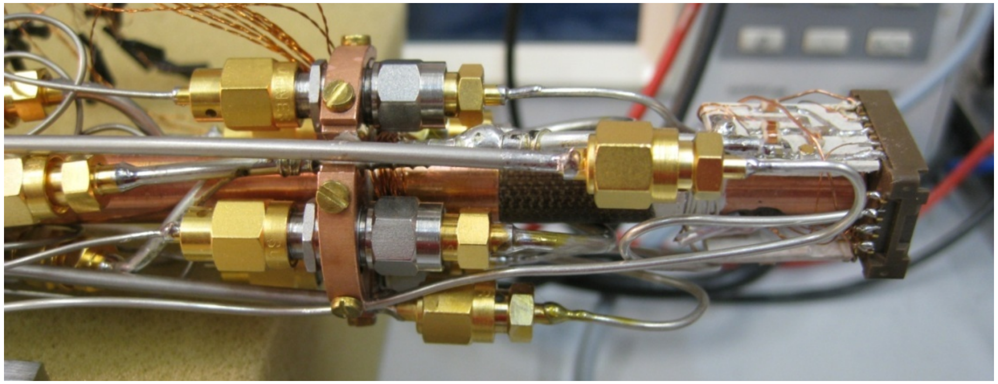
Radio-Frequency Quantum Point Contact Charge Detection



Thomas Müller
Nanophysics Group, ETH Zürich

In collaboration with

J. Güttinger, B. Küng, T. Choi, S. Hellmüller, D. Bischoff, P. Studerus, C. Barengo, K. Ensslin, T. Ihn

GaAs/AlGaAs heterostructures grown by M. Reinwald and W. Wegscheider; S. Schön

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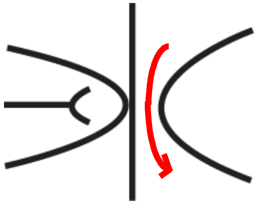
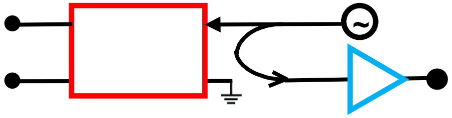
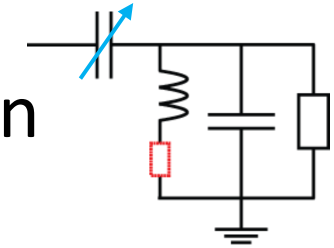
I. QPC charge detection

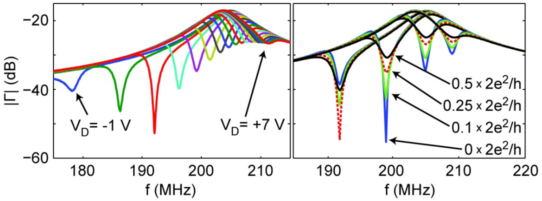


II. Radio-frequency reflectometry

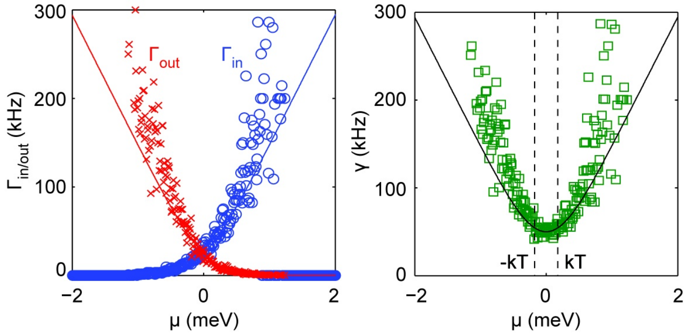


III. Experimental realisation





IV. Multi-level tunneling into a graphene quantum dot connected to a single lead



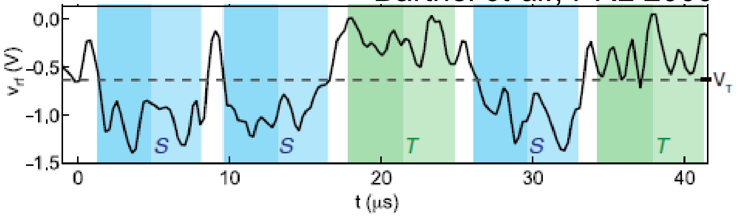
I. Why More Time Resolution?

