Karlsruhe Institute of Technology

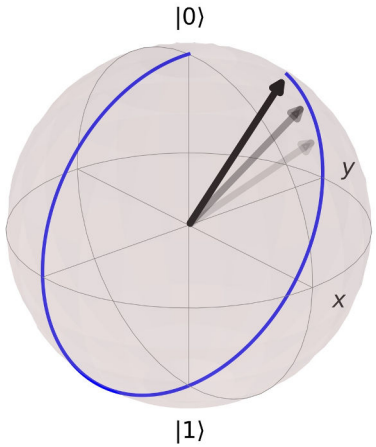
JARA INSTITUTE QUANTUM INFORMATION

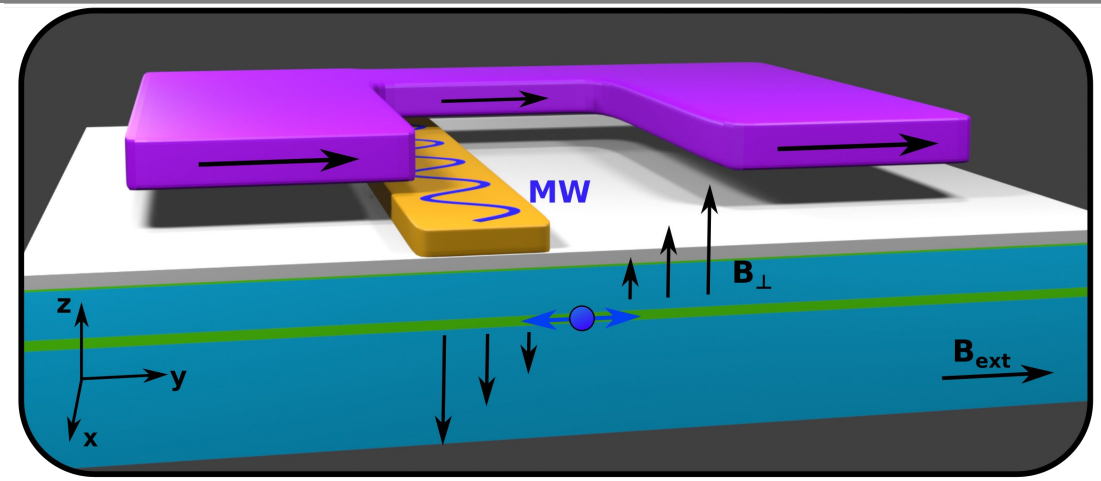
imec

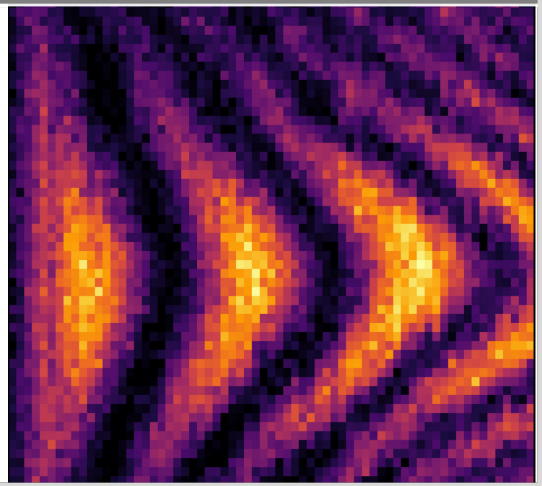
Physikalisches Institut

Fidelity Benchmarking of Industrial Silicon/Silicon-Germanium Qubits

Thomas Koch, AG Wernsdorfer

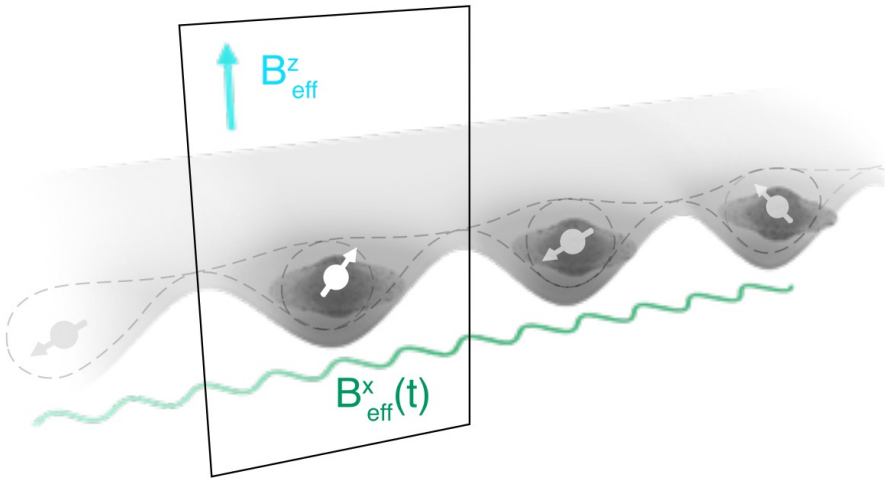






Loss-DiVincenzo qubit

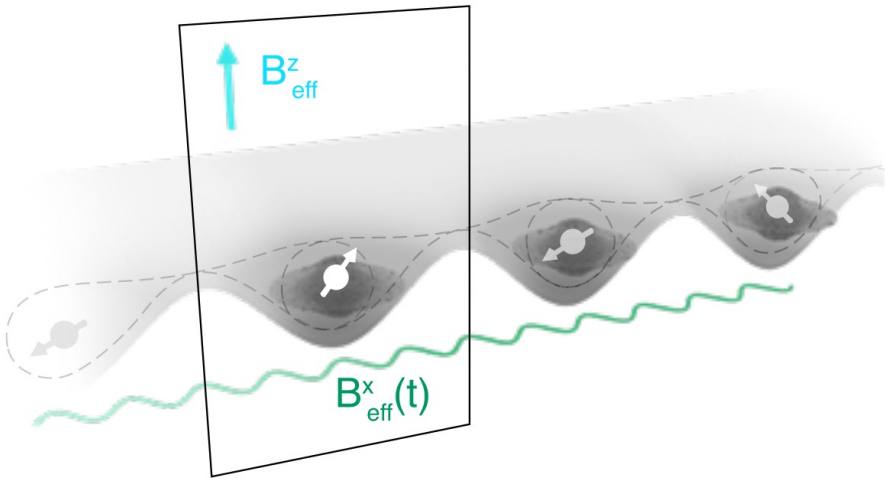
Spin Qubit



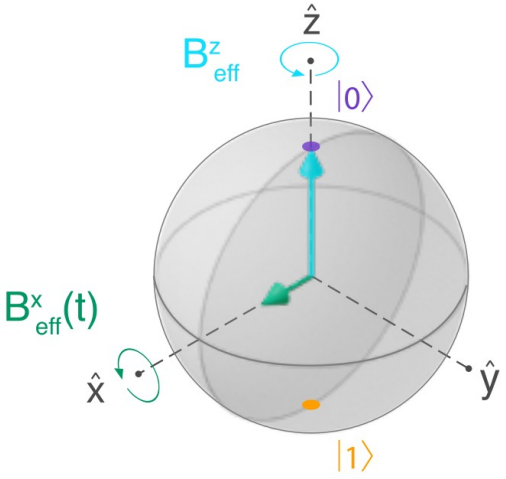
[Burkard, et al. Rev. Mod. Phys. 95, 025003 (2023)]

Loss-DiVincenzo qubit

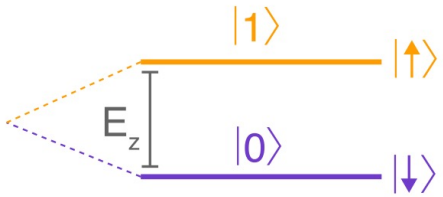
Spin Qubit



Bloch Sphere



Level Diagram



[Burkard, et al. Rev. Mod. Phys. 95, 025003 (2023)]

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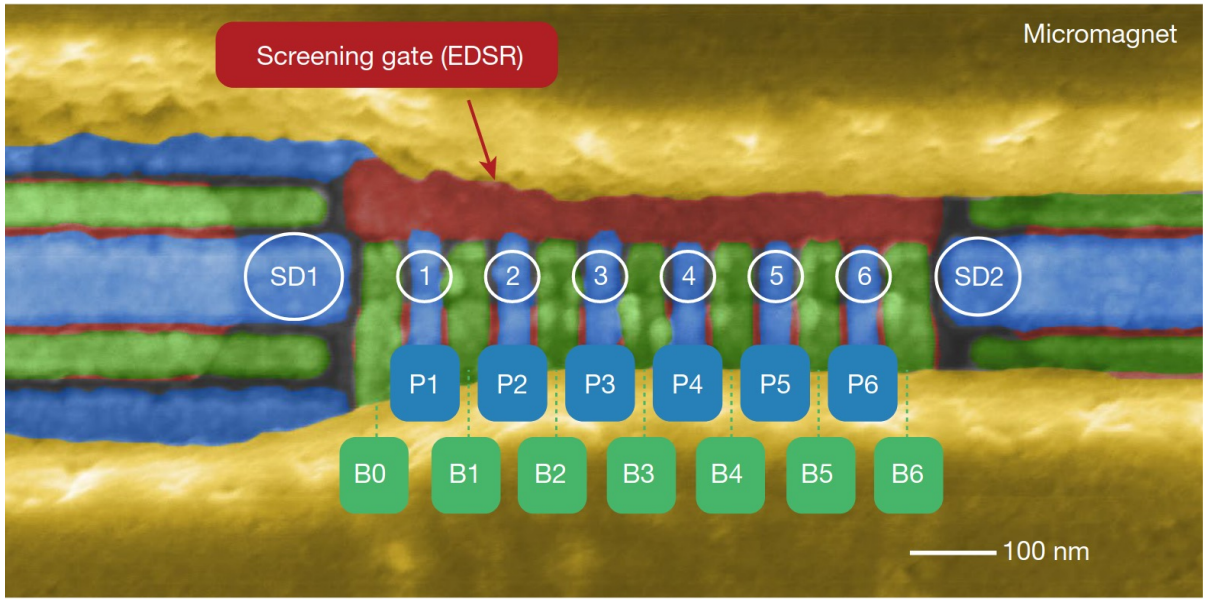
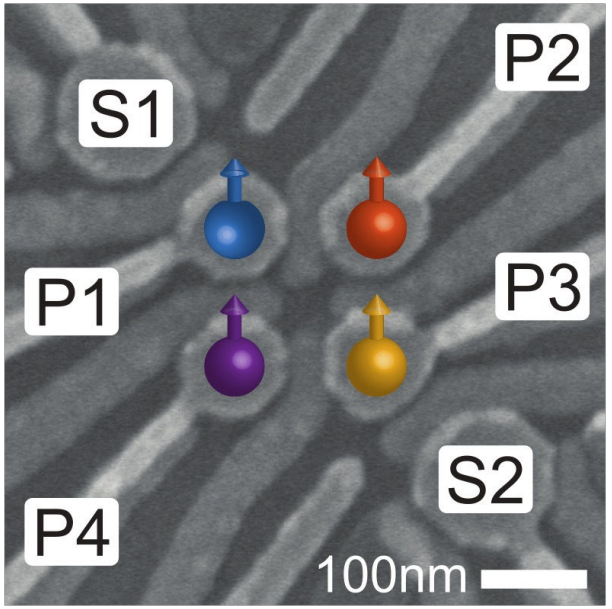
Semiconductor quantum processors

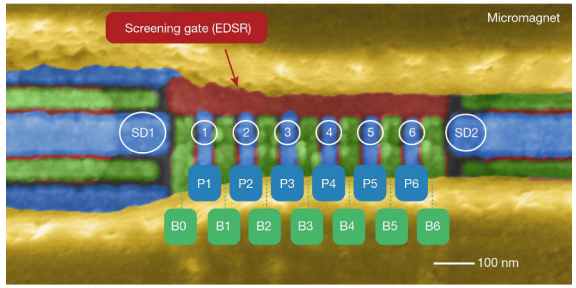


[Philips, et al. Nature 609, 919–924 (2022)]

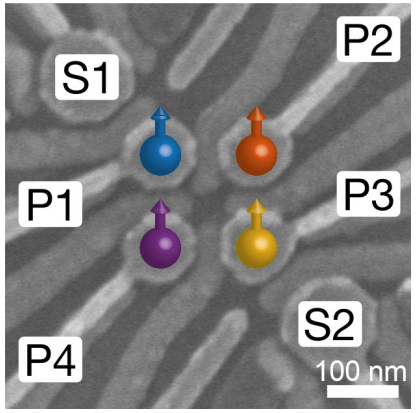


[Hendrickx, et al. Nature 591, 580–585 (2021)]

Semiconductor based qubits



[Philips, et al., Nature 609, 919–924 (2022)]



[Hendrickx, et al., Nature 591, 580–585 (2021)]

- Two qubit gate fidelity > 99%

  [Noiri, A. et al., *Nature* **601**, 338–342 (2022)]

- Two qubit logic at 1.1 K

  [Petit, L et al., *Nature* **580**, 355–359 (2020)]

- High Qubit density in 2D grids

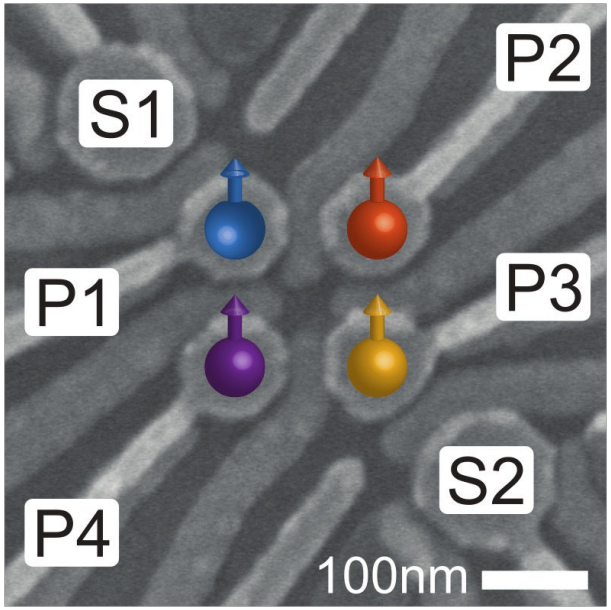
  [Hendrickx, et al., Nature 591, 580–585 (2021)]

- CMOS compatible

  [Maurand, R. et al., Nat Commun 7, 13575 (2016)]

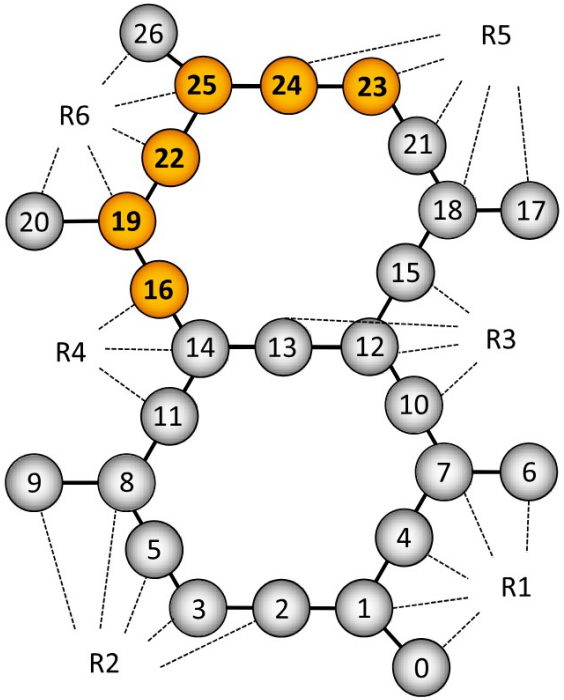
Physical qubit size comparison

Delft 2x2 processor



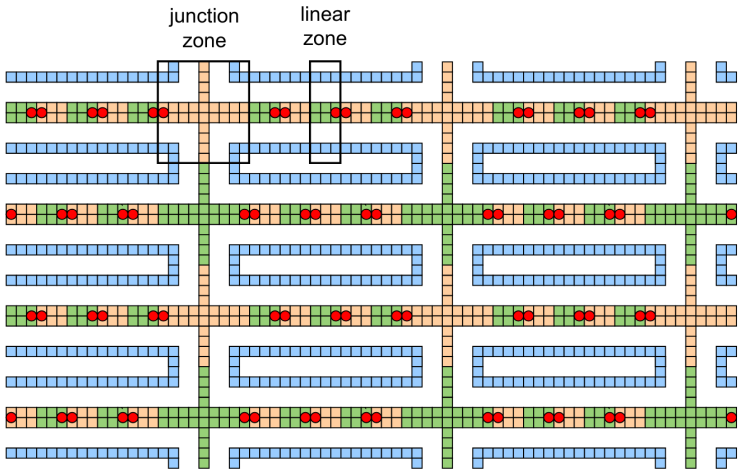
[Hendrickx, et al. Nature 591, 580–585 (2021)]

IBM Falcon



[Jurcevic, et al. *Quantum Sci. Technol.* (2021)]

Proposal for large scale Ion trap processor



[Malinowski, et al. PRX Quantum 4, 040313 (2023)]

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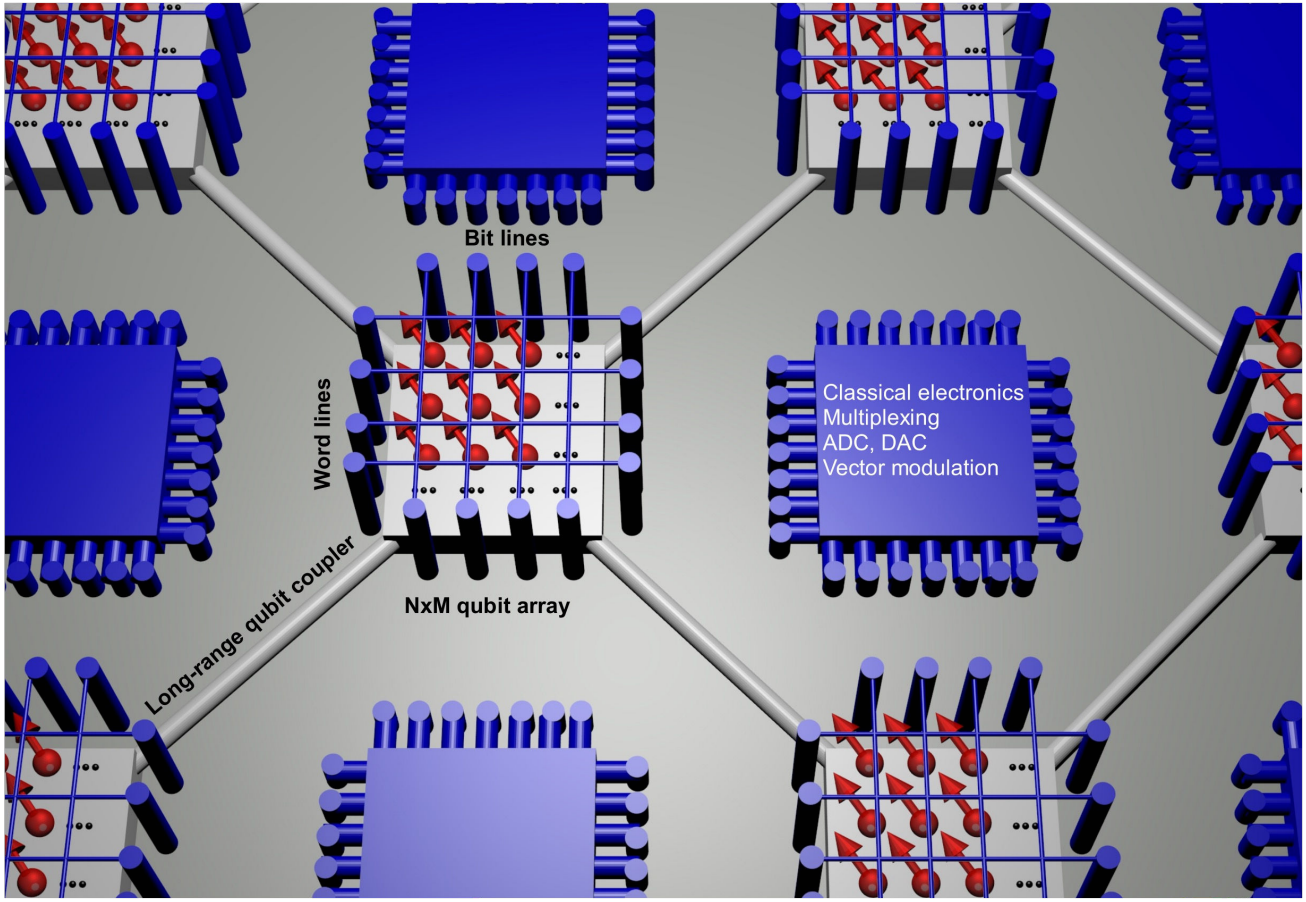
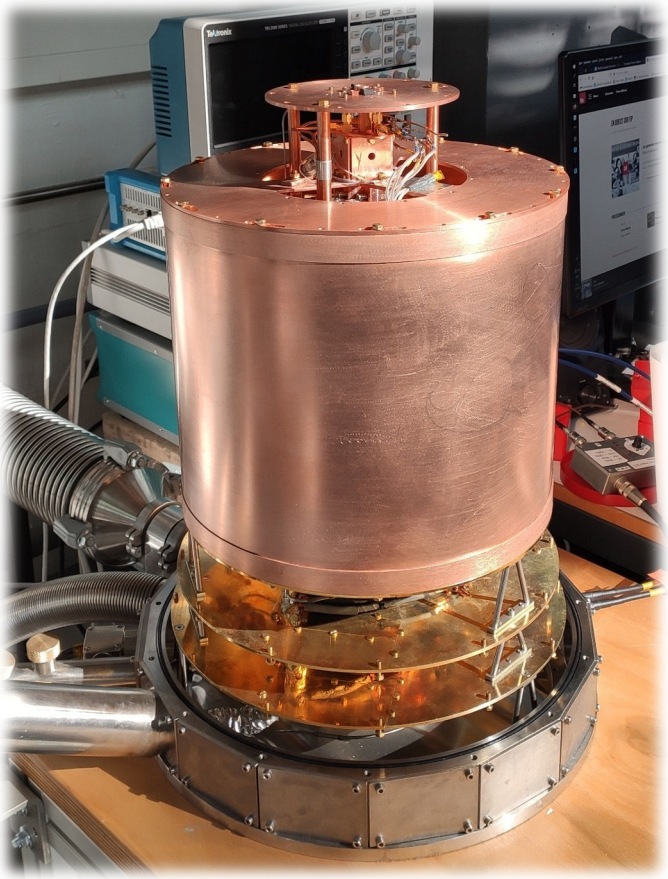
Large scale architecture



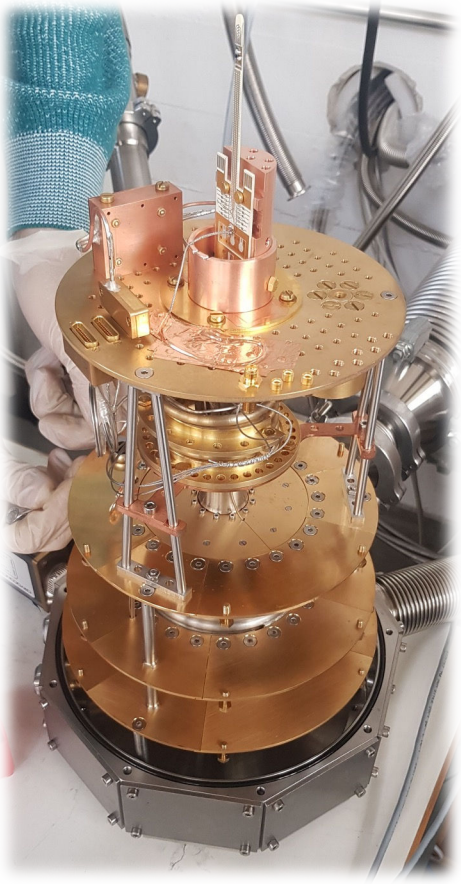
[Vandersypen et al. npj Quantum Inf 3, 34 (2017)]

Our setup



Qinu-type cryostat XL
“Obelix” 2021

- 48 Heavily filtered DC lines
- 6 RF lines + bias-tees



Qinu-type cryostat L
“Idefix” 2023

- 54 Heavily filtered DC lines
- 13 RF lines + bias-tees

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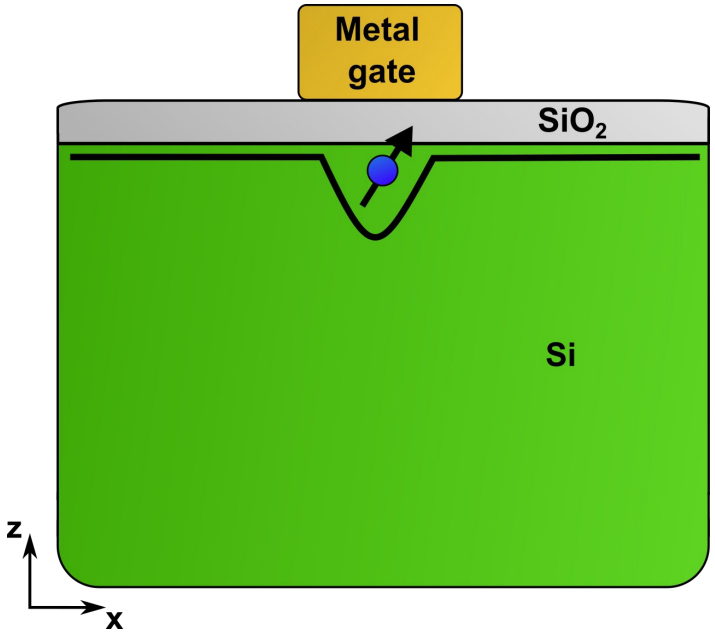
Interuniversity Microelectronics Centre (IMEC)

- Nonprofit company in Leuven, Belgium with 12000 square meters of cleanroom capacity for semiconductor processing

- A unique infrastructure that includes a 2.5-billion-euro 300mm semiconductor pilot line

Silicon based heterostructures for quantum computing

SiMOS:



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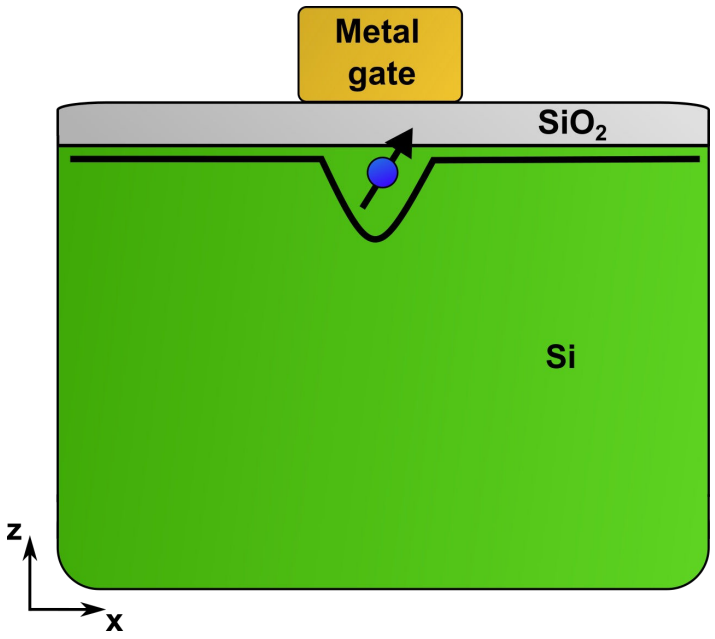
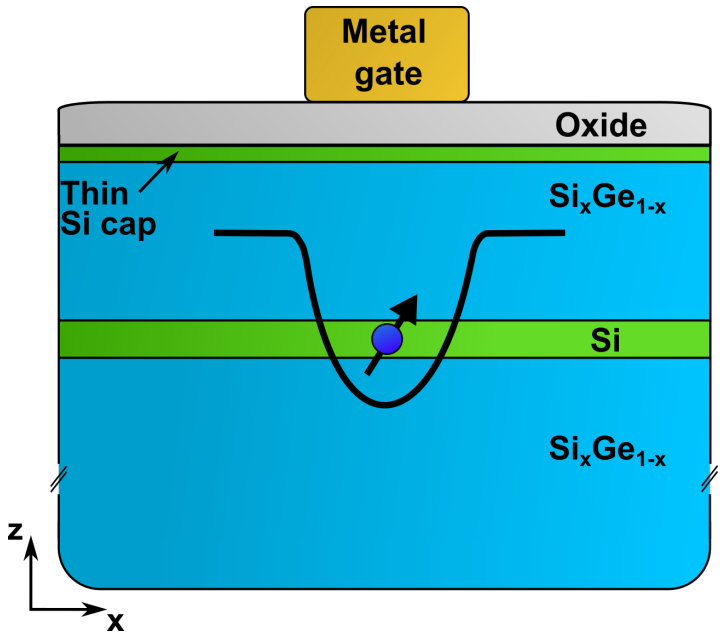
Silicon based heterostructures for quantum computing

SiMOS:



Si/SiGe:



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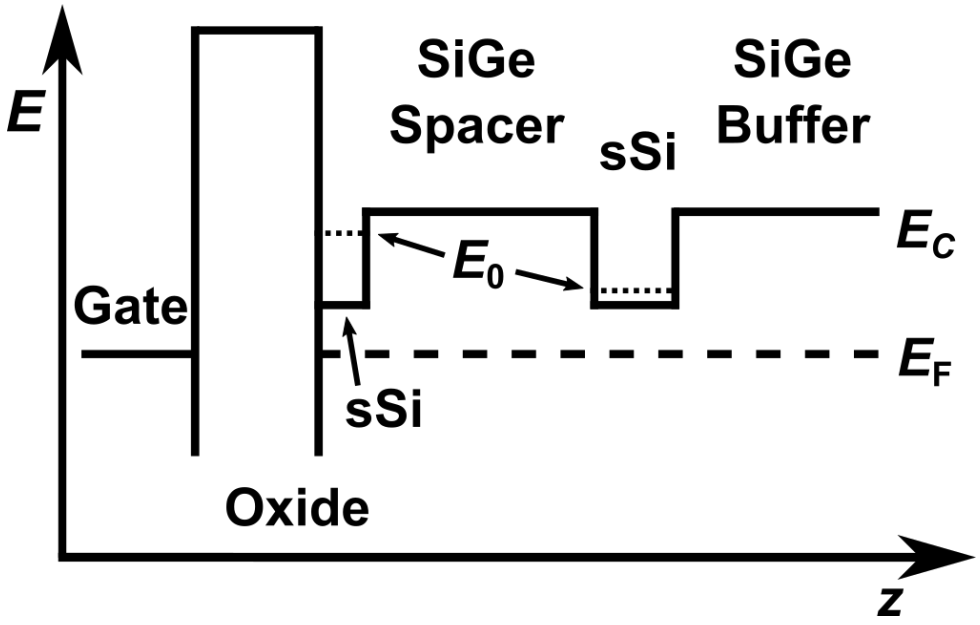
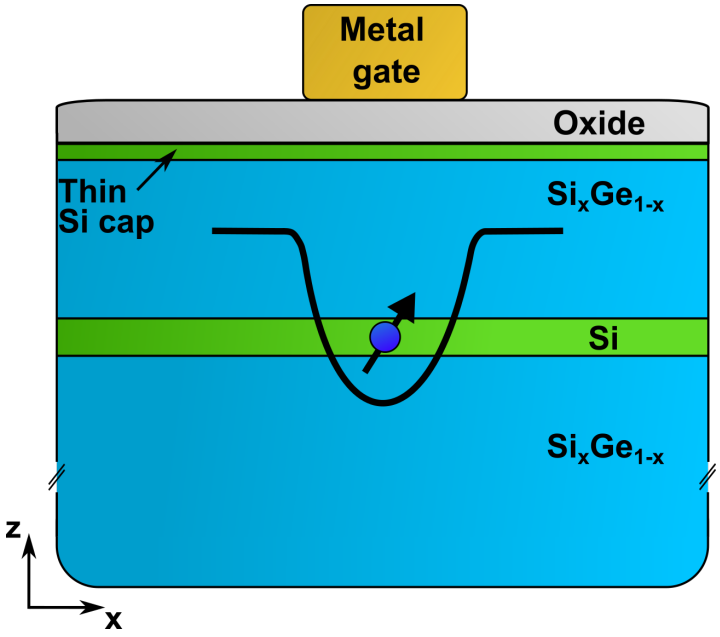
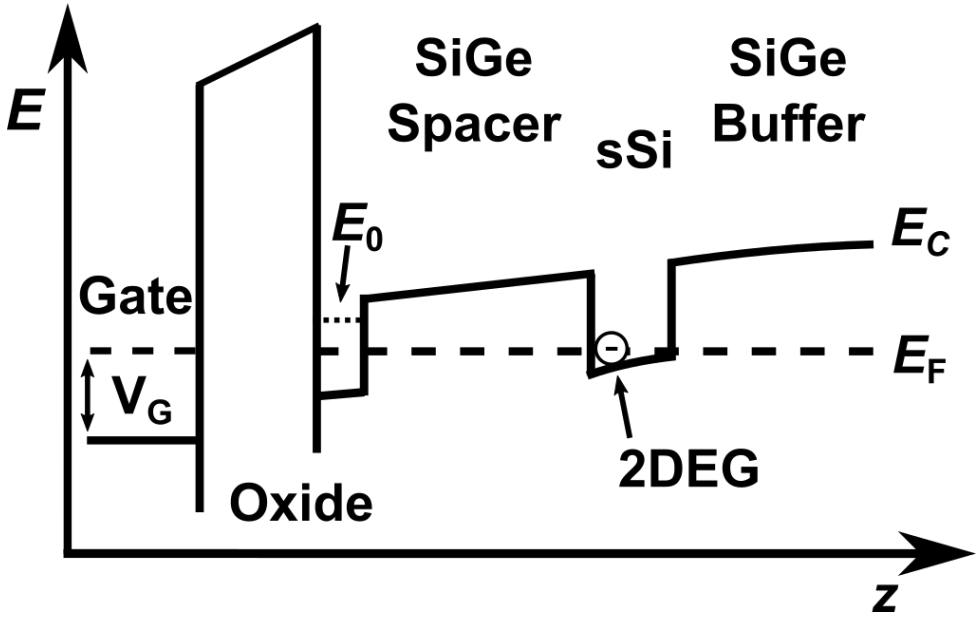
Silicon based heterostructures for quantum computing



Si/SiGe:



Silicon based heterostructures for quantum computing



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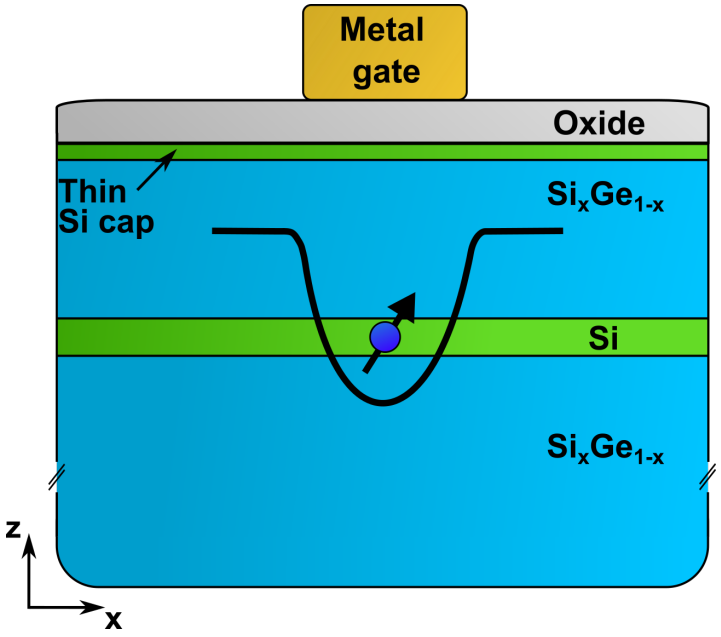
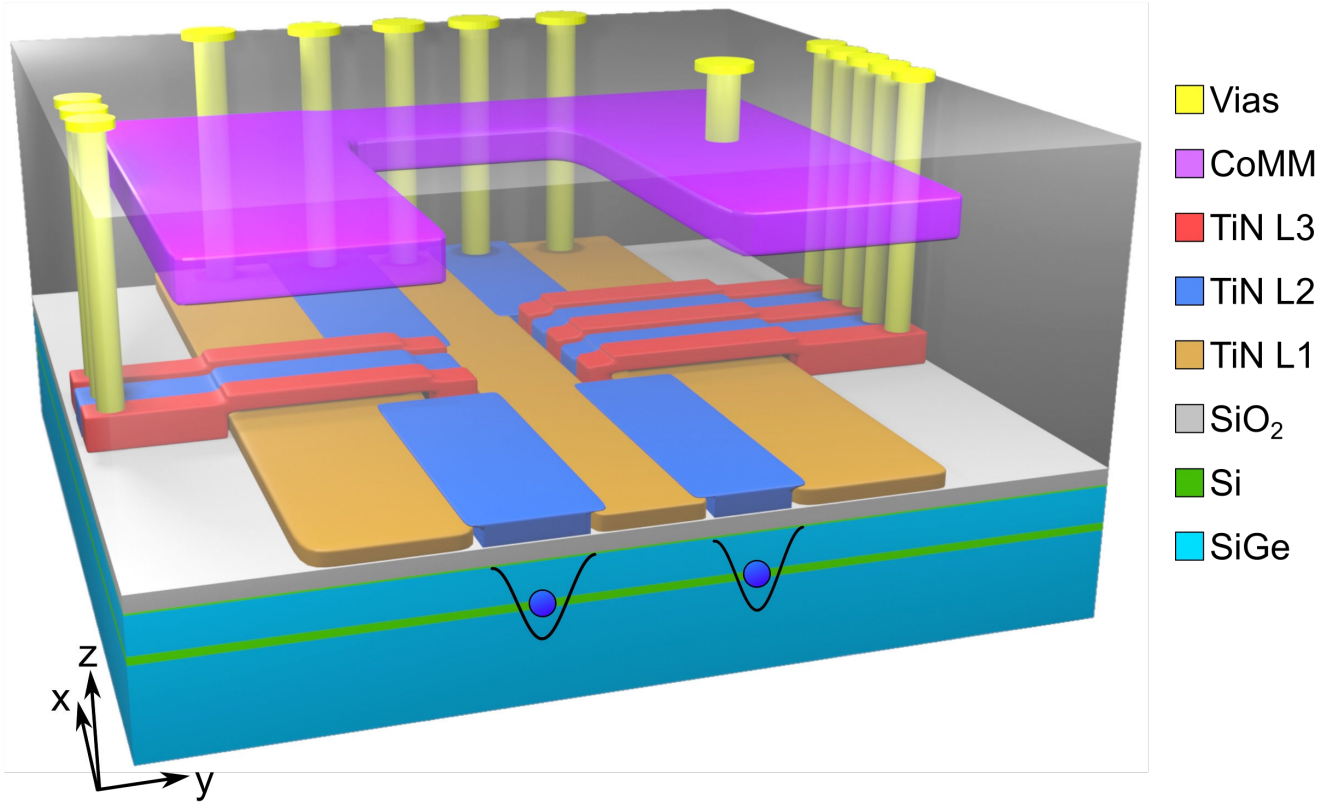


