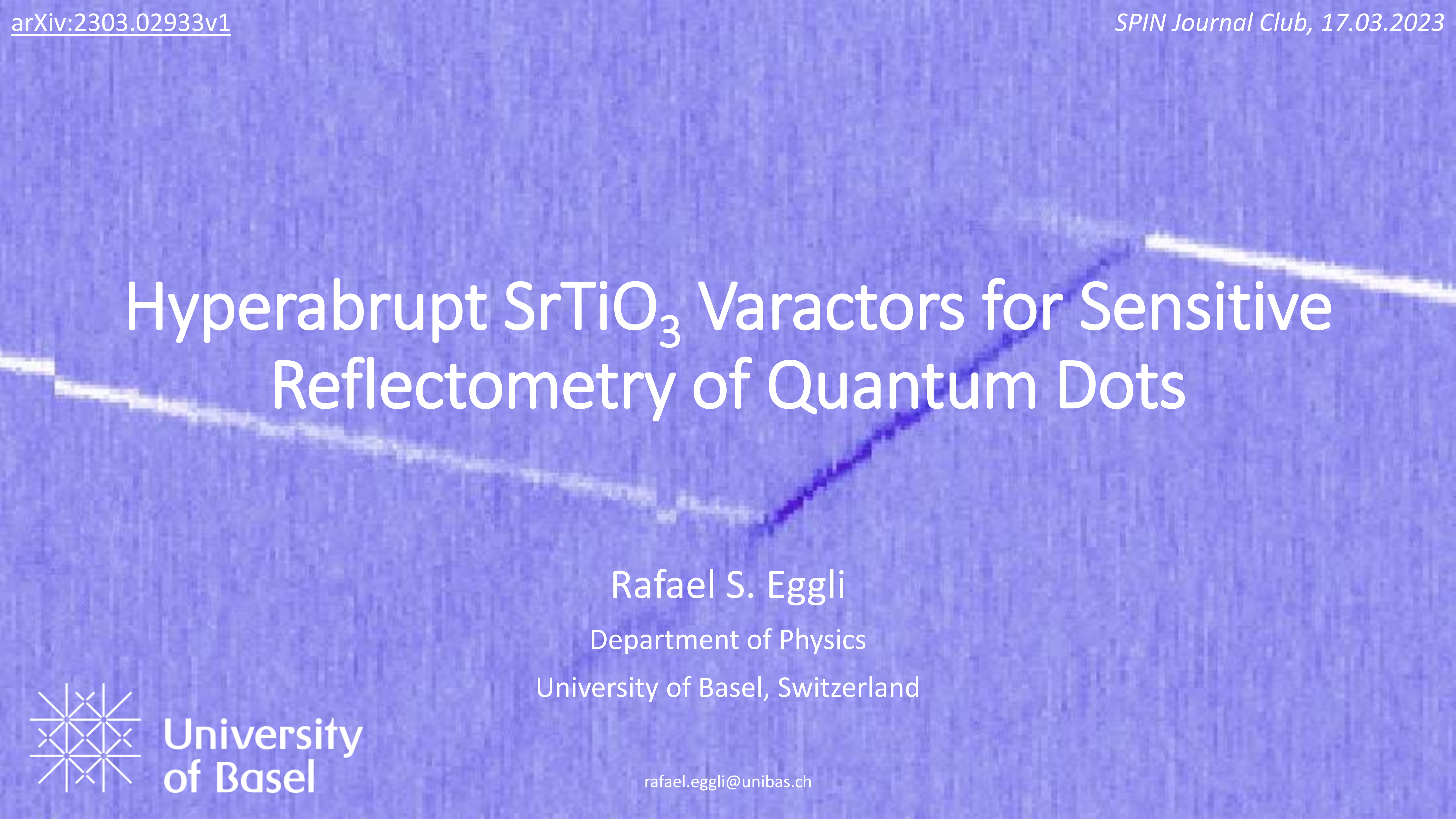
arXiv:2303.02933v1

SPIN Journal Club, 17.03.2023



Hyperabrupt $SrTiO_3$ Varactors for Sensitive Reflectometry of Quantum Dots

Rafael S. Eggli

Department of Physics

University of Basel, Switzerland

University of Basel

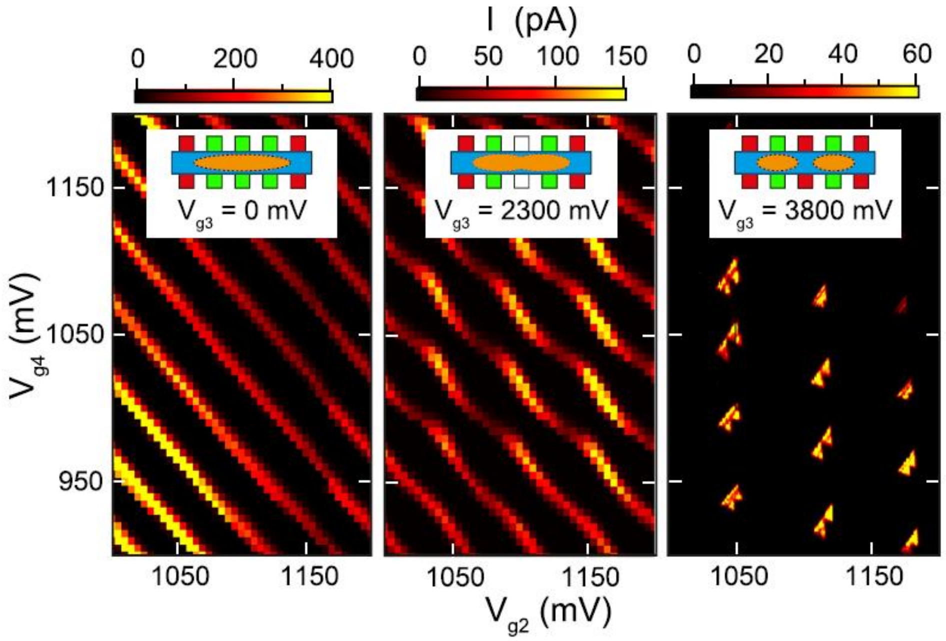
rafael.eggli@unibas.ch

Cryogenic hyperabrupt strontium titanate varactors for sensitive reflectometry of quantum dots

Rafael S. Eggli,[1,*] Simon Svab,[1,†] Taras Patlatiuk,[1] Dominique Trüssel,[1]
Miguel J. Carballido,[1] Pierre Chevalier Kwon,[1] Simon Geyer,[1] Ang Li,[2]
Erik P. A. M. Bakkers,[2] Andreas V. Kuhlmann,[1] and Dominik M. Zumbühl[1,*]
[1] *Department of Physics, University of Basel, Klingelbergstrasse 82,*
CH-4056 Basel, Switzerland
[2] *Department of Applied Physics, TU Eindhoven,*
Den Dolech 2, 5612 AZ Eindhoven, The Netherlands

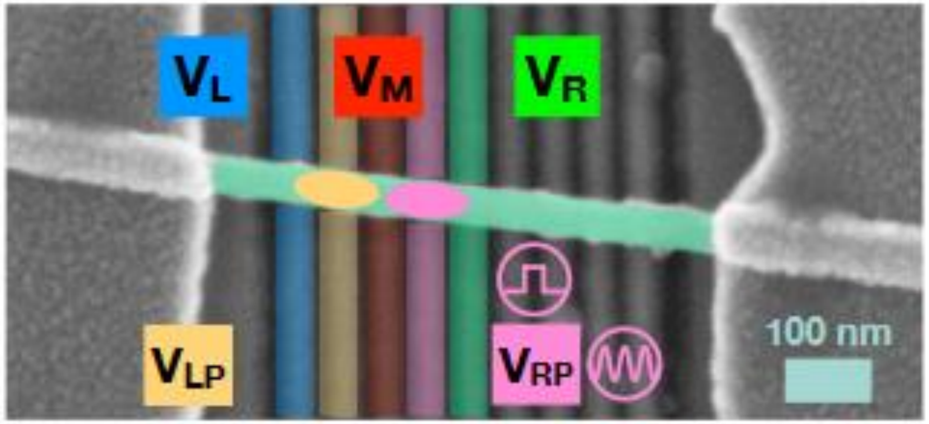
Radio frequency reflectometry techniques enable high bandwidth readout of semiconductor quantum dots. Careful impedance matching of the resonant circuit is required to achieve high sensitivity, which however proves challenging at cryogenic temperatures. Gallium arsenide-based voltage-tunable capacitors, so-called varactor diodes, can be used for in-situ tuning of the circuit impedance but deteriorate and fail at temperatures below 10 K and in magnetic fields. Here, we investigate a varactor based on strontium titanate with hyperabrupt capacitance-voltage characteristic, that is, a capacitance tunability similar to the best gallium arsenide-based devices. The varactor design introduced here is compact, scalable and easy to wirebond with an accessible capacitance range from 45 pF to 3.2 pF. We tune a resonant inductor-capacitor circuit to perfect impedance matching and observe robust, temperature and field independent matching down to 11 mK and up to 2 T in-plane field. Finally, we perform gate-dispersive charge sensing on a germanium/silicon core/shell nanowire hole double quantum dot, paving the way towards gate-based single-shot spin readout. Our results bring small, magnetic field-resilient, highly tunable varactors to mK temperatures, expanding the toolbox of cryo-radio frequency applications.