Single-shot detection

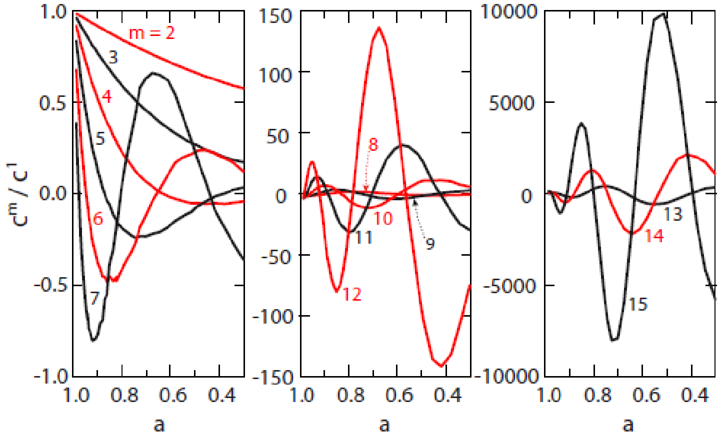
Measurement time

Less restricted by low tunnel rates

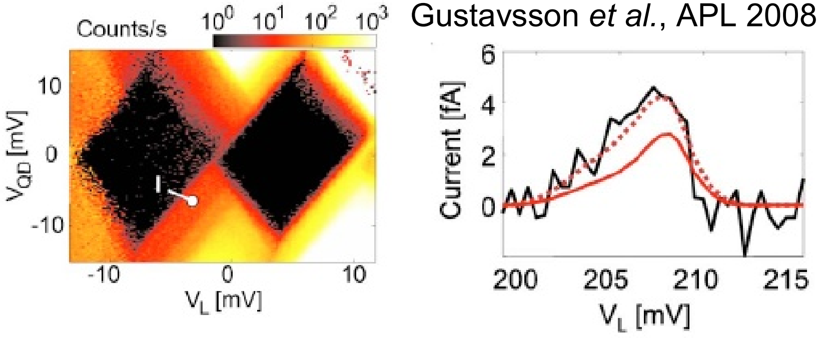
Barthel *et al.*, PRL 2009



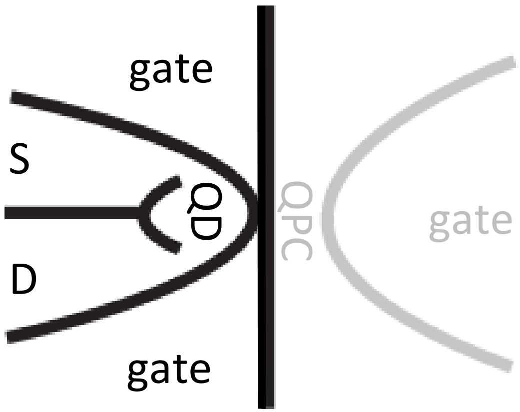
Fricke *et al.*, APL 2010

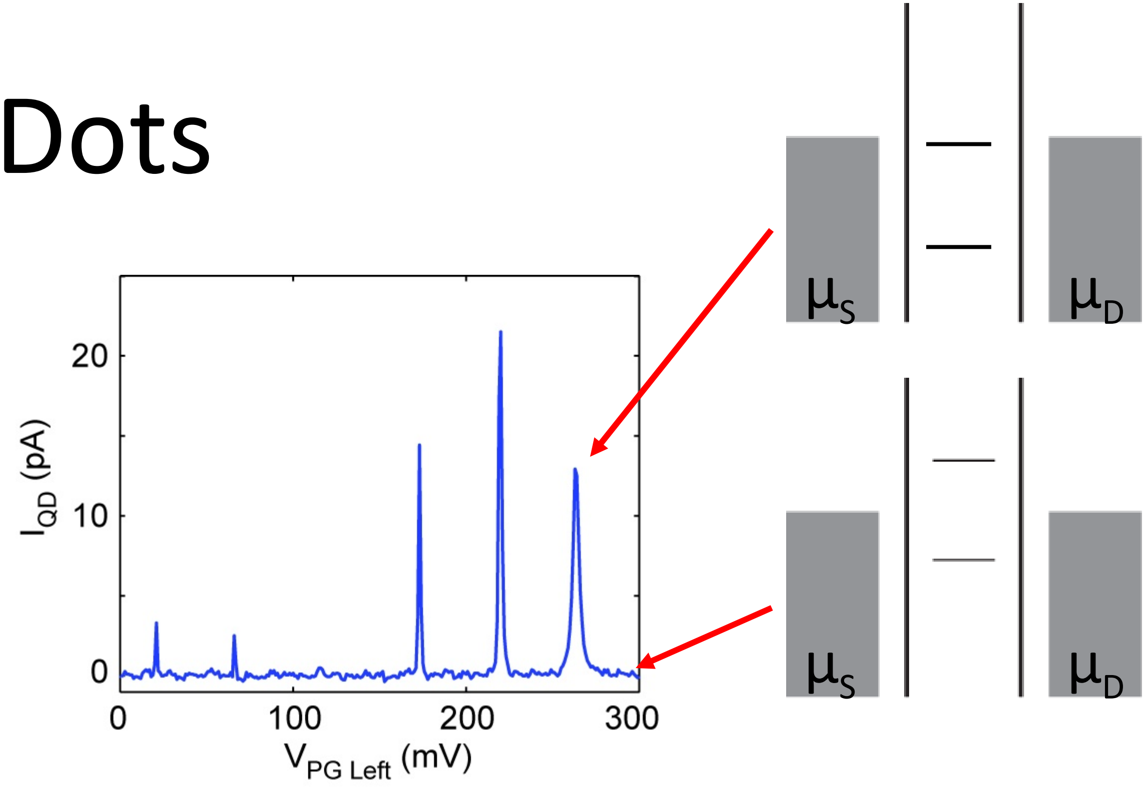


Gustavsson *et al.*, APL 2008

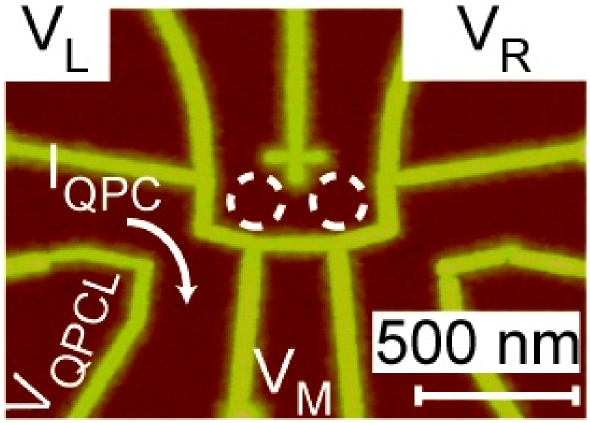


I. Quantum Dots



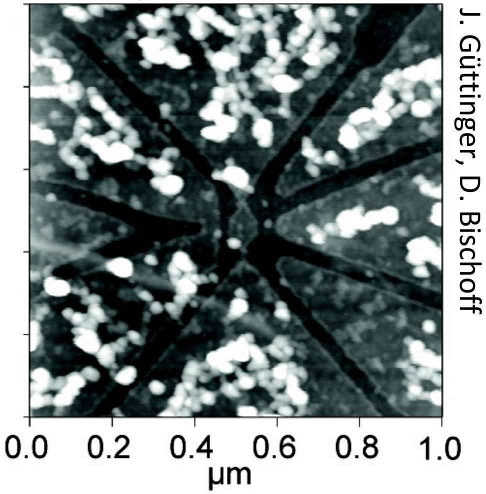


GaAs DQD



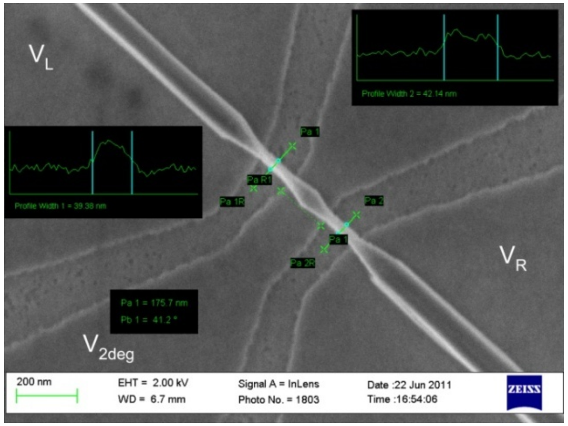
B. Küng

Graphene SQD



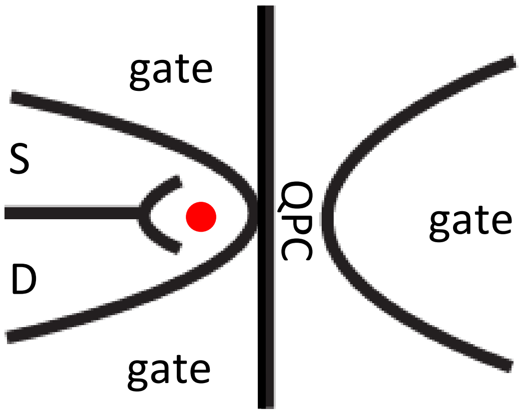
J. Güttinger, D. Bischoff

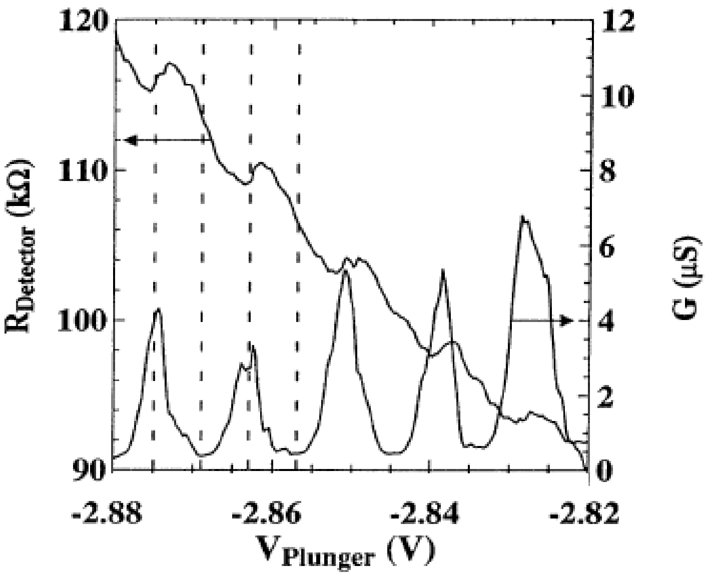
InAs NW SQD



T. Choi

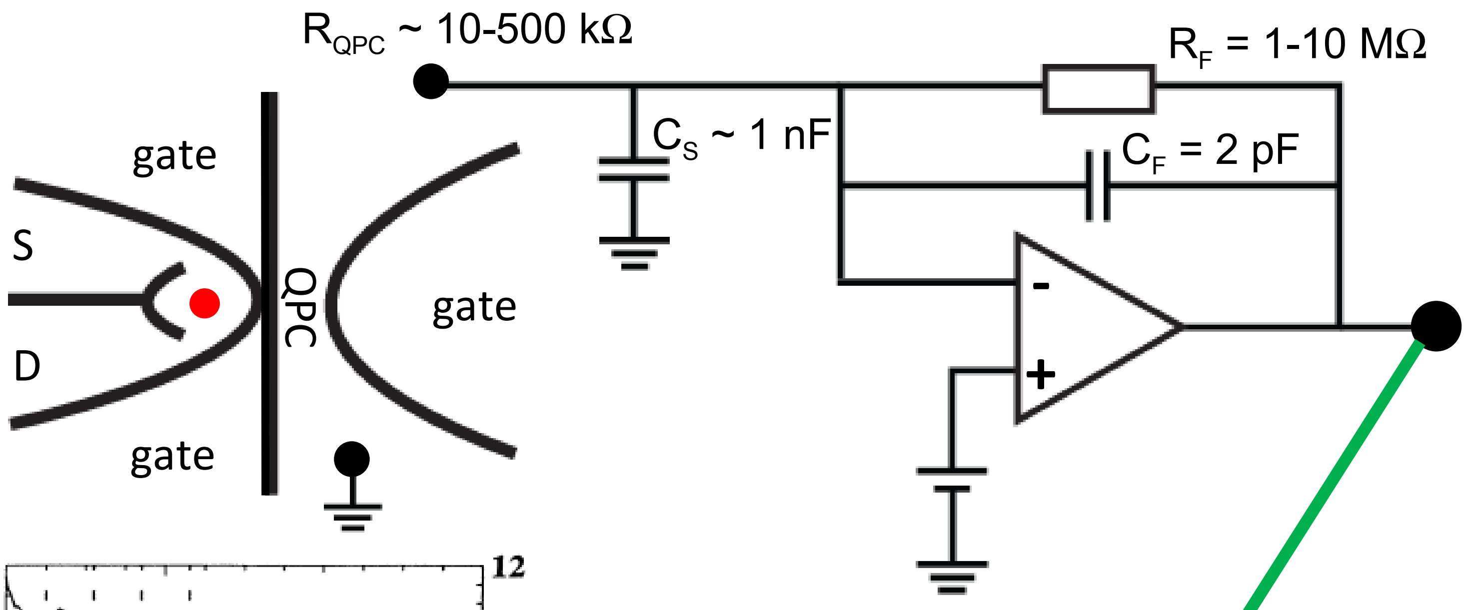
I. QPC Charge Detection

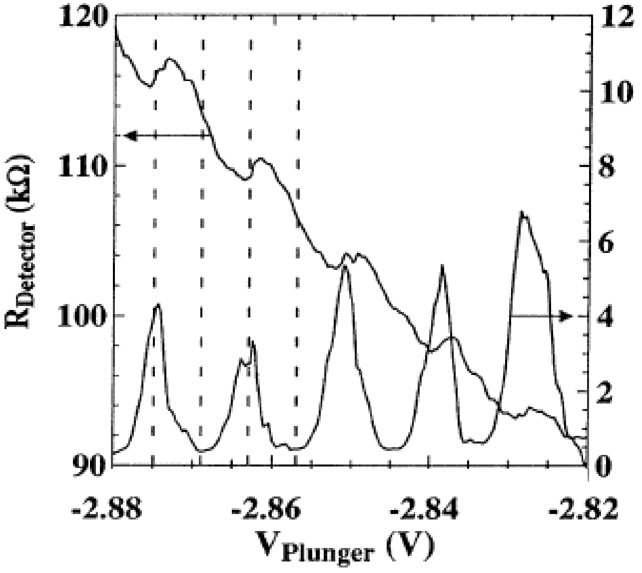




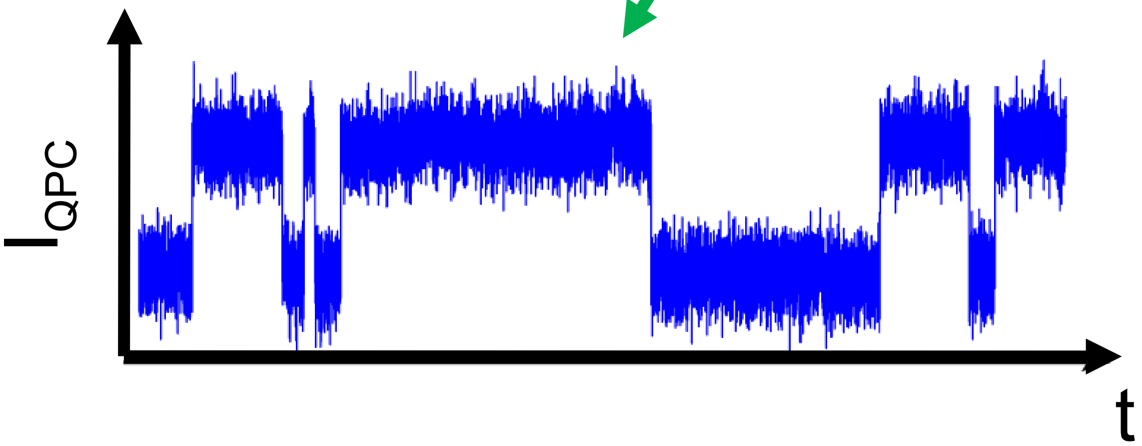
Field *et al.*, PRL 1993

I. Time-Resolved Charge Detection



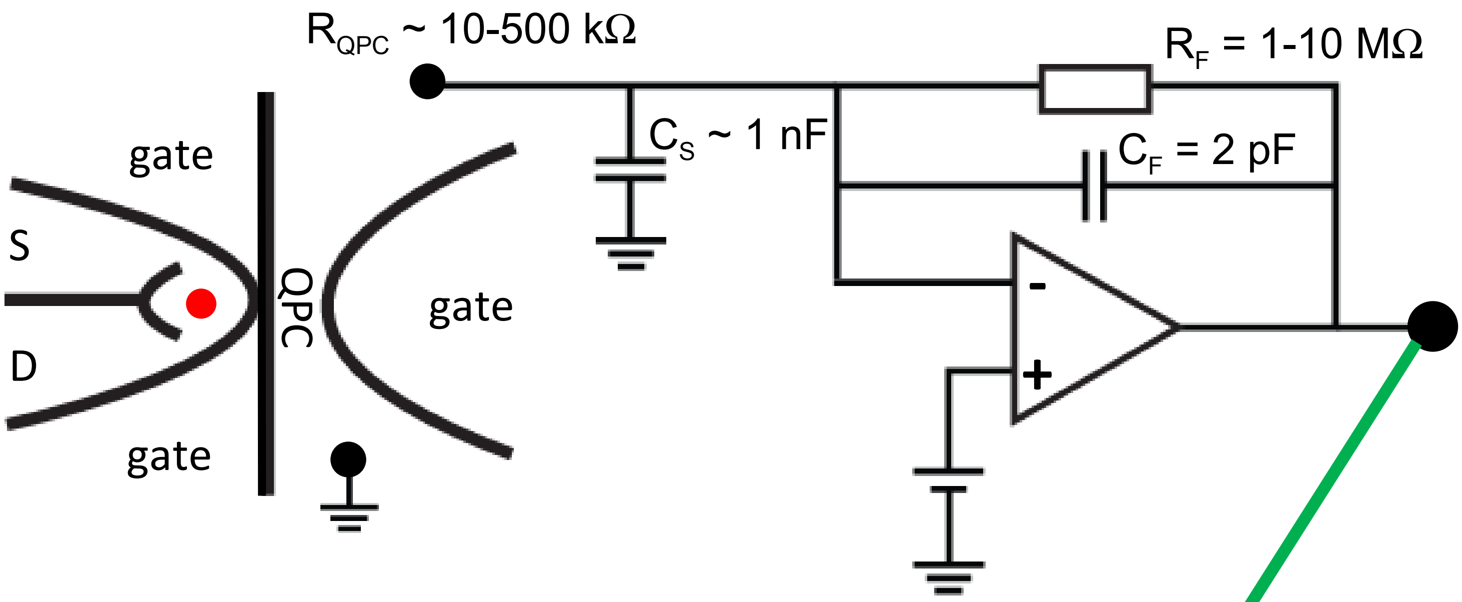


Field *et al.*, PRL 1993



Schleser *et al.*, APL 2004
Vandersypen *et al.*, APL 2004

I. Time-Resolved Charge Detection

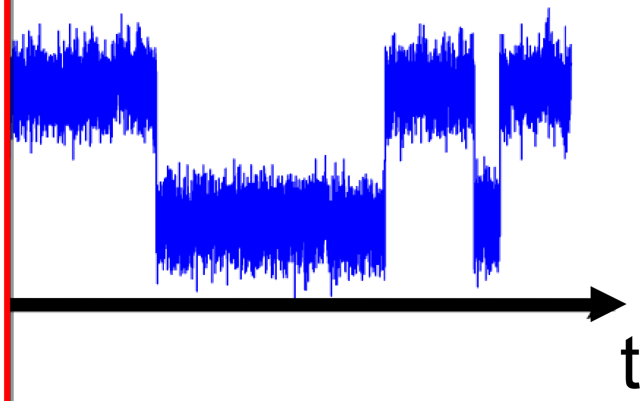


Capacitive noise gain

„Slow“ electronics

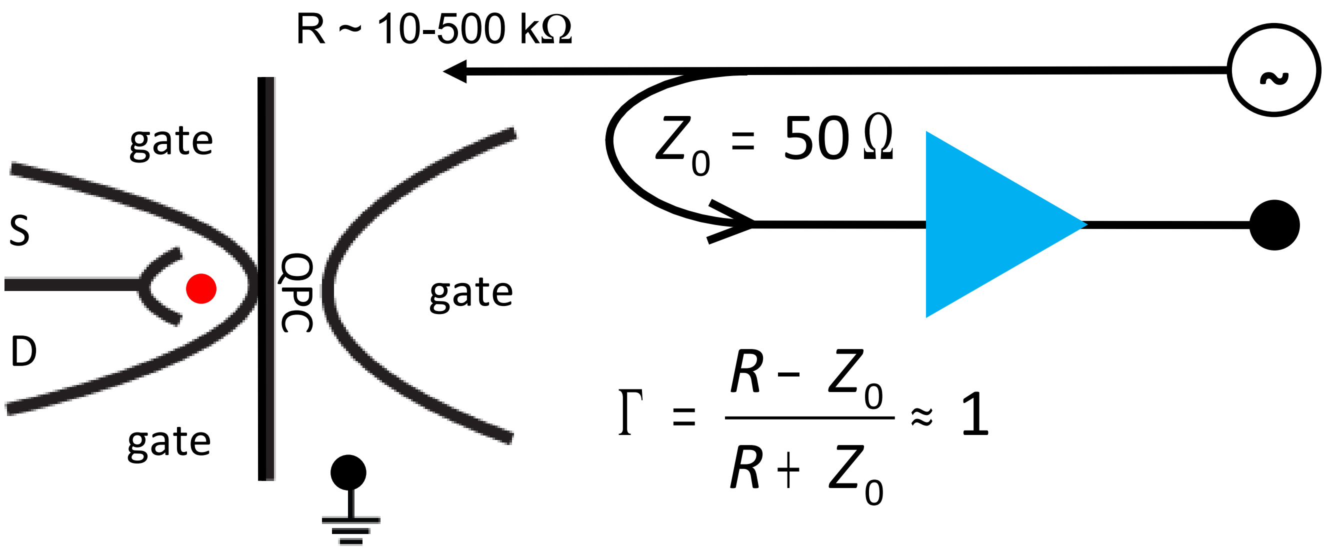
1/f noise

limit bandwidth to ~100 kHz



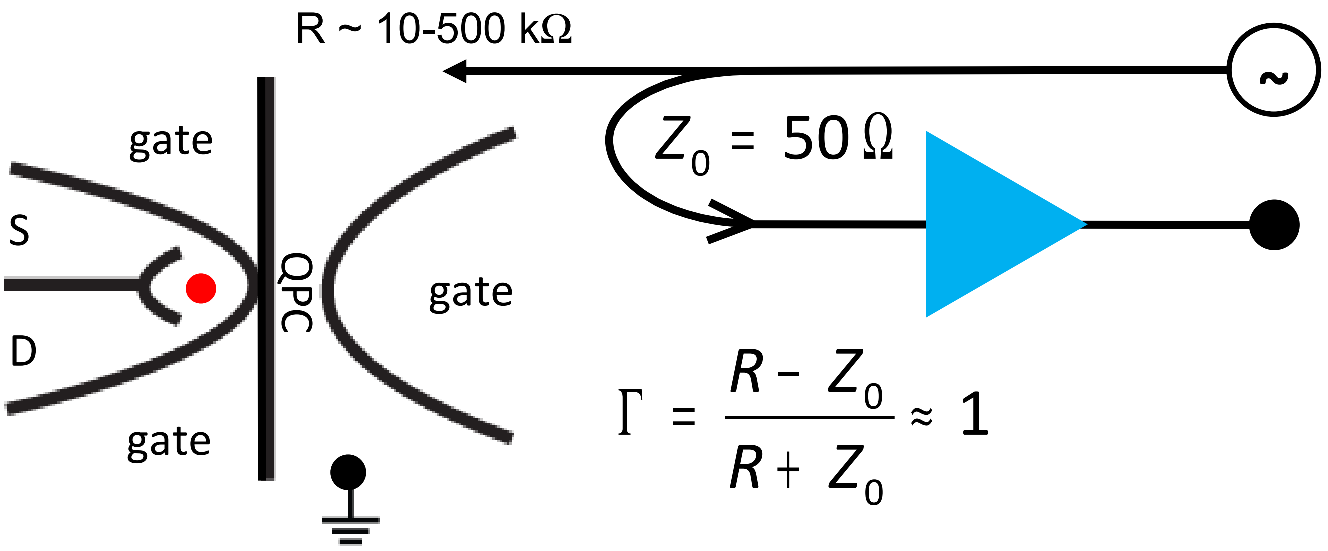
Schleser *et al.*, APL 2004
Vandersypen *et al.*, APL 2004

II. Reflection Coefficient Γ



$$\Gamma = \frac{R - Z_0}{R + Z_0} \approx 1$$

II. Reflection Coefficient Γ



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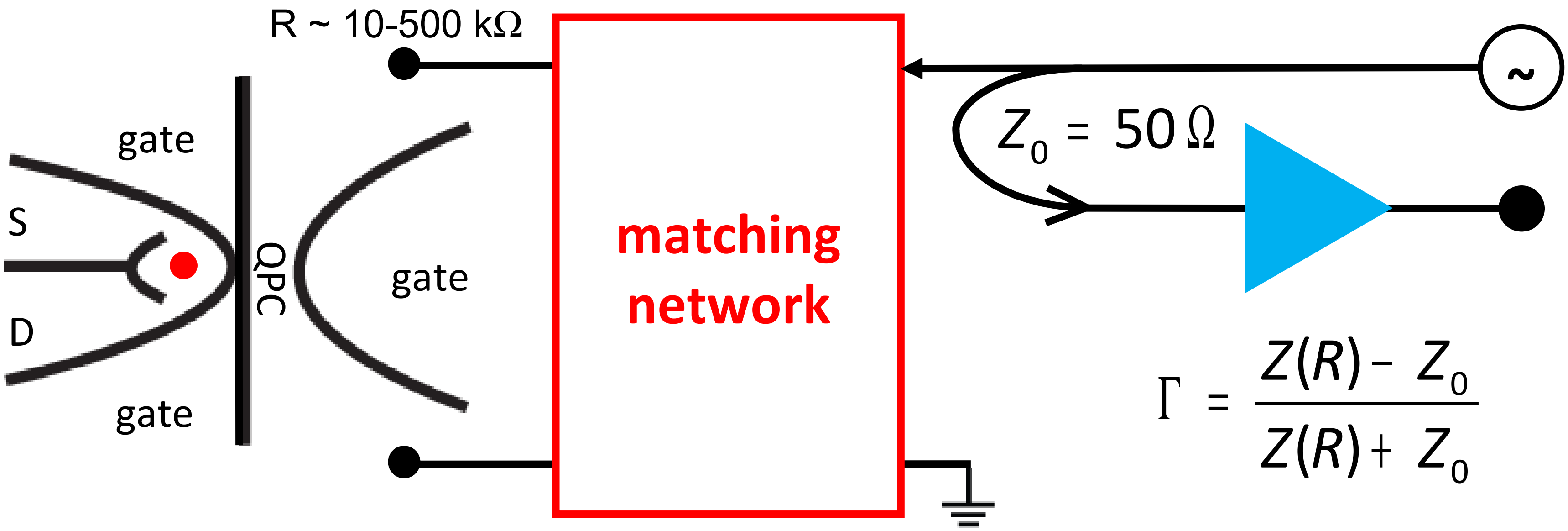
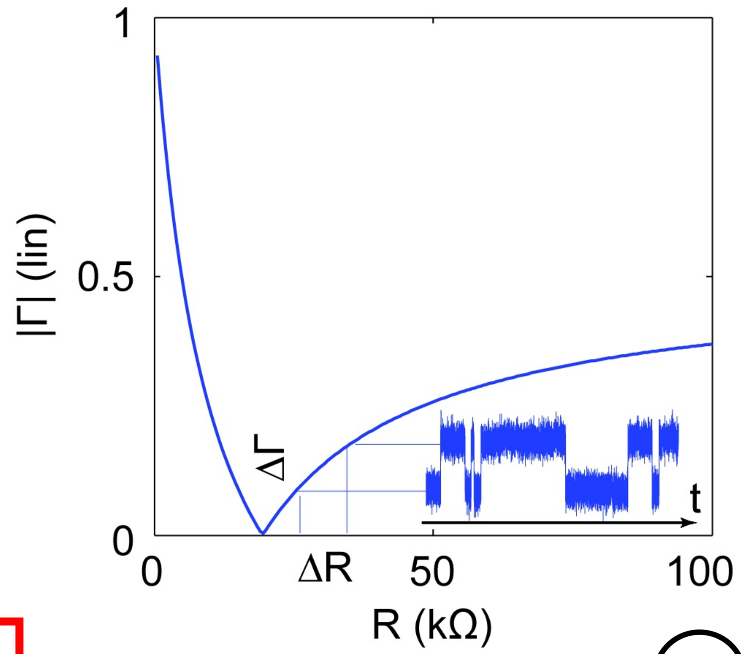
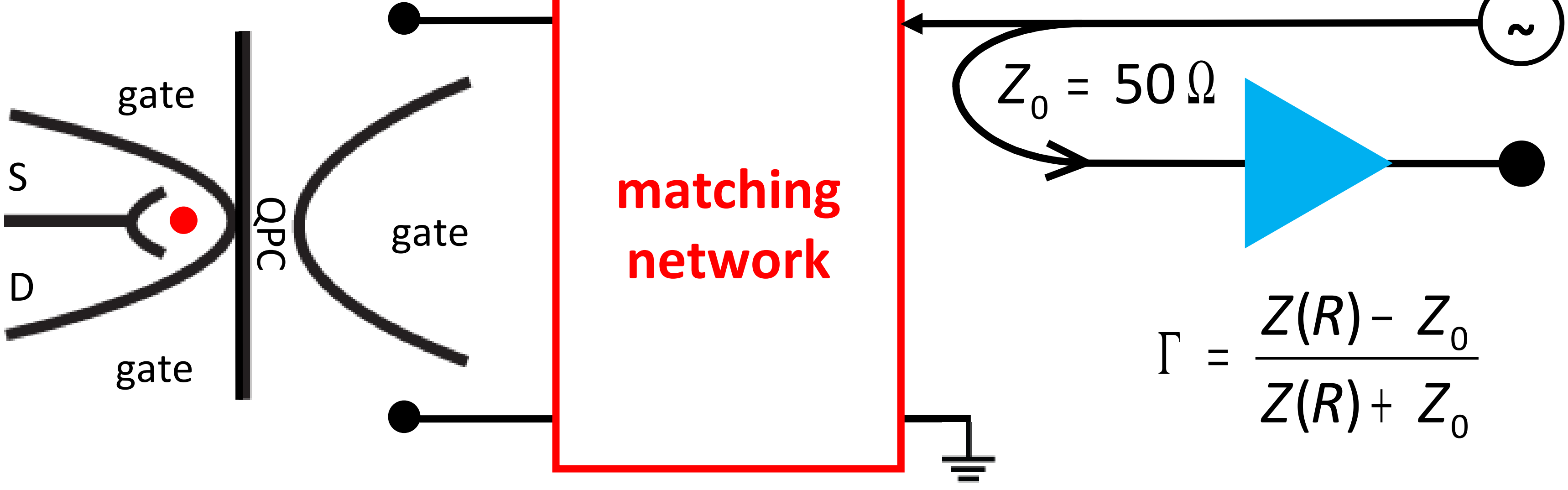


$$\Gamma = \frac{Z(R) - Z_0}{Z(R) + Z_0}$$

II. Reflection Coefficient Γ

Optimise ΔΓ(ΔR)



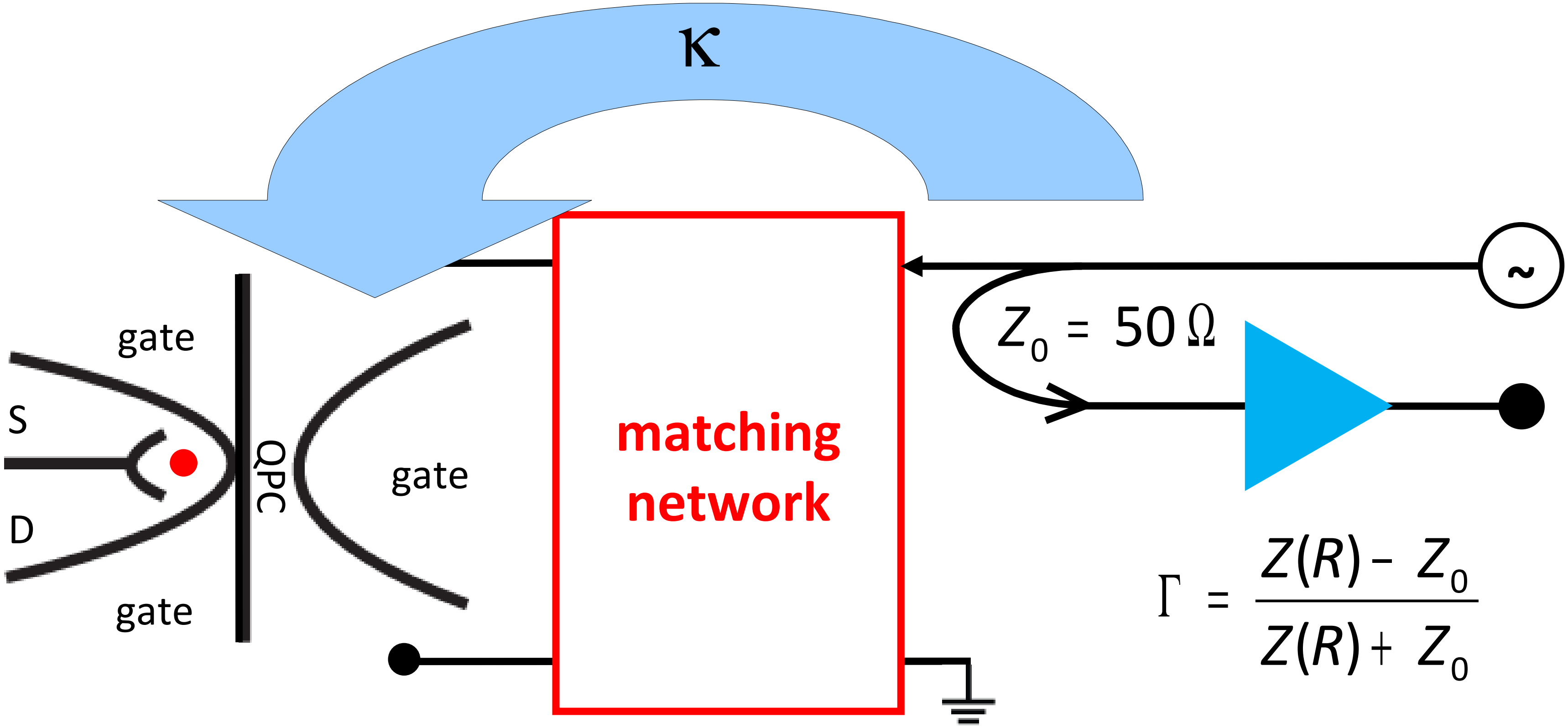


$$\Gamma = \frac{Z(R) - Z_0}{Z(R) + Z_0}$$

II. Signal-to-Noise Ratio

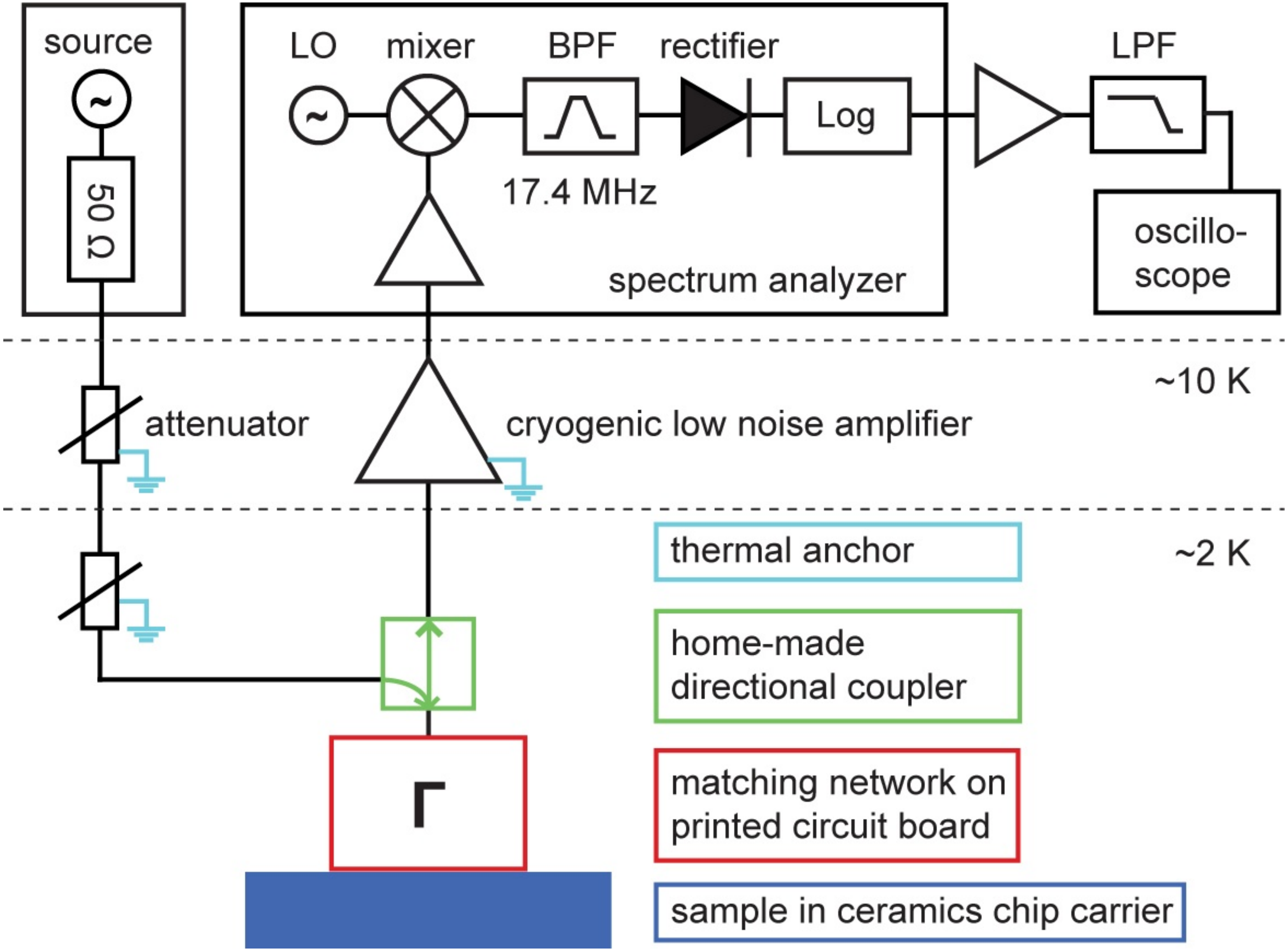
Optimise $\Delta\Gamma(\Delta R)$

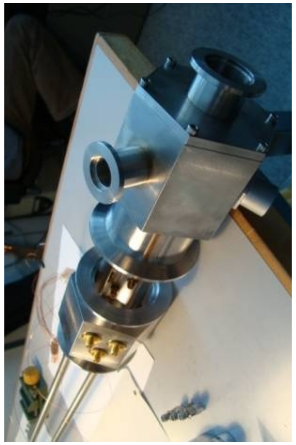
$$\Delta \Gamma = \kappa \, \Delta R / 2R$$

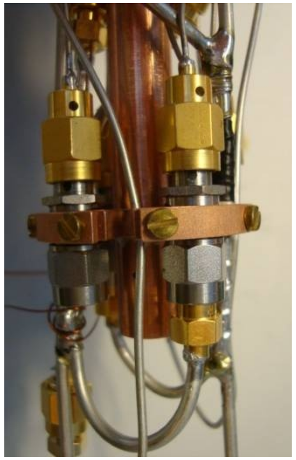


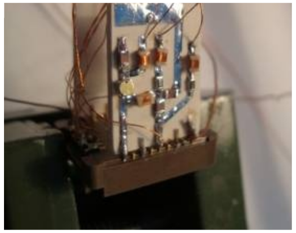
$$\Gamma = \frac{Z(R) - Z_0}{Z(R) + Z_0}$$