IMEC two qubit device



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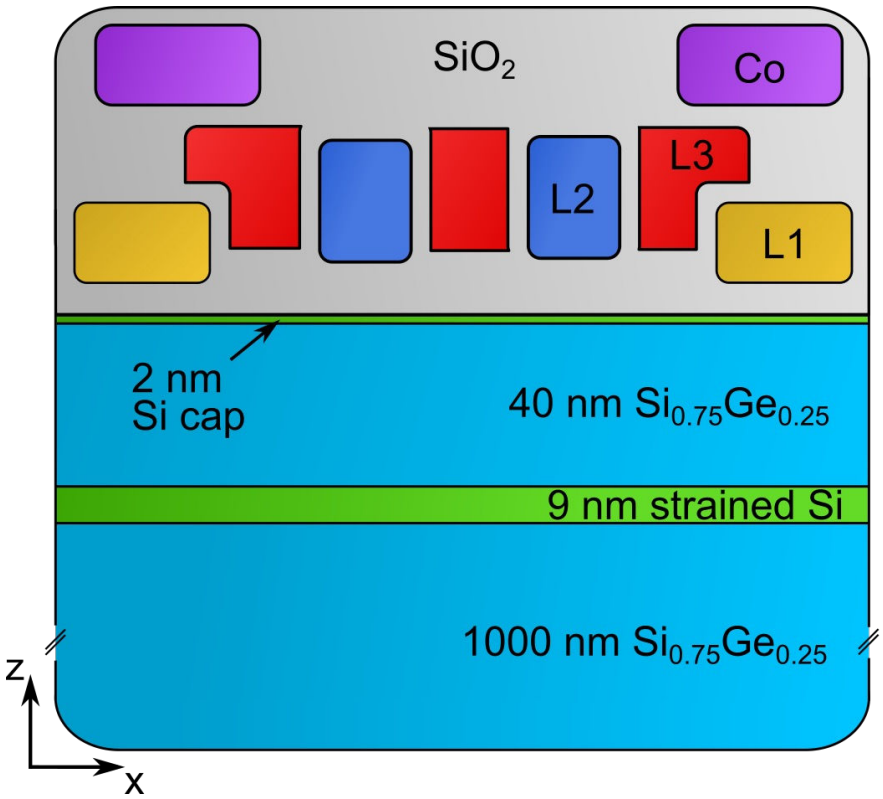
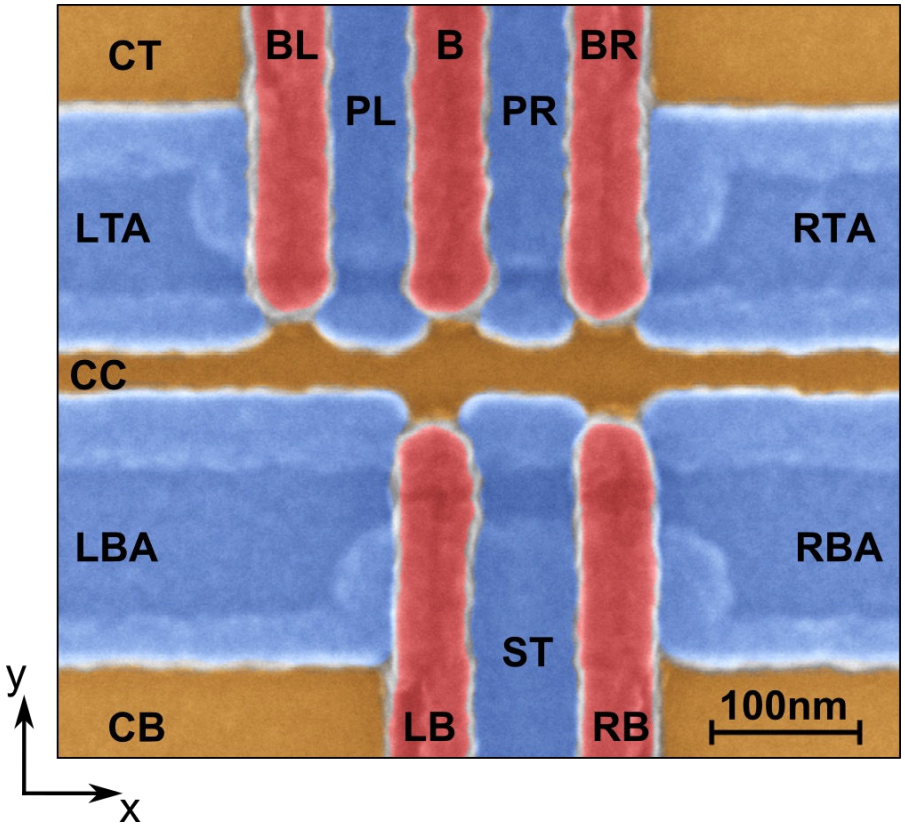
$Si/Si_{0.75}Ge_{0.25}$ heterostructure



CoMM
TiN L3
TiN L2
TiN L1
SiO2
Si
SiGe



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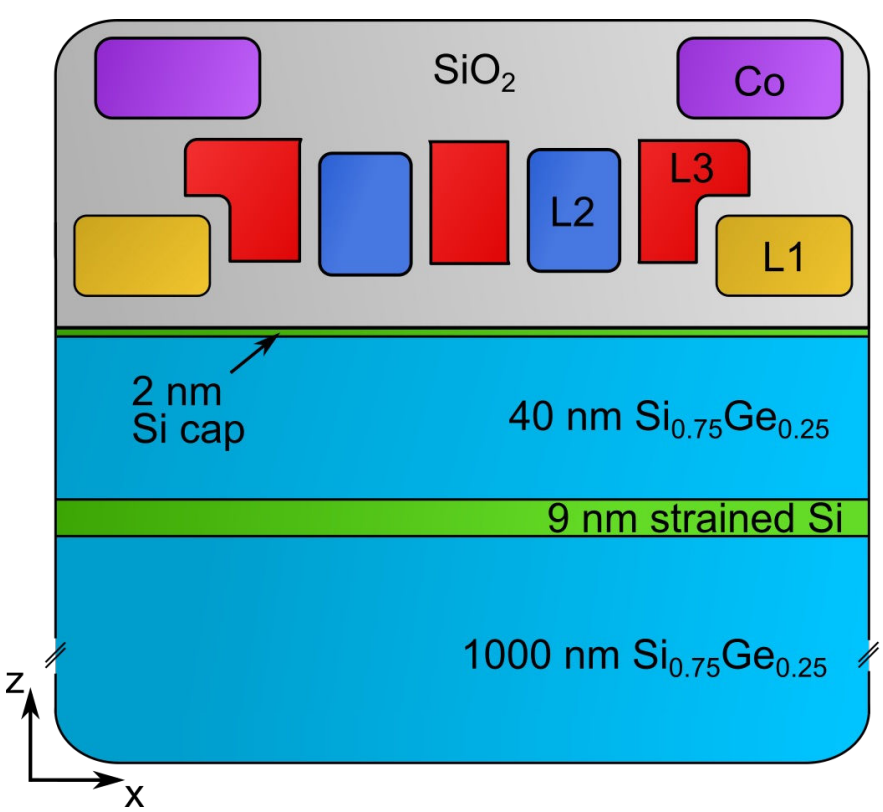
$Si/Si_{0.75}Ge_{0.25}$ heterostructure



CoMM
TiN L3
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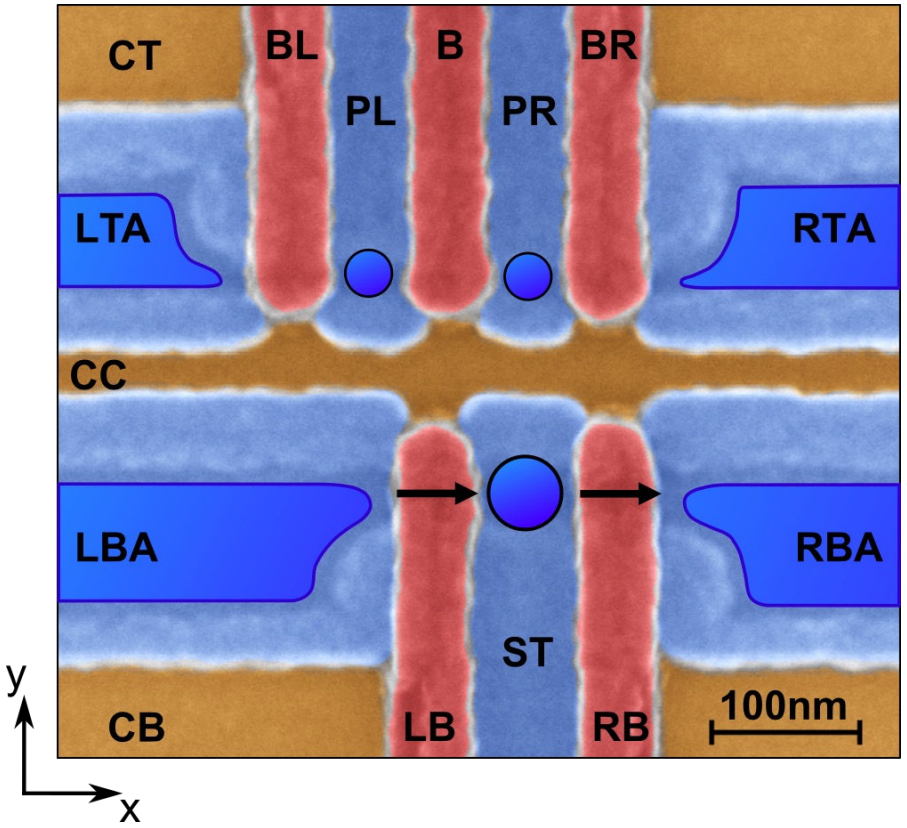

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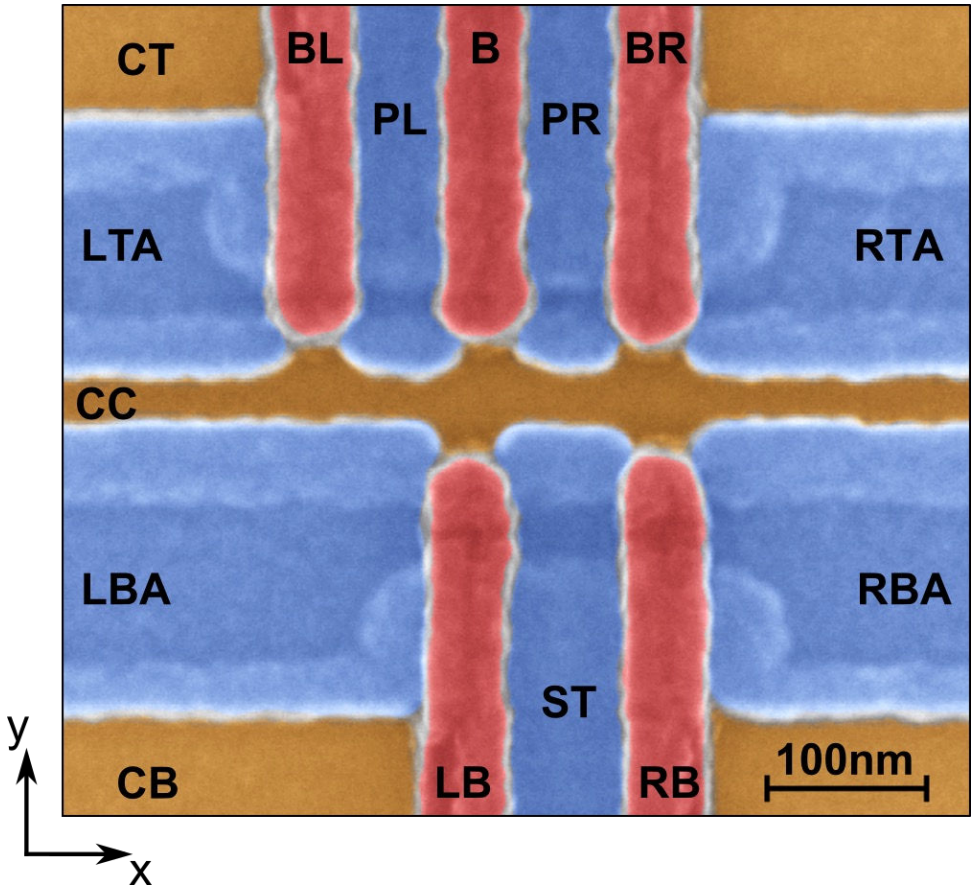
Device architecture



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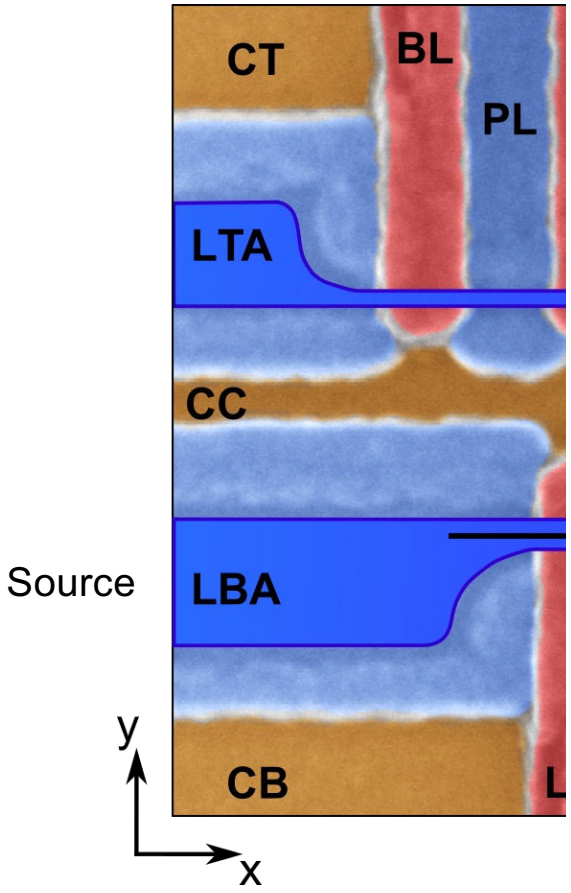
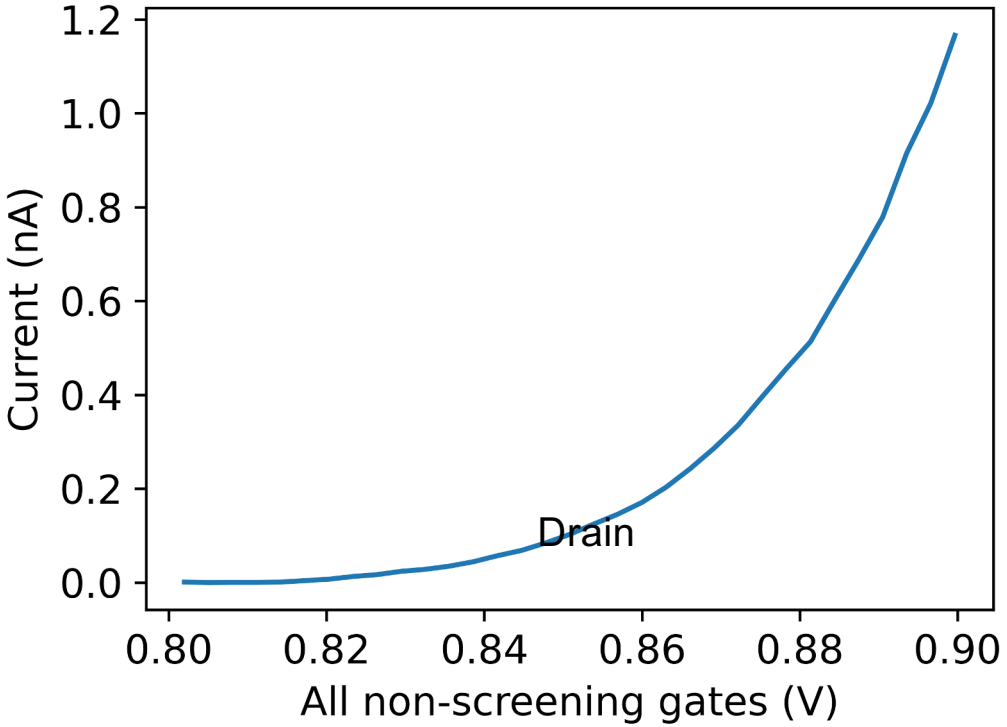
Accumulating the device





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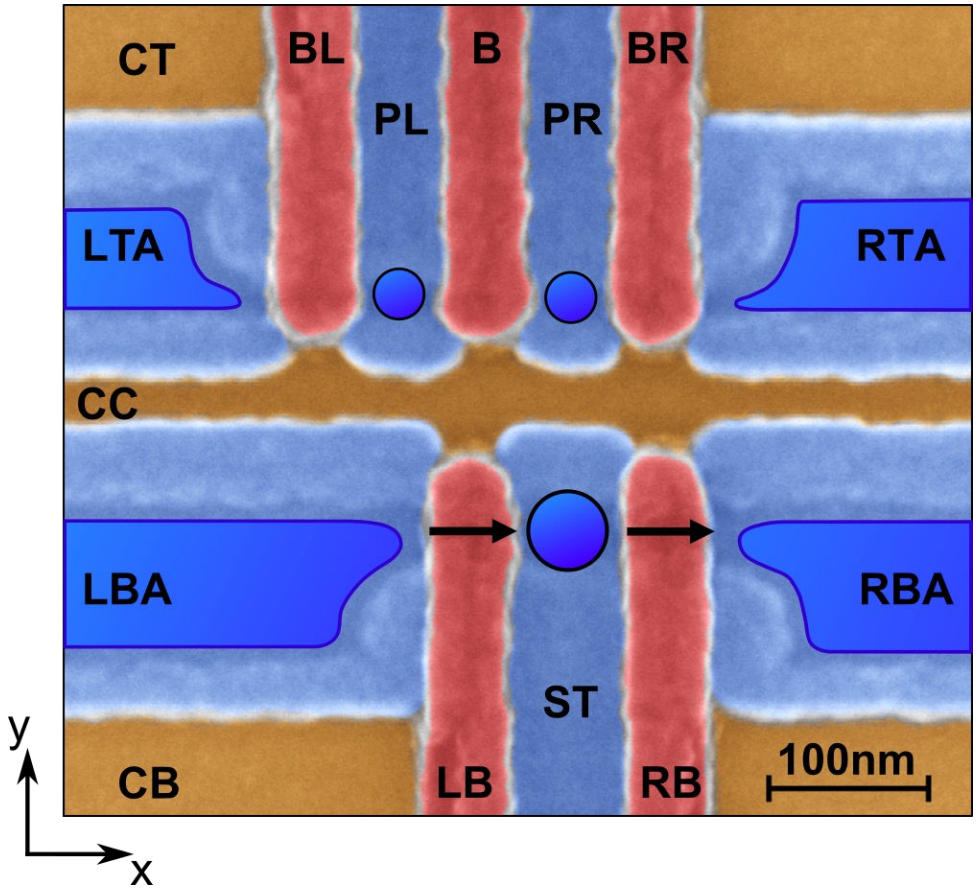
Formation of the quantum dots



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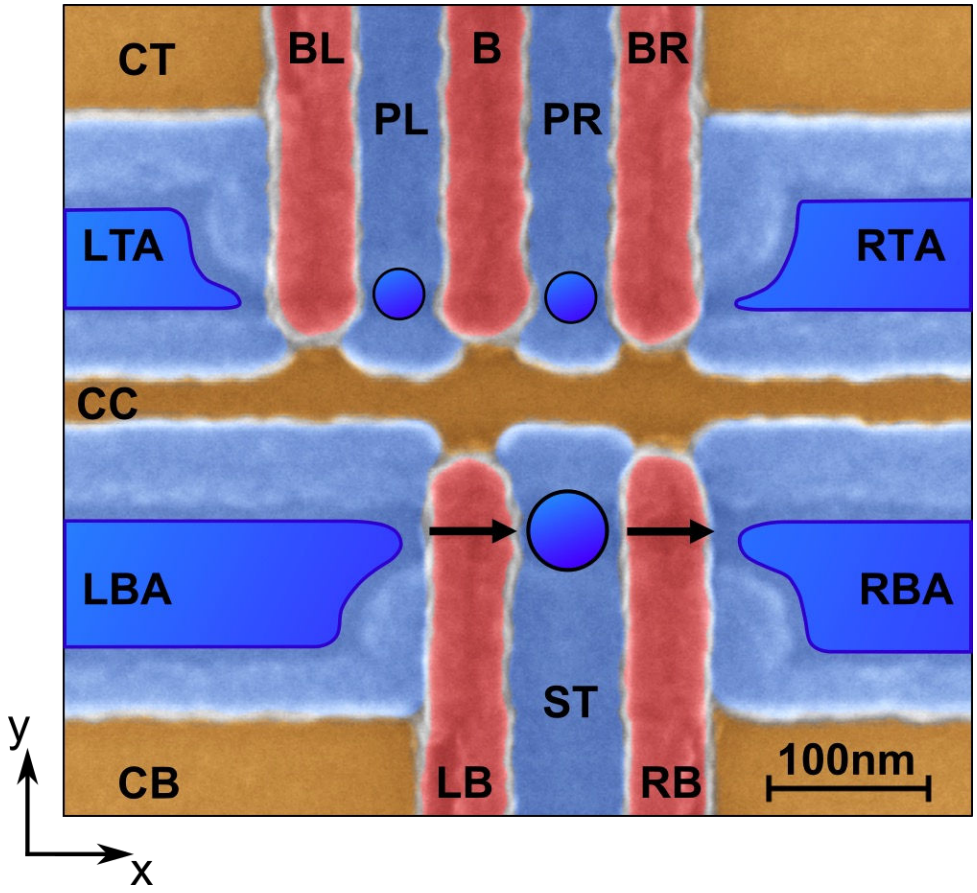
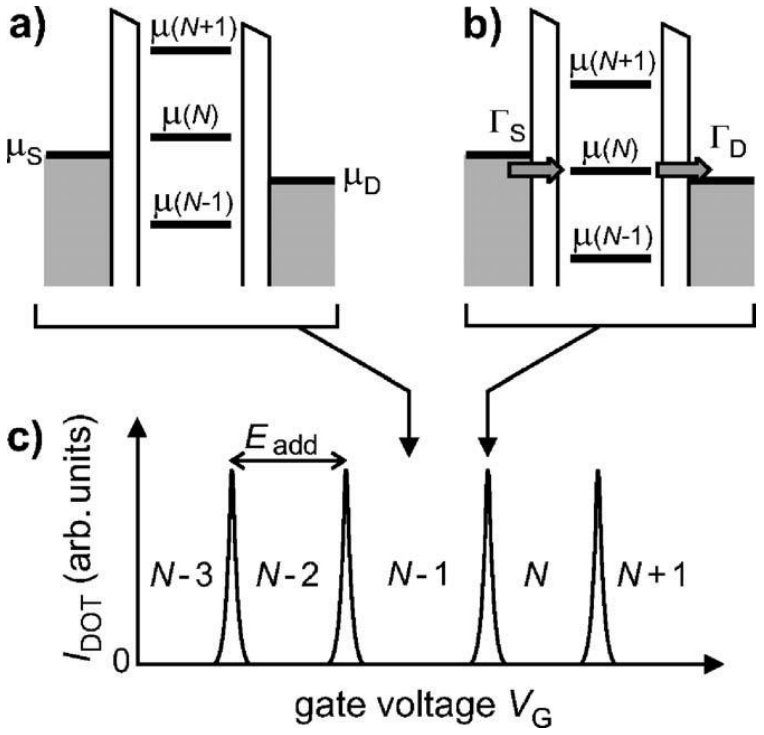
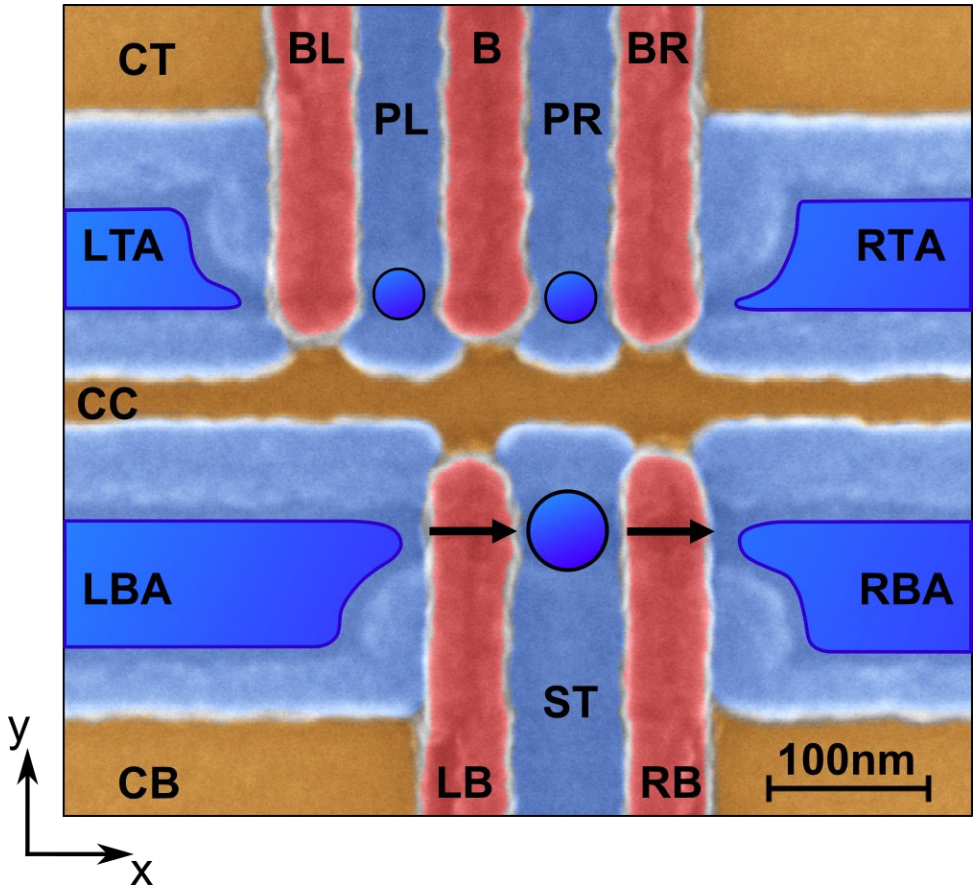
Single electron transistor (SET)

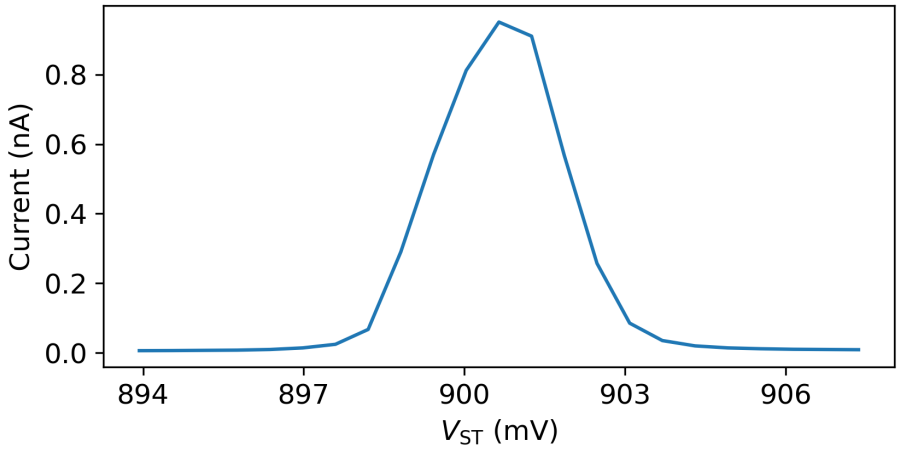




[Hanson et al., Rev. Mod. Phys. 79, 1455 (2007)]

Single electron transistor (SET)





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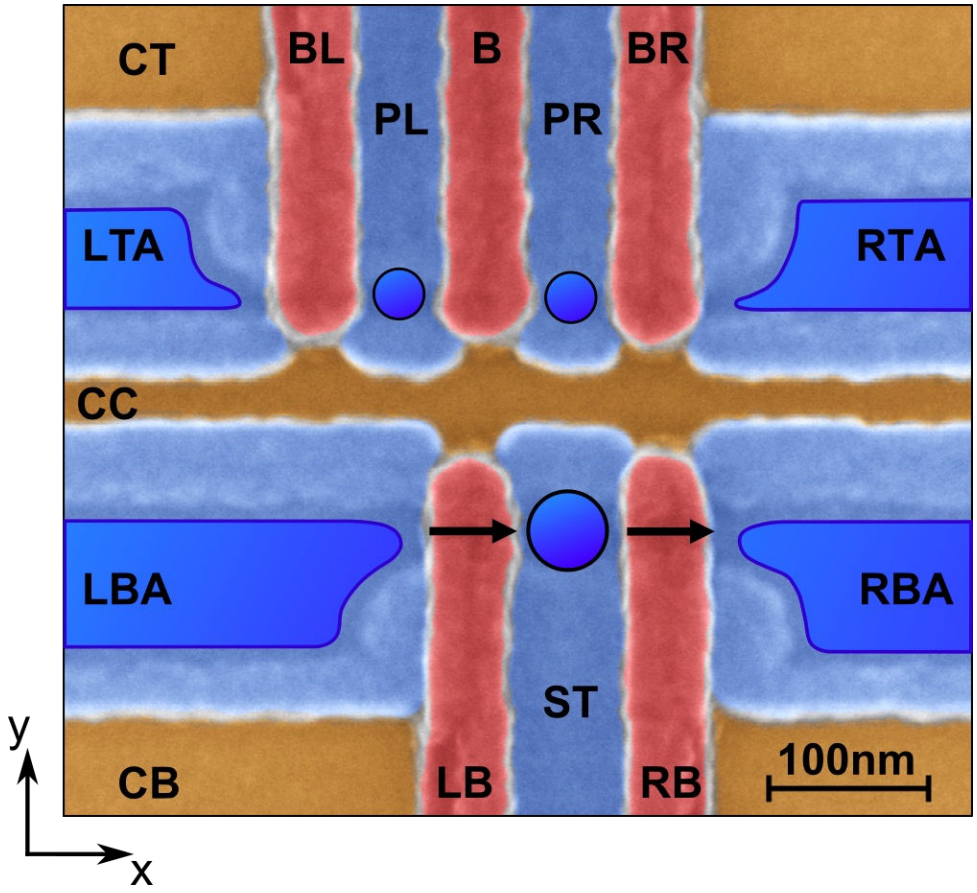

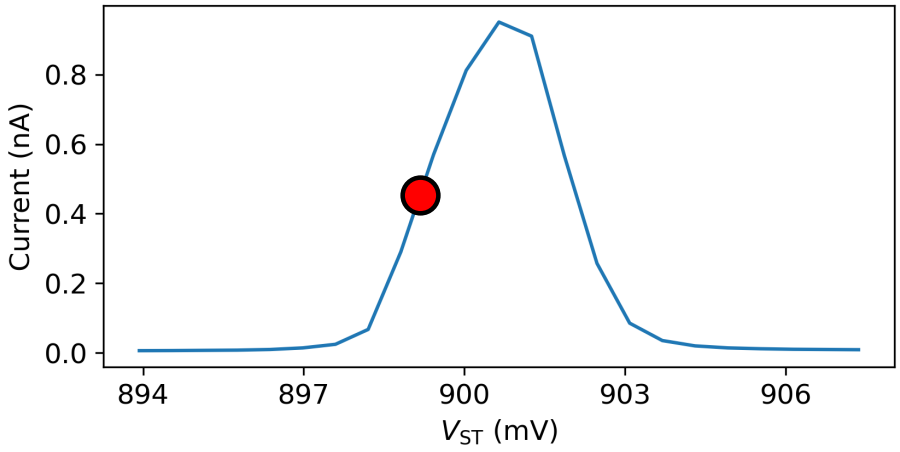

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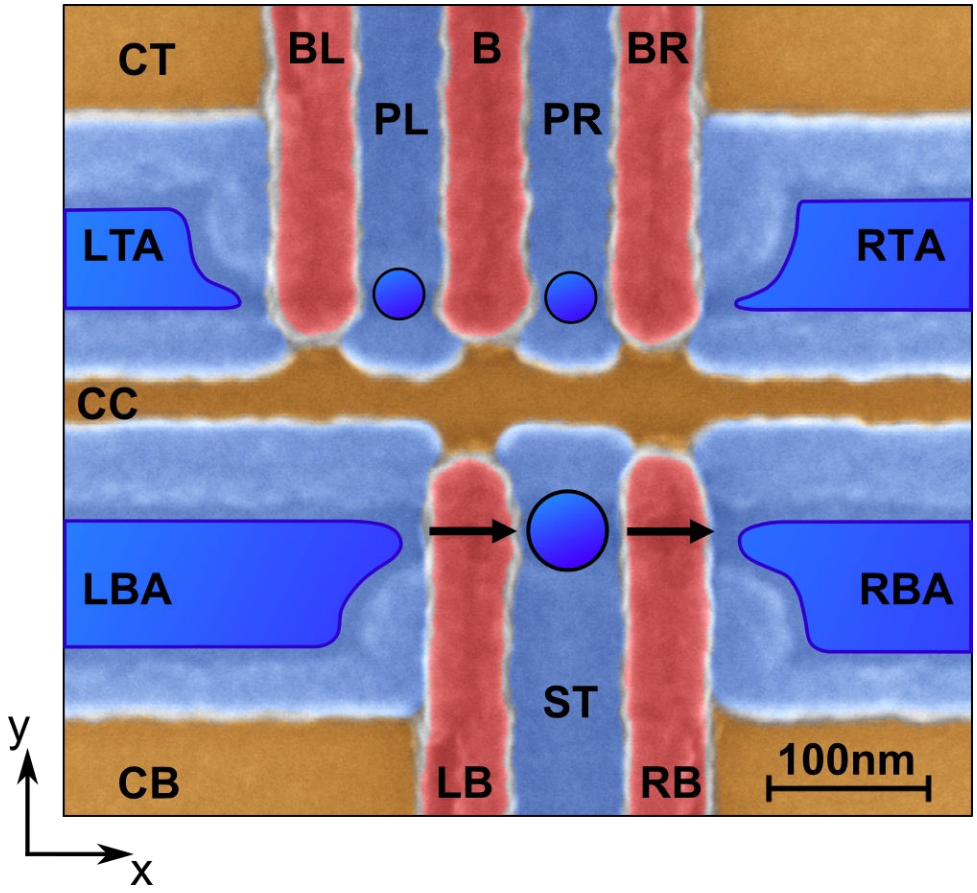
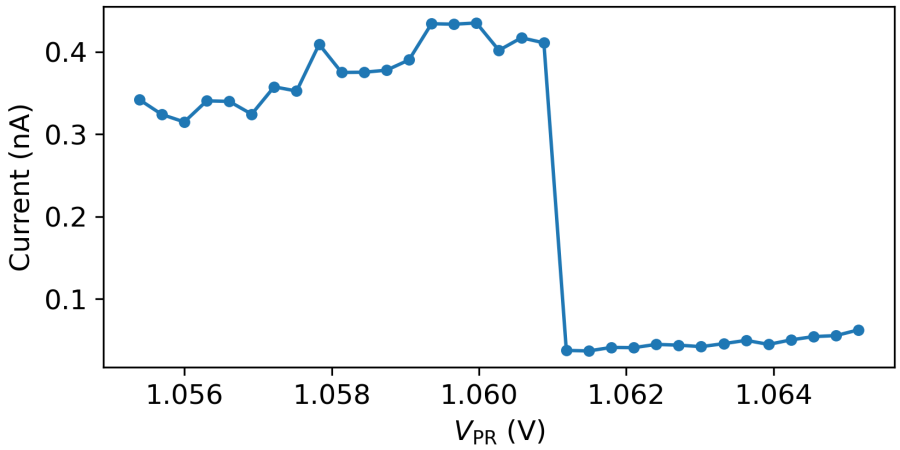
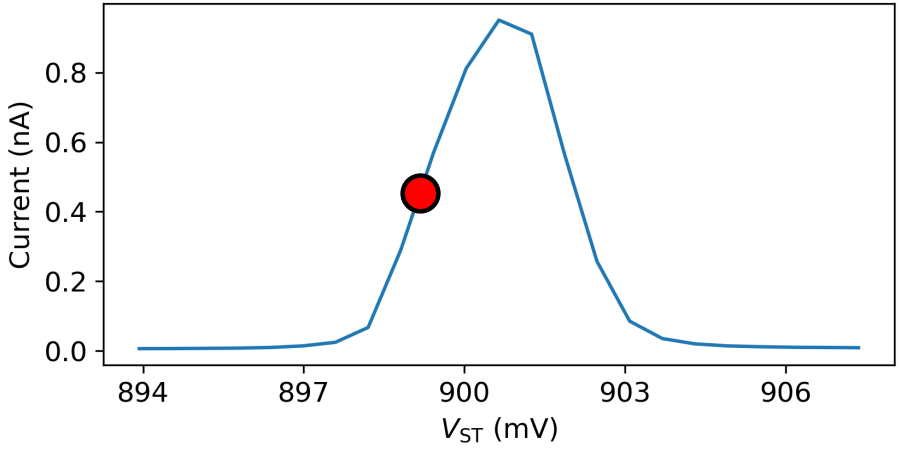
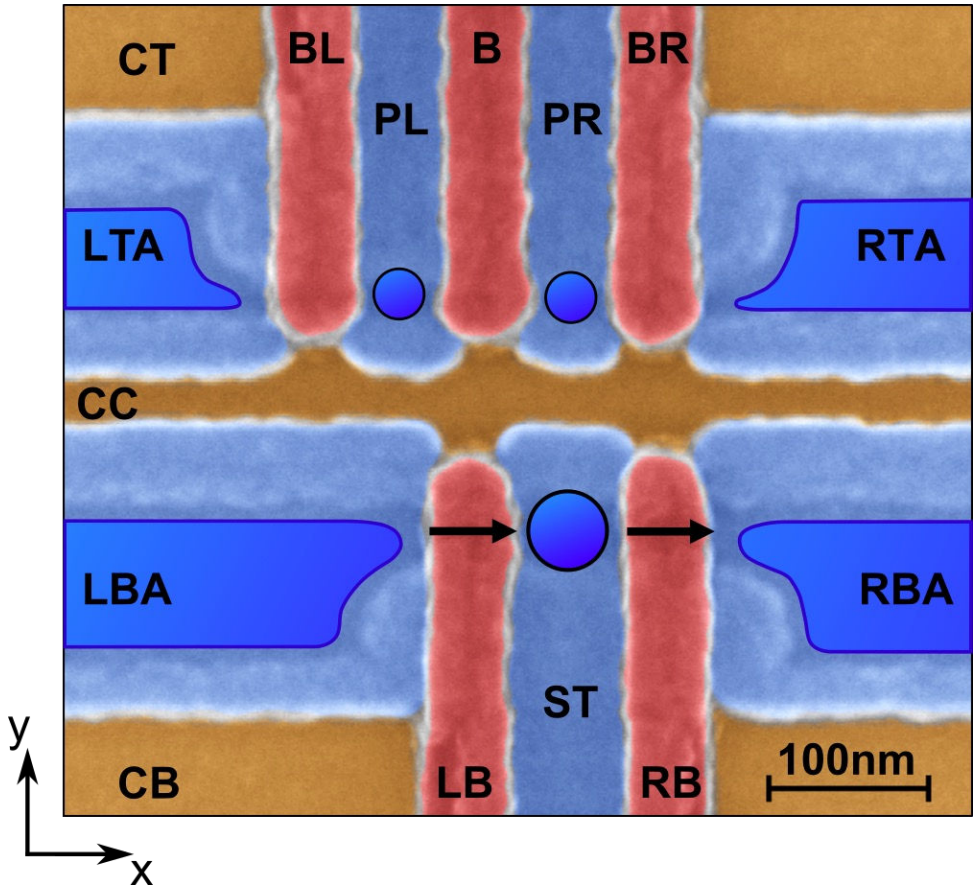
Charge sensing

