University of Basel

Nanowire-based superconducting qubits

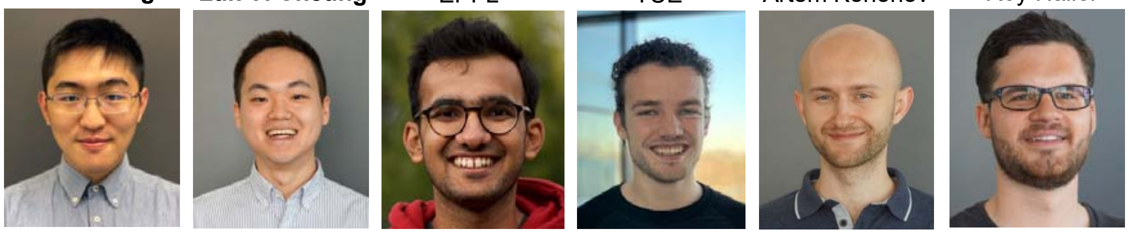
L. Y. Cheung, R. Haller, J. H. Ungerer, C .Ciaccia, A. Kononov, H. Zheng, N. Sangwan, T. Jenniskens T. Kanne, J. Nygard, P. Winkel, T. Reisinger, I. M. Pop, E. P.A.M. Bakkers, J. Ridderbos, A. Baumgartner, Christian Schönenberger

Workshop on Superconductor-Semiconductor Hybrids
March 12-14 2024
Niels Bohr Institute / The University of Copenhagen
by Christian Schönenberger

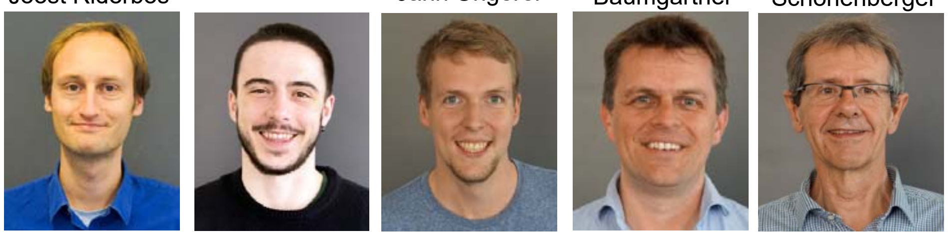
Quantum- and Nanoelectronics group: www.nanoelectronics.ch
Swiss Nanoscience Institute: https://nanoscience.ch/en/
Physics Department of the University of Basel: https://physik.unibas.ch

Nanowire-based superconducting qubits

Han Zheng | **Luk Yi Cheung** | Nikunj Sangwan EPFL | Tom Jennisken TUE | Artem Kononov | Roy Haller



Joost Riderbos | Carlo Ciaccia | Jann Ungerer | Andreas Baumgartner | Christian Schönenberger



acknowledgement:

Group **Jesper Nygard** for continuous support and collaboration — Niels Bohr Institute

Group **Erik Bakkers**, growth of *Ge/Si nanowires* — TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

Univ. of Lund team: **K. Dick**, **C. Thelander** and **V. Maisi** — LUNDS UNIVERSITET

Joost Ridderbos (present address Univ. of Twente) — UNIVERSITY OF TWENTE.

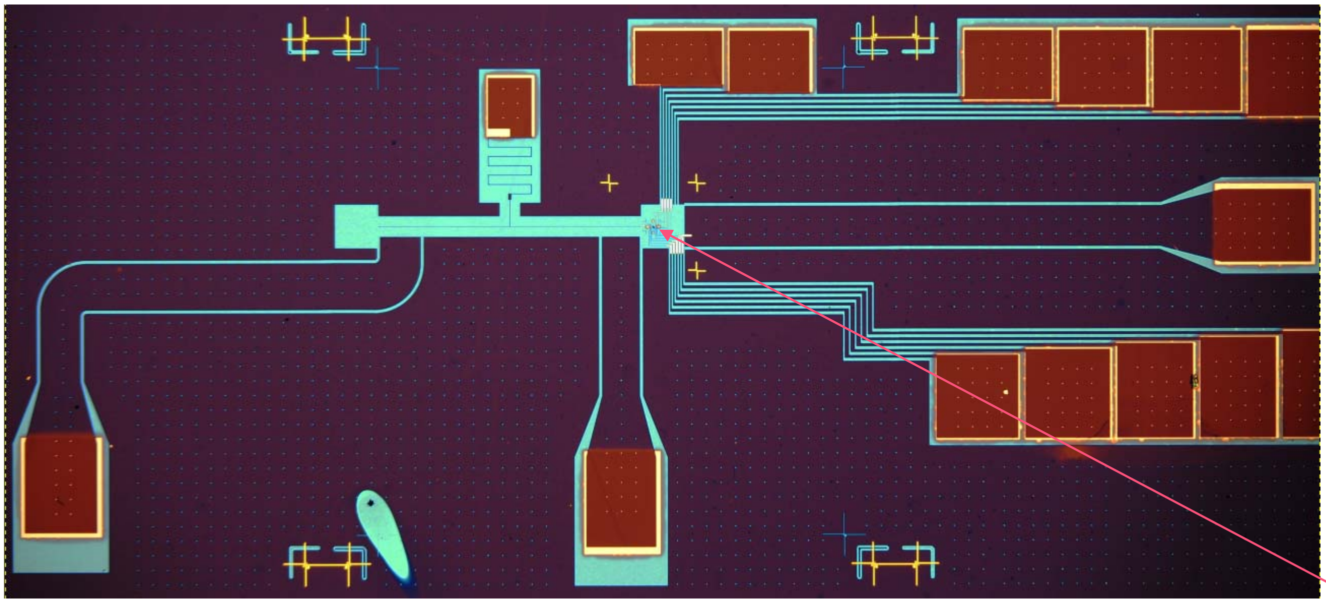
Group **Ioan Pop**, *parametric amplifier* — KIT Karlsruher Institut für Technologie

AndQC | QUANTERA ERA-NET Cofund in Quantum Technologies | Swiss National Science Foundation | erc | TOPSQUAD | SNI Swiss Nanoscience Institute Exzellenzzentrum der Universität Basel und des Kantons Aargau | NCCR SPIN | QSIT Quantum Science and Technology National Centre of Competence in Research

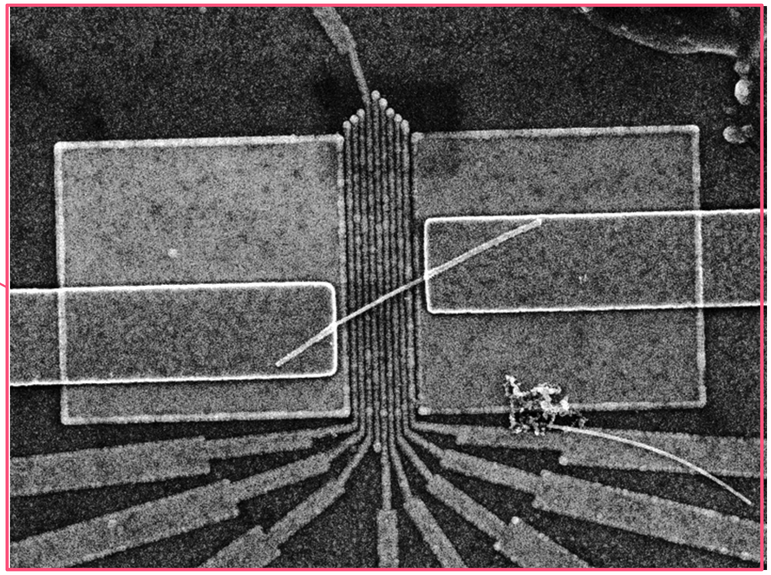
Nanowire-based qubit research at CS's group @ University of Basel

Nanowire-based qubit research at CS's group @ University of Basel

Spin qubits in GeSi core shell nanowires (based on double quantum dots) with Dominik Zumbühl's group

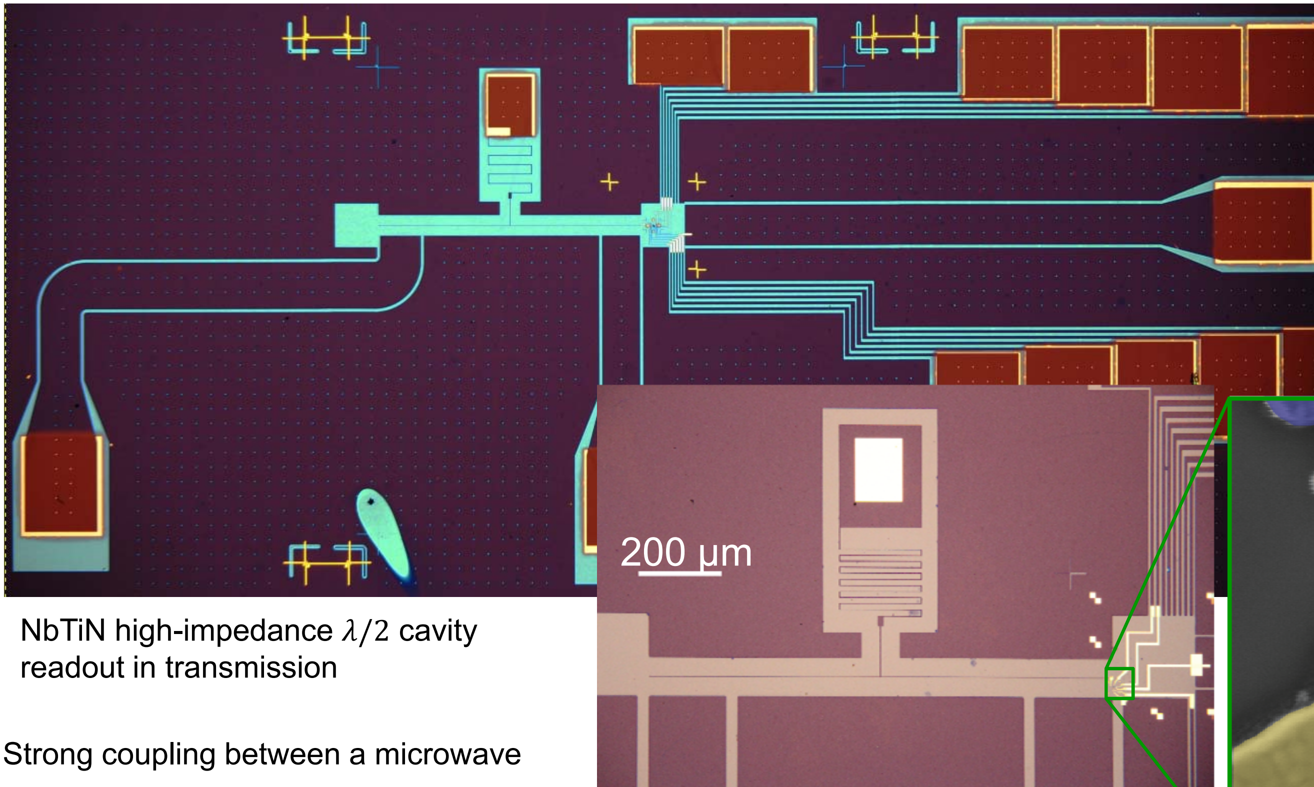


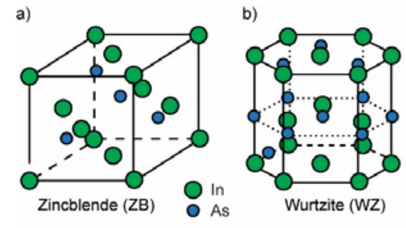
NbTiN high-impedance $\lambda/2$ cavity
readout in transmission

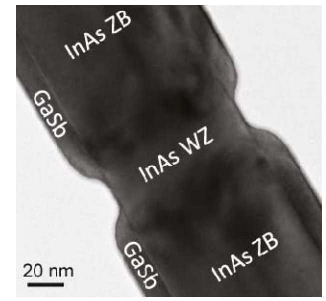


Nanowire-based qubit research at CS's group @ University of Basel

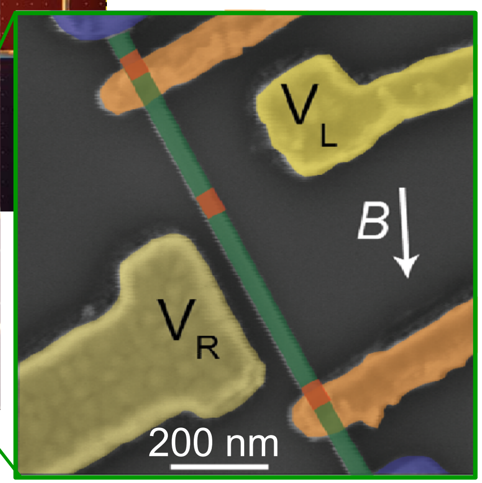
Spin qubits in InAs NWs (based on double quantum dots)







NbTiN high-impedance $\lambda/2$ cavity readout in transmission



Strong coupling between a microwave photon and **a singlet-triplet qubit**,
J. H. Ungerer et al. Nature Comm. 15, 1068 (2024)

excellent NWs from Lund yielding very stable double quantum dot devices

Nanowire-based qubit research at CS's group @ University of Basel

- **Spin qubits** in GeSi core shell nanowires (based on double quantum dots)
- **Spin qubits** in InAs NWs (based on double quantum dots)

Strong coupling between a microwave photon and a singlet-triplet qubit: Nature Comm. 15, 1068 (2024)

Nanowire-based qubit research at CS's group @ University of Basel

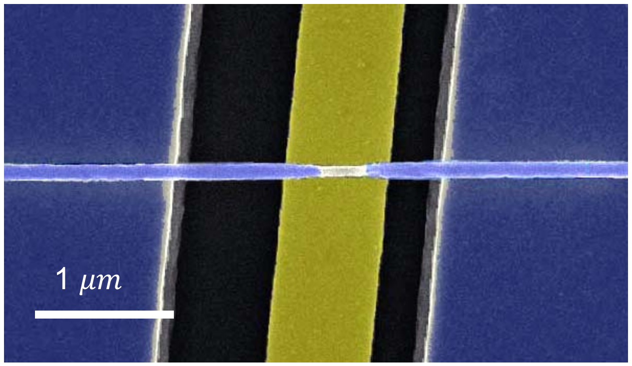
- **Spin qubits** in GeSi core shell nanowires (based on double quantum dots)
- **Spin qubits** in InAs NWs (based on double quantum dots)
- **Andreev (spin) qubits** in InAs nanowires (material from Jesper Nygard's group)
- **Gatemon qubits** in GeSi core shell nanoires (material from Erik Bakkers' group)

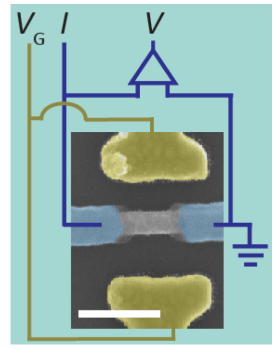
Strong coupling between a microwave photon and a singlet-triplet qubit: Nature Comm. 15, 1068 (2024)

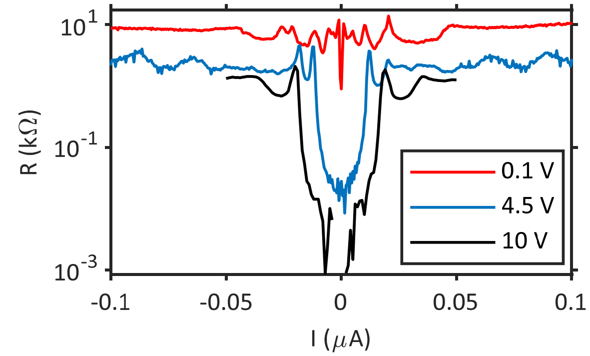
InAs nanowires with in-situ grown Al shell (few facets to full shell)

InAs full (Al) shell nanowires, obtained from **Jesper Nygard** (CPH)

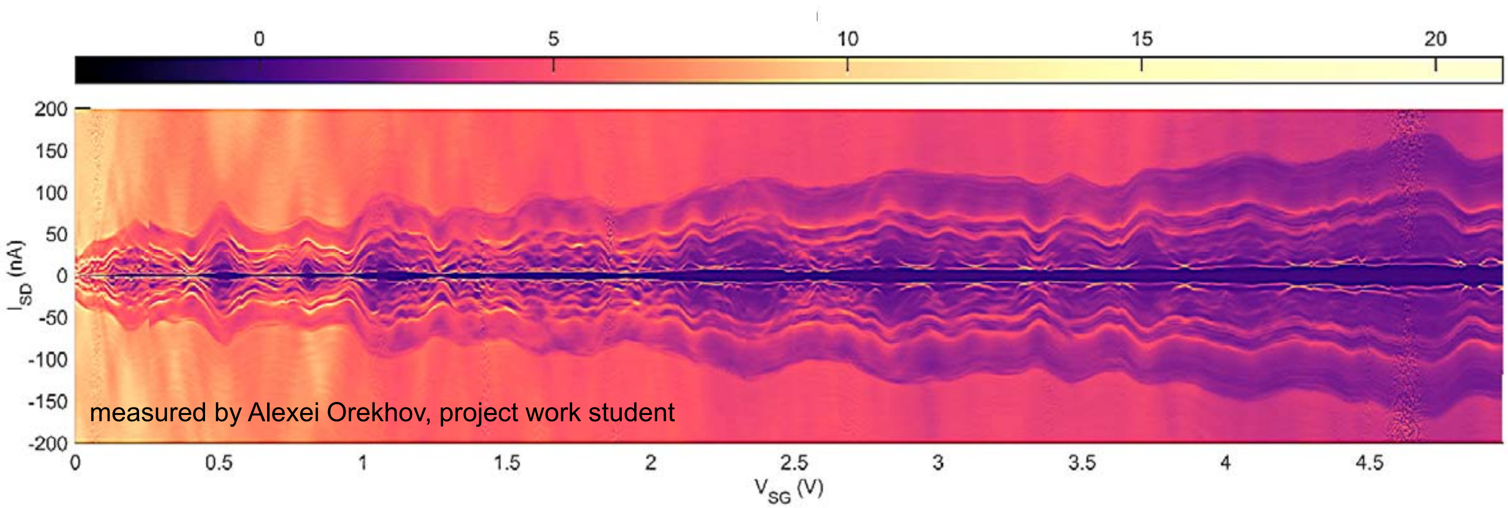
Etched and gated device. Here, the NW is suspended over the gate





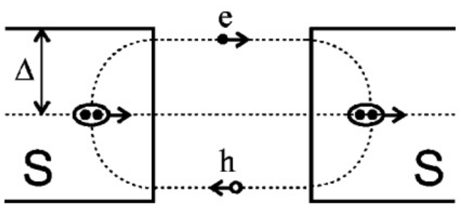


qubit
tuned by gate voltage



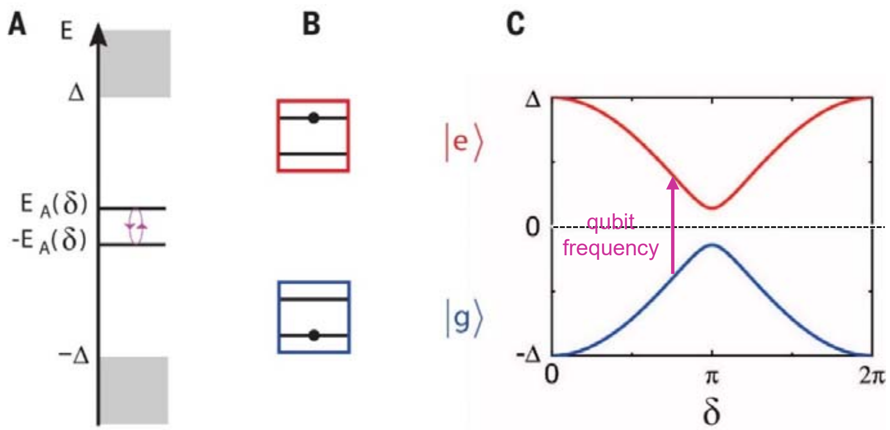
The Andreev Qubit

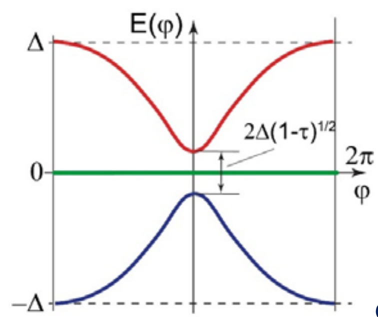
Andreev Bound State



$$E_A(\varphi) = \pm\,\Delta\sqrt{1-\tau sin^2\left(\frac{\varphi}{2}\right)}$$

τ = transmission probability





excited state
(even parity)

odd state
(doublet)

ground state
(even parity)

qubit
tuned by phase bias

see for example: M. F. Goffman et al. Supercurrent in atomic point contacts and Andreev states, Phys. Rev. Lett. 85, 170 (2000).

