carbon nanotube quantum dots

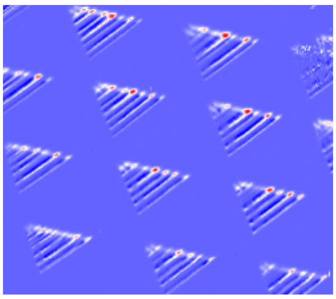
a) with recessed Re gates

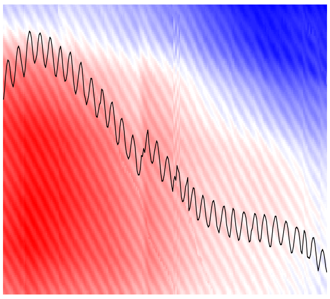
b) by stamping techniques

Minkyung Jung, Thomas Hasler, Vishal Ranjan, Jörg Gramich,
J. Schindele, S. Nau, M. Weiss, A. Baumgartner and C. Schönenberger

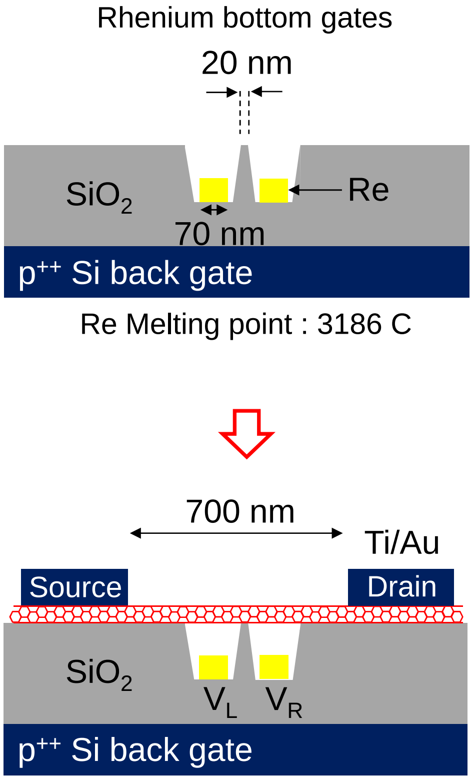
Schönenberger group
Department of Physics
University of Basel, Switzerland

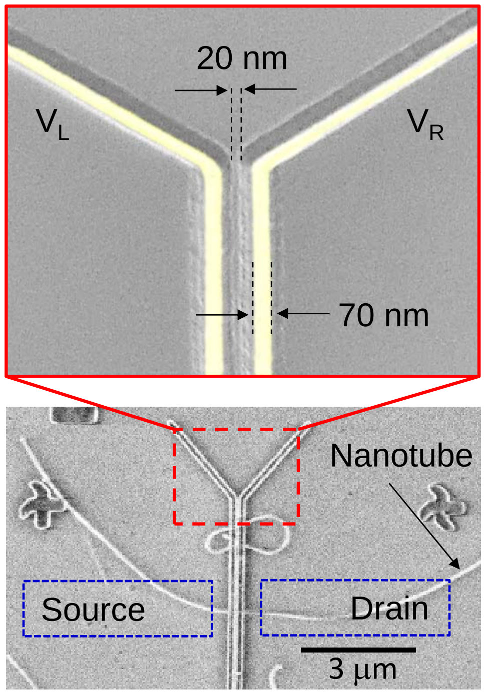






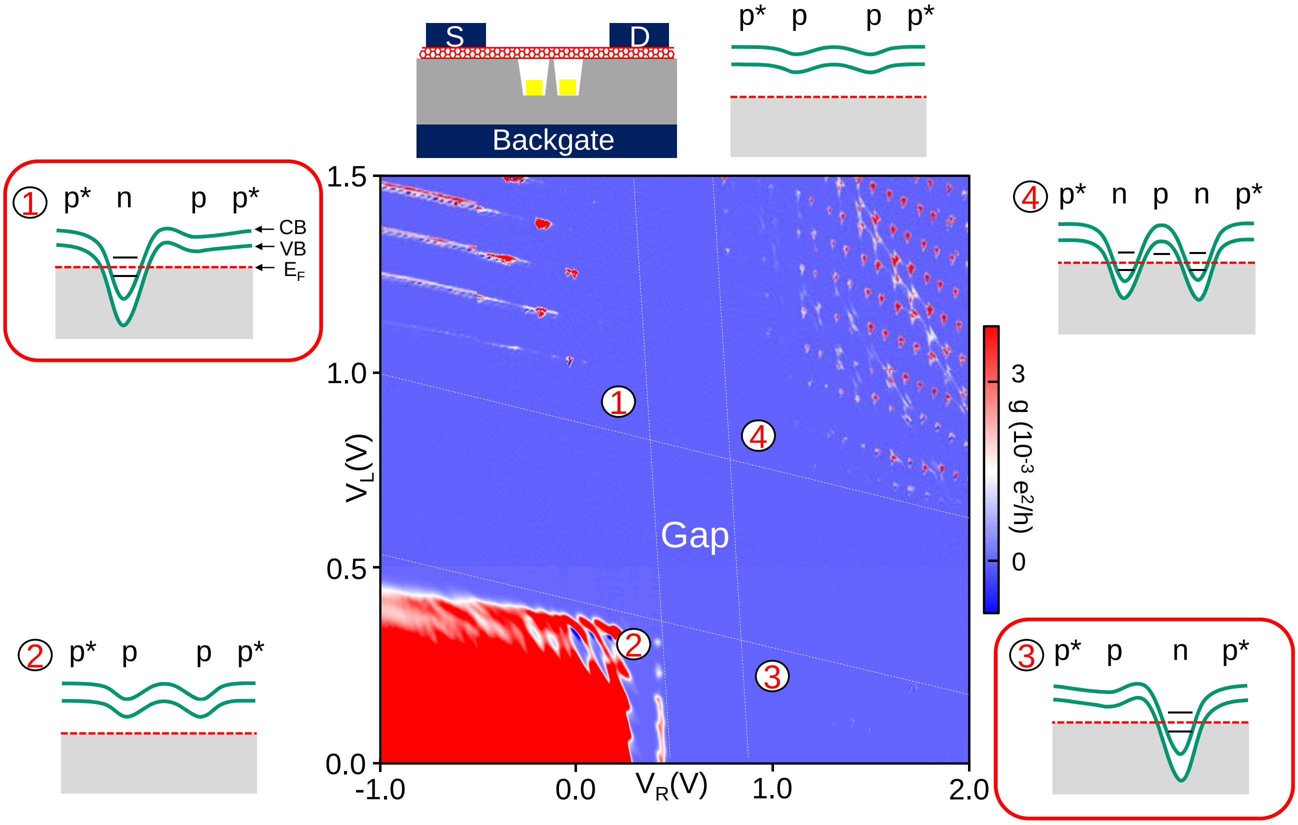
Recessed bottom gate for strong confinement





M. Jung, *et al.*, *Nano Lett*. (2013)

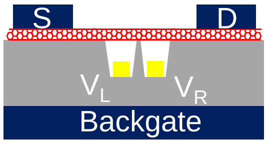
Tunable qdots with recessed bottom gates

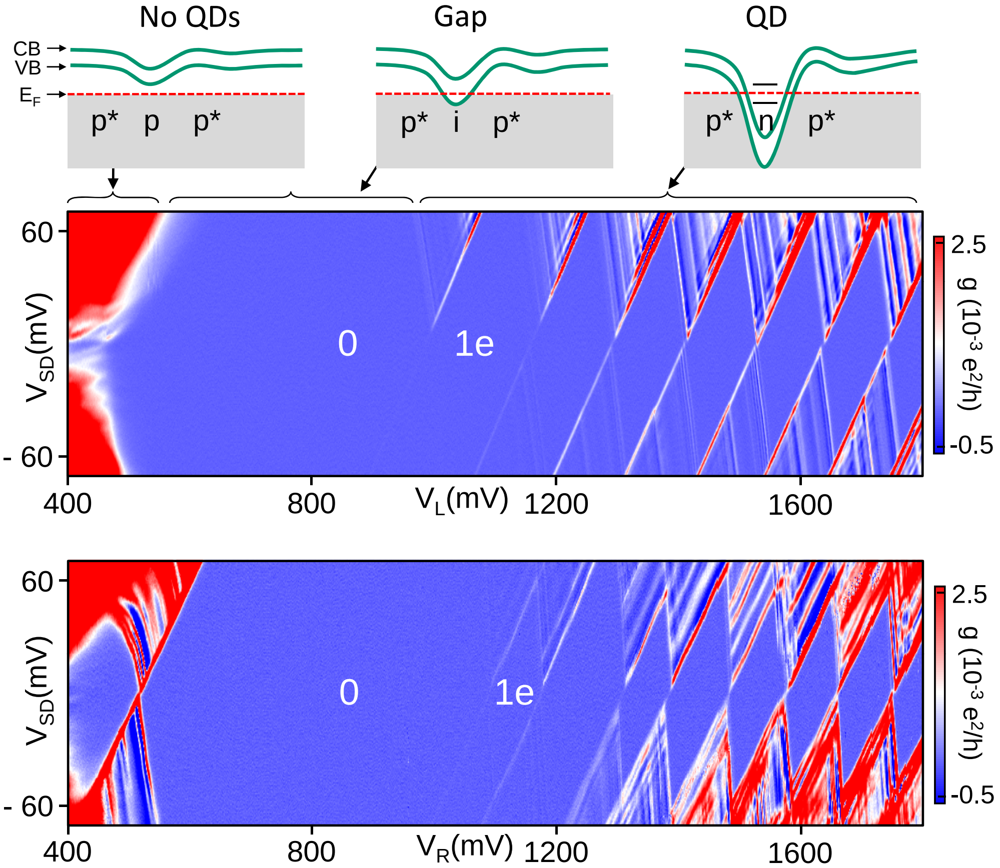


V_B = - 7.5 V, V_{SD} = 10 mV

M. Jung, *et al.*, *Nano Lett*. (2013)

Ultraclean quantum dot





Left Dot

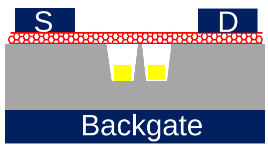
C_G = 1.34 aF
C_S = 0.545 aF
C_D = 0.51 aF

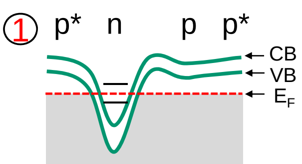
Strong confinement

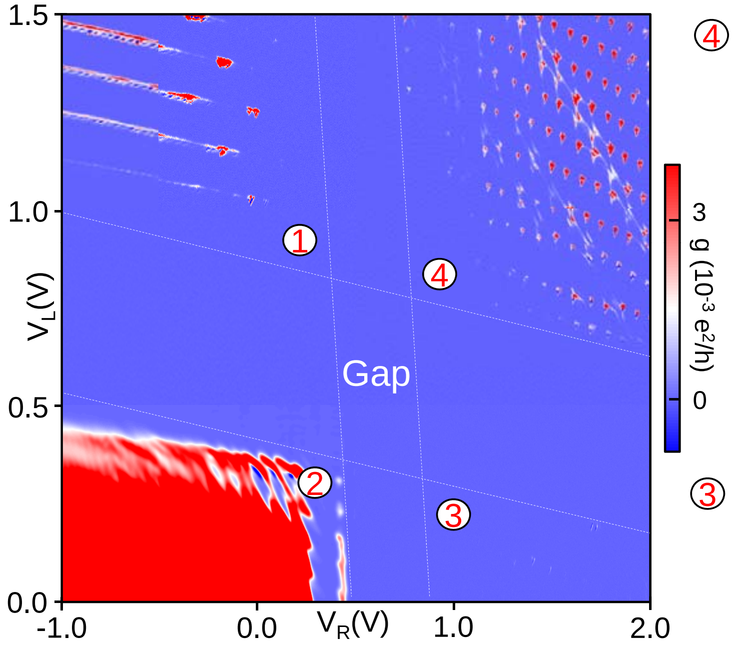
Right Dot

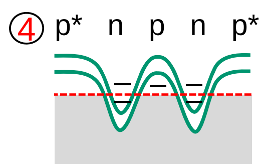
M. Jung, *et al.*, *Nano Lett*. (2013)