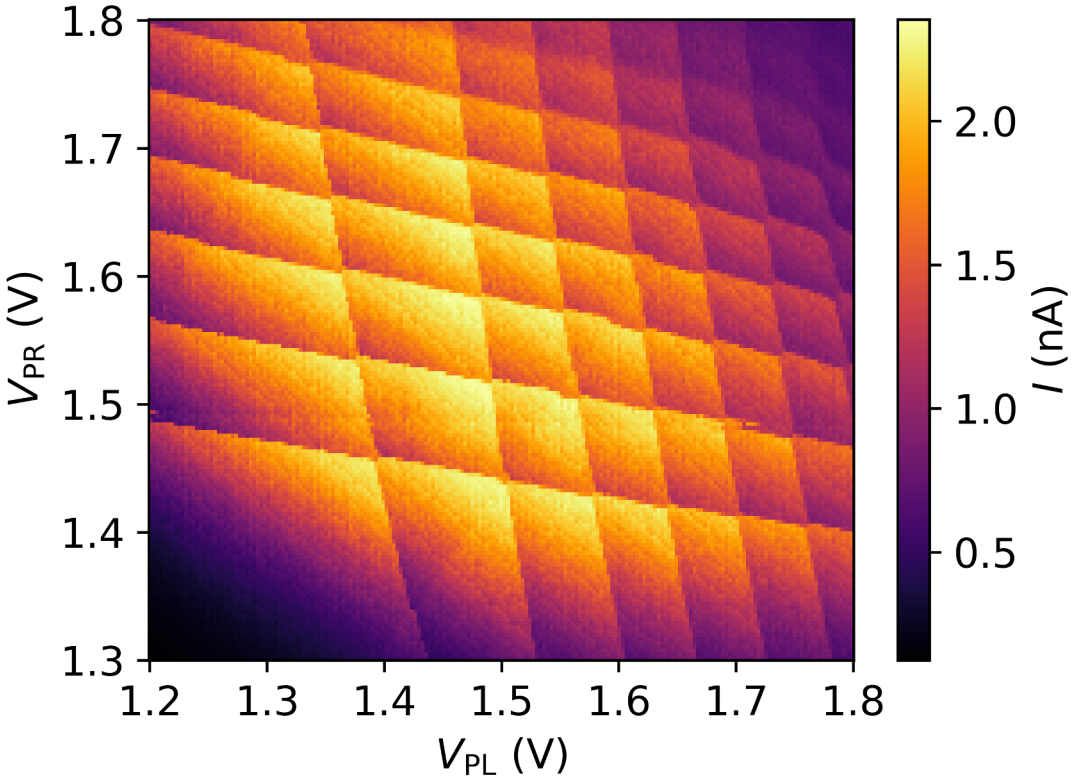






Charge sensing of the double dot





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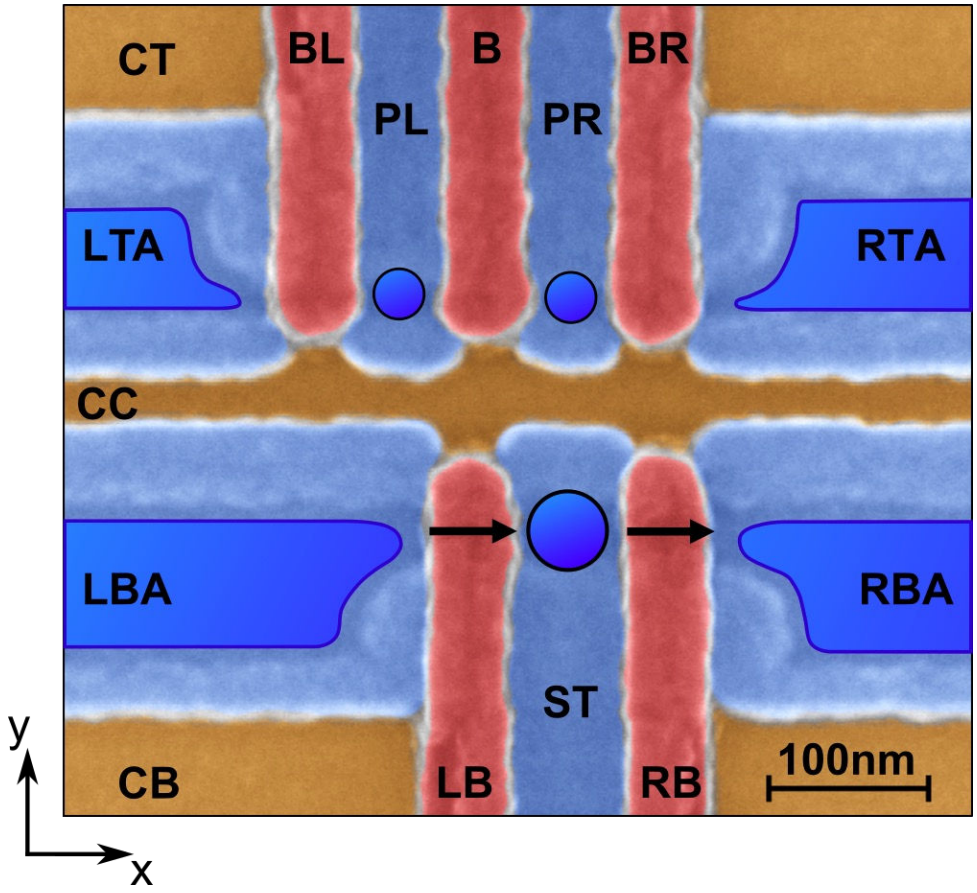

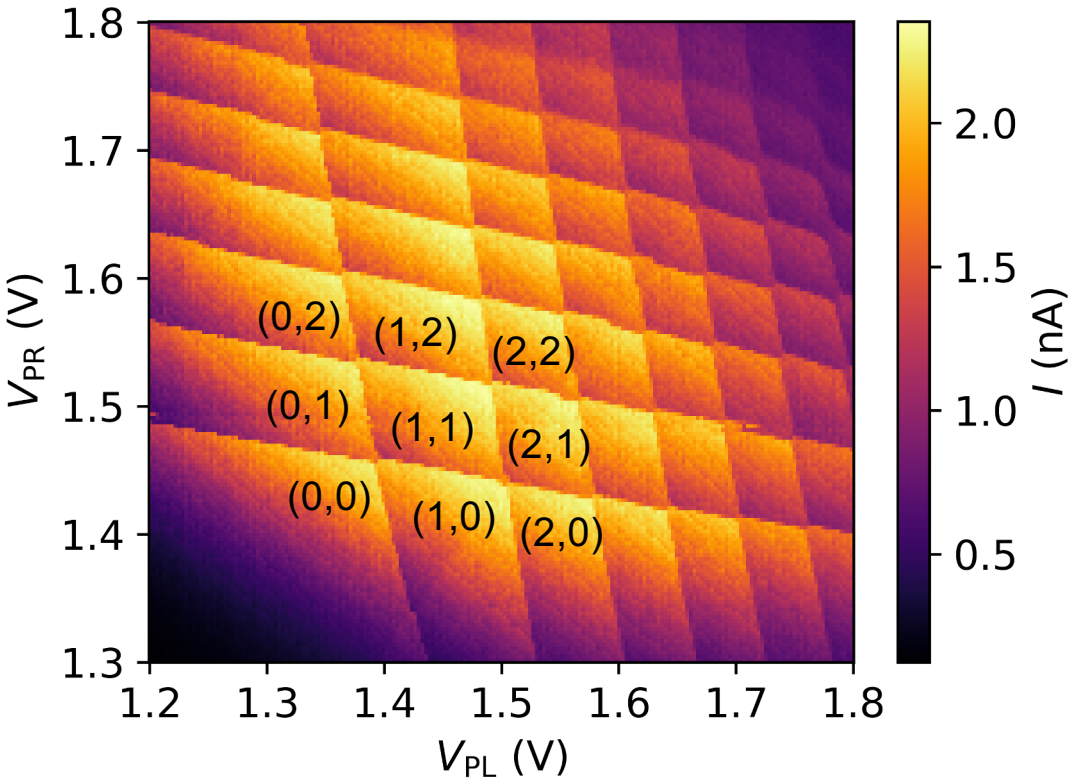

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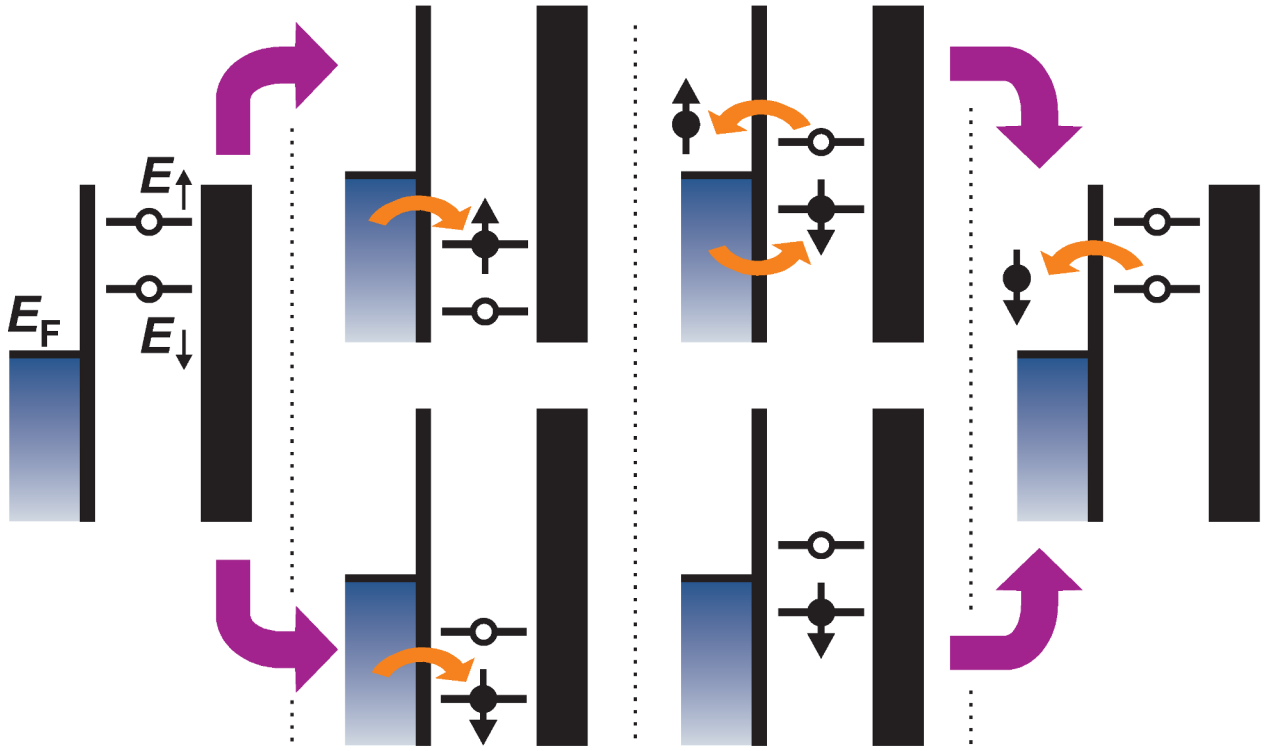
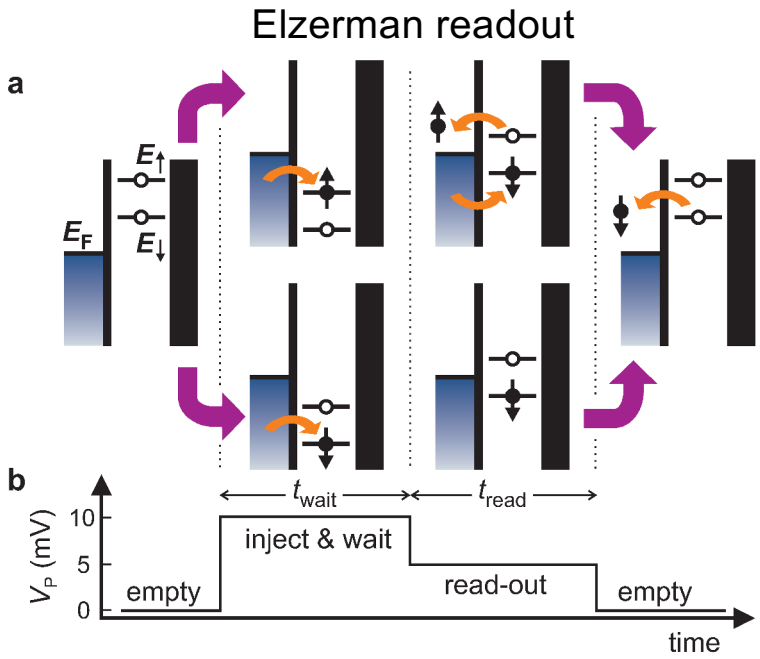
Spin to charge conversion

Elzerman readout



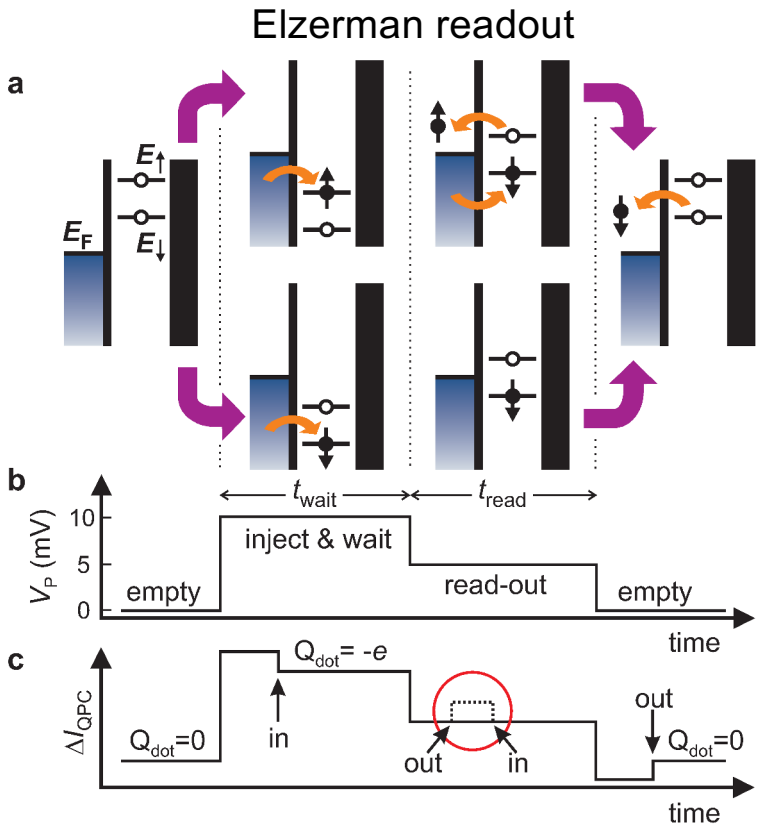
[Elzerman et al. 2004, Nature]

Spin to charge conversion



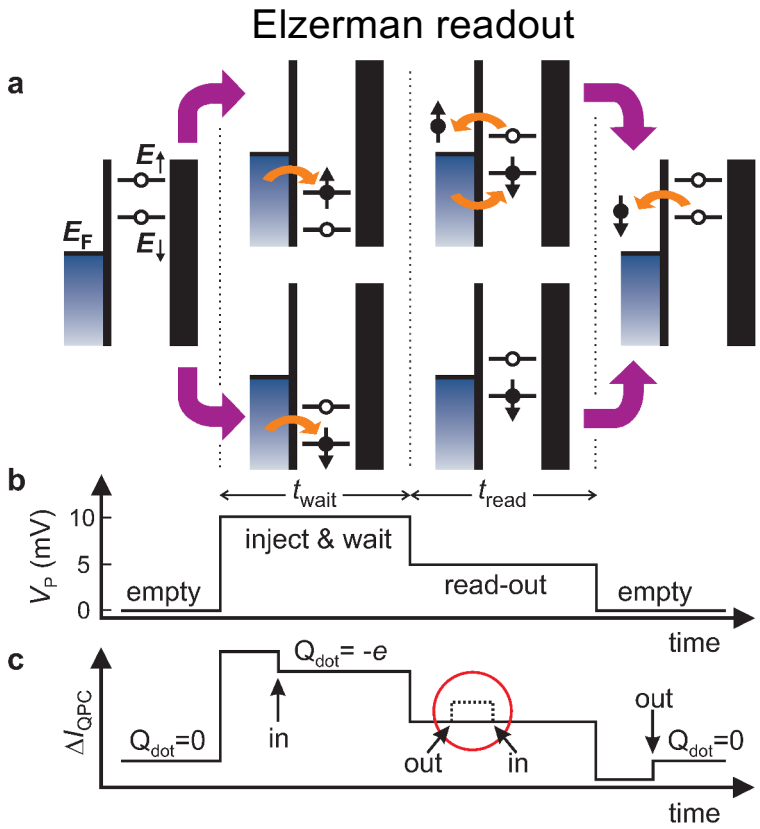
[Elzerman et al. 2004, Nature]

Spin to charge conversion



[Elzerman et al. 2004, Nature]

Spin to charge conversion



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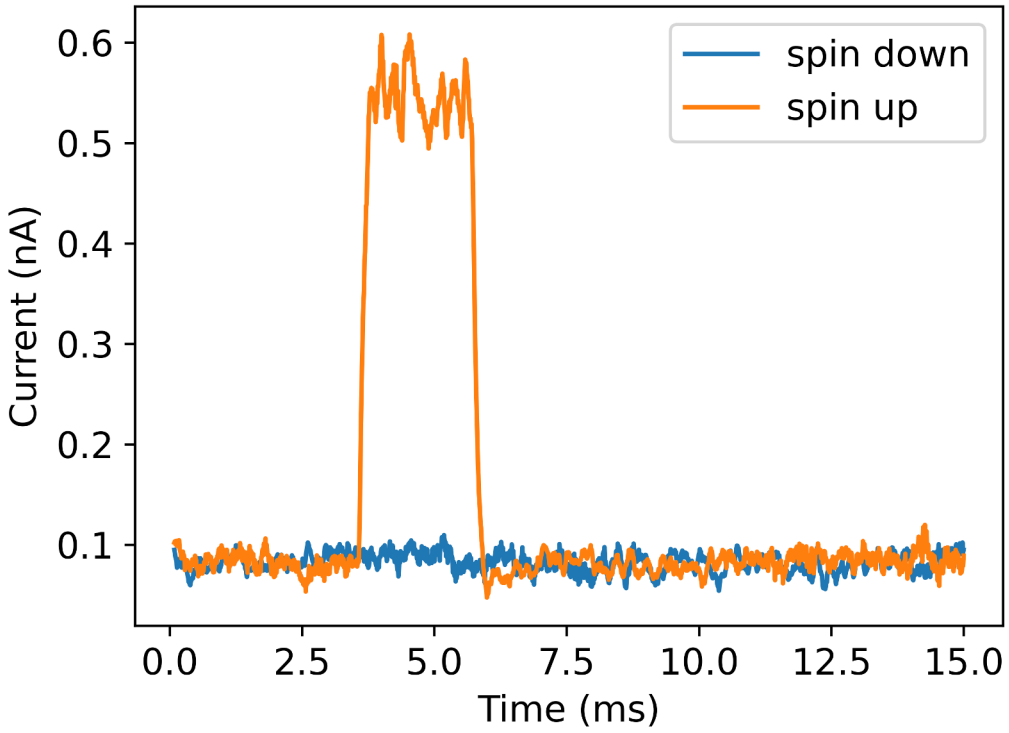

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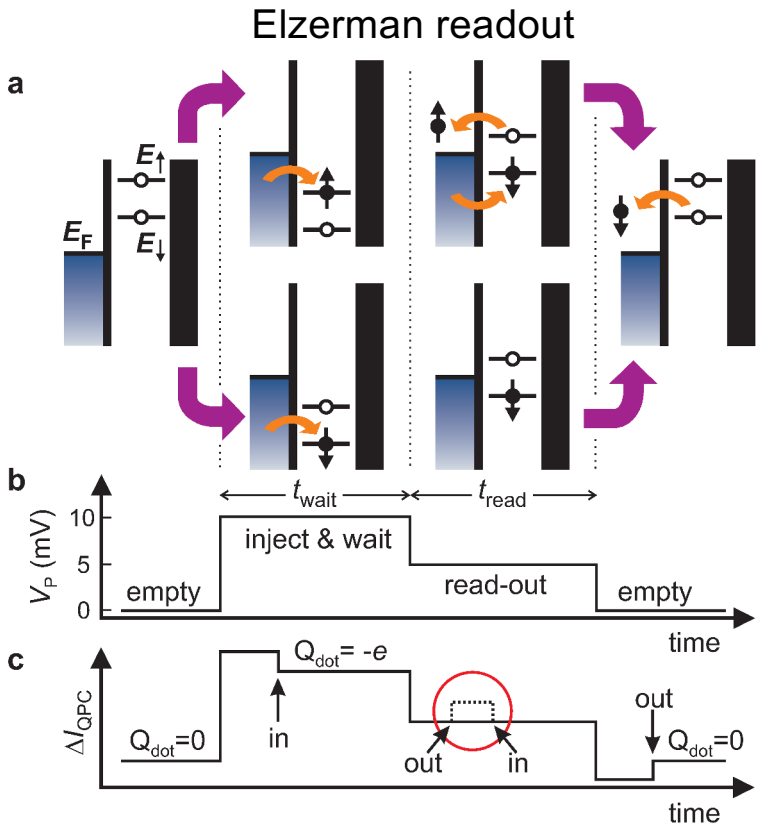

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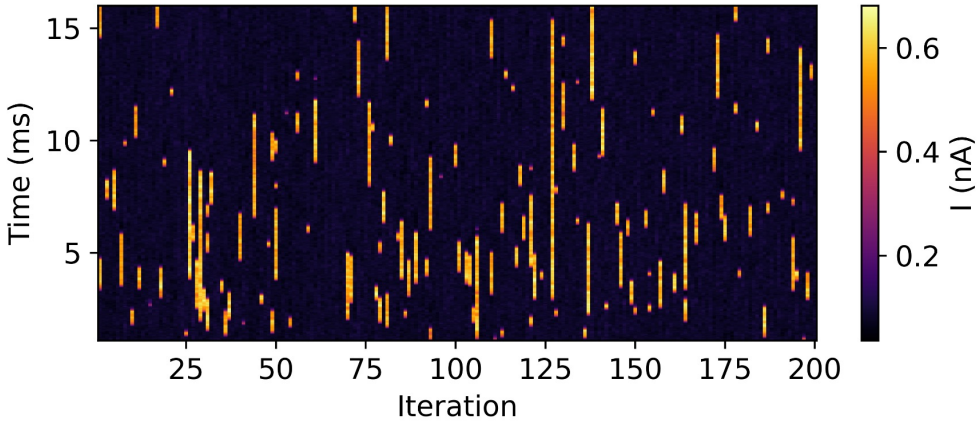

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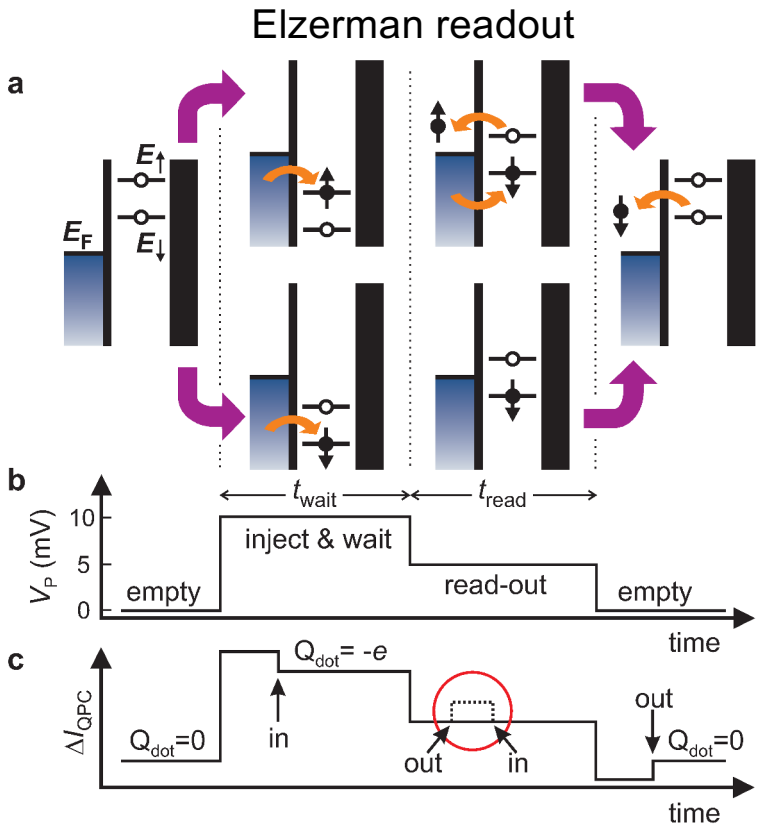
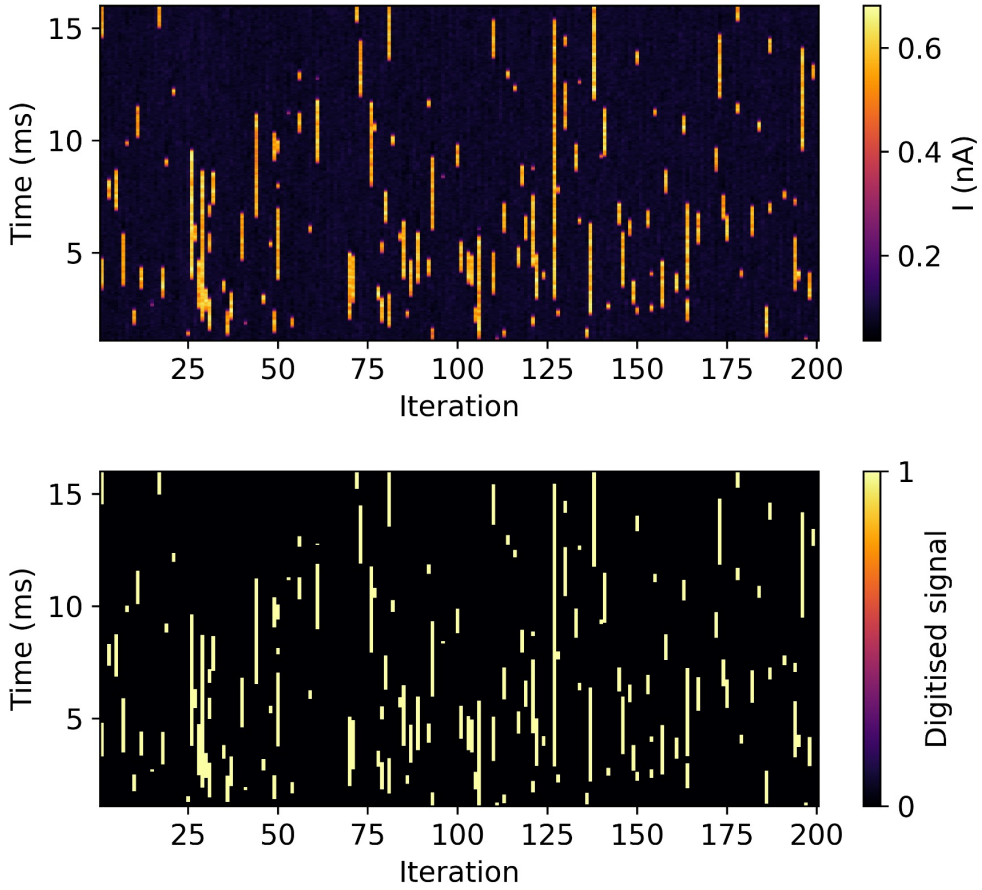


[Elzerman et al. 2004, Nature]



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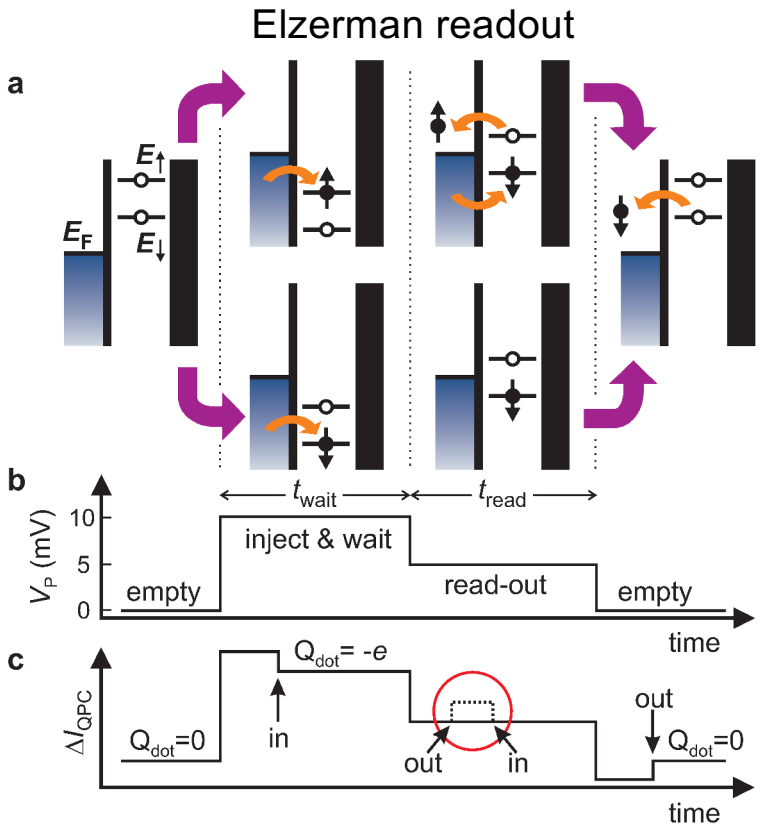
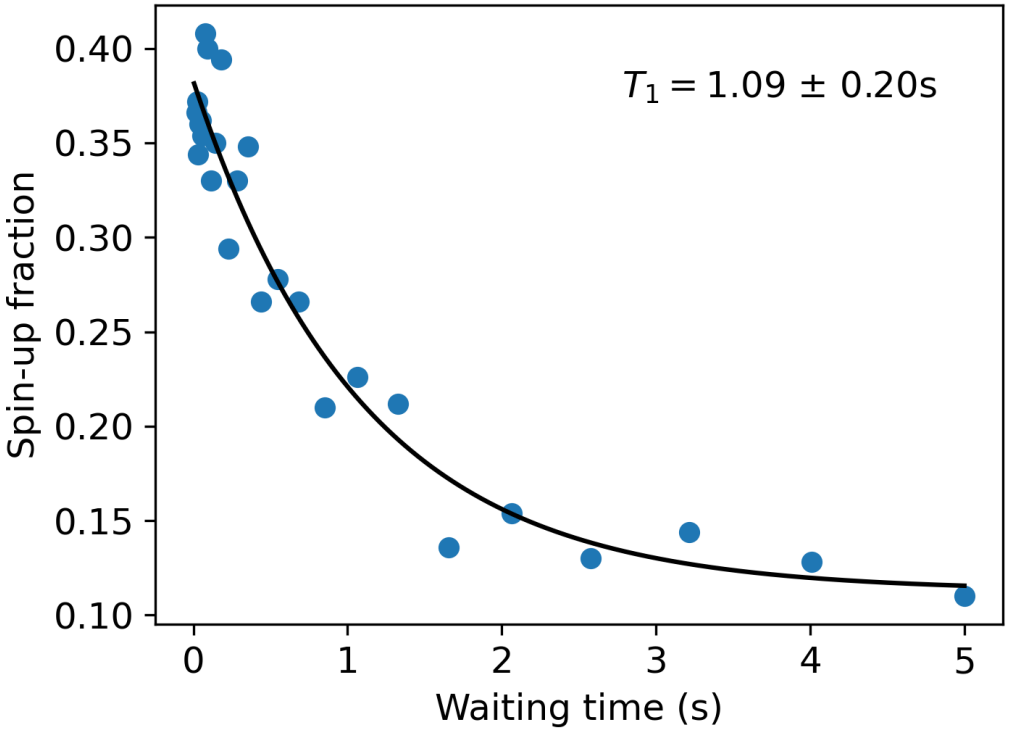
Spin to charge conversion



[Elzerman et al. 2004, Nature]