II. Schematic Measurement Setup

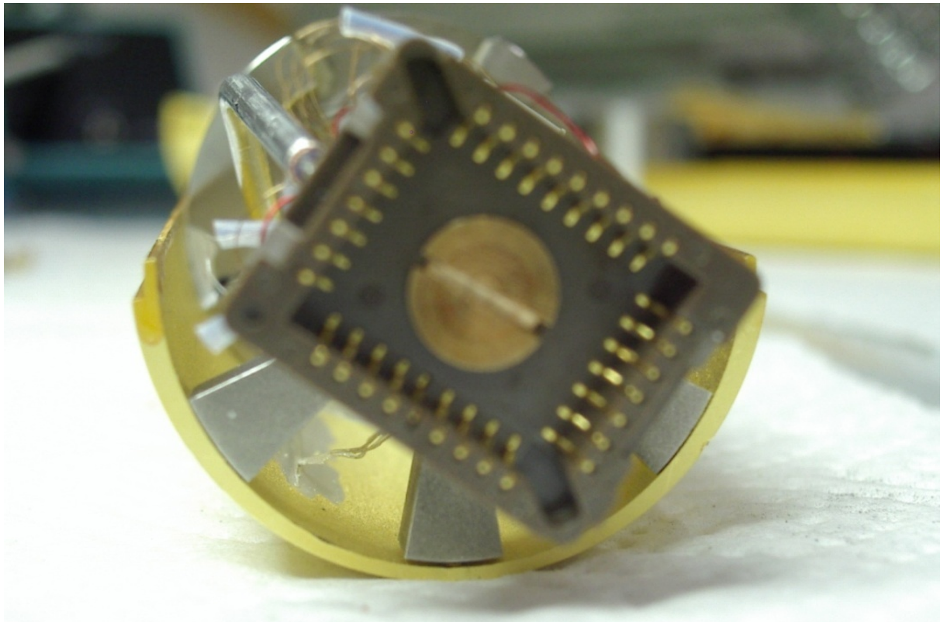


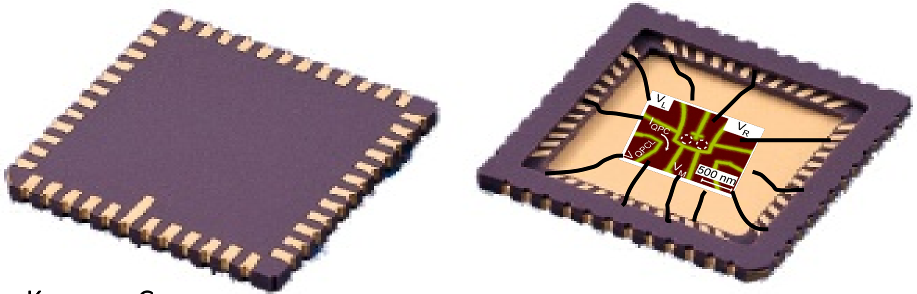




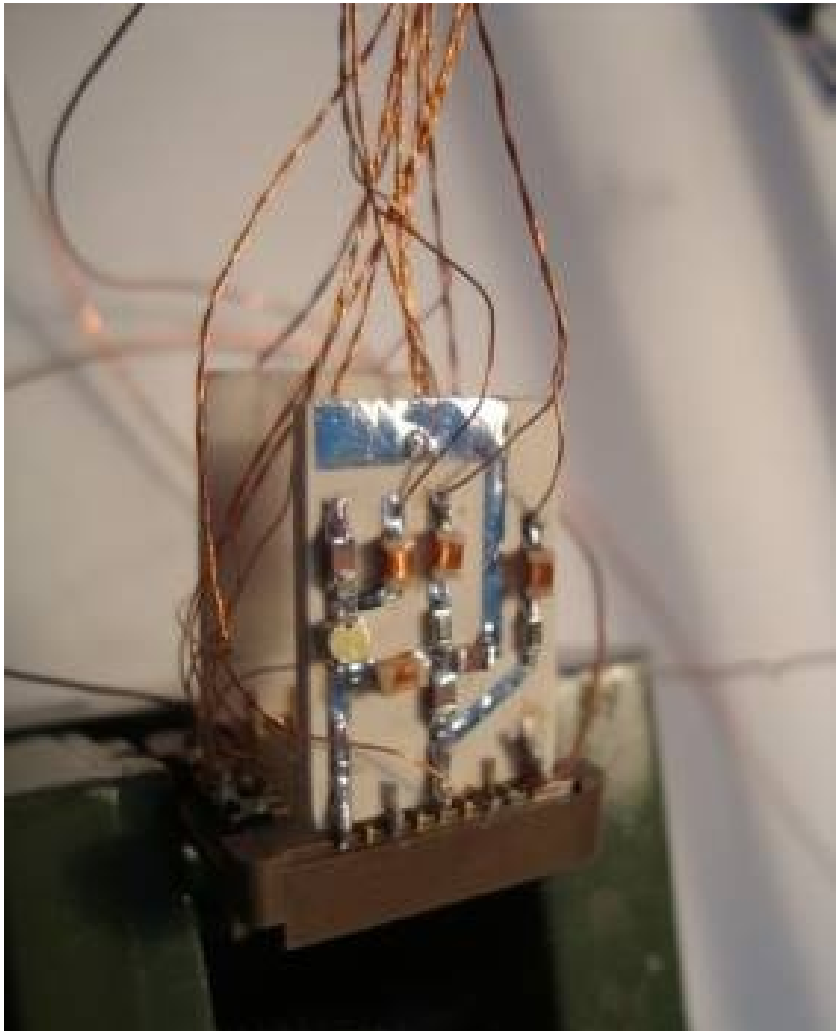


II. Chip Socket and Carrier





Kyocera Corp.



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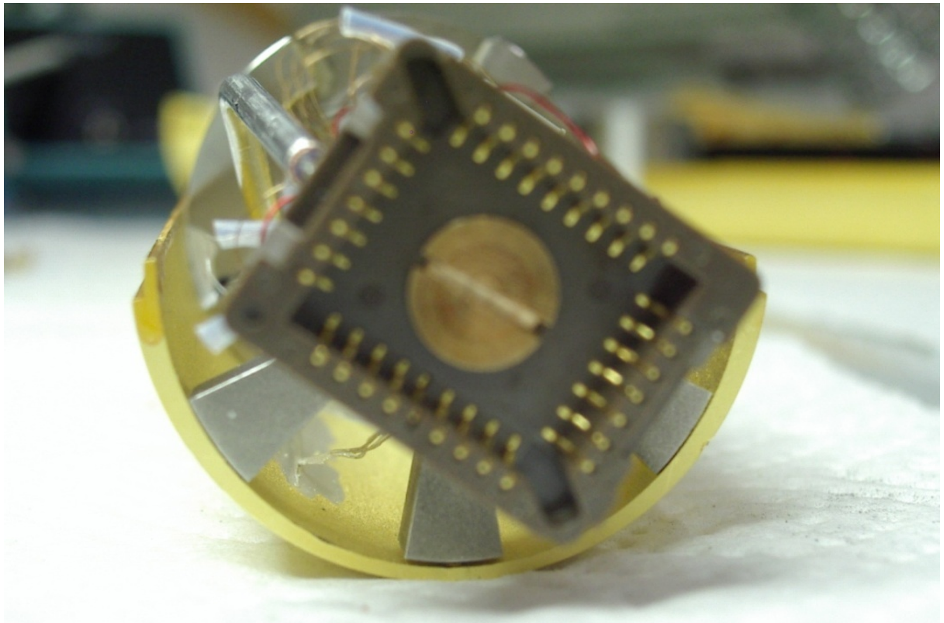

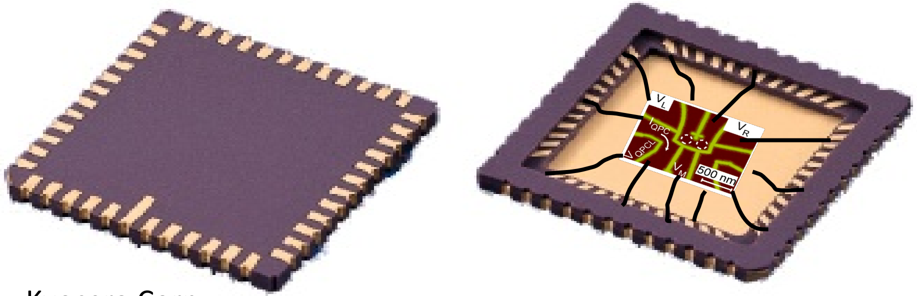

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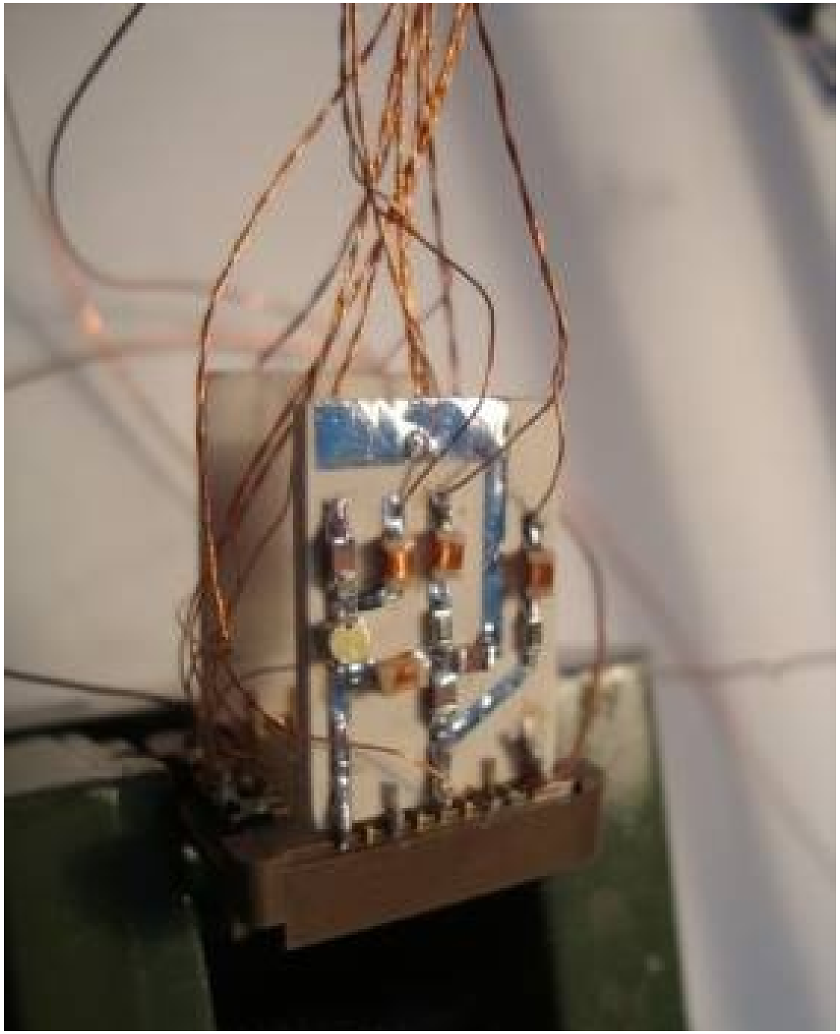
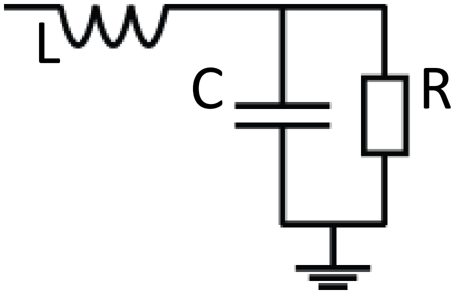


high versatility, but large stray capacitance (> 2 pF)

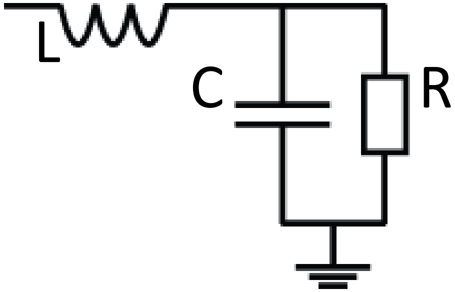
III. „Standard“ Matching Circuit



$$Z(\omega) = i\omega L + \frac{1}{1/R + i\omega C}$$

First used for rf SET reflectometry by Schoelkopf *et al.*, Science 1998

III. „Standard“ Matching Circuit



$$Z(\omega) = i\omega L + \frac{1}{1/R + i\omega C}$$

Matching condition : $\Gamma = \frac{Z - Z_0}{Z + Z_0} \approx 0$

$\mathrm{Re}(Z) = 50\,\Omega$

$\mathrm{Im}(Z) = 0\,\Omega$

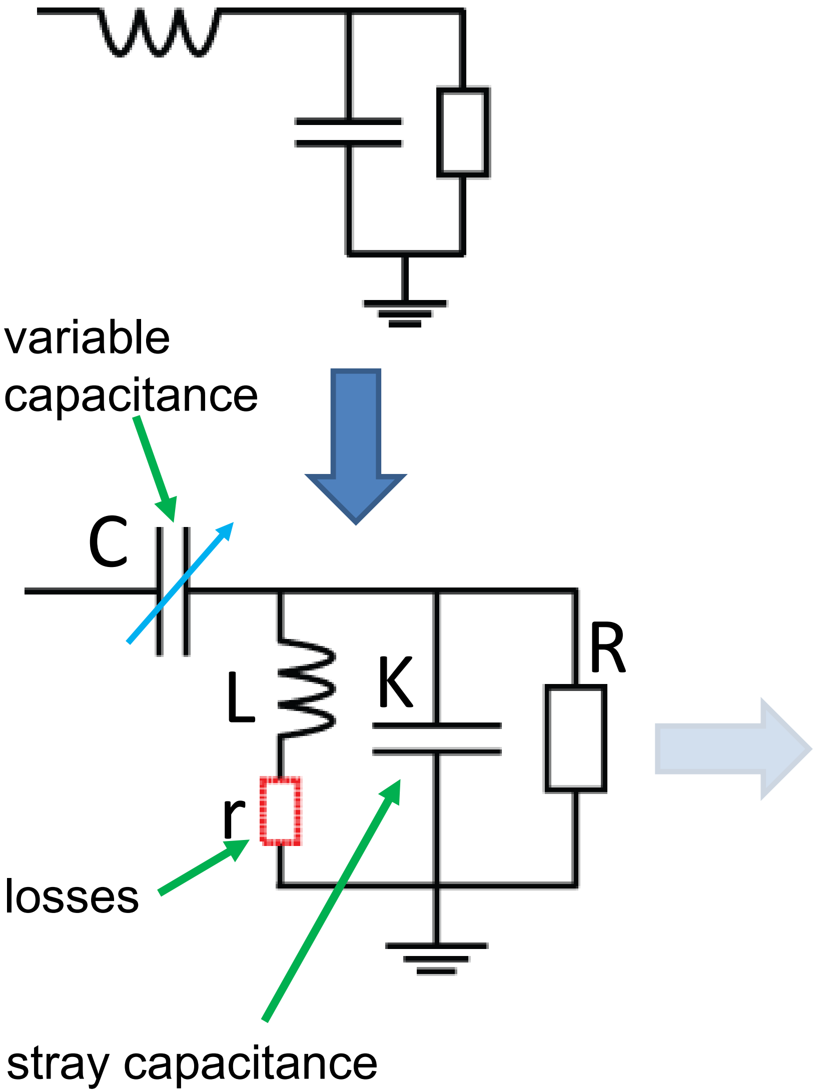
For $\omega = 2\pi \cdot 200\,\mathrm{MHz}$ and $R = 30\,\mathrm{k}\Omega$

$C \approx 0.65\,\mathrm{pF}$

$L \approx 1\,\mu\mathrm{H}$

First used for rf SET reflectometry by Schoelkopf *et al.*, Science 1998

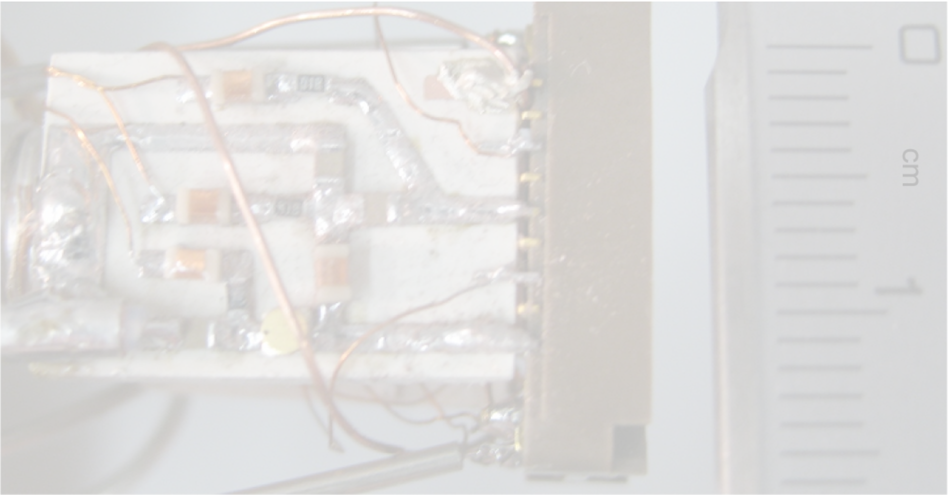
III. Our Circuit Design

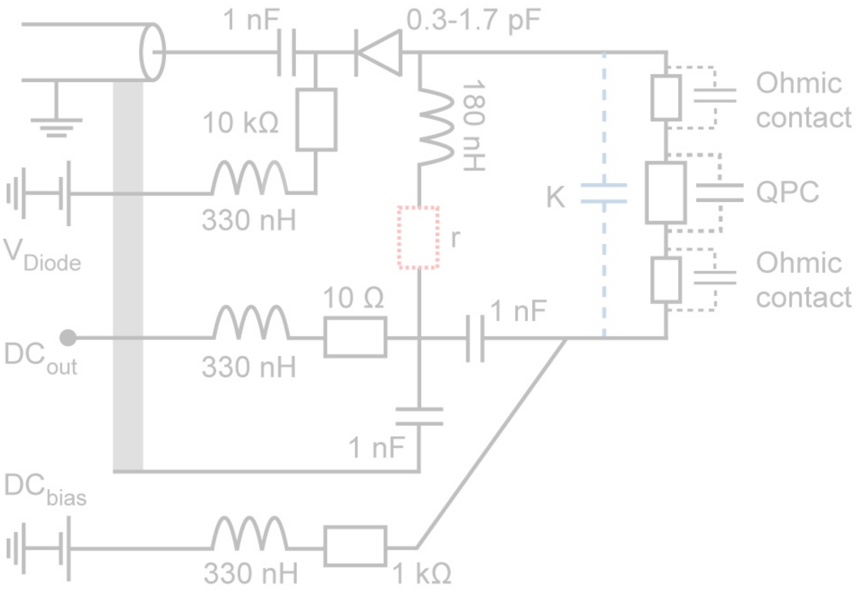


variable capacitance

losses

stray capacitance





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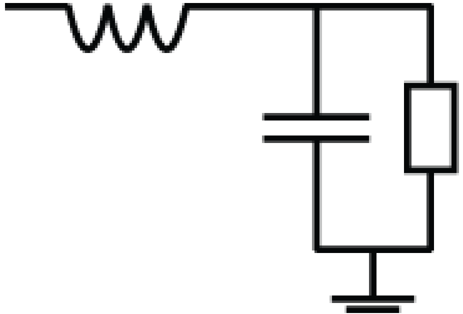

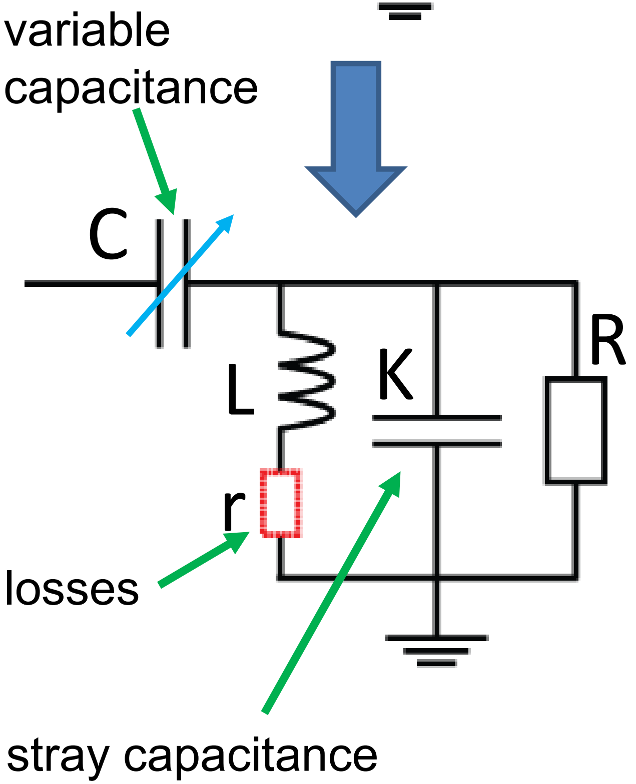

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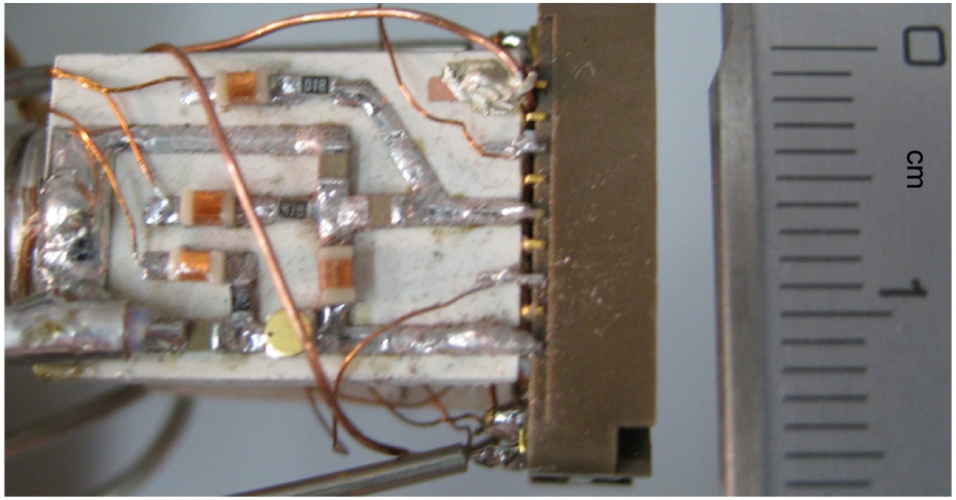

