A high-sensitivity charge sensor for silicon qubits above one kelvin

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(Dated: March 12, 2021)

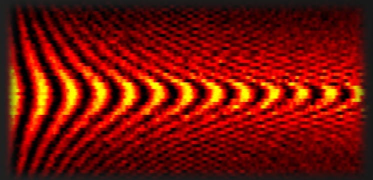
Recent studies of silicon spin qubits at temperatures above 1 K are encouraging demonstrations that the cooling requirements for solid-state quantum computing can be considerably relaxed. However, qubit readout mechanisms that rely on charge sensing with a single-island single-electron transistor (SISET) quickly lose sensitivity due to thermal broadening of the electron distribution in the reservoirs. Here we exploit the tunneling between two quantised states in a double-island SET (DISET) to demonstrate a charge sensor with an improvement in signal-to-noise by an order of magnitude compared to a standard SISET, and a single-shot charge readout fidelity above 99 % up to 8 K at a bandwidth > 100 kHz. These improvements are consistent with our theoretical modelling of the temperature-dependent current transport for both types of SETs. With minor additional hardware overheads, these sensors can be integrated into existing qubit architectures for high fidelity charge readout at few-kelvin temperatures.

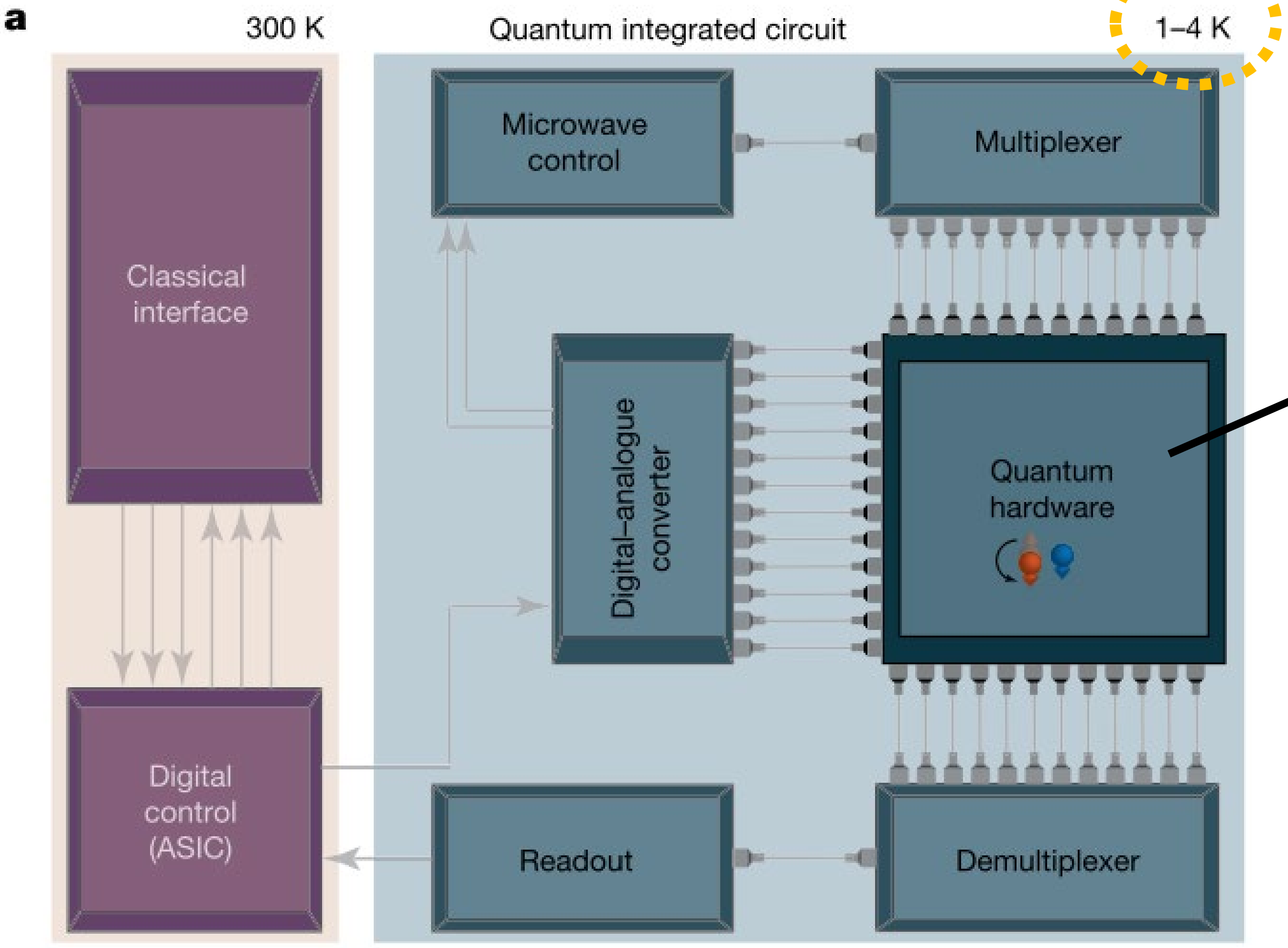
Leon Camenzind

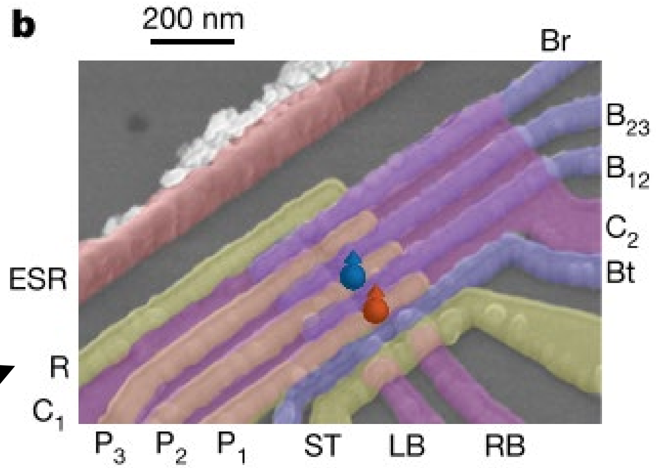
March 29, 2021

SPIN Journal Club

Motivation for hot spin qubits





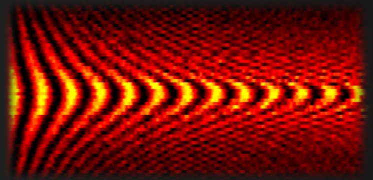


Temperature	cooling power Q
20 mK	1 μW
40 mK	10 μW
100 mK	100 μW
1 K	2.5 mW
1.2 K	**3.2 mW**
4.2 K	17 mW (int.)

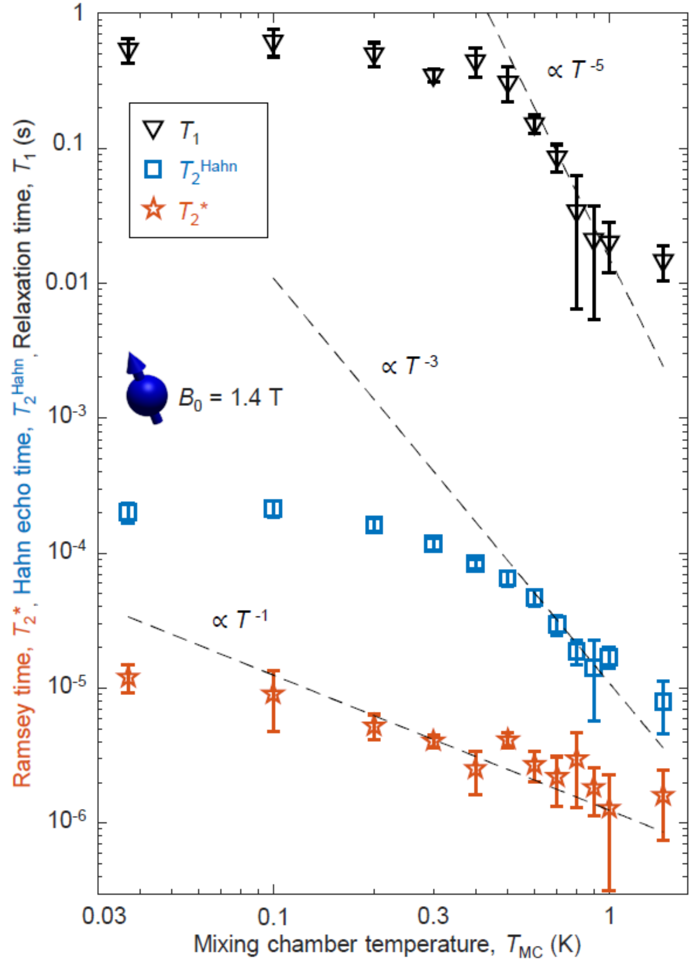
Petit *et al.*, Nature **580** (2020).
Intel Horse Ridge cryogenic controller (3K): Xue et al., arXiv:2009.14185 (2020).

* from MCK50 Manual

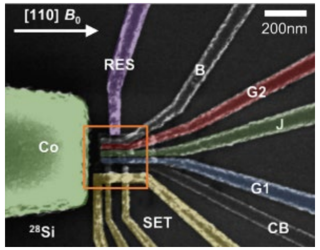
Hot spin qubits



UNSW



Yang *et al.,* Nature **580** (2020). [cited 56]

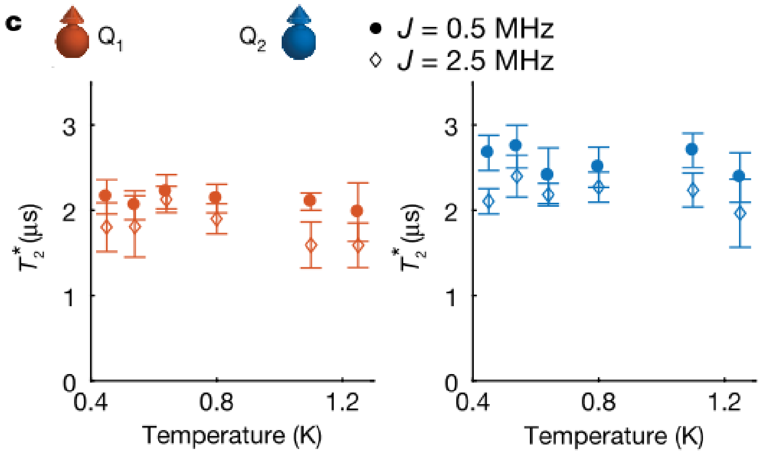


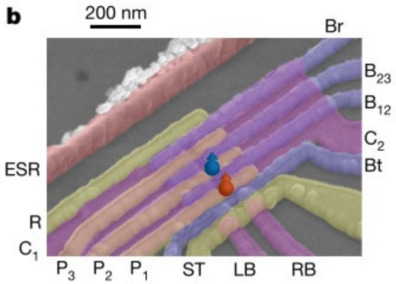
Electrons + MM

$T_\pi \sim 1\ \mu s$
$\rightarrow Q^* \sim T_2^*/T_\pi \sim 2$

TU Delft

Petit *et al.,* Nature **580** (2020). [67]



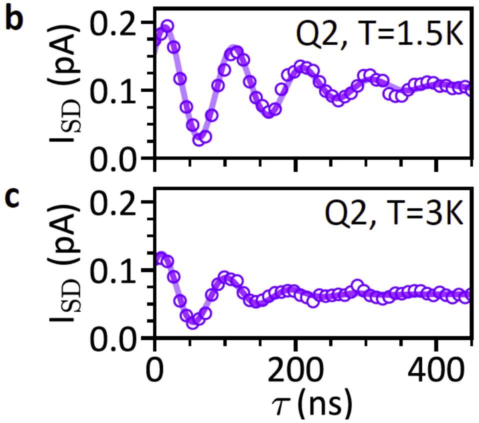


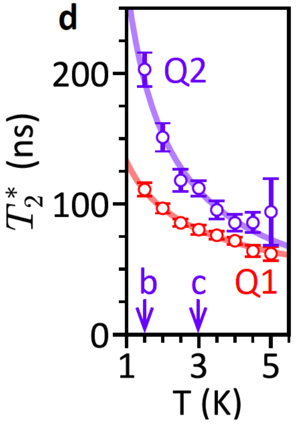
Electrons + antenna

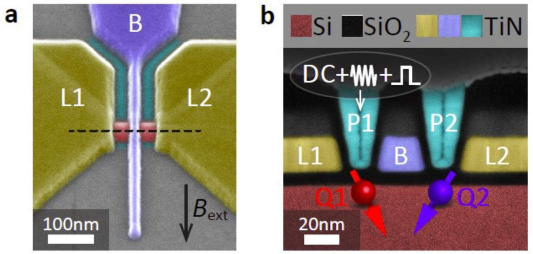
$T_\pi \sim 0.5\ \mu s$
$Q^* \sim 4-5$

Basel / IBM

Camenzind, Geyer et al., arXiv:2103.07369(2021).

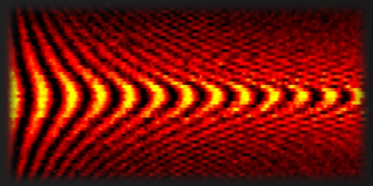




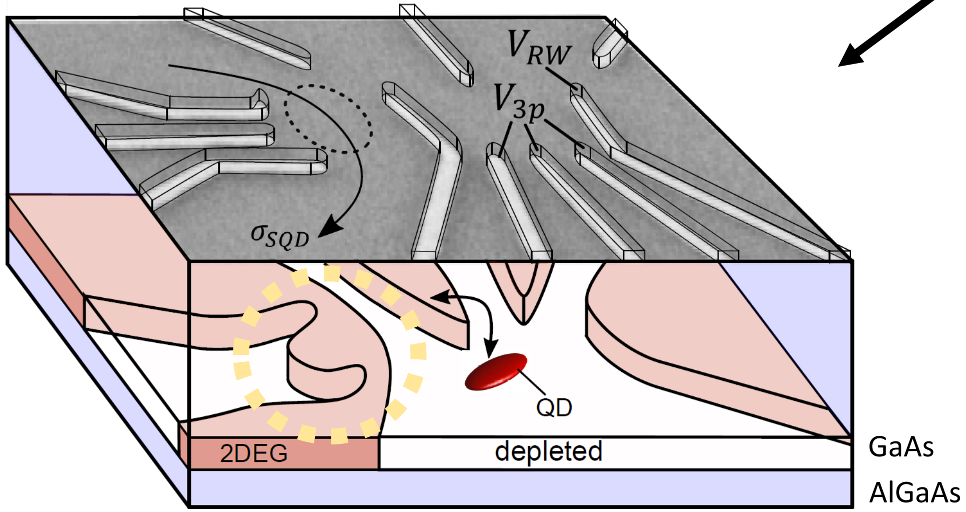


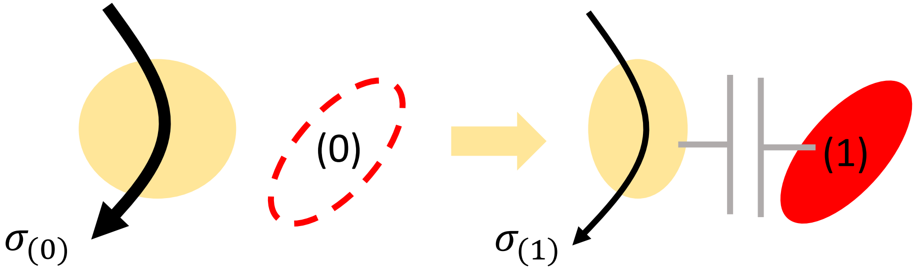
holes (SOI)

$Q^* > 10$ (at 4K!)