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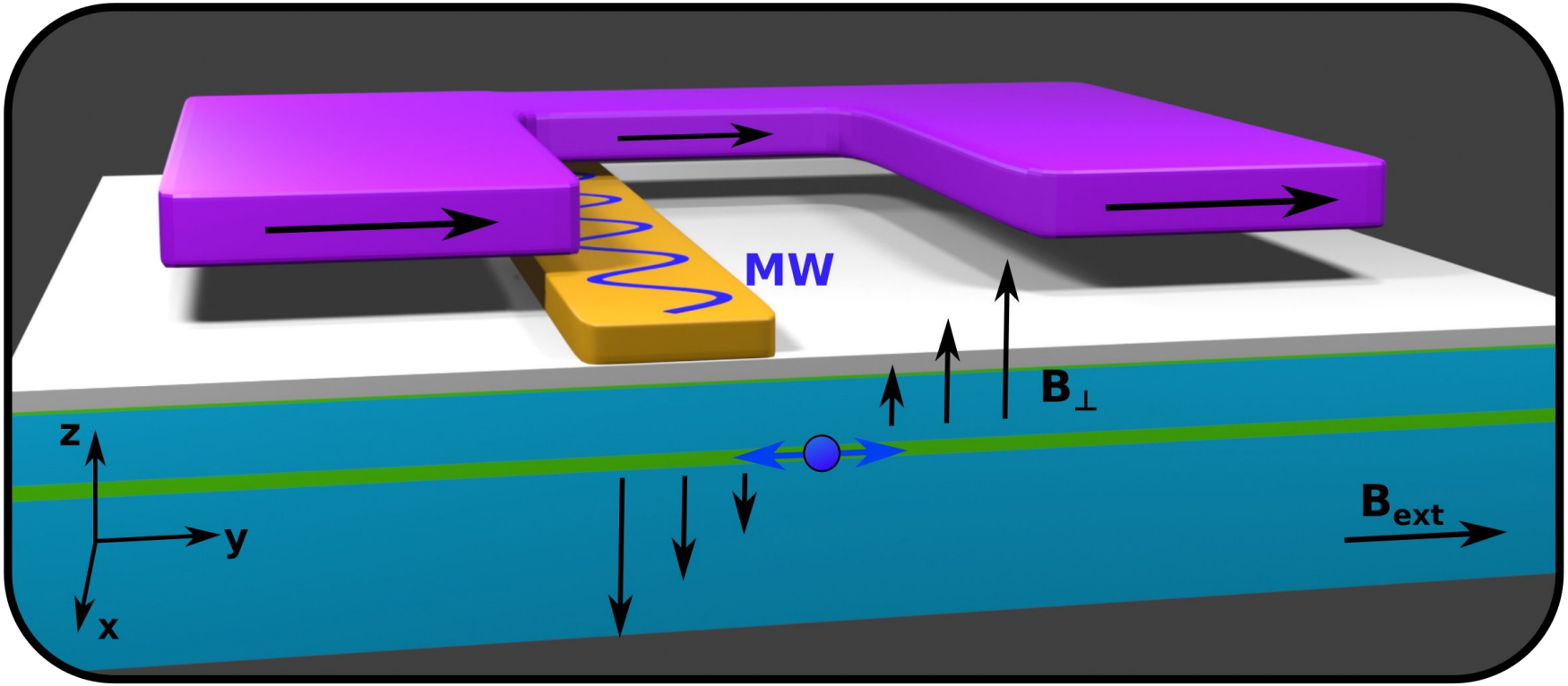
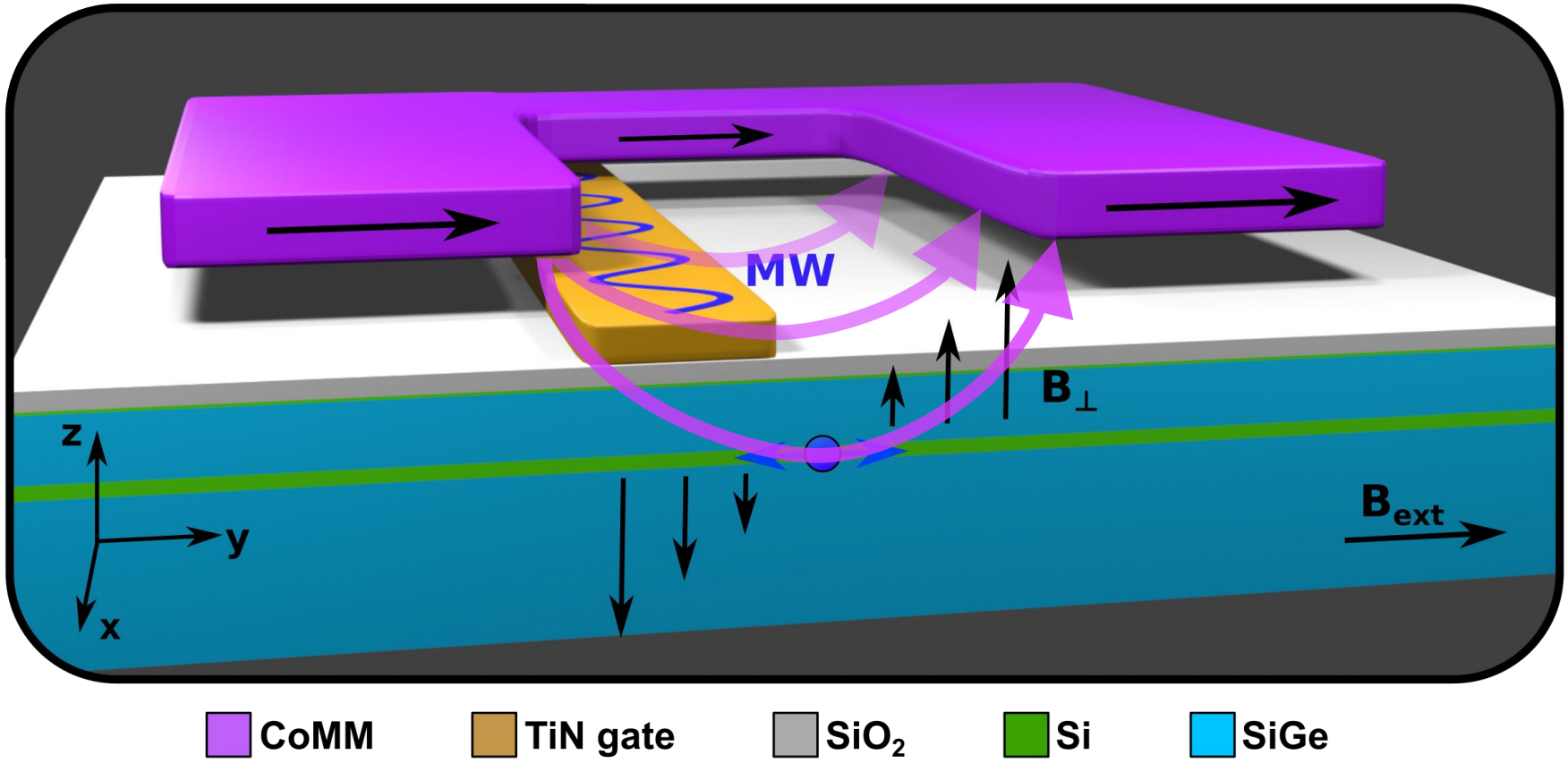
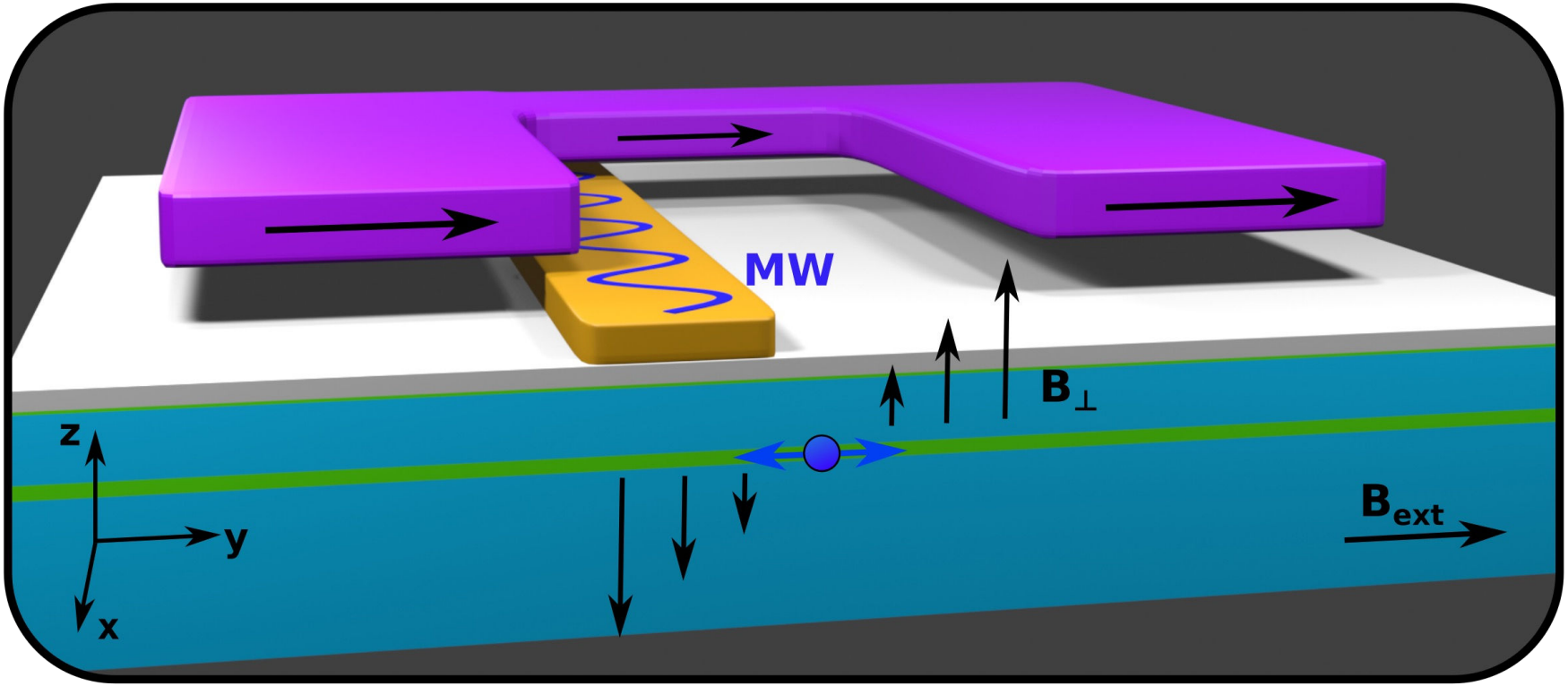
Electric dipole spin resonance (EDSR) qubit manipulation



Electric dipole spin resonance (EDSR) qubit manipulation



Electric dipole spin resonance (EDSR) qubit manipulation



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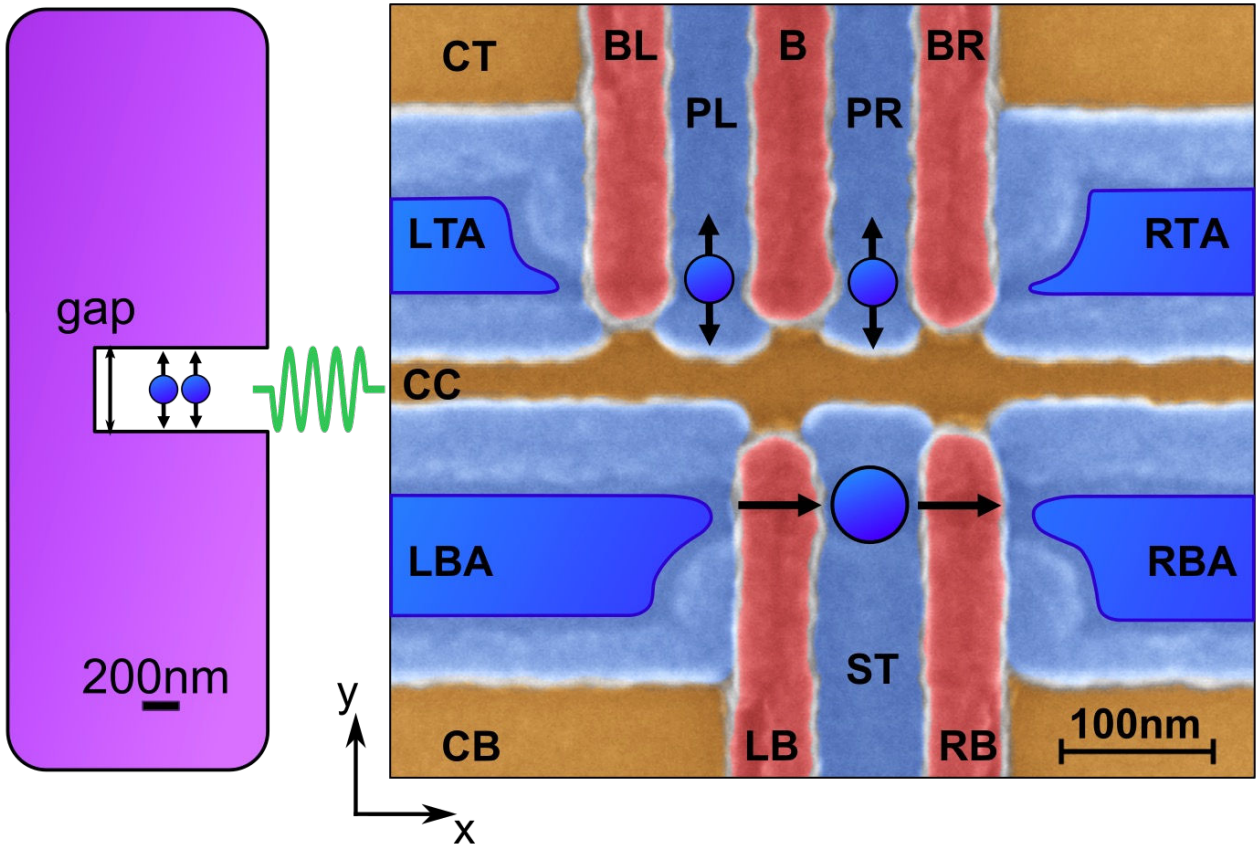
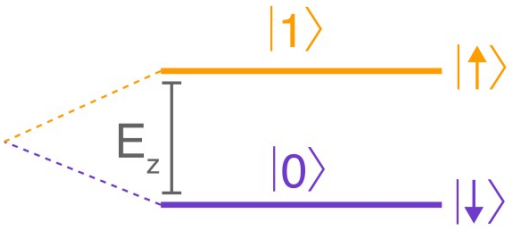
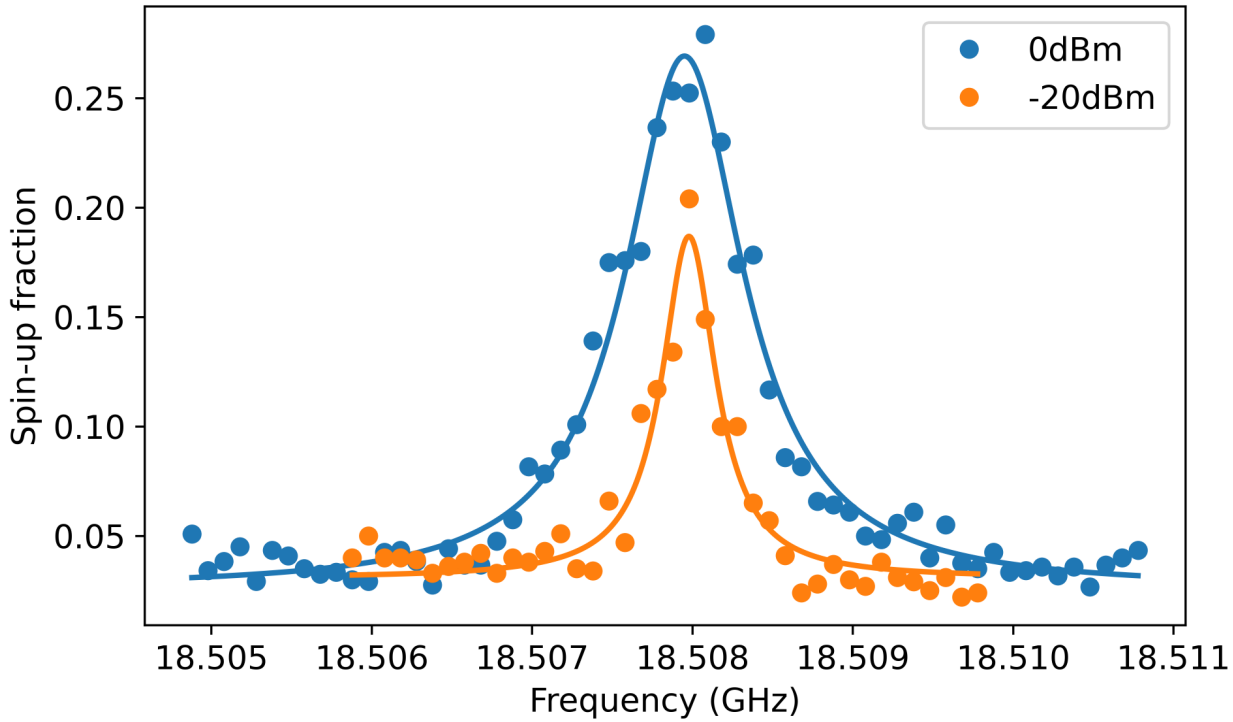
Electric dipole spin resonance (EDSR) qubit



Level Diagram



MW Frequency sweep



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Qubit characterization

- Manipulation speed (Rabi frequency)
- Lifetime and coherence times (T_1, T_2^*, T_2^H)
- Qubit gate fidelity

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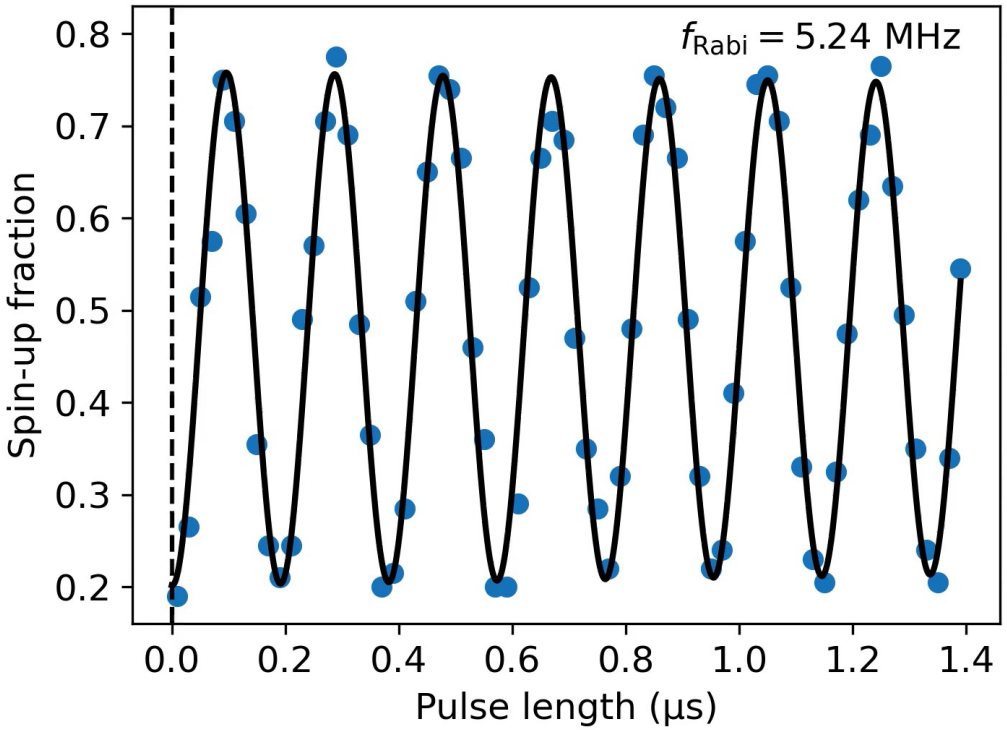
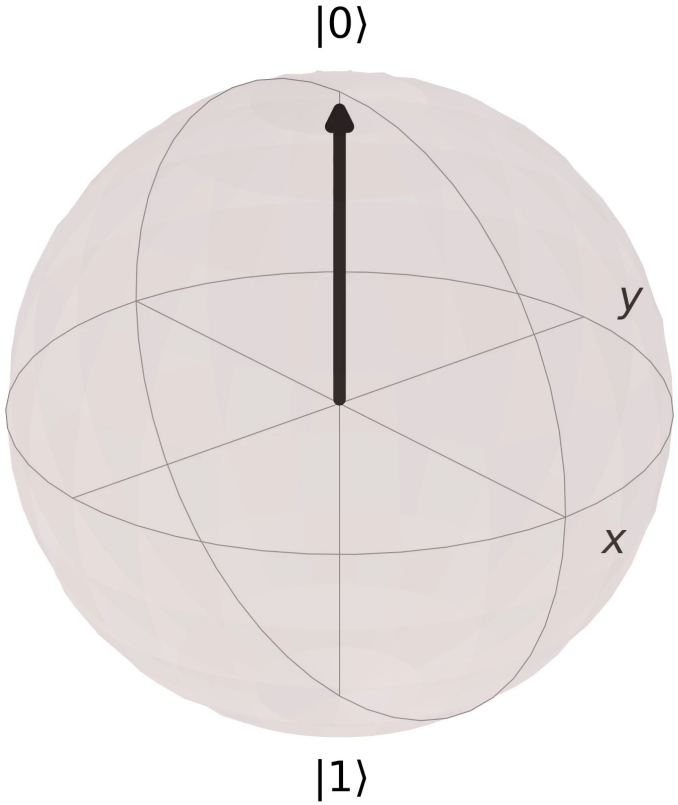
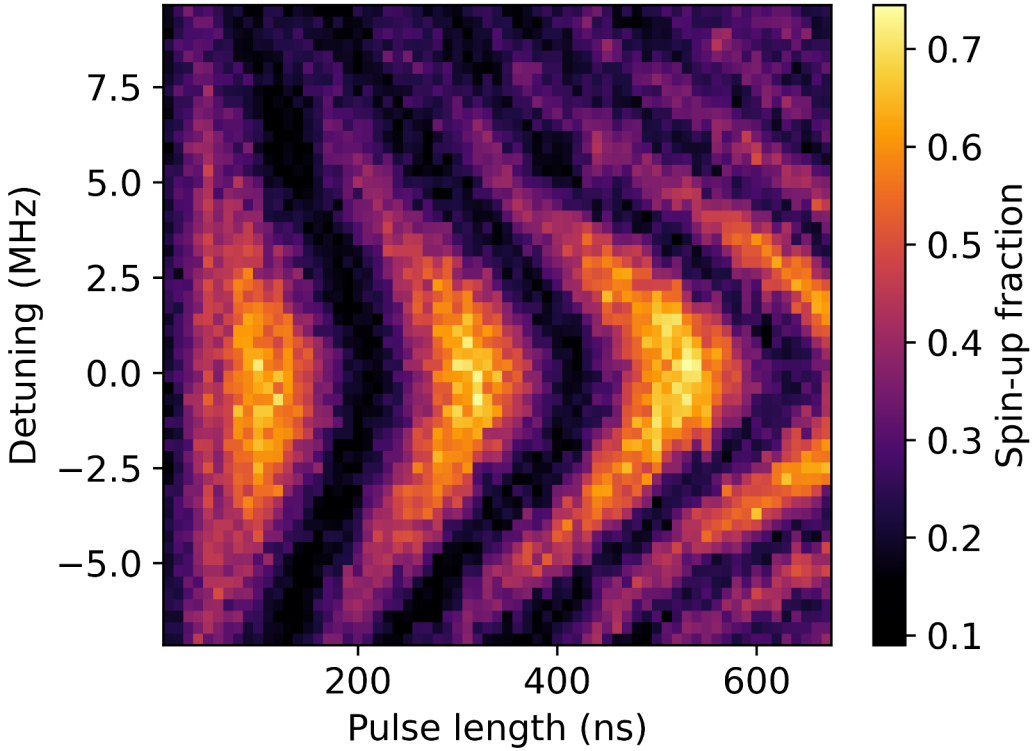
Rabi oszillations

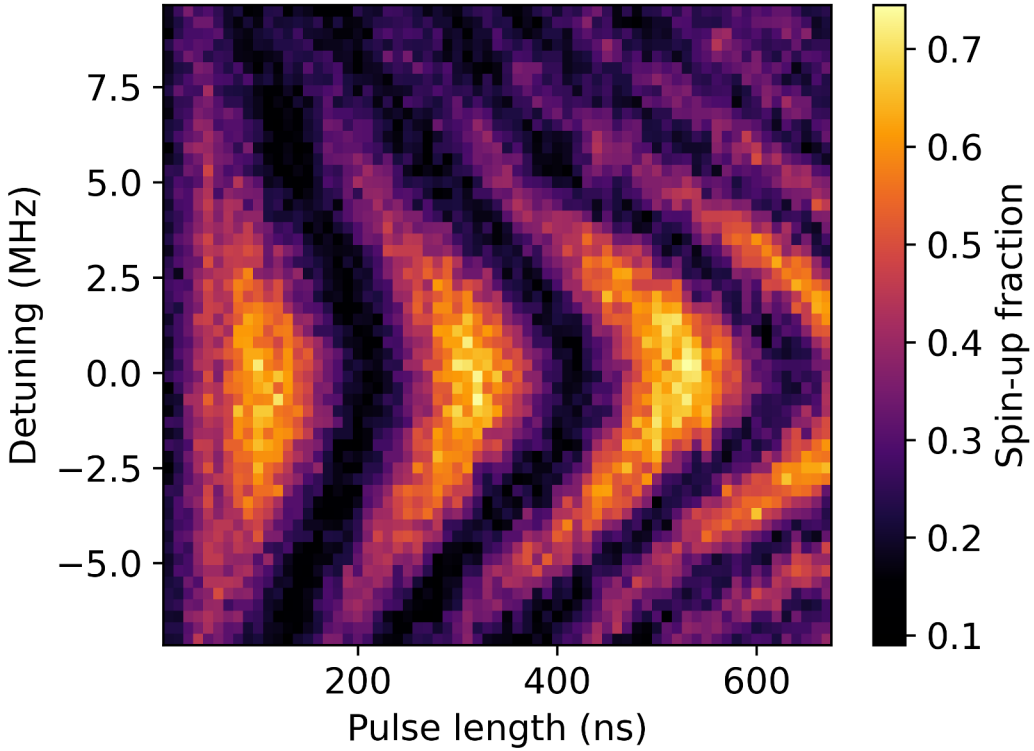


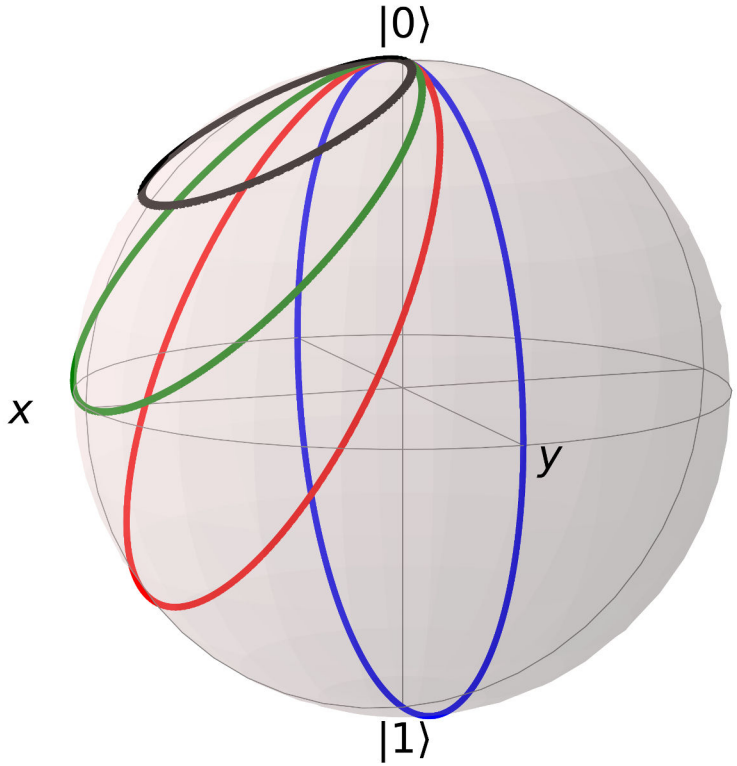


Chevron pattern

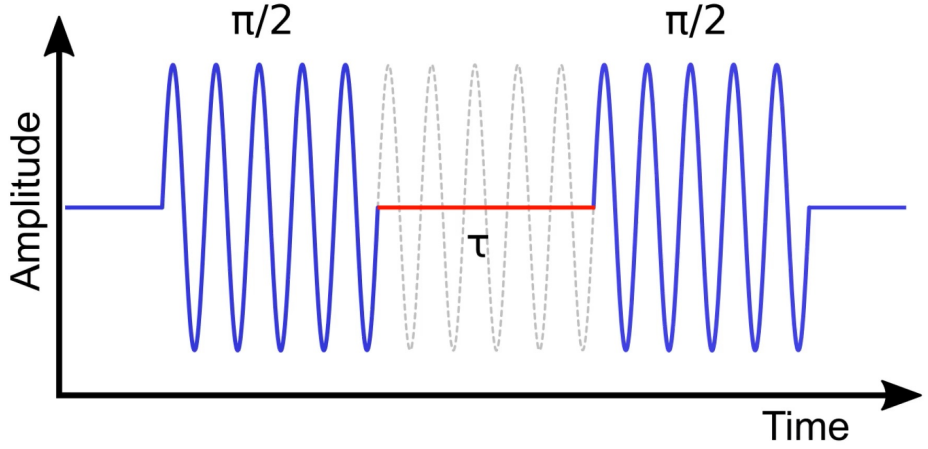


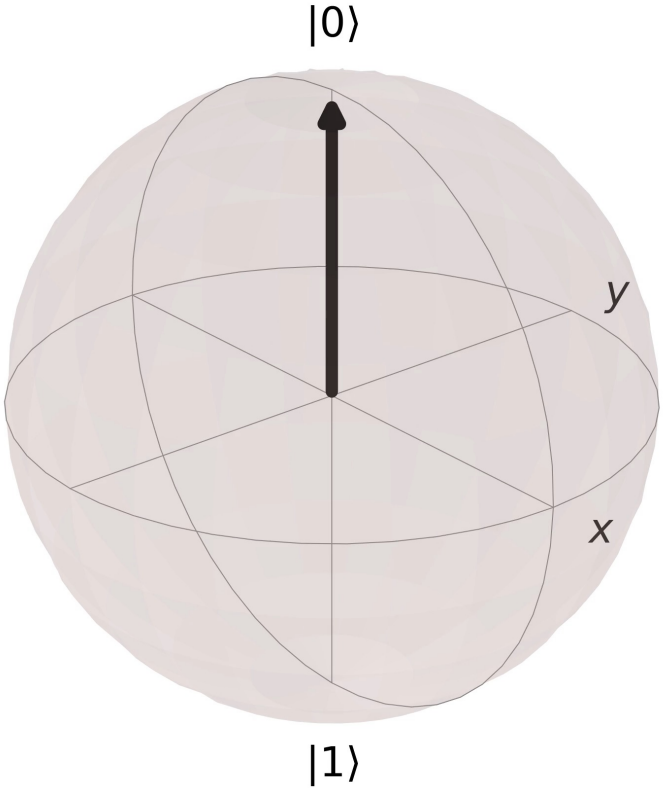
Chevron pattern



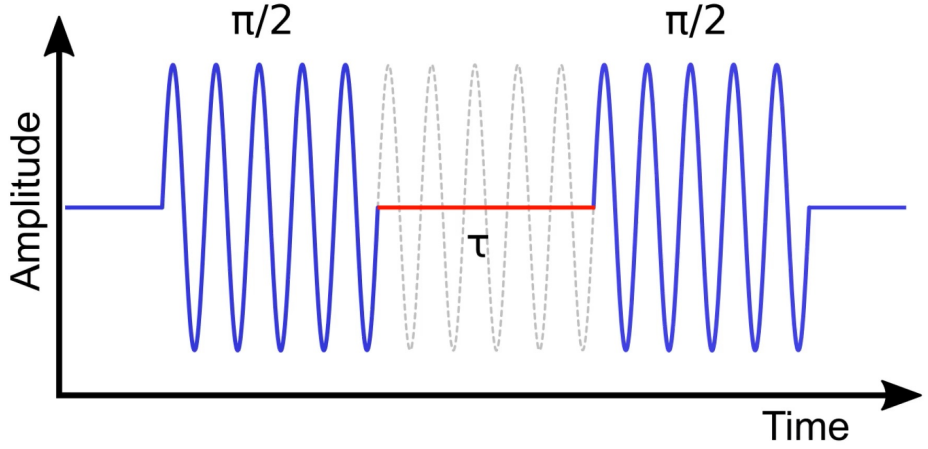


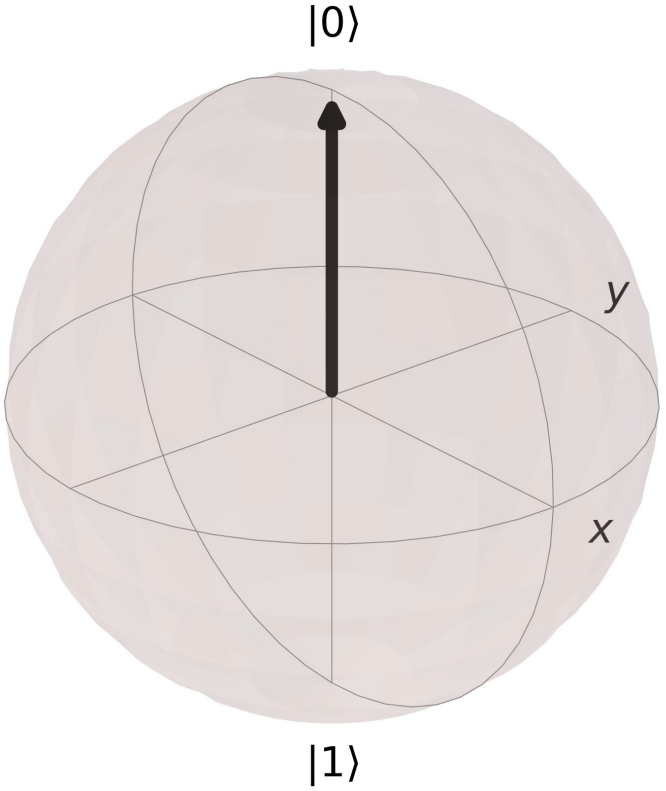
Ramsey sequence



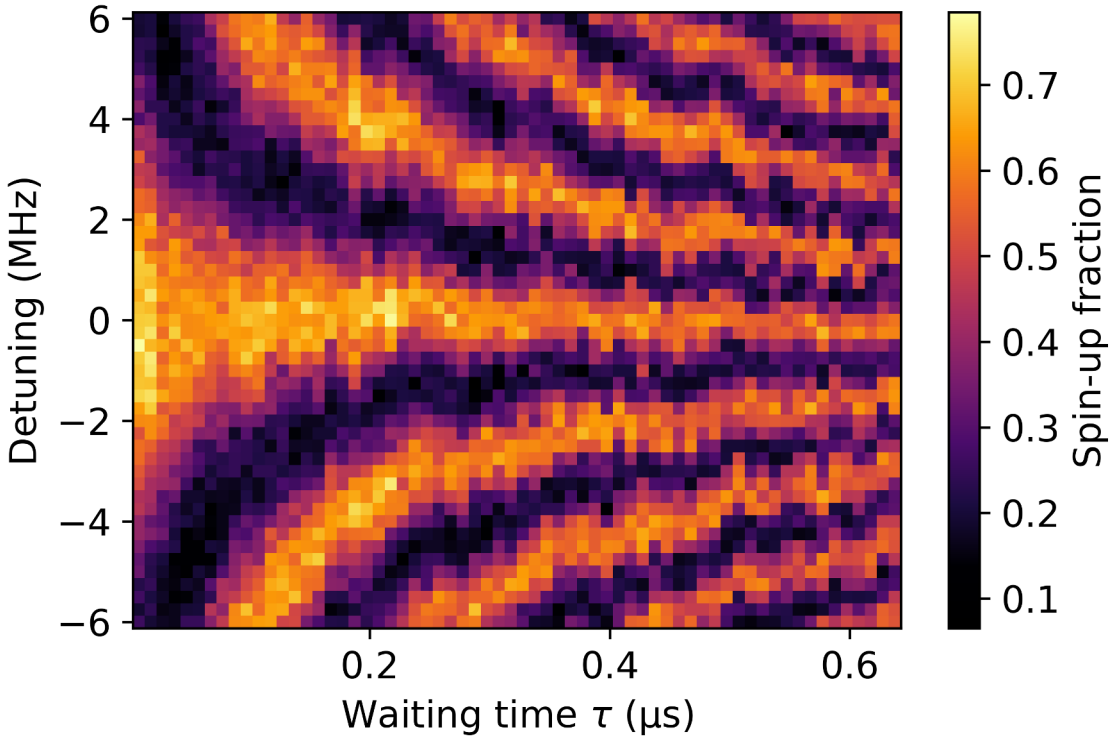


Ramsey sequence detuned





Ramsey sequence



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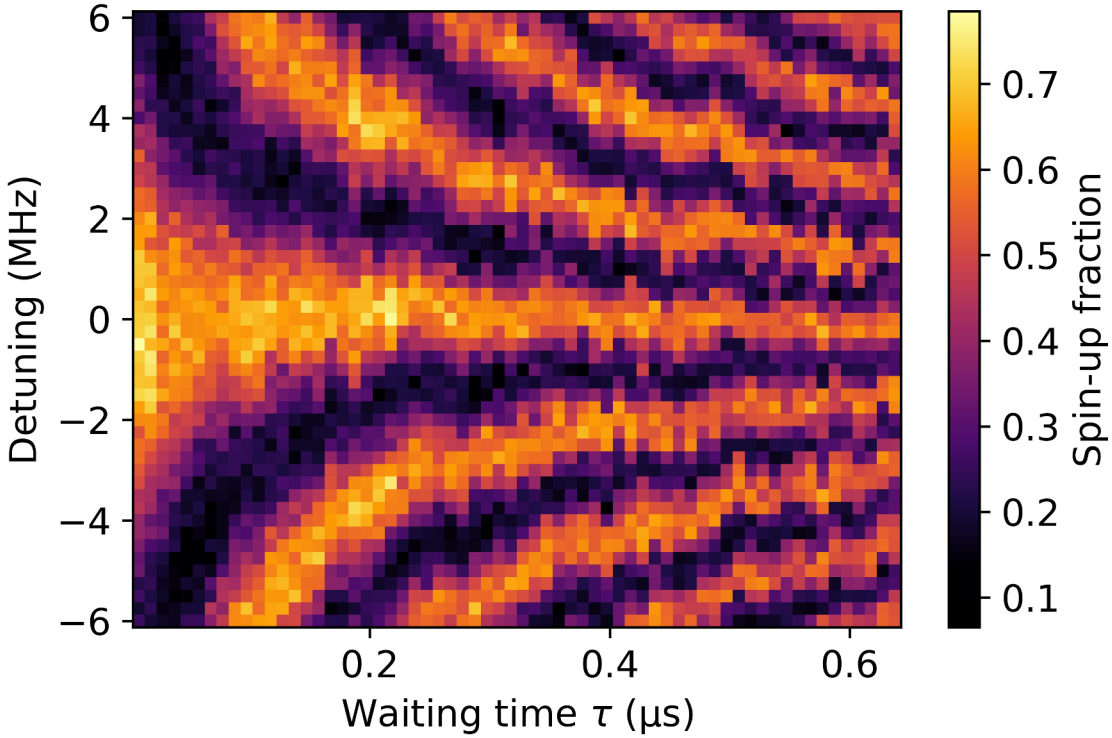
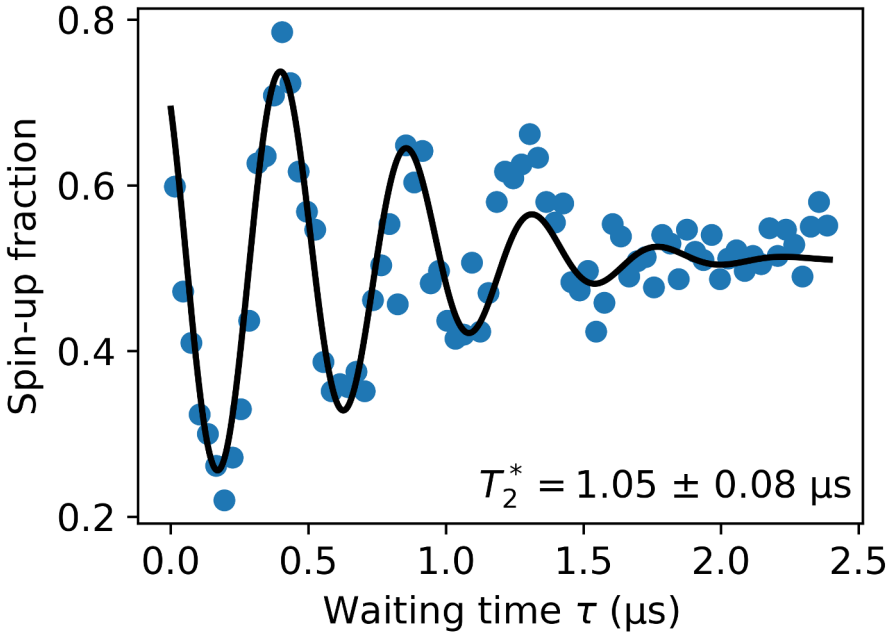
Ramsey sequence 2MHz detuning