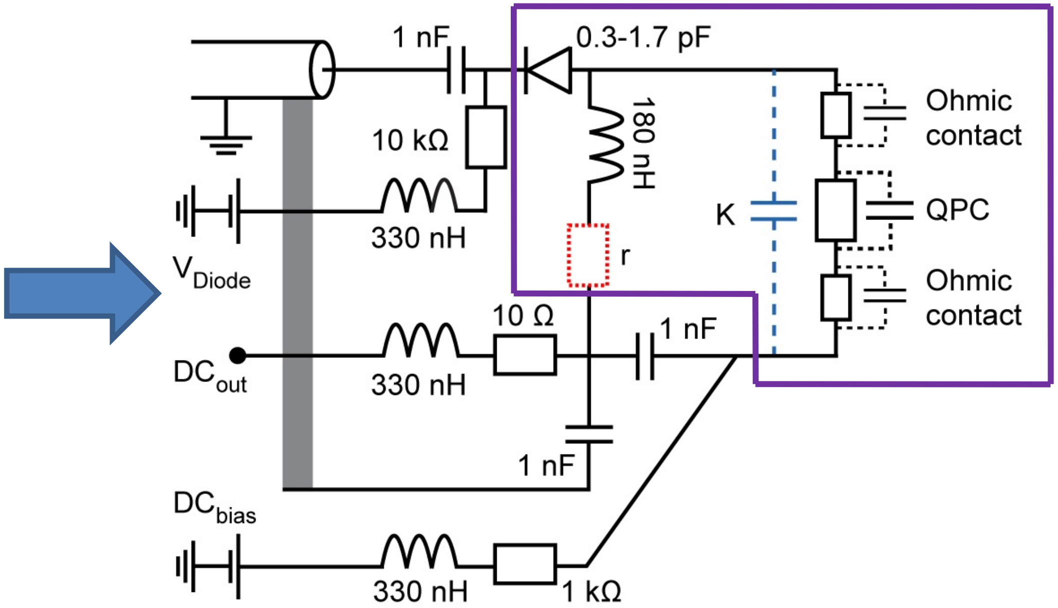

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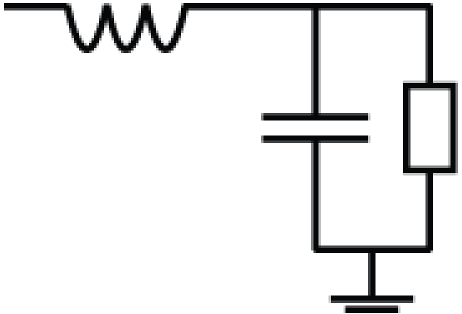

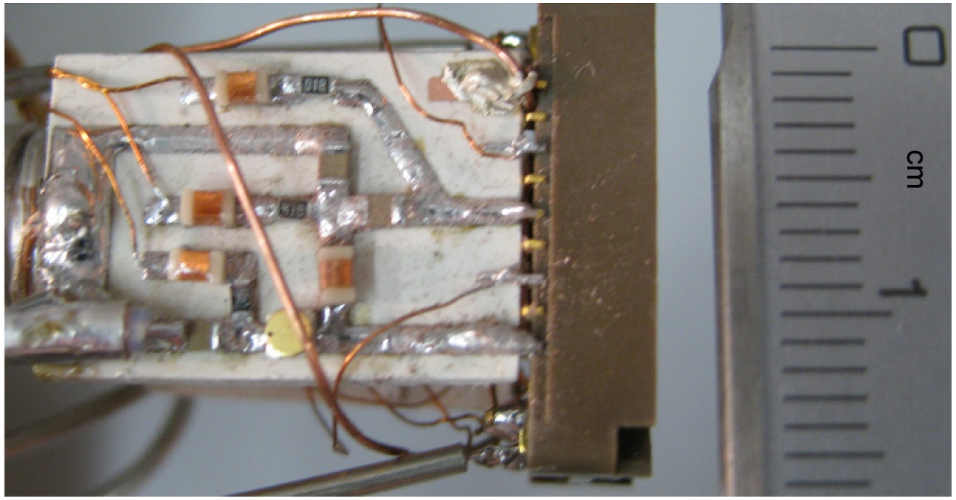

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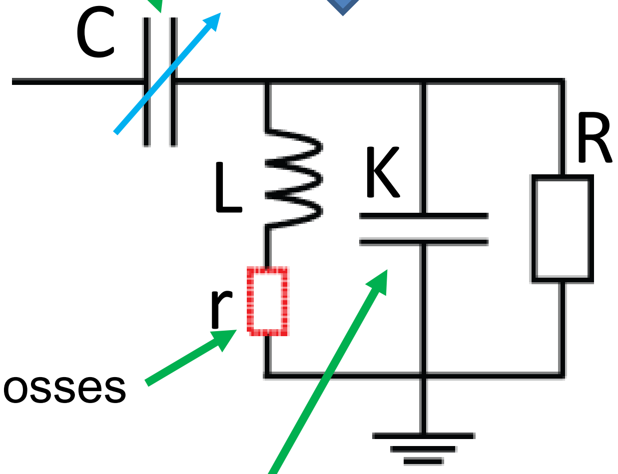
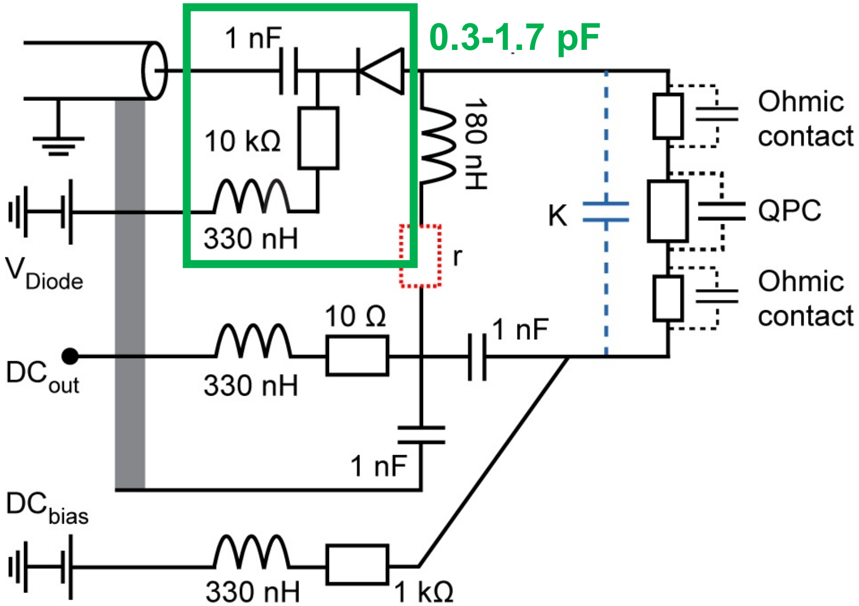


losses

stray capacitance



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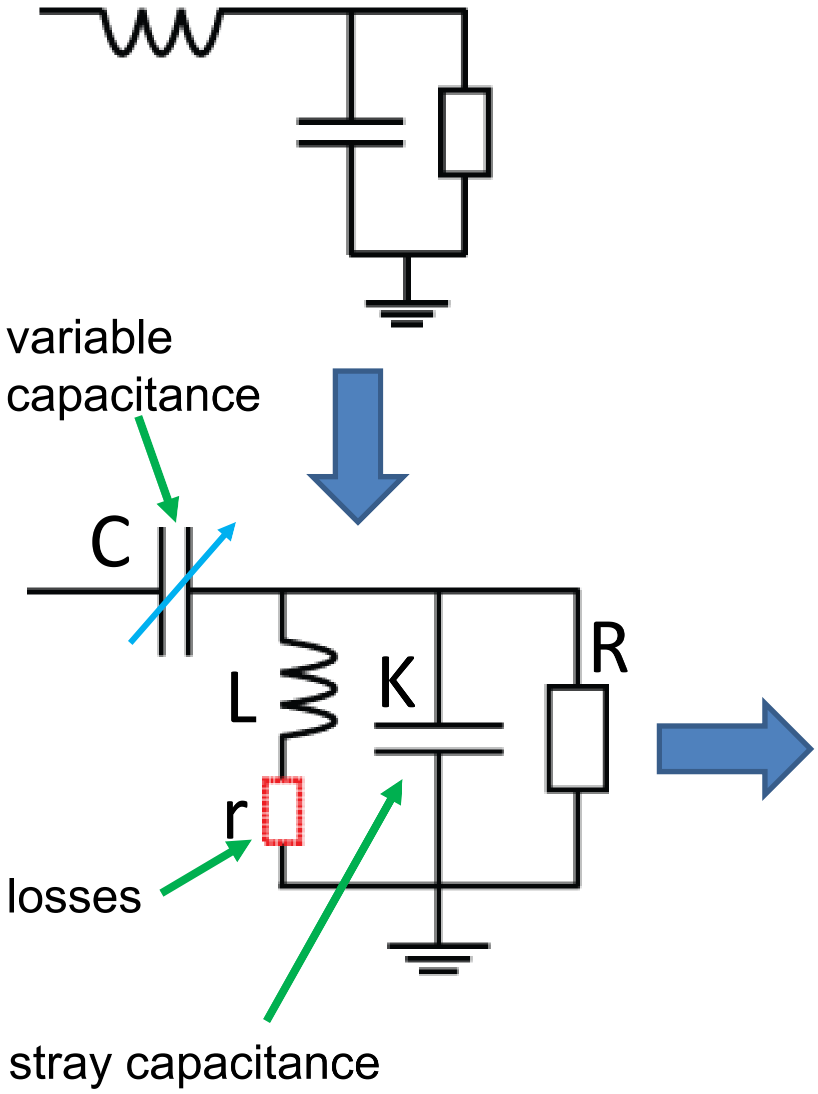

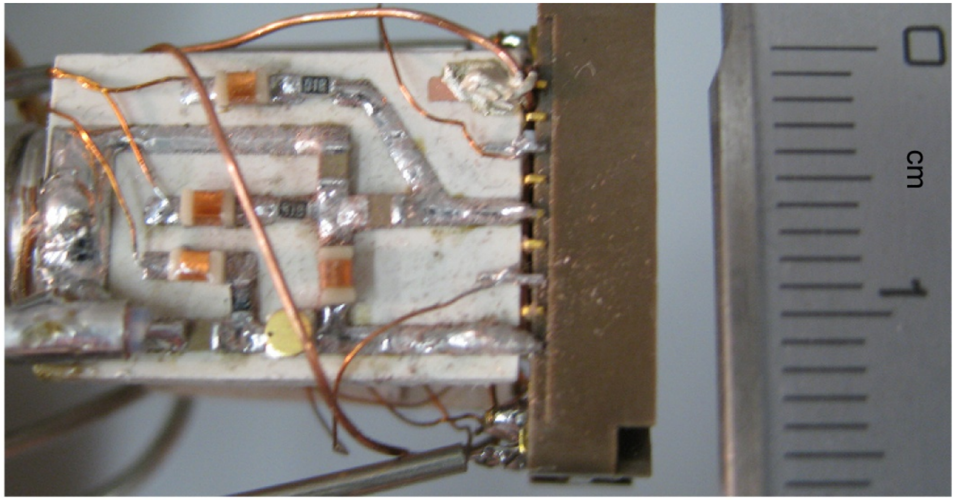

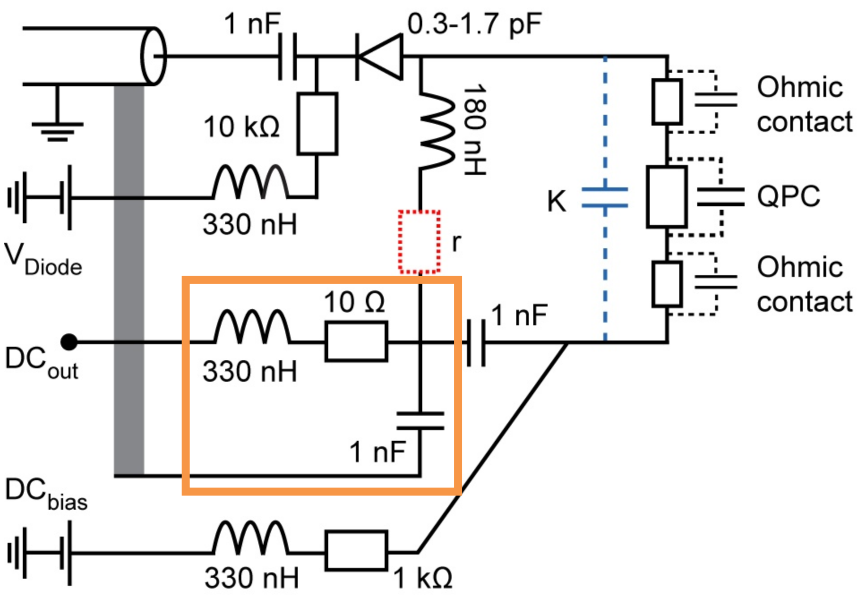

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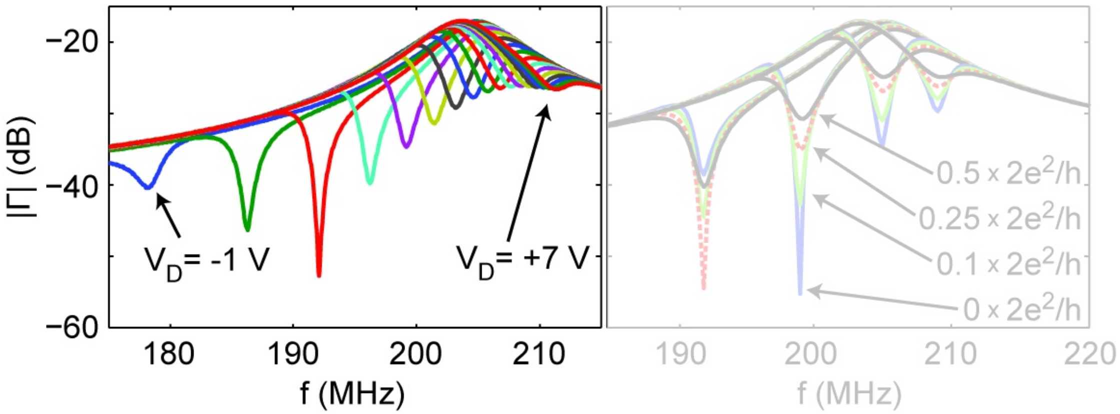
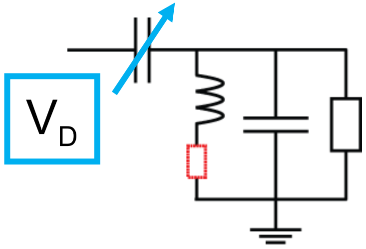
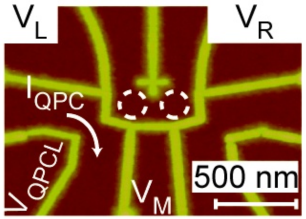


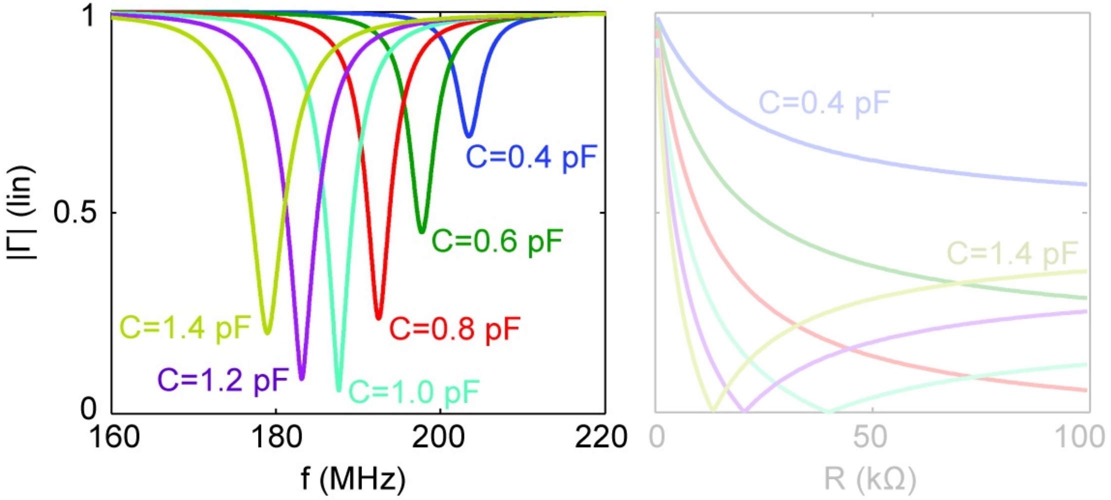
$$\Gamma = \frac{Z - Z_0}{Z + Z_0}$$





Sample processing:
B. Küng

Calculation:



$K = 3$ pF

$L = 180$ nH

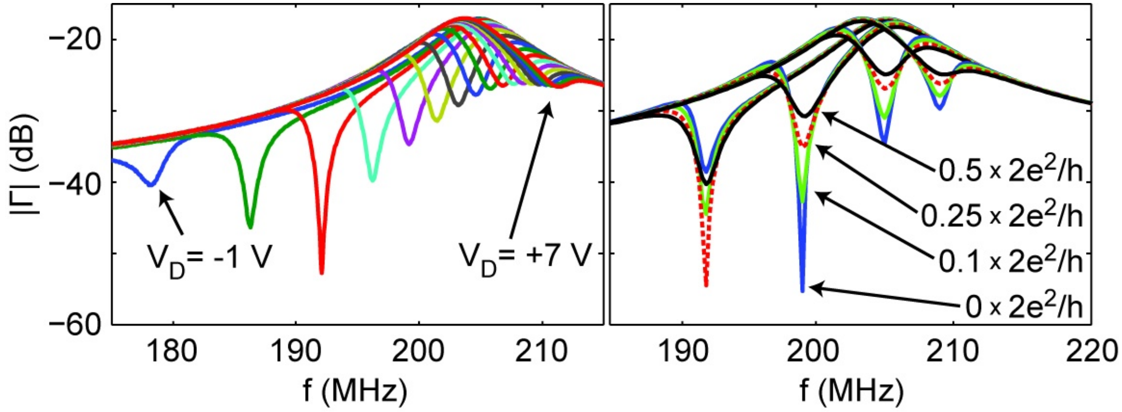
$r = 2\ \Omega$

$R = 30$ kΩ

$$f_{res} \approx \frac{1}{2\pi\sqrt{L(C + K)}}$$

APL **97**, 202104 (2010)

III. Experimental Realisation



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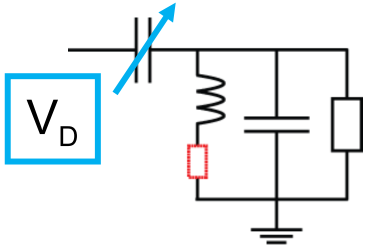

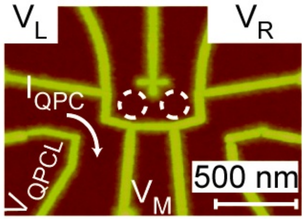

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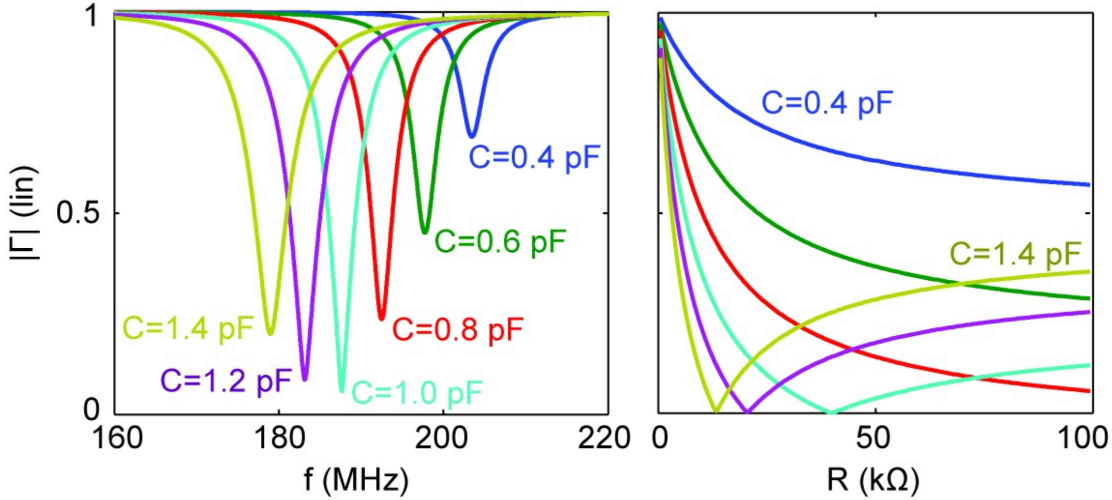

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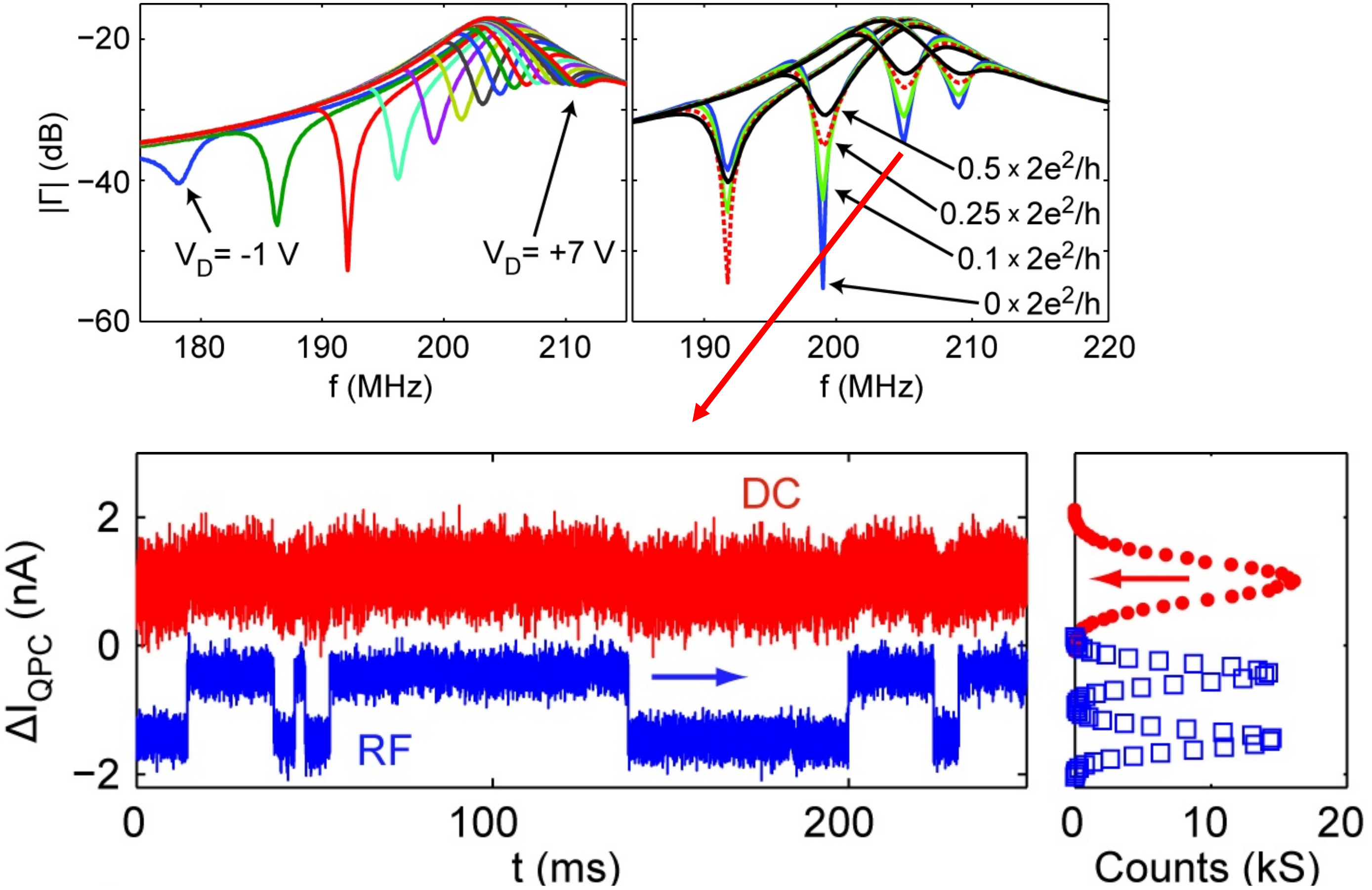