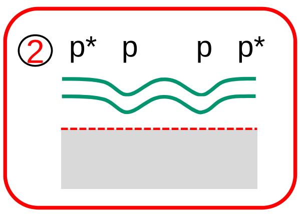
Tunable qdots with recessed bottom gates

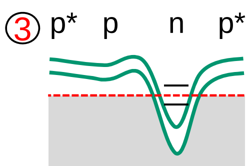








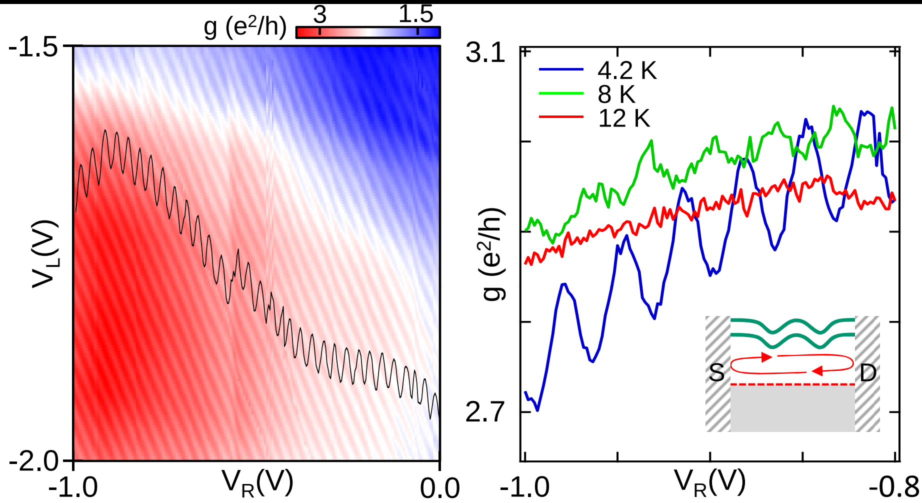




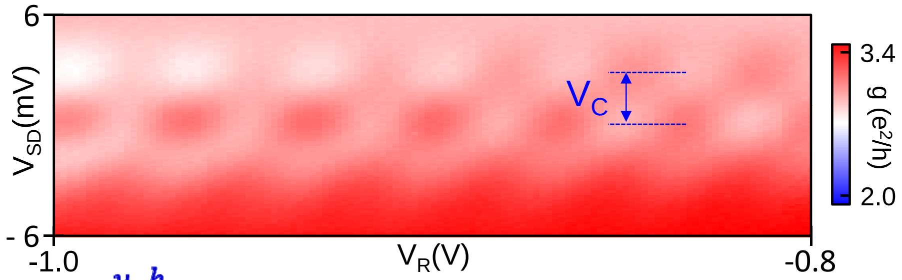
V_B = - 7.5 V, V_{SD} = 10 mV

M. Jung, *et al.*, *Nano Lett*. (2013)

Fabry-Perot interference (open dot regime)

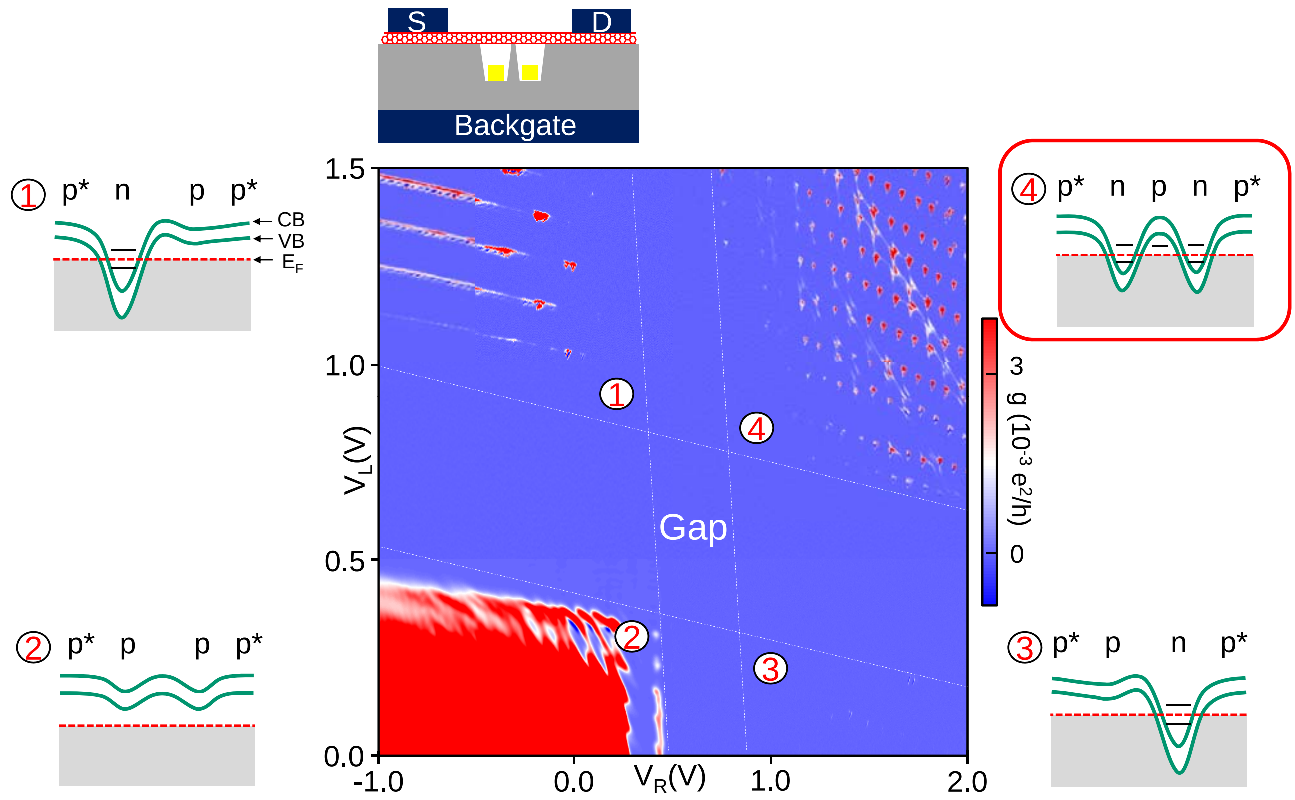


Transmission probability T > 0.8



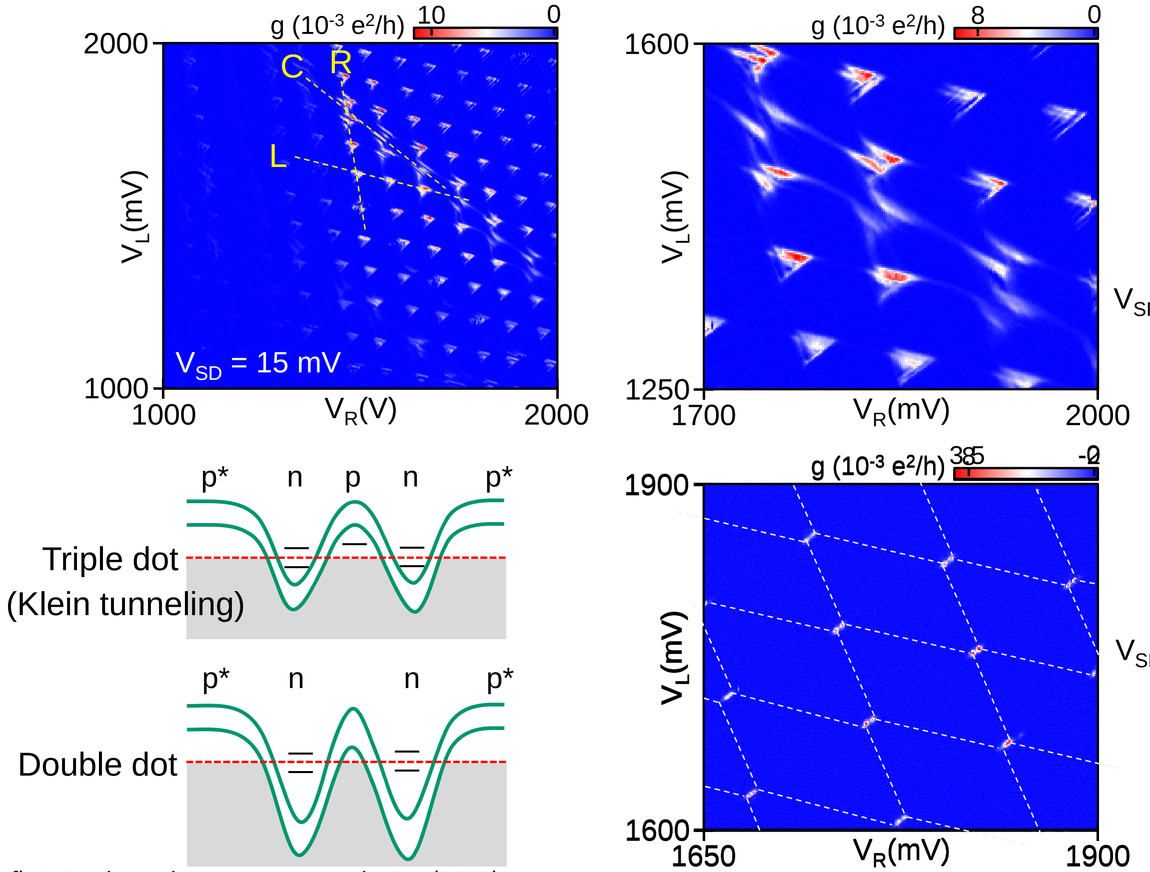
$L = \frac{v_F h}{2V_C}$ V_C ~ 3 mV, resulting in L ~ 700 nm

Tunable qdots with recessed bottom gates



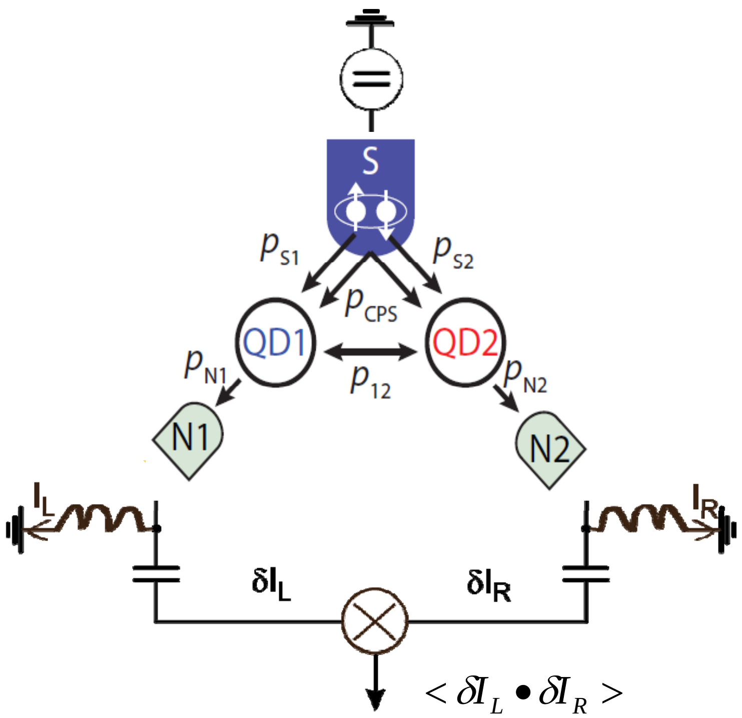
V_B = - 7.5 V, V_{SD} = 10 mV

Ultraclean double and triple QD



Ref) G. Steele et al., Nature Nanotech. 6, 1 (2009)

Towards fast correlation measurements ?