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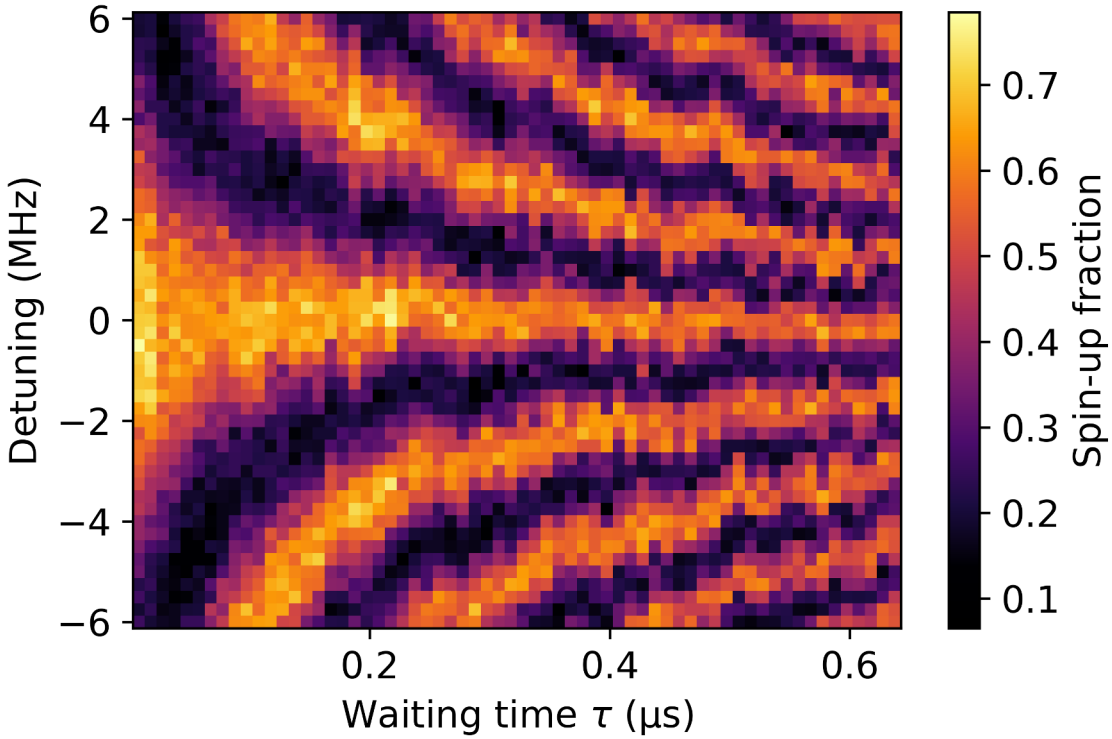
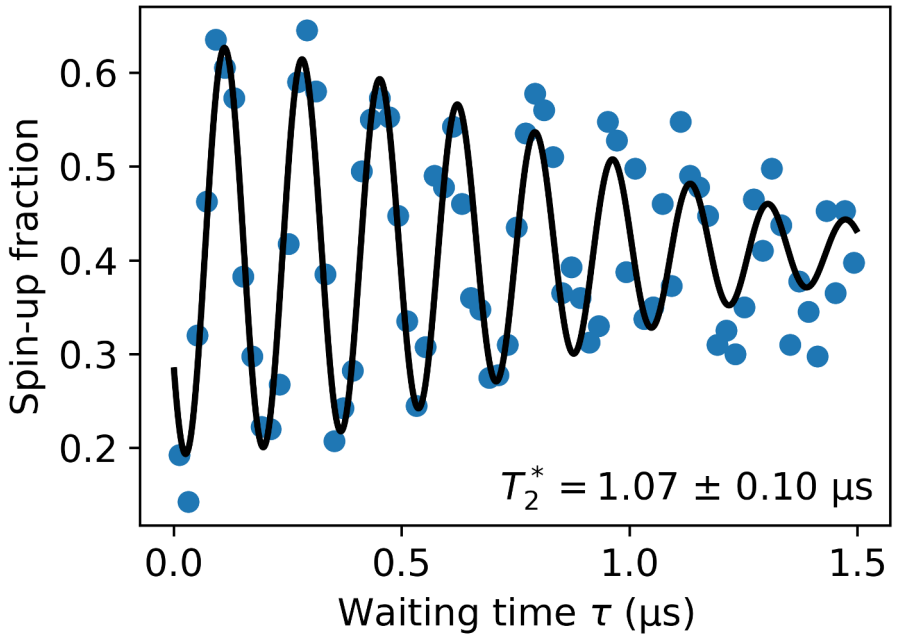
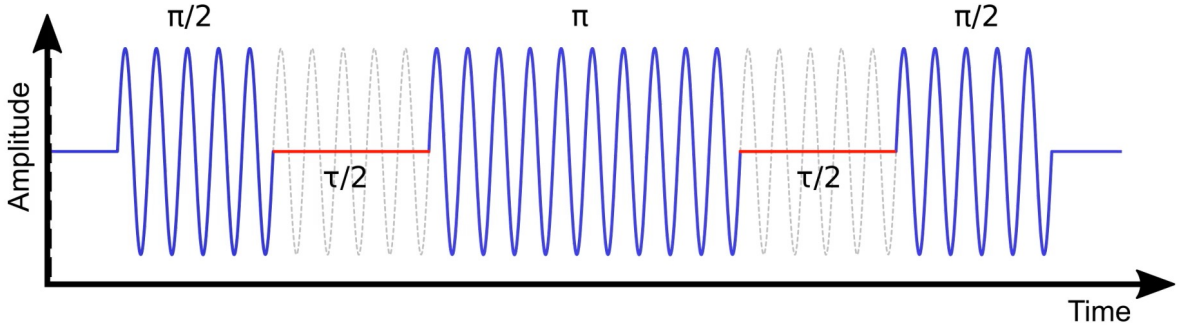
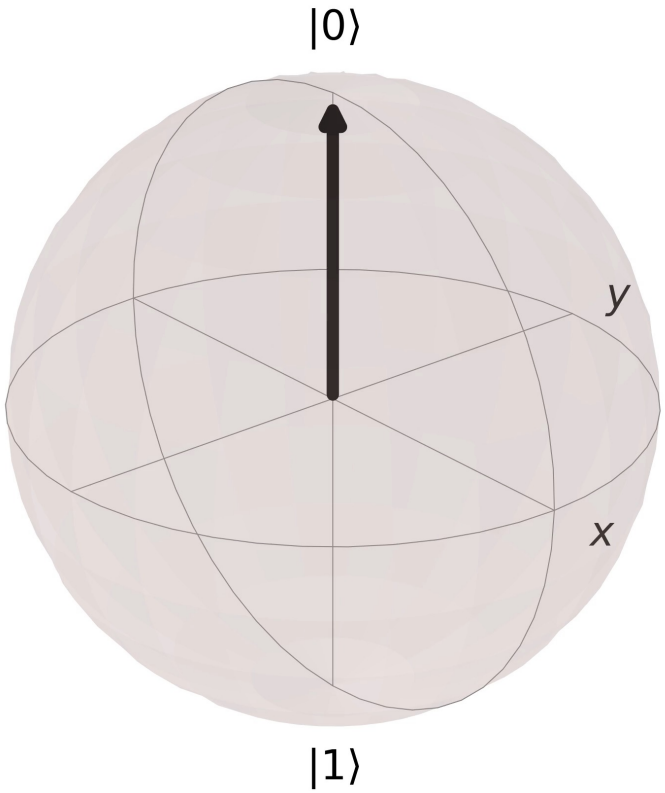
Ramsey sequence 6MHz detuning



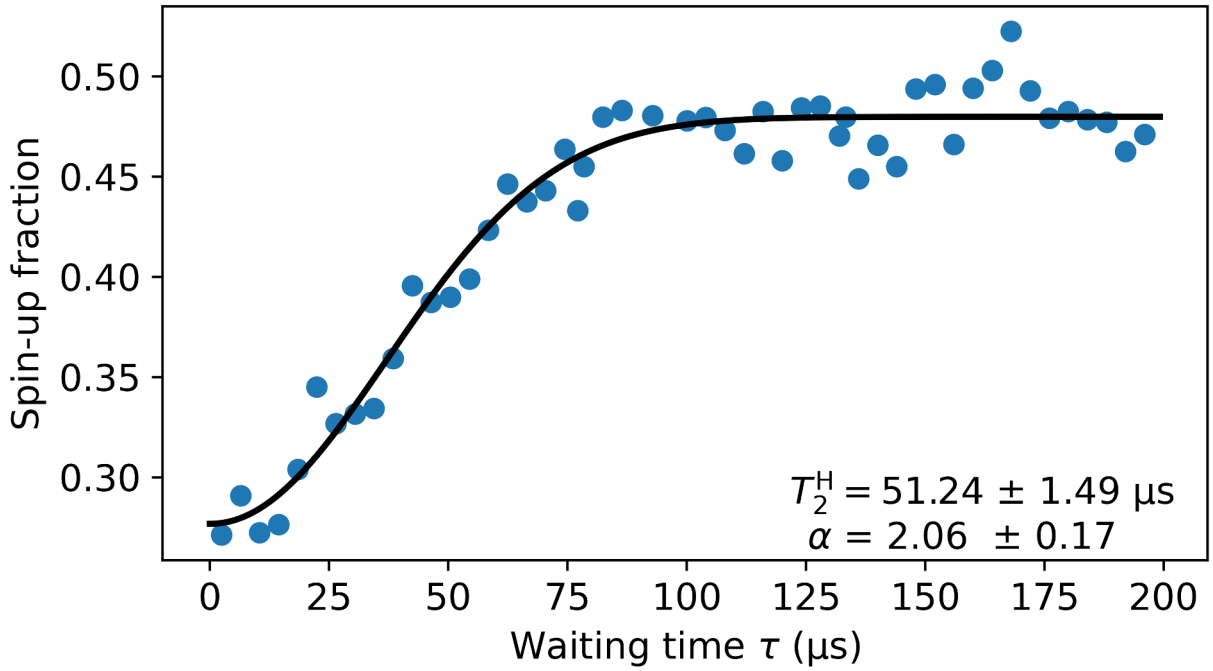


Spin-echo sequence





Spin-echo sequence



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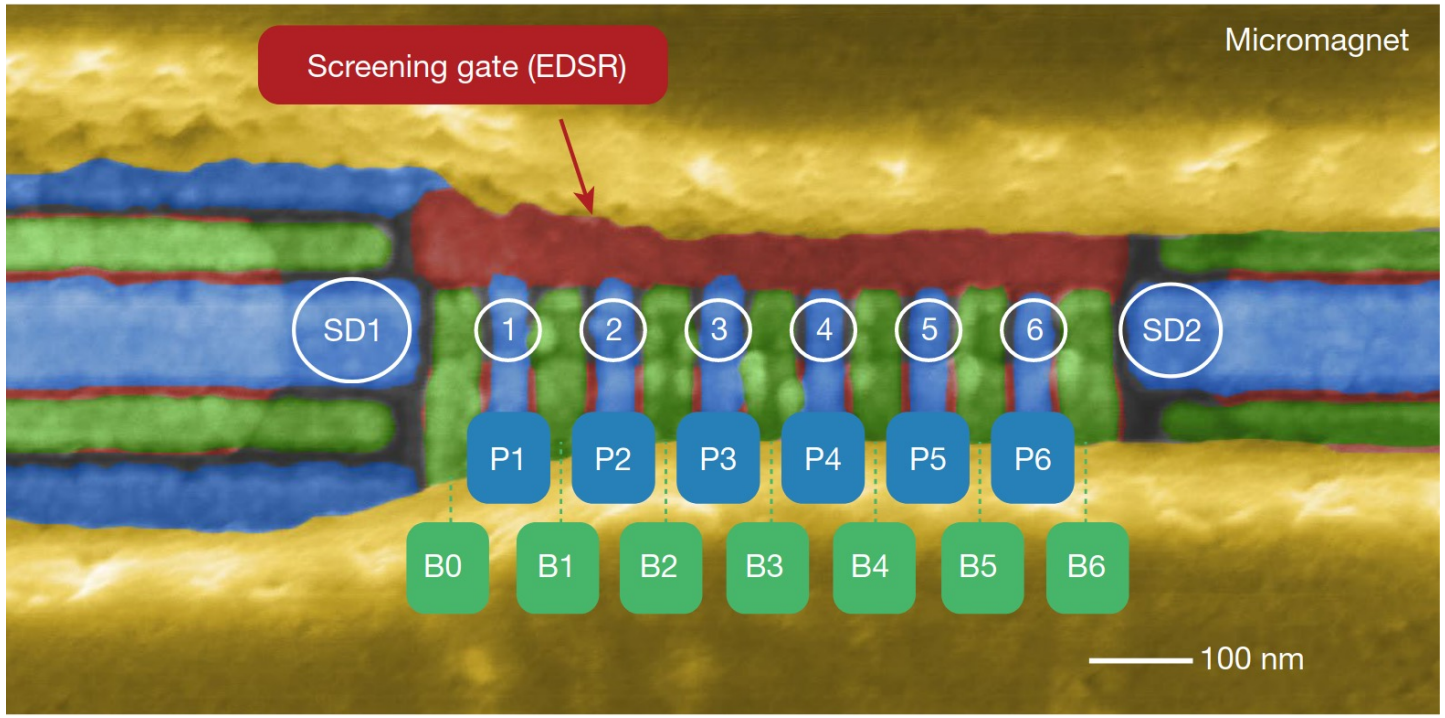
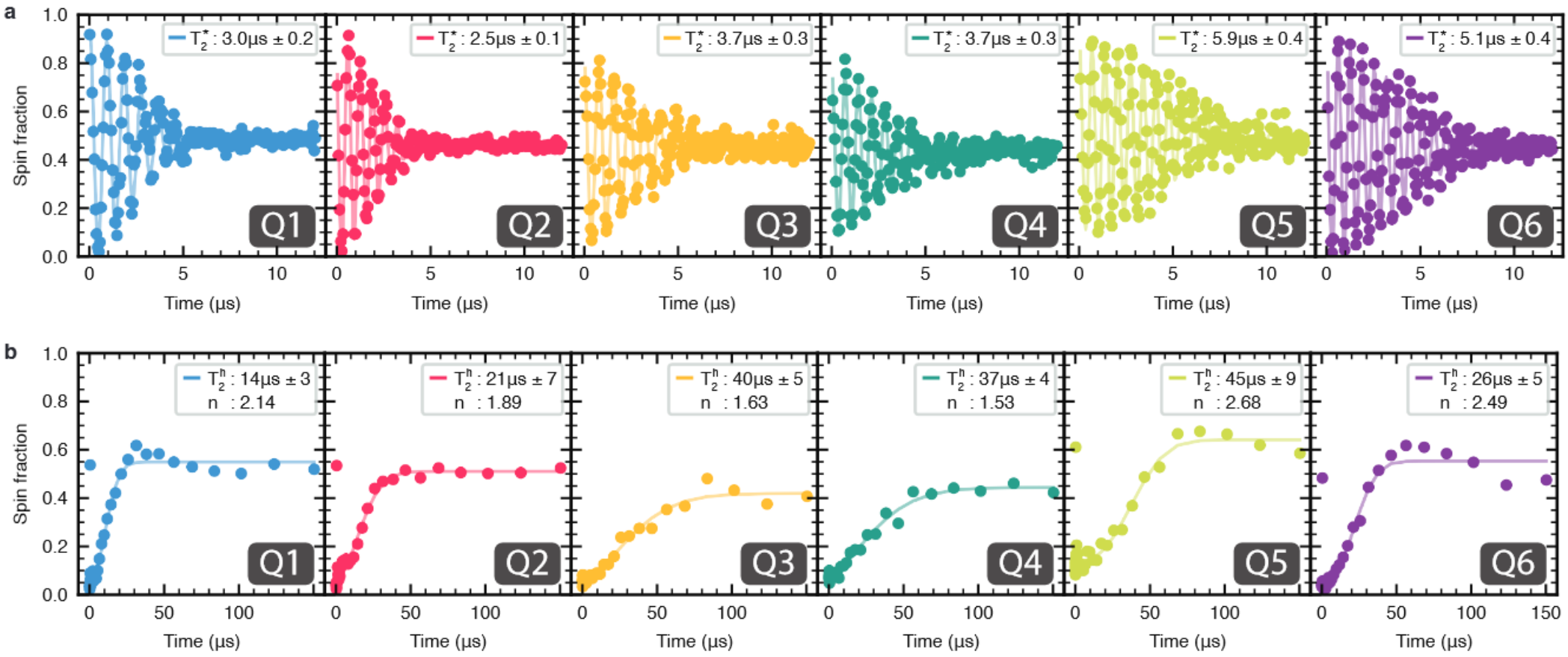
Delft 6 qubit SiGe processor comparison



[Philips, et al., Nature 609, 919–924 (2022)]

Delft 6 qubit SiGe processor comparison



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Qubit characterization

- Manipulation speed (Rabi frequency)
- Lifetime and coherence times (T_1, T_2^*, T_2^H)
- Qubit gate fidelity

Randomized benchmarking

- Initialize in specific state
- Random sequence of *n* qubit gates
- „Invert“ sequence of qubit gates to end up in known end state

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Clifford and Primitive gate sets

- Primitive gate set:
  - $I, \pm X, \pm Y, \pm X^2, \pm Y^2$

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Clifford and Primitive gate sets

- Primitive gate set:
  - I, ±X, ±Y, ±X^2, ±Y^2

Class	X/Y generation	Clifford gates
Pauli	I	$(\mathbb{1})$
	X^2	(π_x)
	Y^2	(π_y)
	Y^2, X^2	(π_z)
$2\pi/3$	X, Y	$(\pi/2_y) \circ (\pi/2_x)$
	$X, -Y$	$(\pi/2_{\bar{y}}) \circ (\pi/2_x)$
	$-X, Y$	$(\pi/2_y) \circ (\pi/2_{\bar{x}})$
	$-X, -Y$	$(\pi/2_{\bar{y}}) \circ (\pi/2_{\bar{x}})$
	Y, X	$(\pi/2_x) \circ (\pi/2_y)$
	$Y, -X$	$(\pi/2_{\bar{x}}) \circ (\pi/2_y)$
	$-Y, X$	$(\pi/2_{\bar{y}}) \circ (\pi/2_x)$
	$-Y, -X$	$(\pi/2_{\bar{x}}) \circ (\pi/2_{\bar{y}})$
$\pi/2$	X	$(\pi/2_x)$
	$-X$	$(\pi/2_{\bar{x}})$
	Y	$(\pi/2_y)$
	$-Y$	$(\pi/2_{\bar{y}})$
	$-X, Y, X$	$(\pi/2_z)$
	$-X, -Y, X$	$(\pi/2_{\bar{z}})$
Hadamard	X^2, Y	$(\pi/2_y) \circ (\pi_x)$
	$X^2, -Y$	$(\pi/2_{\bar{y}}) \circ (\pi_x)$
	Y^2, X	$(\pi/2_x) \circ (\pi_y)$
	$Y^2, -X$	$(\pi/2_{\bar{x}}) \circ (\pi_y)$
	X, Y, X	$(\pi/2_x) \circ (\pi/2_y) \circ (\pi/2_x)$
	$-X, Y, -X$	$(\pi/2_x) \circ (\pi/2_{\bar{y}}) \circ (\pi/2_x)$

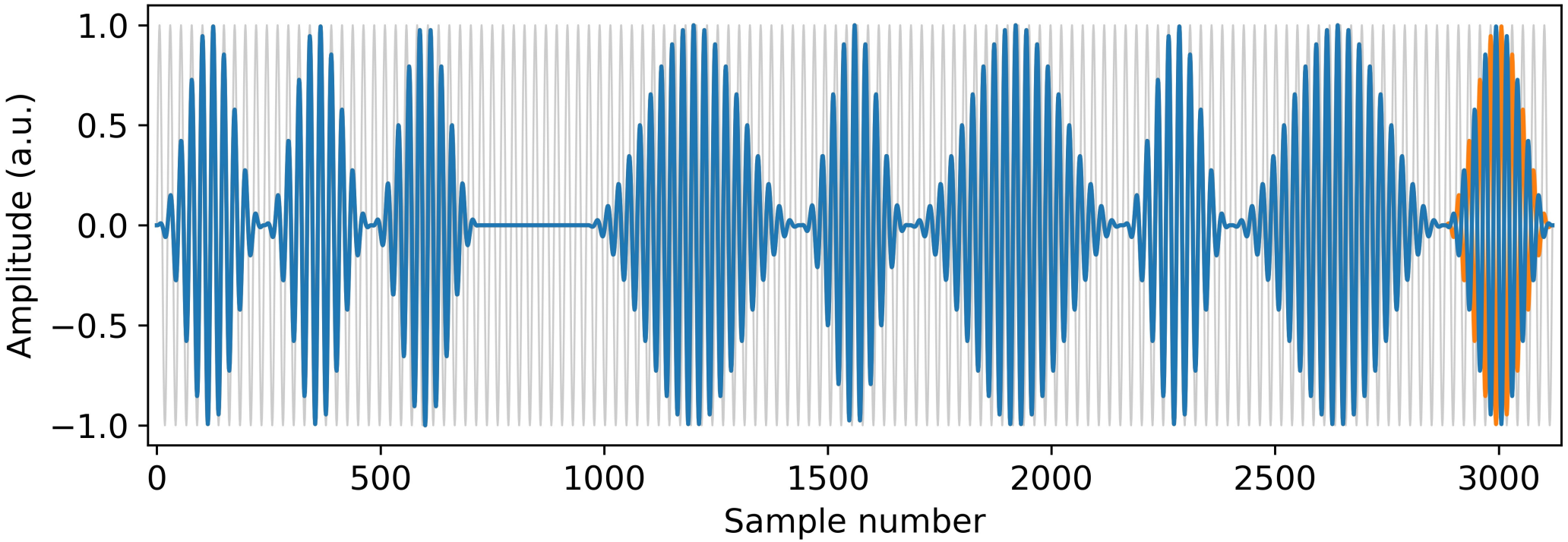
Table a combination of Xue, X. et. al., Phys. Rev. X 9, (2019) and Cerfontaine P. PhD thesis (2019)

Example with n = 9

[“X”, "X", “-Y", "I", "-Y^2", "Y", "Y^2", “X", "-Y^2"]

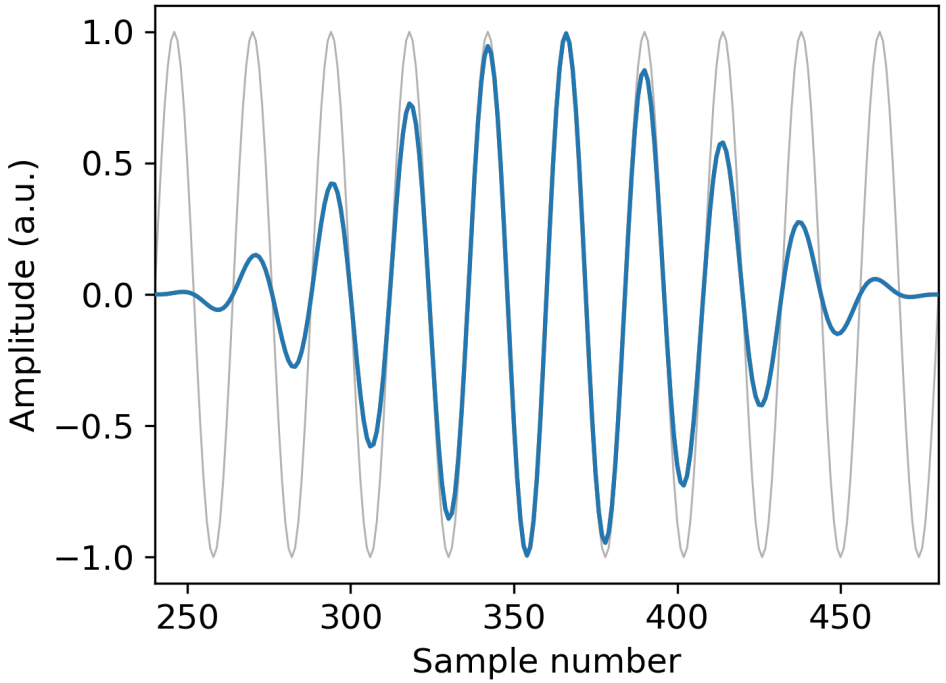
Example with n = 9

[“X”, "X", “-Y", "I", "-Y^2", "Y", "Y^2", “X", "-Y^2"]



Zoom on X Gate

[“X”, "X", "Y", "I", "-Y^2", "-Y", "Y^2", "Y", "-Y^2"]



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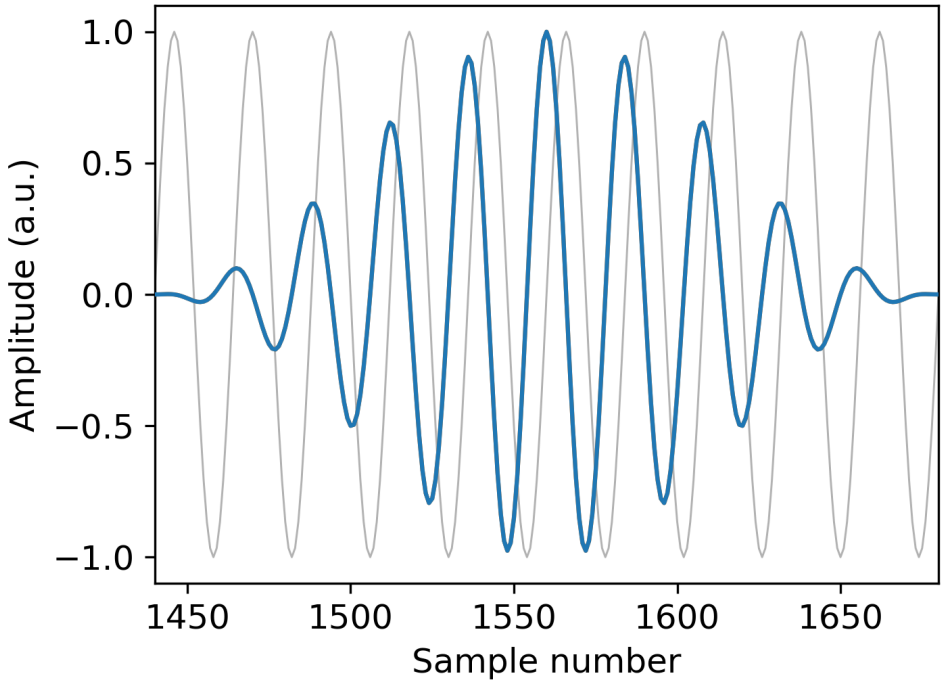
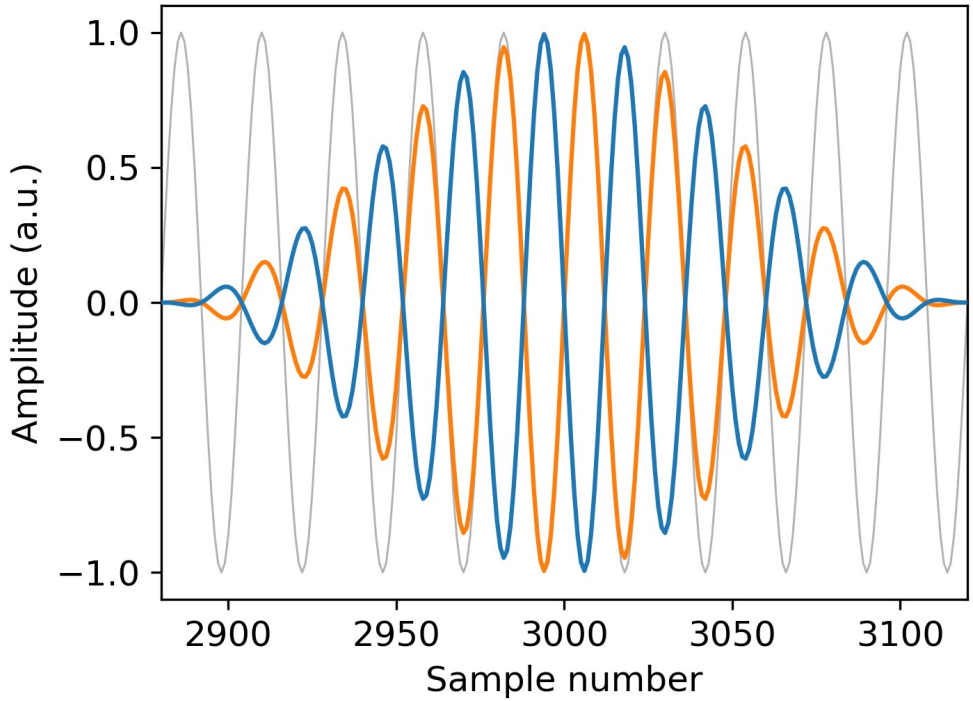
Zoom on Y Gate

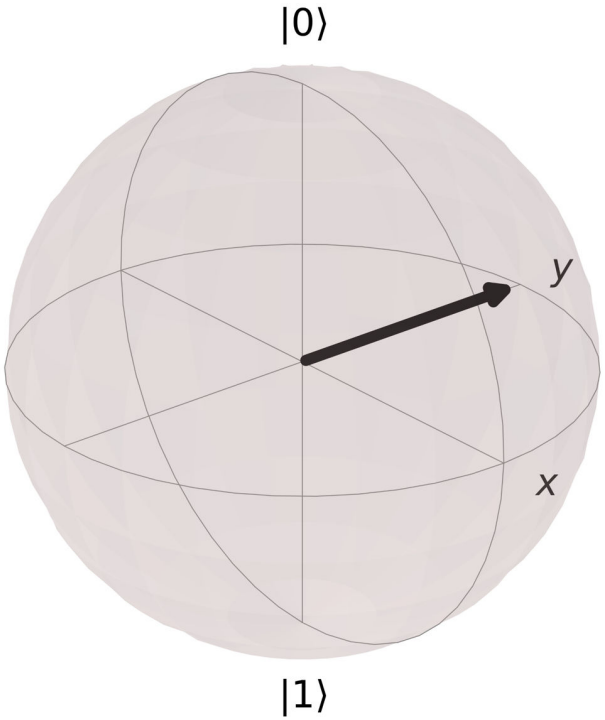
[“X”, "X", "Y", "I", "-Y^2", "-Y", "Y^2", "Y", "-Y^2"]



Zoom on final projection

[“X”, "X", "Y", "I", "-Y^2", "-Y", "Y^2", "Y", "-Y^2"]





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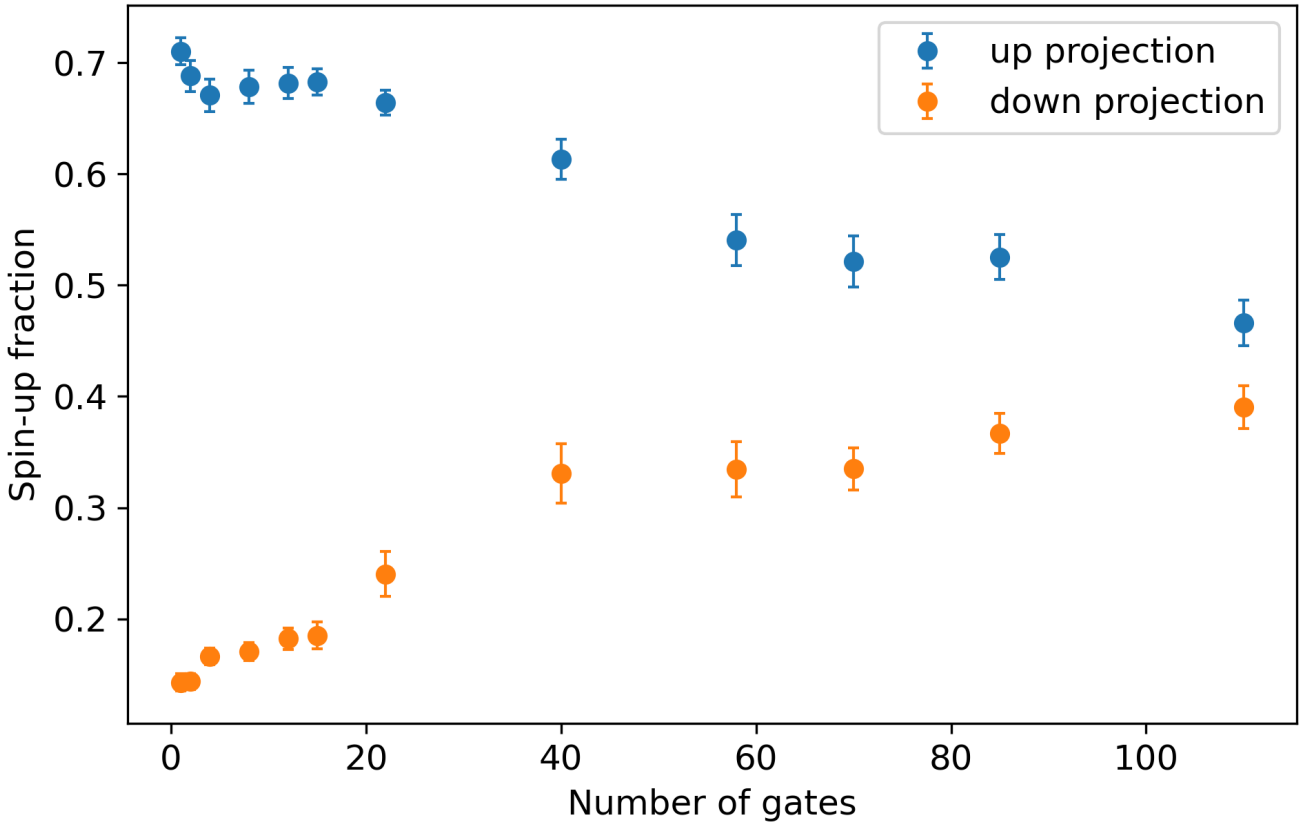
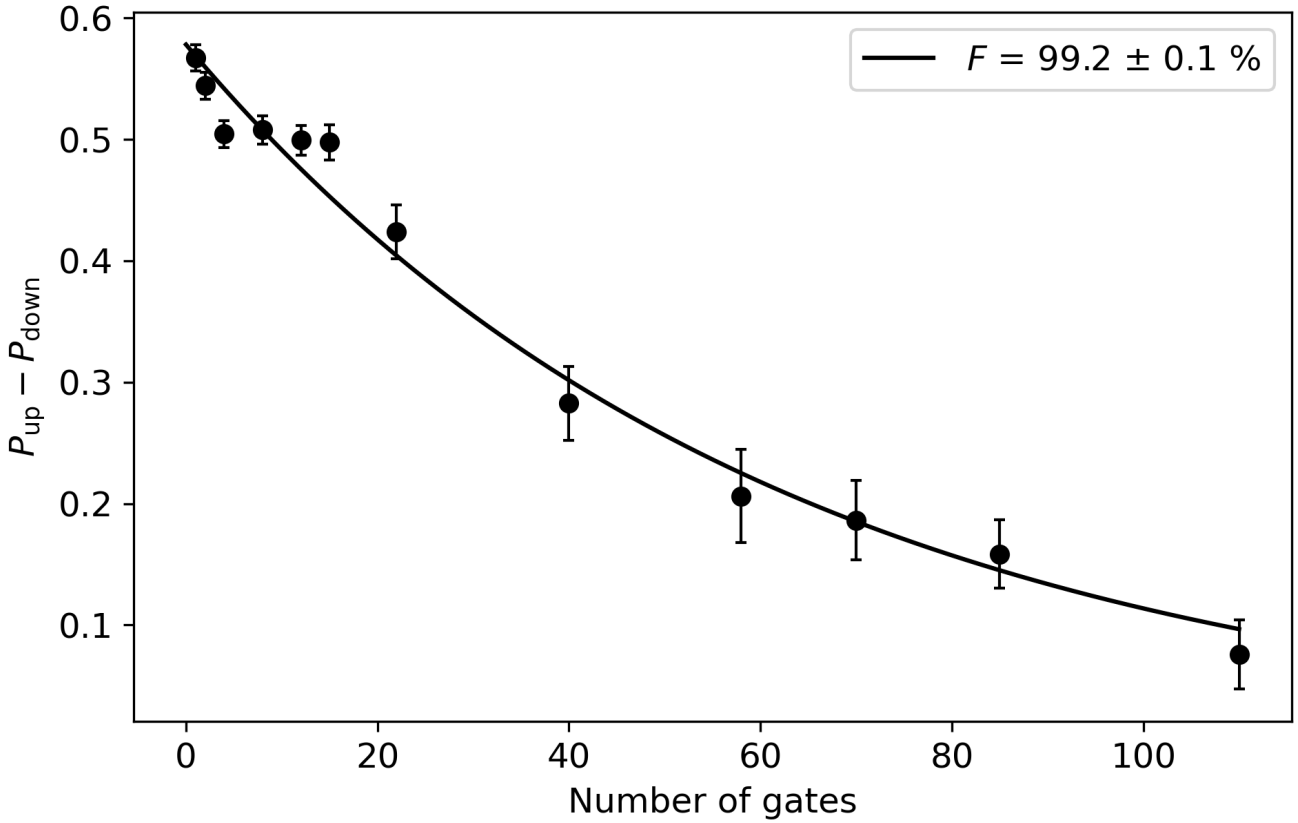
Randomized benchmarking