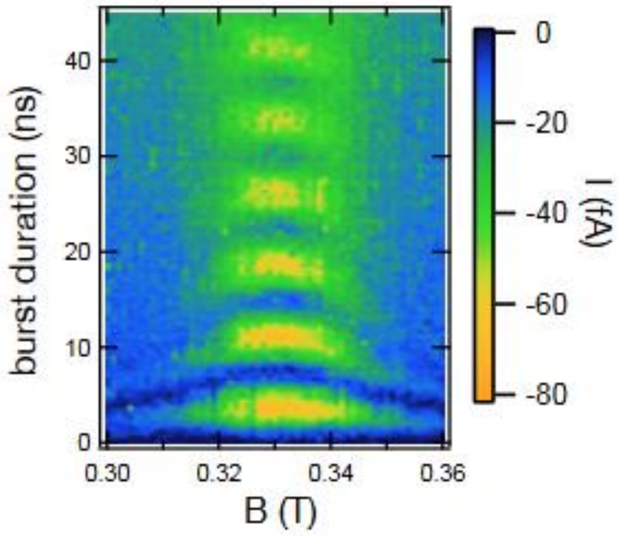
Ge/Si Core/Shell Nanowire Quantum Dots & Qubits

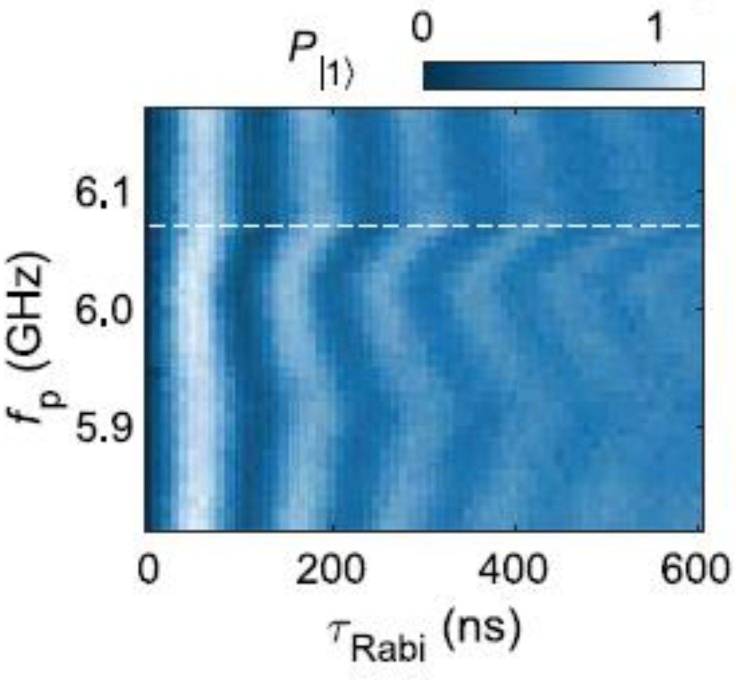


Why these Nanowires?

- Excellent gate-control of QD-formation [1-3]
- Very strong SOI[2] ($l_{SO} \sim 4\,nm$ vs. $l_{SO} \sim 31\,nm$ in FinFETs[4])
- All-electric tunability of: l_{SO}, g, f_{Rabi}, T_2^{Echo}
- Ultrafast $f_{Rabi} \sim 435\,MHz$ @ $f_{Larmor} \sim 3.4\,GHz$
  -> Strong driving: breakdown of RWA (?)
- Anisotropies, Sweetspots, Gatemons, Majoranas (?) etc.







rafael.eggli@unibas.ch

[1] Froning et al. Appl. Phys. Lett. **113** (2018)
[2] Froning et al., Nat. Nanotechnol. **16** (2021)
[3] Carbadillo et al., in preparation.
[4] Geyer et al., arXiv, 2212.02308
[5] Lyu et al., ResearchSquare, 10.21203/rs.3.rs-2324122/v1 (2022)

Measuring Ge/Si Nanowire QDs

Here: Gate-Dispersive Reflectometry with surface-mount inductors

& perfect impedance matching at mK Temperatures and in B-field

Eggli, Svab et al. arXiv:2303.02933v1

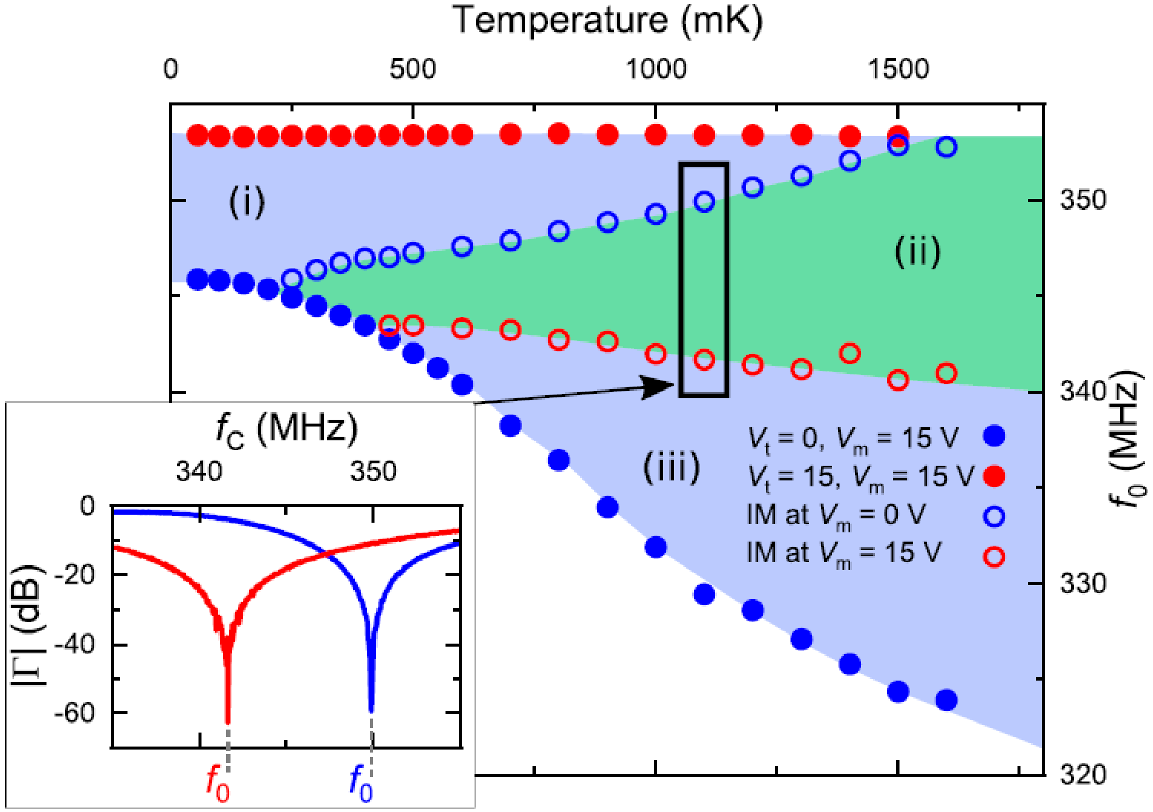
Reflectometry and Impedance Matching

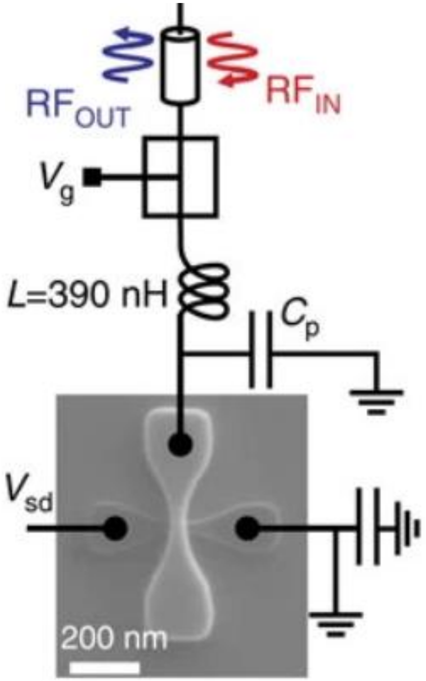
Fundamental problem of high-bandwidth measurements:

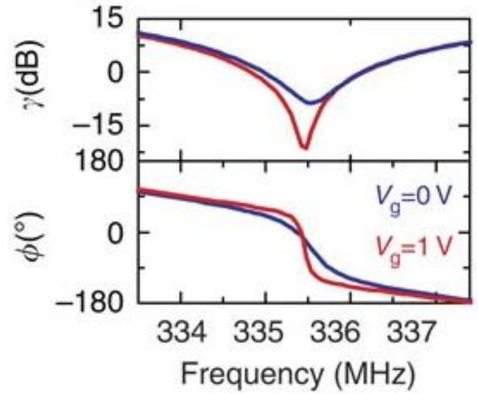
- Quantum devices: $Z(T) \geq \frac{h}{e^2} = 25.8\ k\Omega\ \ to \sim M\Omega$
- Standard RF-electronics: $Z_0 \ \ = 50\ \Omega$

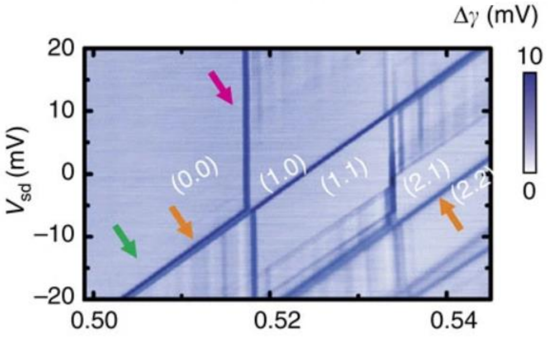
-> LC-resonator for downconversion

-> Voltage-tunable capacitor(s) (**varactor**) for in-situ tuning









Problems with GaAs-varactors:

- Freezing-out of diode
- Susceptible to magnetic fields

[1] Colless et al., PRL. **110** (2013)

[2] Gonzales-Zalba et al., Nat. Comms. **6** (2015)