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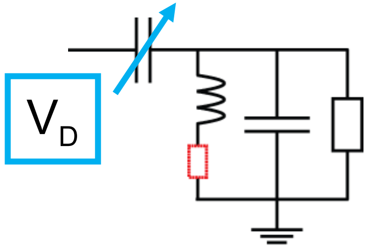
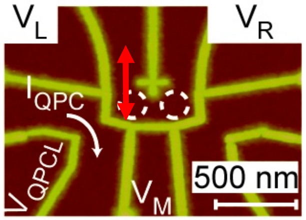




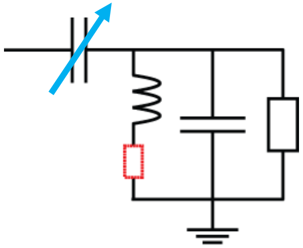
Sample processing:
B. Küng

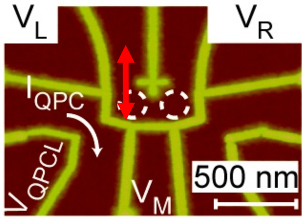
T = 2 K
50 kHz BW
$\Delta G = 0.01\ 2e^2/h \rightarrow \Delta I = 300$ pA

APL **97**, 202104 (2010)

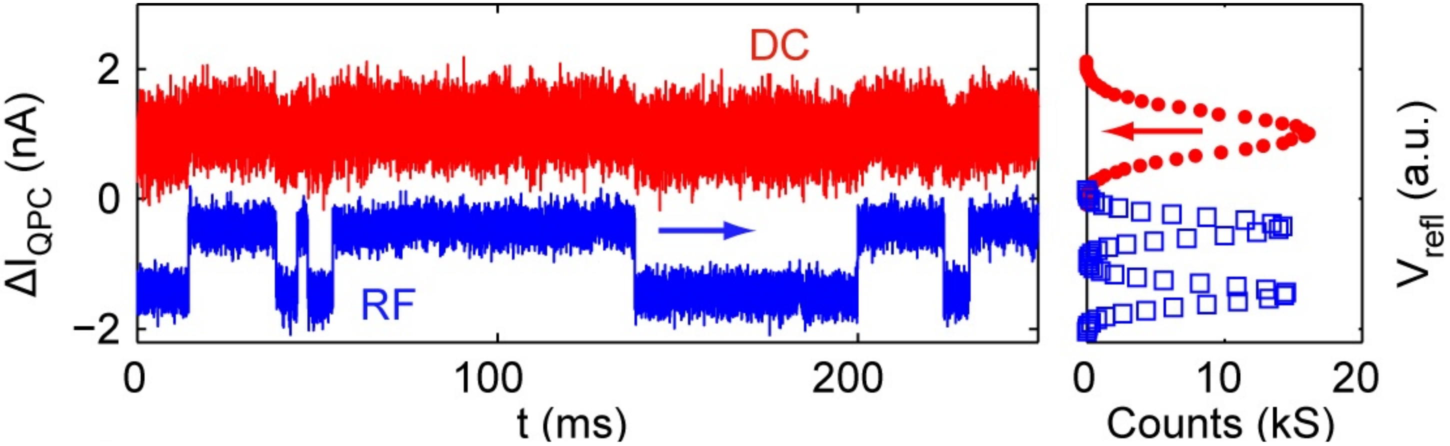
III. Experimental Realisation

✓*In situ*-tunable rf reflectometry setup
✓Performs significantly better than dc





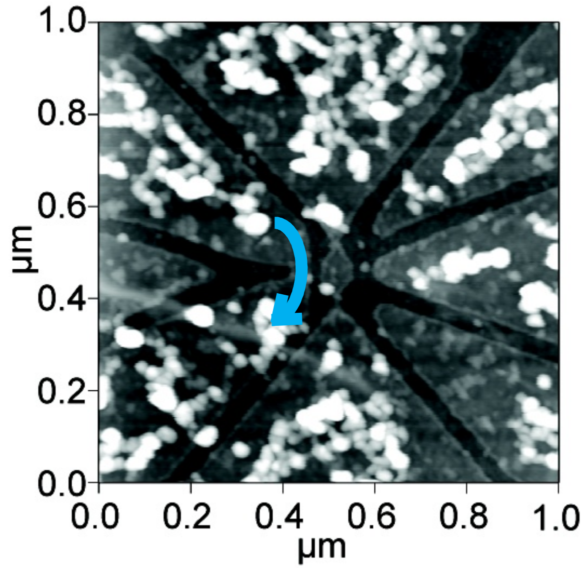
Sample processing:
B. Küng

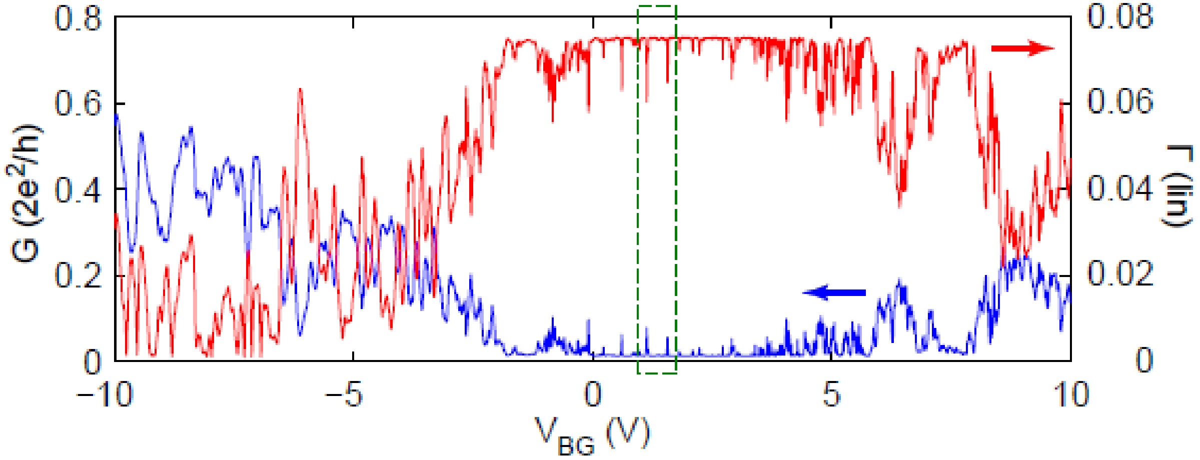


T = 2 K
50 kHz BW
$\Delta G = 0.01\ 2e^2/h \rightarrow \Delta I = 300$ pA

APL **97**, 202104 (2010)

IV. Graphene QD and Charge Detector





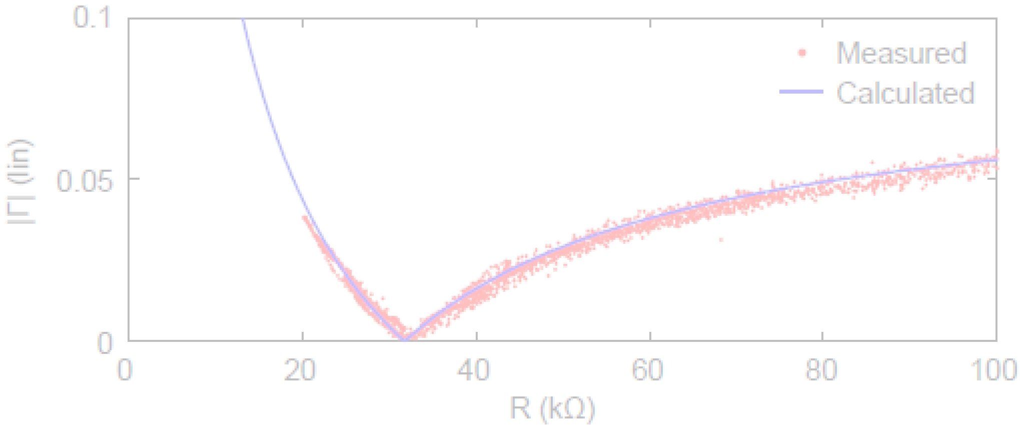
d_{dot} = 80 nm

$w_{barrier}$ ~ 25 nm

$w_{constriction}$ = 45 nm

$d_{dot\text{-}constriction}$ = 15 nm

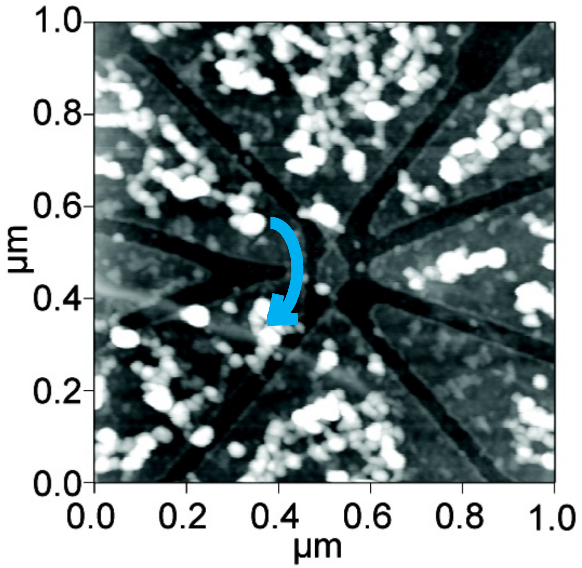
$C_{bondpad}$ ~ 0.5 pF

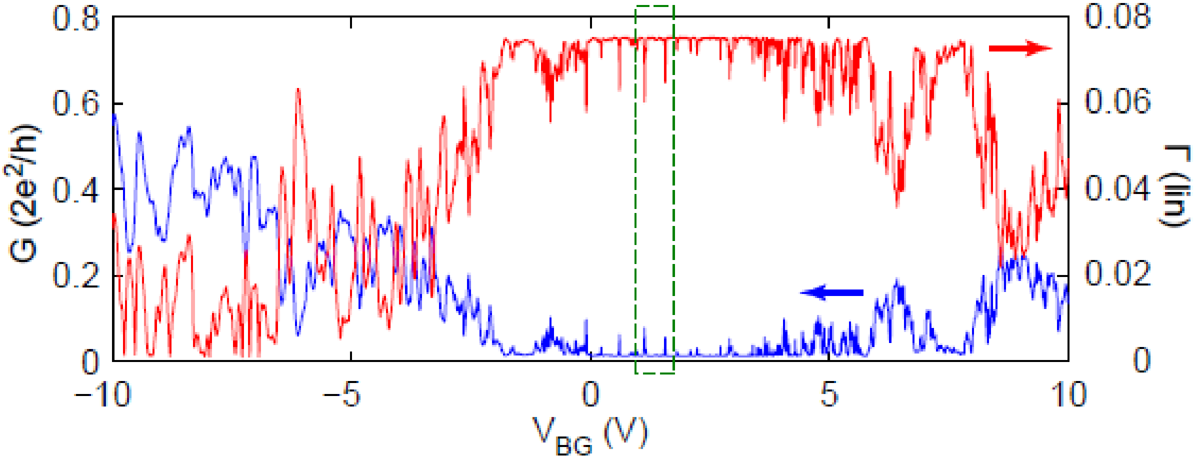


C = 1.2 pF, K = 3.3 pF, L = 100 nH, and r = 3.6 Ω, f = 232 MHz

Sample processing:
J. Güttinger, D. Bischoff

IV. Graphene QD and Charge Detector





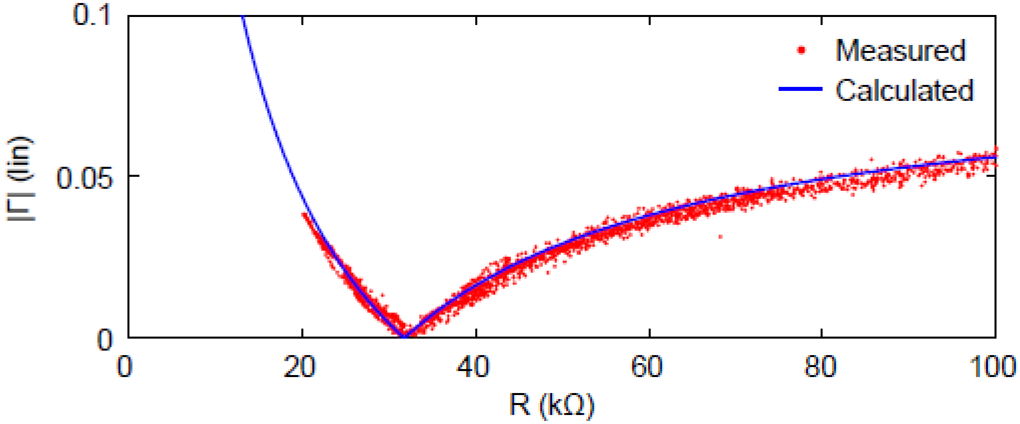
d_{dot} = 80 nm

$w_{barrier}$ ~ 25 nm

$w_{constriction}$ = 45 nm

$d_{dot\text{-}constriction}$ = 15 nm

$C_{bondpad}$ ~ 0.5 pF



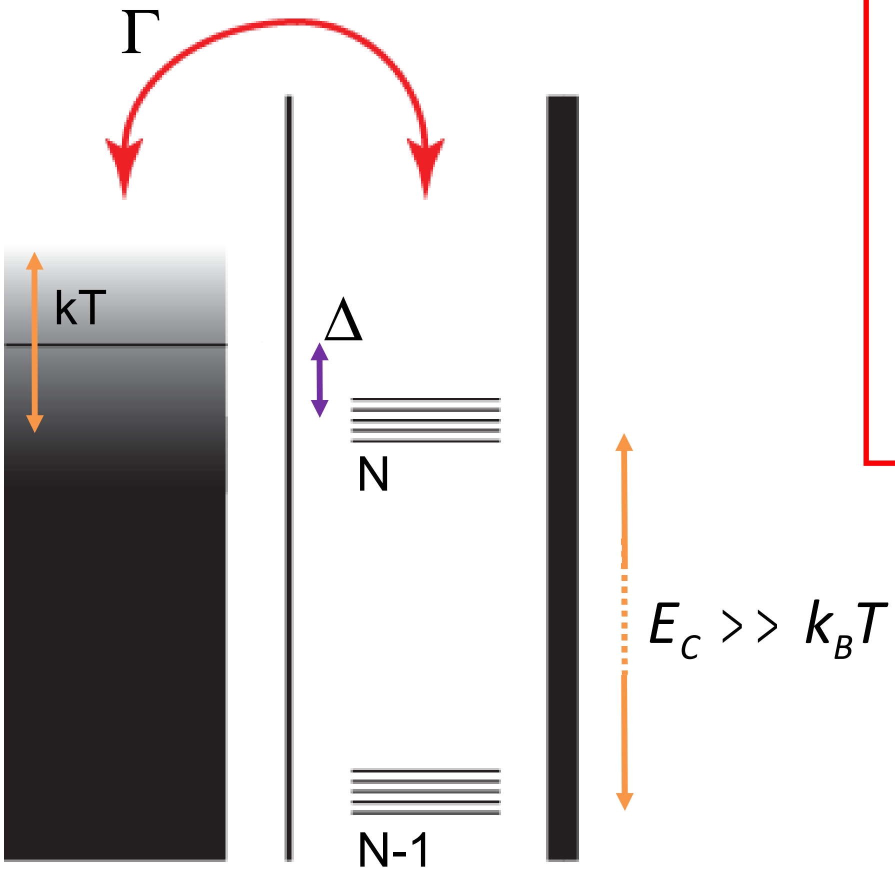
C = 1.2 pF, K = 3.3 pF, L = 100 nH, and r = 3.6 Ω, f = 232 MHz

Sample processing:
J. Güttinger, D. Bischoff

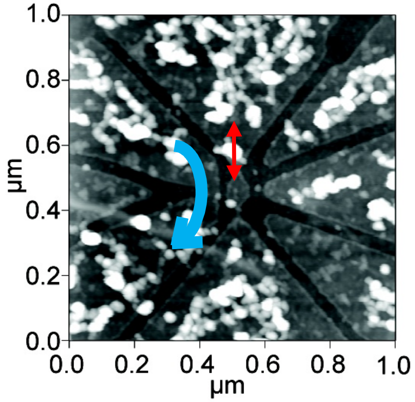
IV. Multi-Level Tunneling to a Single Lead

$$\Gamma_{in} = \sum_p \Gamma_p \left[1 - F_{eq}\left(E_p \middle| N-1\right)\right] \cdot f\left(E_p + U(N) - U(N-1) - E_F\right)$$

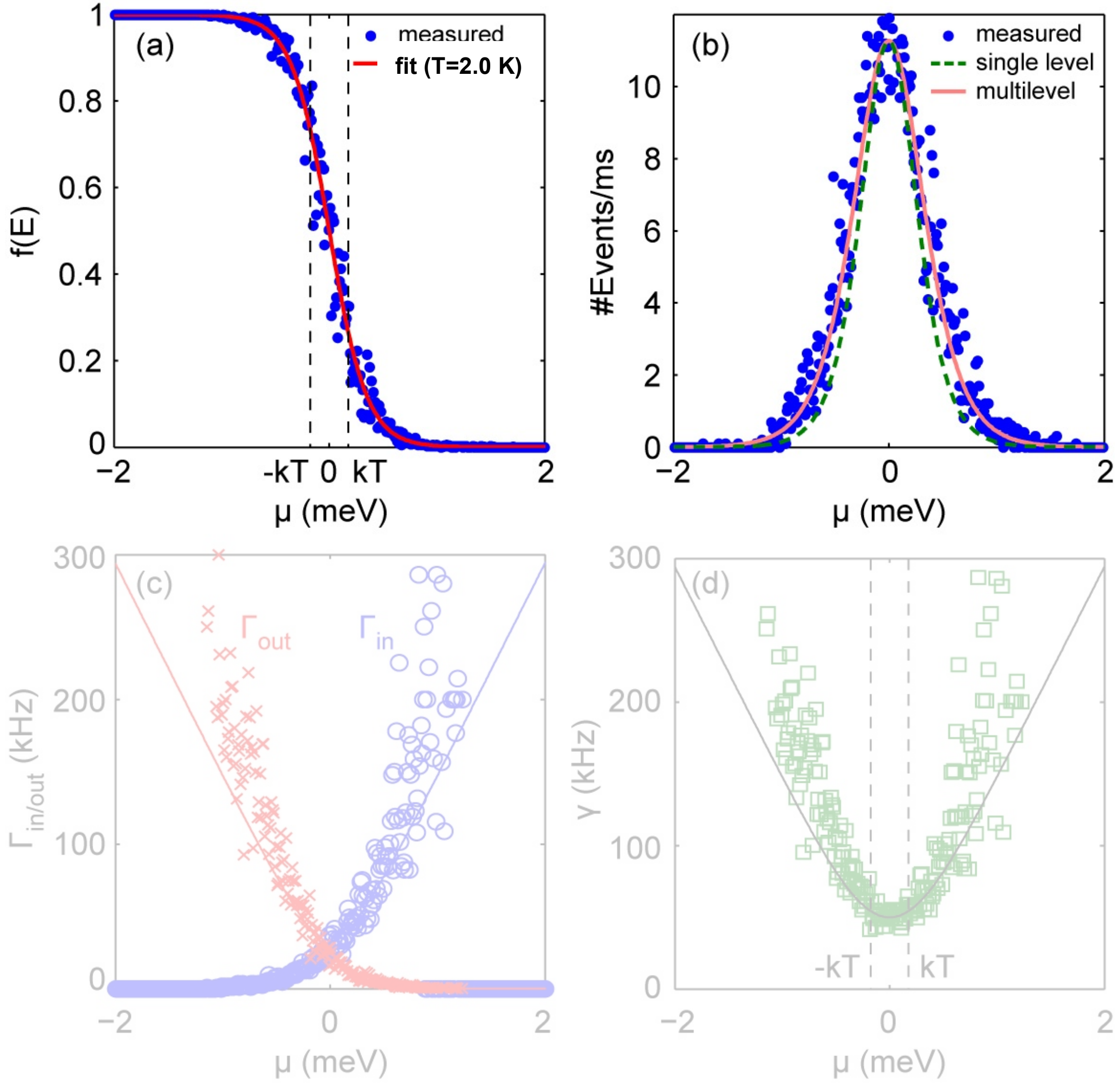
Beenakker, PRB 1991

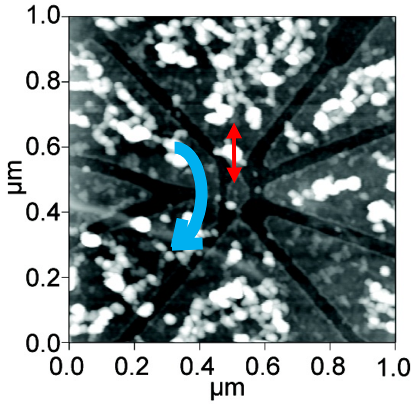


$$\boxed{\begin{aligned} \Gamma_{in} &\approx \rho \cdot \Gamma \cdot \frac{-\Delta}{1 - \exp\left(\Delta / k_BT\right)} \\ \Gamma_{out} &\approx \rho \cdot \Gamma \cdot \frac{\Delta}{1 - \exp\left(-\Delta / k_BT\right)} \end{aligned}}$$



IV. Measurement of Temperature





T = 2 K

200 kHz BW

$$\Gamma_{in} \approx \rho \cdot \Gamma \cdot \frac{-\Delta}{1-\exp\left(\Delta / k_B T\right)}$$