Randomized benchmarking



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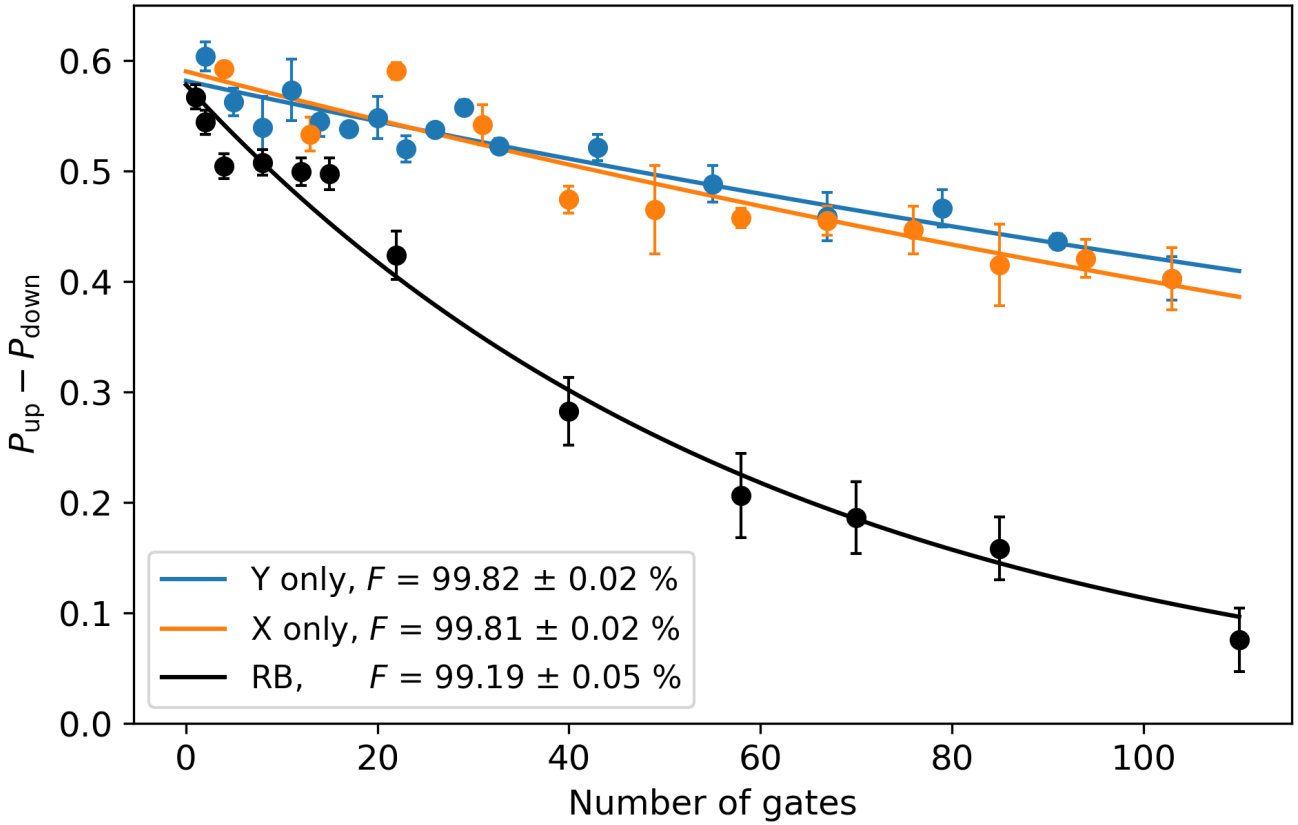
Randomized benchmarking



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Summary

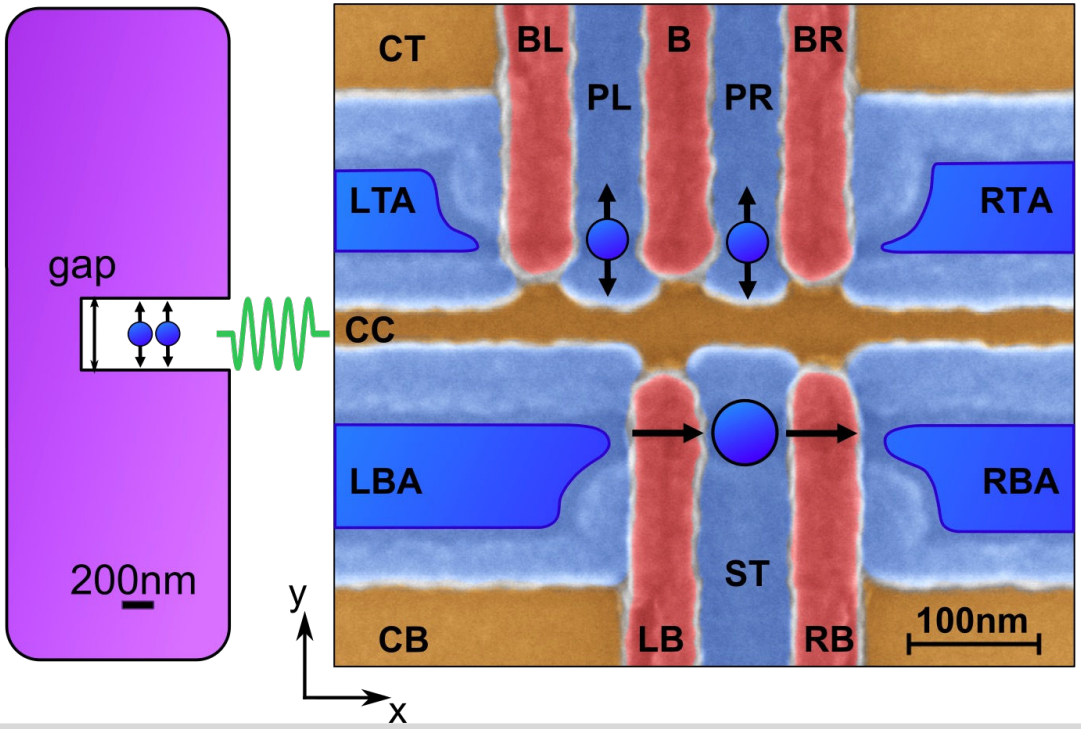
- Coherent control of industrially manufactured Si/SiGe spin qubits
- Rabi frequencies ~ 5MHz
- T_2^*~ 1µs, T_2^H ~ 50µs
- Primitive single qubit gate fidelity ~ 99.2%

Outlook

- Isotopically purified Si^{28}/SiGe for enhanced lifetimes

Outlook

- Isotopically purified Si^{28}/SiGe for enhanced lifetimes
- Two qubit gates!



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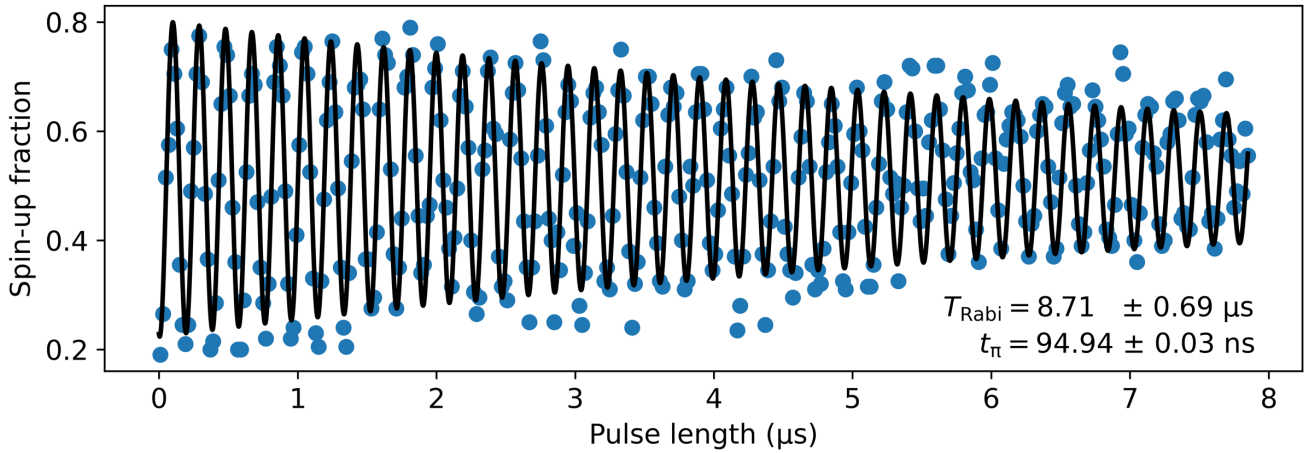
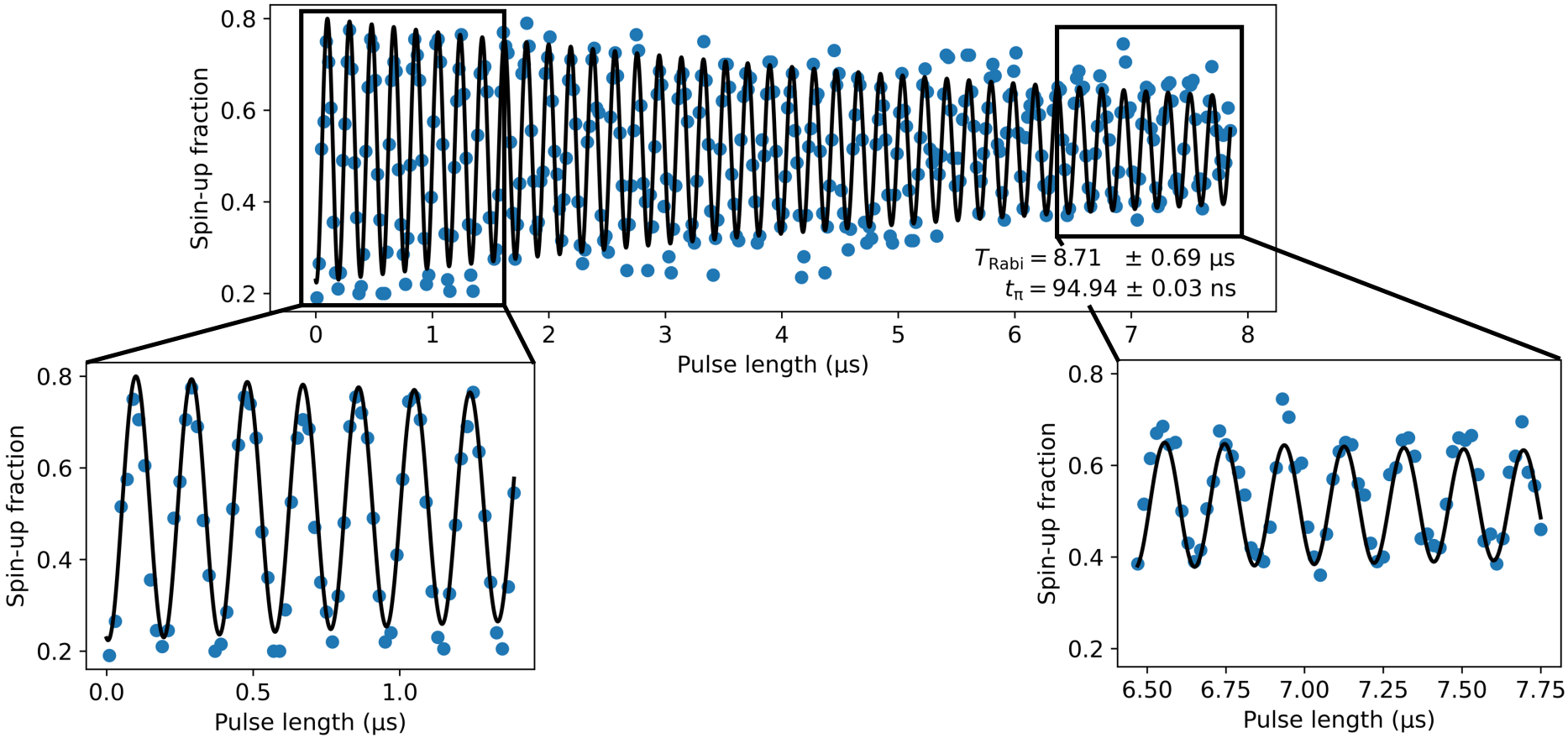
Backup slides

Long Rabi


Spin-up fraction
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
7
8
Pulse length (µs)
$T_{\mathrm{Rabi}} = 8.71 \pm 0.69$ µs
$t_{\pi} = 94.94 \pm 0.03$ ns

Long Rabi


Spin-up fraction
Pulse length (µs)
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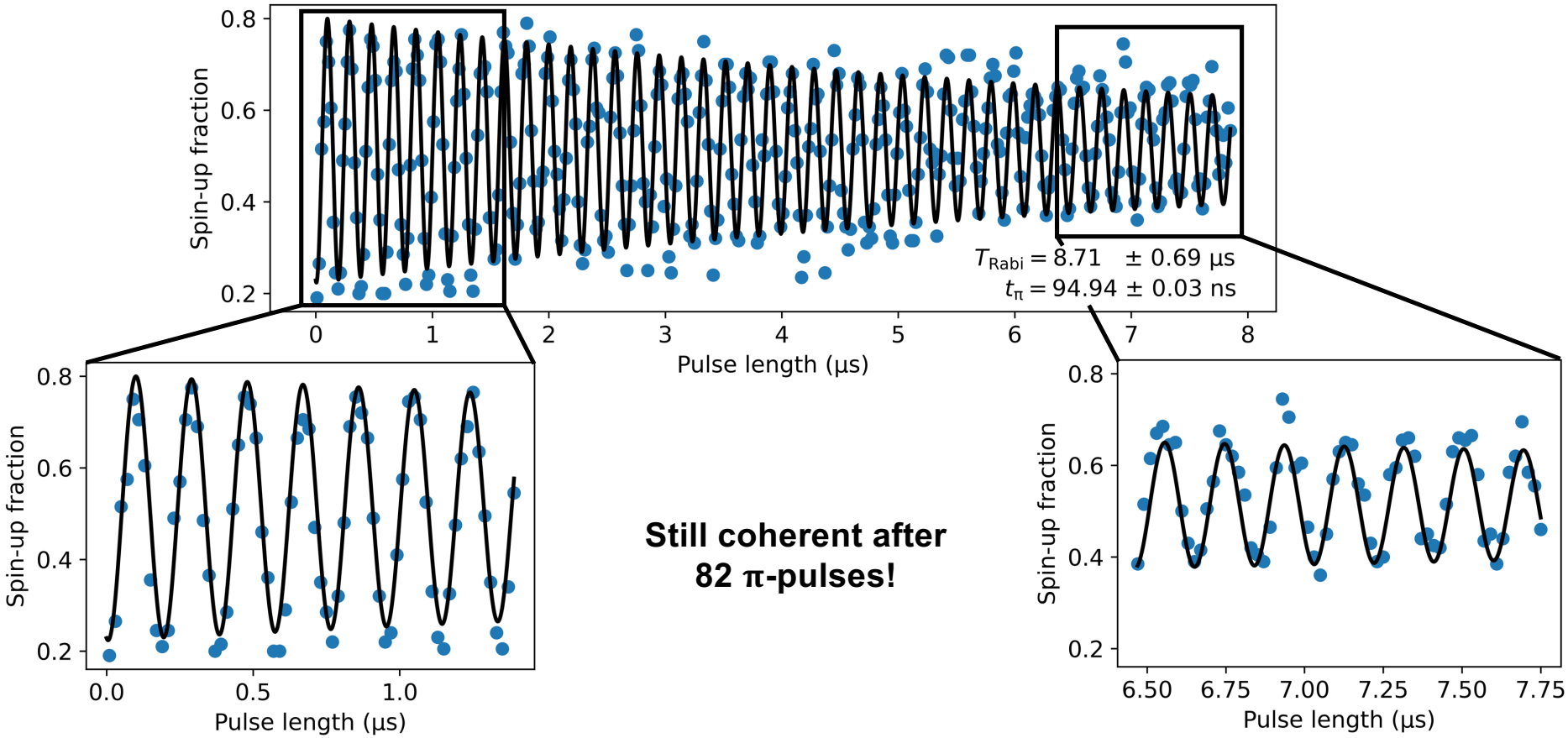
Long Rabi



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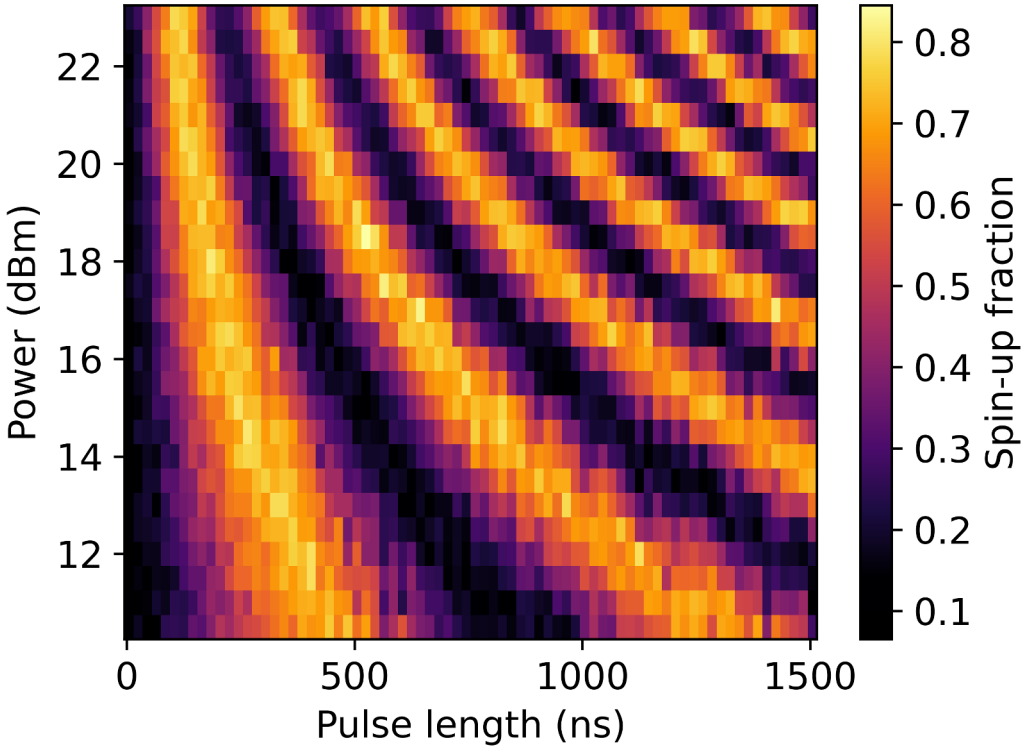
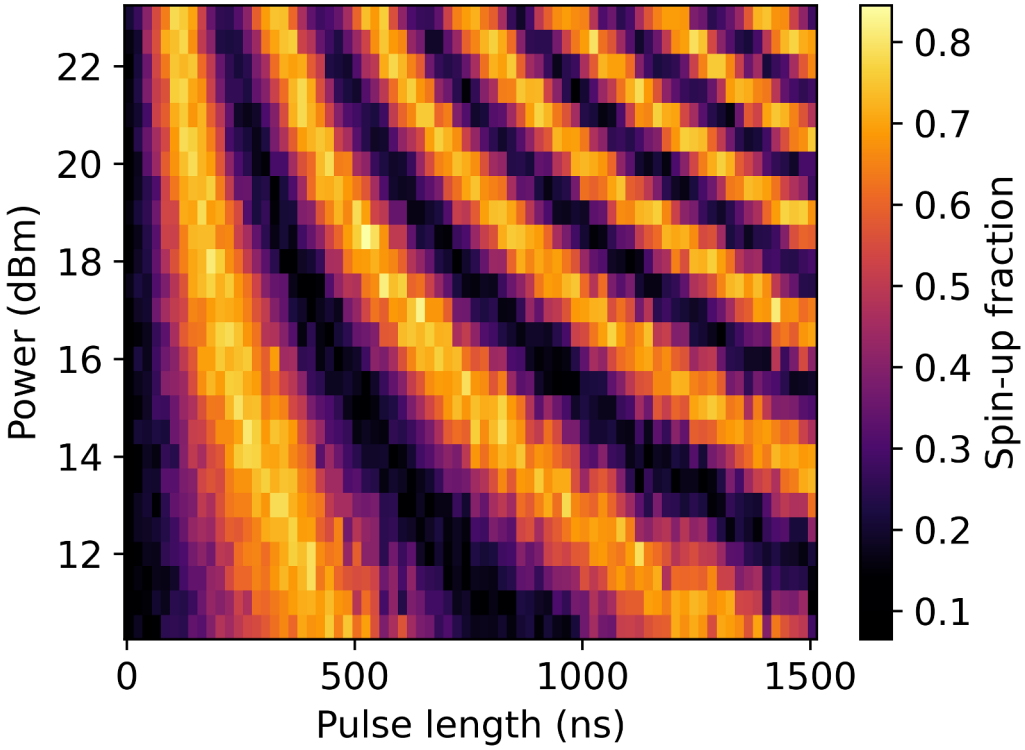
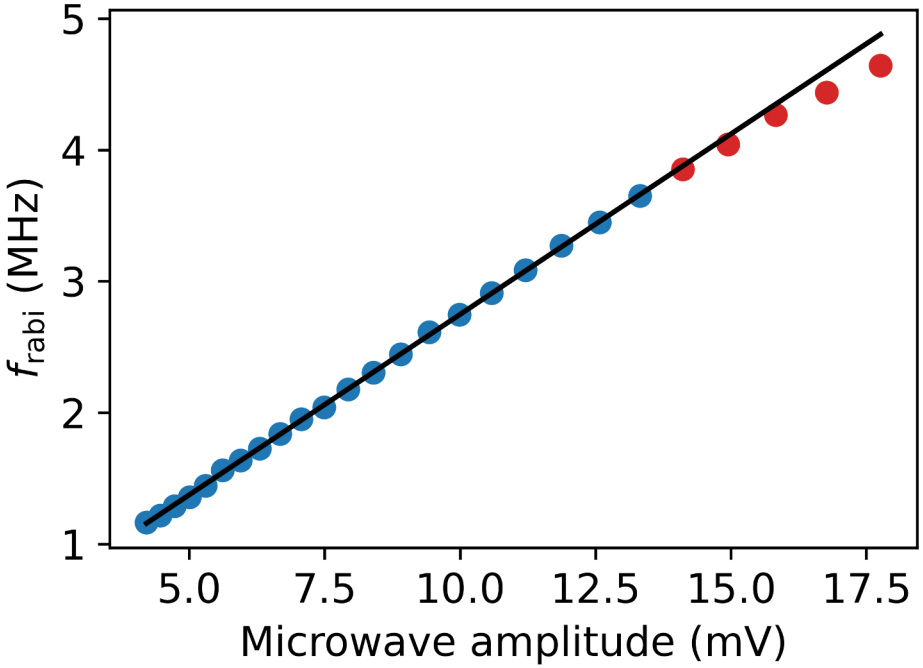
Rabi frequency power dependence



Rabi frequency power dependence





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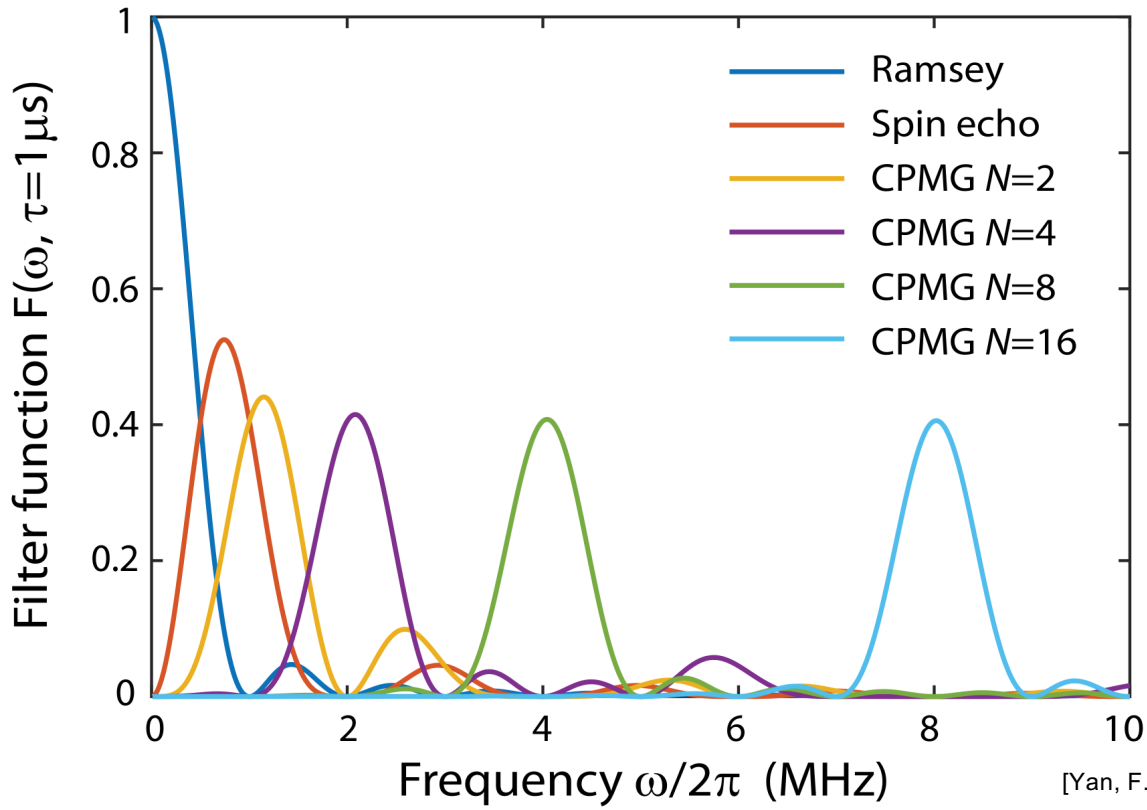
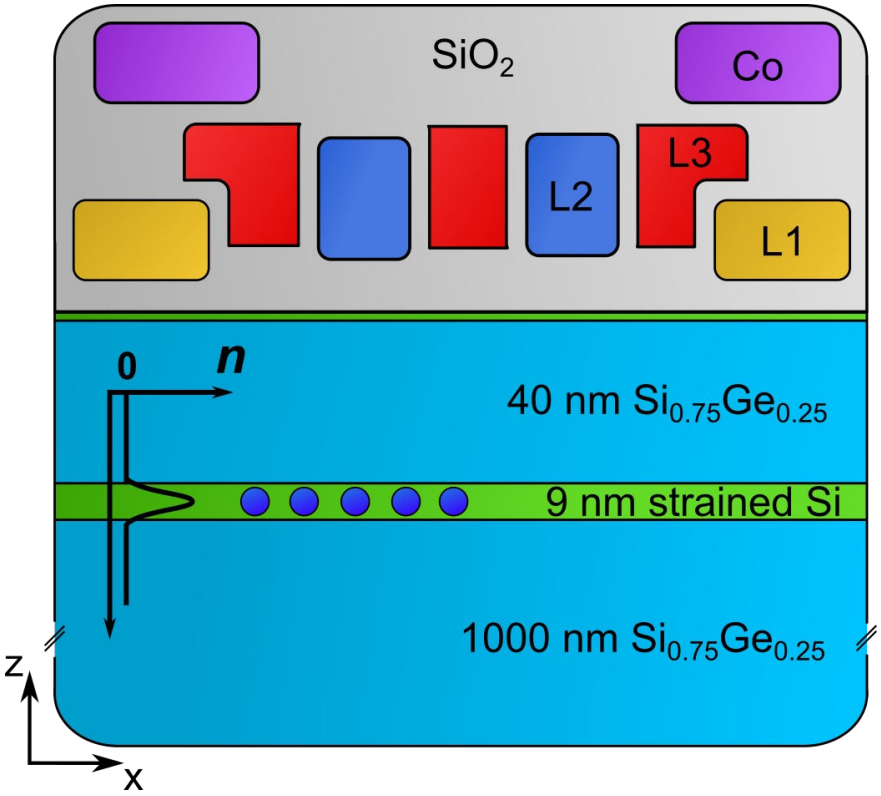
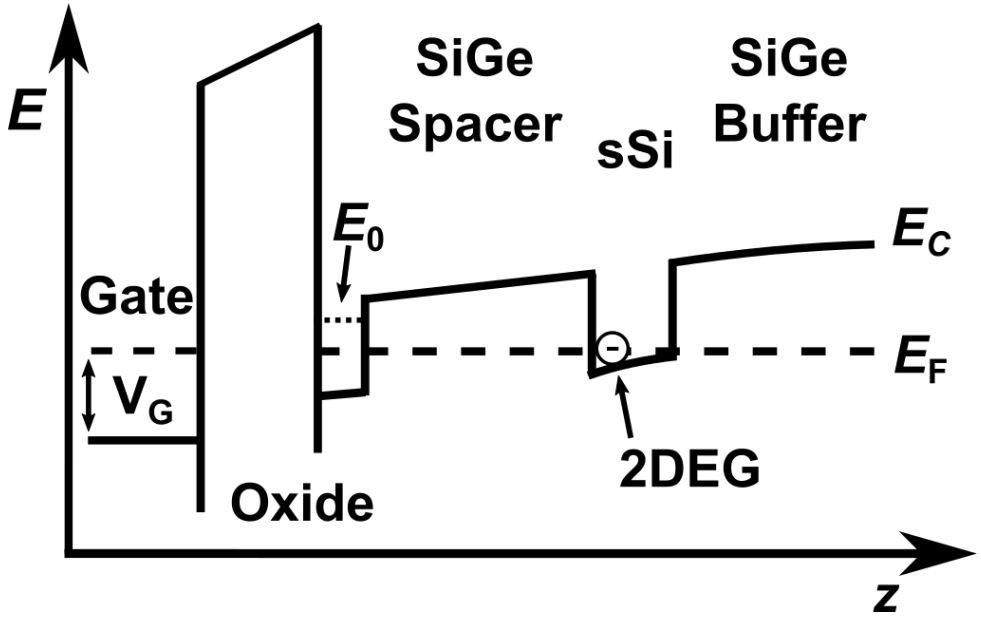
Filter function of pulse sequences



[Yan, F. et. al., Nat Commun 7, (2016)]

$Si/Si_{0.75}Ge_{0.25}$ heterostructure





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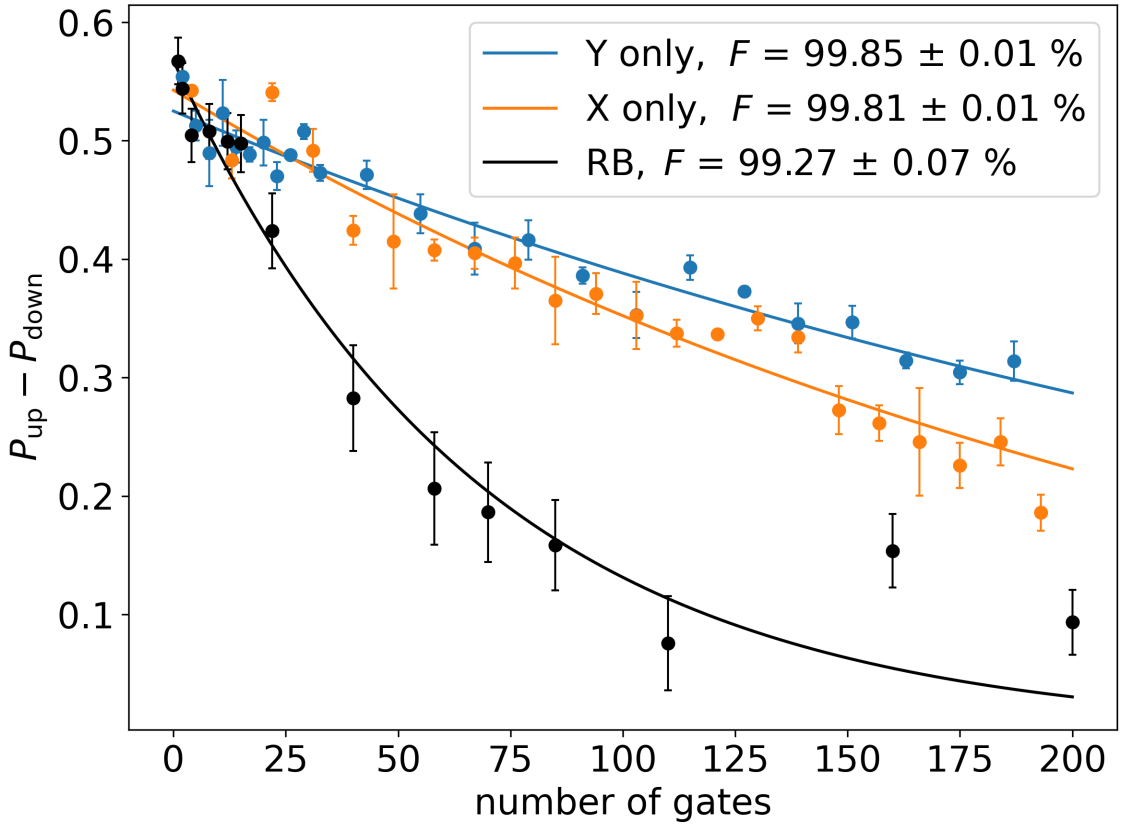
Randomized benchmarking comparisons



Clifford gate fidelity: 98.6 ± 0.1%

Example n = 9

- Fit $a*P^n$ to data where primitive gate fidelity = 1-(1-P)/2
- On average 1.875 primitive gates per Clifford gate
- Clifford gate fidelity the same but use n_c instead of n

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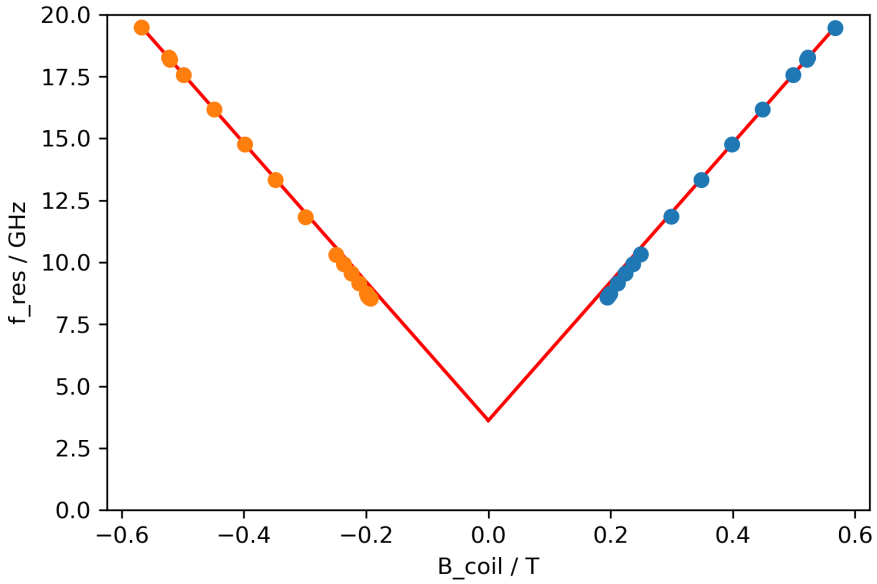
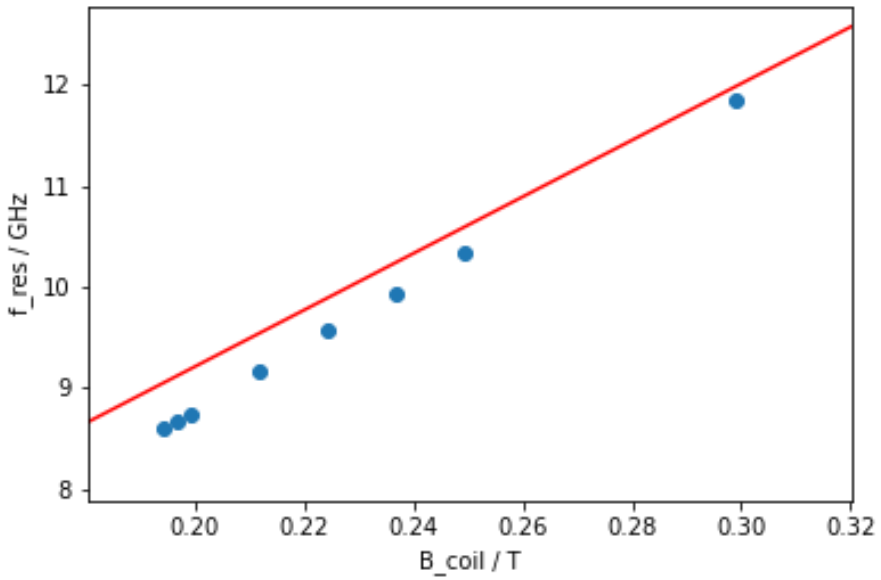
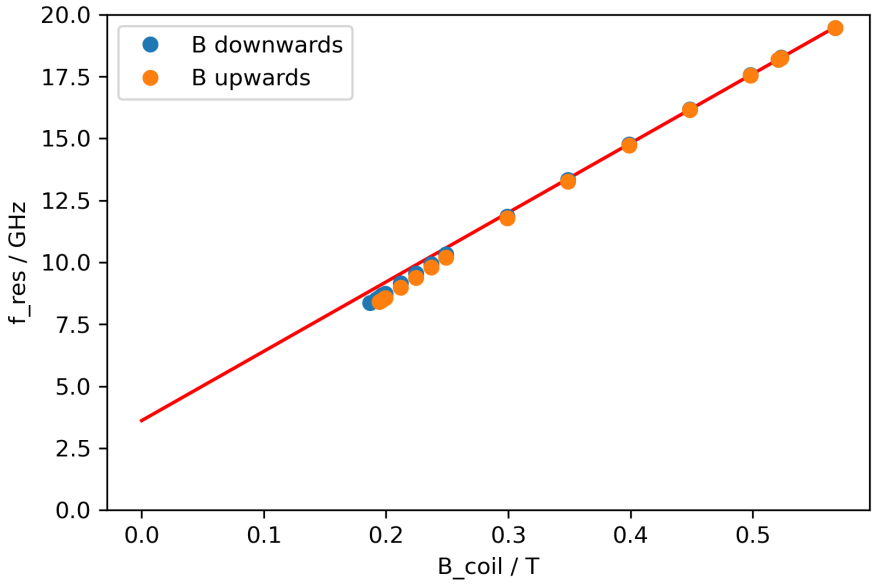
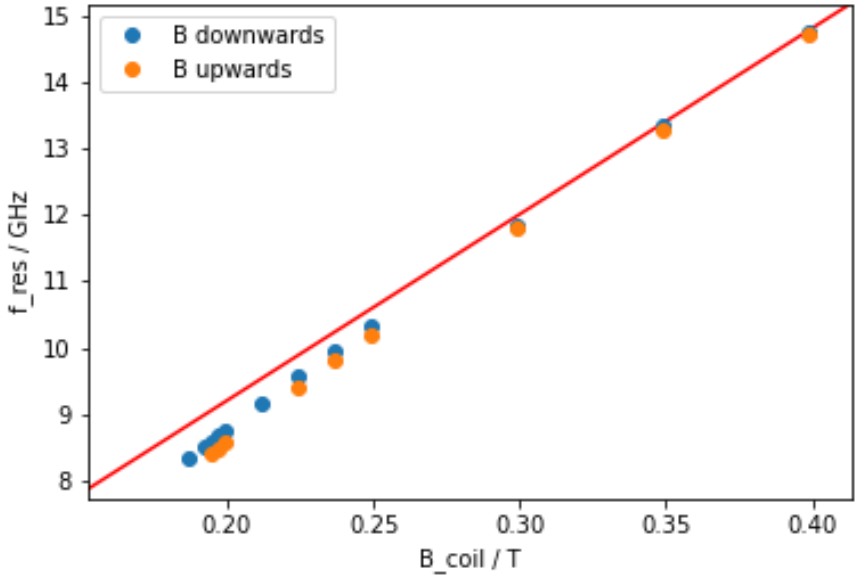
CoMM Magnetization