L. Bretheau et al. Exciting Andreev pairs in a superconducting atomic contact, Nature 499 (7458), 312-315 (2013).

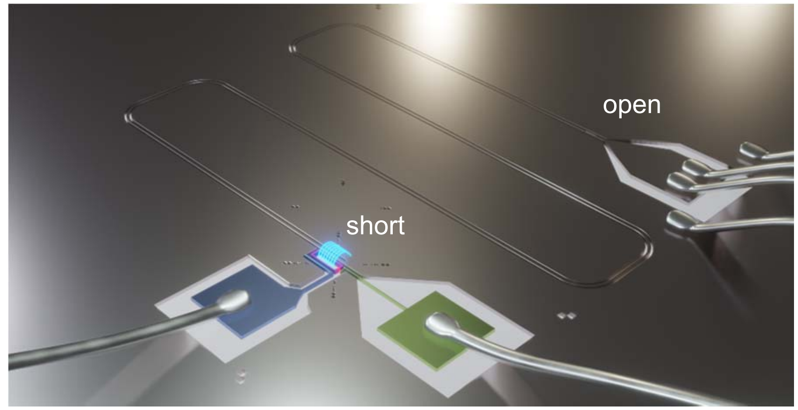
The AndQC FETopen project

AndQC

Andreev qubits for scalable quantum computation

<u>consortium partner</u>

Chalmers
TUDelft
BME
CPH
CNR
UAM
CEA
UBAS



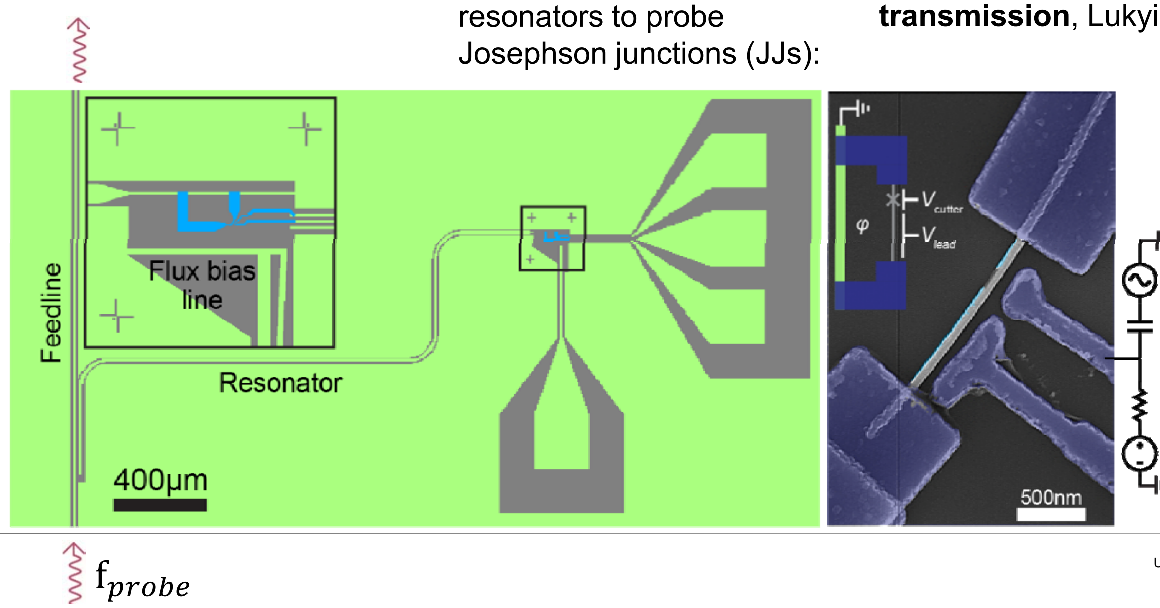
1st generation of rf resonators to probe Josephson junctions (JJs):

$\lambda/4$ resonator in **reflection**, illustration by Roy Haller

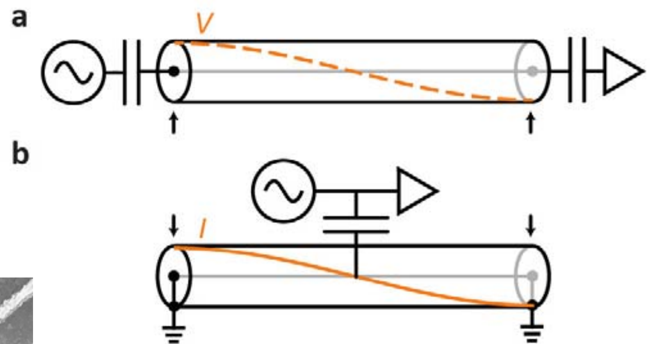
2nd generation of rf resonators to probe Josephson junctions (JJs):

$\lambda/4$ resonator with **feedline in transmission**, Lukyi Cheung et al

Our goal is to establish the foundations of a ***radically new*** solid state platform for scalable quantum computation, based on **Andreev qubits**. To carry out this research program, we rely on the instrumental combination of experimentalists, theorists and material growers, together having the necessary expertise on all aspects of the proposed research



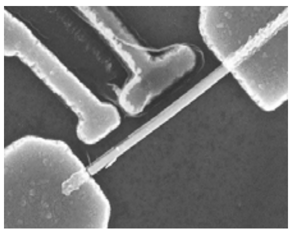
Remote Qubit-Qubit coupling

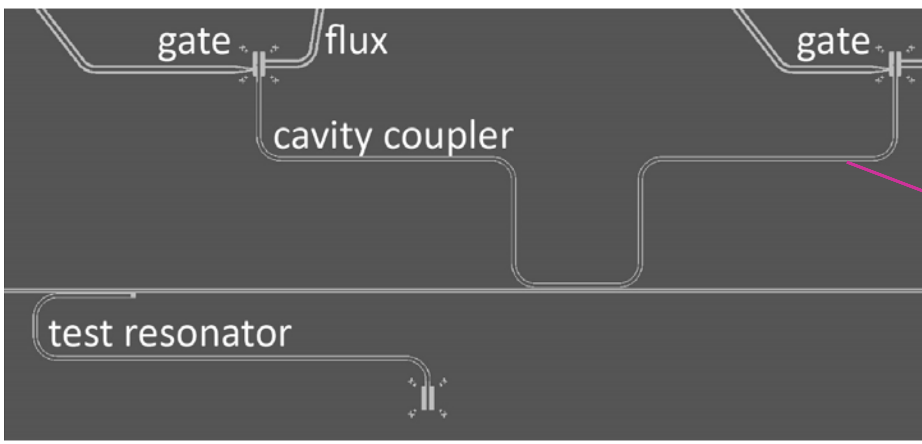


$\lambda/2$ resonator in
open-cavity-open configuration

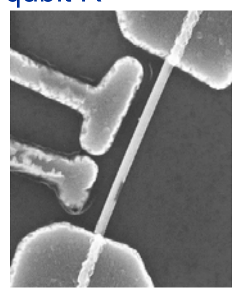
$\lambda/2$ resonator in
short-cavity-short configuration

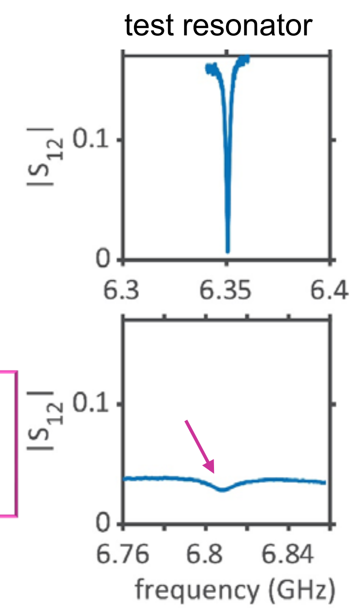
qubit L





qubit R

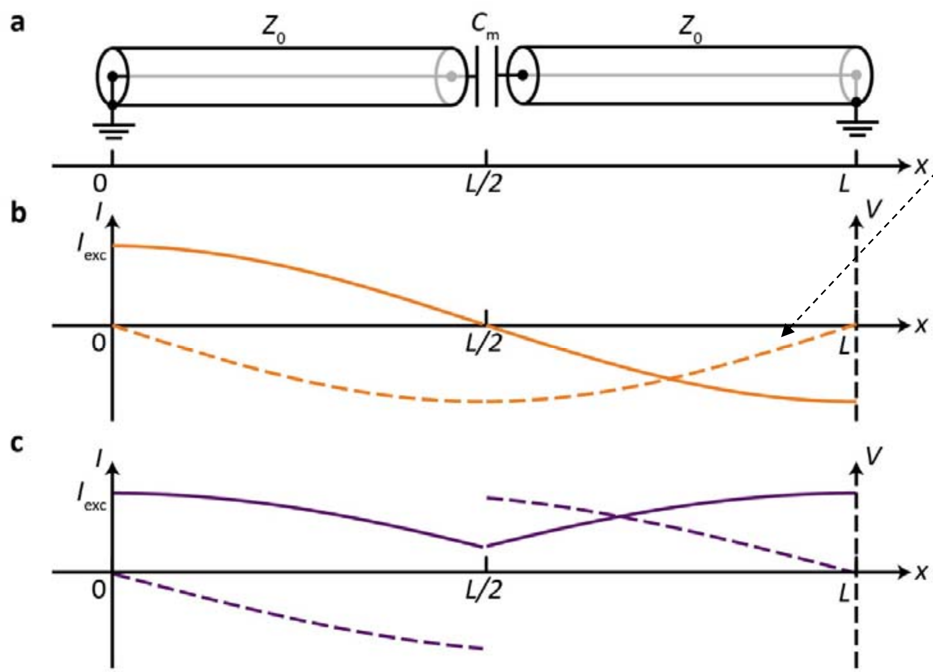




cavity coupler
shallow dip ?
$Q_i < 10^3$

Remote Qubit-Qubit coupling

cut the “ground loop”
2 coupled $\lambda/4$ resonators



voltage is shown as **dashed** lines

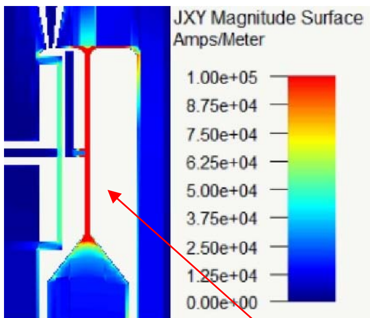
even (in voltage) mode
symmetric mode f_s

odd (in voltage) mode
antisymmetric mode f_a

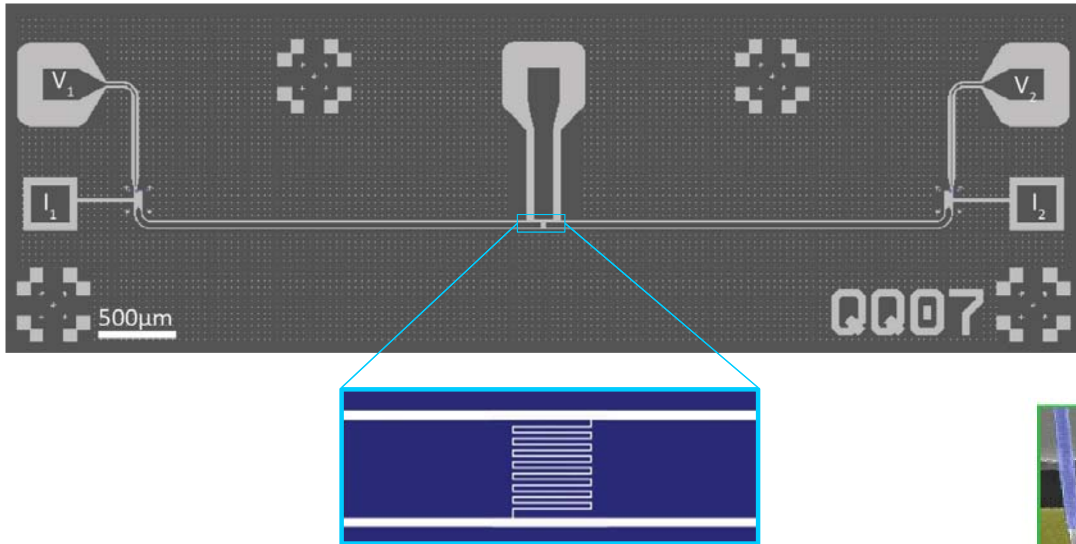
design rule: $f_s - f_a \sim 5g \cong 500$ MHz