Spin qubit read-out

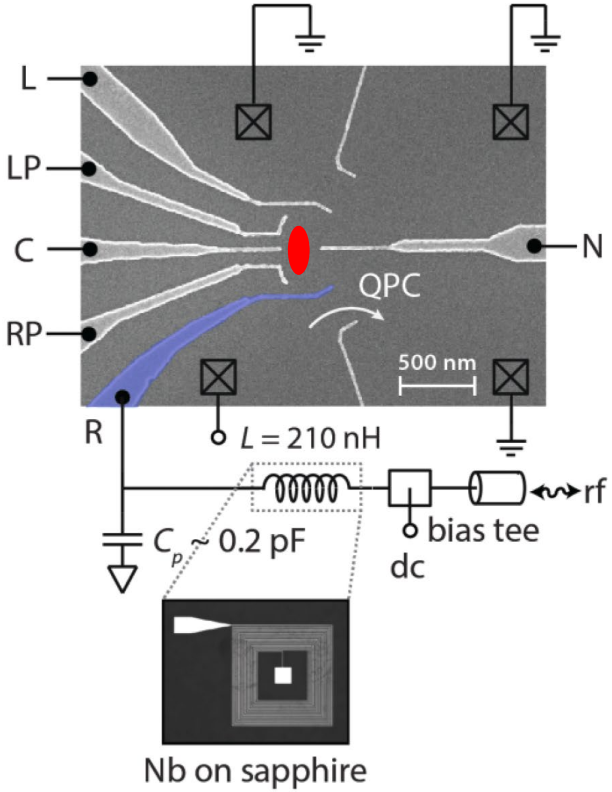




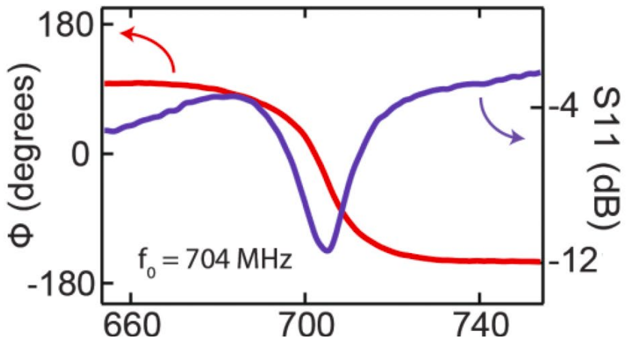
Sensors: QPCs, QDs, **SETs**
Also tank circuit: RF-QPC etc.

Field et al., PRL (1993), Elzerman et al., PRB (2003),
Lu et al., Nature (2003), Vandersypen et al., APL (2004).
RF-QPC: Reilly et al., APL (2007)
RF-SET: Schoelkopf et al., Science (1998)
RF-QD: Barthel et al., PRB (2010)

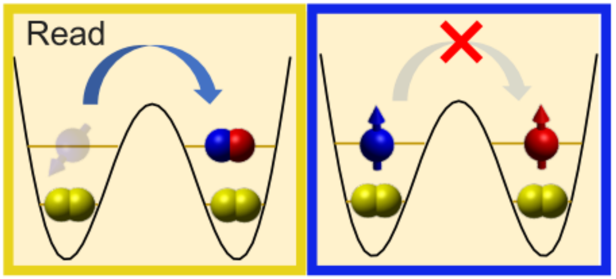
Gate sensor: tank circuit sensitive to quantum capacitance (tunneling)



Colless et al., PRL (2013)



single shot (parity) read-out

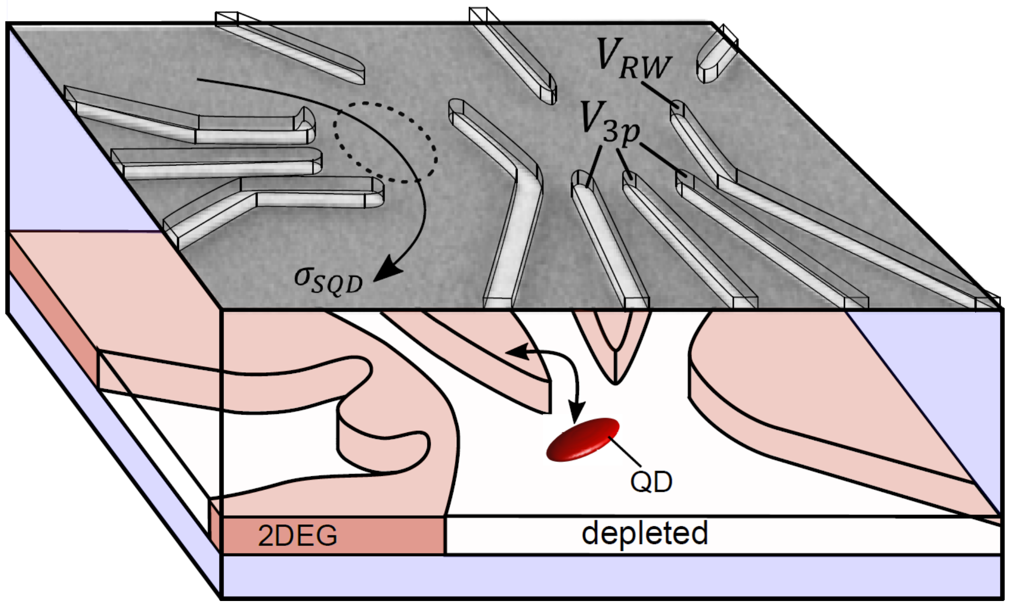


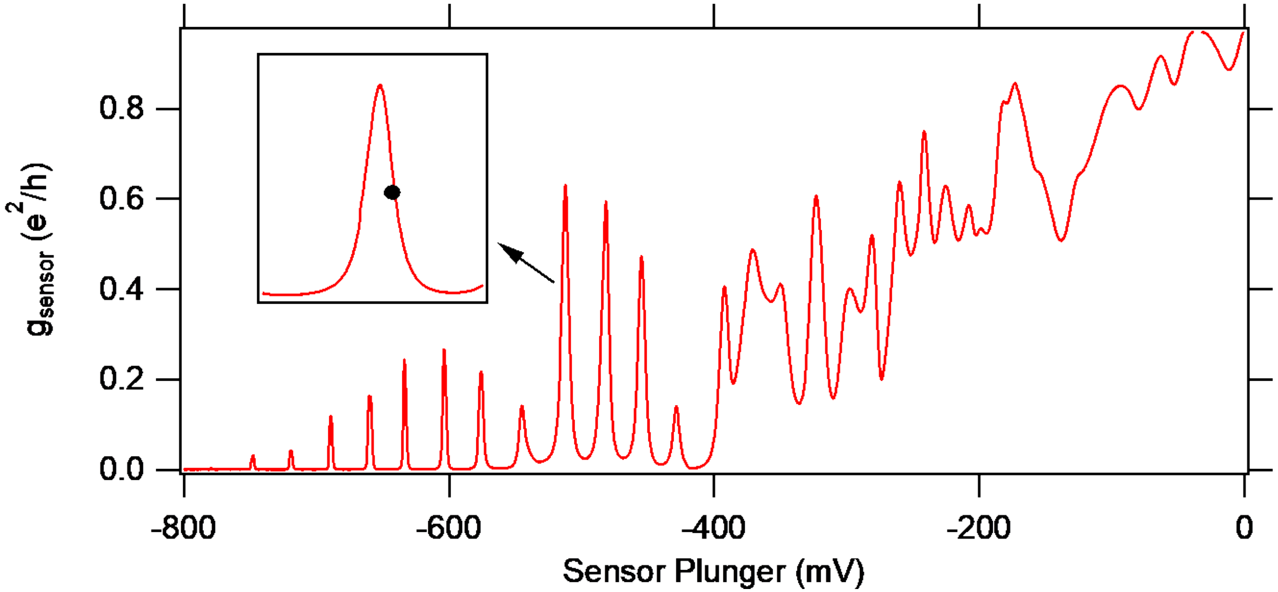
Yang et al., Nature (2021)

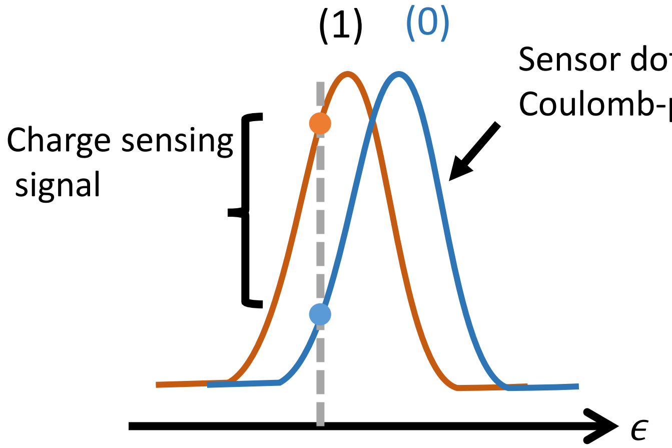
Advantage: scalability + temperature

West et al. Nat. Nano (2019), Pakkiam et al., PRX (2018),
Urdampilleta et al., Nat. Nano (2019).