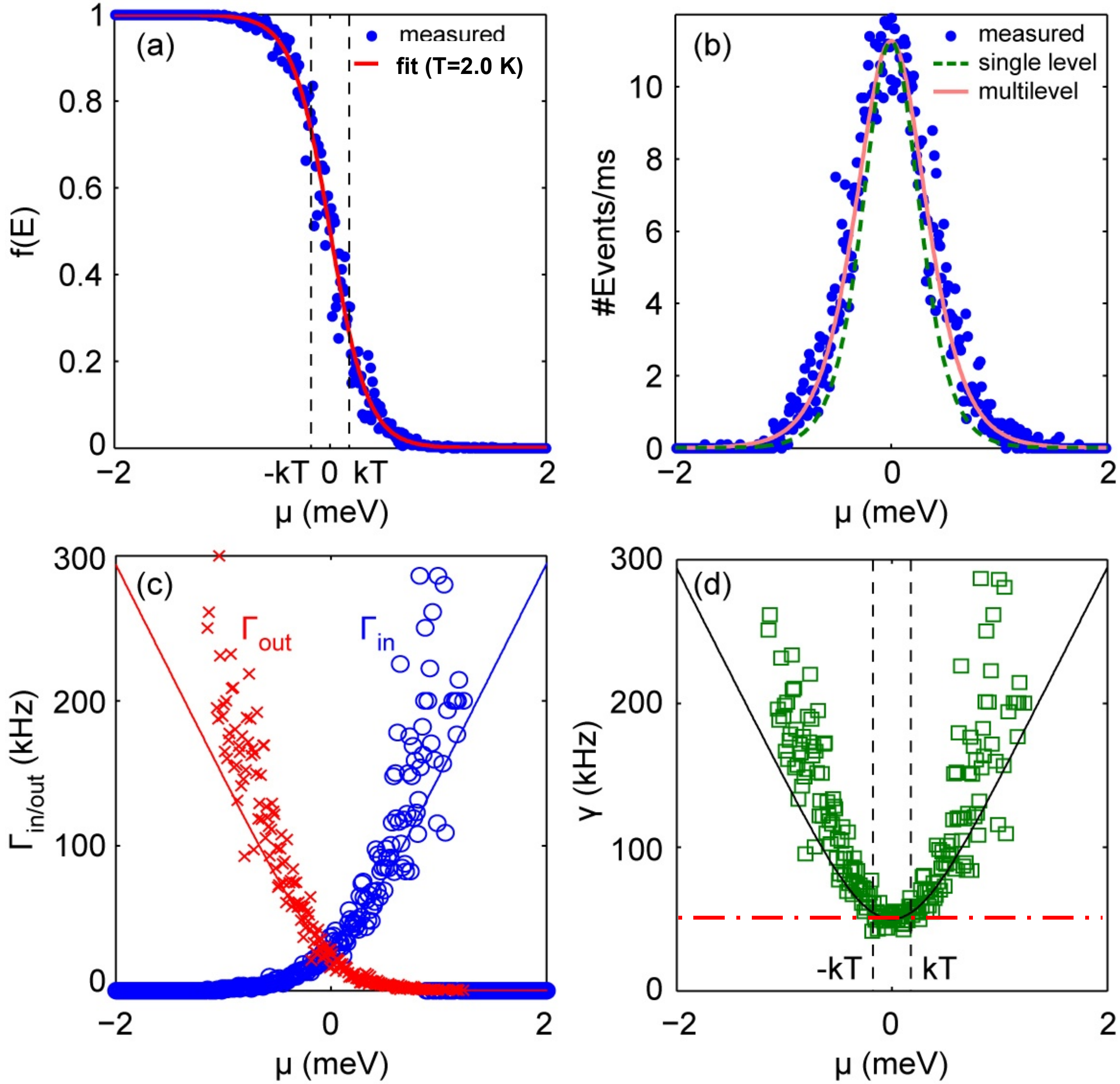
$$\Gamma_{out} \approx \rho \cdot \Gamma \cdot \frac{\Delta}{1-\exp\left(-\Delta / k_B T\right)}$$

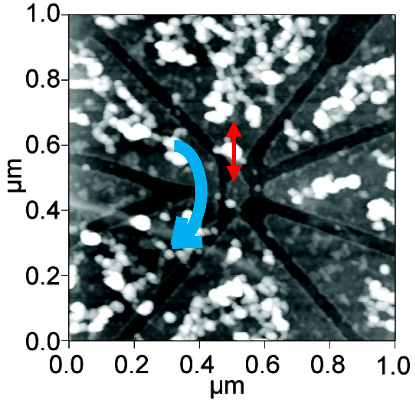
$$\Delta = -\mu$$

$$\gamma = \Gamma_{in} + \Gamma_{out}$$

APL **191**, 012104 (2012)

IV. Measurement of Tunnel Rates





T = 2 K
200 kHz BW

$$\Gamma_{in} \approx \rho \cdot \Gamma \cdot \frac{-\Delta}{1-\exp\left(\Delta / k_B T\right)}$$

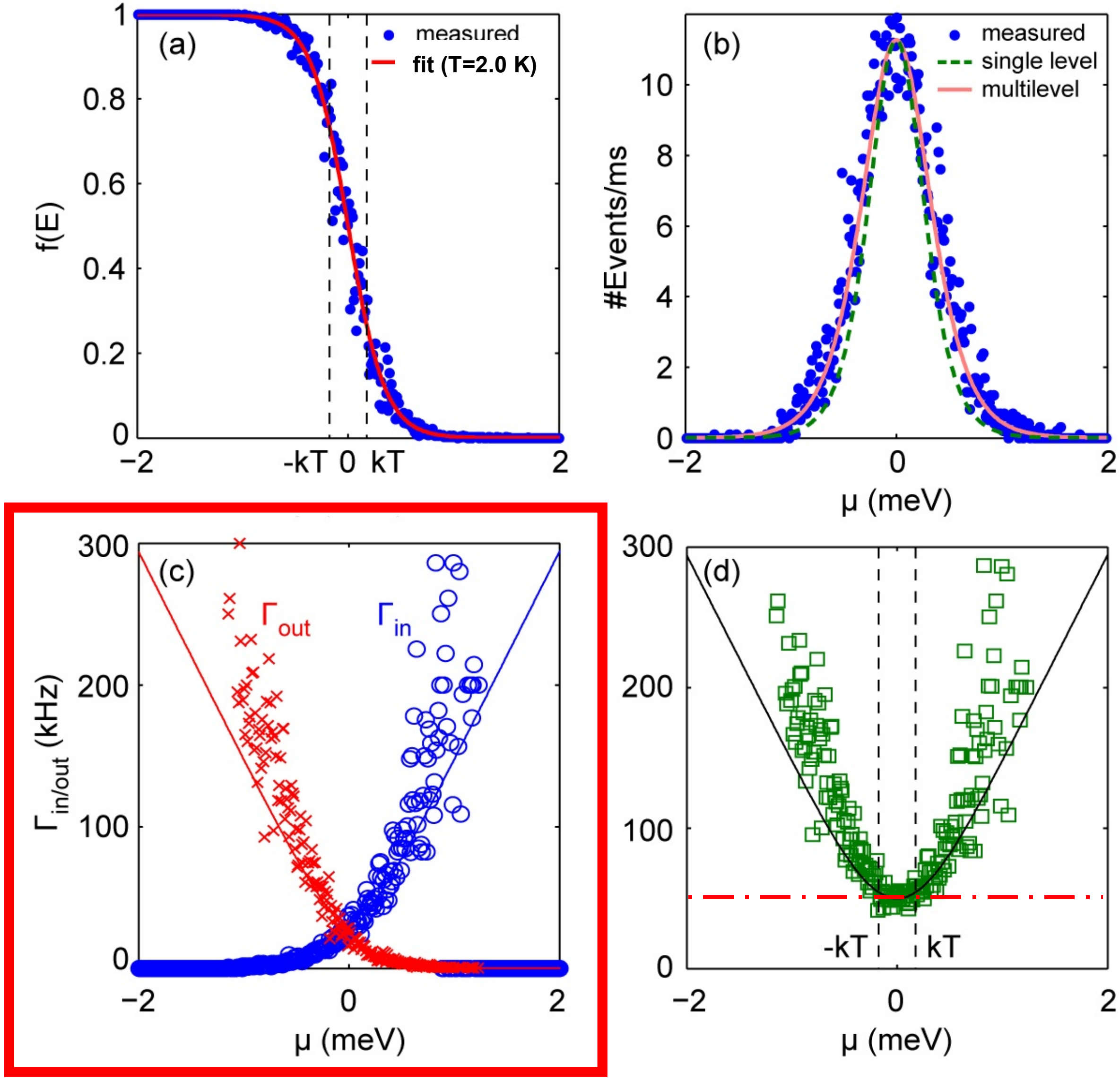
$$\Gamma_{out} \approx \rho \cdot \Gamma \cdot \frac{\Delta}{1-\exp\left(-\Delta / k_B T\right)}$$

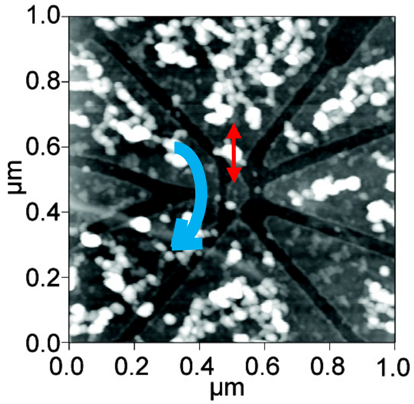
$$\Delta = -\mu$$

$$\gamma = \Gamma_{in} + \Gamma_{out}$$

APL **191**, 012104 (2012)

IV. Measurement of Tunnel Rates





T = 2 K
200 kHz BW

$$\Gamma_{in} \approx \rho \cdot \Gamma \cdot \frac{-\Delta}{1-\exp\left(\Delta / k_B T\right)}$$

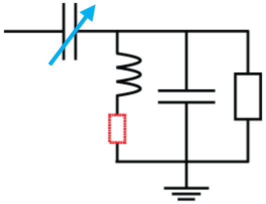
$$\Gamma_{out} \approx \rho \cdot \Gamma \cdot \frac{\Delta}{1-\exp\left(-\Delta / k_B T\right)}$$

$$\Delta = -\mu$$

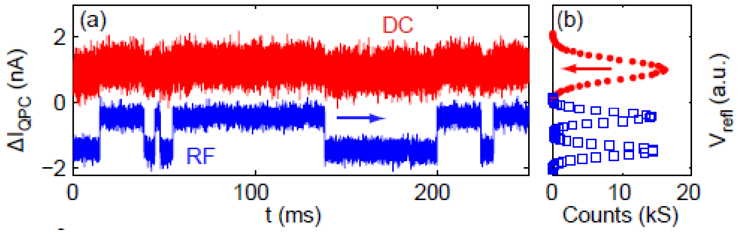
$$\gamma = \Gamma_{in} + \Gamma_{out}$$

APL **191**, 012104 (2012)

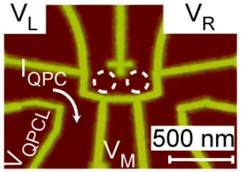
V. Conclusion

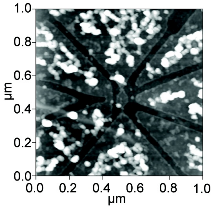


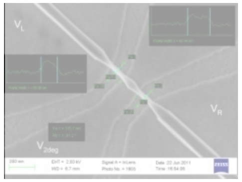
High-performance *in situ*-tunable matching network



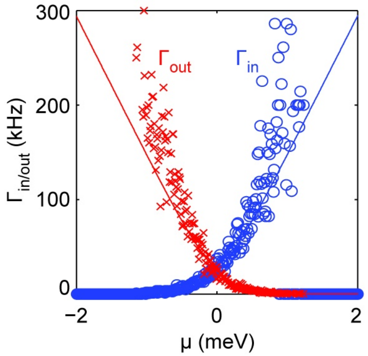
Measurements on different types of material systems

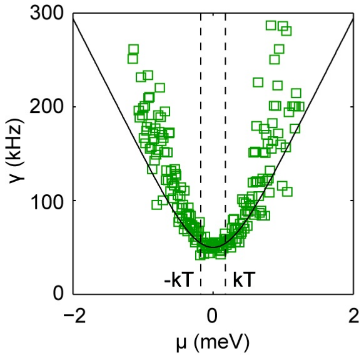






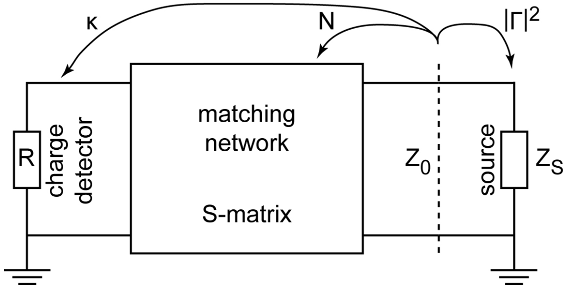
Determination of tunnel rates to a single lead in a multi-level regime



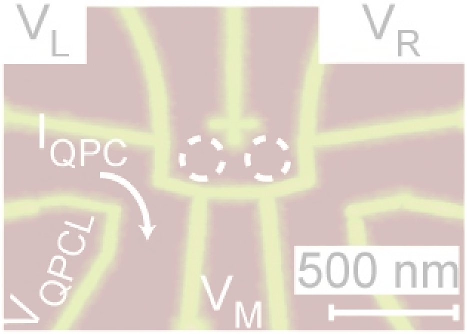


VI. Outlook

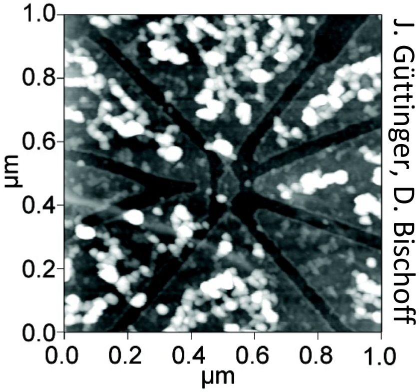
Lower temperatures for better performance



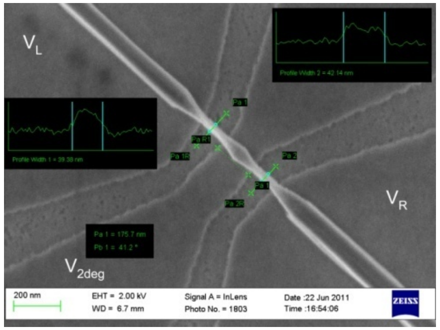
Study charge transport in „exotic“ material systems (graphene, InAs, p-GaAs)



B. Küng

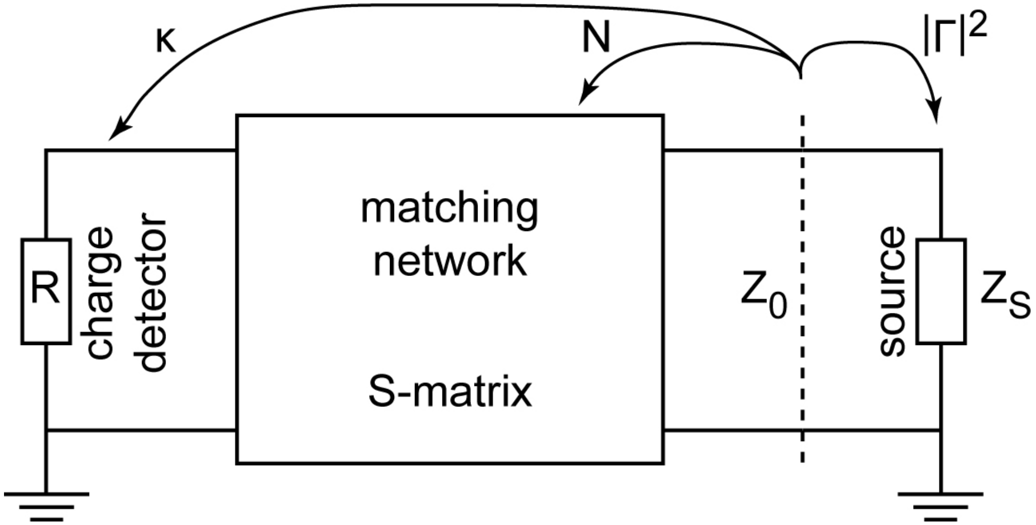


J. Güttinger, D. Bischoff



T. Choi

VII. Appendix: Power Transfer and Noise



$$T_\Sigma = T_N + \kappa T_{QPC} + N T_{circ}$$

$$\approx 2 - 15\,\mathrm{K} + \frac{1}{3}\cdot 2\,K + \frac{2}{3}\cdot 5\,\mathrm{K}$$

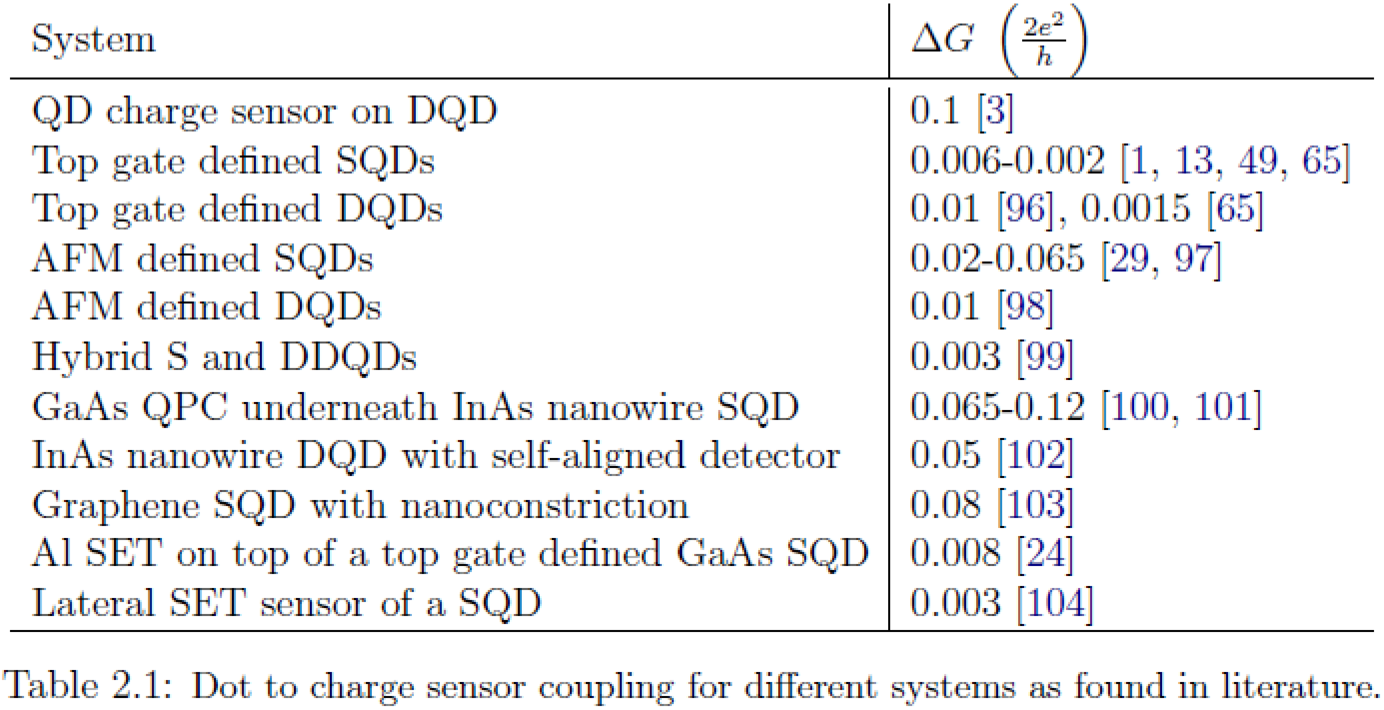
$$\approx 6 - 20\,\mathrm{K}$$

$$\Delta\Gamma = \frac{\Delta R}{R}\cdot\kappa$$

$$\text{Signal} \propto \left(\Delta\Gamma\cdot V_{in}\right)^2 \propto \frac{\Delta\Gamma^2}{\kappa\cdot R} \propto \Delta G^2$$

Figure adapted from Roschier *et al.*, JAP 2004

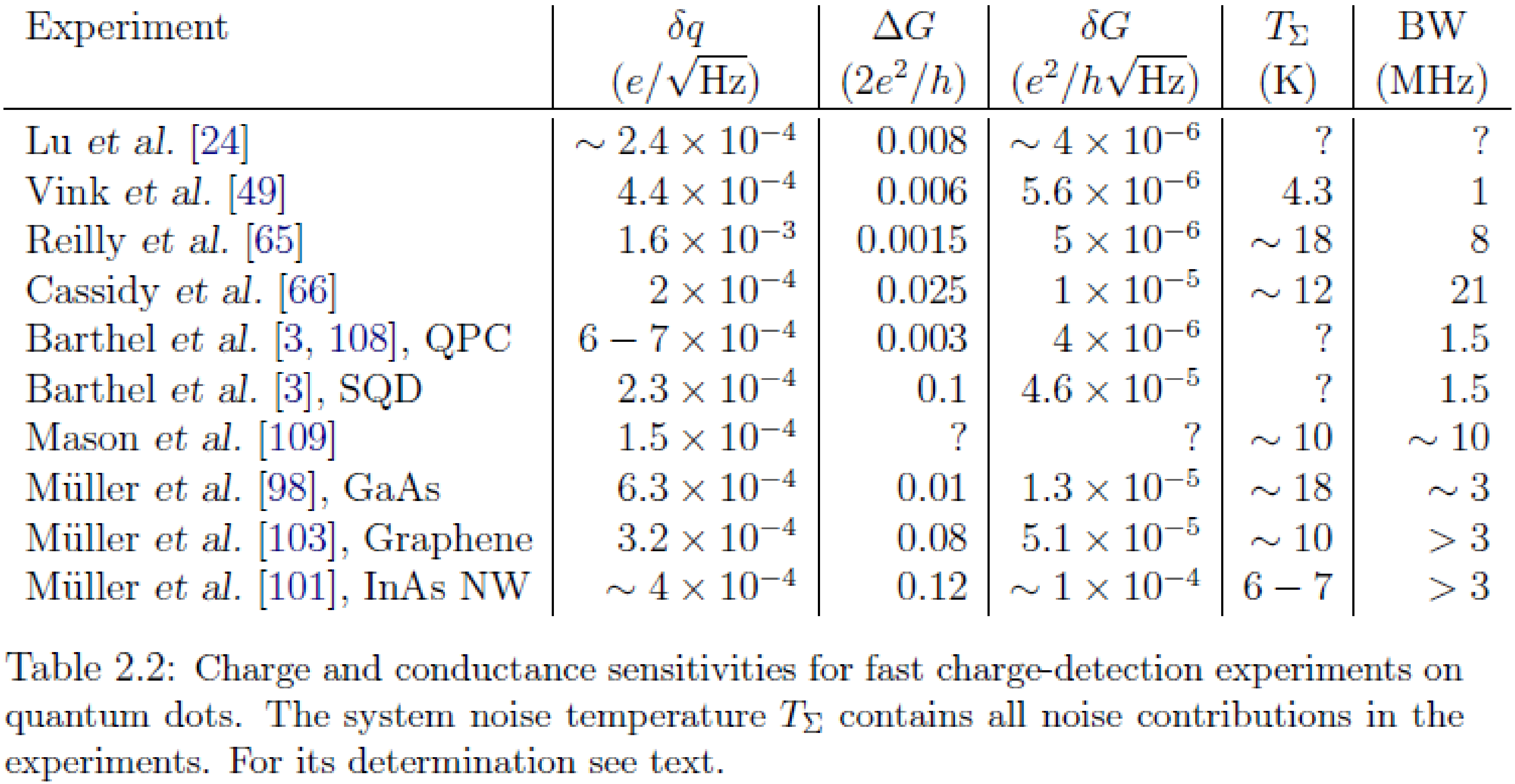
VII. Appendix – ΔG



System	$\Delta G \; \left(\frac{2e^2}{h}\right)$
QD charge sensor on DQD	0.1 [3]
Top gate defined SQDs	0.006-0.002 [1, 13, 49, 65]
Top gate defined DQDs	0.01 [96], 0.0015 [65]
AFM defined SQDs	0.02-0.065 [29, 97]
AFM defined DQDs	0.01 [98]
Hybrid S and DDQDs	0.003 [99]
GaAs QPC underneath InAs nanowire SQD	0.065-0.12 [100, 101]
InAs nanowire DQD with self-aligned detector	0.05 [102]
Graphene SQD with nanoconstriction	0.08 [103]
Al SET on top of a top gate defined GaAs SQD	0.008 [24]
Lateral SET sensor of a SQD	0.003 [104]

Table 2.1: Dot to charge sensor coupling for different systems as found in literature.