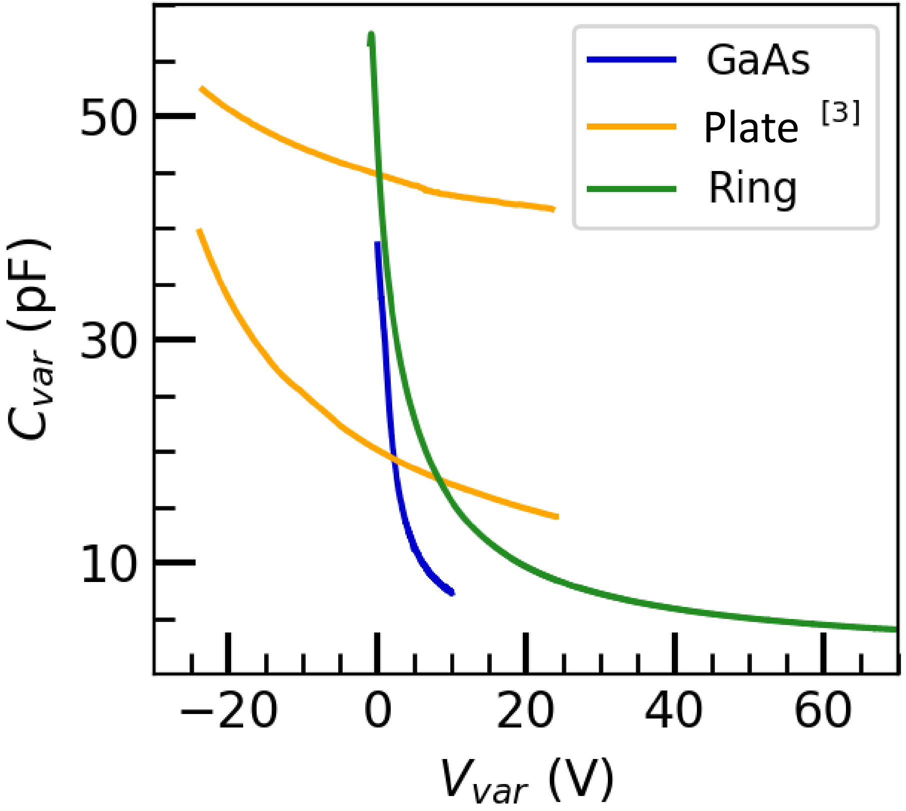
[3] Vigneau et al., arXiv. 2202.10516

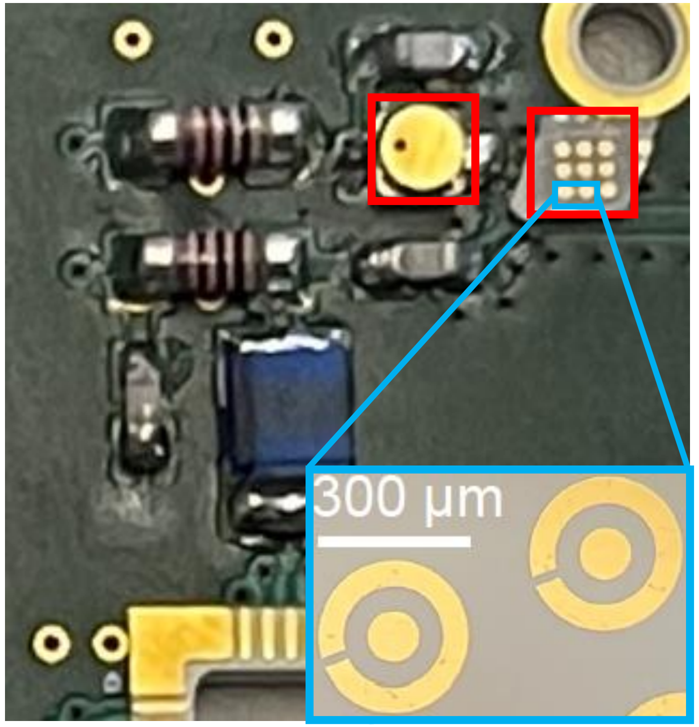
[4] Müller et al., Appl. Phys. Lett. **97** (2010)

[5] Ares et al., Phys. Rev. Appl. **5** (2016)

[6] Ibberson et al. Appl. Phys. Lett. **114** (2019)

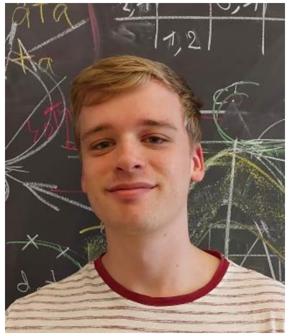
Strontium Titanate Varactors





Anisotropic dielectric constant below $10\ K$:
$\varepsilon_{r,(111)} \sim\ 12'000 \quad \varepsilon_{r,(001)} \sim\ 24'000$
Highly tunable by large electric fields
-> Voltage-tunable capacitor

The engineering challenge:
Small C_{max} $(\leq 50\ pF)$
Large fields in the crystal $\left(\sim 500\ \frac{V}{mm}\right)$

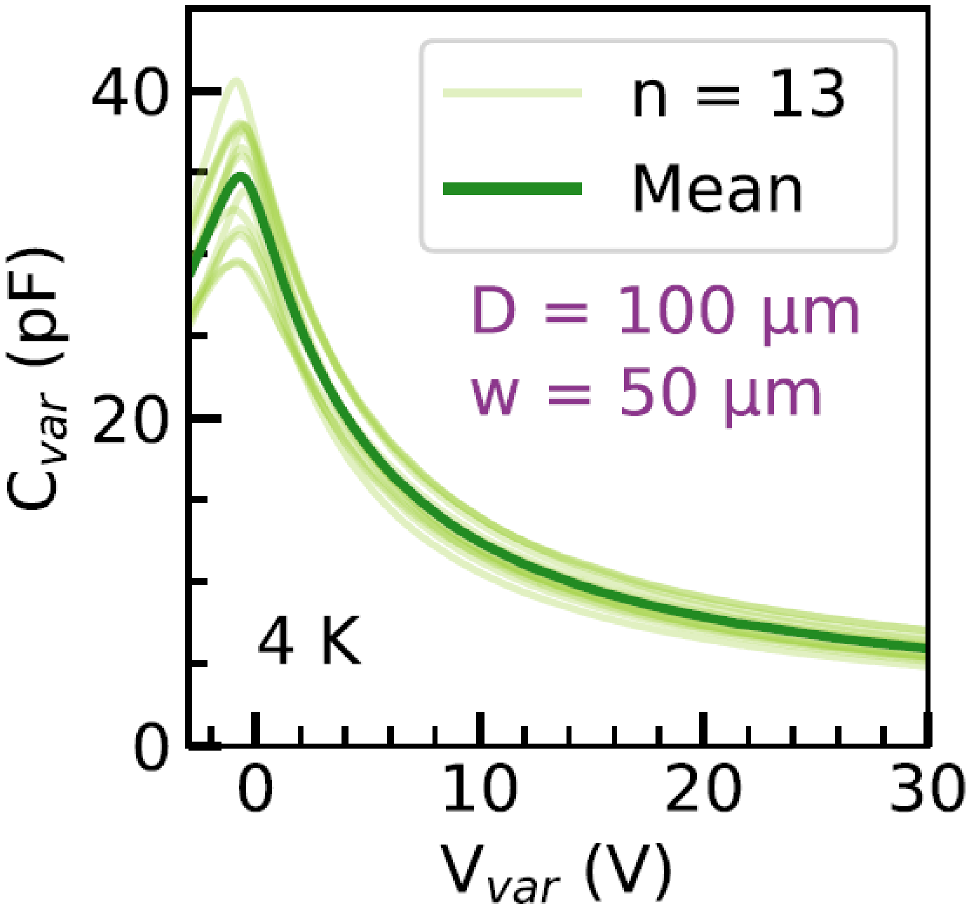


Dominique Trüssel

[1] Neville et al., J. Appl. Phys. **43** (1972)
[2] Hemberger et al., Phys. Rev. B. **52** (1995) [3] Apostolidis et al., arXiv. 2007.03588

rafael.eggli@unibas.ch

Varactor Performance



$$C_{var}(V_{var}) = \frac{K}{(V_{var} + \Phi_{diode})^{\gamma}}$$

Hyperabrupt varactors:

$$\gamma > 0.5$$

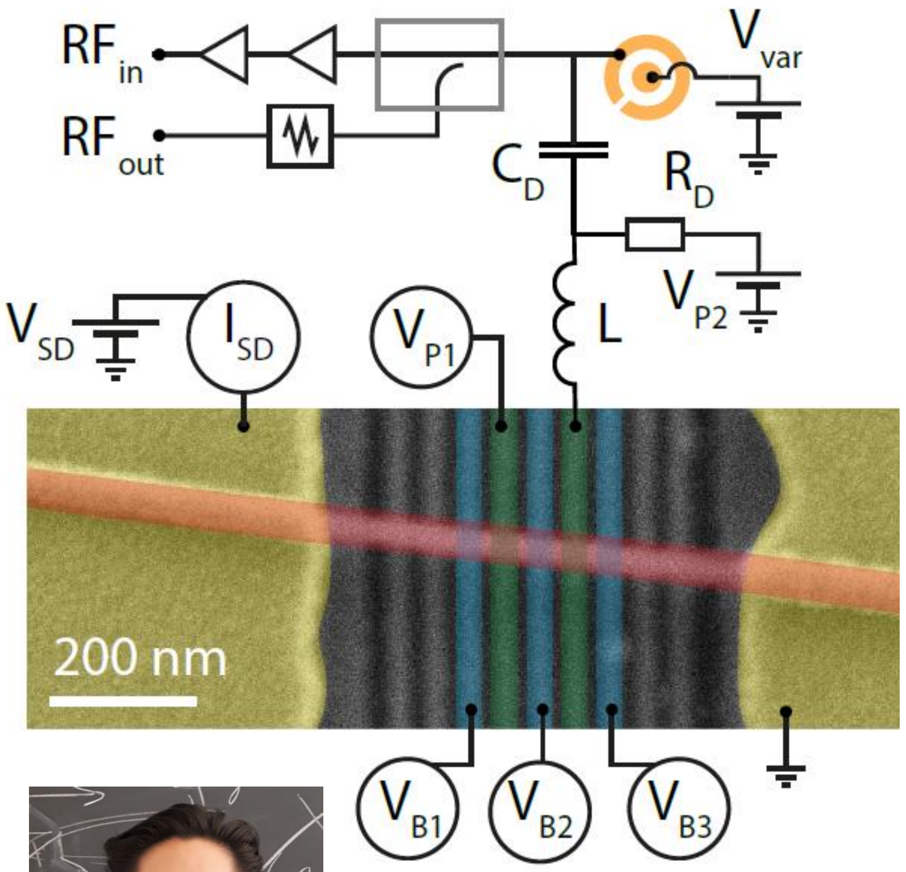
Tuning range:

$$V_{var} = 0 - 100\,V \leftrightarrow 45 - 3.2\,pF$$

[1] Heo et al., phys. stat. sol. **212** (2014)