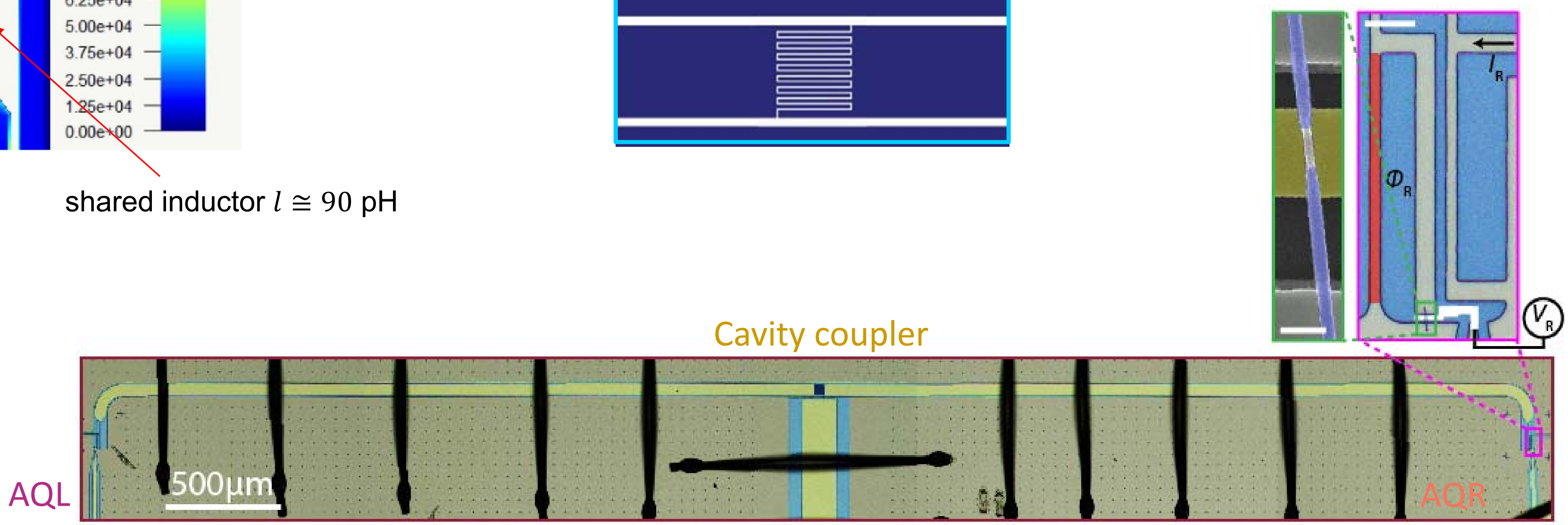
Remote Qubit-Qubit coupling

AndQC



shared inductor $l \cong 90$ pH

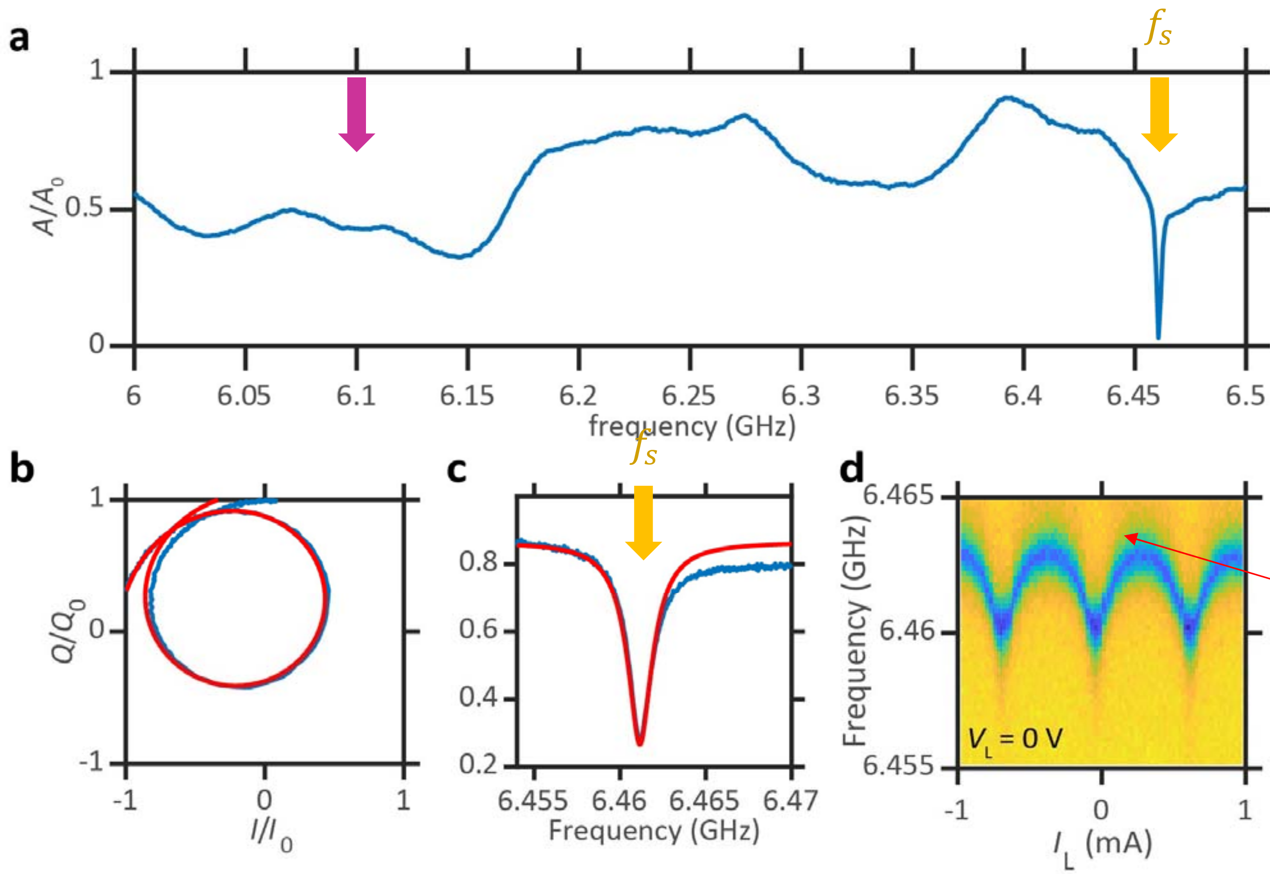




$\lambda/2$

Remote Qubit-Qubit coupling

Resonator characterization:

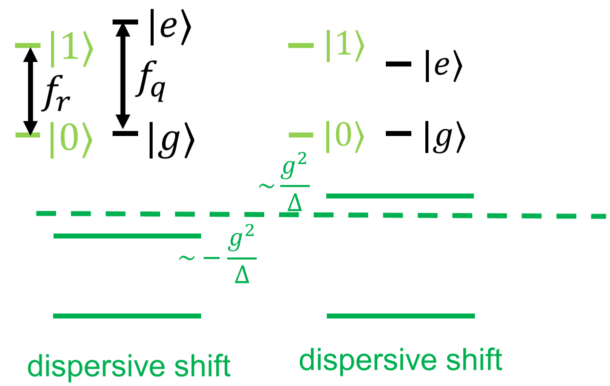


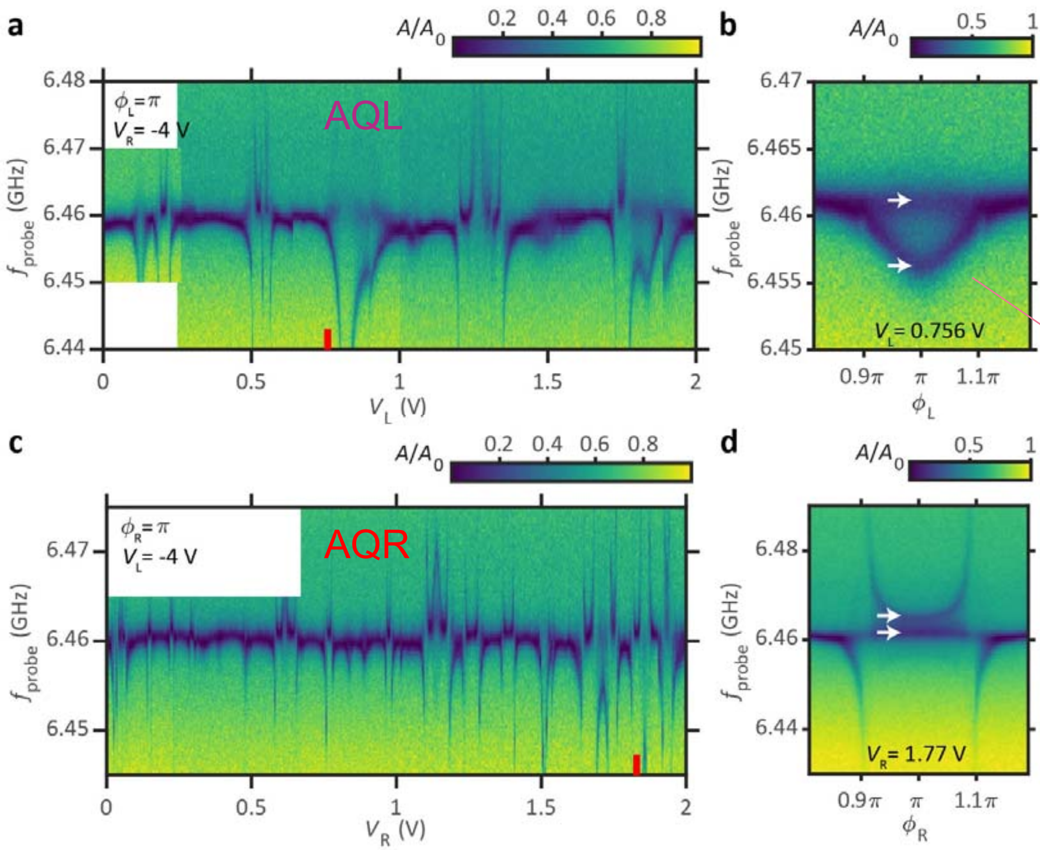
$\kappa_i/2\pi = 0.7$ MHz

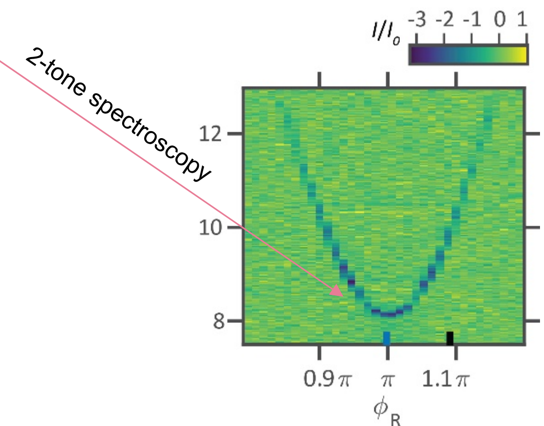
$\kappa_{cs}/2\pi = 1.2$ MHz

periodic dispersive shift due to AQL being phase-tuned by the flux-bias given in current

Interaction of AQL & AQR with f_s







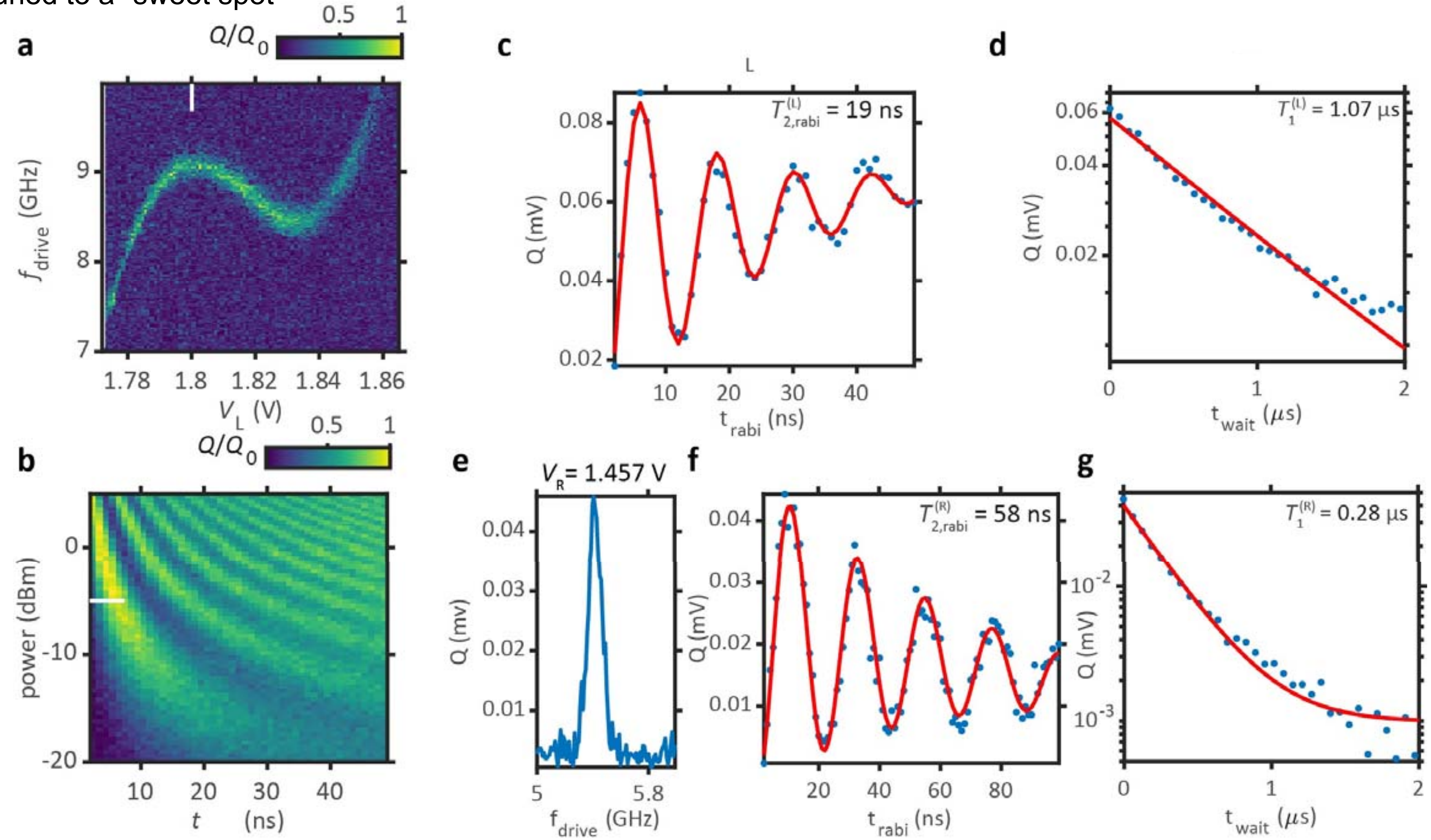
dispersive shift $\frac{g^2}{\Delta} \cong 5.5$ MHz

with a detuning $\Delta \cong 1.8$ GHz, yields

a coupling strength $g = \mathbf{100}$ **MHz**

Coherence of Single Qubits

AQL tuned to a “sweet spot”

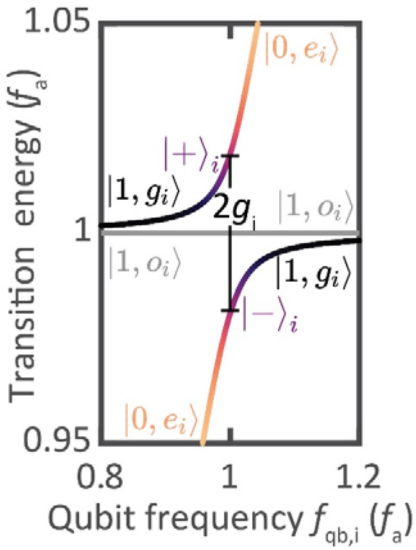


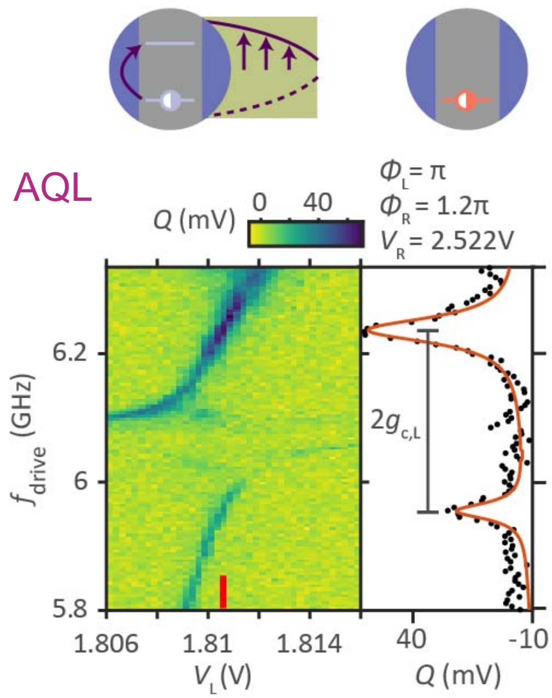
$T_1 \cong 1\,\mu s$ and $T_{2,rabi} \sim 50\,ns$

Qubit Coupling to the Asymmetric Mode f_a

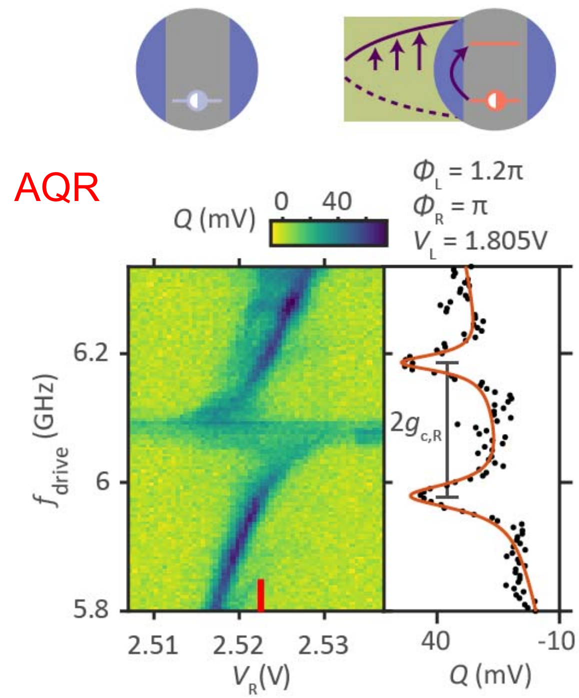
Pulsed differential two-tone spectroscopy at $f \sim f_a$ with a probe tone at $f \sim f_s$

AndQC





$g_{c,L} = 141\text{MHz}$
$\gamma_L = 77\text{MHz}$



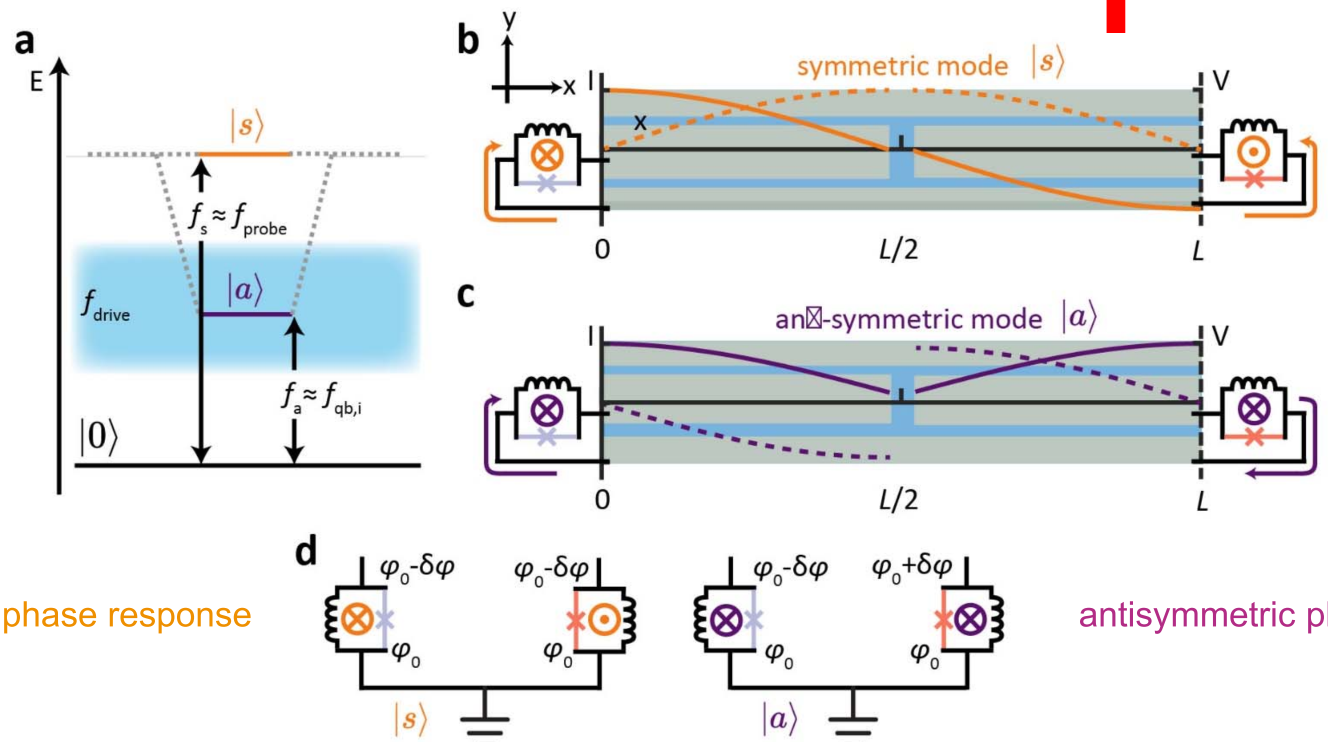
$g_{c,R} = 104\text{MHz}$
$\gamma_R = 82\text{MHz}$