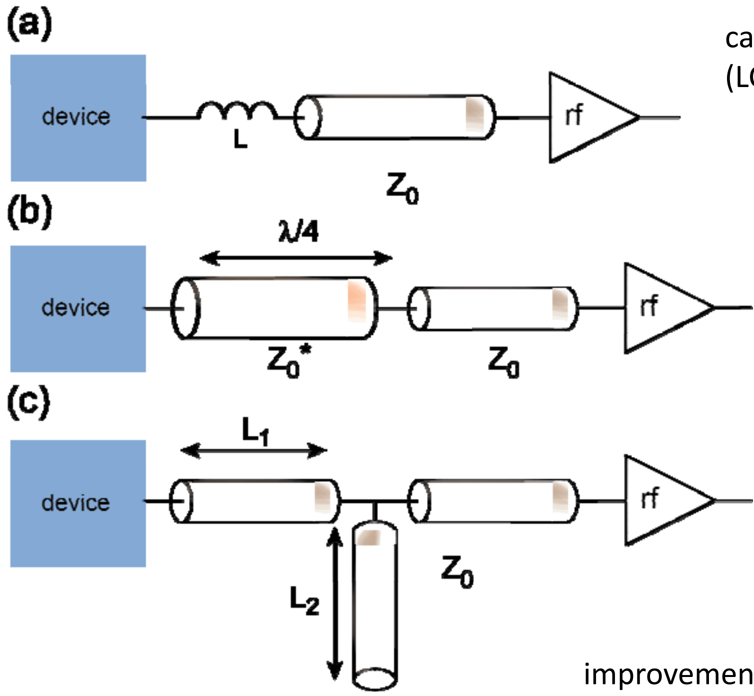
- some early experiments, but all at relatively low frequencies
- would like to do noise correlation measurements at GHz
- high impedance of QDs is a problem

*B. R.Choi et al., Phys. Rev. B **72** 024501 (2005)*

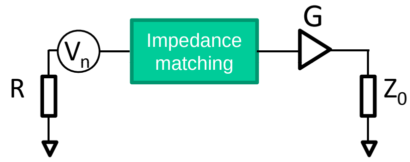
J. Wei and V. Chandrasekhar, Nature Phys. 6, 494 (2010)

JA. Das, Y. Ronen, M. Heiblum, D. Mahalu, A.V. Kretinin, and H. Shtrikman, Nat. Com.3, 1165 (2012)

Approach: impedance matching



can also be made by lumped elements (LC circuit) alone for f < 1GHz.



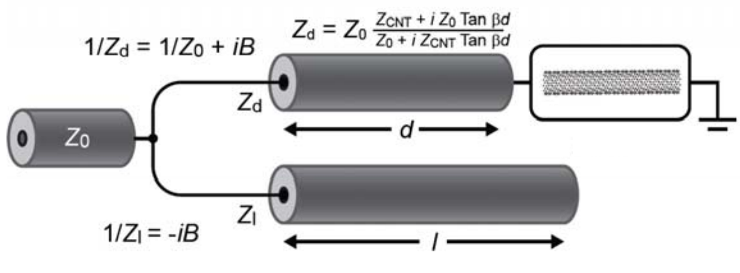
improvement in SNR relative to a broadband scheme can easily exceed a factor of 1’000 !

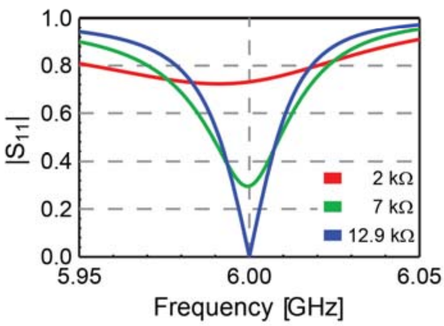
Stub impedance matching

Two pieces of transmission line (each ~λ/4),

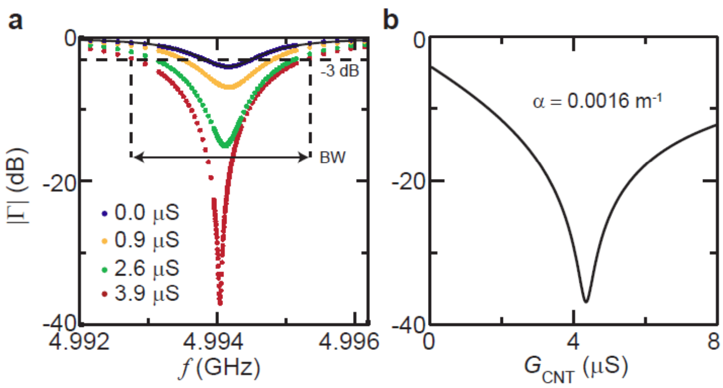
choose lengths D_1 & D_2 such, that

$$Y_{stub} = Y_{D1} + Y_{D2} = 1/Z_0$$





Gabriel Puebla-Hellmann, thesis ETHZ (2012)

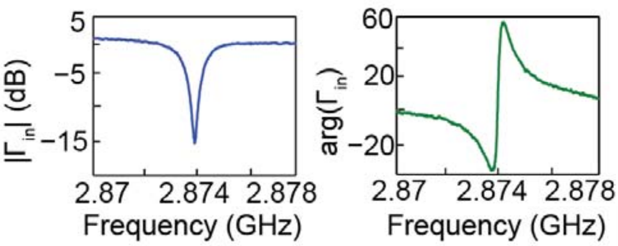


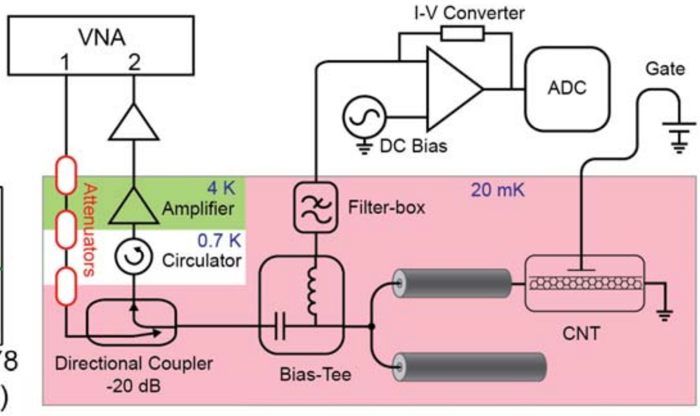
D. M. Pozar, *Microwave Engineering* (2005)
G. Puelbla-Hellmann *et al., APL* (2012)
S. Hellmuller *et al., APL* (2012)

Setup

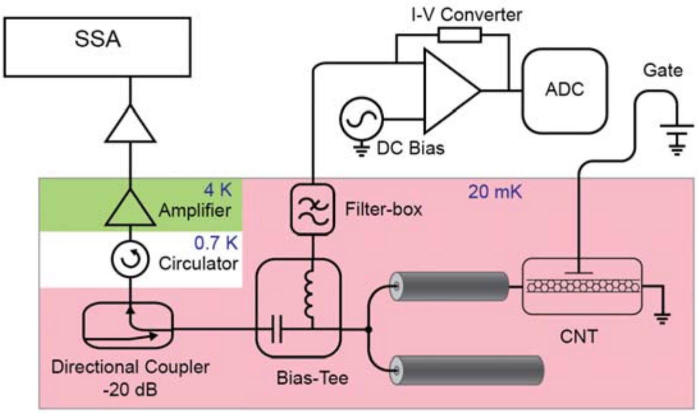
Reflection setup: $\Gamma_{in} = \frac{V_{reflected}}{V_{in}}$

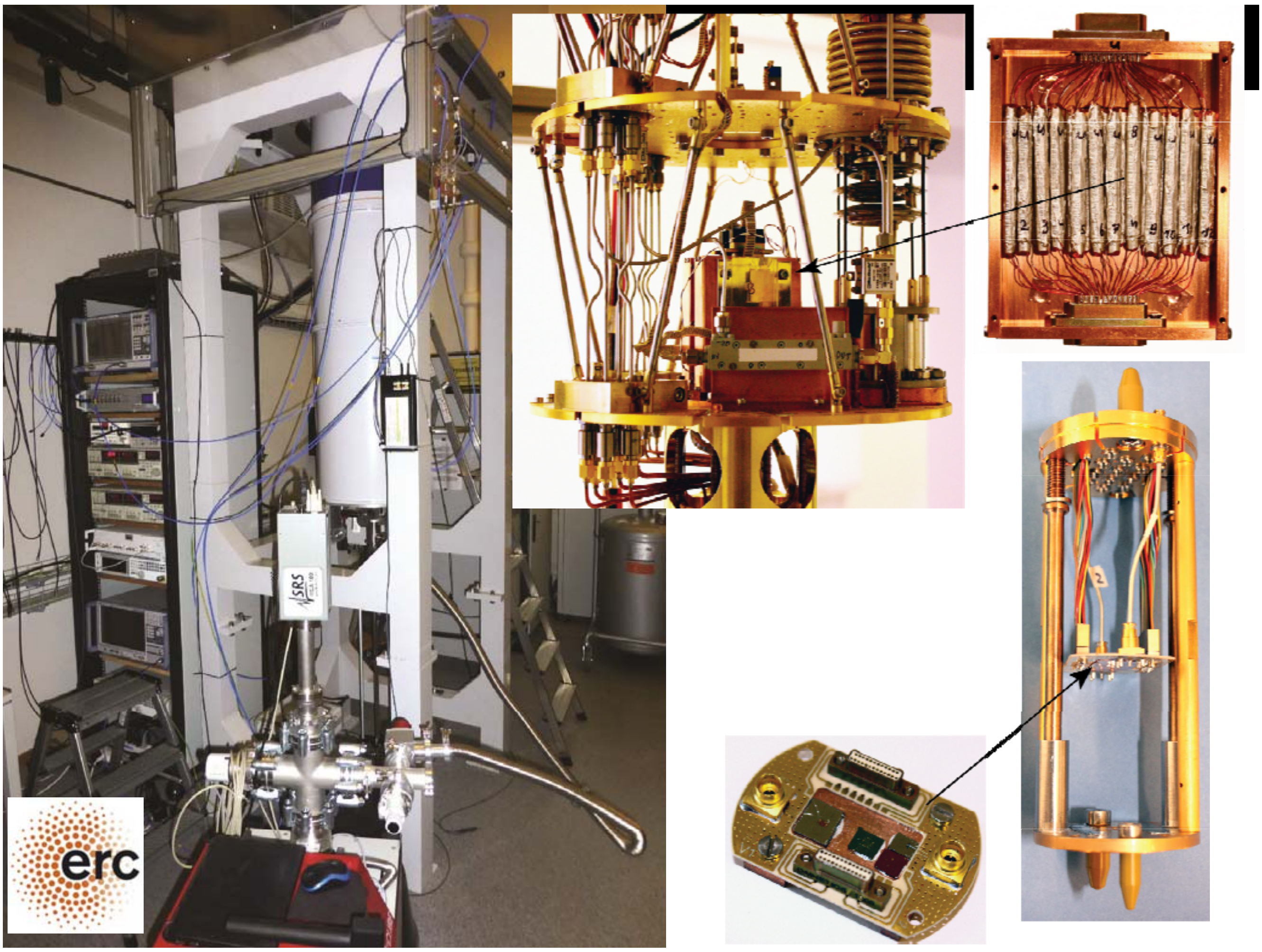
Open stub response at 4.2 K:



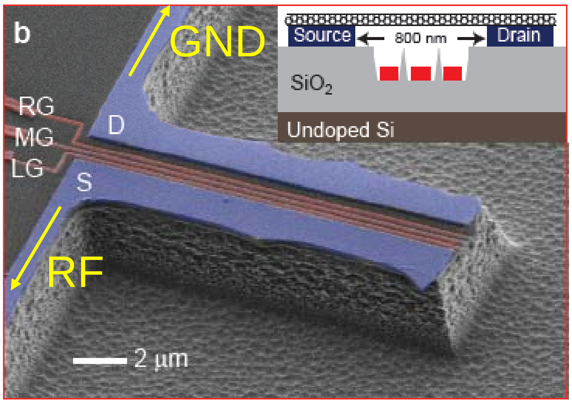


can also be used for **noise measurements**, signal from device is input to a spectrum analyzer





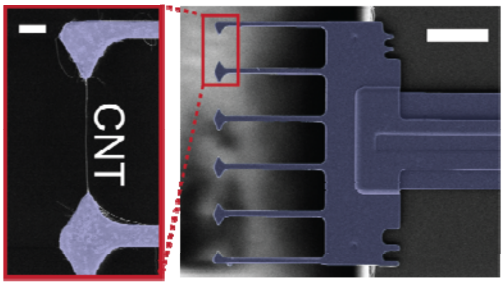
Ultraclean CNTs by stamping

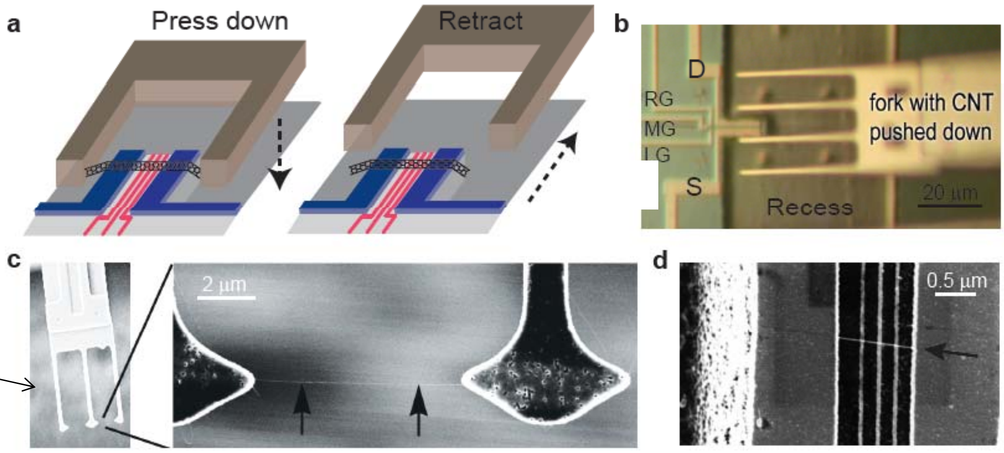


Similar techniques by:

F. Pei et al., Nature Nanotech. 7, 630 (2012)

J. Waissman et al., Nature Nanotech. 8, 569 (2013)

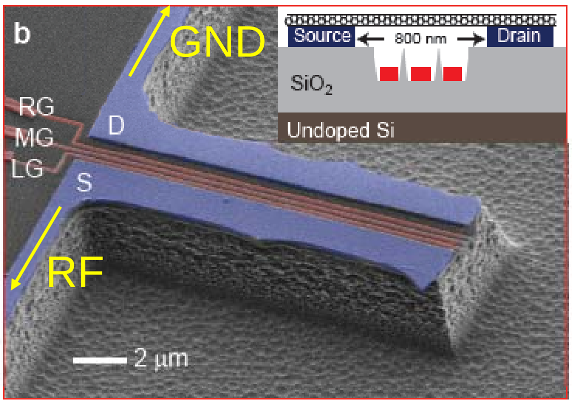


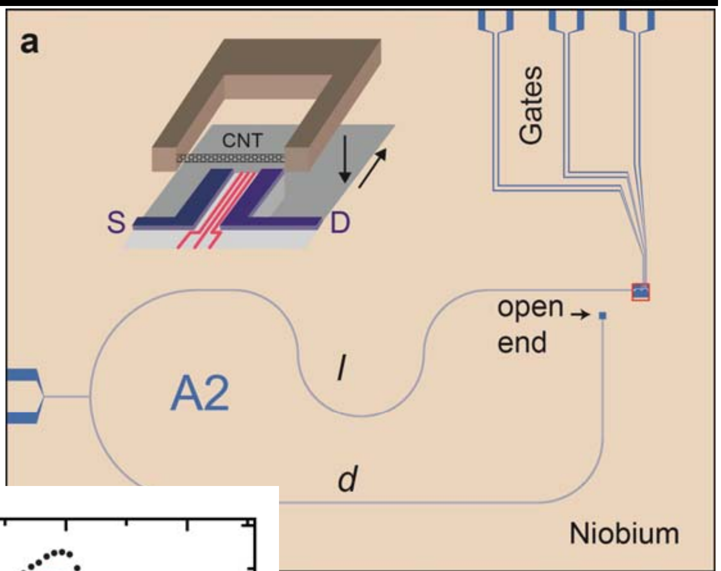


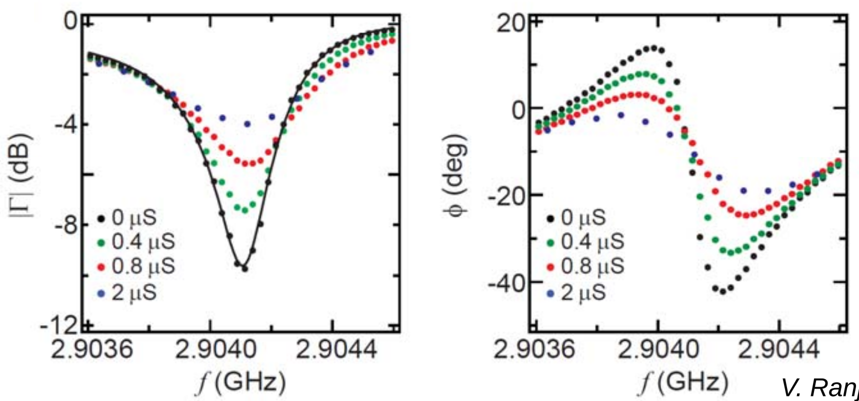
Fork

V. Ranjan et al.

stamped CNT coupled to stub resonator



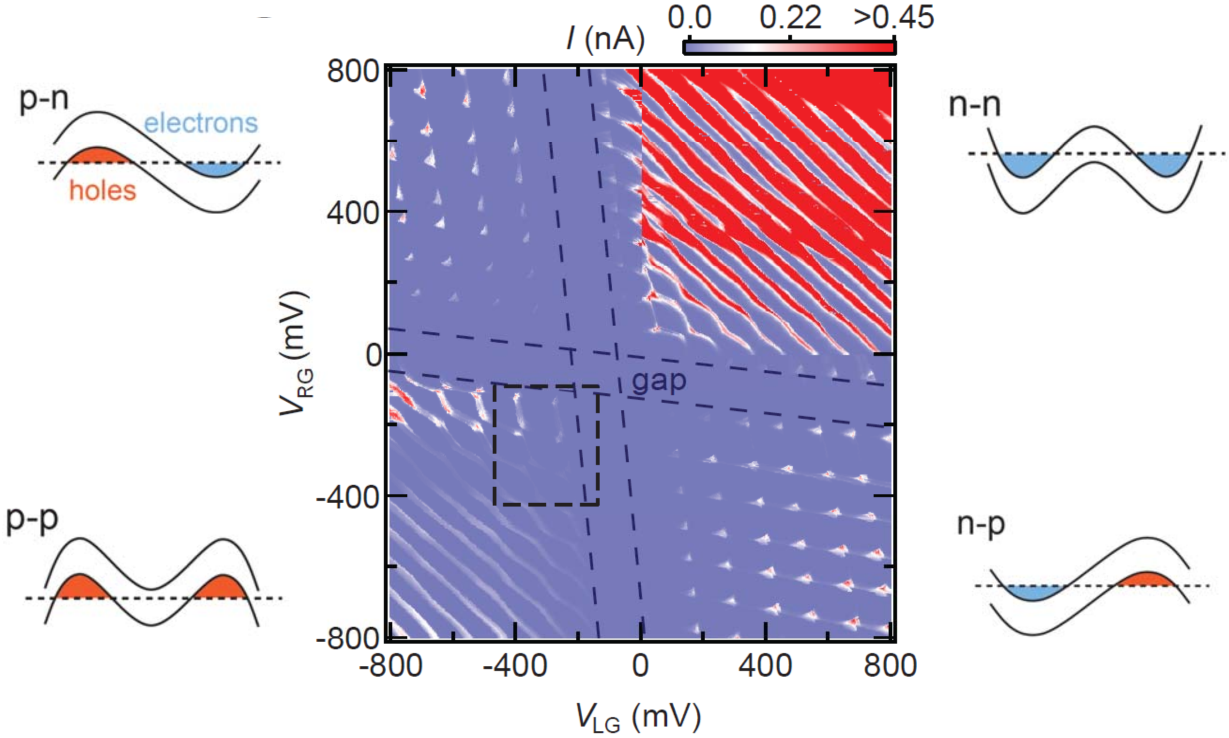




$f_r \sim 2.9$ GHz, $Q \sim 10{,}000$

V. Ranjan et al. Nature Comm. 6, 7165 (2015)

Charge stability diagram of double qdot

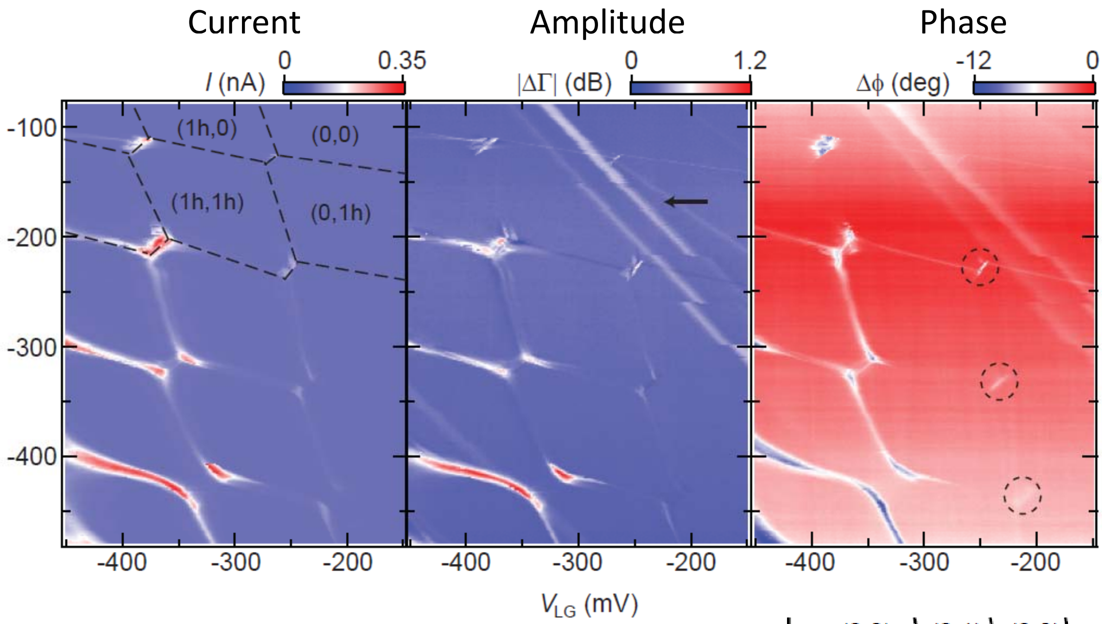


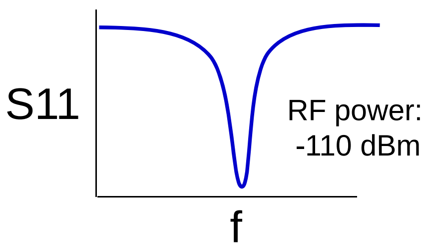
F. Pei *et al., Nature Nanotech.* 7, 630 (2012)
M. Jung, *et al., Nano Lett*. (2013)