[2] Buisman et al., IEEE MTT-s internat. microwave symp. dig. (2005)

Perfect Impedance Matching at 15 mK

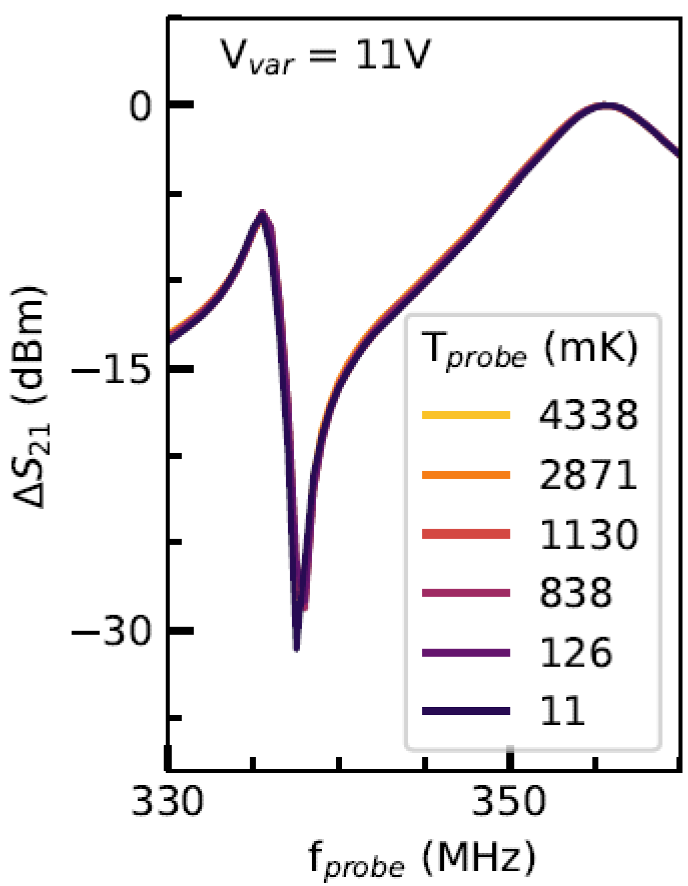


Simon Svab

Ge/Si core/shell nanowire quantum dot device

Perfect impedance matching:

- moderate V_{var}
- only 1 varactor

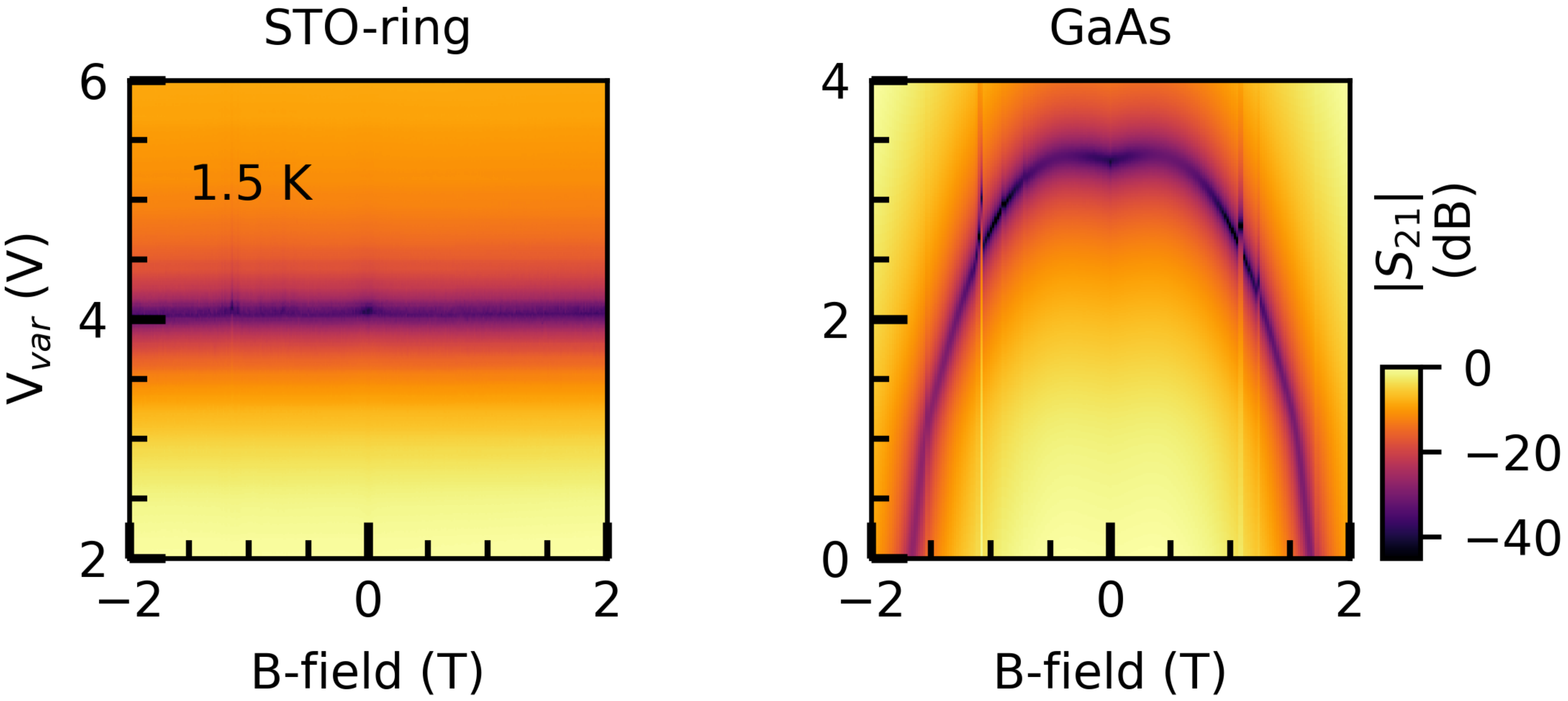


Highly resilient to temperature-changes

[1] Conesa-Boj et al., Nano Lett. **7** (2017)
[2] Froning et al., Nat. Nanotechnol. **16** (2021)
[3] Eggli, Svab et al., **in preparation. ARXIV!!**

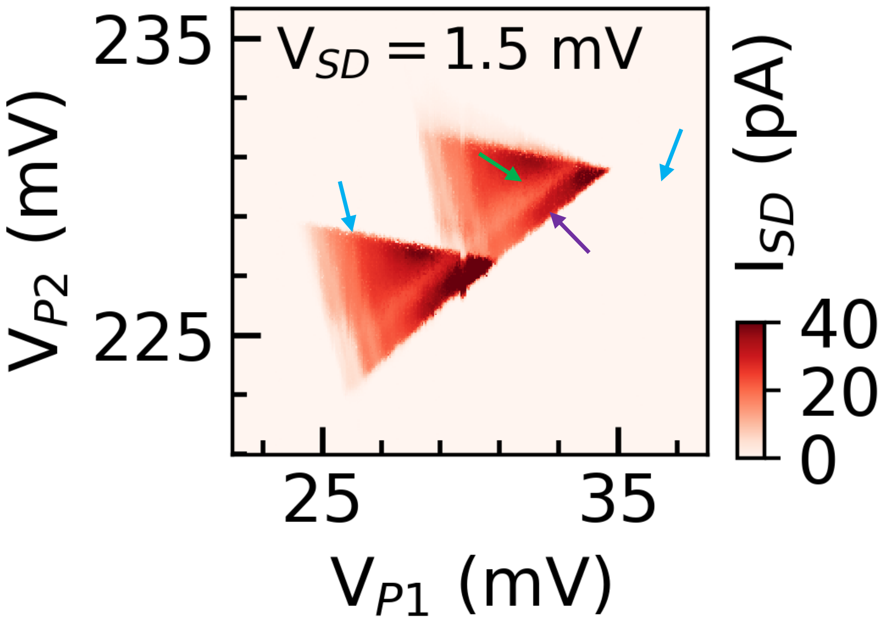
rafael.eggli@unibas.ch

Field-Resilience of Matching with STO



rafael.eggli@unibas.ch

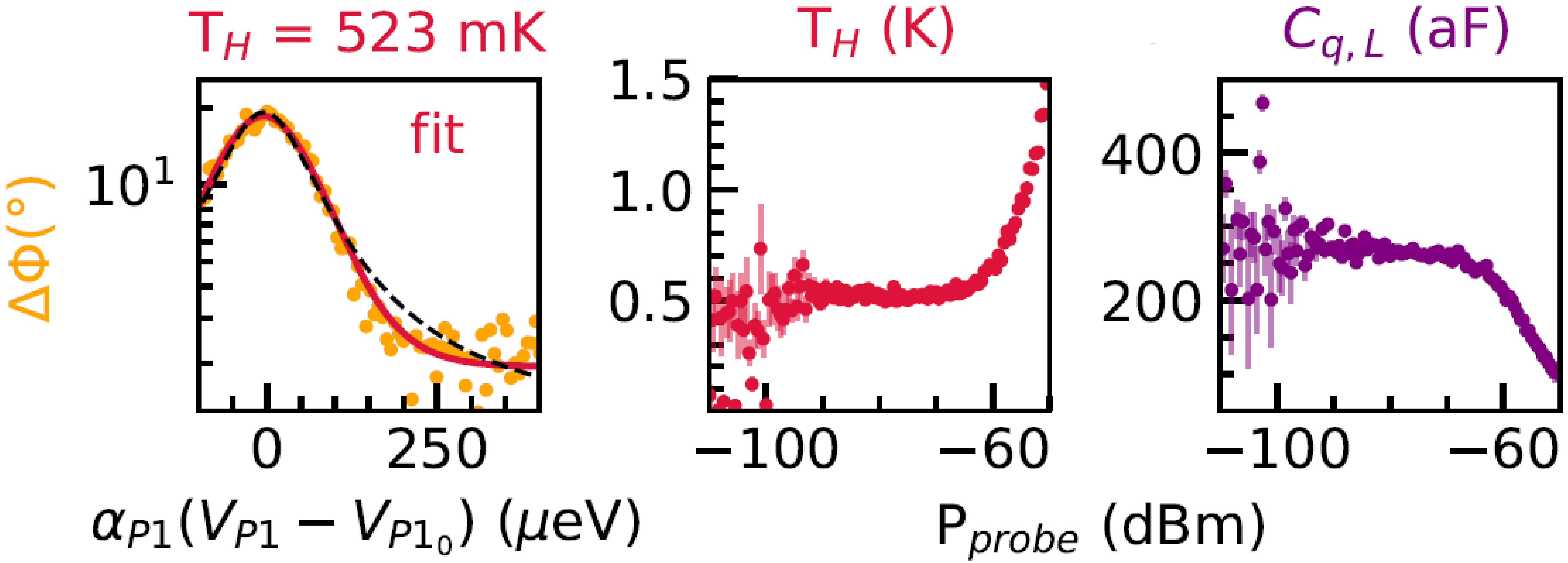
Charge Sensing



Bias triangles in DC current: DQD

Interdot transition coincides with triangle baseline
Lead transitions of right dot
Faint excited state signature