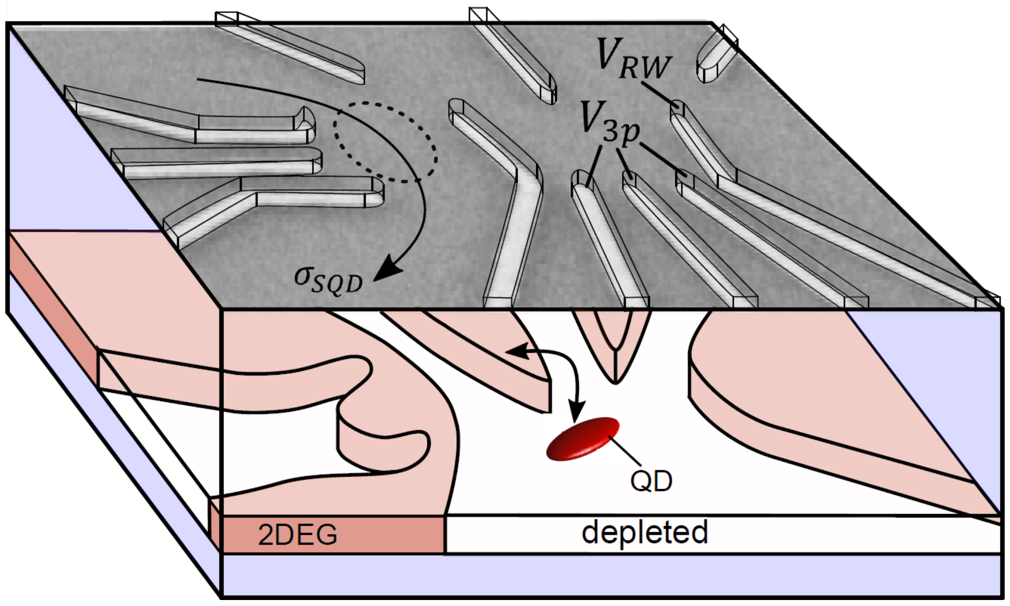
Charge sensing

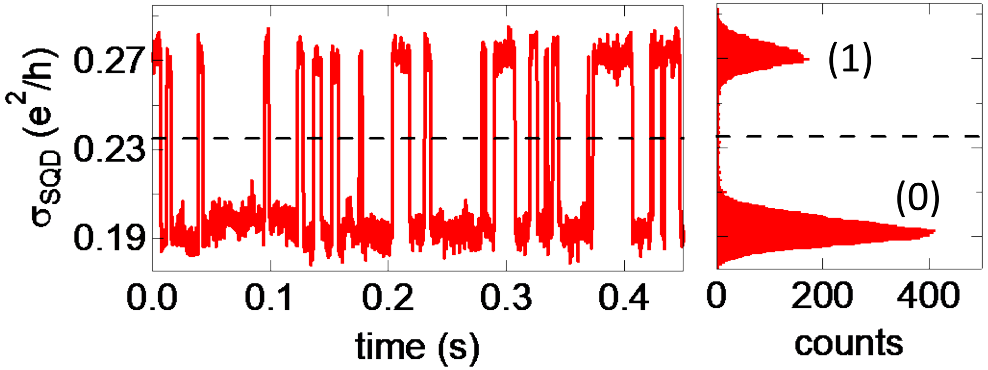


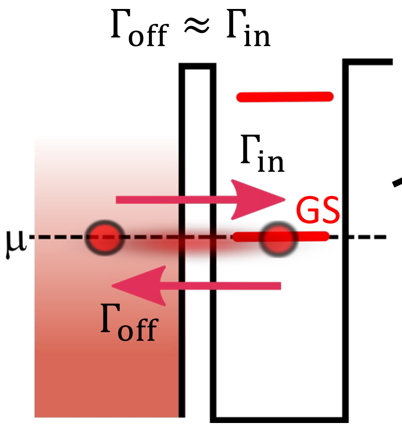


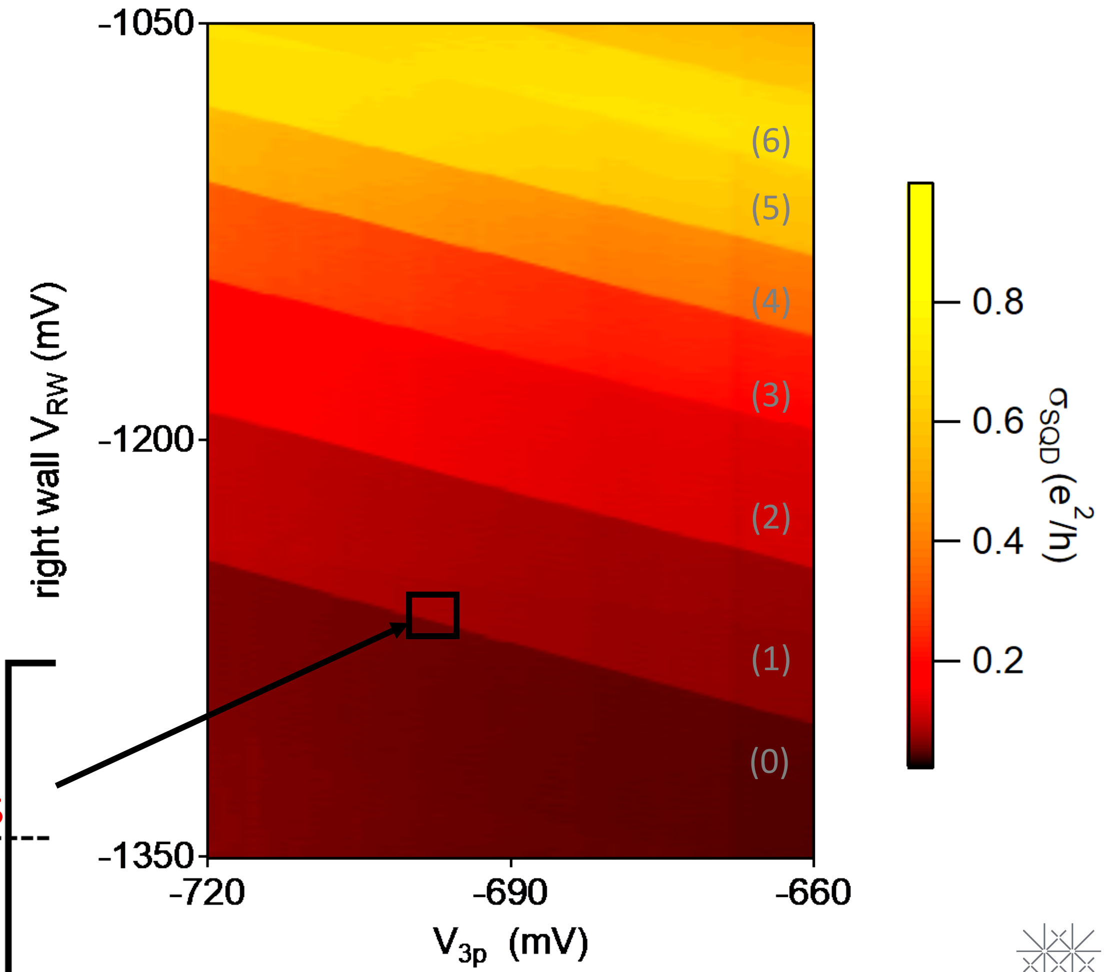


Charge sensing

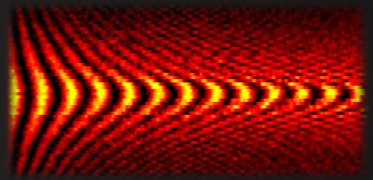




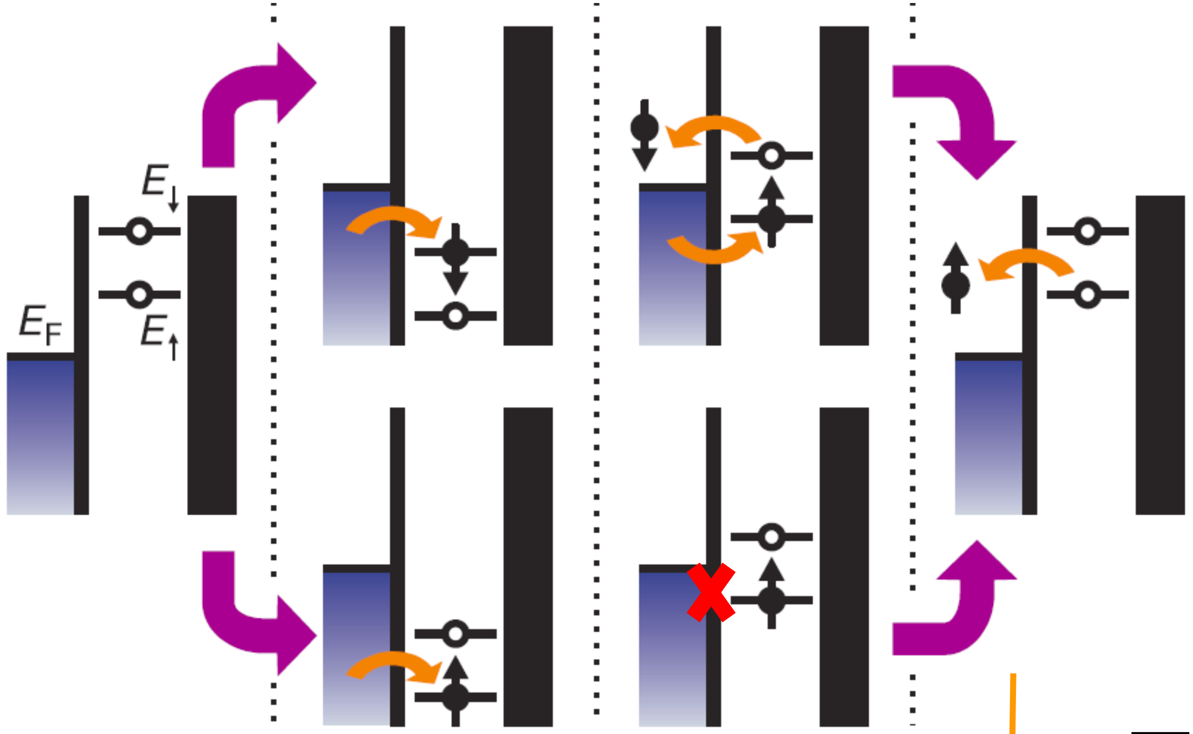


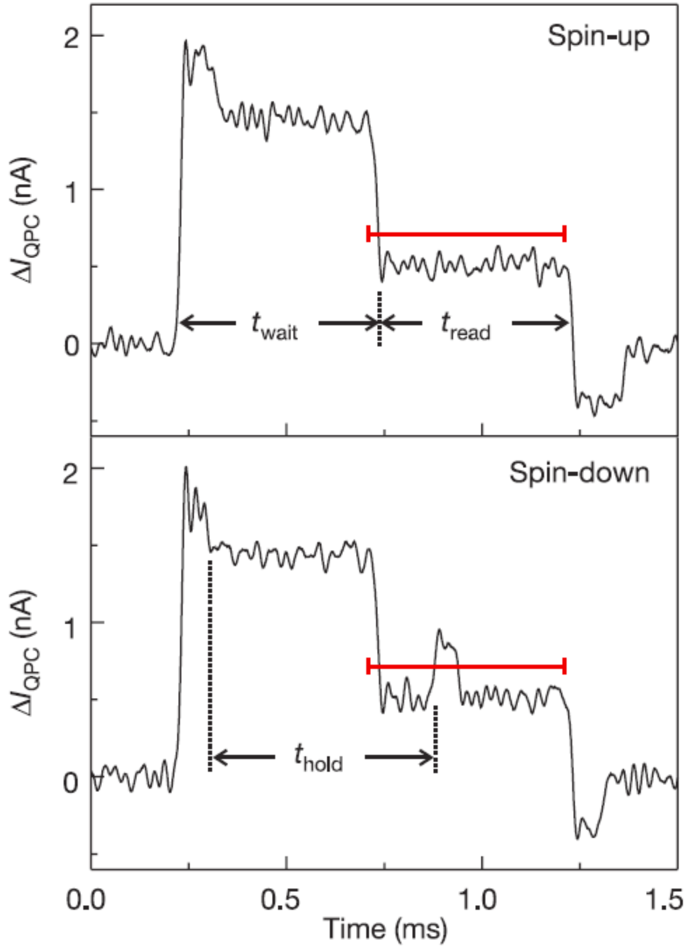


Energy selective read-out (Elzerman)



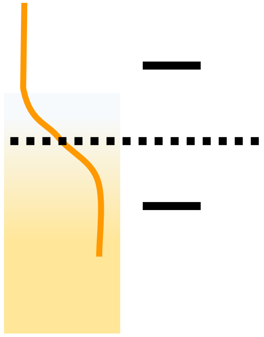
Readout + Initialisation





Elzerman et al., Nature (2004).

Limits:
T_1
speed (TR / BW)
temperature

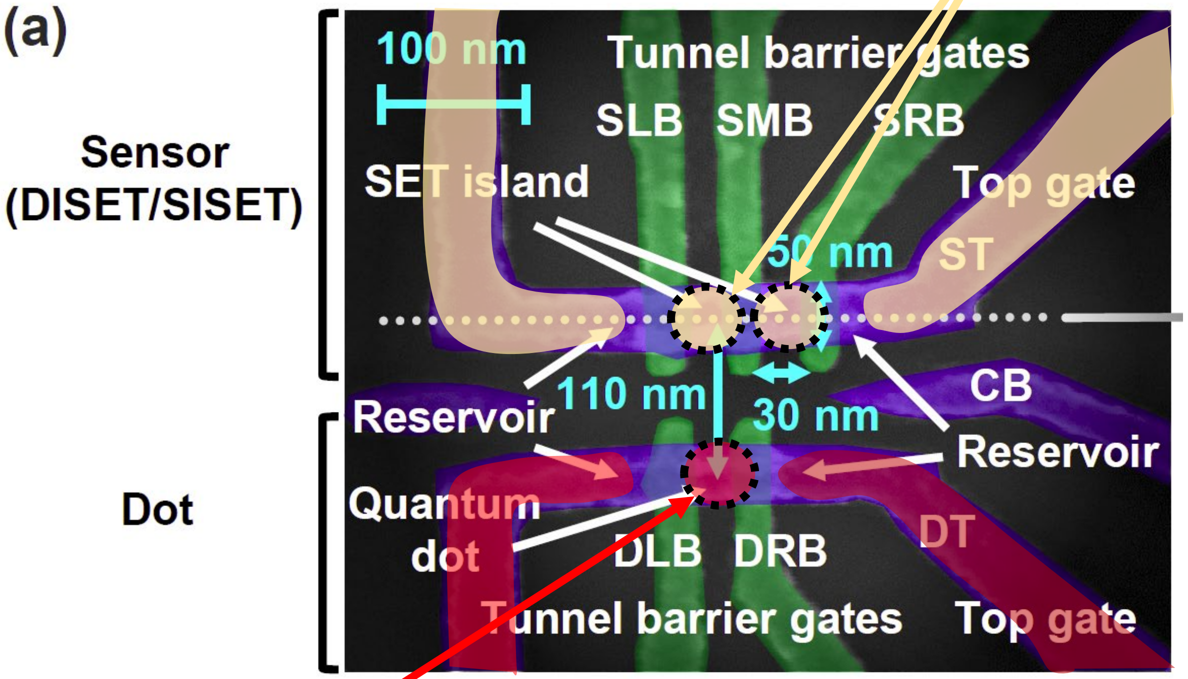


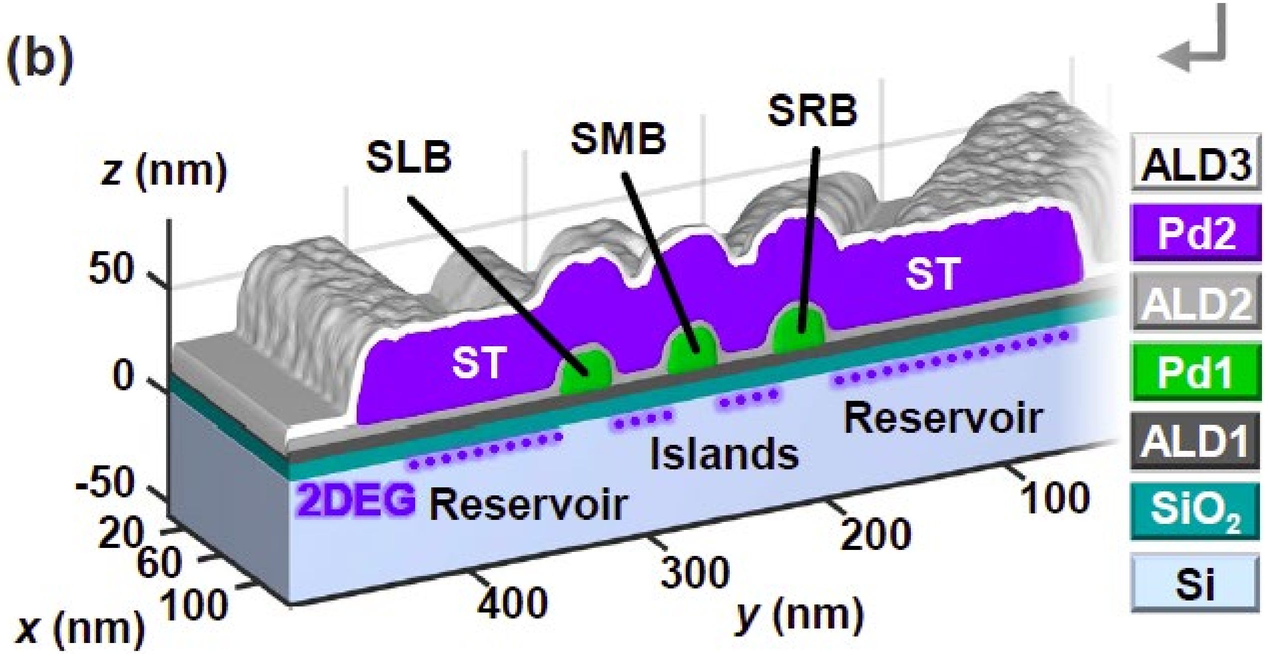
Device overview

Device

Cross-section

single-island SET (SISET)
double-island SET (DISET)