Sign of Qubit-Qubit Coupling depends on Symmetry

Tavis-Cummings Hamiltonian

$$H_{\mathrm{TC}} = \frac{hf_{\mathrm{qb,L}}}{2}\sigma_{\mathrm{z,L}} + hf_a\left(a^\dagger a\right) + \frac{hf_{\mathrm{qb,R}}}{2}\sigma_{\mathrm{z,R}} + \hbar g_{\mathrm{c,L}}\left(a\sigma_{+,\mathrm{L}} + a^\dagger\sigma_{-,\mathrm{L}}\right) - \hbar g_{\mathrm{c,R}}\left(a\sigma_{+,\mathrm{R}} + a^\dagger\sigma_{-,\mathrm{R}}\right)$$

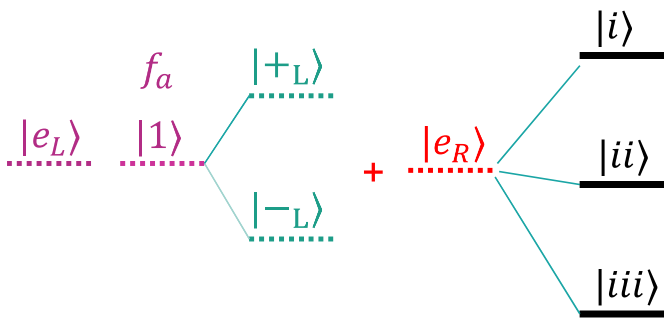
conceptional idea:
use asymmetric mode as qubit-qubit coupler mode and the symmetric one for qubit readout

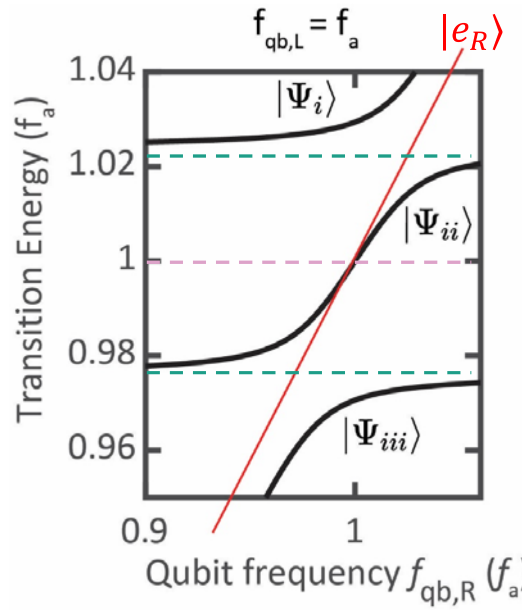


symmetric phase response

antisymmetric phase response

Strong Qubit-Qubit-Resonator Coupling





dressed states under resonance condition:

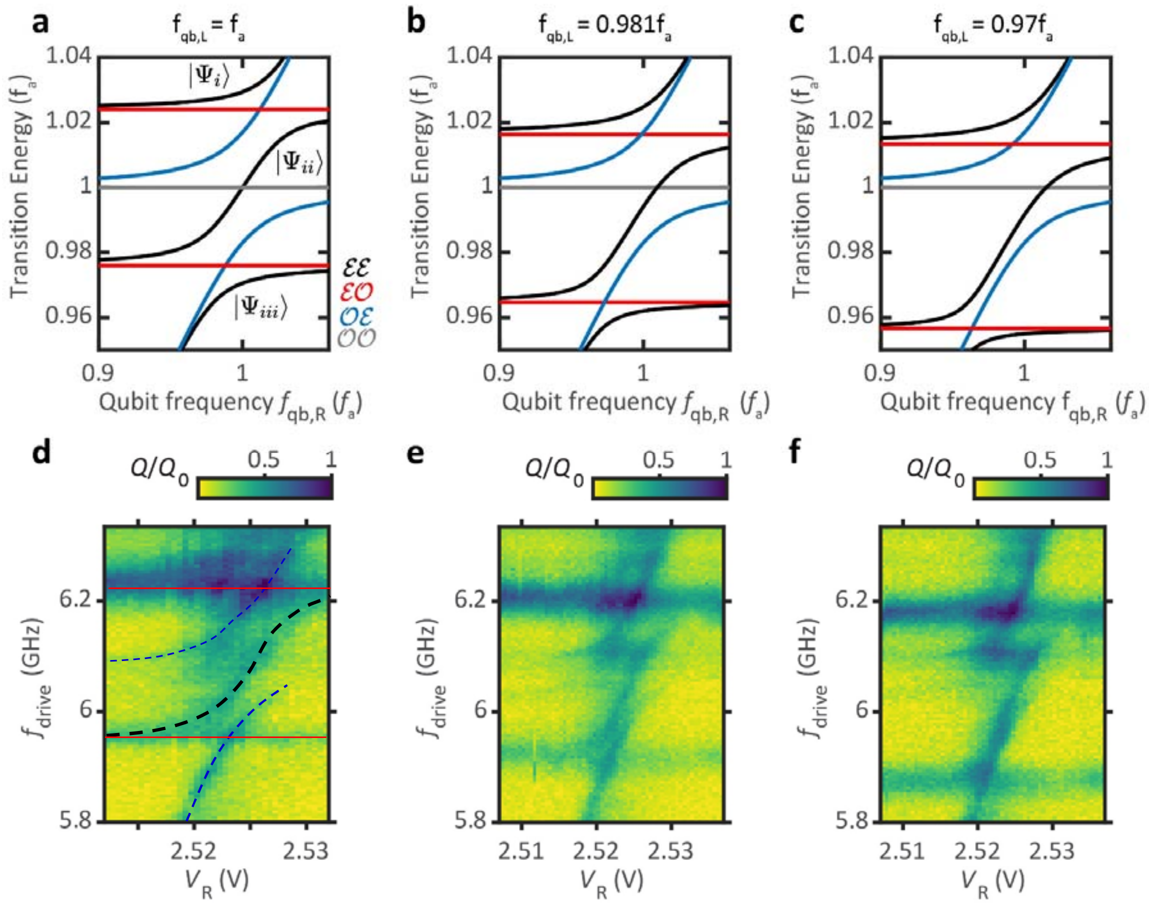
$$|\Psi_i\rangle \to |\Psi_\mathrm{s}\rangle = \frac{1}{\sqrt{2}}\Big(|1, g_\mathrm{L}, g_\mathrm{R}\rangle + \frac{1}{\sqrt{2}}\big(|0, e_\mathrm{L}, g_\mathrm{R}\rangle + |0, g_\mathrm{L}, e_\mathrm{R}\rangle\big)\Big) \tag{7.7}$$

$$|\Psi_{ii}\rangle \to |\Psi_\mathrm{q}\rangle = \frac{1}{\sqrt{2}}\big(|0, e_\mathrm{L}, g_\mathrm{R}\rangle - |0, g_\mathrm{L}, e_\mathrm{R}\rangle\big) \tag{7.8}$$

$$|\Psi_{iii}\rangle \to |\Psi_\mathrm{a}\rangle = \frac{1}{\sqrt{2}}\Big(|1, g_\mathrm{L}, g_\mathrm{R}\rangle - \frac{1}{\sqrt{2}}\big(|0, e_\mathrm{L}, g_\mathrm{R}\rangle + |0, g_\mathrm{L}, e_\mathrm{R}\rangle\big)\Big). \tag{7.9}$$

Strong Qubit-Qubit-Resonator Coupling

AndQC

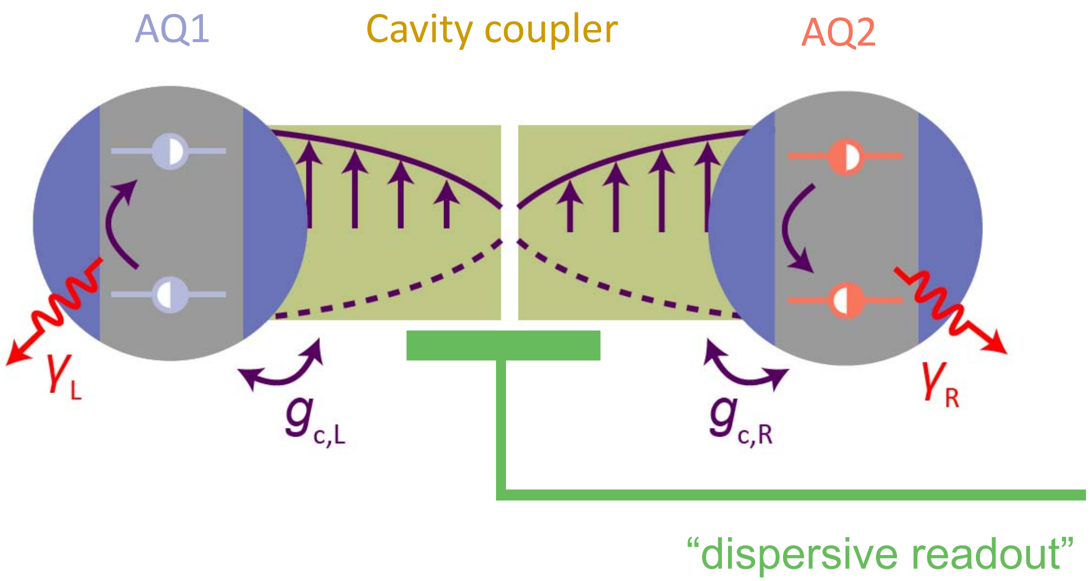


$|\psi_i\rangle$ & $|\psi_{iii}\rangle$ barely visible, why? → Symmetry of coupling

(control experiment with symmetric mode)

Coupling two Andreev Qubits via a Cavity Photon

AndQC



<u>what's next:</u>

- two-qubit gates (timed)
- fidelity, coherence
- address spin degree and try to couple two Andreev **spin qubits**
- can we **improve coherence** (now in the 10 ns range), sweet spots ?

University of Basel

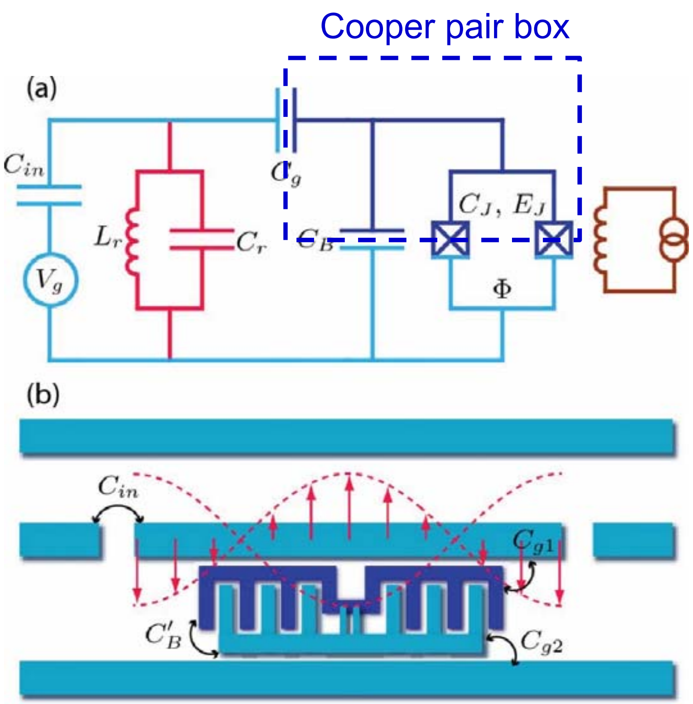
Ge/Si based gatemon as an alternative qubit

Han Zheng, Luk Yi Cheung, Nikunj Sangwan, Tom Jennisken, Artem Kononov, Roy Haller,
Joost Ridderbos, Carlo Ciaccia, Jann Hinnerk Ungerer, Erik P.A.M. Bakkers,
Andreas Baumgartner, and Christian Schönenberger

EQTC – European Quantum Technology Conference
Oct. 16.10-20.10.2023, Hannover, Germany
by Christian Schönenberger

Quantum- and Nanoelectronics group: www.nanoelectronics.ch
Swiss Nanoscience Institute: https://nanoscience.ch/en/
Physics Department of the University of Basel: https://physik.unibas.ch

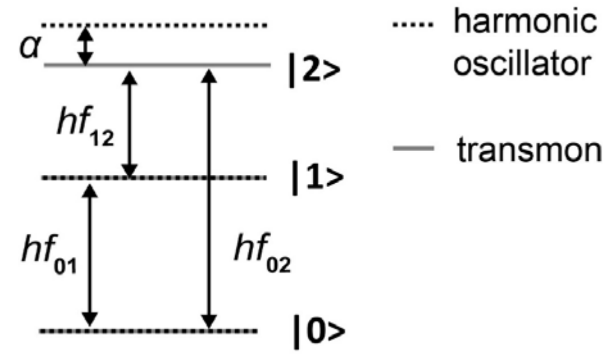
The Transmon Qubit



J. Koch et al. PRA 76, 042319 (2007)

"weakly" non-linear LC circuit
shunted by a large capacitance such that
$E_J \gg E_c$

$$hf_q = hf_{01}$$
$$= \sqrt{8E_cE_J} - E_c$$

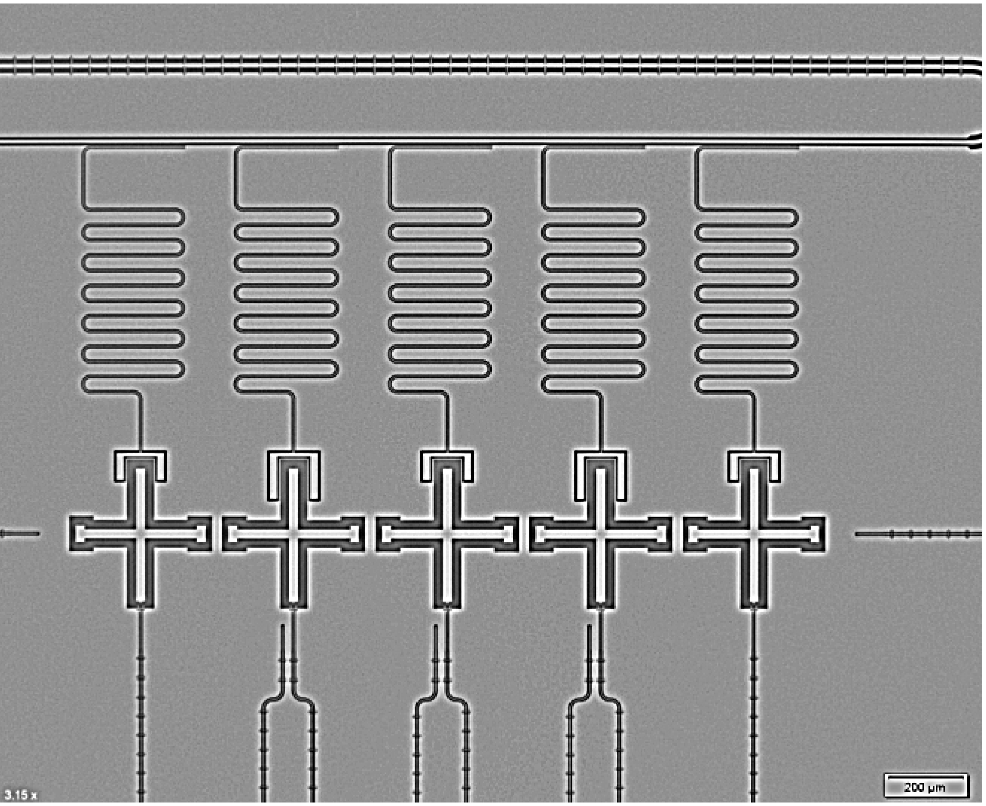


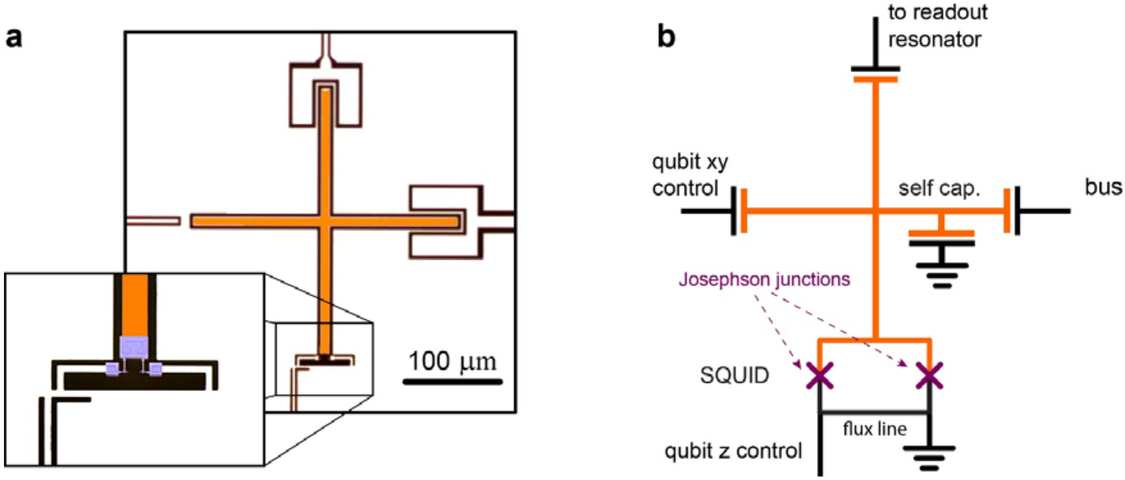
anharmonicity $\alpha \coloneqq hf_{12} - hf_{01} \cong -E_c$ "small"