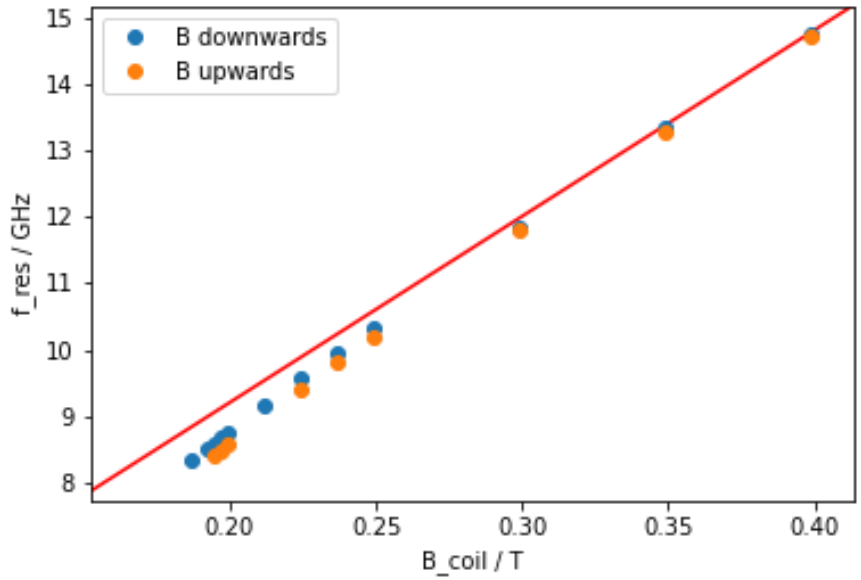


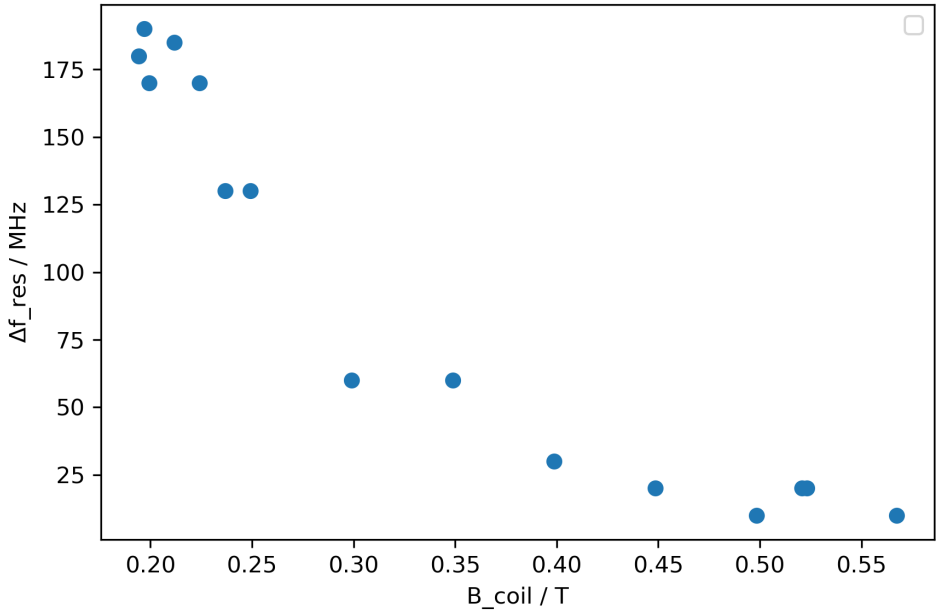
CoMM Magnetization





CoMM Magnetization





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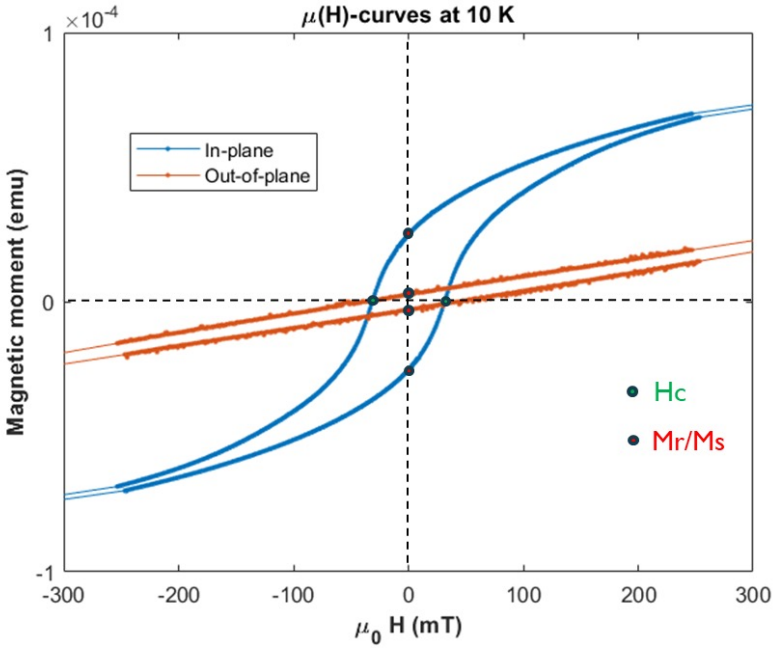
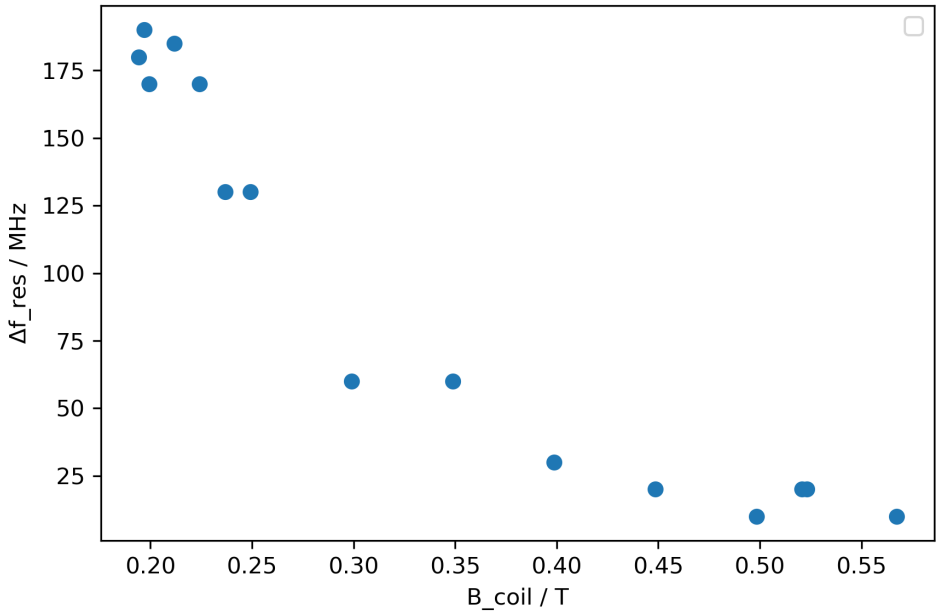
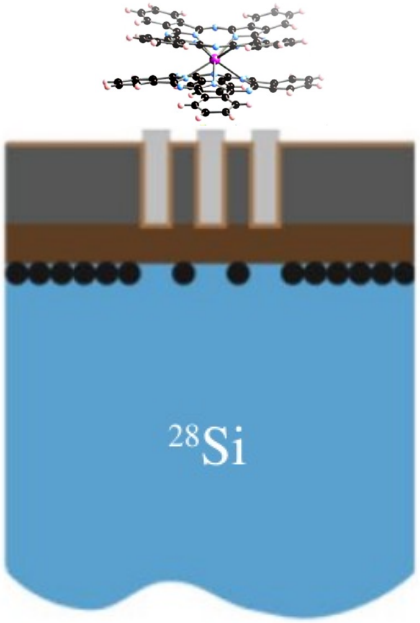
CoMM Magnetization



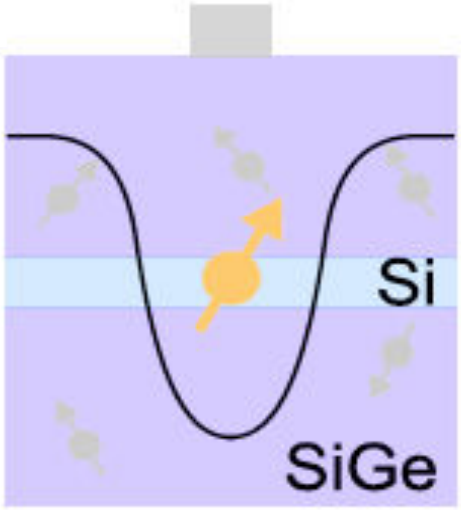


Heterostructures used for quantum computing

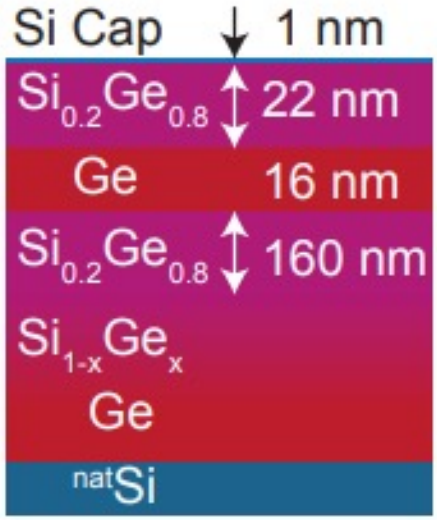
SiMOS + molecules:



Si/SiGe:

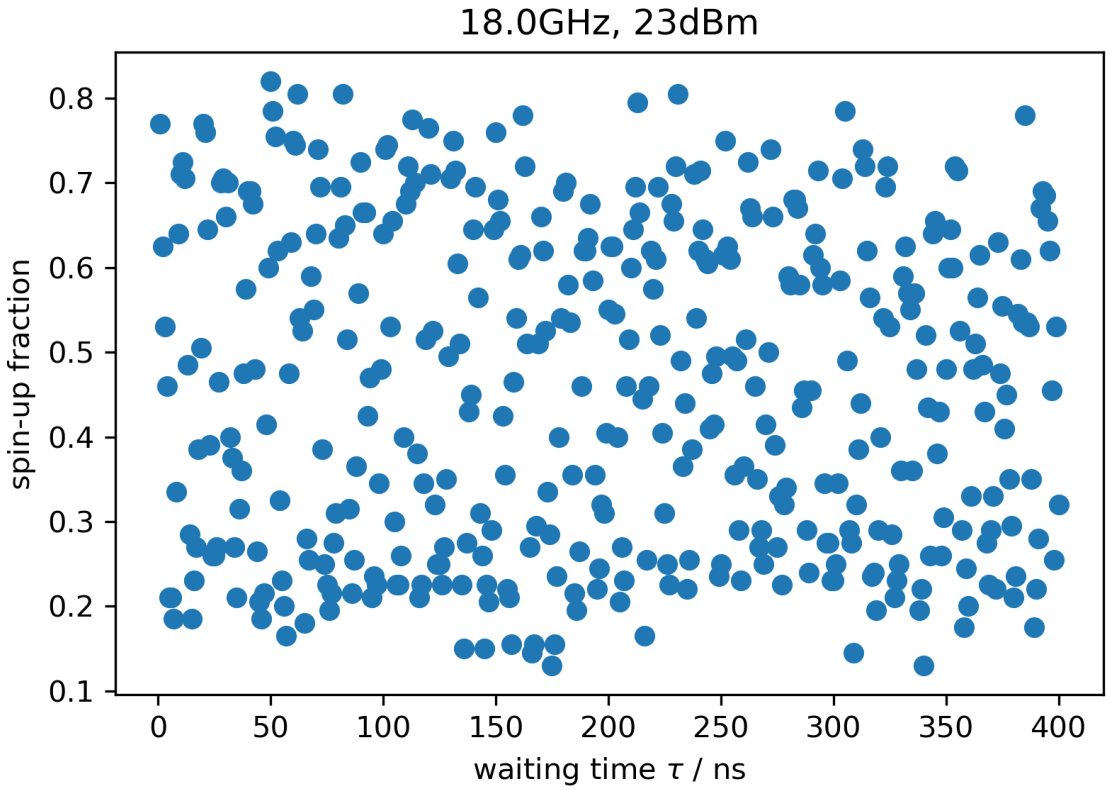


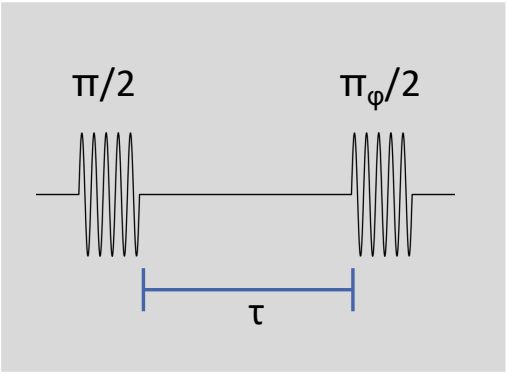
Ge/SiGe:



Images from: DOI: 10.1063/5.0002013 and Dumoulin-Stuyck, N., (2021). Design and Characterization of Quantum Sillicon-Based Devices for Semiconducting Qubit Implementation.
Effective Masses :http://apachepersonal.miun.se/~gorthu/halvledare/Effective%20mass%20in%20semiconductors.htm

Ramsey phase control of 2nd pi/2 pulse





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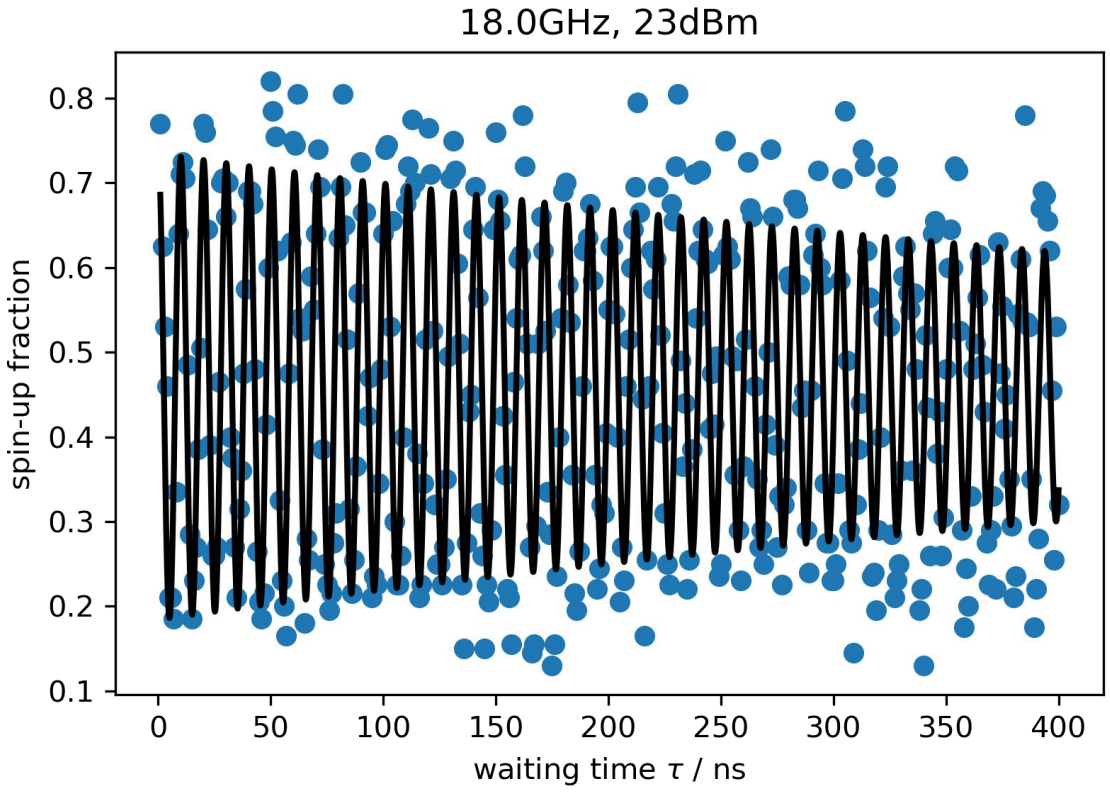

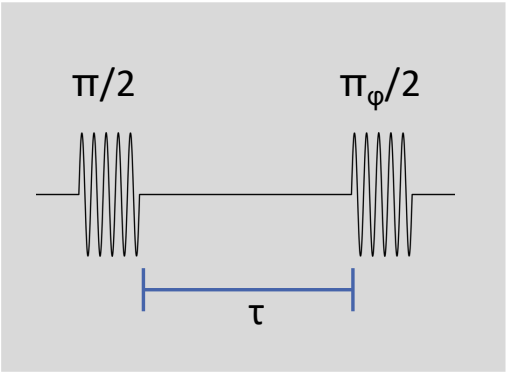

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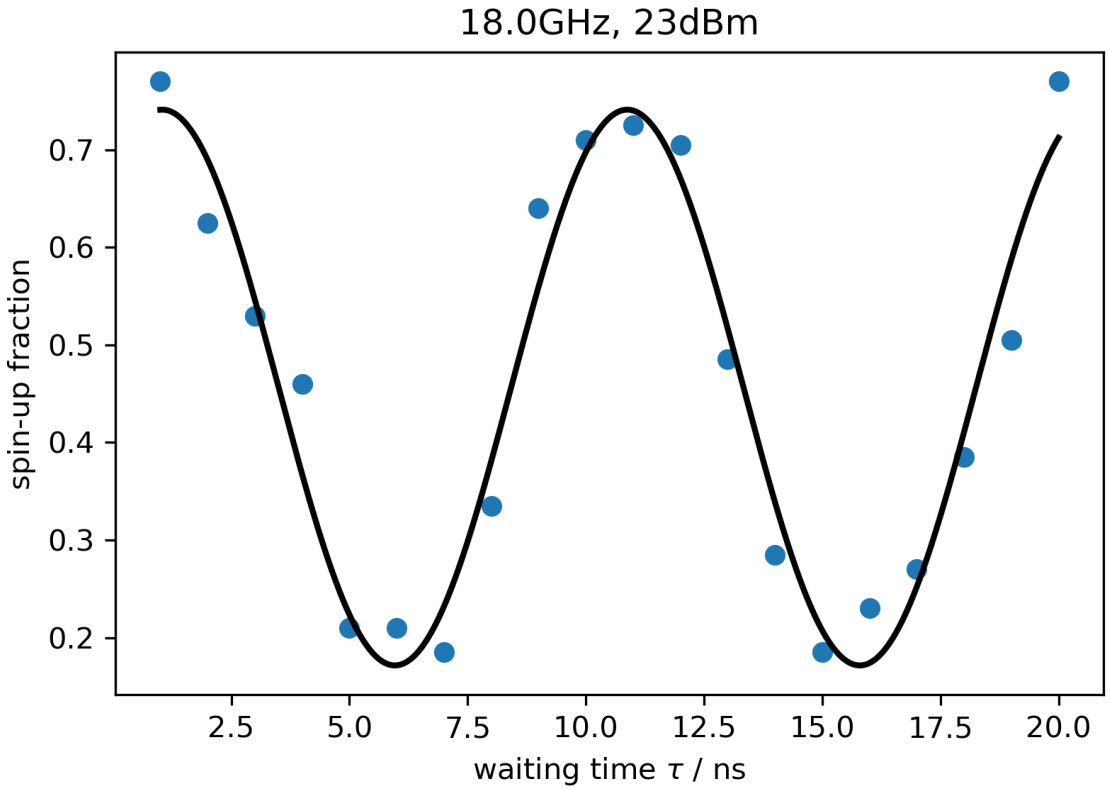
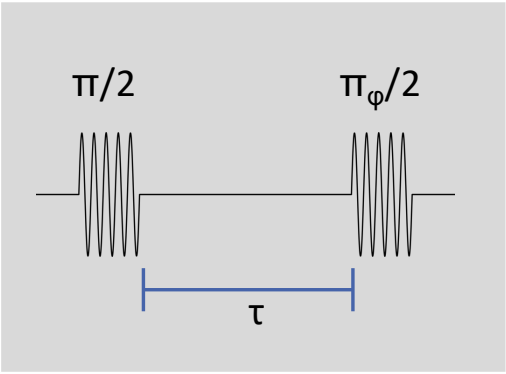
Ramsey phase control of 2nd pi/2 pulse





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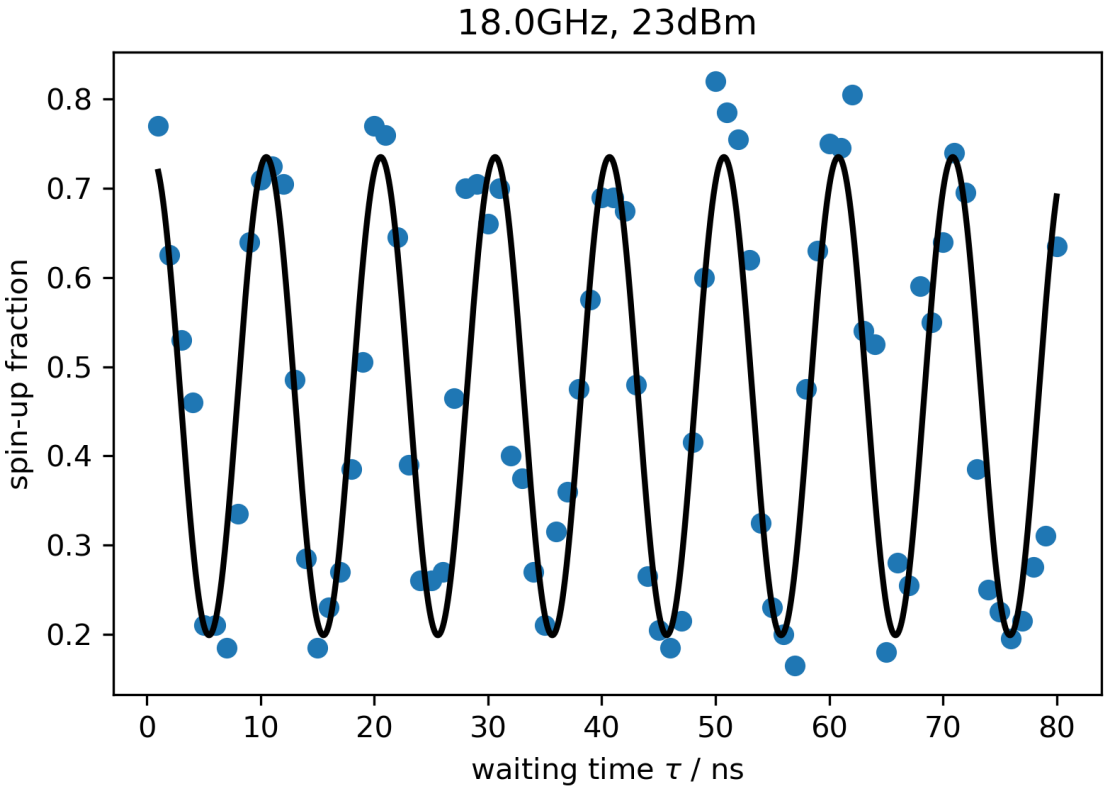
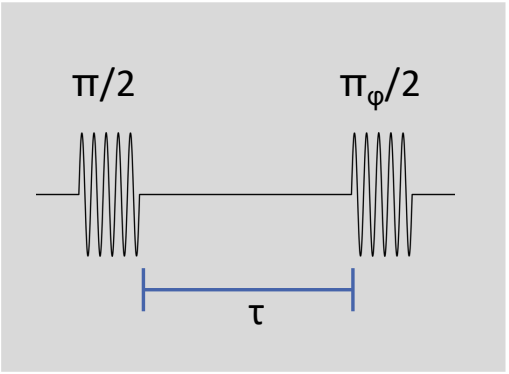
Ramsey phase control of 2nd pi/2 pulse





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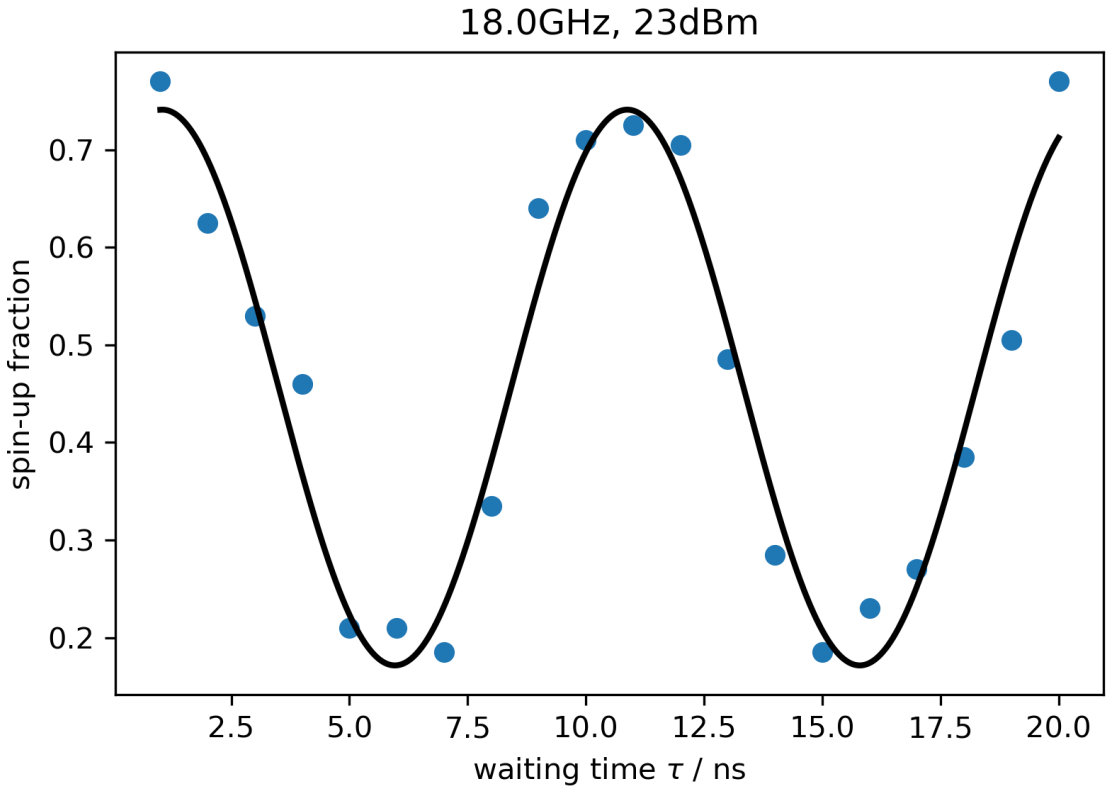
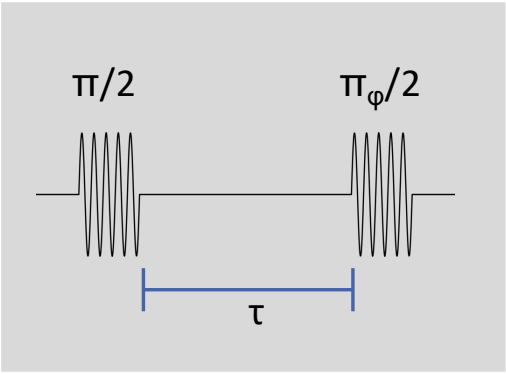
Ramsey phase control of 2nd pi/2 pulse





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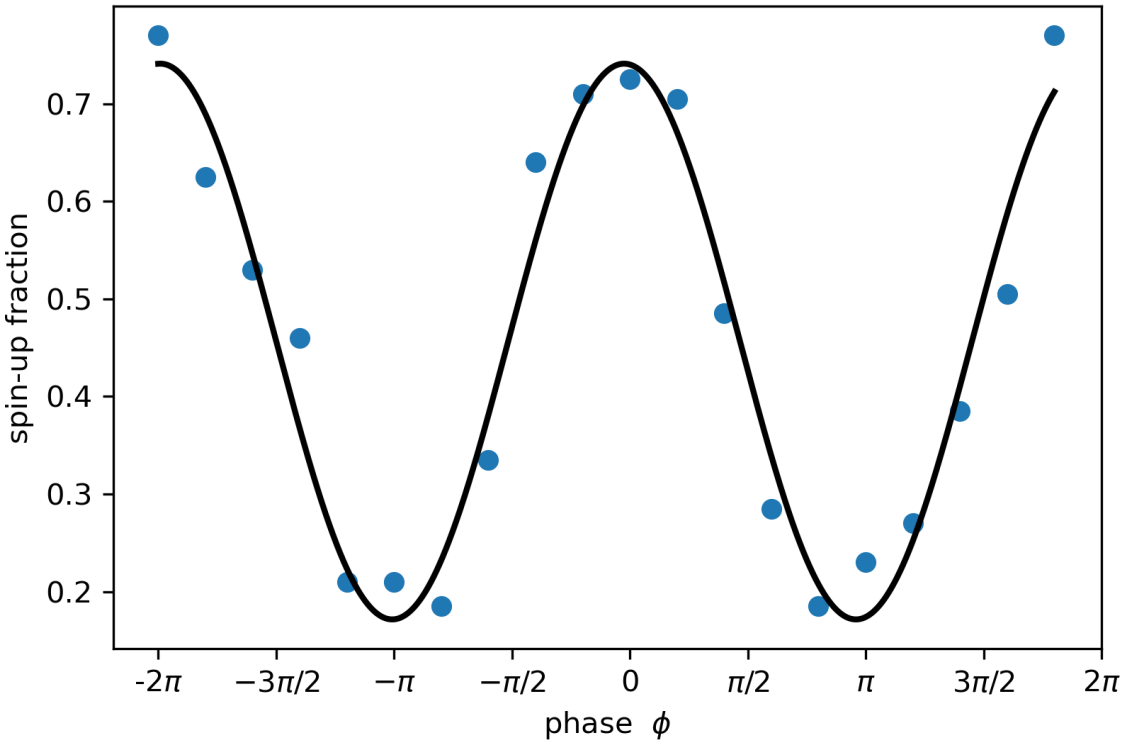
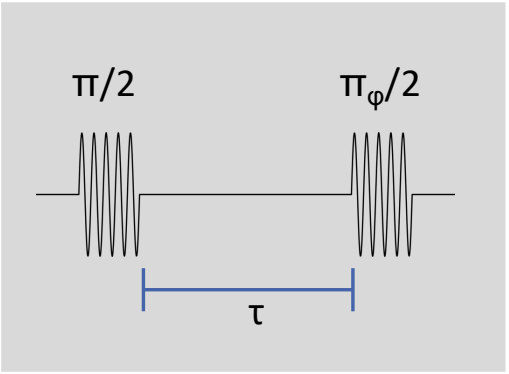
Ramsey phase control of 2nd pi/2 pulse





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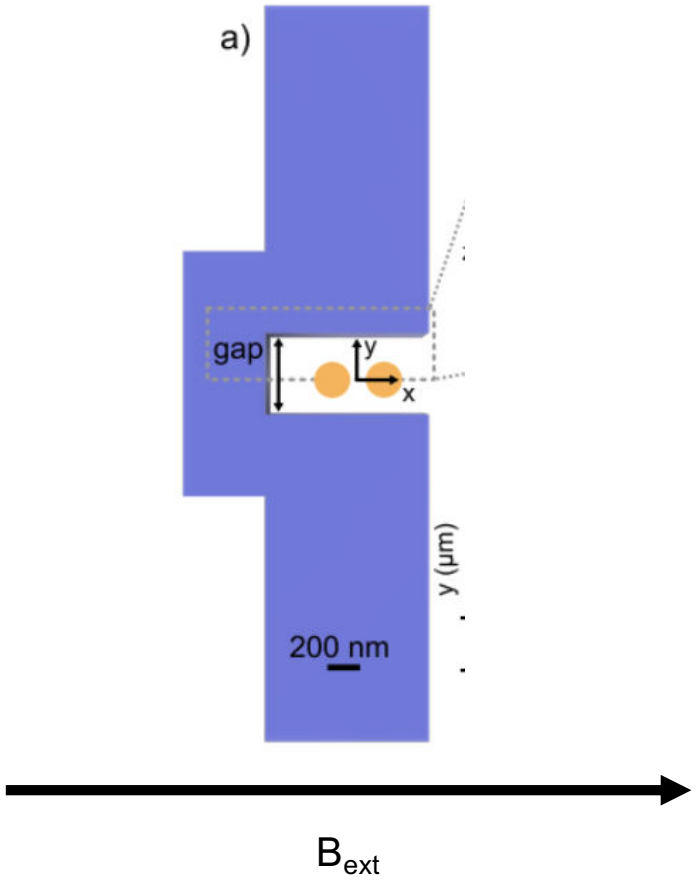
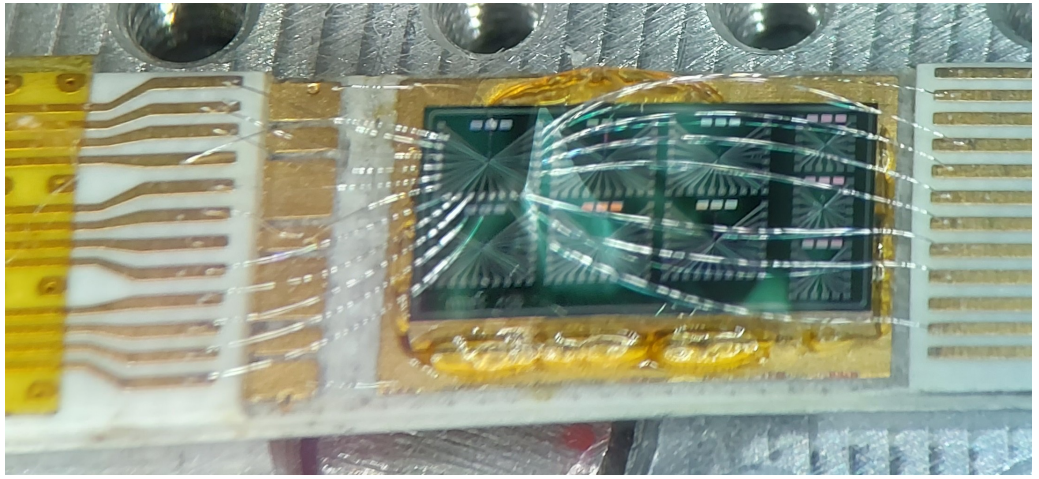
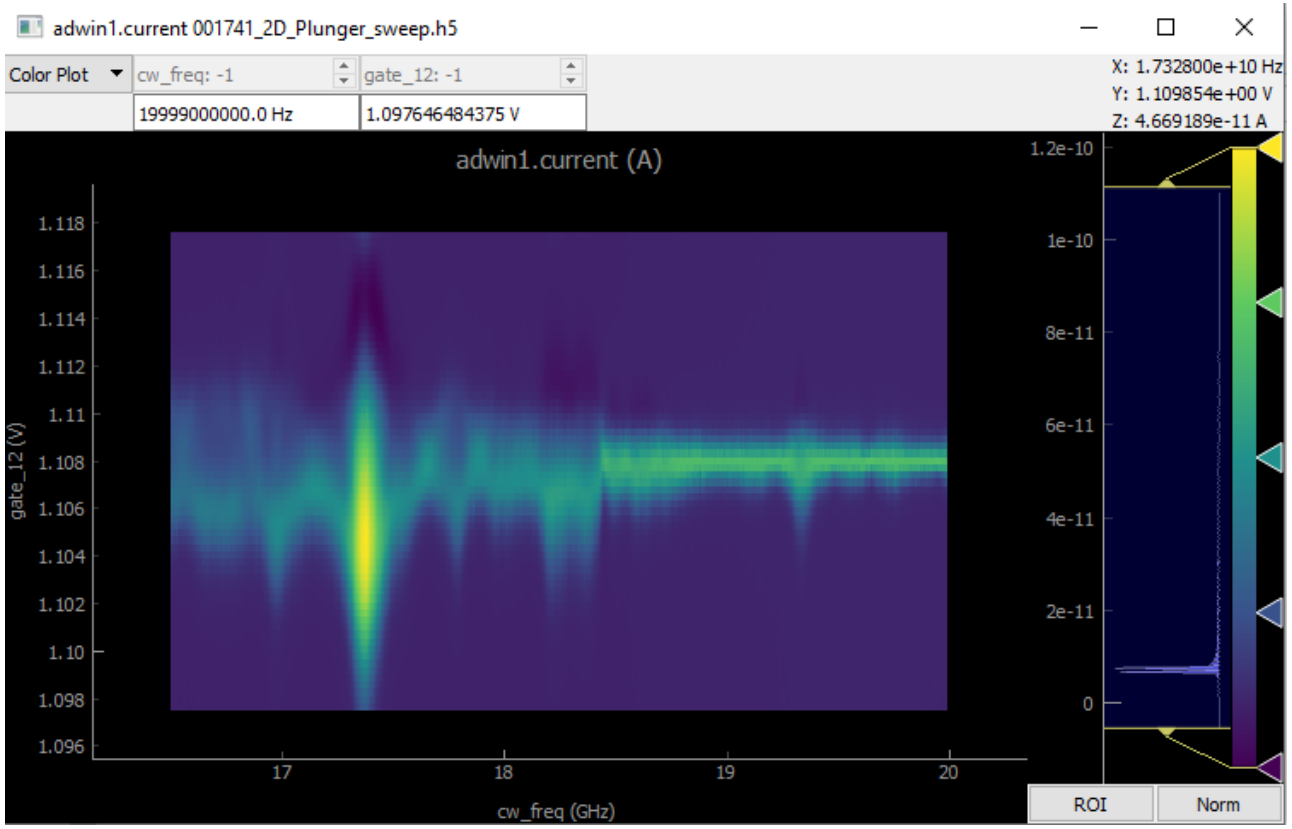
Wrong direction of external field?