Lineshape Fitting: Lead Transition



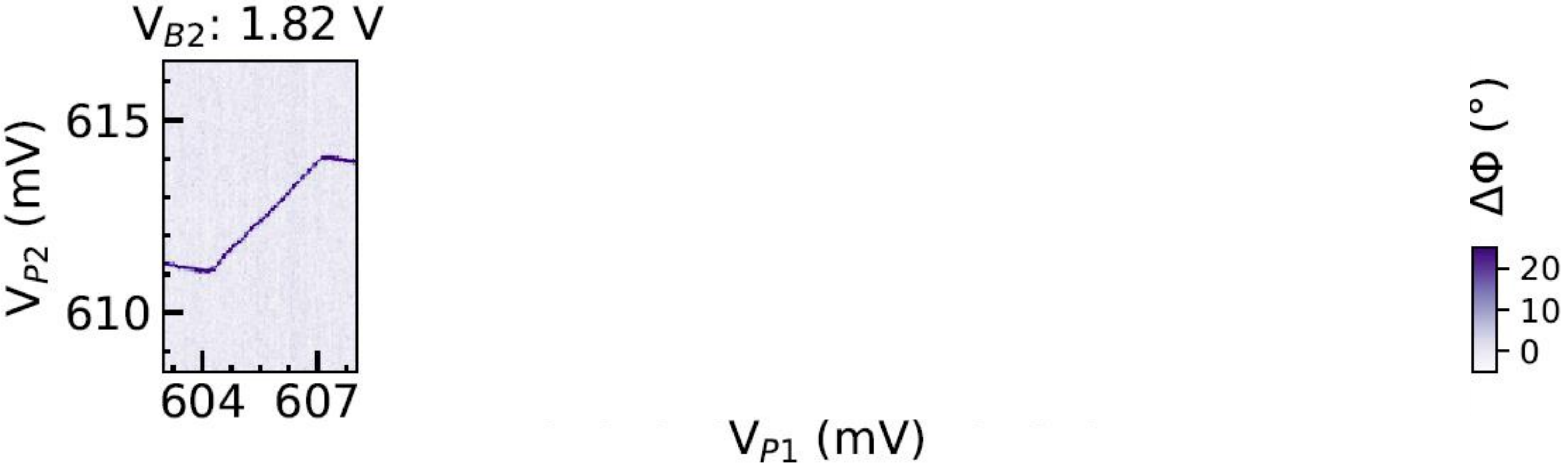
$$\Delta\Phi = \Delta\Phi_{max} \cdot cosh^{-2}\left(\frac{\alpha_{P1}(V_{P1} - V_{P1_0})}{2k_BT_H}\right)$$

$$T_H \approx (520 \pm 20)\,\mathrm{mK}$$

$$C_{q,L} = (266 \pm 8)\,\mathrm{aF}$$

rafael.eggli@unibas.ch

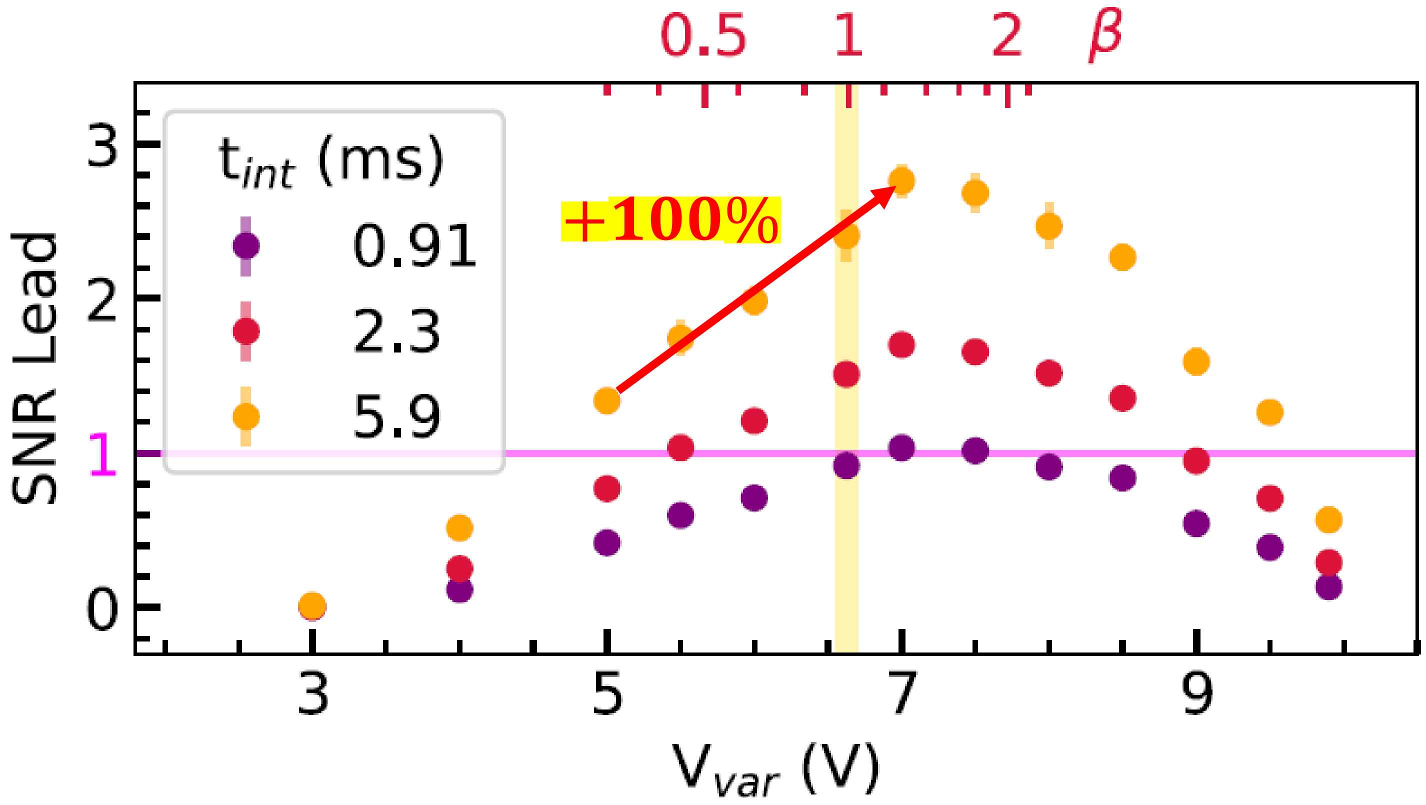
Tuning the Interdot Tunnel-Coupling

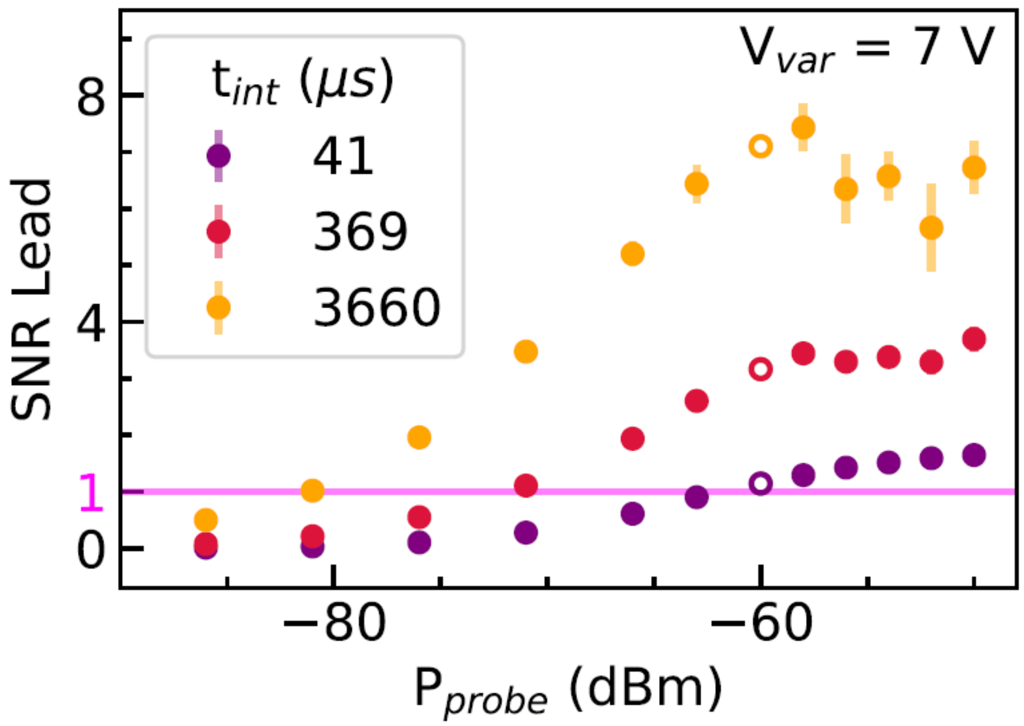


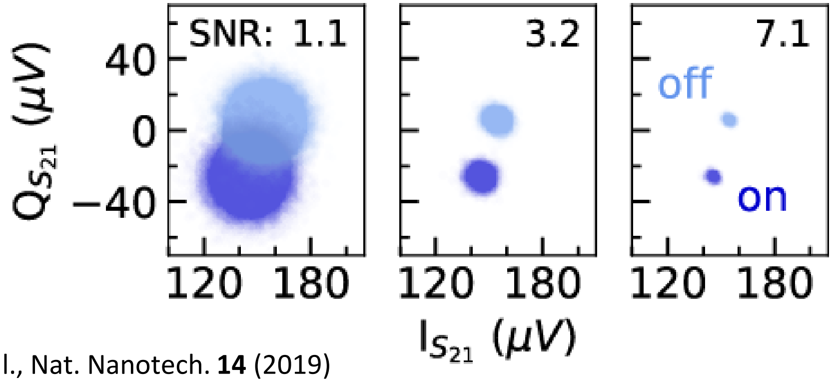
Selective control over interdot-tunnel rate

rafael.eggli@unibas.ch

Impact of Impedance Matching on SNR







Time-Domain SNR of charge transitions[1]