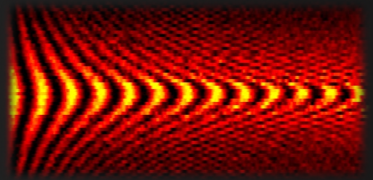




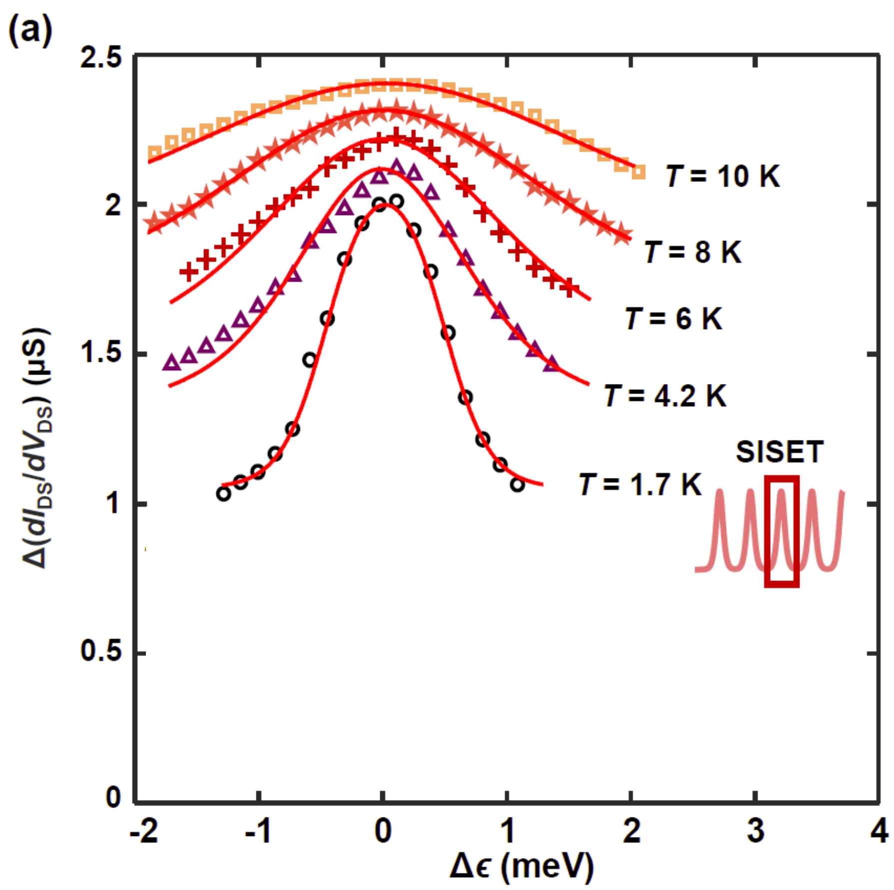
«Qubit»

- ^{nat}Si MOS
- 2x Pd gate layers
- 3x ALD: Al_xO_y

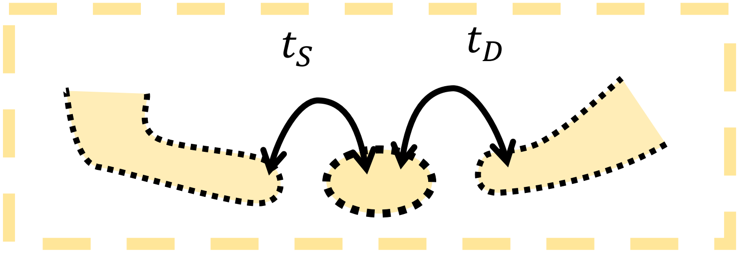
SISET transport characteristics

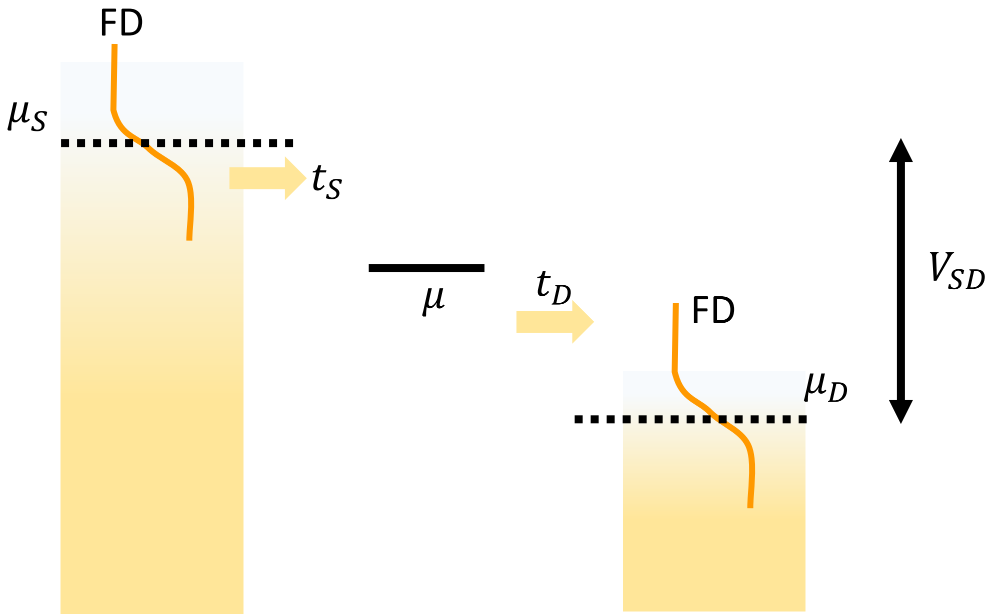


SISET transport



$t_S, t_D \approx 42$ GHz

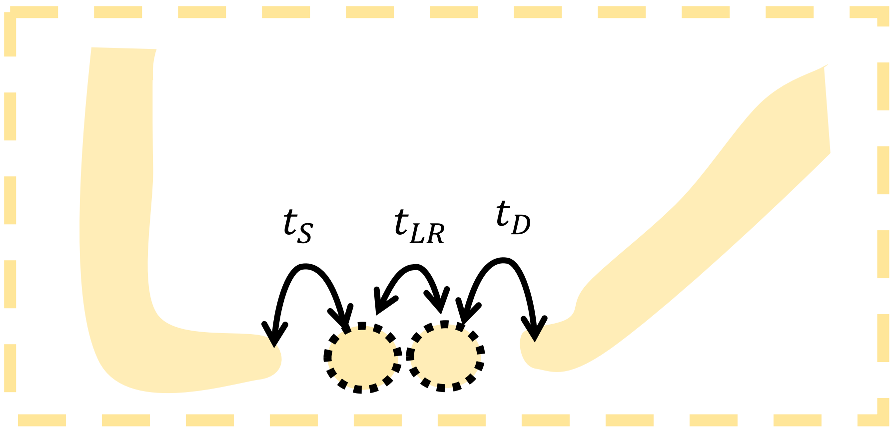


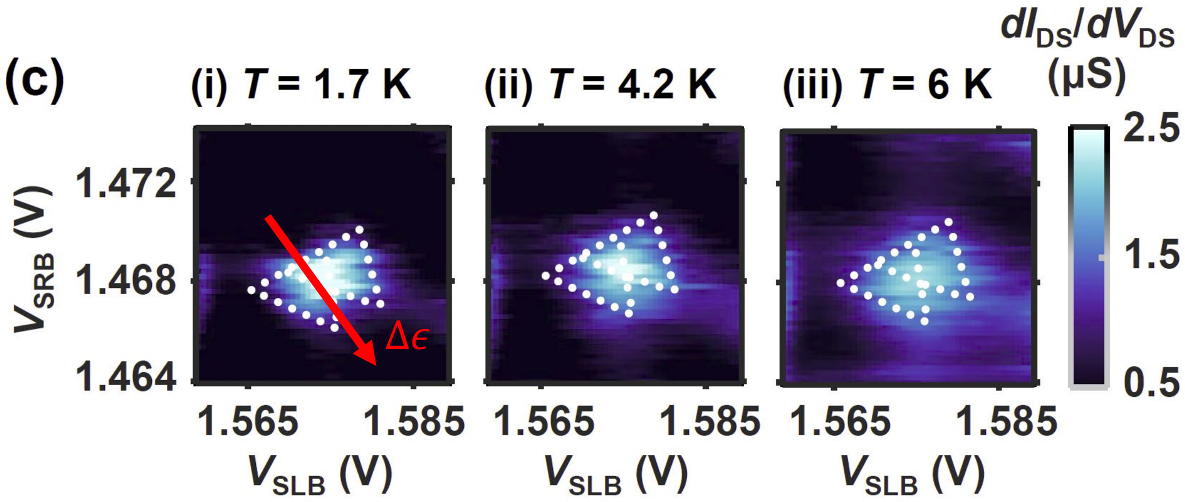


$$I_{DS} = -e\frac{t_S t_D}{t_S + t_D}\left[f_{FD}(\mu_S, T; \mu) - f_{FD}(\mu_D, T; \mu)\right]$$

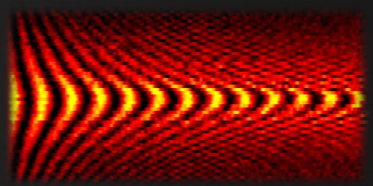
$$f_{FD}(\mu_1, T; \mu_2) = \frac{1}{\exp\left(\frac{\mu_2 - \mu_1}{k_B T}\right) + 1}$$

DISET charge sensor

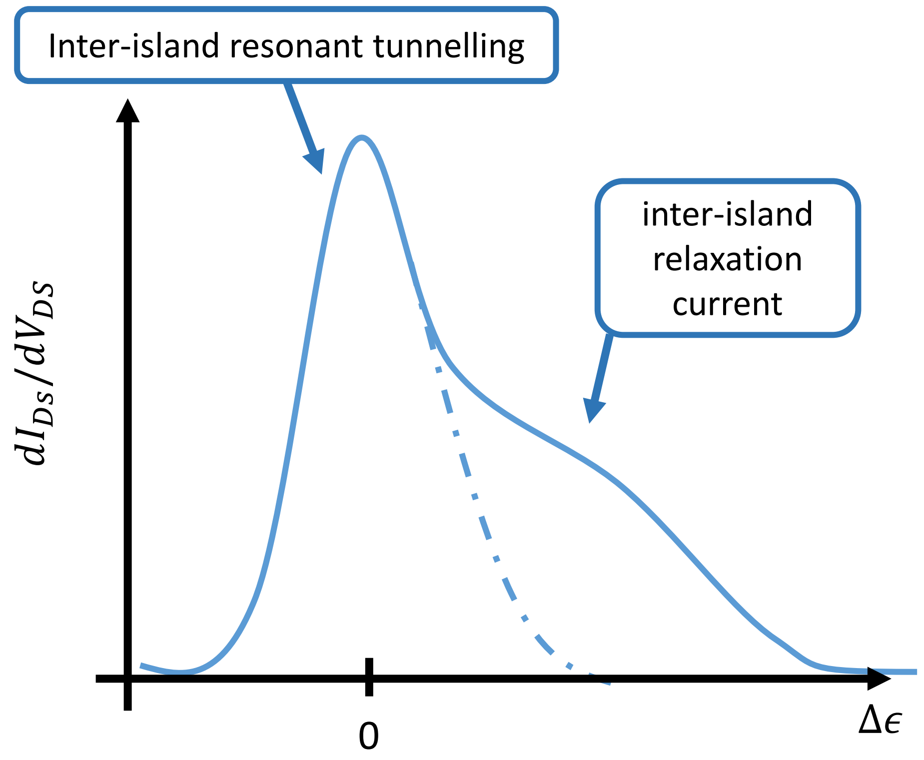


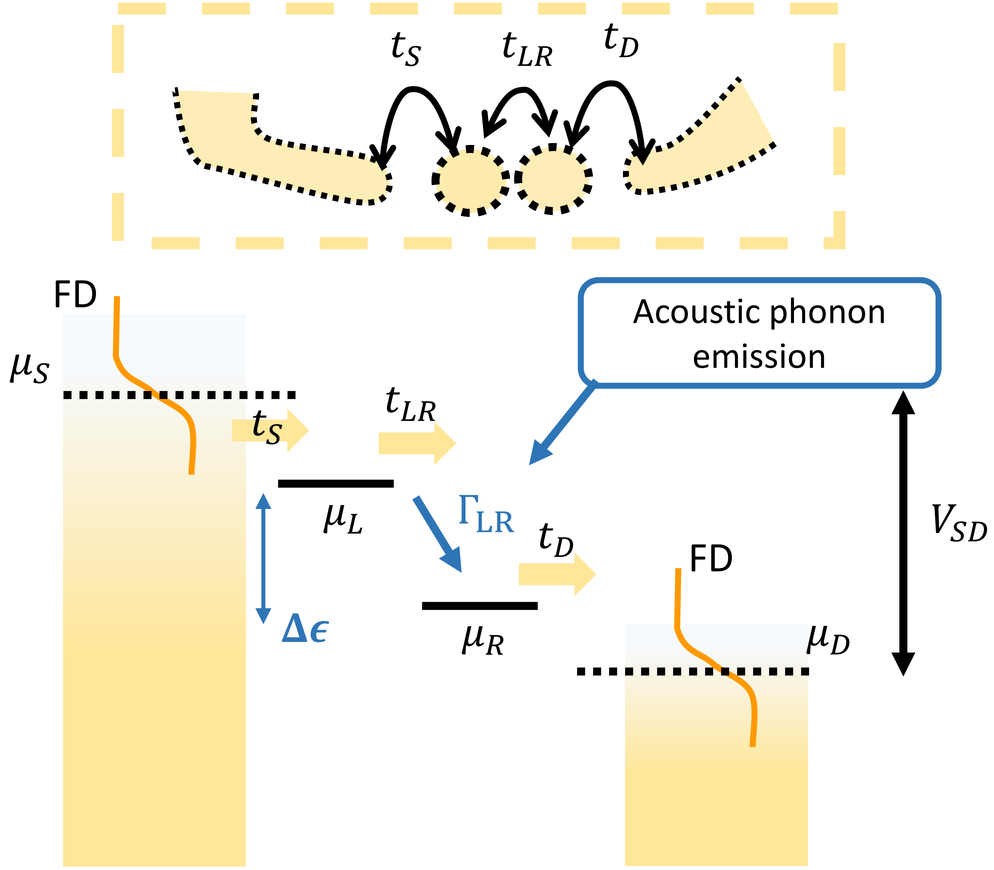


DISET transport characteristics



DIFET transport





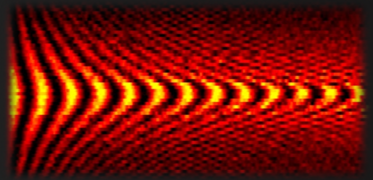
$$I_{SD} = -e\,\frac{\Gamma_{02}\Gamma_{12}\Gamma_{10} - \Gamma_{01}\Gamma_{12}\Gamma_{20} + (\Gamma_{01}\Gamma_{20} - \Gamma_{10}\Gamma_{02})\Delta}{\Gamma_{\Sigma}}$$