Plunger sweep over frequency at 15dBm



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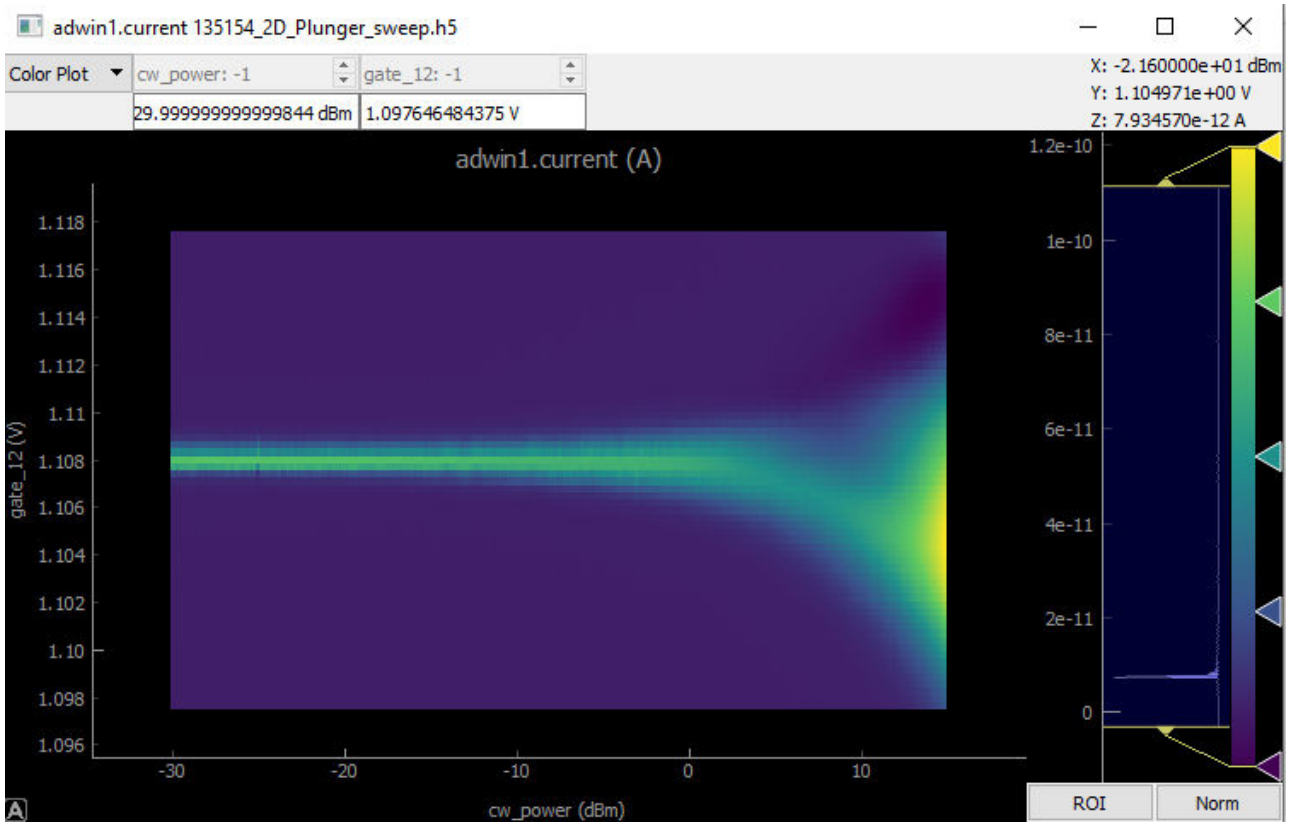
Power sweep 17.37GHz



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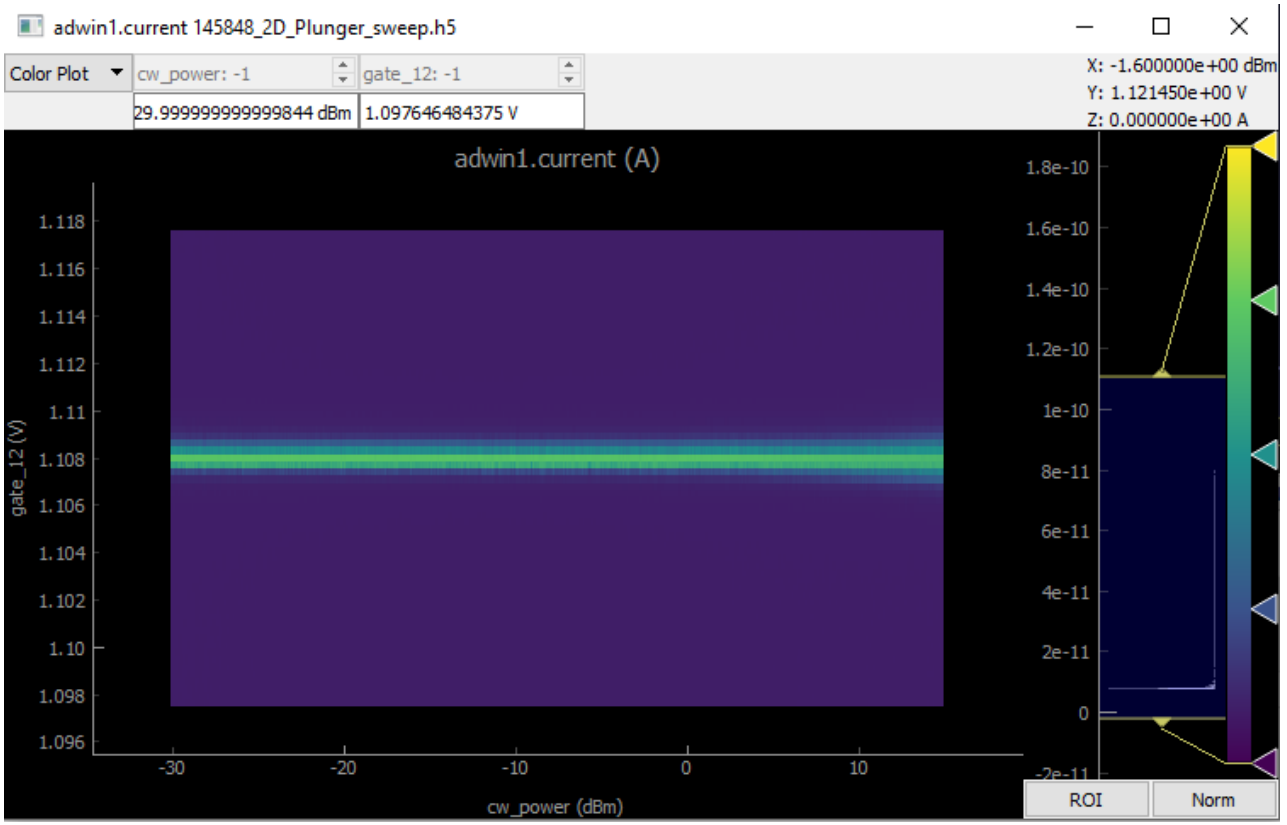
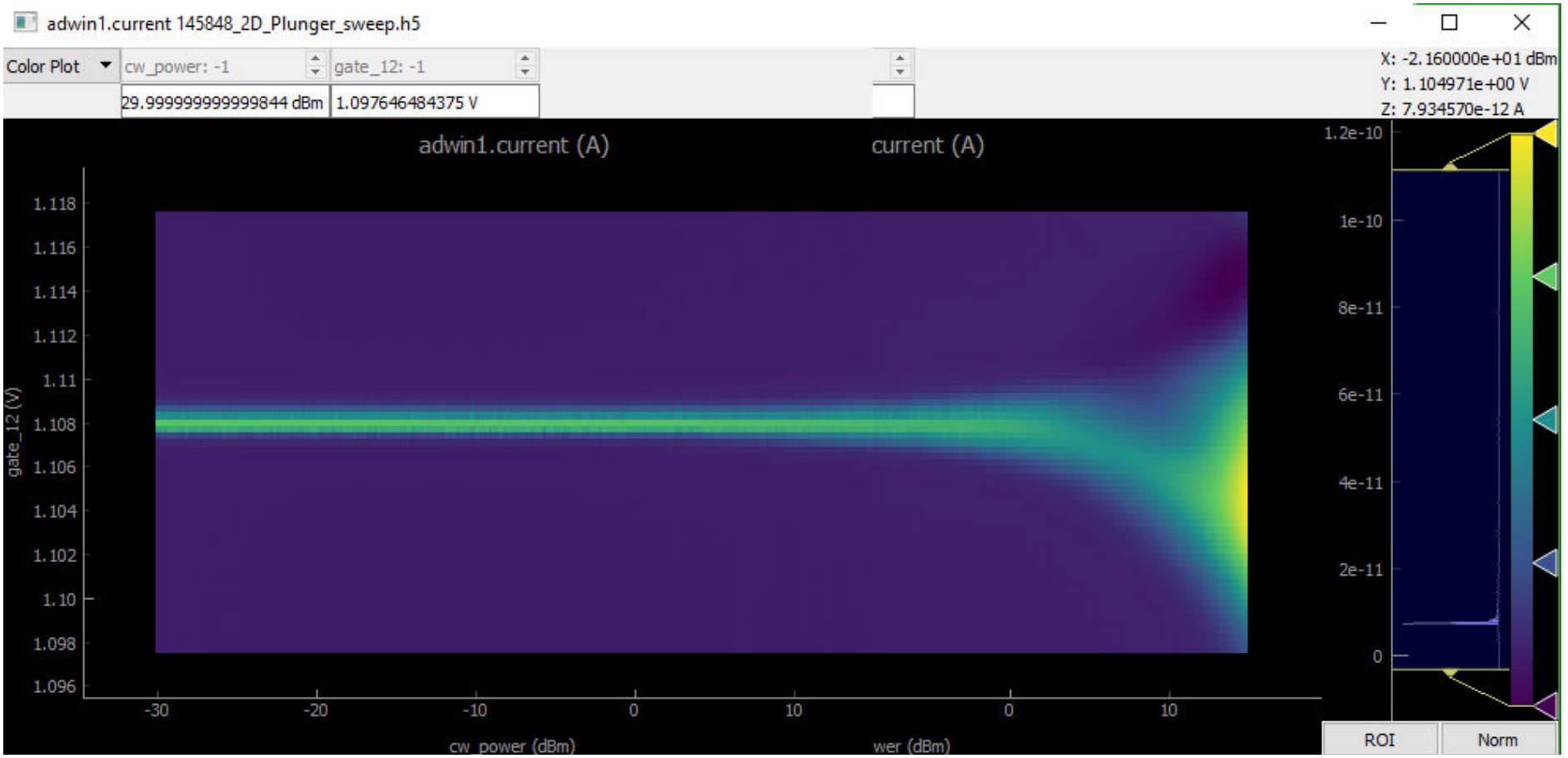
Power sweep 20GHz



Combined power sweeps



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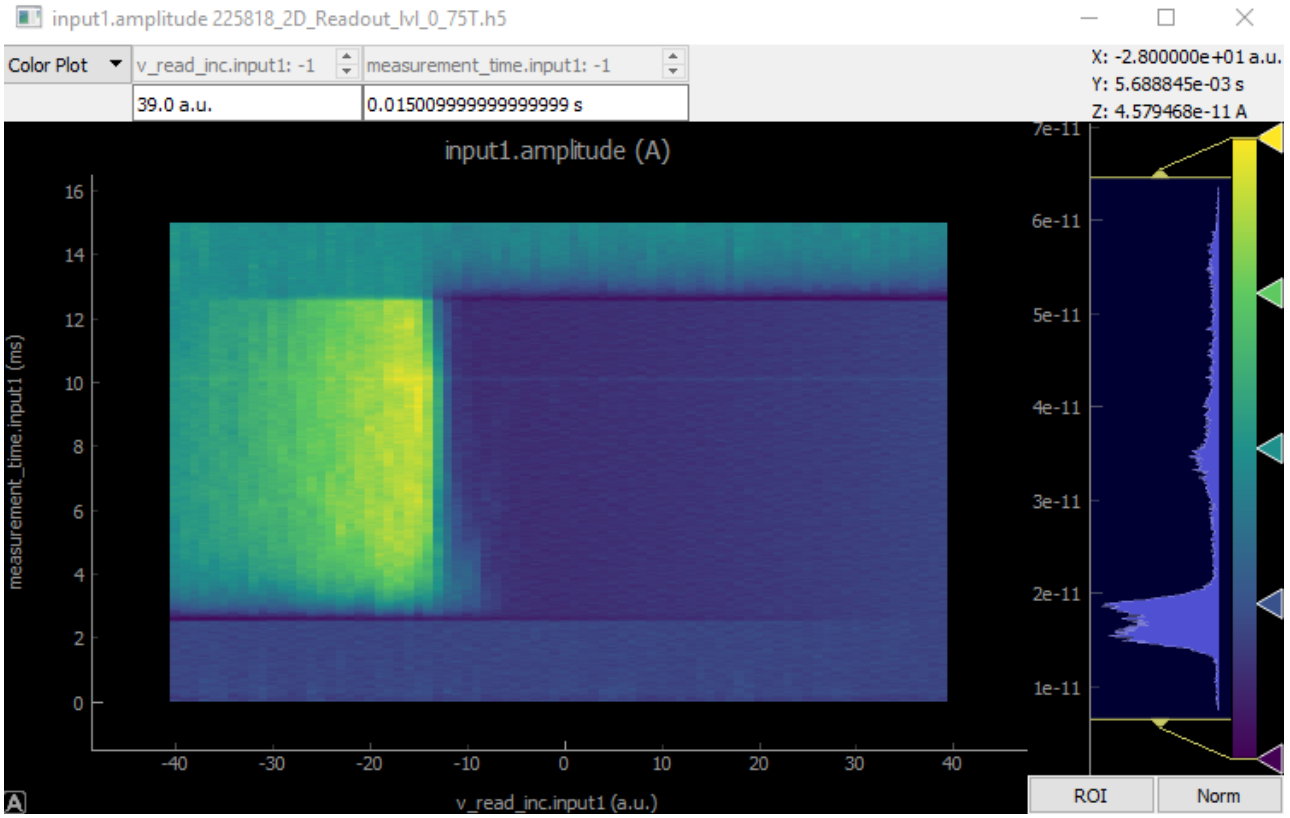
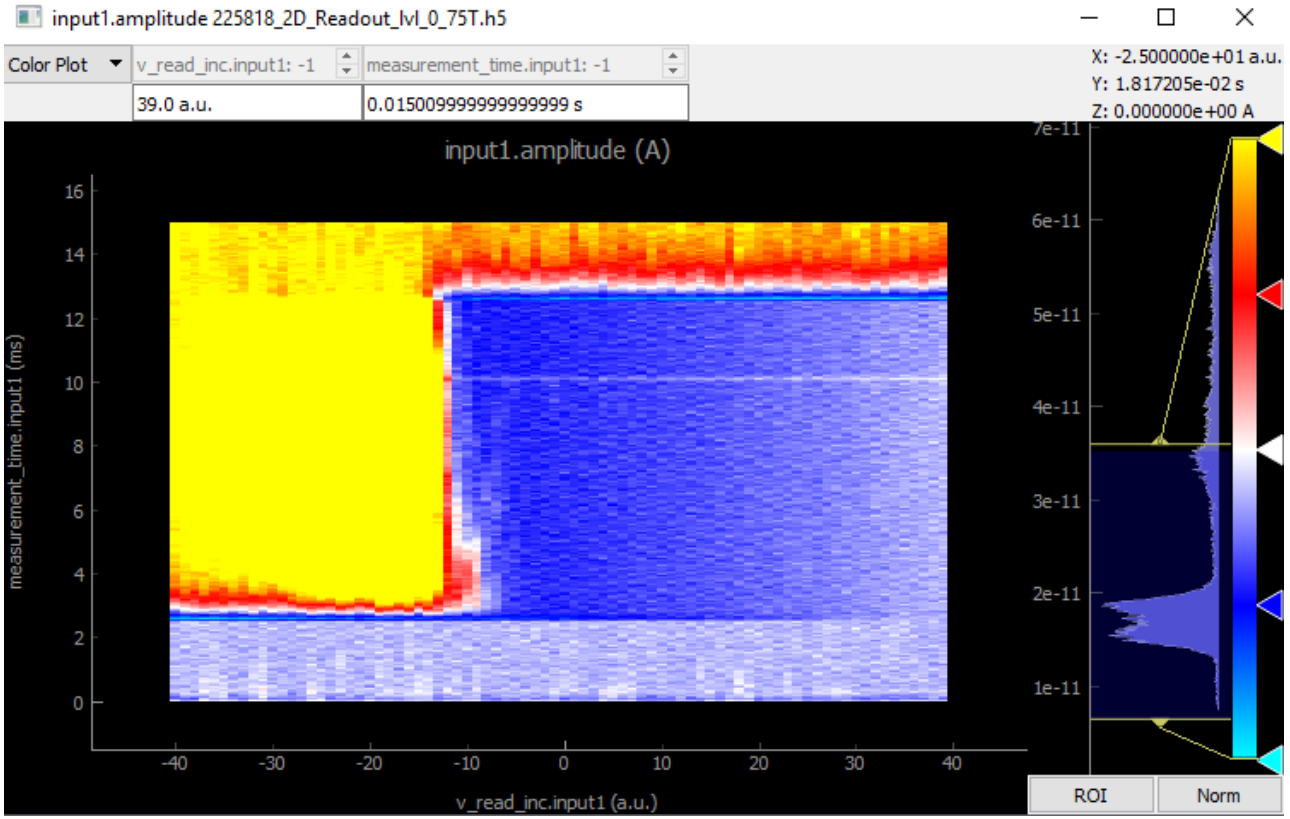
Finding voltage level for readout

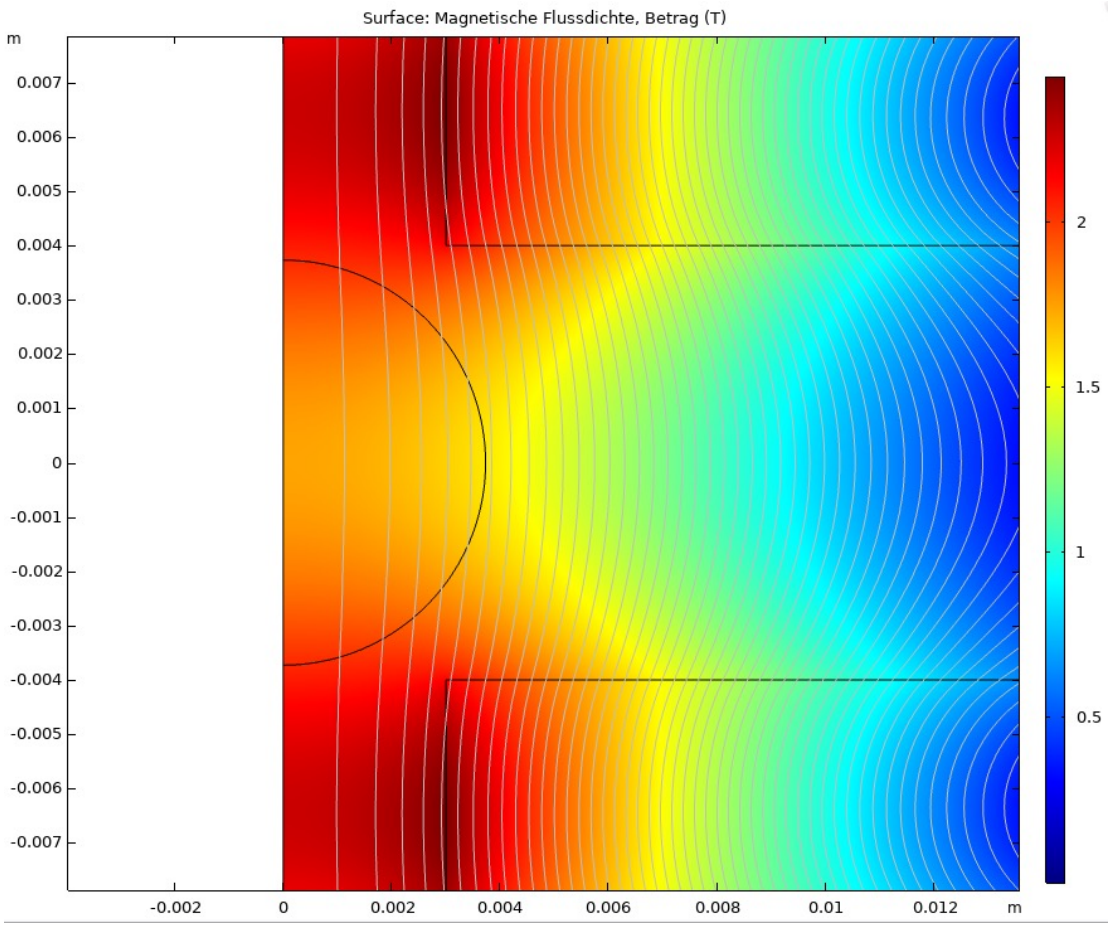


Finding voltage level for readout



Helmholtz pair close to each other

- 0.24936 T/A
- 1.7455T at 7A



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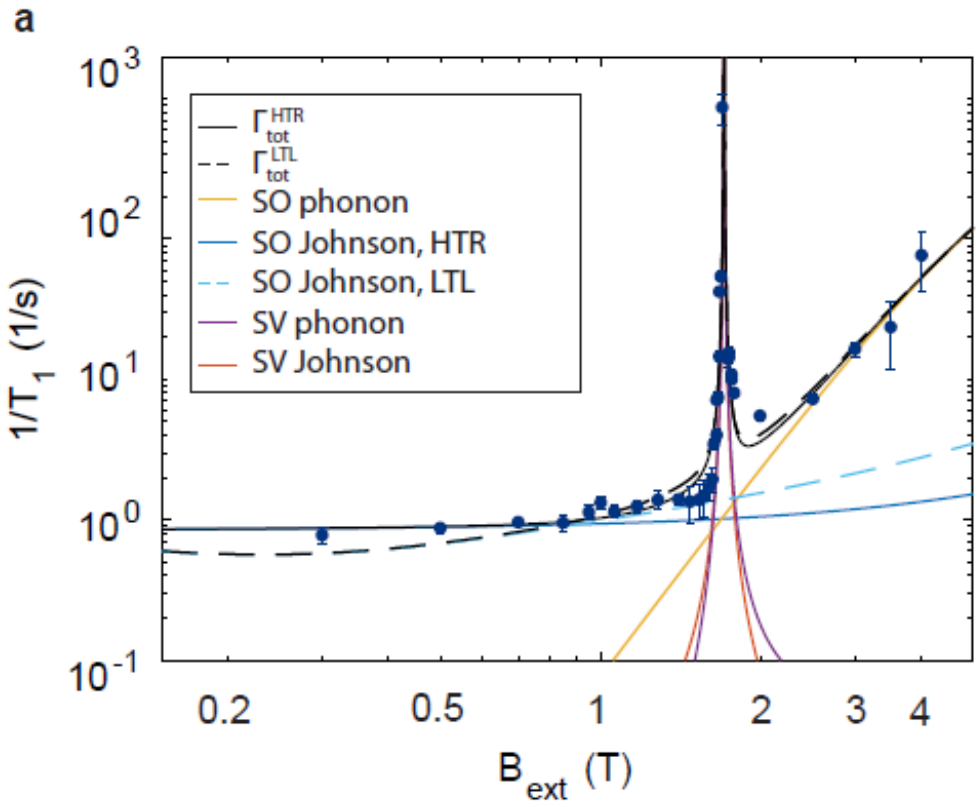
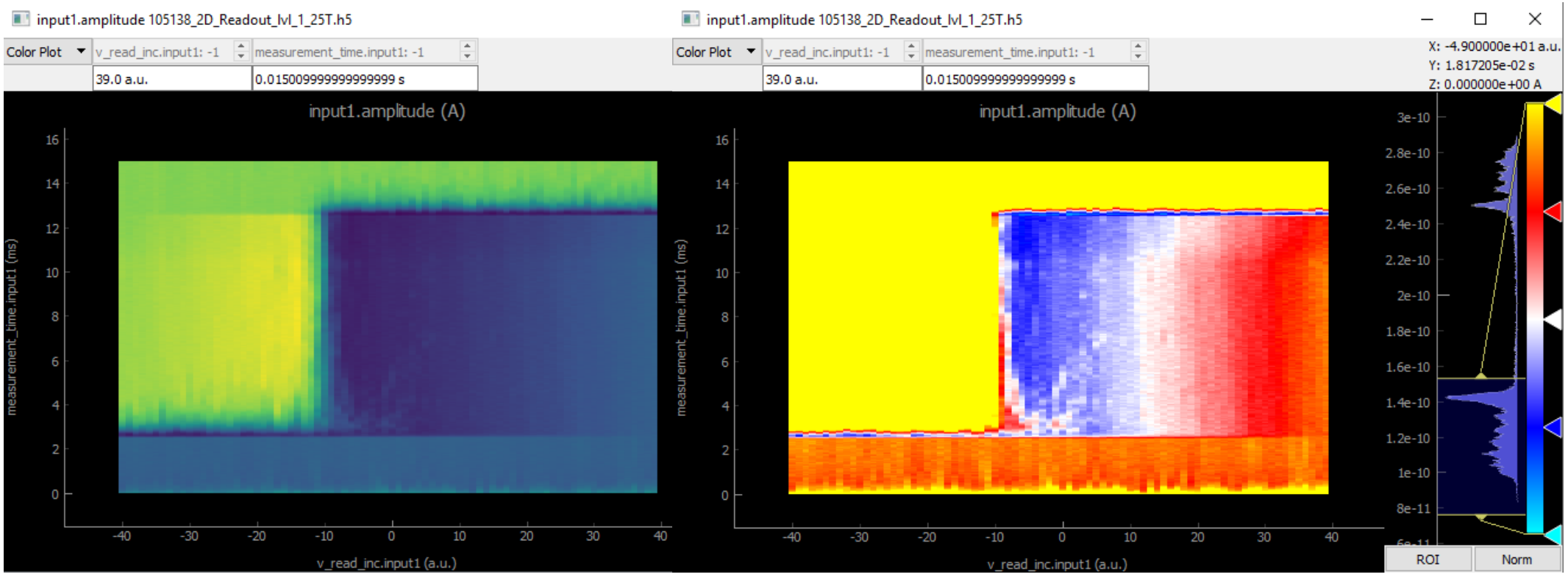
Aachen valley hotspot measurement



$$\Gamma_{tot} = \Gamma_{SV,J} + \Gamma_{SO,J} + \Gamma_{SV,ph} + \Gamma_{SO,ph},$$

Finding T1 readout voltage



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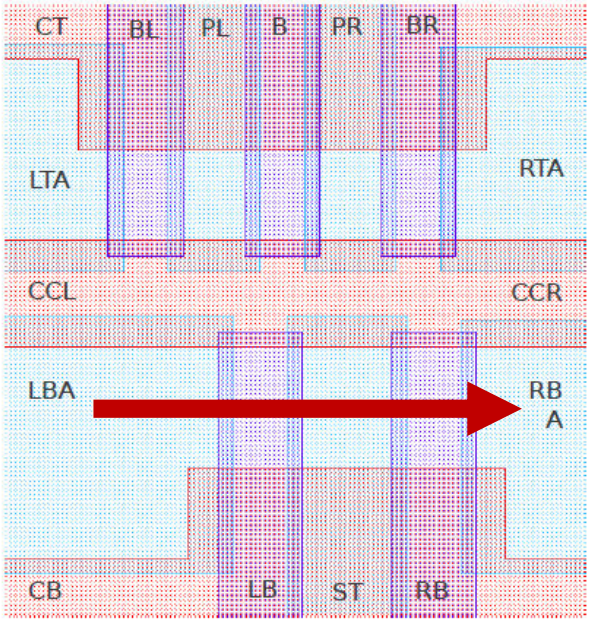
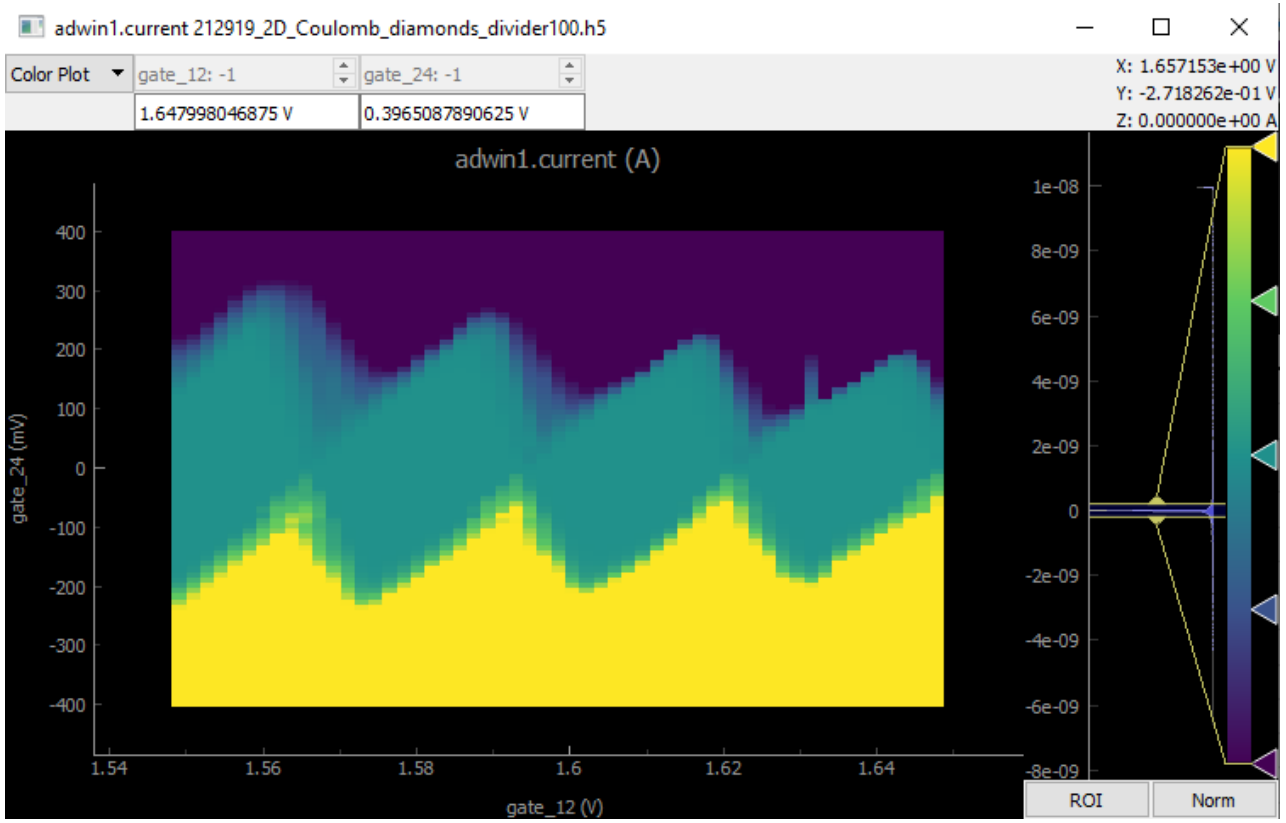
Vanished when switching Ohmic lines



GL1

GL2

GL3



Leverarm: 0.102eV/V

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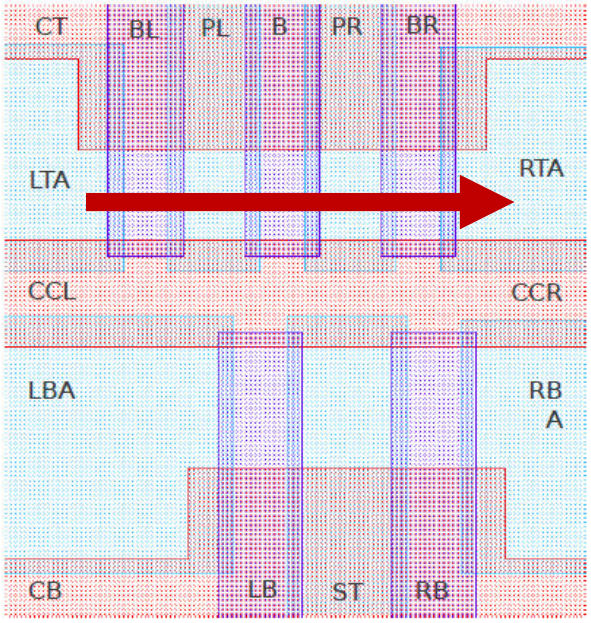
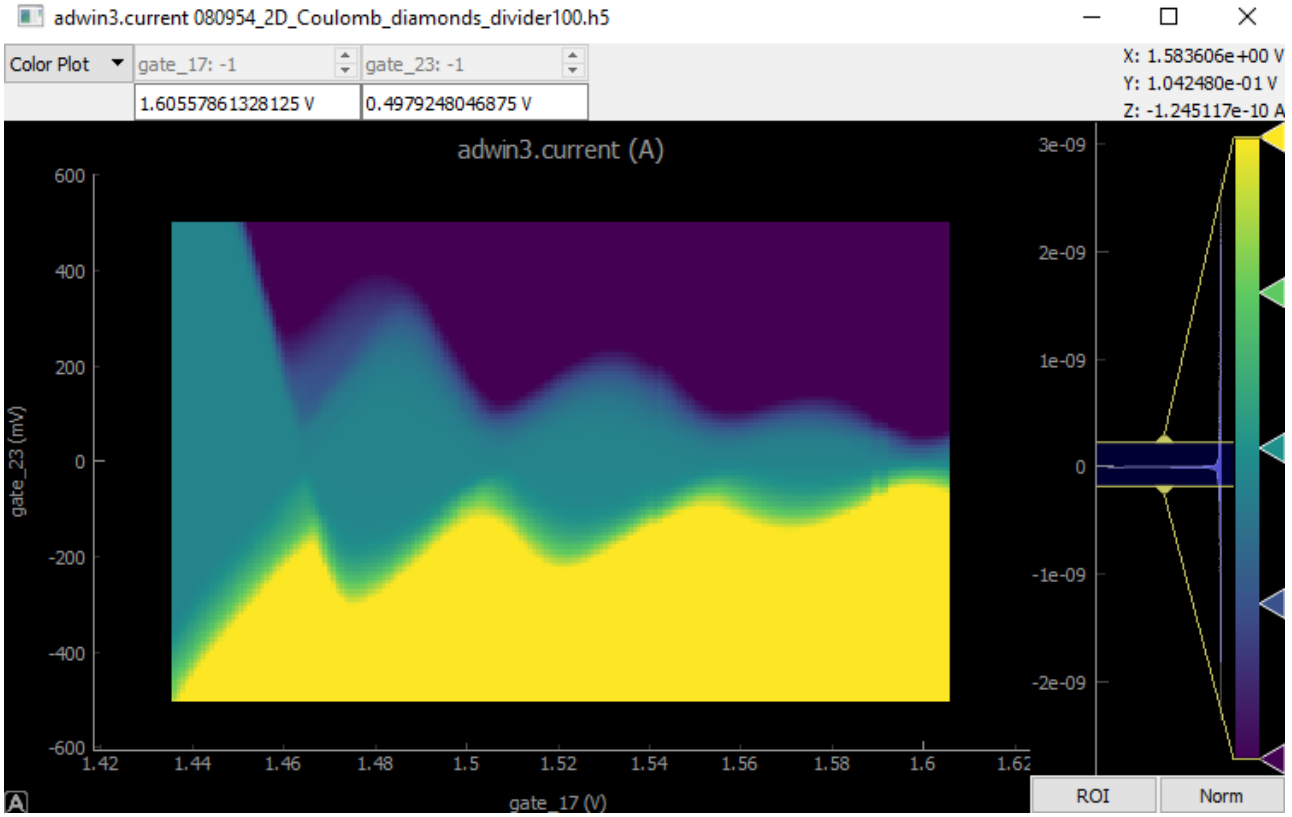
Upper Dot CDs



GL1

GL2

GL3



Leverarm: 0.042eV/V
But 1.5MOhm Line resistance
Real leaverarm ~ 0.1eV/V

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