The Transmon Qubit

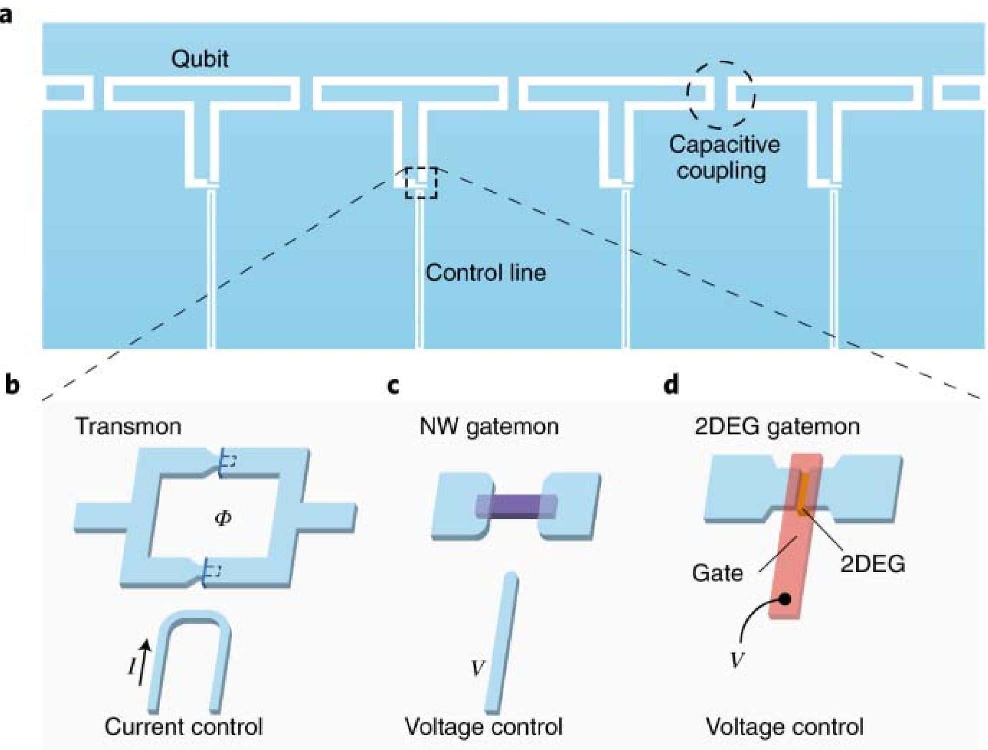
The **Xmon** qubit

adapted from PRL 111, 080502 (2013) J. Martins' group





Transmon versus Gatemon Qubit



Transmon:

- flux control
- heating (dissipation)
- crosstalk
- small anharmonicity
- “insensitive” to charge noise by construction

Gatemon:

- gate control
- no bias current (lower dissipation)
- voltage is easier to screen
- (even) smaller anharmonicity
- sensitive to charge noise (through gate)

Previous Gatemon Devices

first gatemon devices, both based on **InAs nanowires**

. 115, 127001 (2015)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending 18 SEPTEMBER 2015

Semiconductor-Nanowire-Based Superconducting Qubit

2015

T. W. Larsen,[1] K. D. Petersson,[1] F. Kuemmeth,[1] T. S. Jespersen,[1] P. Krogstrup,[1] J. Nygård,[1,2] and C. M. Marcus[1]
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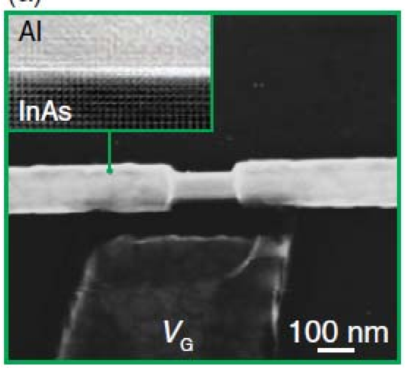
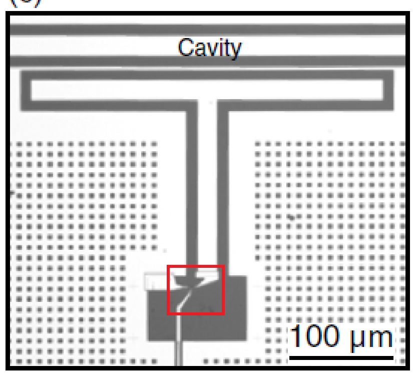
(Received 28 March 2015; published 14 September 2015)

(a)



(c)



$T_1 \approx 0.8\ \mu s$

$T_2^* \approx 1\ \mu s$

superconductor = Al

PRL 115, 127002 (2015)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending 18 SEPTEMBER

Realization of Microwave Quantum Circuits Using Hybrid Superconducting-Semiconducting Nanowire Josephson Elements

2015

G. de Lange,[1] B. van Heck,[2] A. Bruno,[1] D. J. van Woerkom,[1] A. Geresdi,[1] S. R. Plissard,[3] E. P. A. M. Bakkers,[1,3] A. R. Akhmerov,[1] and L. DiCarlo[1]
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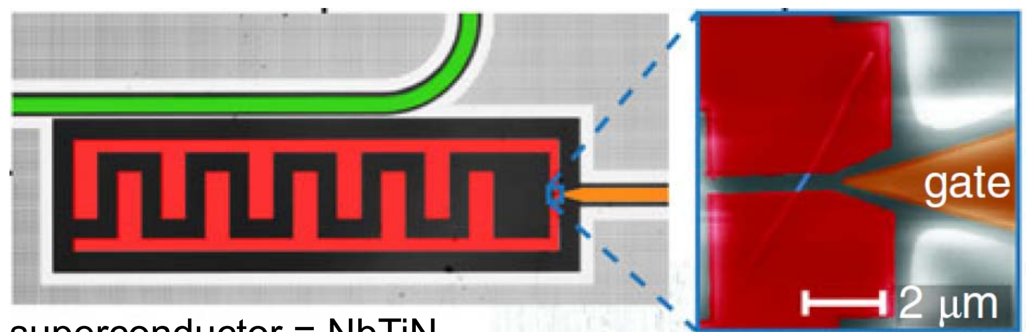
[3]*Department of Applied Physics, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands*
(Received 30 March 2015; published 14 September 2015)



superconductor = NbTiN

looked additionally into SQUID junctions tuned
to half-flux quantum (different spectrum, fluxonium)

Previous Gatemon Devices

first gatemon devices, both based on **InAs nanowires**

PRL **116,** 150505 (2016) PHYSICAL REVIEW LETTERS week ending 15 APRIL 2016

2016

Gatemon Benchmarking and Two-Qubit Operations

L. Casparis,[1] T. W. Larsen,[1] M. S. Olsen,[1] F. Kuemmeth,[1] P. Krogstrup,[1] J. Nygård,[1,2]
K. D. Petersson,[1] and C. M. Marcus[1]
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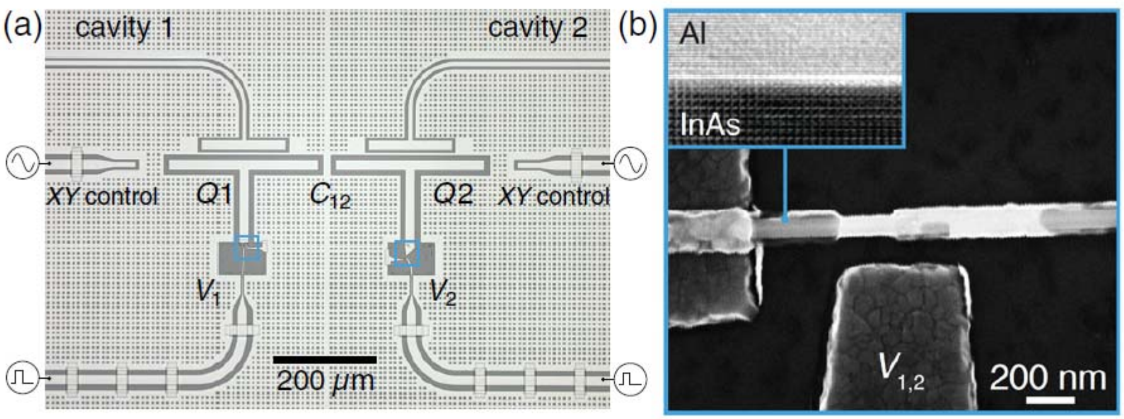
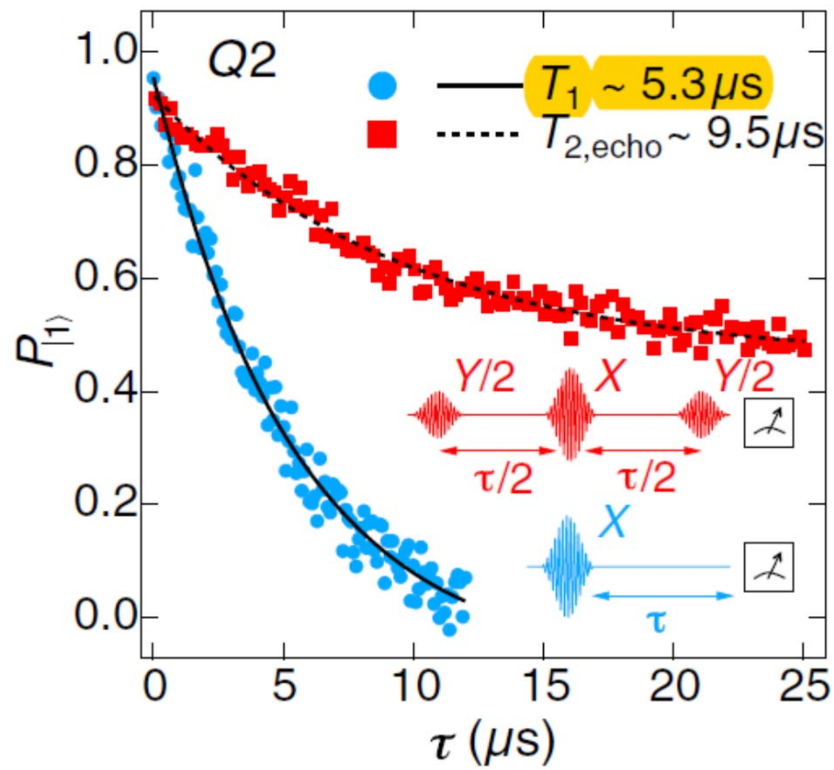
(Received 30 December 2015; published 15 April 2016)





Previous Gatemon Devices

first gatemon devices, both based on **InAs nanowires**

PHYSICAL REVIEW LETTERS **120,** 100502 (2018)

Evolution of Nanowire Transmon Qubits and Their Coherence i

F. Luthi,[1,2] T. Stavenga,[1,2] O. W. Enzing,[1,2] A. Bruno,[1,2] C. Dickel,[1,2] N. K. Lan
T. S. Jespersen,[3] J. Nygård,[3,4] P. Krogstrup,[3] and L. DiCarlo[1]
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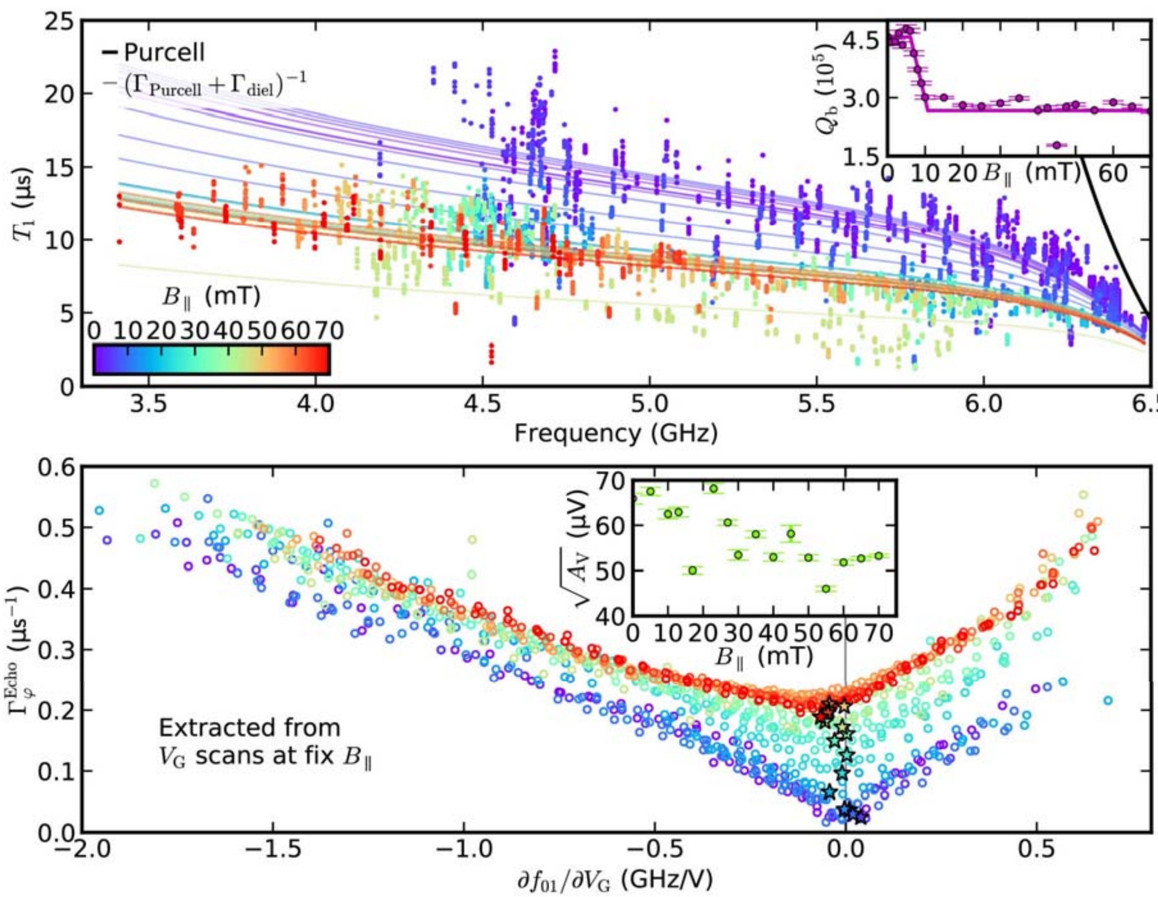
(Received 22 November 2017; published 9 March 2018)



obtained $T_2^{echo} \cong \mathbf{40}\ \boldsymbol{\mu s}$
at sweet spot and at $B = 0$!

Previous Gatemon Devices

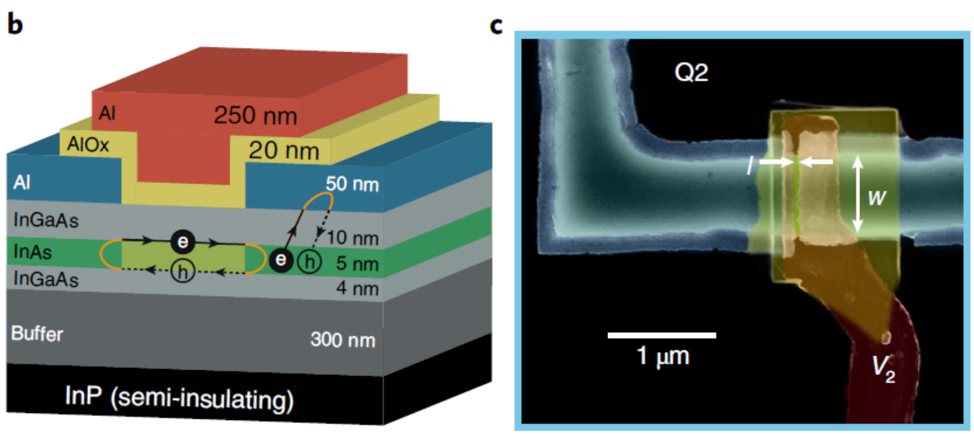
InAs quantum wells

nature nanotechnology
LETTERS
https://doi.org/10.1038/s41565-018-0207-y

2018

Superconducting gatemon qubit based on a proximitized two-dimensional electron gas

Lucas Casparis[1,8], Malcolm R. Connolly[1,8], Morten Kjaergaard[1,7], Natalie J. Pearson[1,2], Anders Kringhøj[1], Thorvald W. Larsen[1], Ferdinand Kuemmeth[1], Tiantian Wang[3,4], Candice Thomas[3,4], Sergei Gronin[4], Geoffrey C. Gardner[4], Michael J. Manfra[3,4,5,6], Charles M. Marcus[1] and Karl D. Petersson[1]*



$T_1 \cong 1\ \mu s$ $T_2^* \cong 400$ ns $T_2^{echo} \cong 2.2\ \mu s$

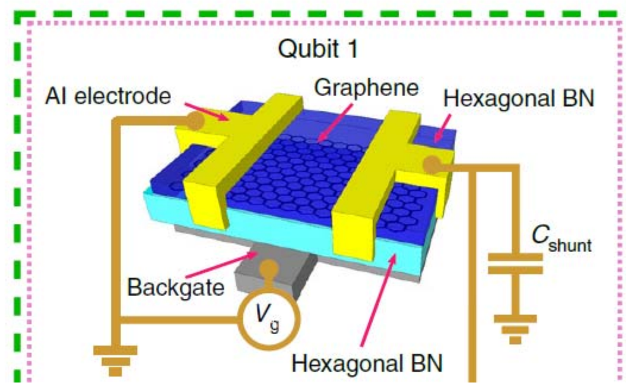
Graphene Gatemon

LETTERS
https://doi.org/10.1038/s41565-018-0329-2
nature nanotechnology

2019

Coherent control of a hybrid superconducting circuit made with graphene-based van der Waals heterostructures

Joel I-Jan Wang[1,7]*, Daniel Rodan-Legrain[2,7], Landry Bretheau[3], Daniel L. Campbell[1], Bharath Kannan[1,4], David Kim[5], Morten Kjaergaard[1], Philip Krantz[1], Gabriel O. Samach[4,5], Fei Yan[1], Jonilyn L. Yoder[5], Kenji Watanabe[6], Takashi Taniguchi[6], Terry P. Orlando[1,4], Simon Gustavsson[1], Pablo Jarillo-Herrero[2]* and William D. Oliver[1,2,5]*



$T_1 \cong 36$ ns
$T_2^* \cong 55$ ns

Previous Gatemon Devices

Carbon Nanotube Gatemon 2021

PHYSICAL REVIEW APPLIED **15**, 064050 (2021)

Circuit Quantum Electrodynamics with Carbon-Nanotube-Based Superconducting Quantum Circuits

Matthias Mergenthaler,[1,2,*,‡] Ani Nersisyan,[1] Andrew Patterson,[1] Martina Esposito,[1] Andreas Baumgartner,[3] Christian Schönenberger,[3] G. Andrew D. Briggs,[2] Edward A. Laird,[4,2] and Peter J. Leek[1,†]

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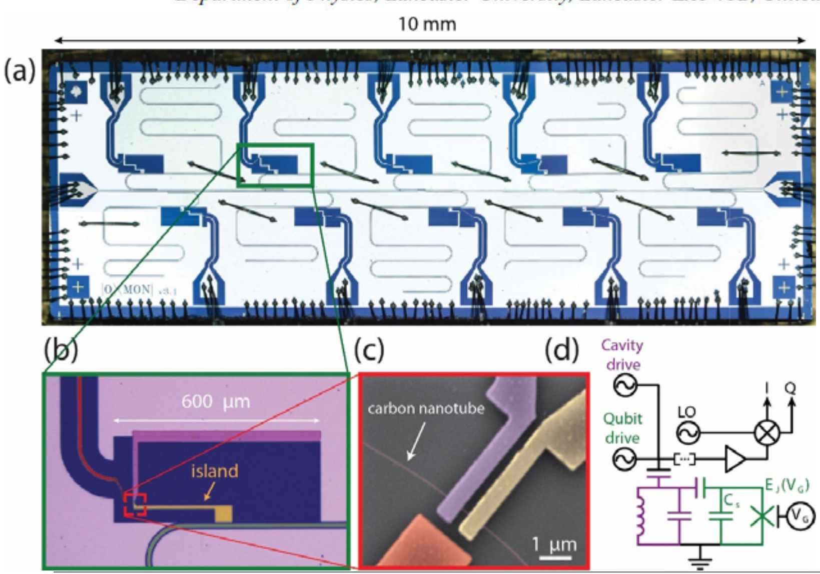
[2] *Department of Materials, University of Oxford, Oxford OX1 3PH, United Kingdom*
[3] *Department of Physics, University of Basel, Klingelbergstrasse 82, Basel CH-4056, Switzerland*
[4] *Department of Physics, Lancaster University, Lancaster LA1 4YB, United Kingdom*



$T_1 < 200$ ns

$T_2' \cong 10$ ns

(linewidth)

Two examples of type-IV materials (graphene and CNT) for hybrid super-semi Josephson junctions (JJs).