Signal boost by matching: $\Delta V_{var} = 2V \leftrightarrow \Delta C_{var} = 4\,pF$

At higher power: $SNR = 1.1$ for $t_{int} = 41\,\mu s$

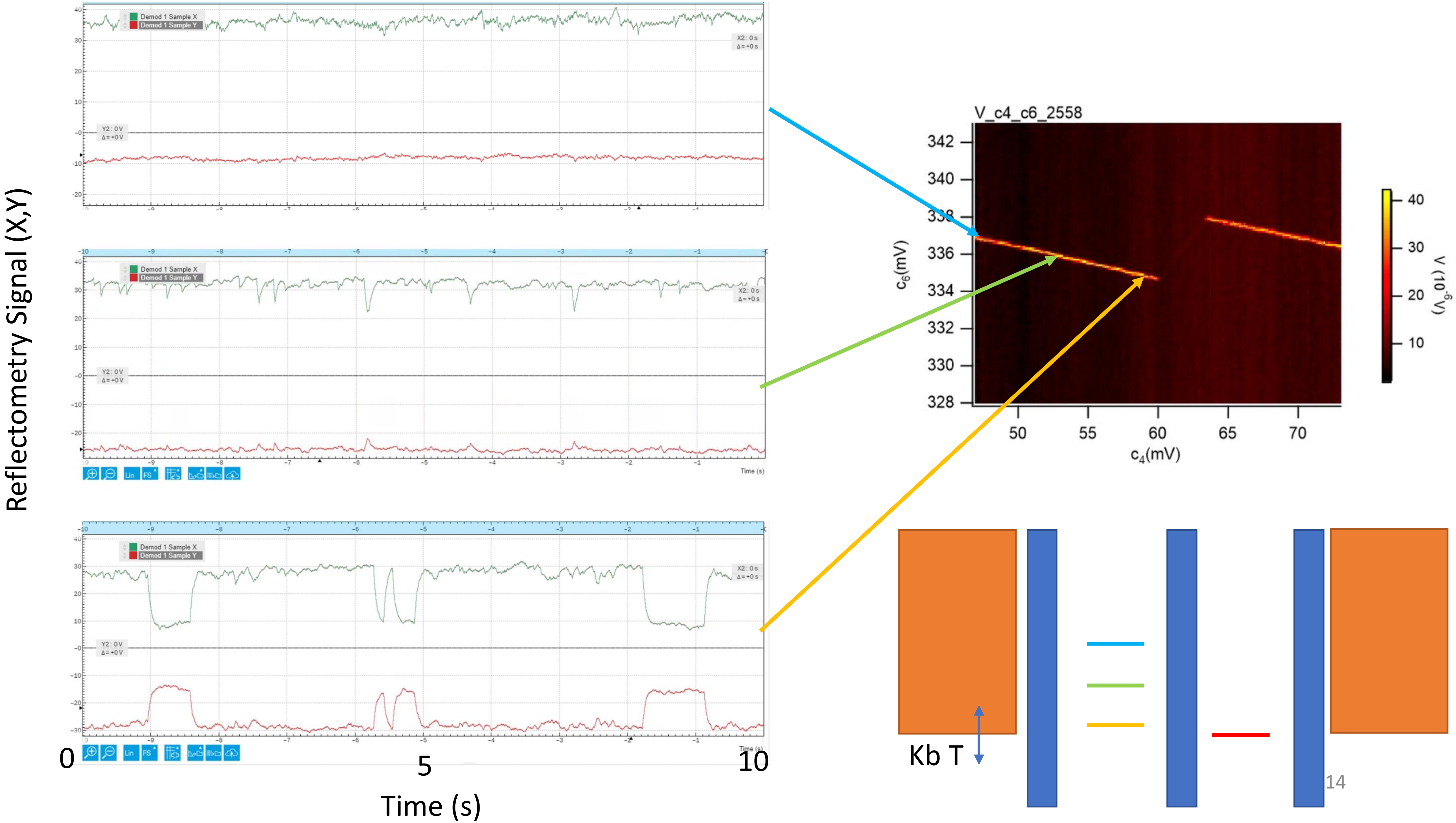
---

[1] West et al., Nat. Nanotech. **14** (2019)

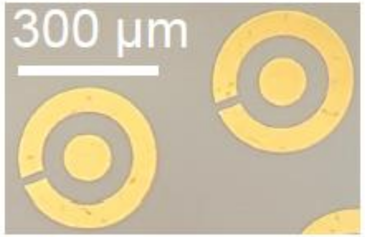
Eggli, Svab et al., arXiv. 2303.02933

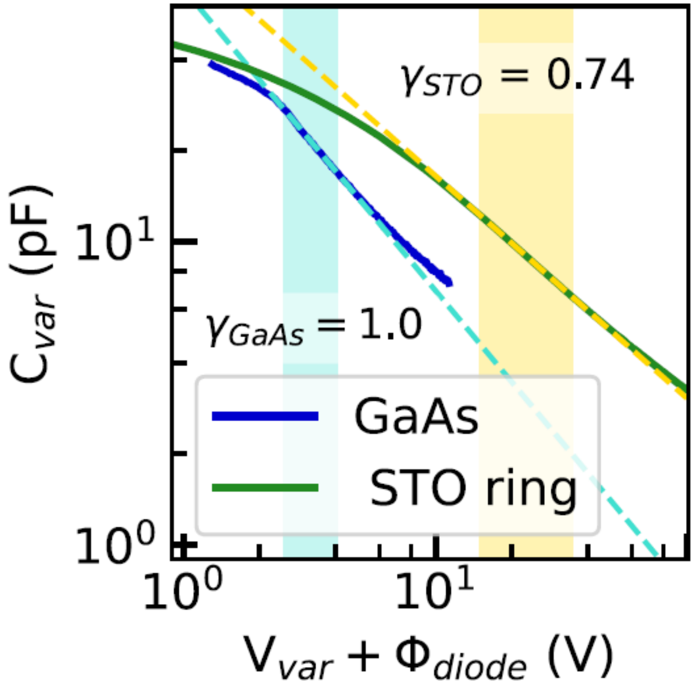
rafael.eggli@unibas.ch

Outlook: Real-Time Charge Sensing



Conclusions & Outlook





Compact hyperabrupt STO varactor:

- Resilient to magnetic field & cryogenic temperatures

-> More complex matching networks (multiplexing)

-> Matching with NbTiN high Q-inductors

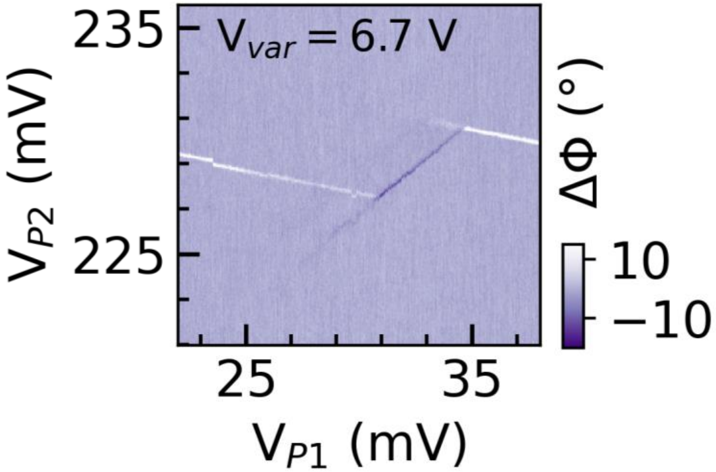
Gate-dispersive charge sensing with a Ge/Si nanowire DQD:

- Significant SNR-gains by optimisation of impedance matching

-> Last hole: currently >50 holes!

-> Short enough t_{int}: single-shot spin readout

-> T_1, 2-qubit gate benchmarking, scaling



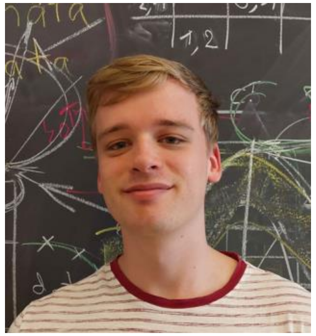
Eggli, Svab et al., arXiv. 2303.02933

rafael.eggli@unibas.ch

Acknowledgments

Simon Svab

Dominique Trüssel



Taras Patlatiuk

Dominik Zumbühl

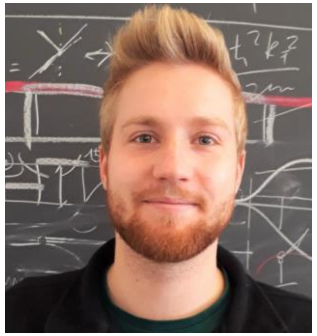
Nanowire growth:

Erik Bakkers & group

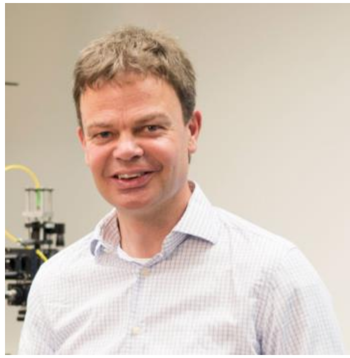
TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