no RF power, V_{SD} = -10 mV

V. Ranjan et al. Nature Comm. 6, 7165 (2015)

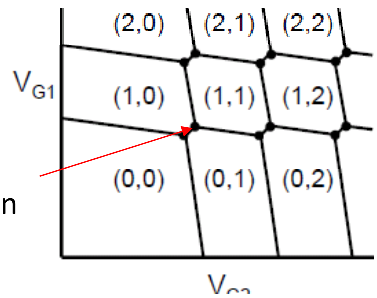
Reflectometry in double dot region





DQD →
Charge diagram

Interdot transition
btw two dots

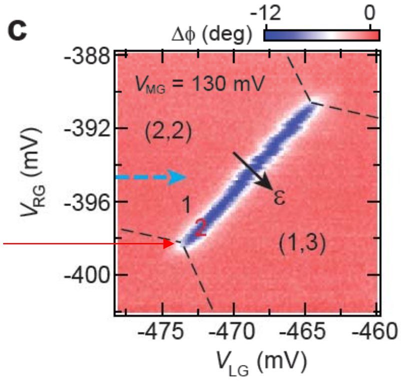


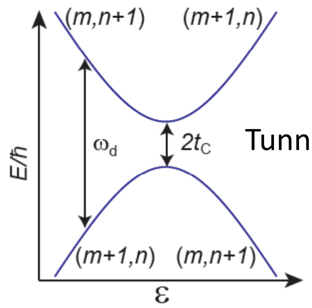
Reflectometry response of inter-dot coupling

Phase response at (2,2)-(1,3) transition

V_{SD} = 0 mV

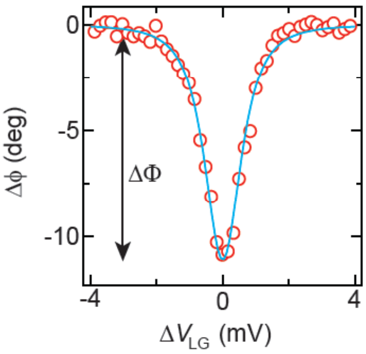
Triple point

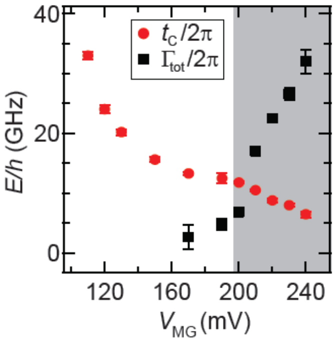




Tunnel coupling

$g_0/2p$ = 37 MHz

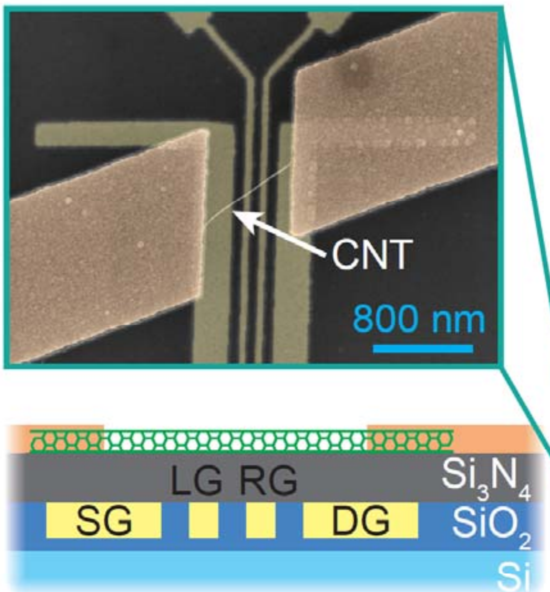


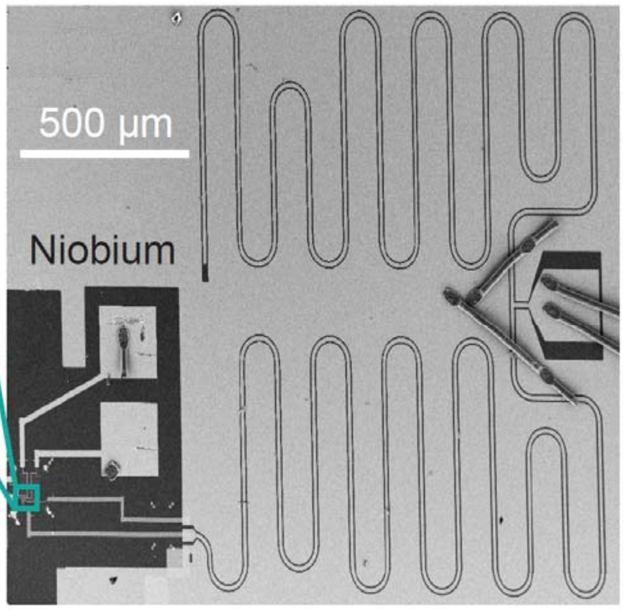


$$2\pi\Delta f = -\mathrm{Re}\left[\frac{(2g_0 t_c/\omega_d)^2}{\Delta + i\Gamma_{tot}}\langle\hat{\sigma}_Z\rangle\right]$$

V. Ranjan et al. Nature Comm. 6, 7165 (2015)

Stub impedance matching

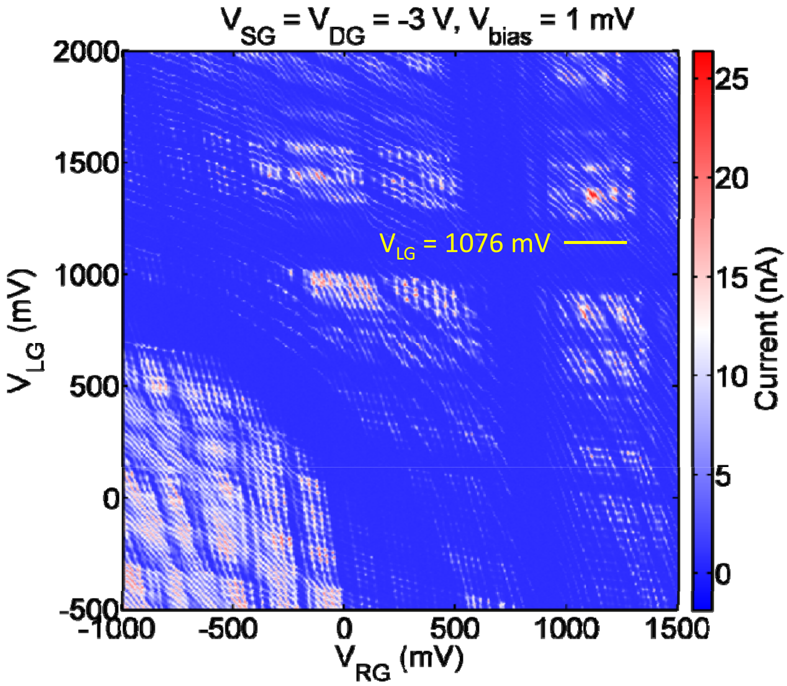


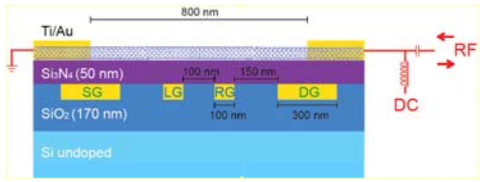


Stub-tuner made out of 150 nm niobium

T. Hasler et al. *method introduced by J. J. Viennot, J. Palomo, and T. Kontos, APL 104, 113108 (2014)*

Device characterization



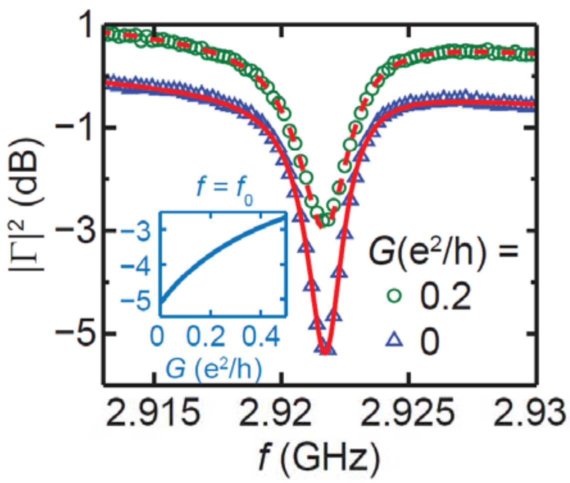


T = 20 mK

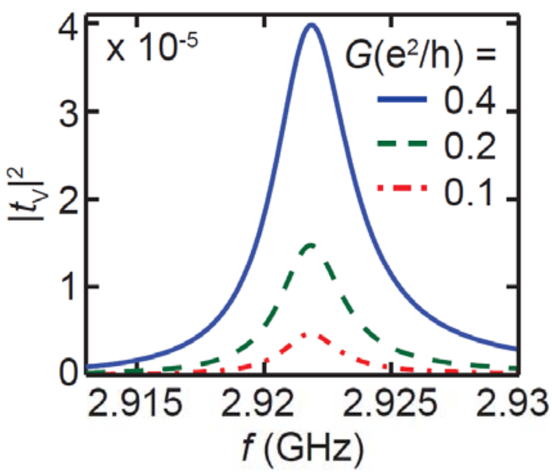
T. Hasler et al.