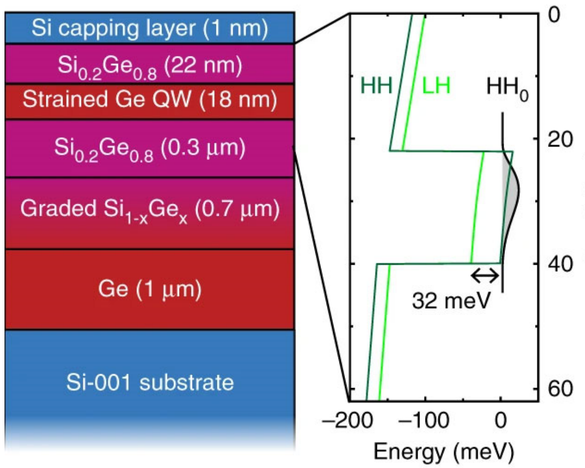
What about **Silicon** and **Germanium**?

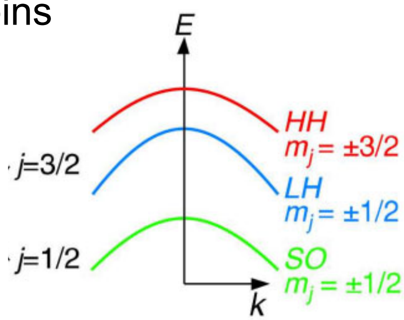
Type-IV semiconductors

Scappucci and Veldhorst et al.
Gate-controlled quantum dots and superconductivity in planar ***germanium:*** Nature Comm. 9;2835 (2018)

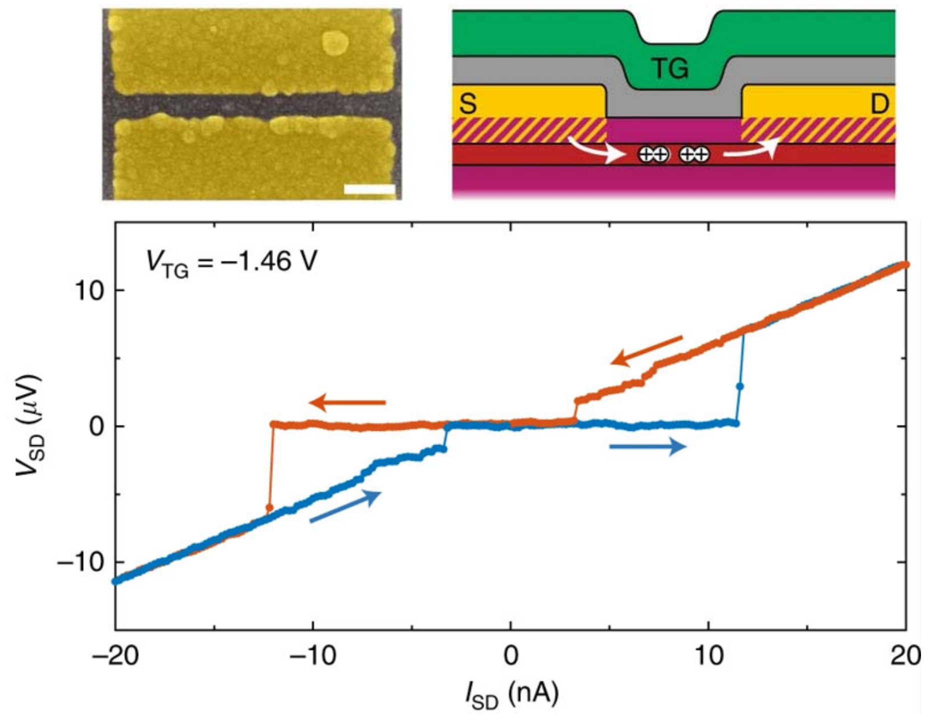
<u>**Germanium**</u>:

- highest hole mobility $> 1 \cdot 10^6\ cm^2/Vs$
- no valley structure (a single band maximum)
- strained
- gate-tunable large spin-orbit interaction
- very low coupling to nuclear spins





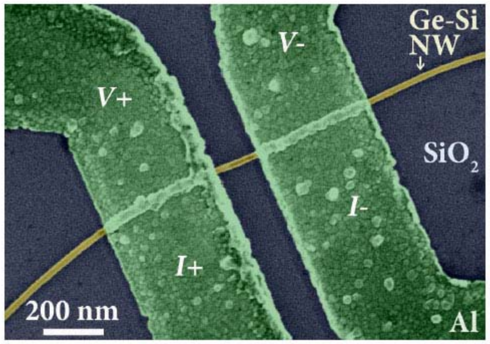
induced superconductivity through Al contacts



but, in this early results the $I_c \cdot R_N$ product was way lower than the ideal ballistic limit of:
$I_c = e\Delta/\hbar$ (per channel) -→ $I_c \cdot R_N = \pi\Delta/e$

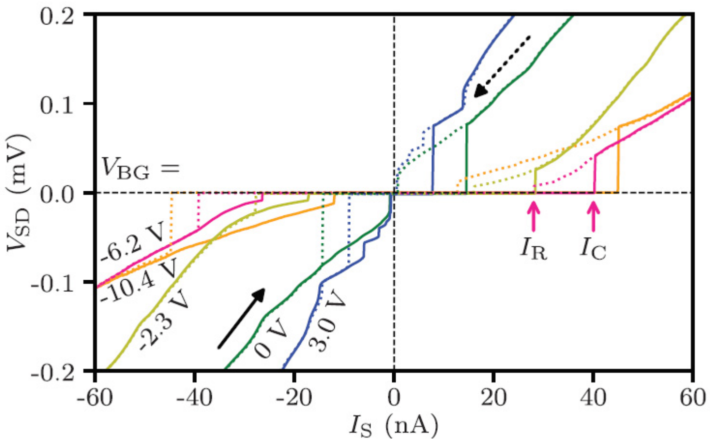
Germanium Josephson FET

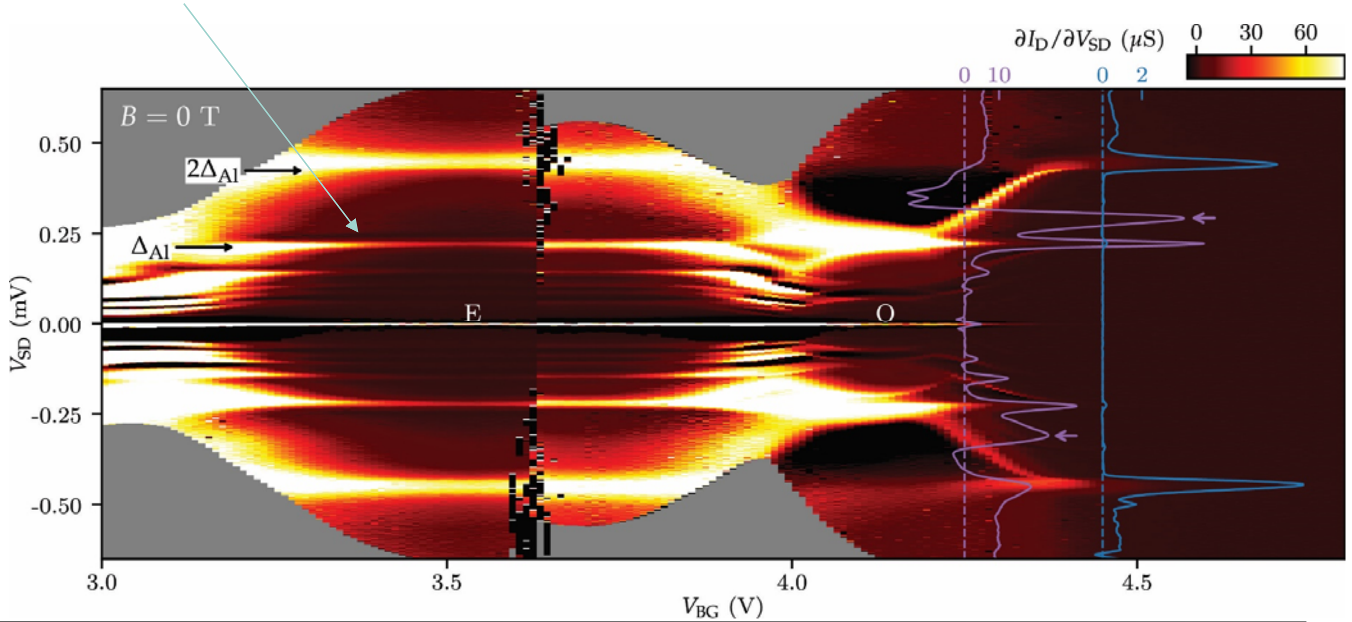
Josephson Effect in a Few-Hole Quantum Dot
Joost Ridderbos et al. Adv. Mat. 30: 1802257 (2018) & Nano Lett. 20: 122 (2020)



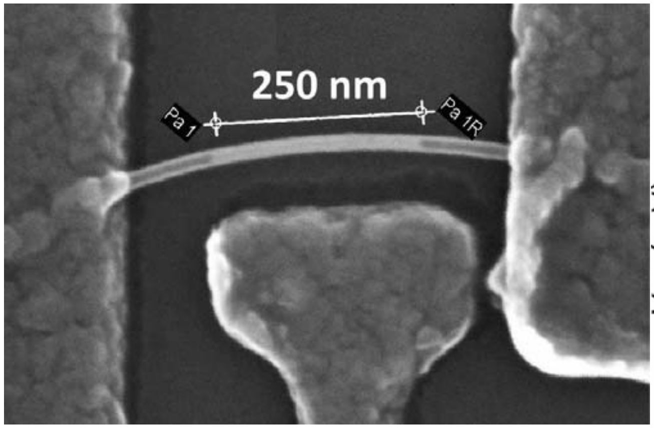
GeSi core-shell nanowires (from TUE, E. Bakker's group)

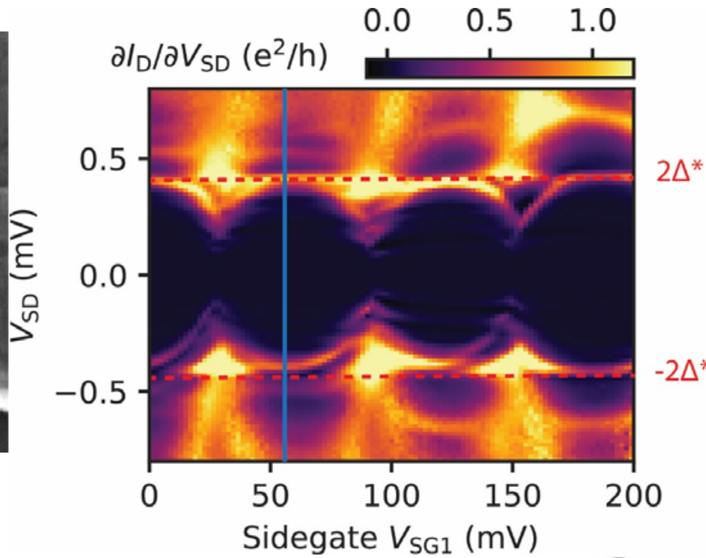
- large $I_c \cdot R_N$ product of order $200\ \mu eV$
- hard gap in tunnelling regime
- **multiple Andreev reflection** (MAR) at larger transmission probability

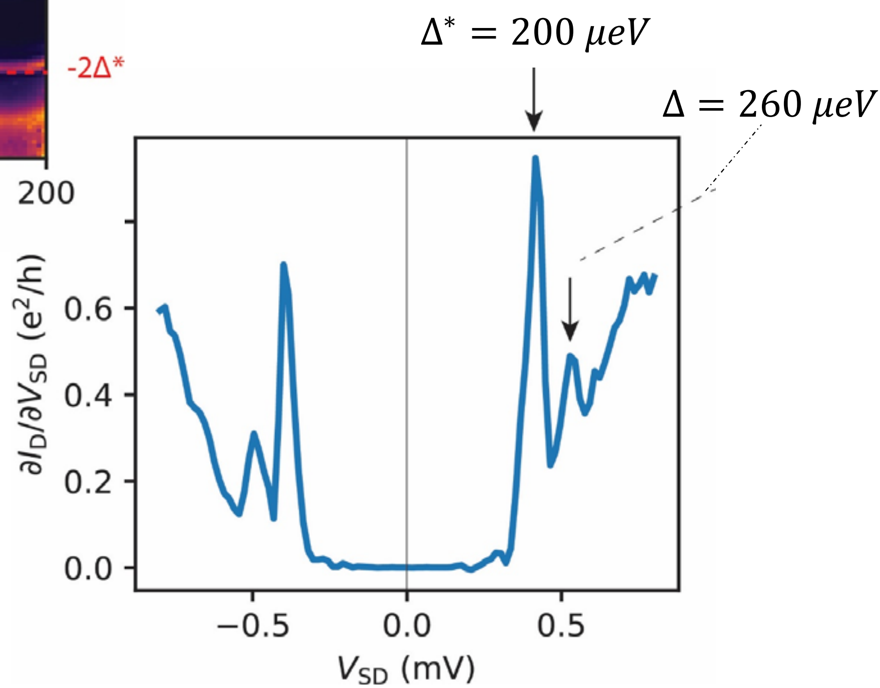




Germanium Josephson FET

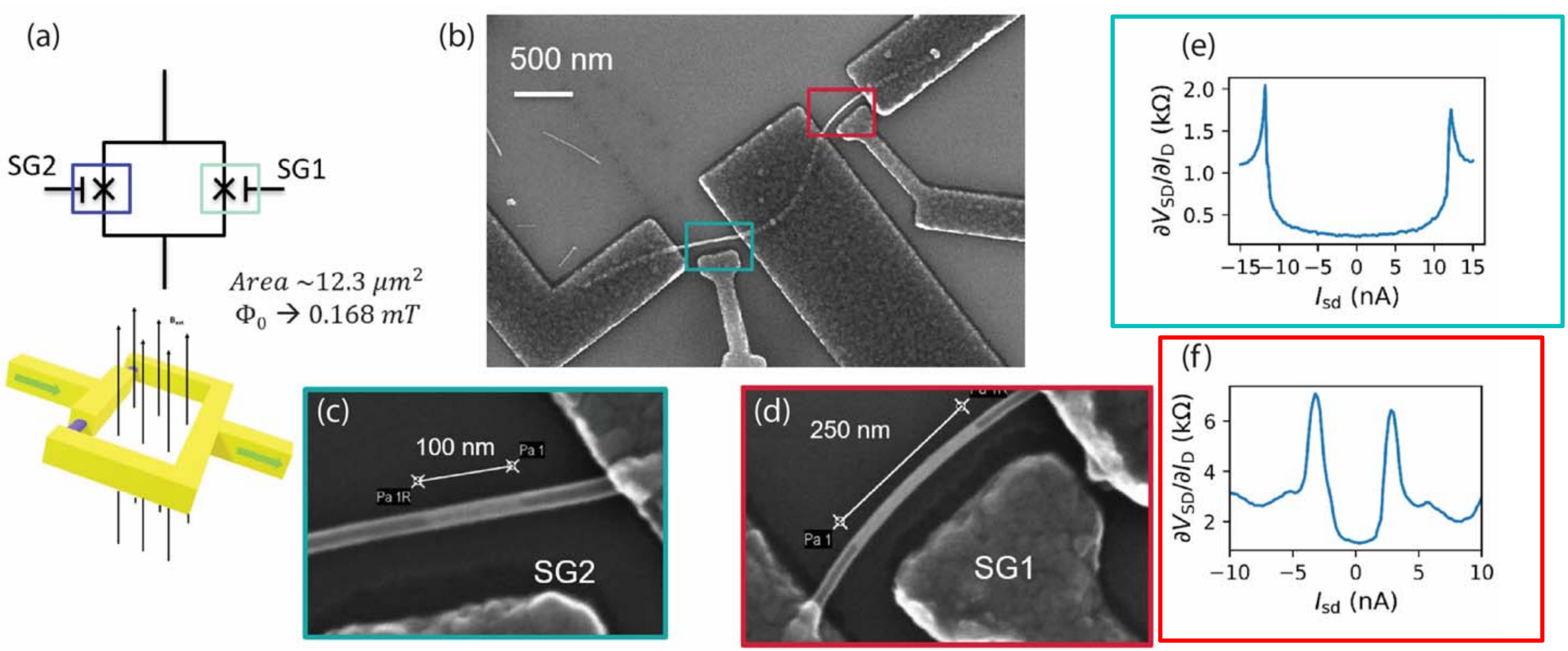






Han Zheng, Tom Jennisken, J. Ridderbos (unpublished)