Miguel J. Carballido

Pierre Chevalier-Kwon



Simon Geyer



Richard Warburton

Andreas Kuhlmann

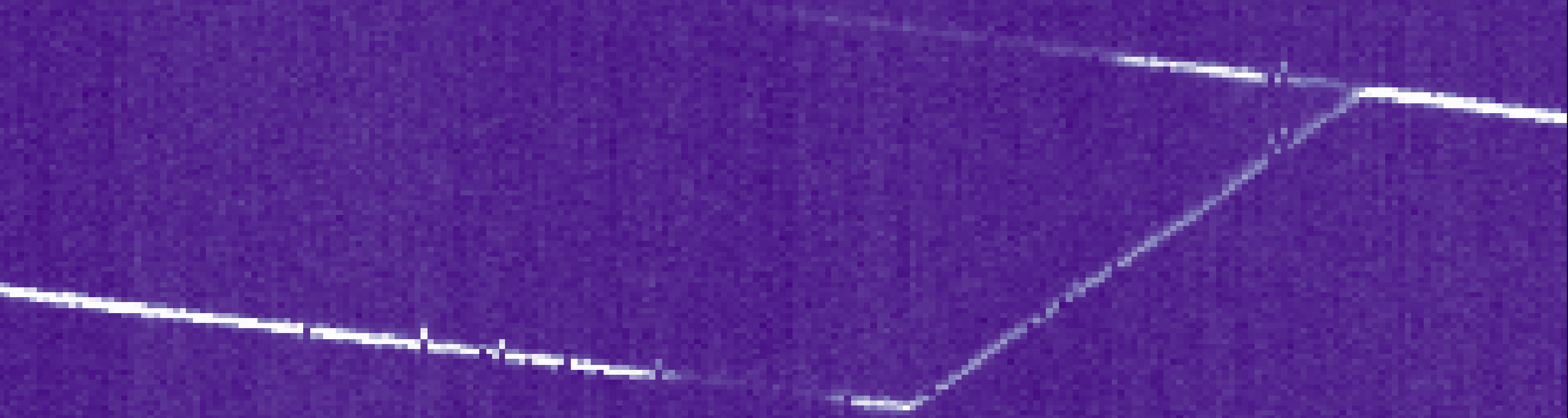
NCCR SPIN

Swiss National Science Foundation

TOPSQUAD

University of Basel

arXiv:2303.02933v1

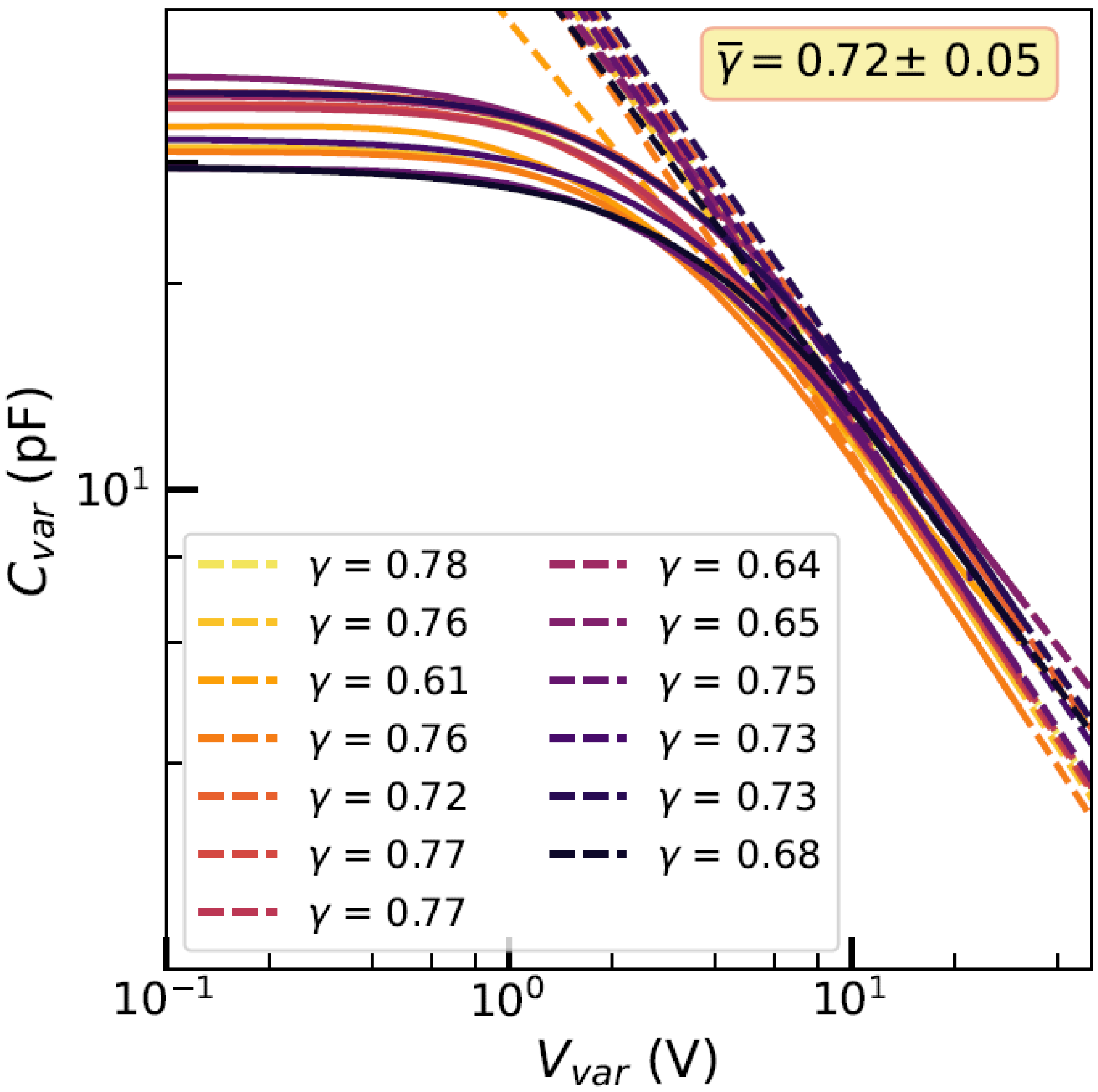


Thanks for your attention!