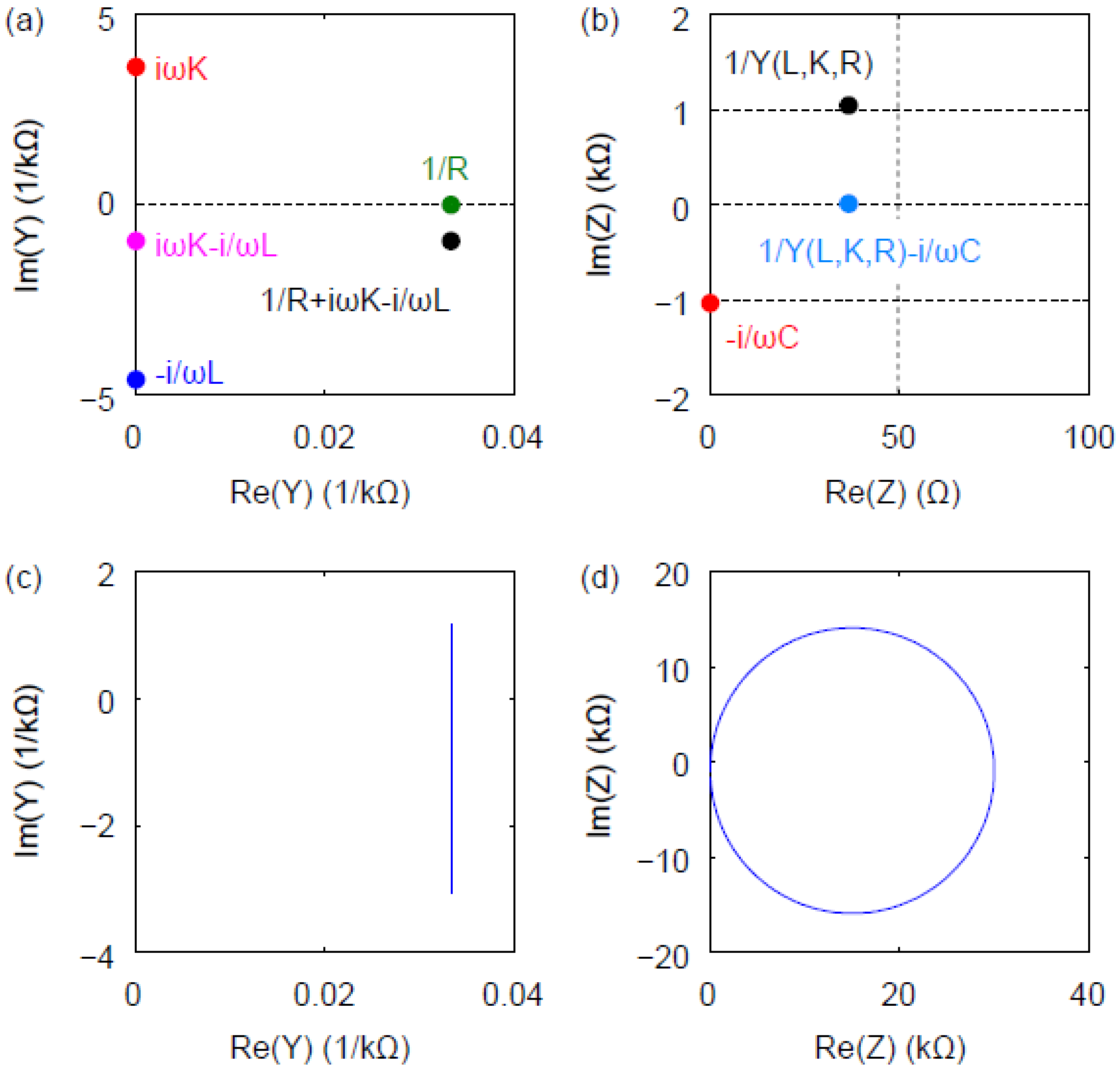
VII. Appendix – rf Performance

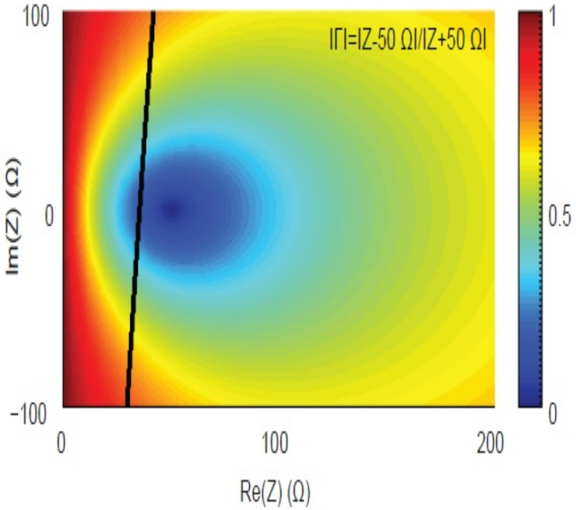


Experiment	δq $(e/\sqrt{\text{Hz}})$	ΔG $(2e^2/h)$	δG $(e^2/h\sqrt{\text{Hz}})$	T_Σ (K)	BW (MHz)
Lu *et al.* [24]	$\sim 2.4 \times 10^{-4}$	0.008	$\sim 4 \times 10^{-6}$	?	?
Vink *et al.* [49]	4.4×10^{-4}	0.006	5.6×10^{-6}	4.3	1
Reilly *et al.* [65]	1.6×10^{-3}	0.0015	5×10^{-6}	~ 18	8
Cassidy *et al.* [66]	2×10^{-4}	0.025	1×10^{-5}	~ 12	21
Barthel *et al.* [3, 108], QPC	$6 - 7 \times 10^{-4}$	0.003	4×10^{-6}	?	1.5
Barthel *et al.* [3], SQD	2.3×10^{-4}	0.1	4.6×10^{-5}	?	1.5
Mason *et al.* [109]	1.5×10^{-4}	?	?	~ 10	~ 10
Müller *et al.* [98], GaAs	6.3×10^{-4}	0.01	1.3×10^{-5}	~ 18	~ 3
Müller *et al.* [103], Graphene	3.2×10^{-4}	0.08	5.1×10^{-5}	~ 10	> 3
Müller *et al.* [101], InAs NW	$\sim 4 \times 10^{-4}$	0.12	$\sim 1 \times 10^{-4}$	$6 - 7$	> 3

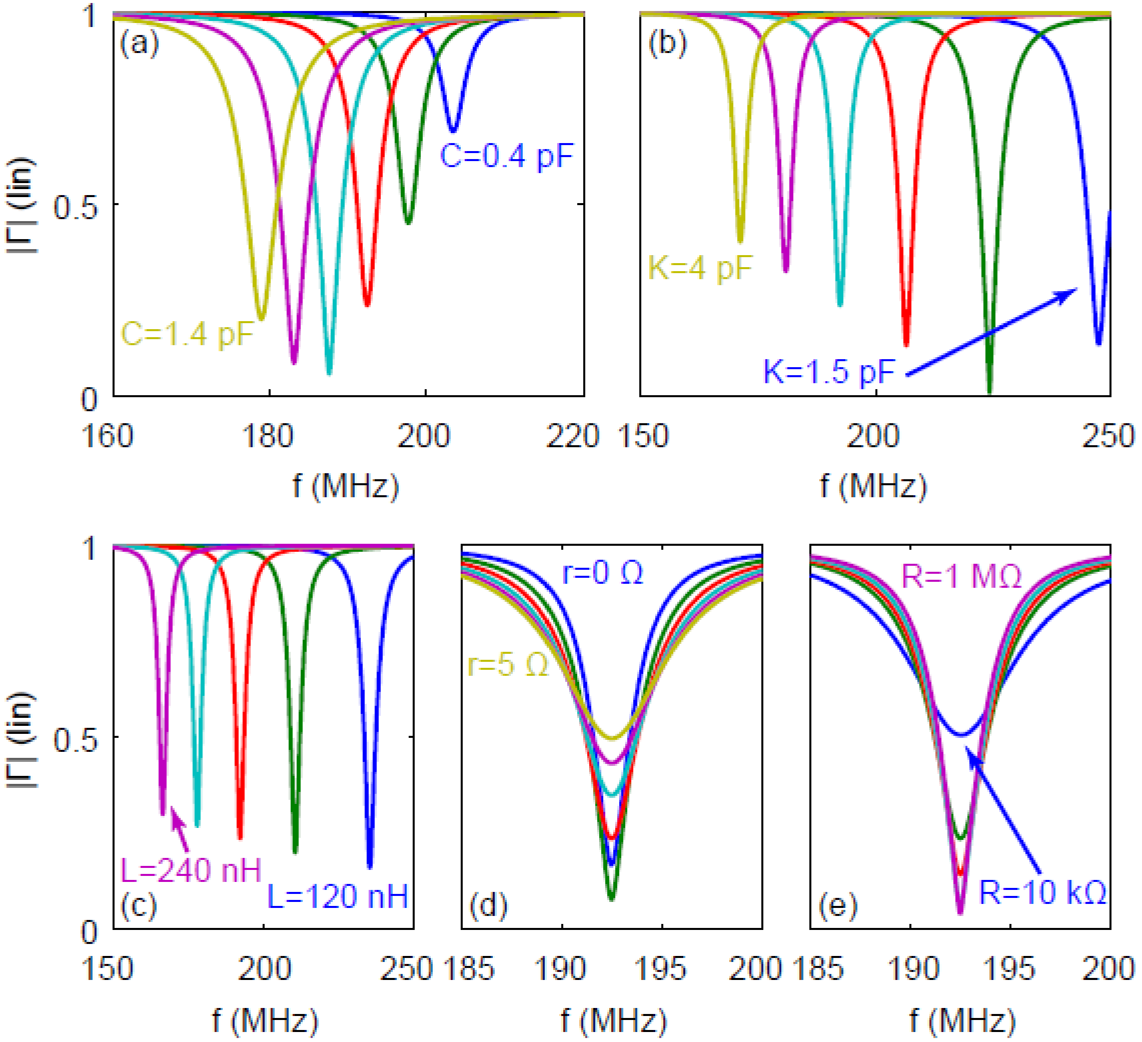
Table 2.2: Charge and conductance sensitivities for fast charge-detection experiments on quantum dots. The system noise temperature T_Σ contains all noise contributions in the experiments. For its determination see text.