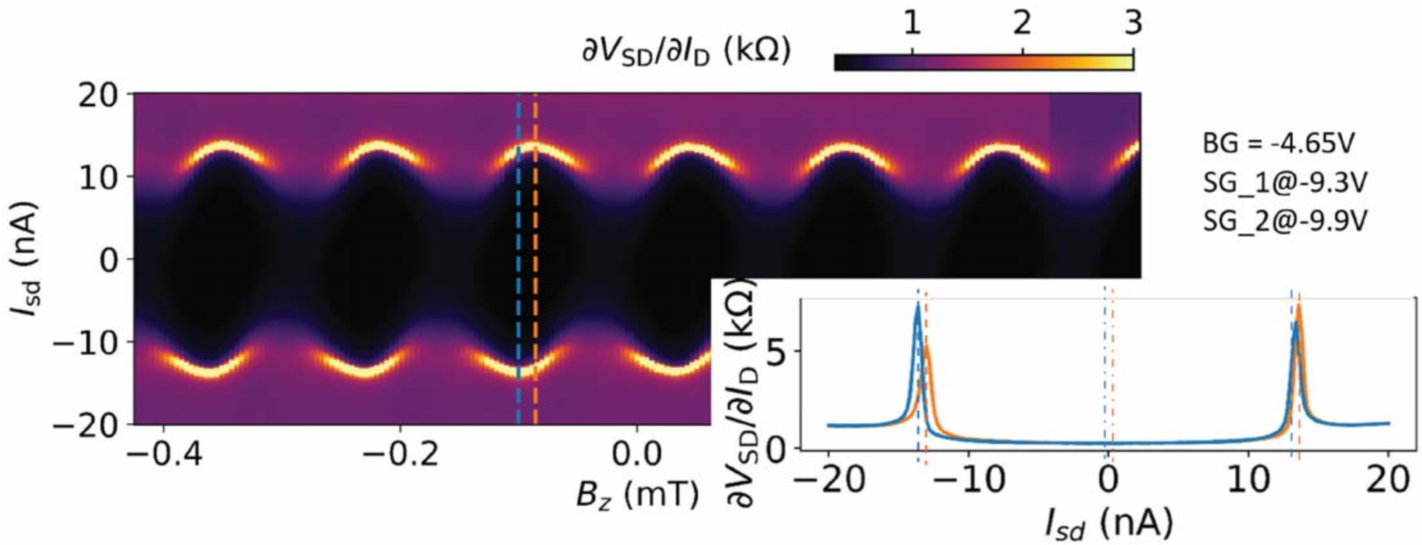
Germanium Josephson FET



Han Zheng, Tom Jennisken, J. Ridderbos (unpublished)

Current-Phase Relation of a GeSi core-shell nanowire JJ

In an **asymmetric SQUID** with a **strong reference JJ** having at least 10 times higher critical current, one can obtain the **CPR of the weaker junction** by measuring the critical current of the SQUID as a function of flux through the SQUID loop.



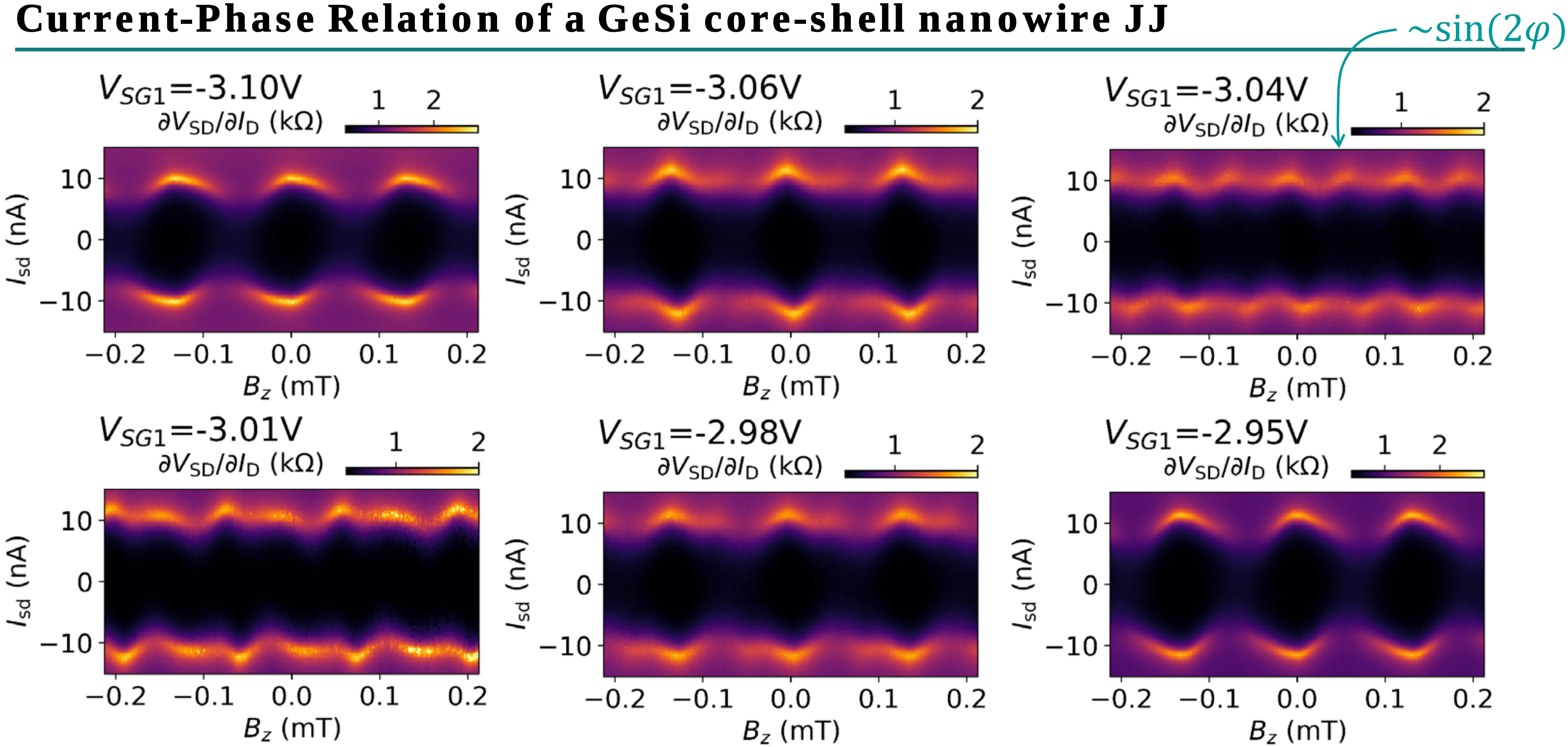
observe:

- non-sinusoidal CPR (indication of transparent JJ)
- diode effect (also caused by non-sinusoidal character)
- good tunability of supercurrent

Diode effect due to non-sinusoidal CPR. See: C. Ciaccia et al. (Schönenberger group), Phys. Rev. Research 5, 33131 (2023) and see also M. Valentini et al. (Katsaros' group) arXiv:2306.07109.

Han Zheng, Tom Jennisken, J. Ridderbos (unpublished)

Current-Phase Relation of a GeSi core-shell nanowire JJ



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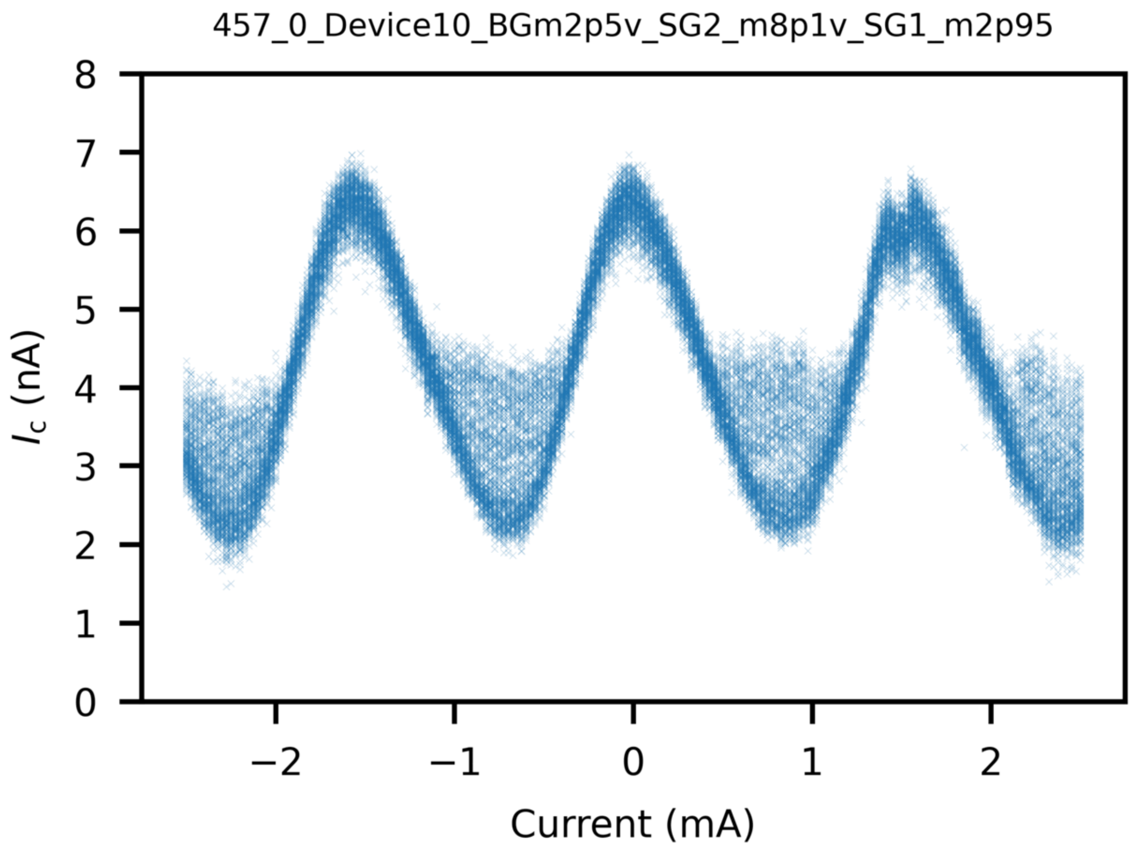
Current-Phase Relation of a GeSi core-shell nanowire JJ



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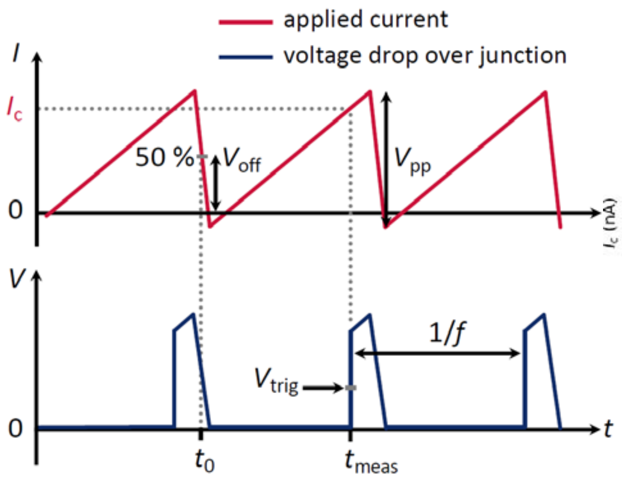
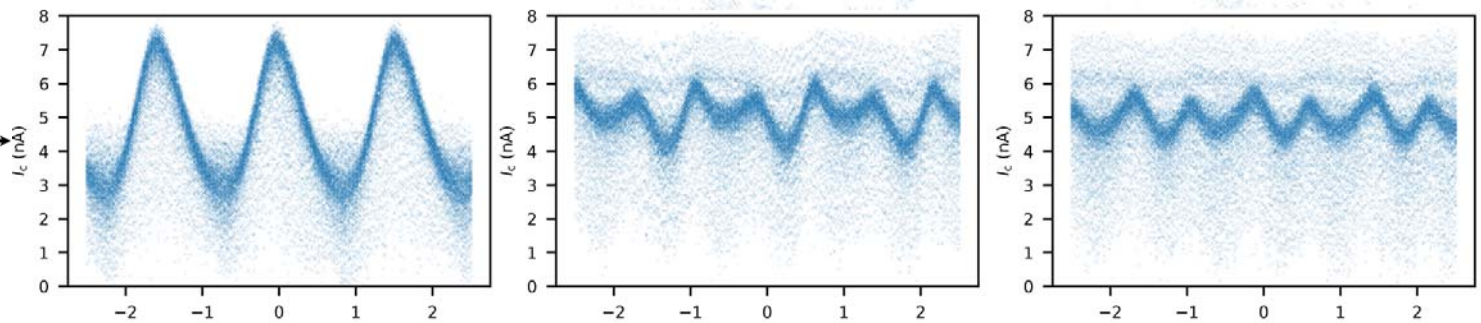
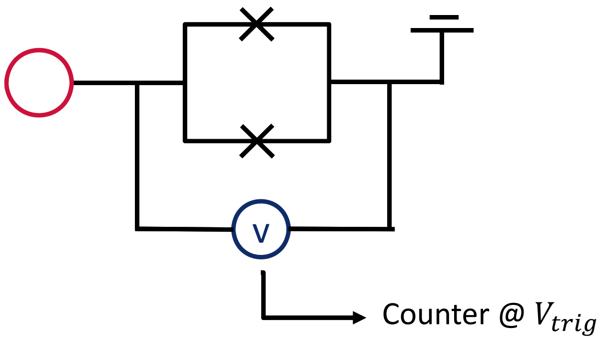
Current-Phase Relation of a GeSi core-shell nanowire JJ





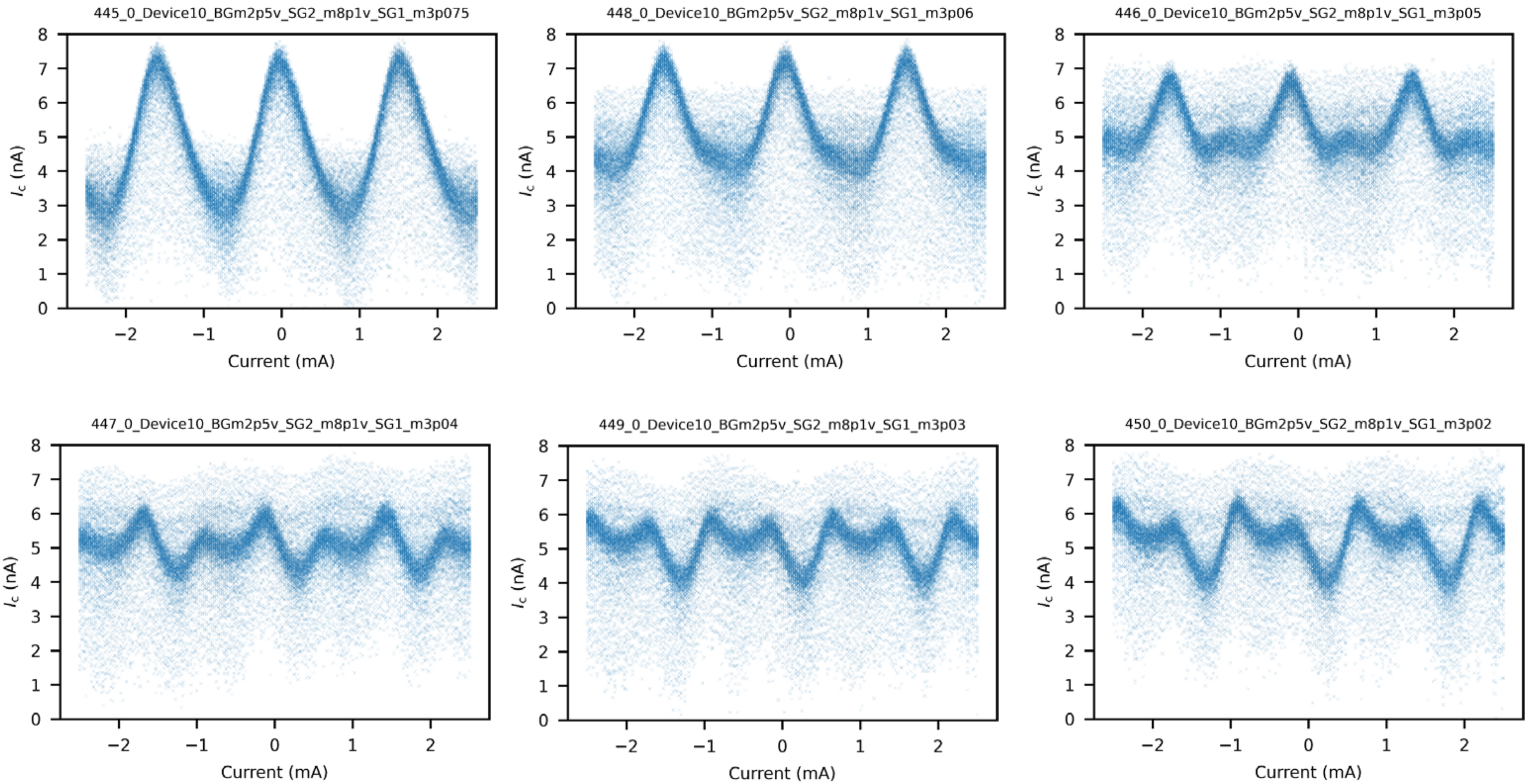
The **anomalous CPR** is also seen in a dynamic experiment, where the current is periodically swept up and down