Stub-tuner characterization

Reflection



Transmission



–Coplanar transmission line: Z_0 = 45 Ω, ε_{eff} = 6 (from Sonnet simulations)

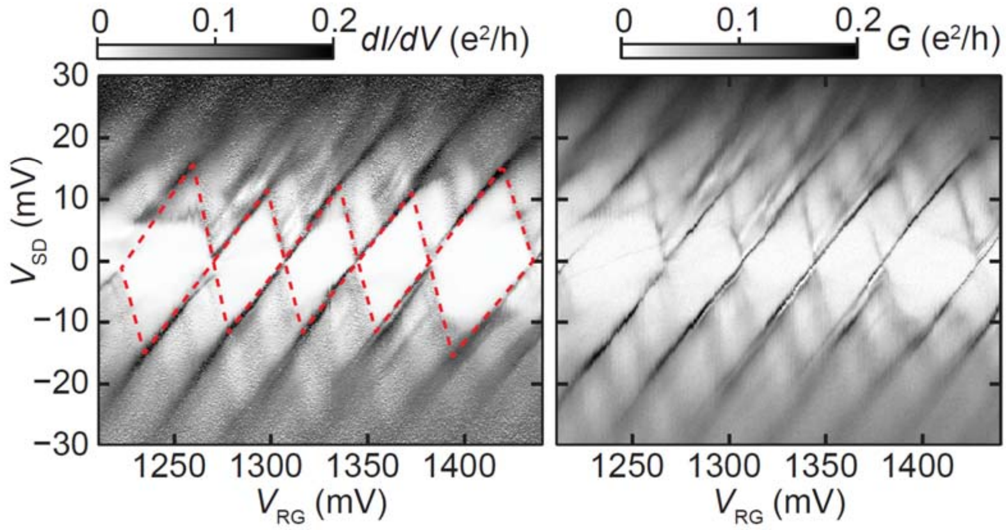
–Stub-parameters from reflection: Fit at G = 0 with the free parameters D_1, D_2 and loss α

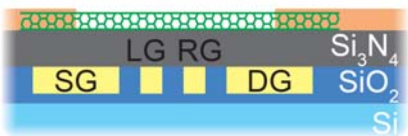
–Transmission through matching circuit calculated with those parameters

T. Hasler et al.

Single quantum dot: conductance

Derived for DC-current: Derived from reflectometry:

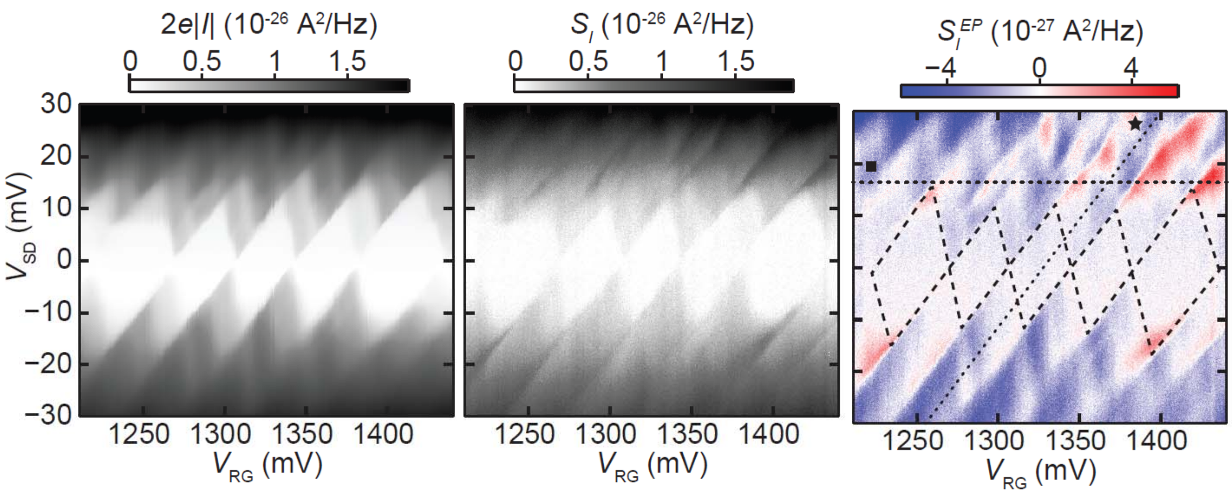




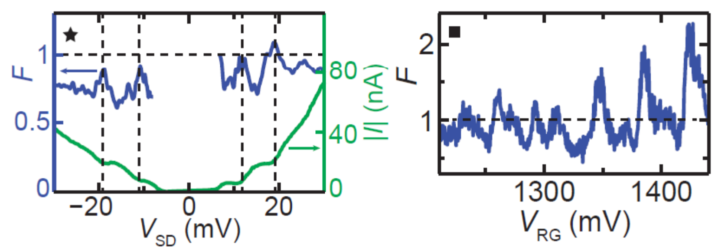
SG & DG set to -3 V to get p-doped leads
LG fixed at 1076 mV

T. Hasler et al.

Single quantum dot: noise



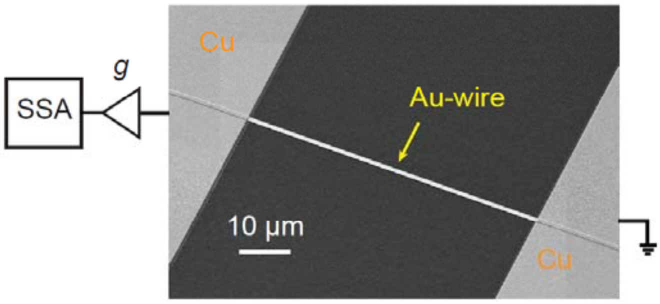
Noise measured at f_0 = 2.9218 GHz and integrated over bandwidth of 20 MHz

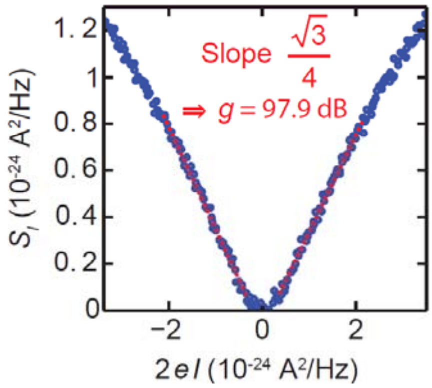


T. Hasler et al.

Calibration

Replace sample with 40 Ω Au-wire (no stub-tuner)





Metal wire in the **hot-electron regime**

Length L = 50 µm, width 680 nm, thickness 30 nm

$l_{e\text{-}e} < L < l_{e\text{-}ph}$

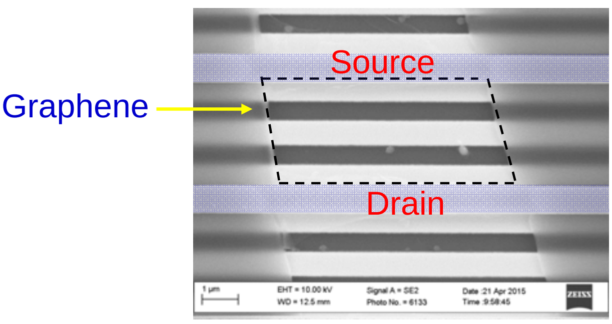
Same frequency and bandwidth as for CNT measurements

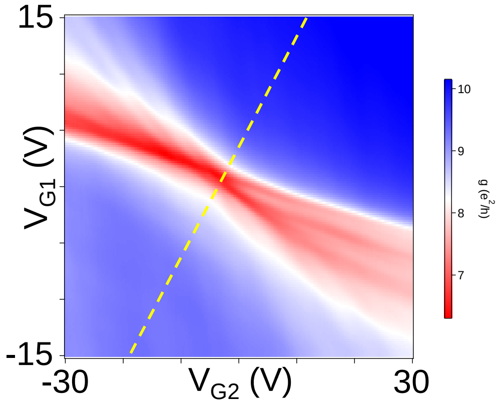
f_0 = 2.9218 GHz, bandwidth 20 MHz

A. H. Steinbach, J. M. Martinis, and M. H. Devoret, Phys. Rev. Lett. 76, 3806 (1996).

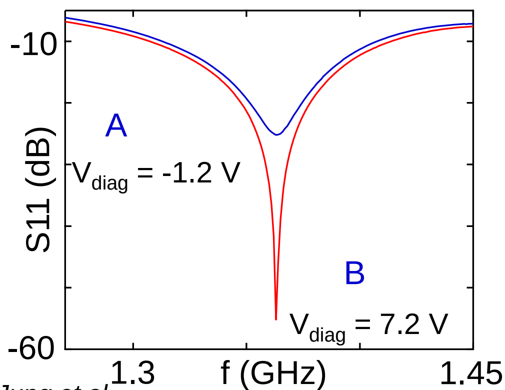
Fano factor in suspended graphene

W/L = 2.17

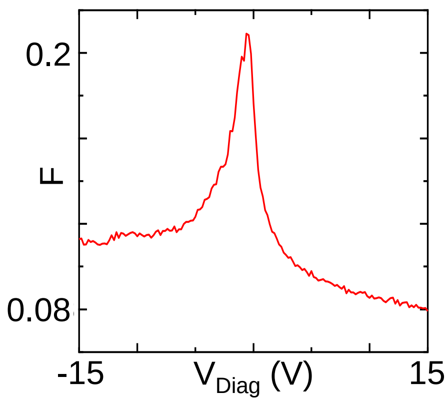




Resonance



From fitting
L = 17.03 nH
C = 0.798 pF
R_{loss} = 42.0 Ω

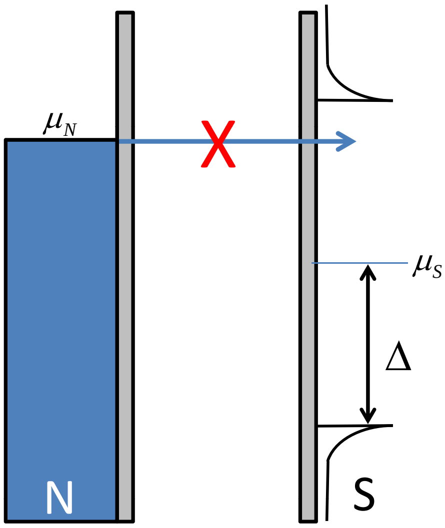


M. Jung et al.

Resonant Andreev tunneling through a QD

Single-electron transport through a S-QD-N device

$$G \propto D_N(\mu_N) \cdot D_S(\mu_N + eV_{sd}) \cdot T_{QD}(\mu_N)$$



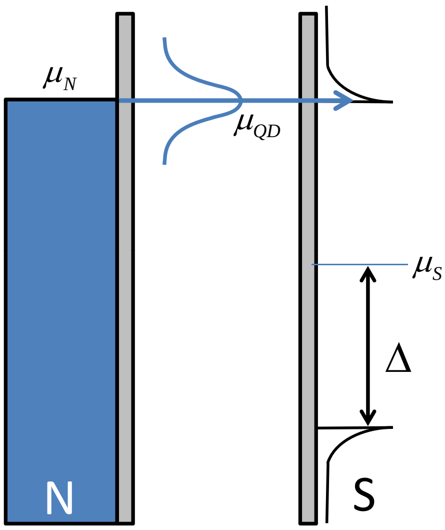
Transport gap: $eV_{sd} = \Delta$

Jörg Gramich et al.