$$\Gamma_{12} = f_{fD}(\mu_L, T; \mu_R)\Gamma_{\mathrm{LR}}$$

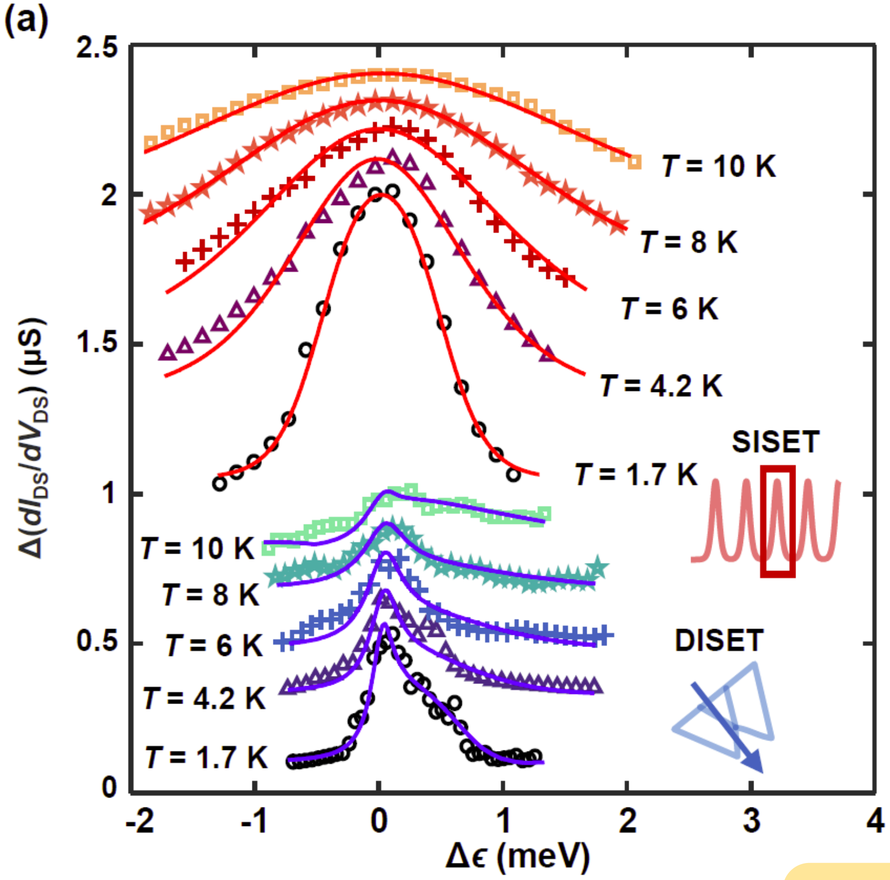
$$\Gamma_{01} = f_{fD}(\mu_S, T; \mu_L)\, t_S$$

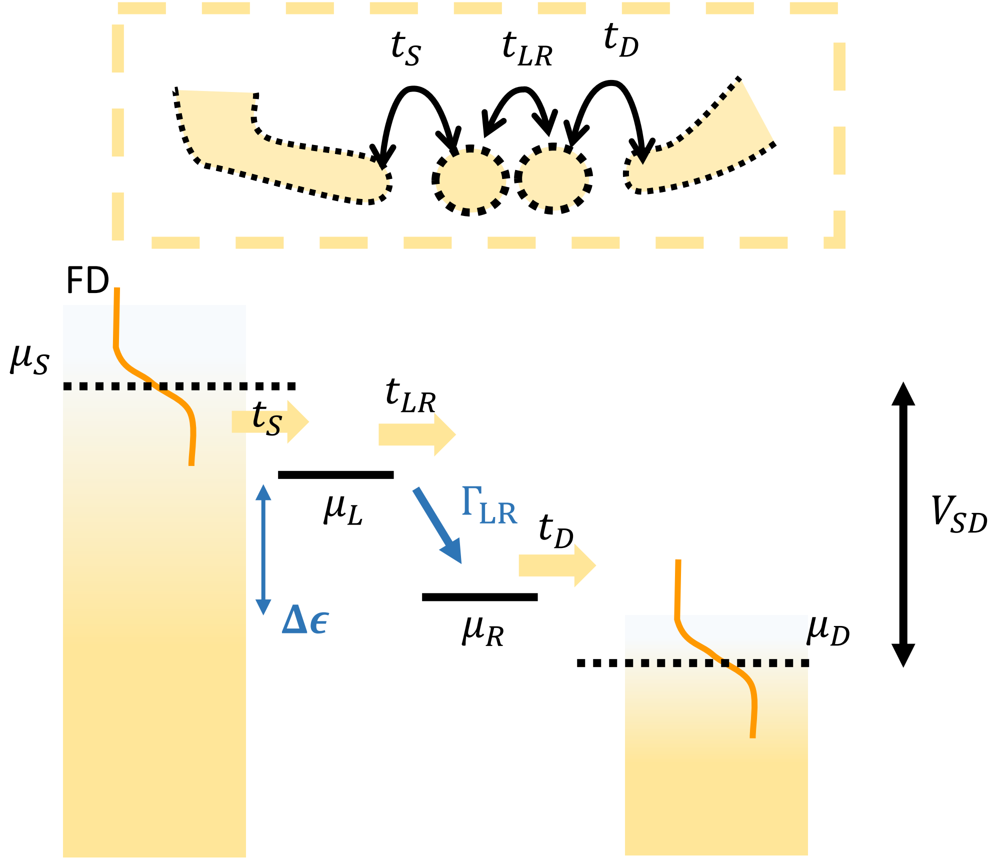
$$\Delta = \boldsymbol{t_{LR}^2}\,\frac{\Gamma_{01} + \Gamma_{20} + \Gamma_{LR}}{\left(\frac{\Gamma_{01} + \Gamma_{20} + \Gamma_{LR}}{2}\right)^2 + \left(\frac{\mu_L - \mu_R}{h}\right)^2}$$

DISET transport characteristics



SISET/DIFET transport





$$I_D = -e\frac{\Gamma_{02}\Gamma_{12}\Gamma_{10} - \Gamma_{01}\Gamma_{12}\Gamma_{20} + (\Gamma_{01}\Gamma_{20} - \Gamma_{10}\Gamma_{02})\Delta}{\Gamma_{\Sigma}}$$

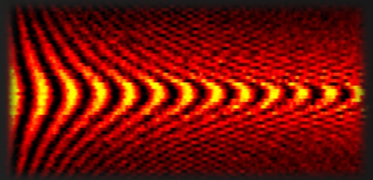
$t_{LR} \approx 20$ GHz
$t_S, t_D \approx 40$ GHz
$\Gamma_{LR} \approx 6$ GHz

$$\Gamma_{12} = f_{fD}(\mu_L, T; \mu_R)\Gamma_{\mathrm{LR}}$$

$$\Gamma_{01} = f_{fD}(\mu_S, T; \mu_L)\, t_S$$

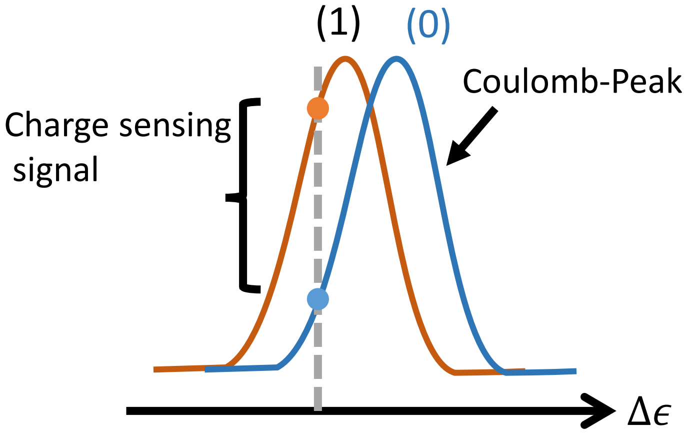
$$\Delta = t_{LR}^2 \frac{\Gamma_{01} + \Gamma_{20} + \Gamma_{LR}}{\left(\frac{\Gamma_{01} + \Gamma_{20} + \Gamma_{LR}}{2}\right)^2 + \left(\frac{\mu_L - \mu_R}{h}\right)^2}$$

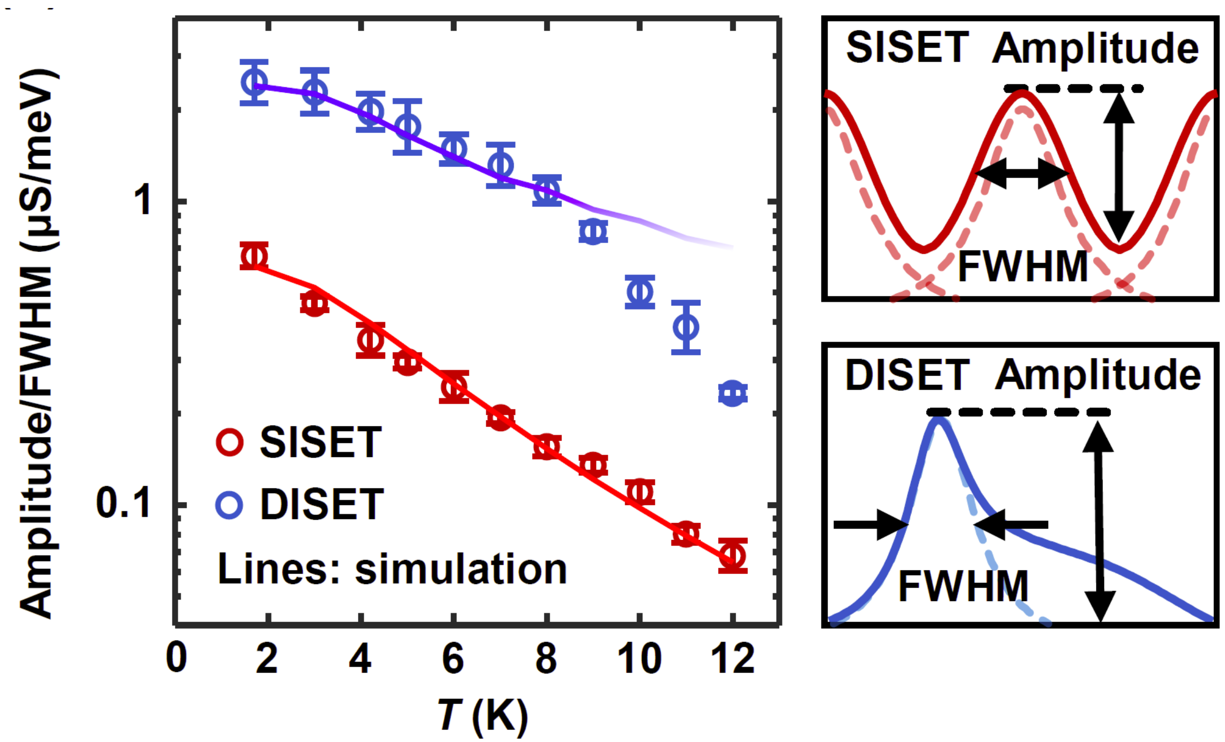
Temperature dependenence of transport characteristics



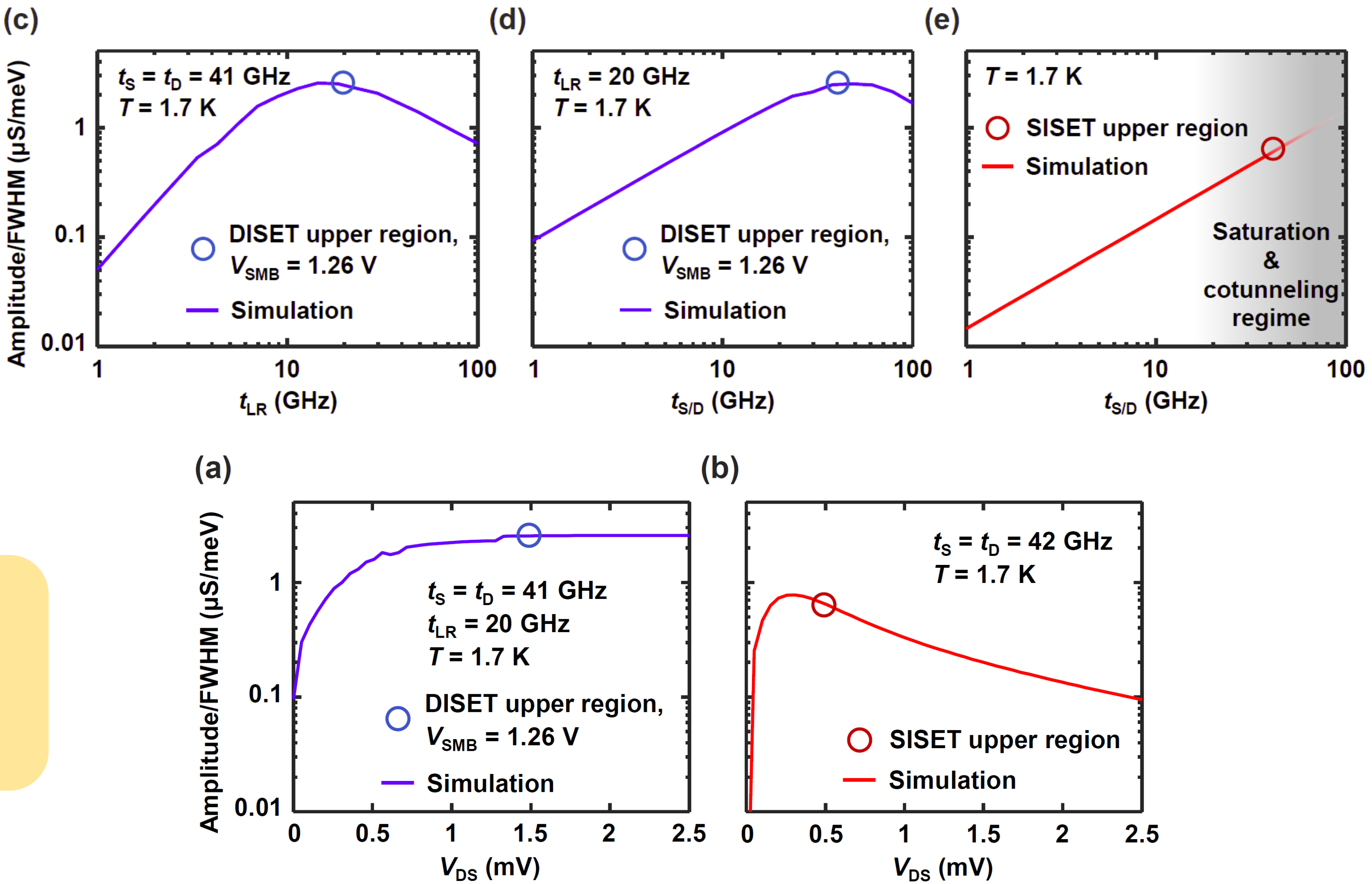
Sensitivity:

Peak «steepness»





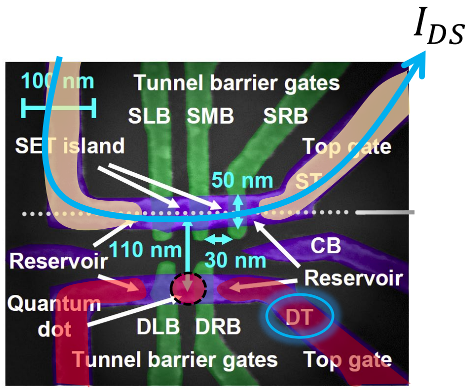
Model: optimizing the sensitivities



with model:
fine-tuning
charge sensor

UNI BASEL

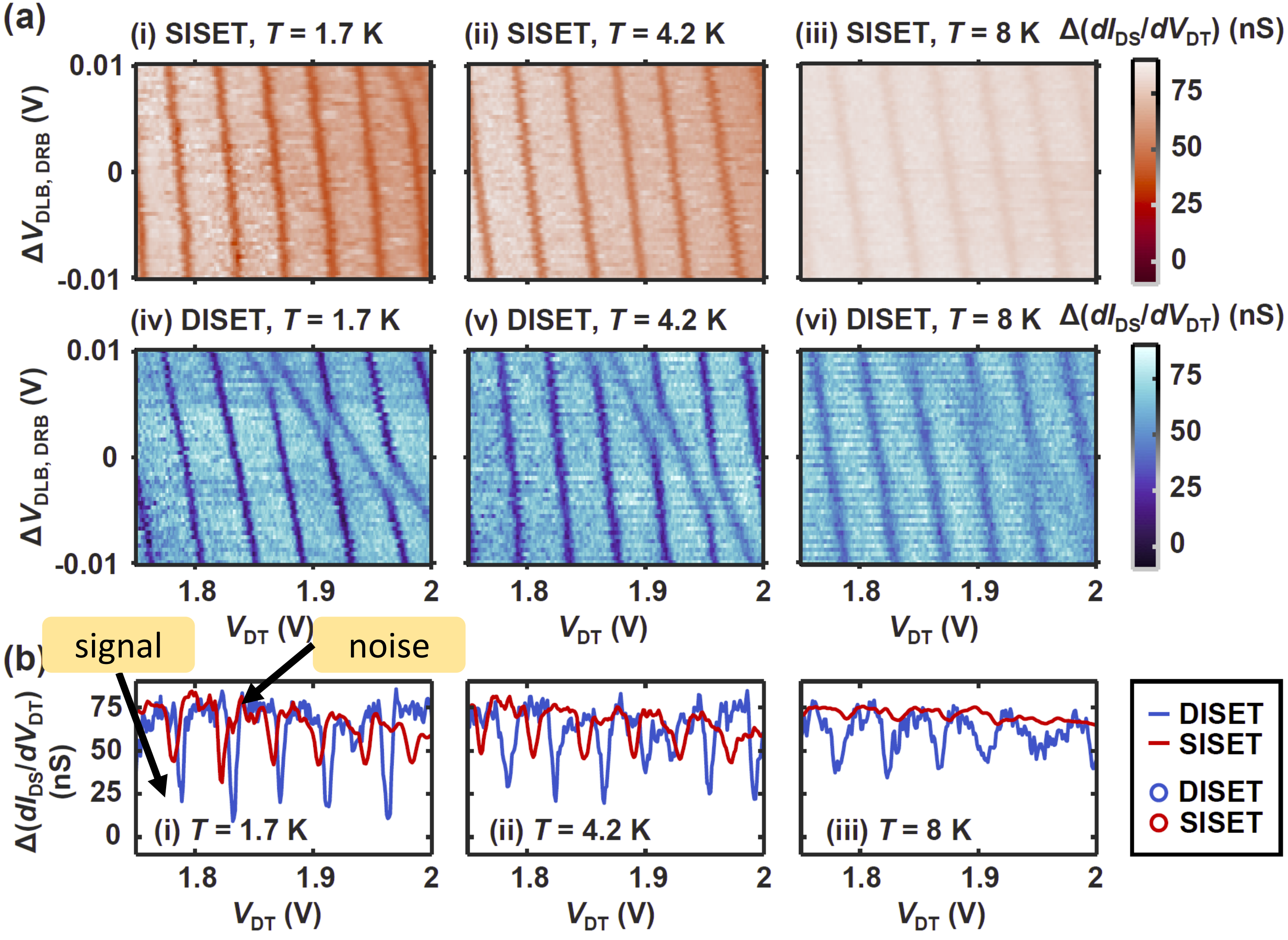
Charge sensing of quantum dot



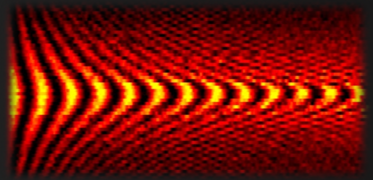
Lockin excitation at accumulation gate DT

Dynamical compensation
DISET: ST, SLB, SRB
SISET: ST

Yang et al., AIP Adv. (2011)

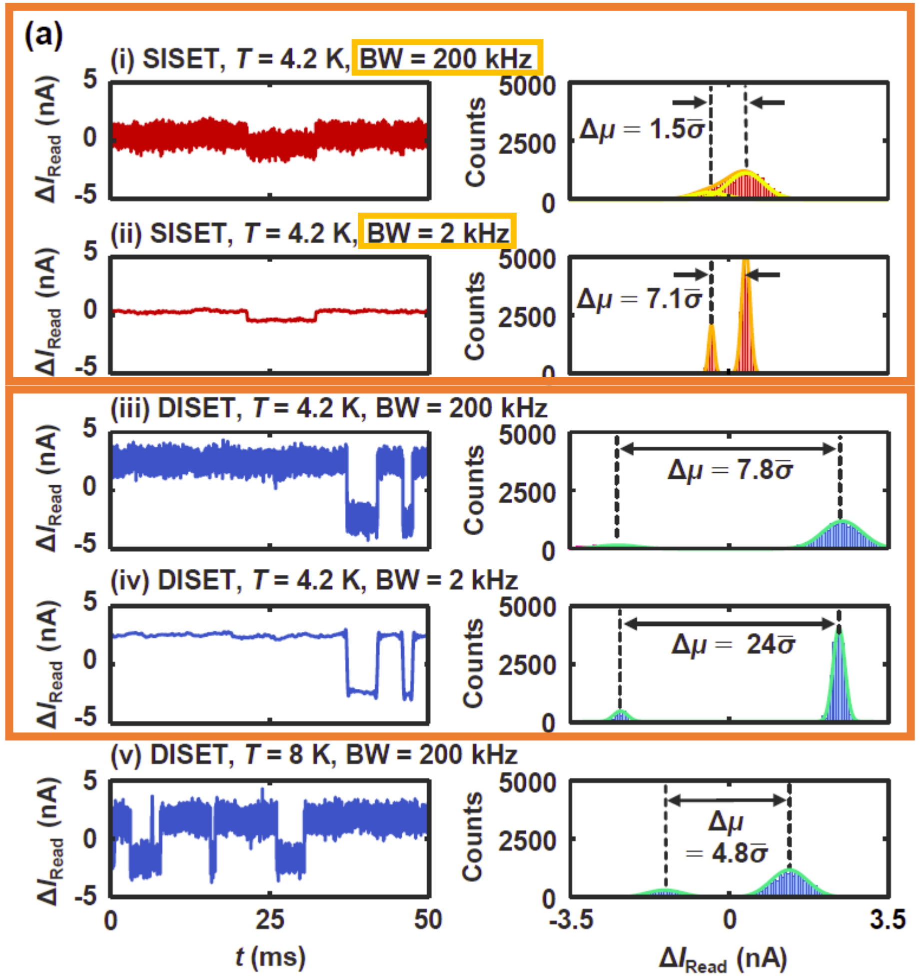


Real time «single shot» charge read-out



SISET

DISET



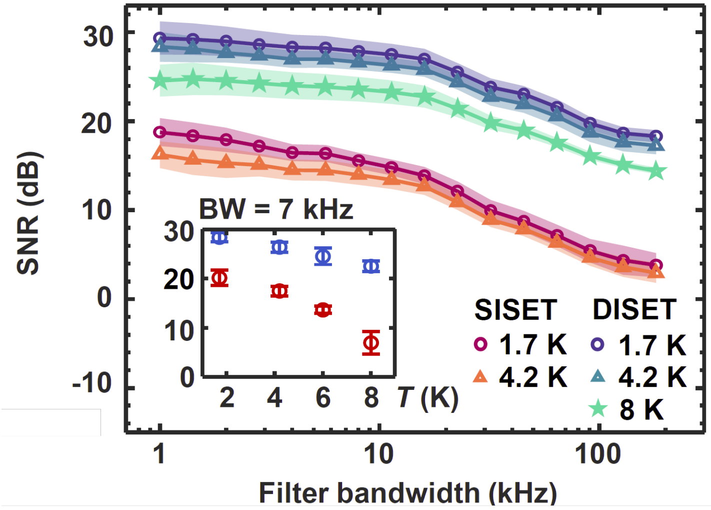
$\Delta\mu$: signal

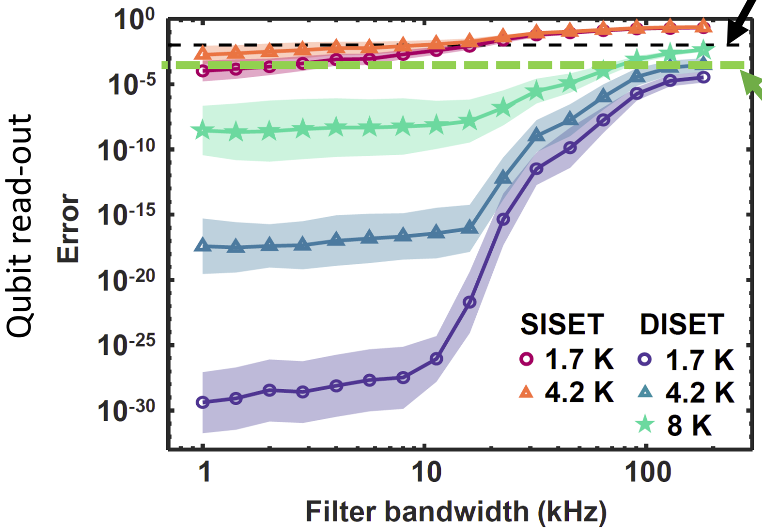
$\bar{\sigma}$: standard deviation

$f_s = 500$ kHz

Setup BW: 200 kHz (amplifier)
Filter BW: Software LP

$SNR = 20\log(\Delta\mu/\bar{\sigma})$

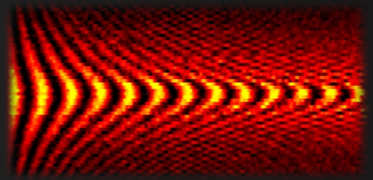


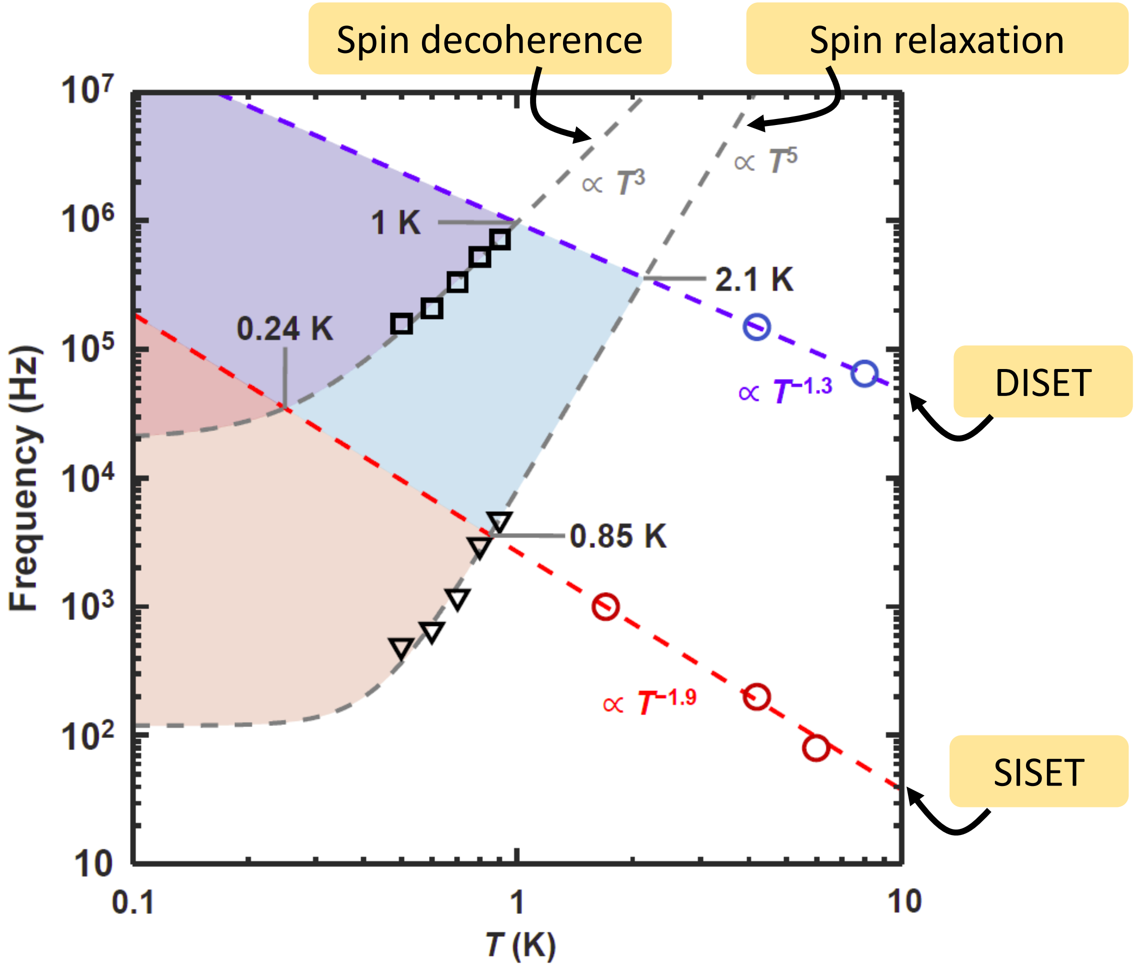


Fault tolerant threshold (99%)