University
of Basel

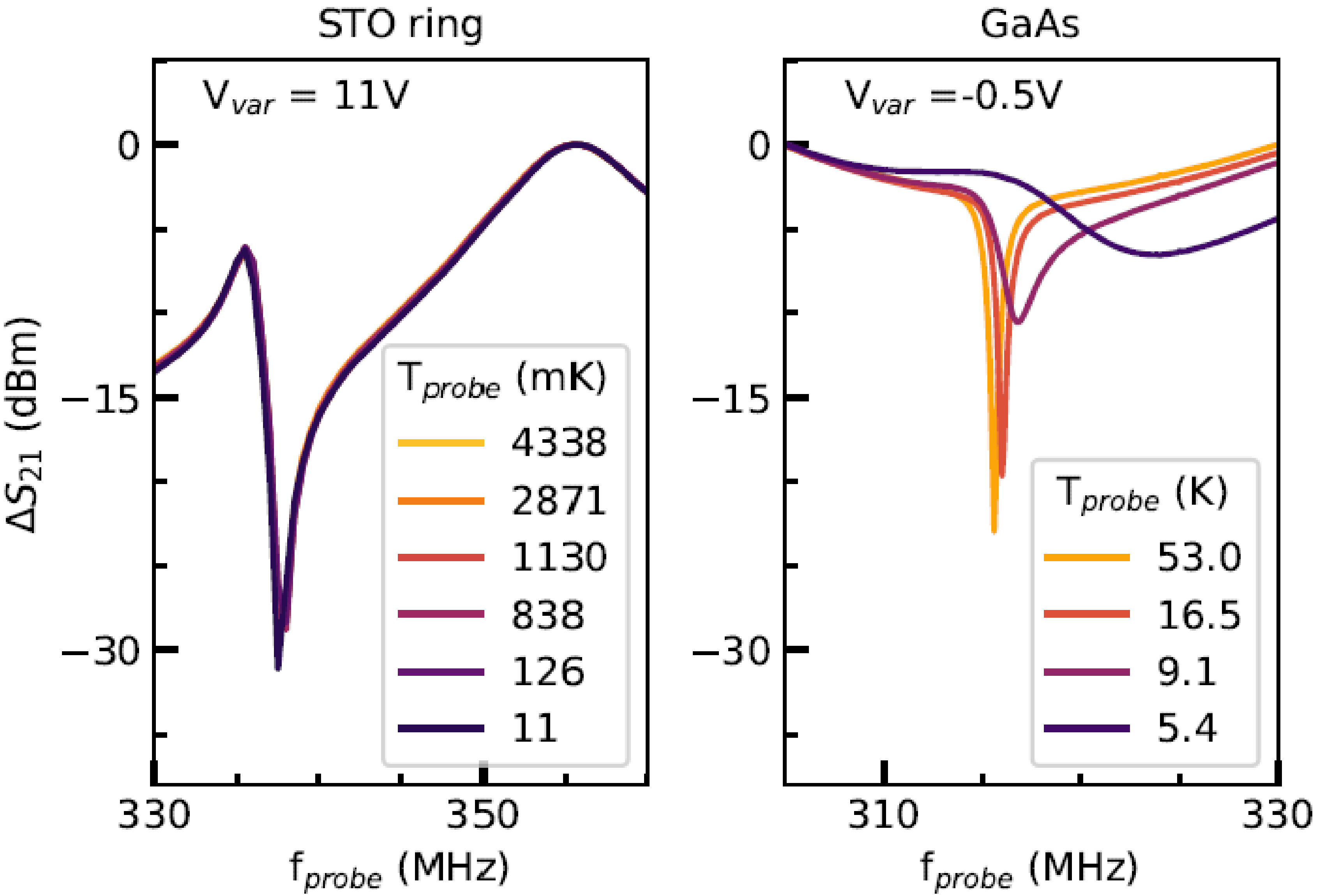
rafael.eggli@unibas.ch

Consistent Hyperabrupticity



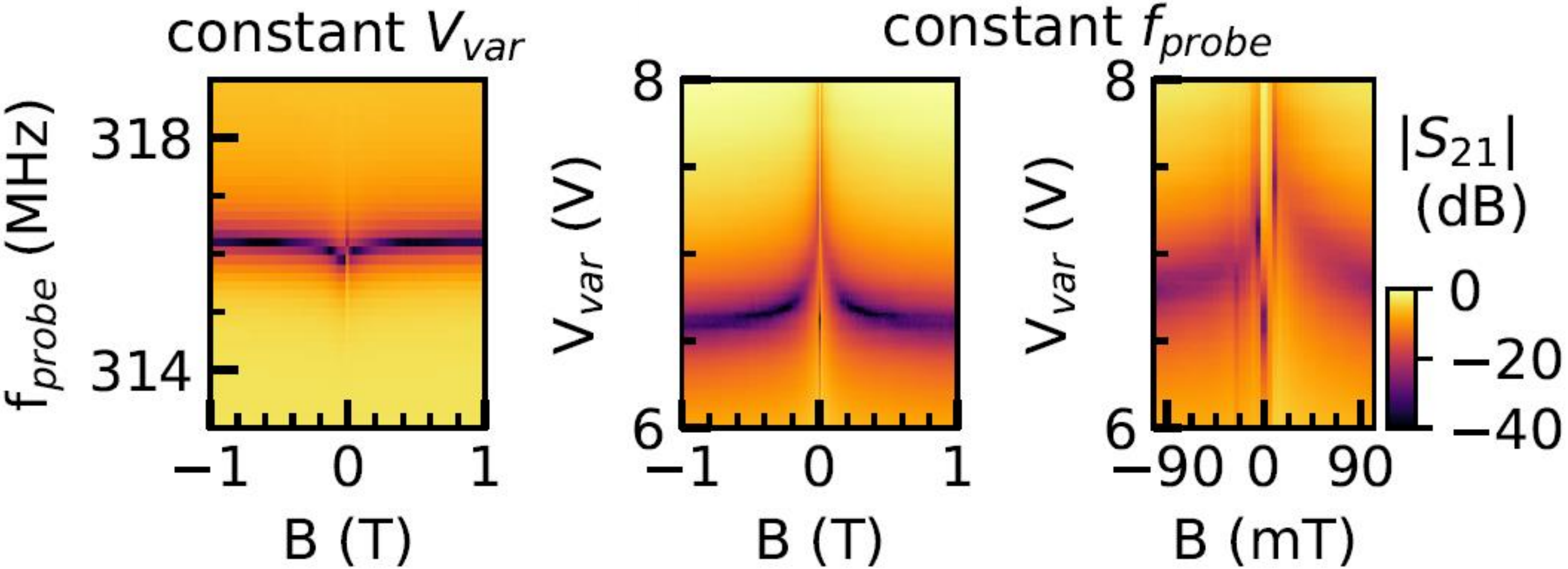
rafael.eggli@unibas.ch

Temperature-dependence: GaAs vs STO

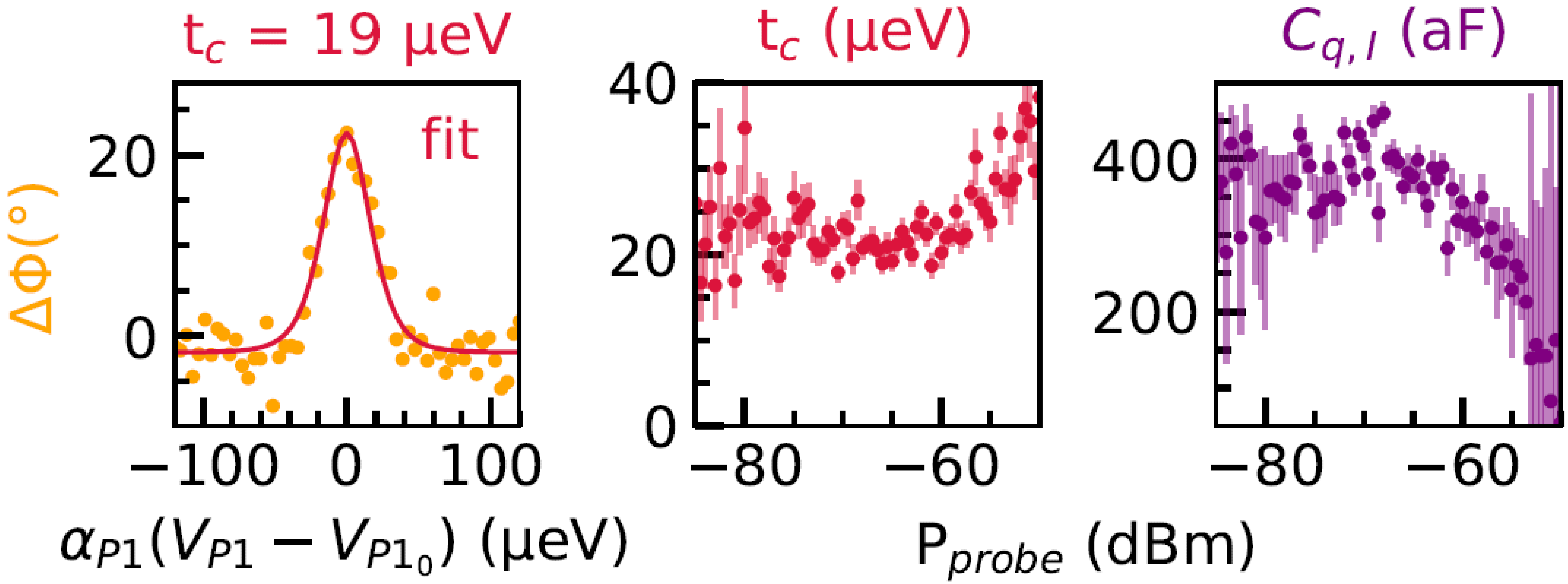


rafael.eggli@unibas.ch

Zero-Field Anomaly at mK



Lineshape Fitting: Interdot Transition



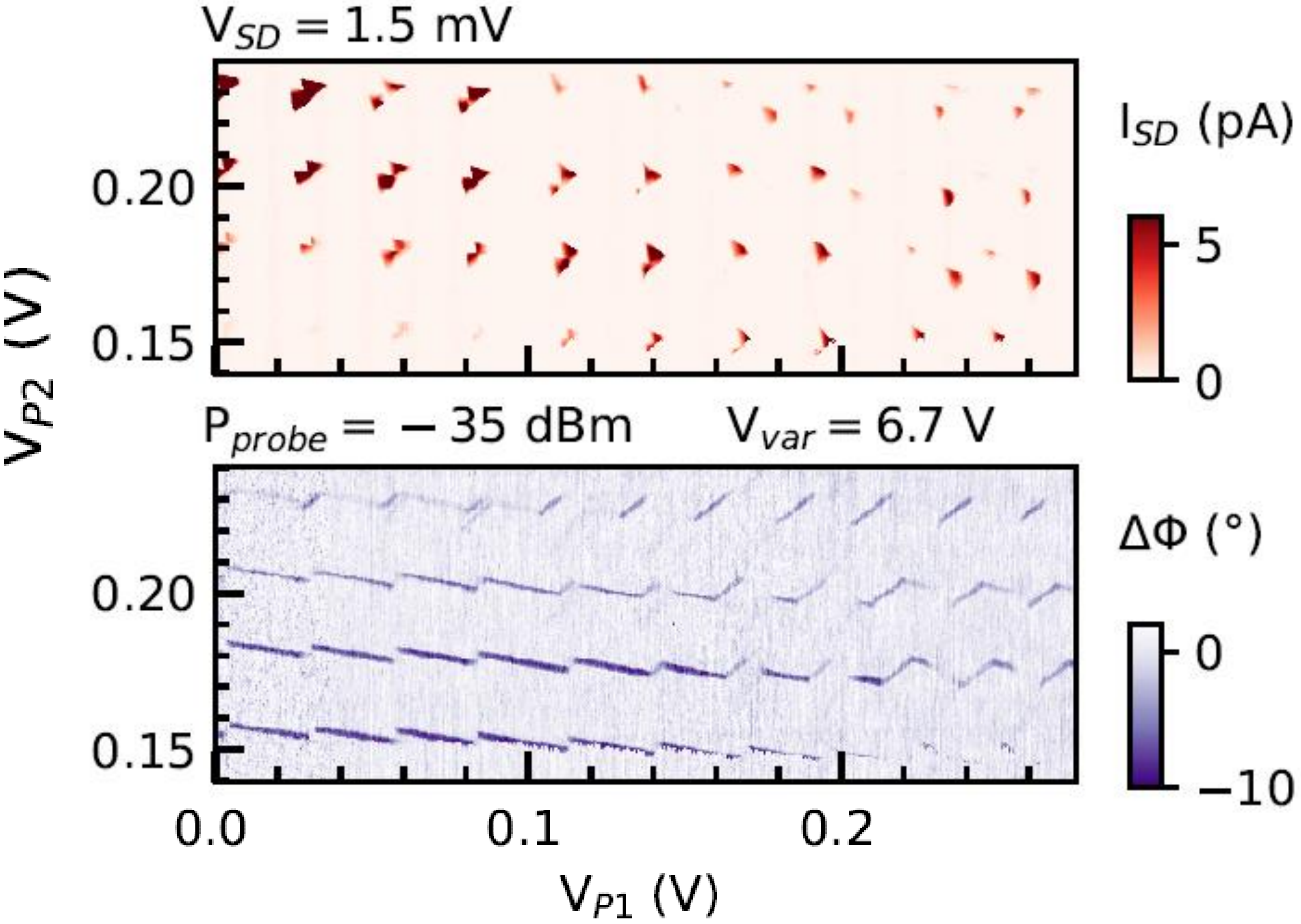
$$\Delta\Phi = \Phi_0 \cdot t_c^2 \left(\left(\frac{\alpha_{P1}(V_{P1} - V_{P1_0})}{2\sqrt{2}}\right)^2 + t_c^2\right)^{-3/2}$$

$$t_c \approx (22 \pm 5)$$

$$C_{q,I} \approx (380 \pm 70)\,\mathrm{aF}$$

rafael.eggli@unibas.ch

Large-Scale Charge Stability Map



rafael.eggli@unibas.ch