Resonant Andreev tunneling through a QD

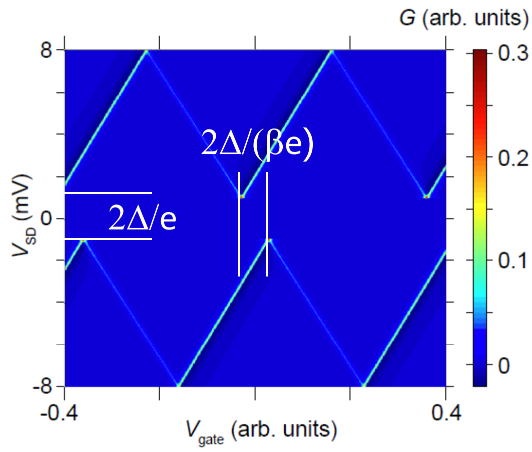
Single-electron transport through a S-QD-N device

$$G \propto D_N(\mu_N) \cdot D_S(\mu_N + eV_{sd}) \cdot T_{QD}(\mu_N)$$



Transport gap: 2Δ
Diamond ‚shift': 2Δ/(βe)

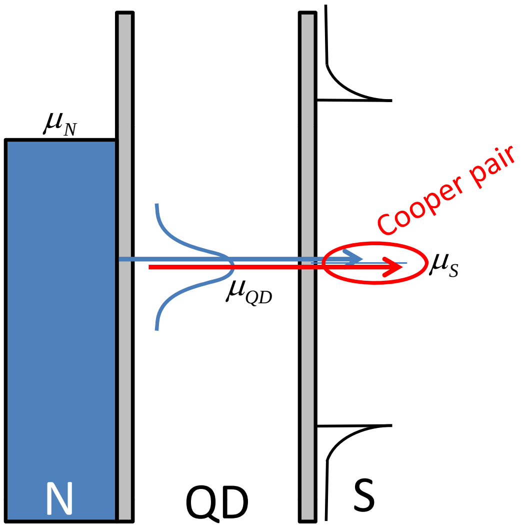
β: negative slope of diamond

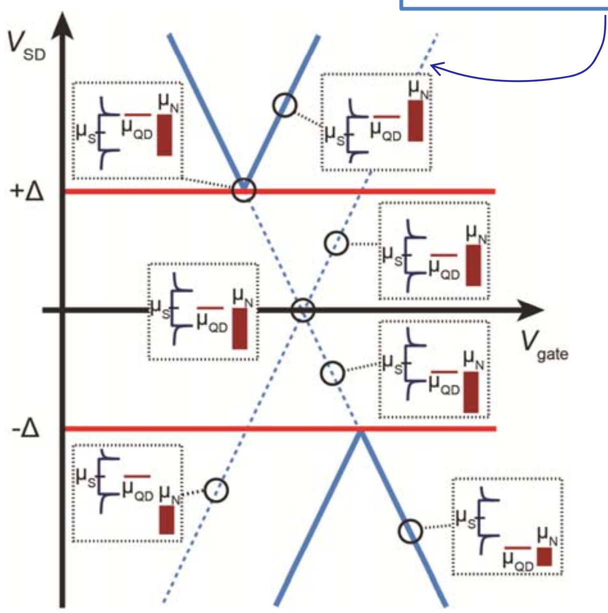


Jörg Gramich et al.

Resonant Andreev tunneling

resonance for $\mu_S = \mu_{QD}$

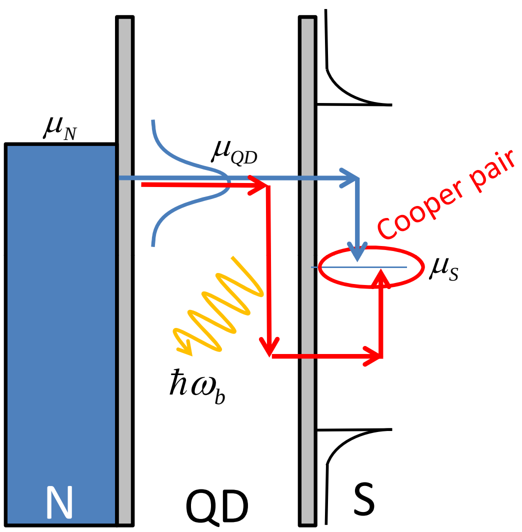




note: as a function of bias, there will be current peak (because of capcitive coupling to the level), yielding negative differential resistance

C.W.J. Beenakker, Phys. Rev. B 46, 12841 (1992).

Inelastic Andreev tunneling



discrete modes of bosonic bath absorb or emit energy

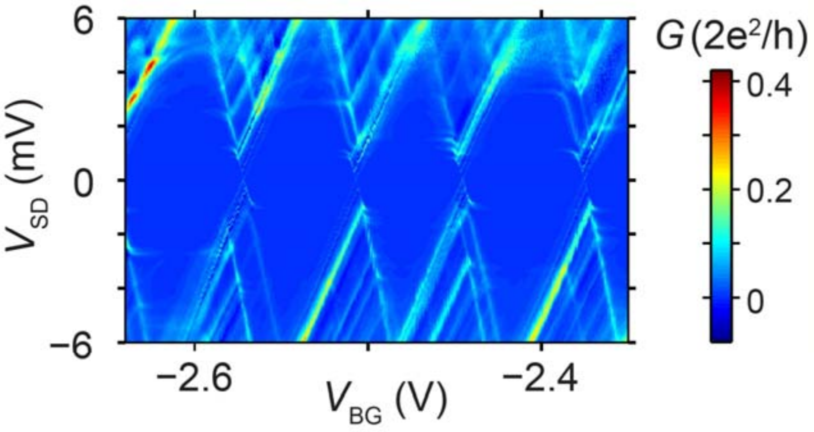
$$\mu_{QD} = \mu_S + \frac{n}{2}\hbar\omega_b$$

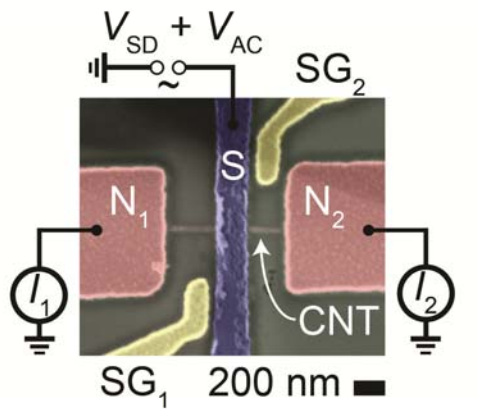
→ lines parallel to resonant AT

Zhang et al., Phys. Rev. B 86, 104513 (2012)

Experiment

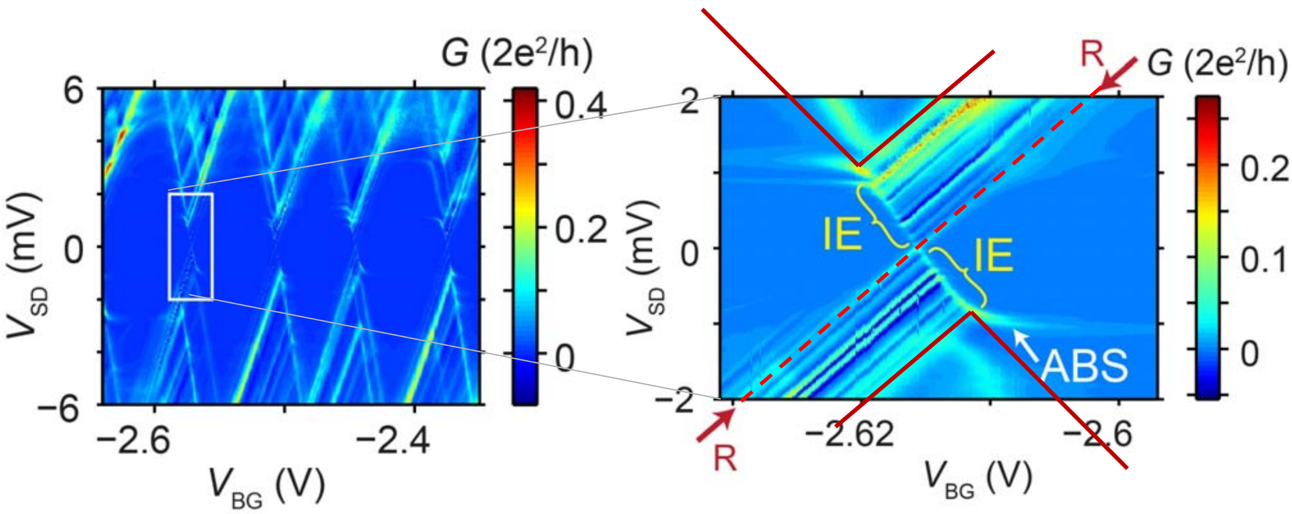
Nb contact

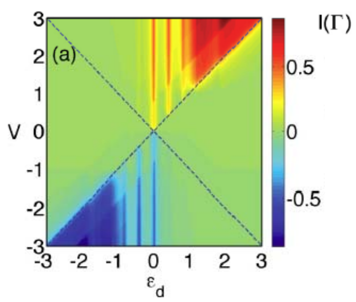




Jörg Gramich et al. (unpublished)

Experiment

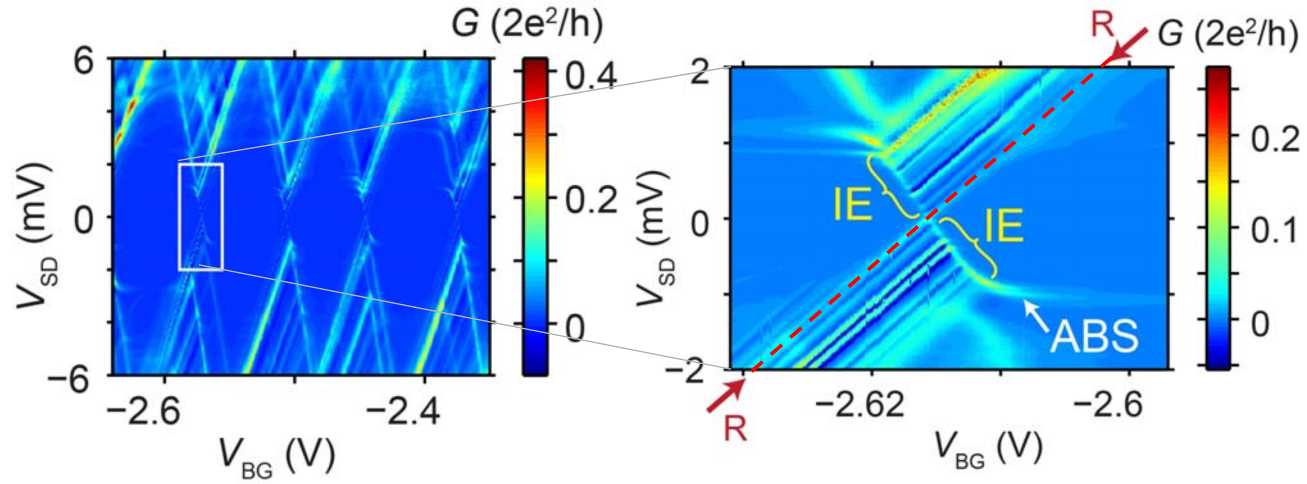




Zhang *et al.*,
Phys. Rev. B 86,
104513 (2012)

Jörg Gramich et al. (unpublished)

Experiment



resonant AT (R):

- crosses full transport gap
- for QD level aligned with μ_S

inelastic AT (IE):

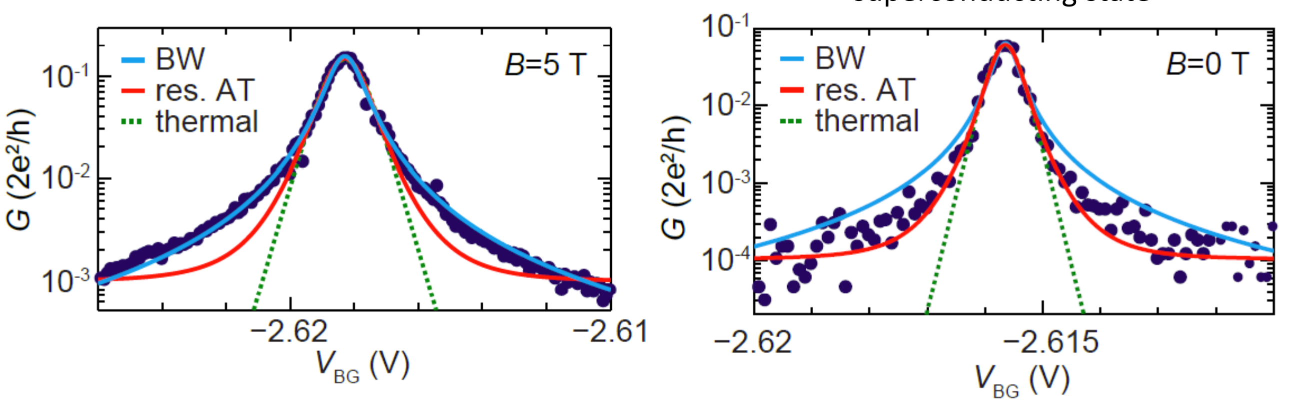
- parallel to resonant AT
- average spacing: $½\hbar\omega_b$= 145 ± 30 μeV
- constant amplitudes vs gate and bias