99.9%

Temperature limit for quit readout





Set RO error threshold to 0.1%
→ max meas. BW

Compare to 99% of T_1-decay
(T_1 limits read-out)

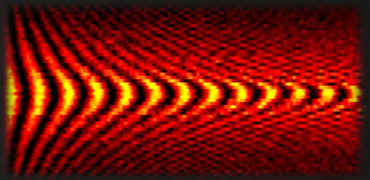
Max. BW for SET readout F > 99.9 %
○ DISET ○ SISET

Qubit properties (Ref. 13)
□ 1 % phase flip error
▽ 1 % bit flip error

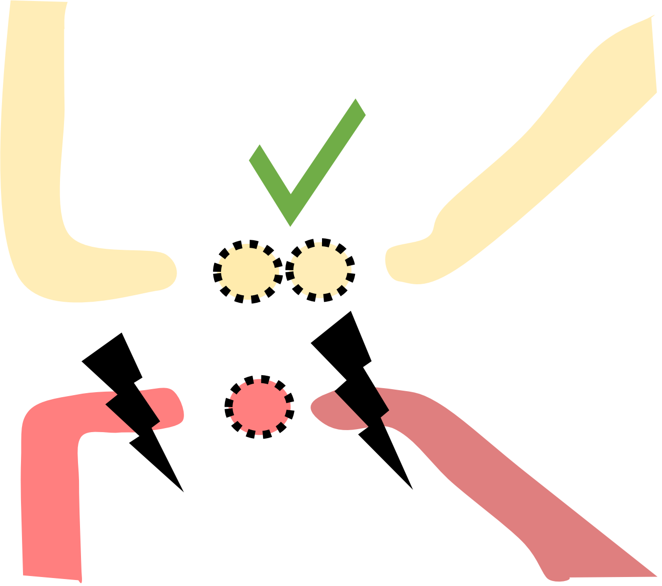
	Readout within 1 % of T_2^{Hahn} decay	Readout within 1 % of T_1 decay
DISET	$T < 1$ K	$T < 2.1$ K
SISET	$T < 0.24$ K	$T < 0.85$ K

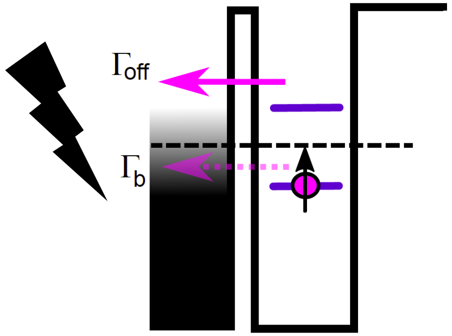
Qubit data: Yang *et al.*, Nature **580** (2020).

Single-shot still very temperature sensitive



Traditional Elzerman RO



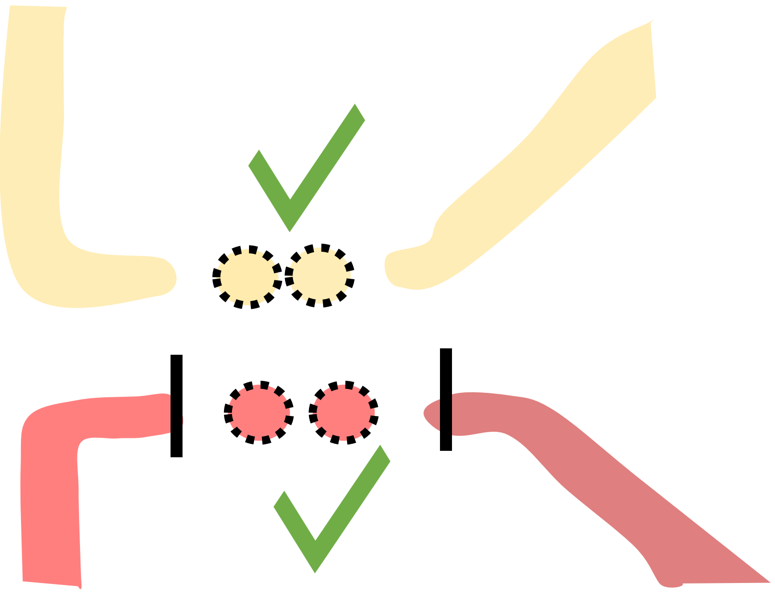


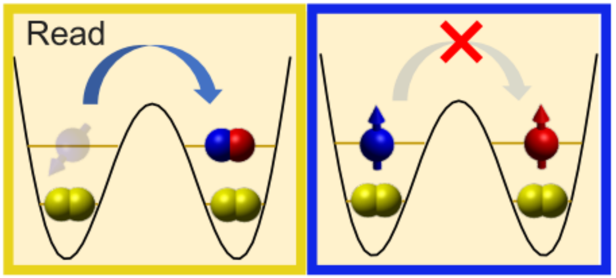
For high fidelity RO:

$$k_bT \ll g\mu_B B$$

$$k_b = 86\ \mu eV/K$$
$$\mu_B = 58\ \mu eV/T$$
$(1\ \text{GHz} = 4.1\ \mu eV)$

Isolated mode operation



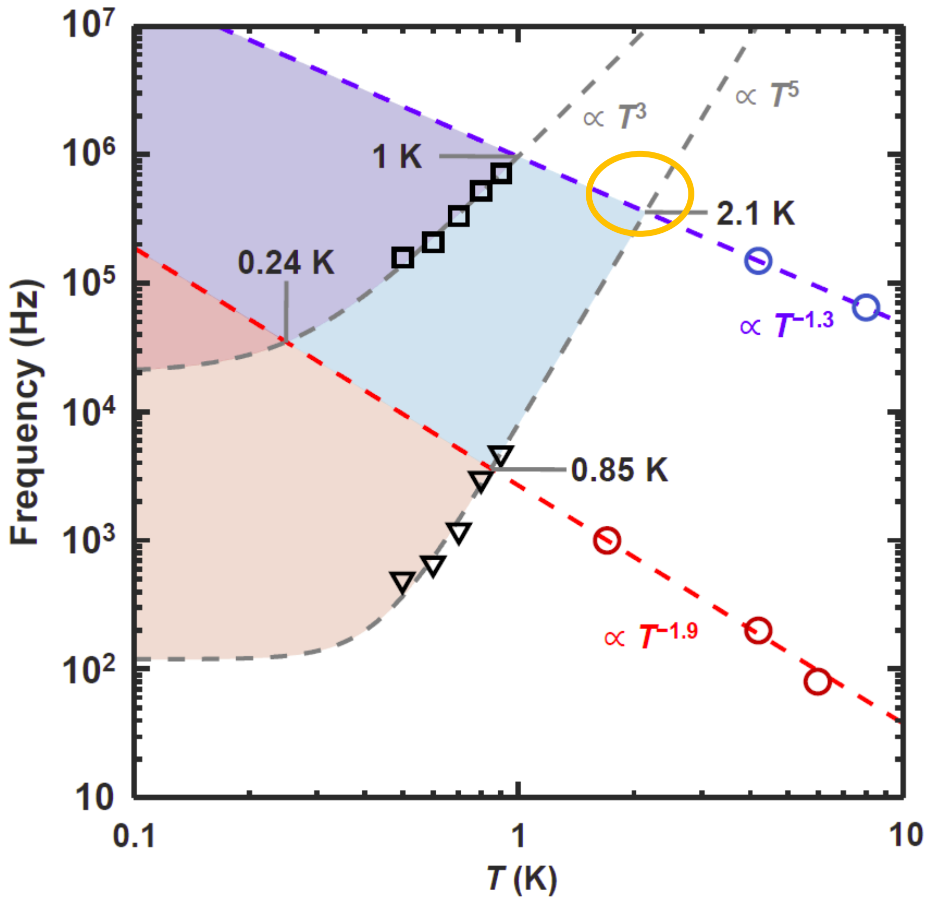


Yang et al., Nature (2020).

Conclusions

"A high-sensitivity charge sensor for silicon qubits above one kelvin",
Huang et al., arXiv:2103.06433 (2021).

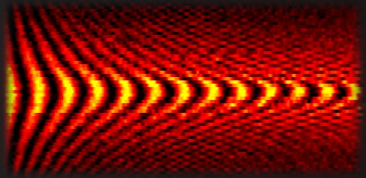
- DISET more **sensitive**
  more **temperature** robust than SISET
- RO Fidelity >99% at 8K (>100 kHZ)
- RO Fidelity >99.9% at 2.1 K (200 kHZ)



Interesting technology for hot qubits

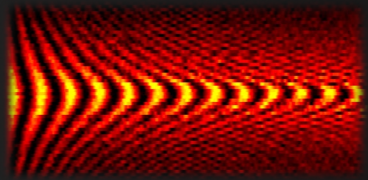
Thank you for your attention!

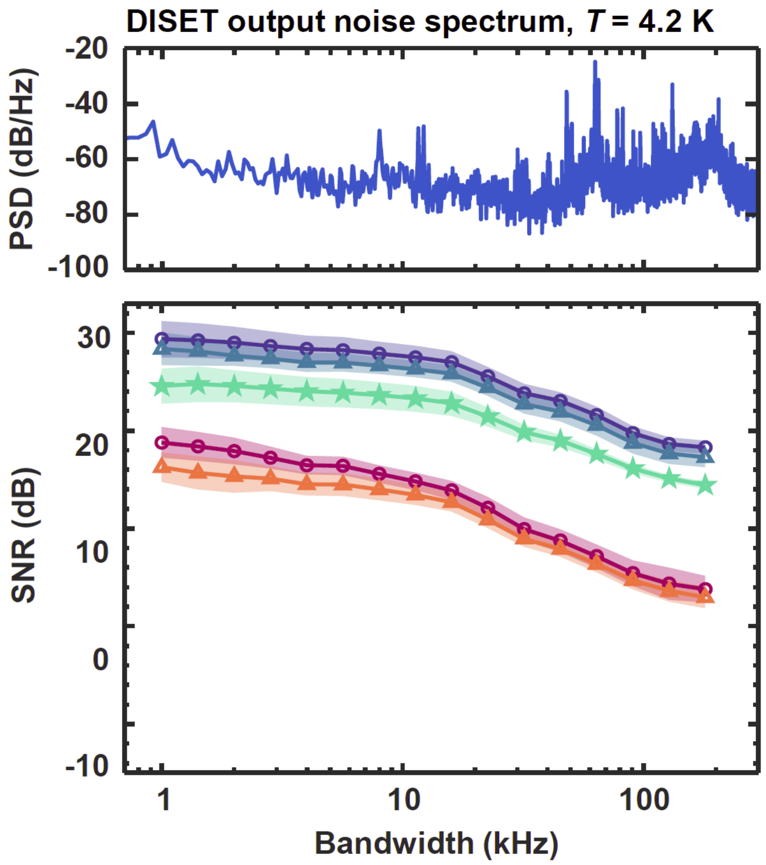
Goodbye Florian!