VII. Appendix – Impedance Trafo





VII. Appendix – Parameter Influence: f



C = 0.8 pF

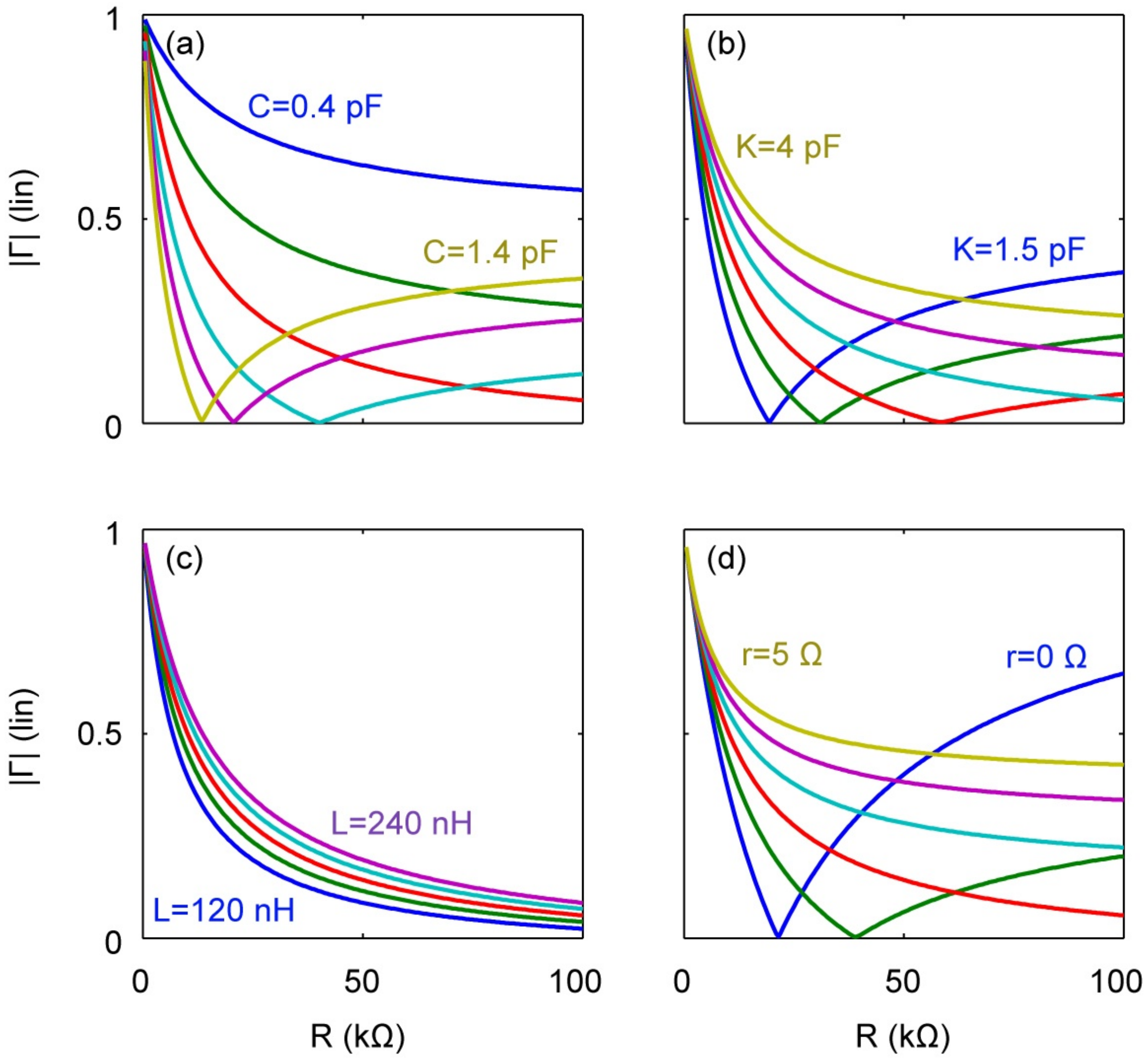
K = 3 pF

L = 180 nH

r = 2 Ω

R = 30 kΩ

VII. Appendix – Parameter Influence: R



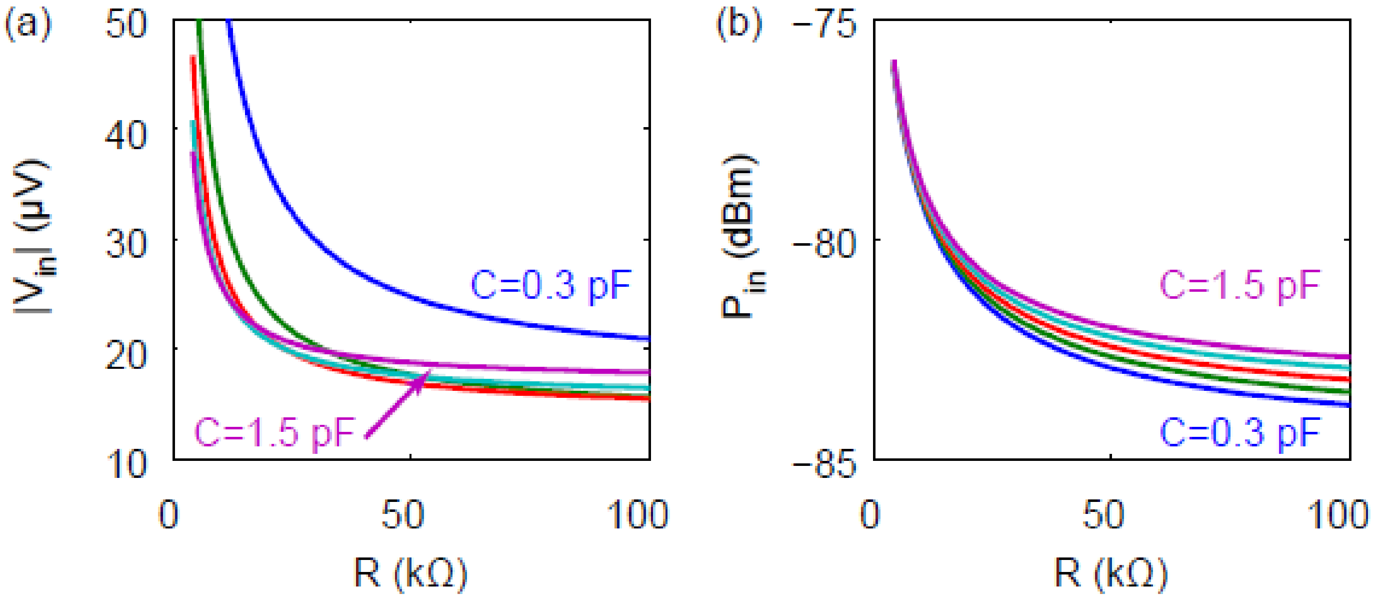
$C = 0.8$ pF

$K = 3$ pF

$L = 180$ nH

$r = 2\ \Omega$

VII. Appendix – Apllicable Power

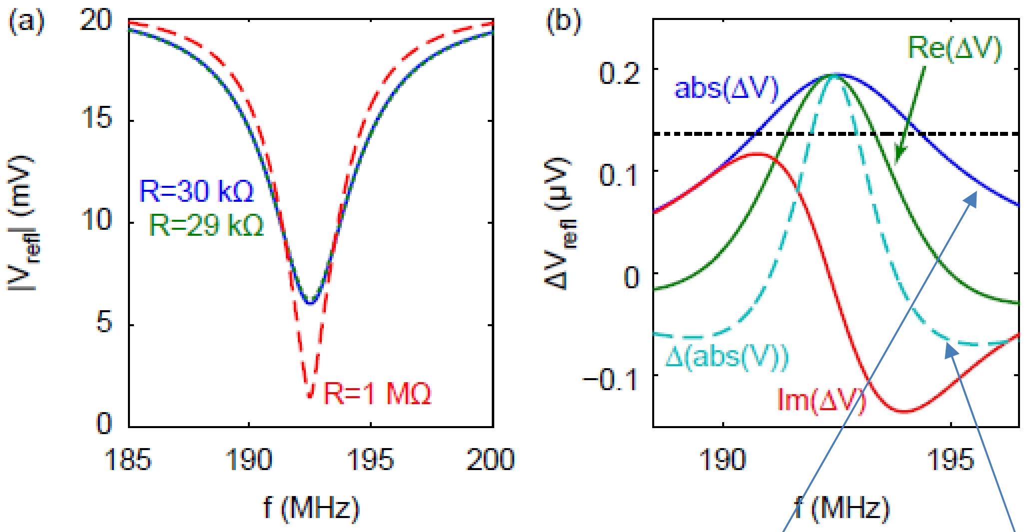


K = 3 pF

L = 180 nH

r = 2 Ω

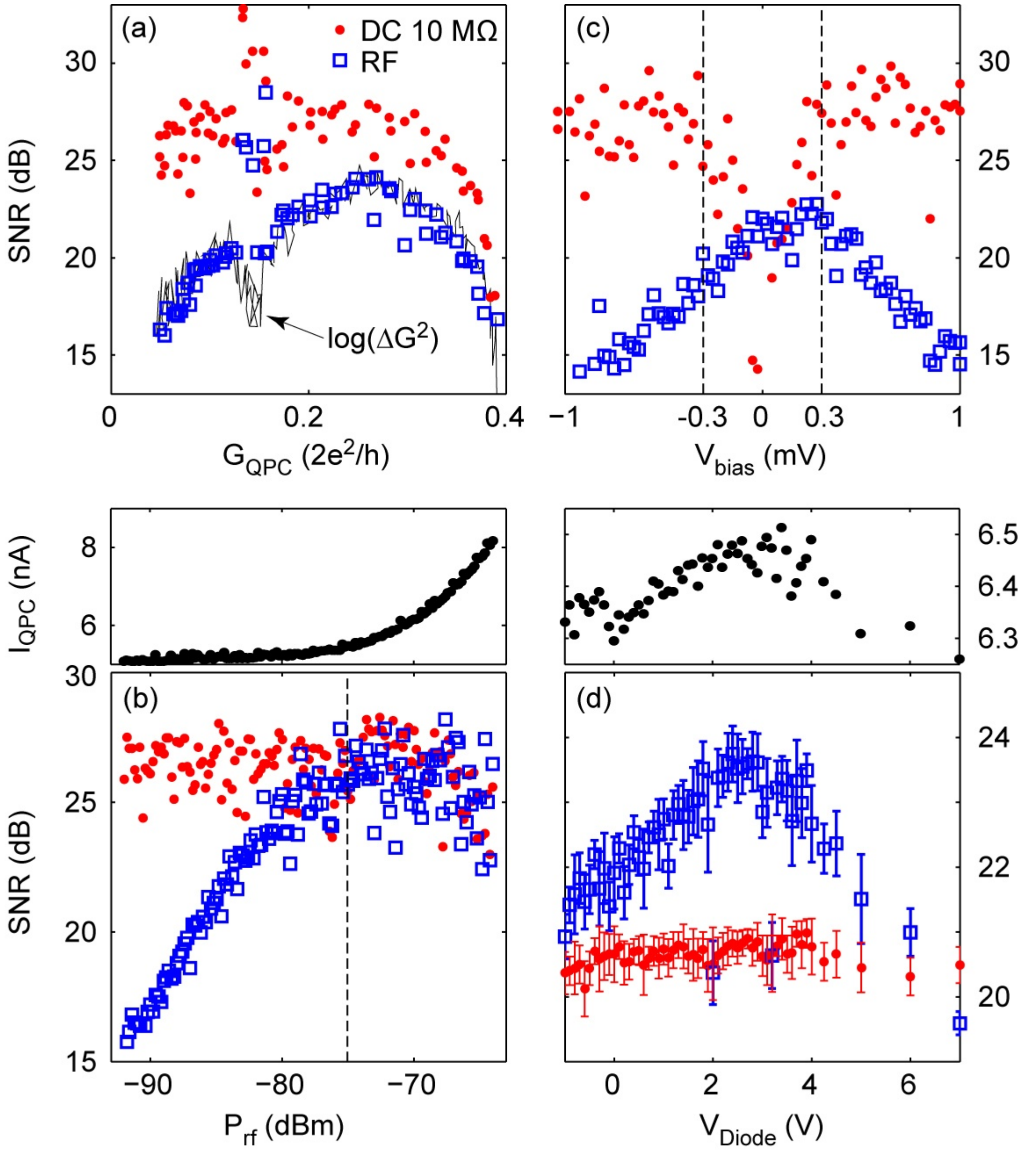
VII. Appendix: Frequency Response

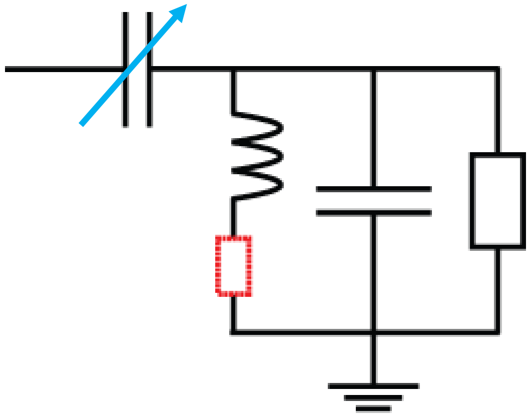


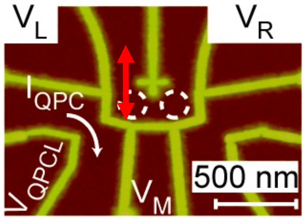
IF-mixing

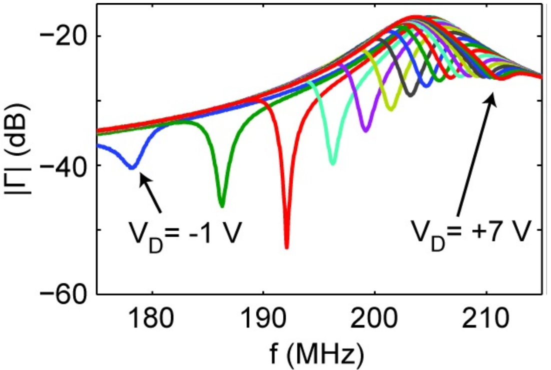
IQ-mixing

VII. Optimization of the Tunable Circuit





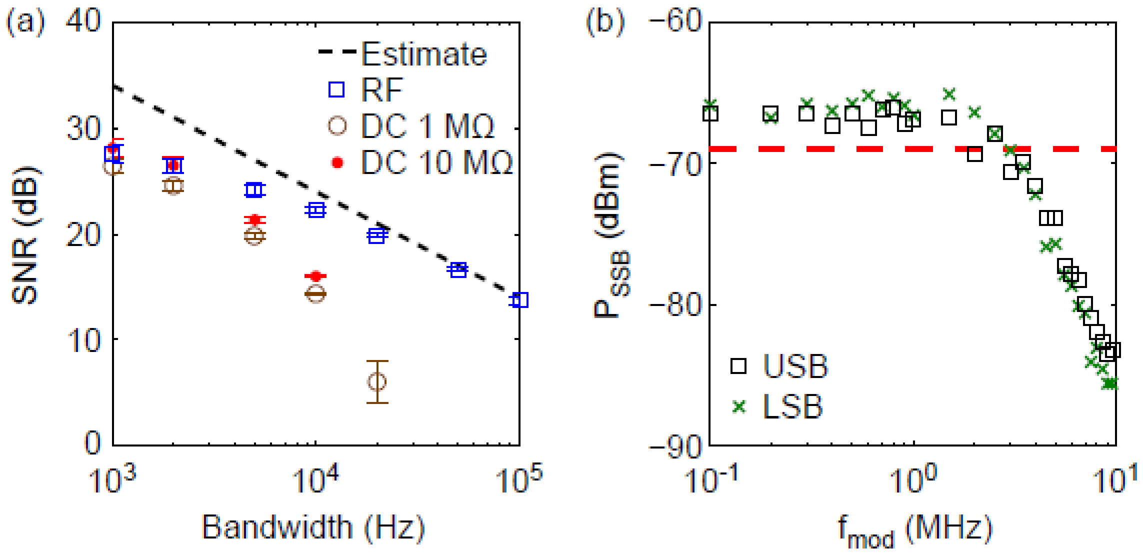




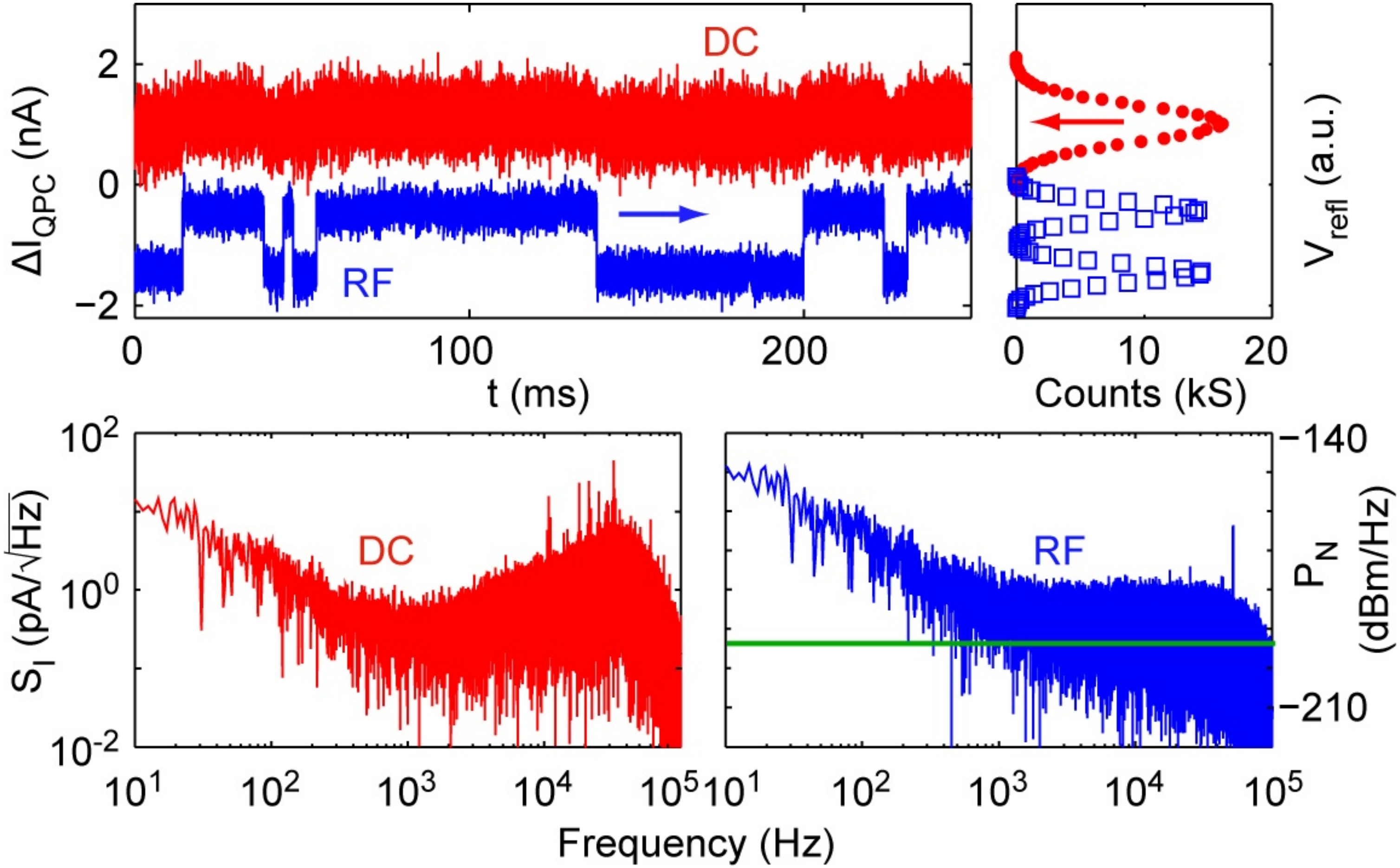
T = 2 K

1 kHz BW (a-c), 5 kHz BW (d)

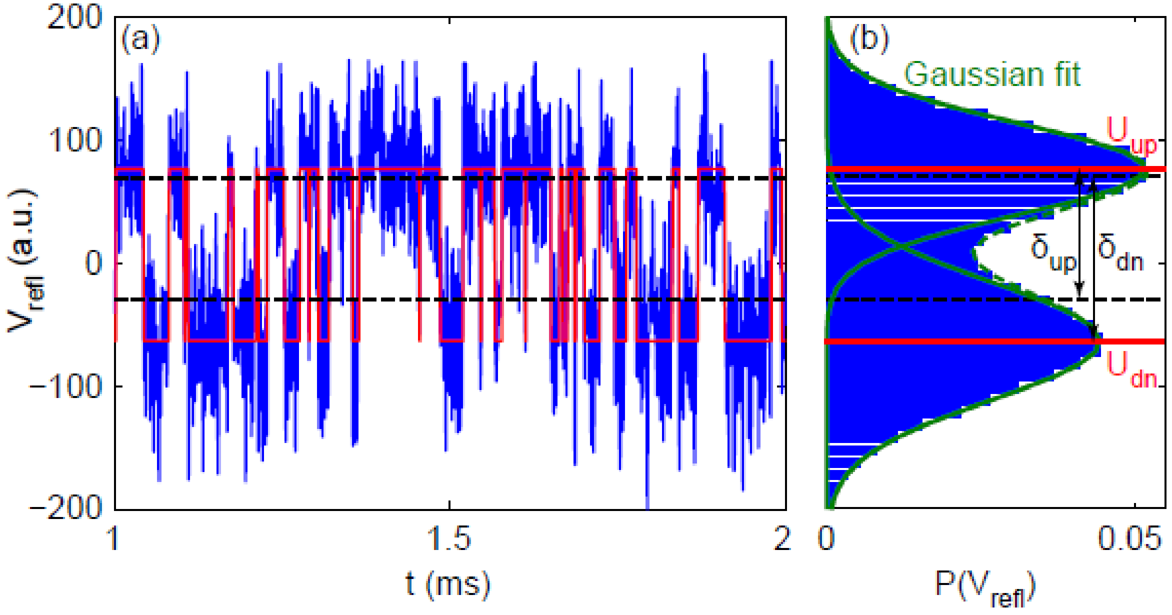
VII. Appendix – Bandwidth



VII. Appendix: PSD



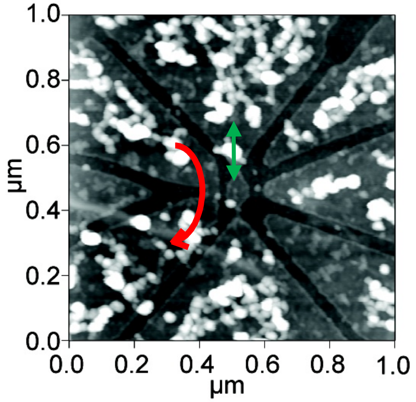
VII. Appendix: Counting Algorithm



if point *n*-1 is „up“, then

$$P_{up}(V_n) = \frac{G_{up}(V_n)}{A_{up}} \cdot \left(1 - \frac{\Delta t}{\tau}\right)$$

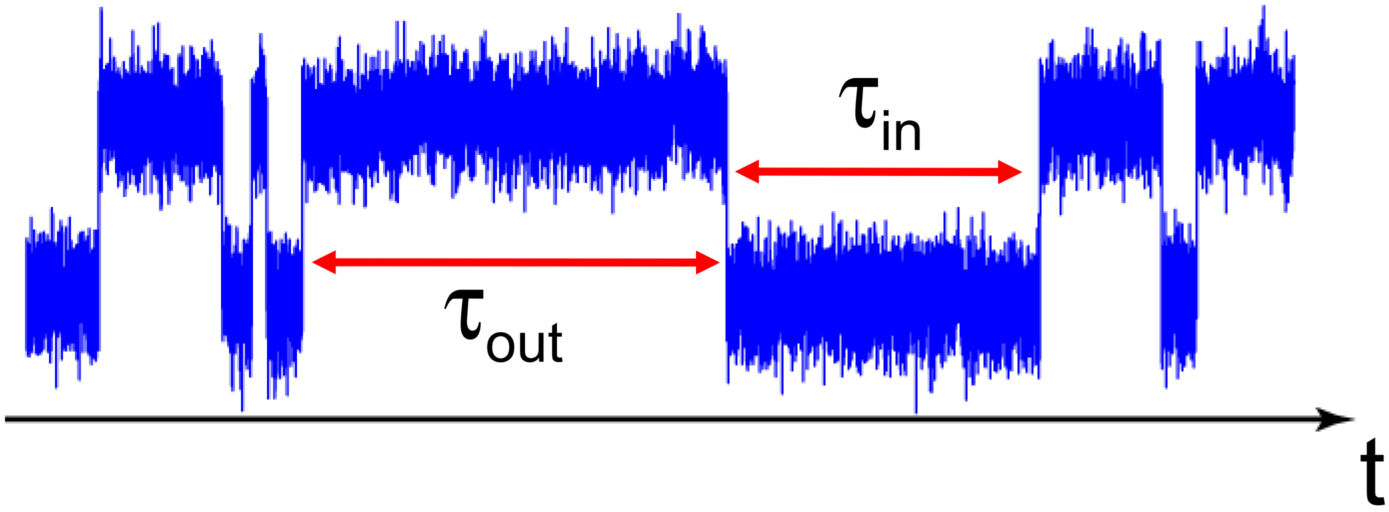
$$P_{dn}(V_n) = \frac{G_{dn}(V_n)}{A_{dn}} \cdot \frac{\Delta t}{\tau}$$

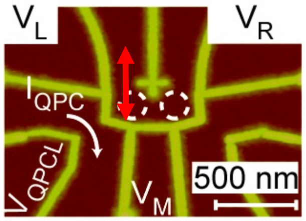


T = 2 K
800 kHz BW

Algorithm: Yuzhelevski *et al.*, RSI 2000

Interlude: Extraction of Tunnel Rates





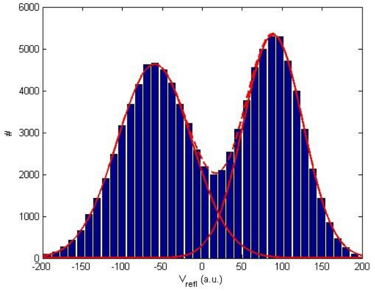
$$\Gamma_{in} = 1/\langle\tau_{out}\rangle$$

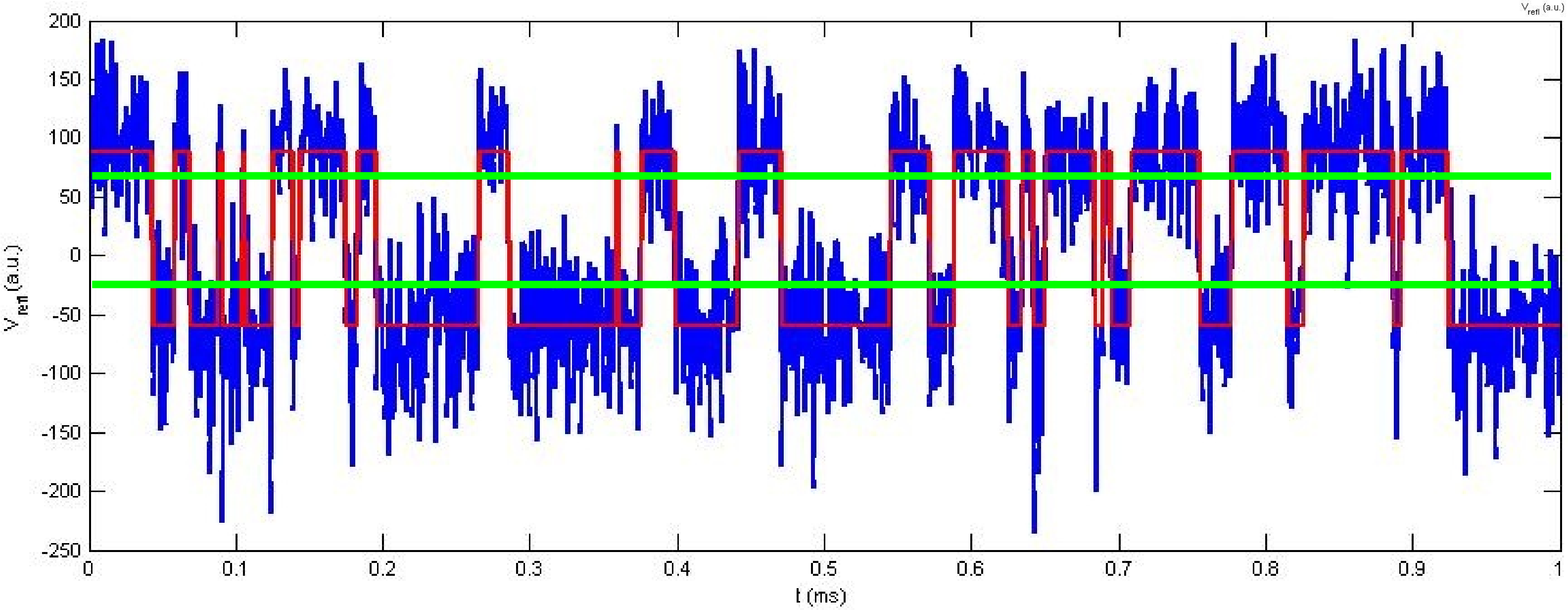
$$\Gamma_{out} = 1/\langle\tau_{in}\rangle$$

$$\gamma = \Gamma_{in} + \Gamma_{out} = 1/\langle\tau_{in}\rangle + 1/\langle\tau_{out}\rangle$$

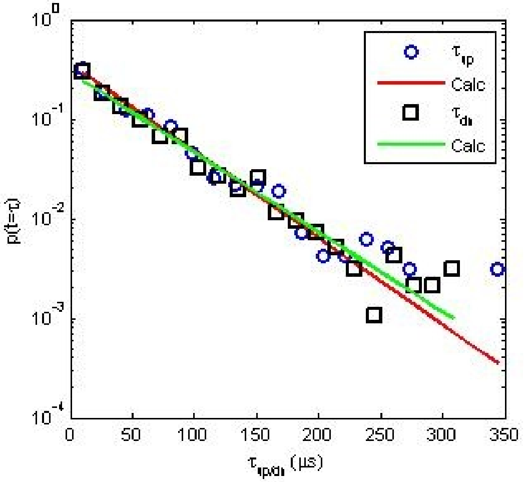
$$\tau = 1/\Gamma_{in} + 1/\Gamma_{out} = \langle\tau_{in}\rangle + \langle\tau_{out}\rangle = 1/r_E$$

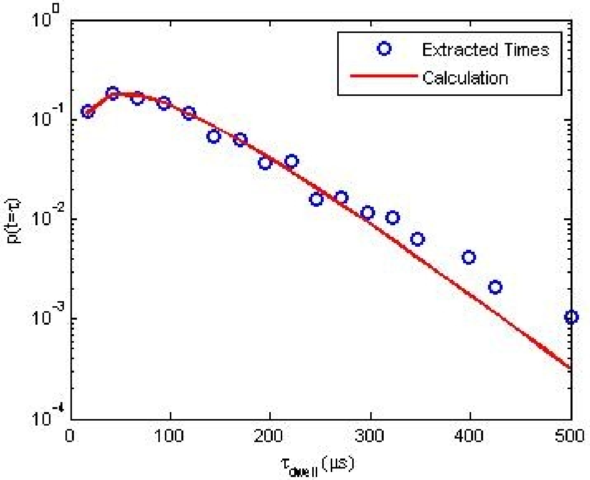
VII. Appendix: Extraction of Parameters

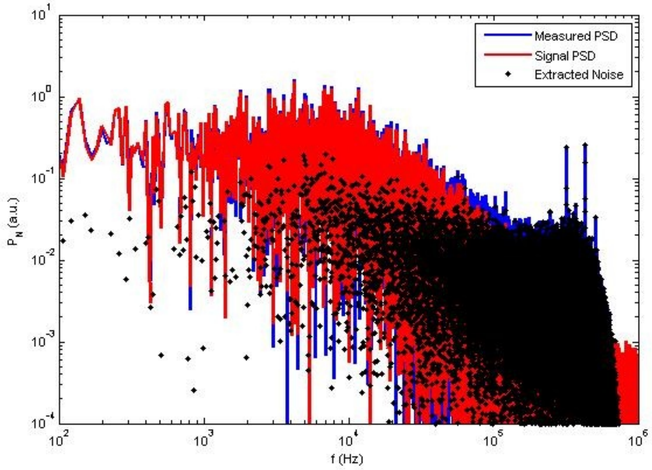




500 kHz





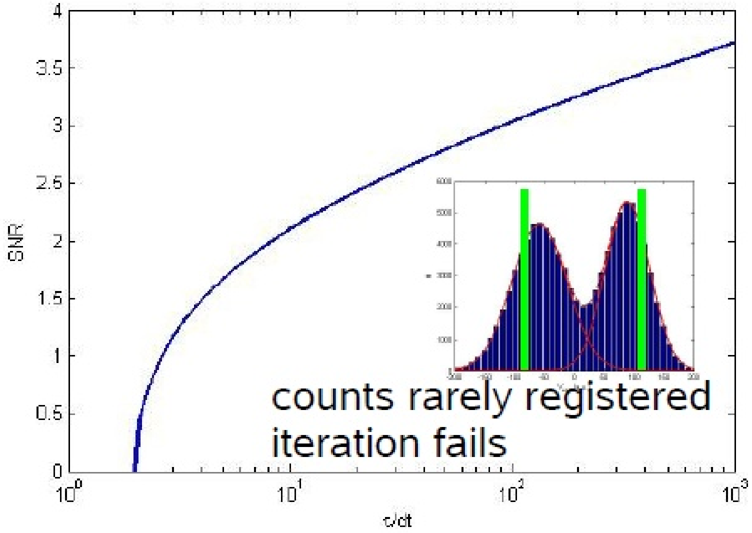


VII. Appendix – Algorithm Limitations

Signal to noise ratio

$$\frac{\Delta V}{\sigma} \geqslant \sqrt{2\ln\left(\frac{\tau}{\Delta t}-1\right)}.$$

thresholds have to be closer than the 2nd peak



counts rarely registered
iteration fails

Measurement bandwidth

If bandwidth is too small, Gaussians are not properly fitted