Jörg Gramich et al. (unpublished)

Resonant Andreev tunneling

normal state

superconducting state



Resonant AT $$G = \frac{2e^2}{h}\left(\frac{2\Gamma_1\Gamma_2}{4(E-E_0)^2+\Gamma_1^2+\Gamma_2^2}\right)^2$$

Breit-Wigner $$G(V_{\mathrm{BG}}) = \frac{e^2}{h}\cdot\frac{\Gamma_1\Gamma_2}{(E_{\mathrm{F}}-E_0)^2+\Gamma^2/4}$$

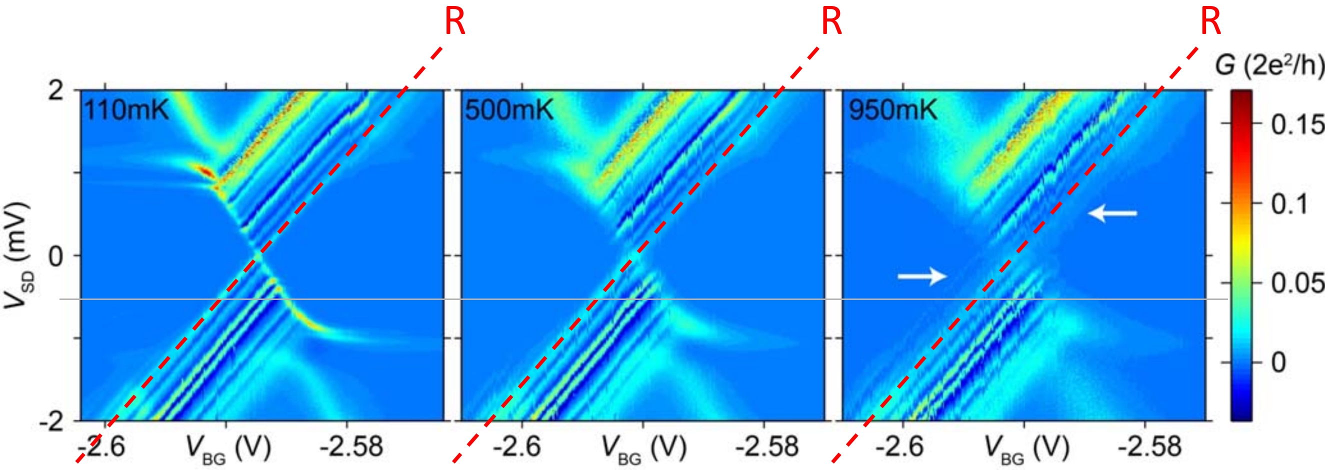
thermal broadening $$G = \frac{e^2}{h}\frac{1}{4k_{\mathrm{B}}T}\frac{\Gamma_1\Gamma_2}{\Gamma}\cosh^{-2}\left(\frac{E-E_0}{2kT}\right)$$

obtain consistent values:
$\Gamma_1 \approx 10$ μeV, $\Gamma_2 \approx 100$ μeV
both for N and S state

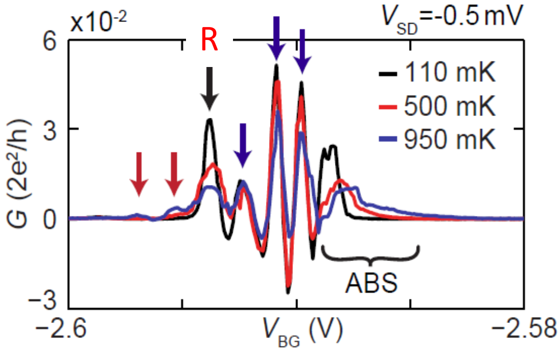
Jörg Gramich et al. (unpublished)

C.W.J. Beenakker, Phys. Rev. B 46, 12841 (1992)

Temperature dependence

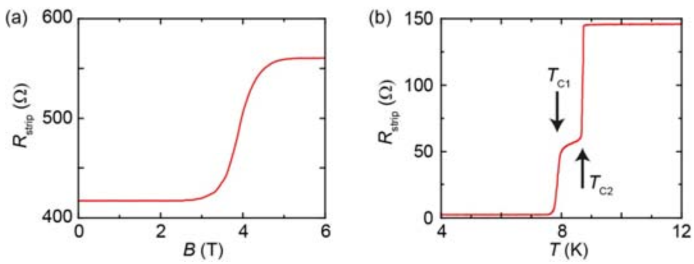


– lines are not thermally broadened
– at higher temperature other side-bands appear (photon-assisted)

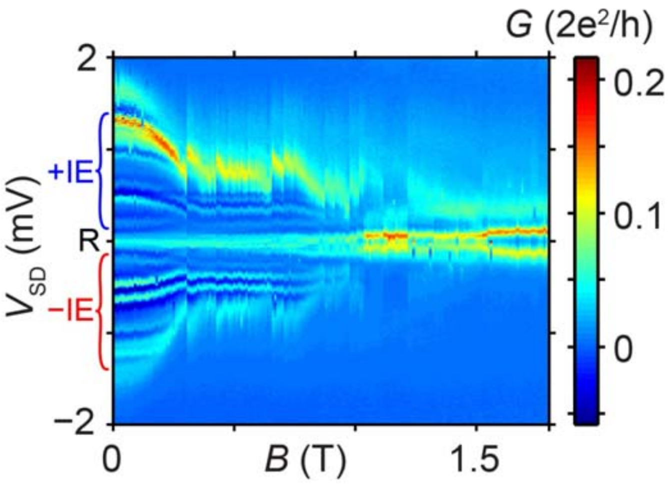


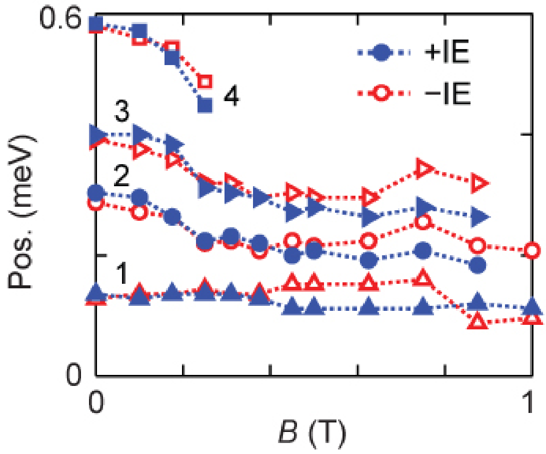
Jörg Gramich et al. (unpublished)

Magnetic field dependence



Nb test strip

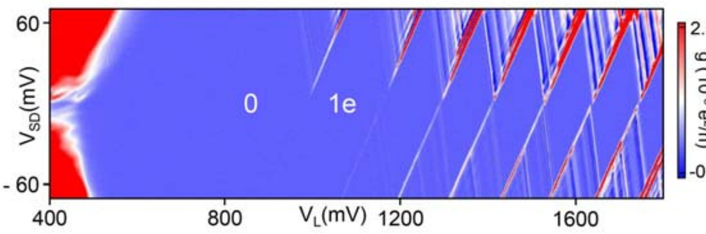


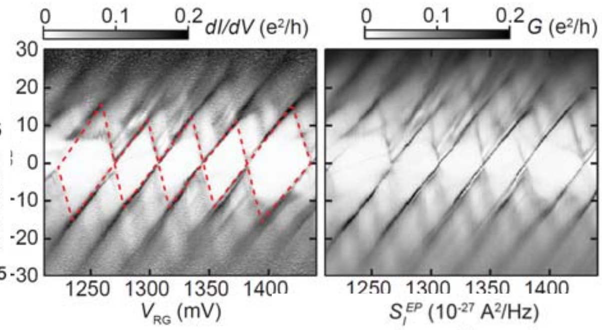


- replica 1 exhibits different B-dependence than 2-4
- different bosons? E.g. IE1 a phonon and the other of em origin

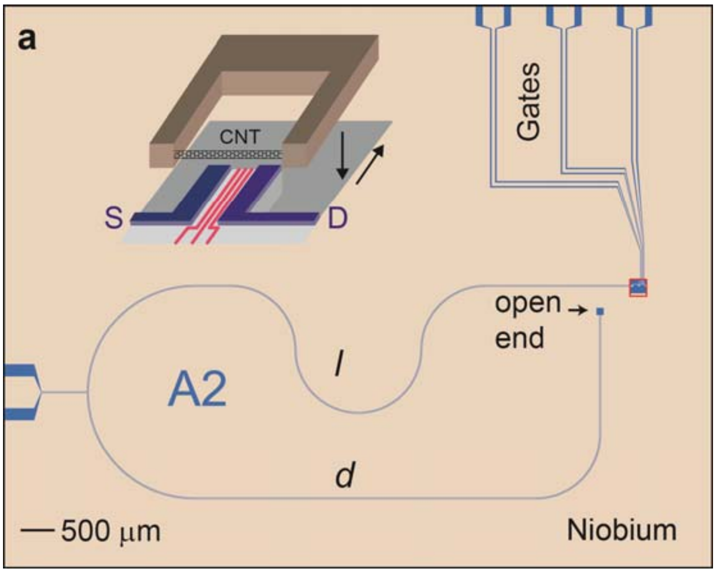
Jörg Gramich et al. (unpublished)

Summary

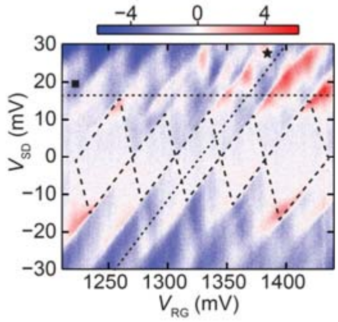




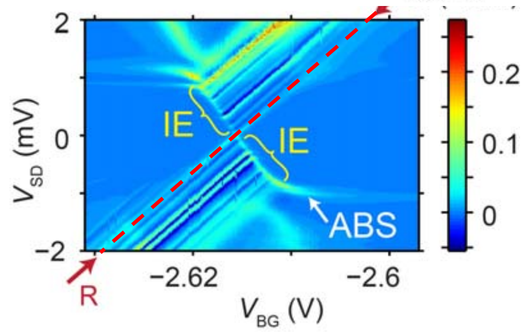
clean CNT double QD devices coupled to rf matching circuits



reflectometry and noise in CNT QD



Andreev-tunneling in S-N junctions



Gate-defined clean nanodevices coupled to impedance matching circuits at GHz frequencies (+ new results on S-dot-N)

V. Ranjan, T. Hasler, M. Jung, J. Gramich, J. Schindele, S. d'Holosy, L. Hofstetter, A. Baumgartner, C. Schönenberger, *Univ. of Basel*

G. Puebla-Hellmann, M. Muoth, C. Hierold, A. Wallraff, *ETHZ*

G. Fülöp, S. Csonka, *Budapest Univ. of Technology and Economics*

M. H. Madsen, M. Aagesen, J. Nygard, *Univ. of Copenhagen*

F. Domingues, A. Levy-Yeyati, *Univ. of Madrid*