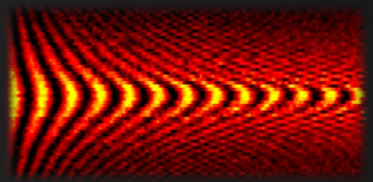
UNI
BASEL

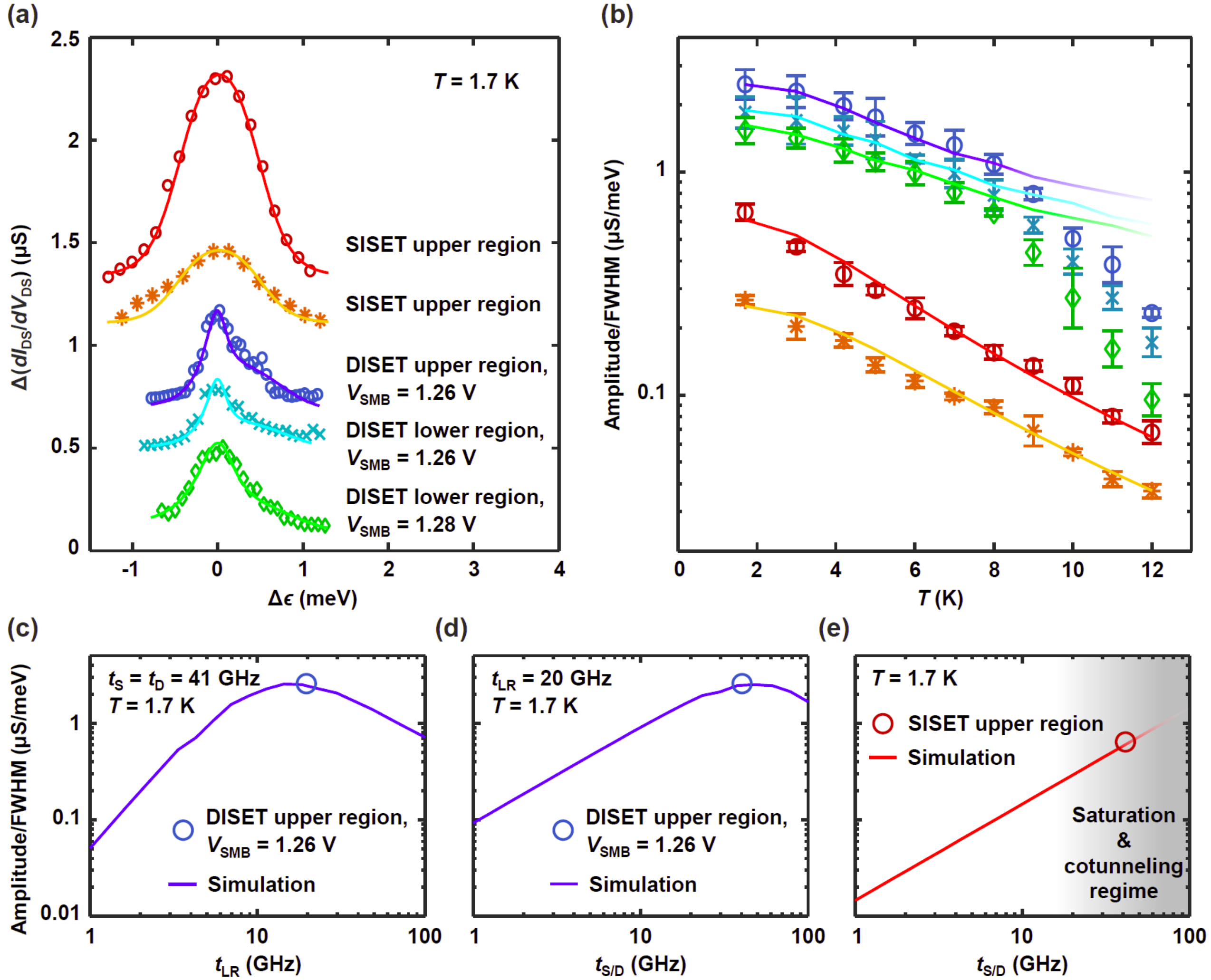
SNR and output spectrum

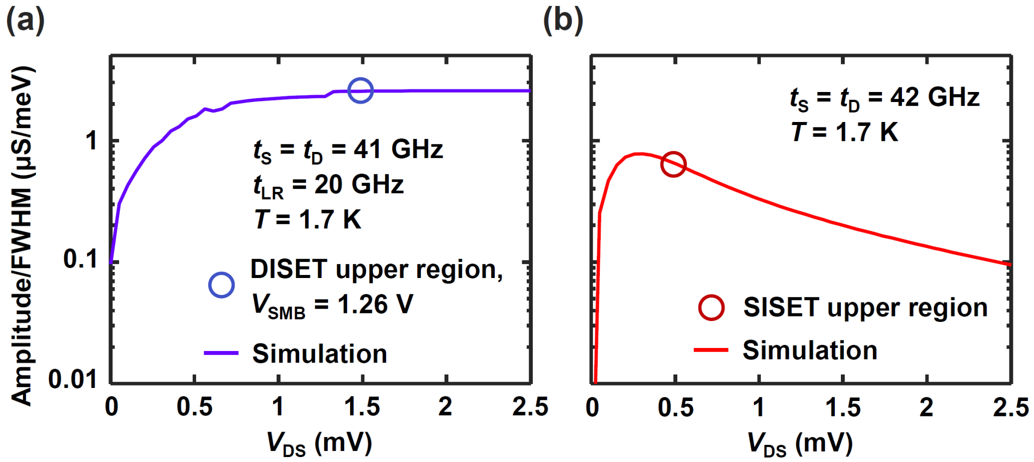


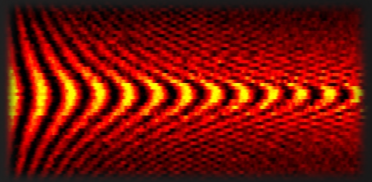


Model: optimizing the sensitivities

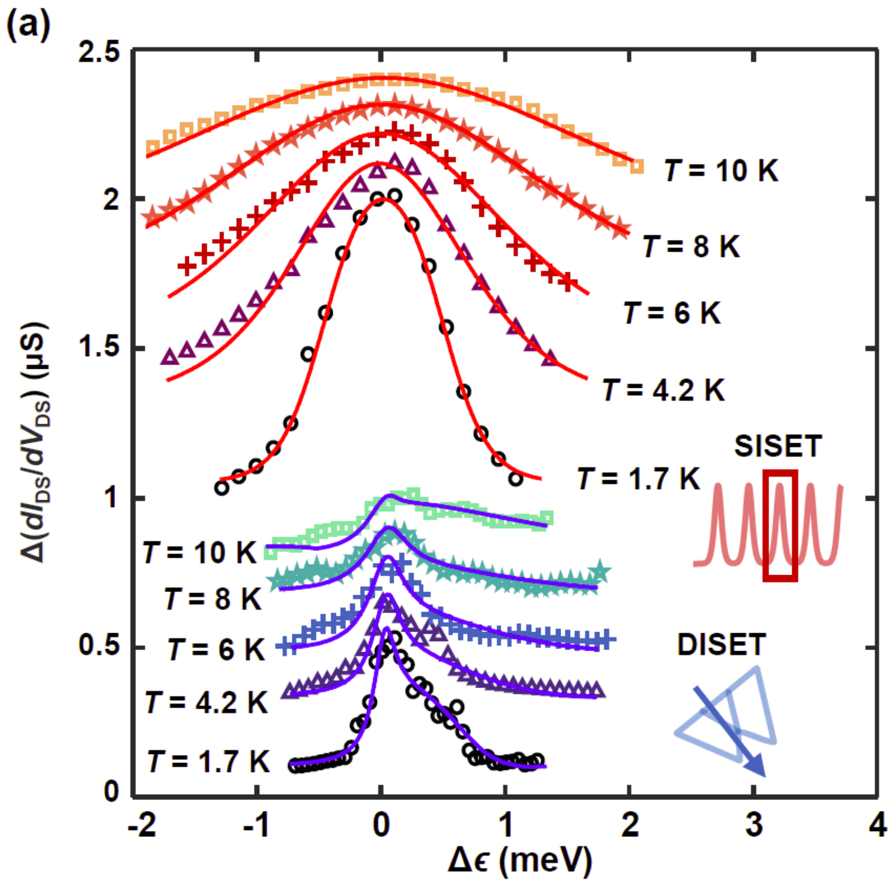








SISET/DIFET transport



$|0\rangle$: empty $|1\rangle$: left $|2\rangle$:right
e.g. Γ_{12} = transition rate left to right

$$I_{\mathrm{DS}} = e\frac{\Gamma_{02}\Gamma_{21}\Gamma_{10} - \Gamma_{01}\Gamma_{12}\Gamma_{20} + (\Gamma_{01}\Gamma_{20} - \Gamma_{10}\Gamma_{02})\Delta}{\Gamma_{\Sigma}},$$

$$\Delta = t_{\mathrm{LR}}^2 \frac{\Gamma_{10}+\Gamma_{20}+\Gamma_{\mathrm{LR}}}{(\frac{\Gamma_{10}+\Gamma_{20}+\Gamma_{\mathrm{LR}}}{2})^2 + (\frac{\mu_{\mathrm{L}}-\mu_{\mathrm{R}}}{h})^2} \qquad (2)$$

$$\Gamma_{01} = f_{\mathrm{fD}}(\mu_{\mathrm{S}}, T; \mu_{\mathrm{L}})t_{\mathrm{S}}, \quad \Gamma_{10} = t_{\mathrm{S}} - \Gamma_{01}, \qquad (3)$$

$$\Gamma_{02} = f_{\mathrm{fD}}(\mu_{\mathrm{D}}, T; \mu_{\mathrm{R}})t_{\mathrm{D}}, \quad \Gamma_{20} = t_{\mathrm{D}} - \Gamma_{02}, \qquad (4)$$

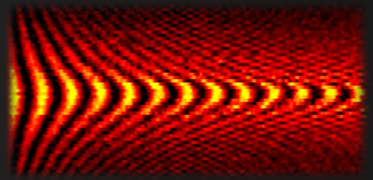
leads

$$\begin{cases} \Gamma_{12} = f_{\mathrm{fD}}(\mu_{\mathrm{L}}, T; \mu_{\mathrm{R}})\Gamma_{\mathrm{LR}} \\ \Gamma_{21} = \Gamma_{\mathrm{LR}} - \Gamma_{12} \end{cases}, \quad \mu_{\mathrm{L}} > \mu_{\mathrm{R}} \qquad (5)$$

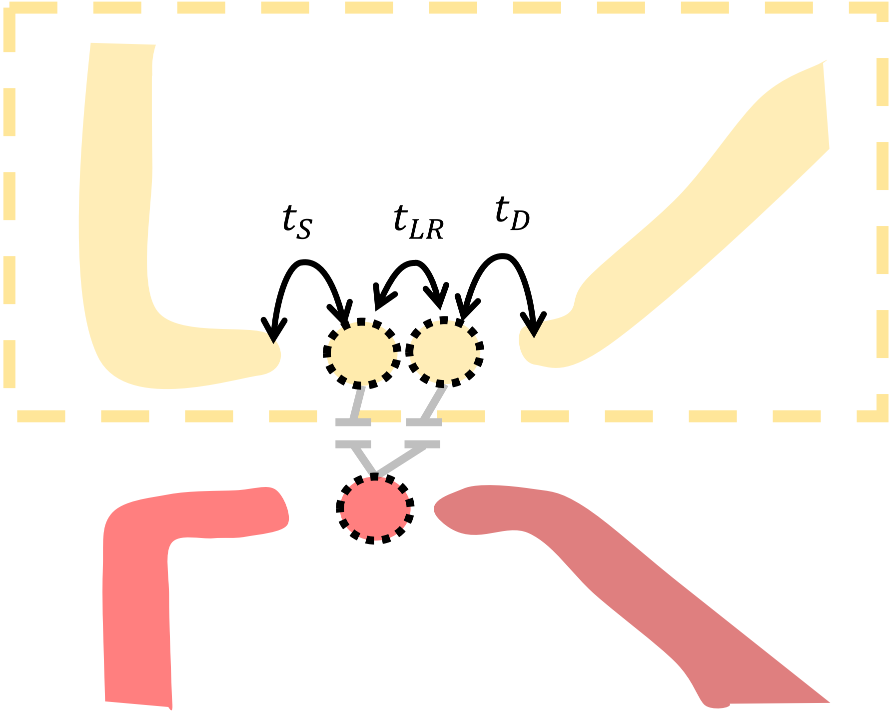
$$\begin{cases} \Gamma_{21} = f_{\mathrm{fD}}(\mu_{\mathrm{R}}, T; \mu_{\mathrm{L}})\Gamma_{\mathrm{LR}} \\ \Gamma_{12} = \Gamma_{\mathrm{LR}} - \Gamma_{21} \end{cases}, \quad \mu_{\mathrm{L}} \le \mu_{\mathrm{R}}. \qquad (6)$$

Inter-dot

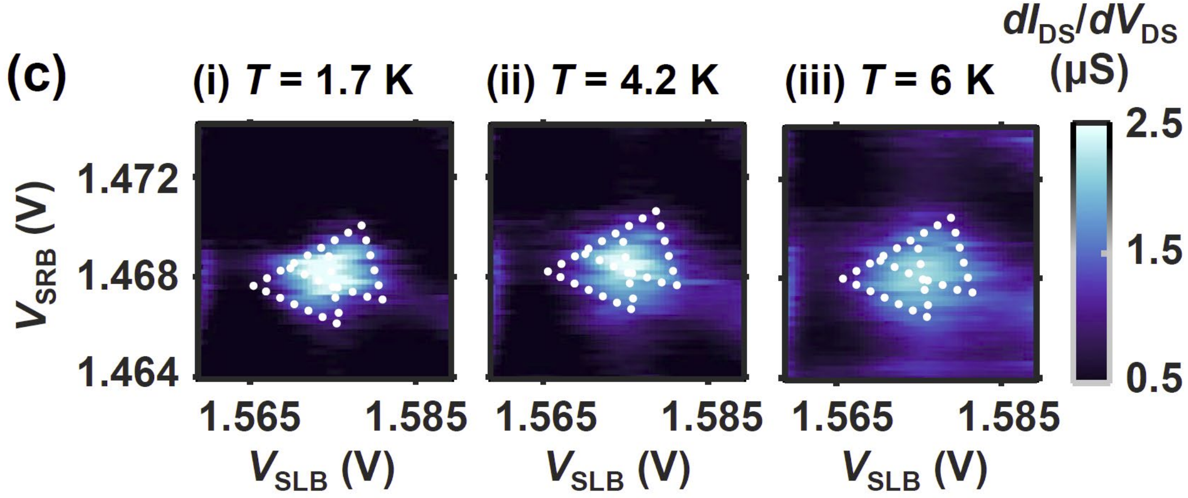
DISET Charge sensor

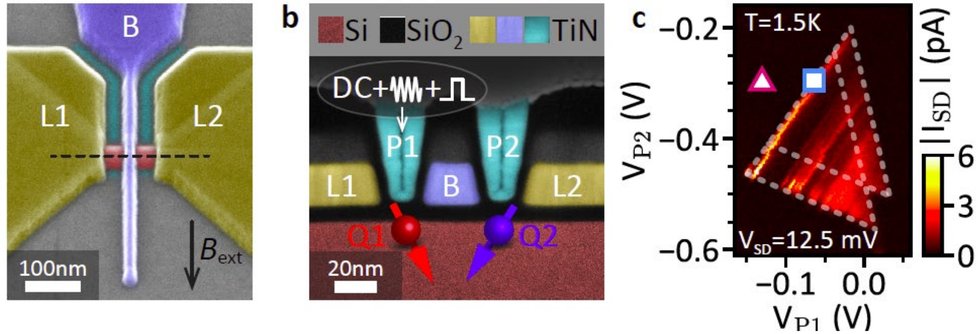


Device



DISET





Camenzind, Geyer et al., arXiv:2103.07369(2021)