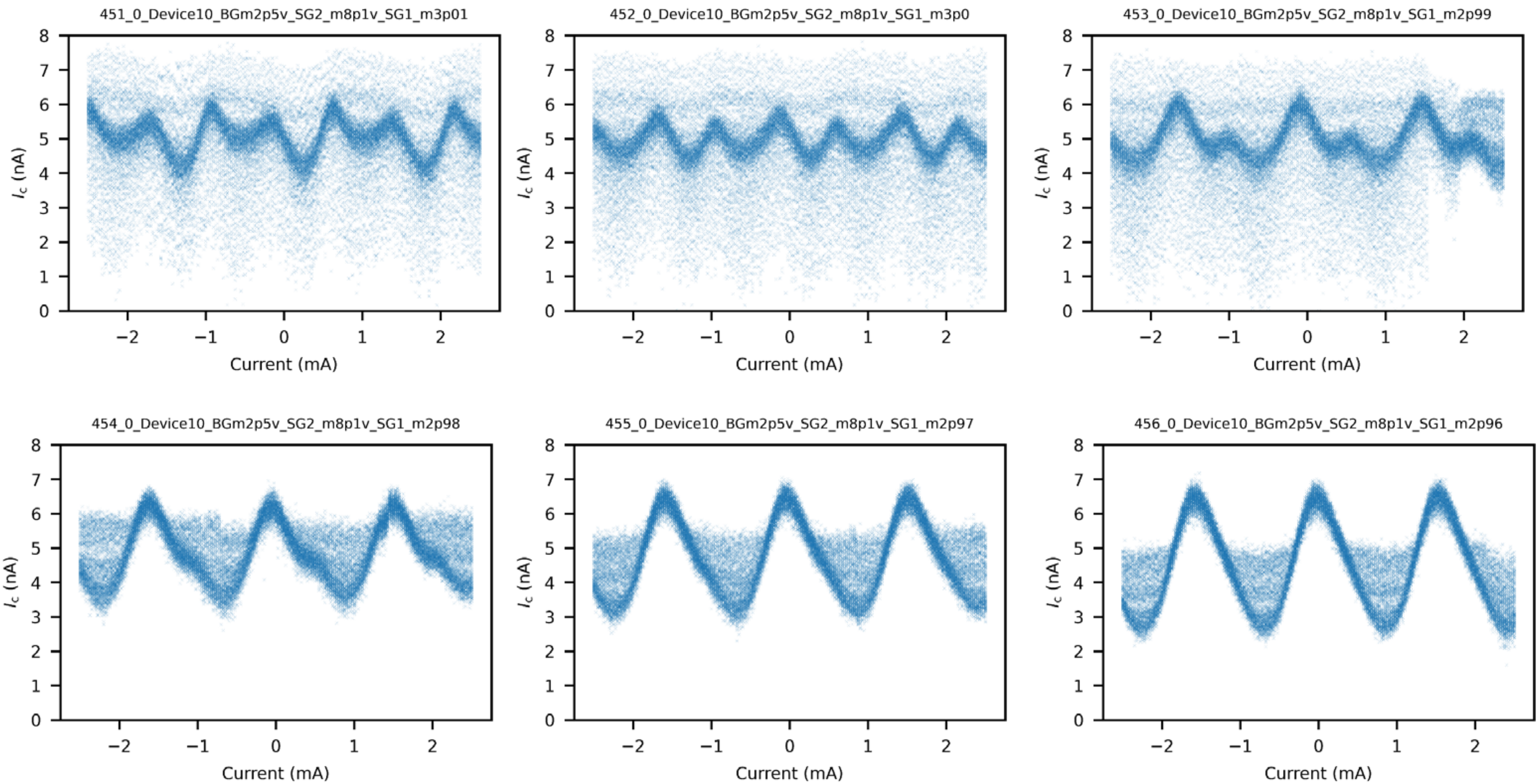


Origin:

1. Spin-orbit effect combined with magnetic field
2. Interference of the supercurrent of two Andreev-bound states for which the fundamental $\sin(\varphi)$ contributions cancel each other (has application for a parity protected qubit)

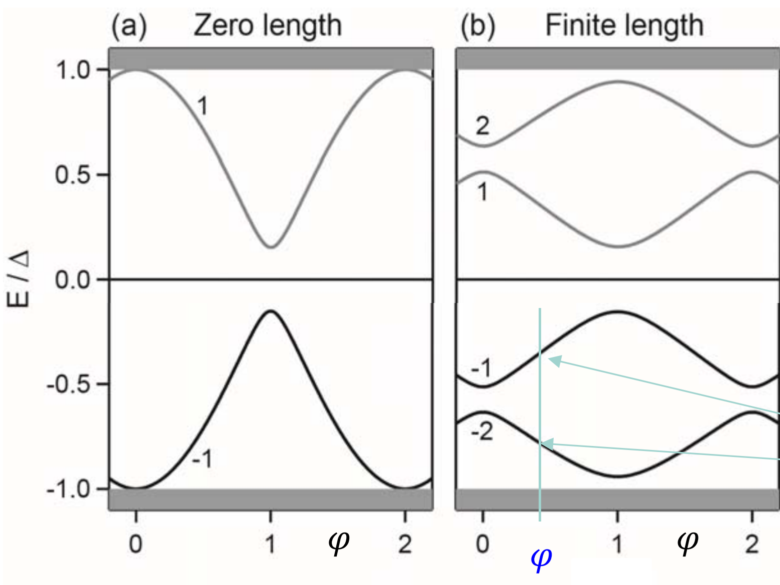
Han Zheng, Tom Jennisken, J. Ridderbos (unpublished)


445_0_Device10_BGm2p5v_SG2_m8p1v_SG1_m3p075
448_0_Device10_BGm2p5v_SG2_m8p1v_SG1_m3p06
446_0_Device10_BGm2p5v_SG2_m8p1v_SG1_m3p05
447_0_Device10_BGm2p5v_SG2_m8p1v_SG1_m3p04
449_0_Device10_BGm2p5v_SG2_m8p1v_SG1_m3p03
450_0_Device10_BGm2p5v_SG2_m8p1v_SG1_m3p02
I_c (nA)
Current (mA)


451_0_Device10_BGm2p5v_SG2_m8p1v_SG1_m3p01
452_0_Device10_BGm2p5v_SG2_m8p1v_SG1_m3p0
453_0_Device10_BGm2p5v_SG2_m8p1v_SG1_m2p99
454_0_Device10_BGm2p5v_SG2_m8p1v_SG1_m2p98
455_0_Device10_BGm2p5v_SG2_m8p1v_SG1_m2p97
456_0_Device10_BGm2p5v_SG2_m8p1v_SG1_m2p96
I_c (nA)
Current (mA)

Current-Phase Relation of a GeSi core-shell nanowire JJ

$\sim \sin(2\varphi)$ junction ?



short JJ, **one ABS** longer JJ, **two ABS**

$$I(\varphi) = \frac{2\pi}{\Phi_0}\frac{\partial E(\varphi)}{\partial \varphi}$$

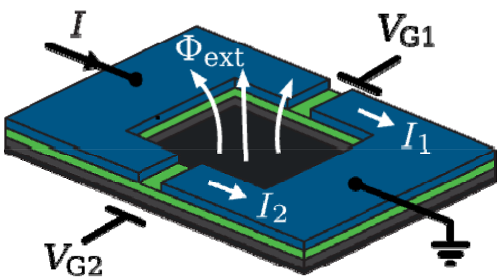
opposite slope → partial cancelation of supercurrent*

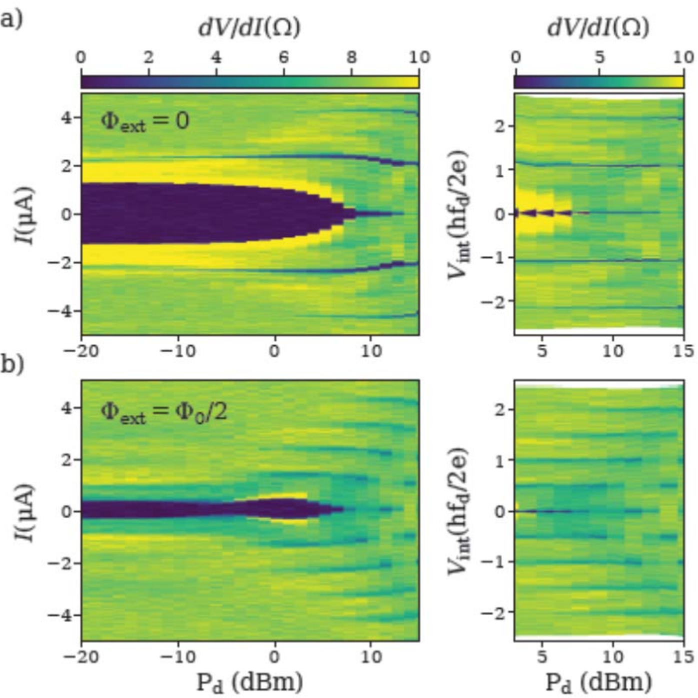
Hence, it can happen that the fundamental contributions $\sin(\varphi)$ of the two ABSs cancel each other. The 1st non-zero harmonics would then follow $\sin(2\varphi)$ → $\mathbf{sin(2\varphi)}$ **junction**

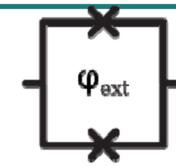
*idea by Jelena Klinovaja

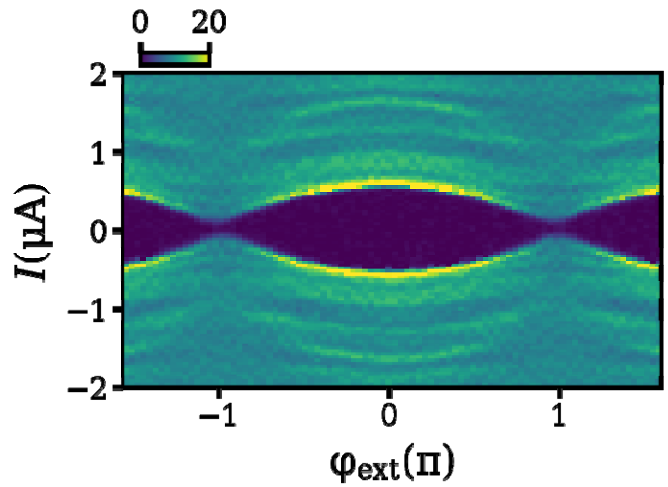
Han Zheng, Tom Jennisken, J. Ridderbos (unpublished)

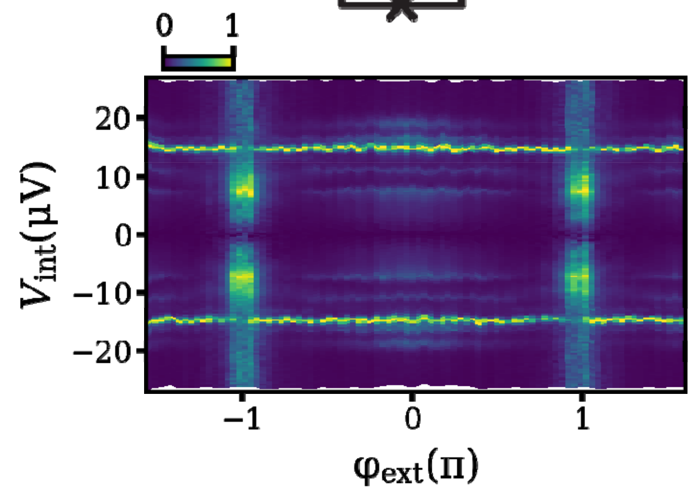
Engineering a cos(2phi) junction with a SQUID

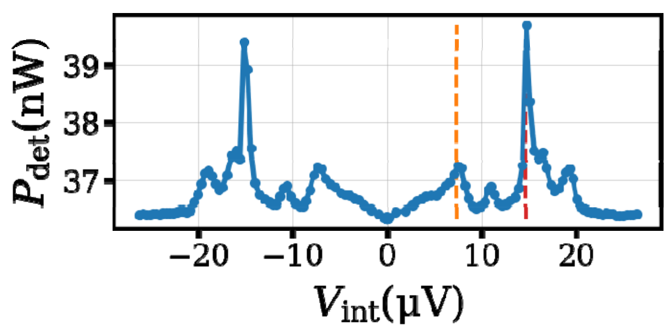


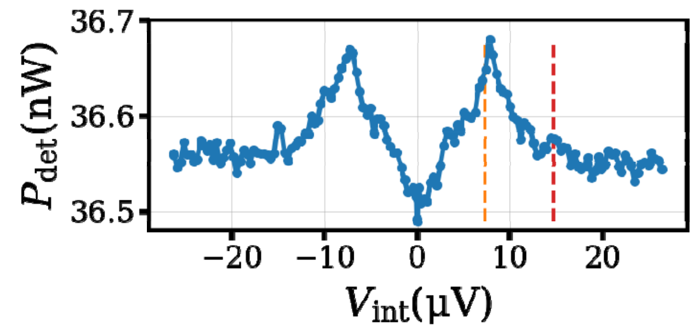




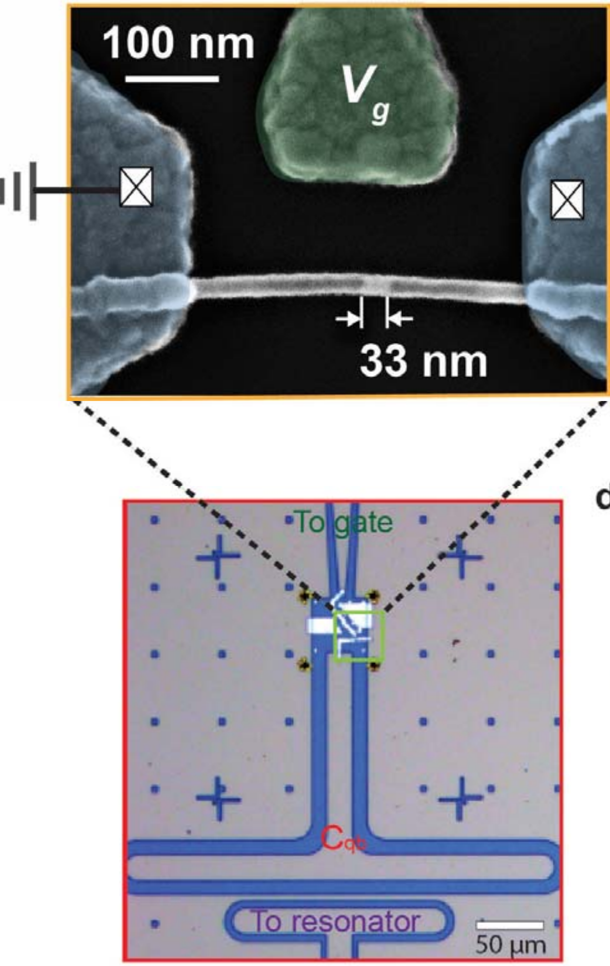


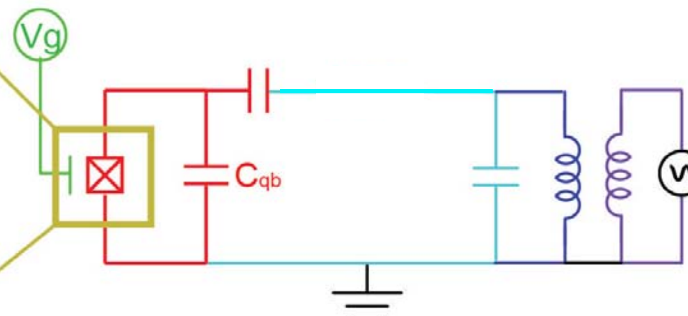




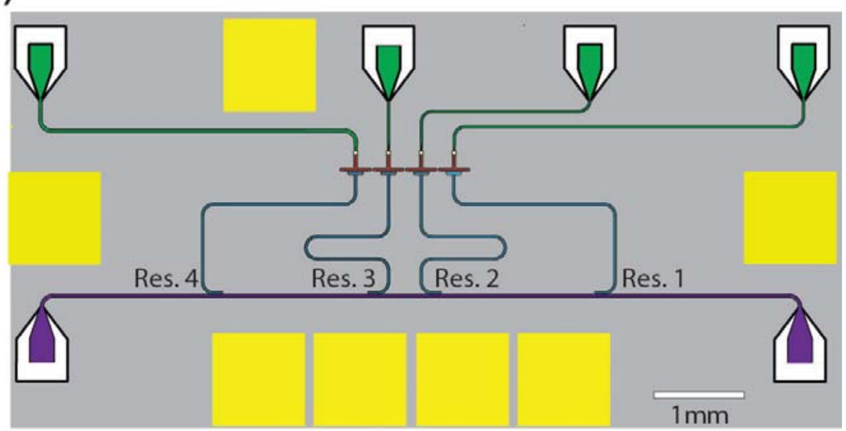


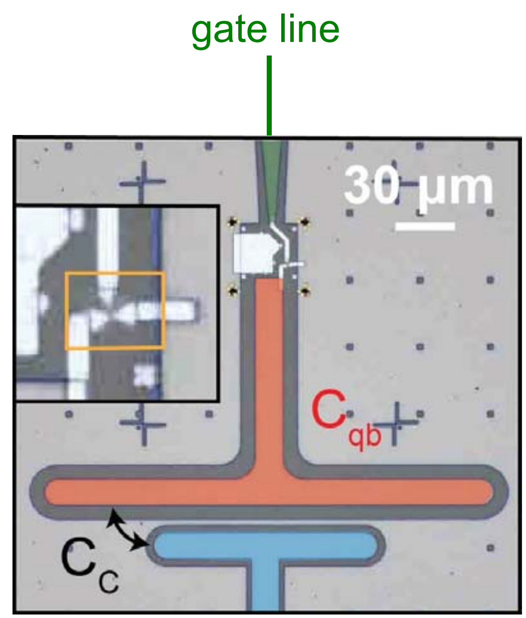
GeSi core-shell nanowire Gatemon





d)

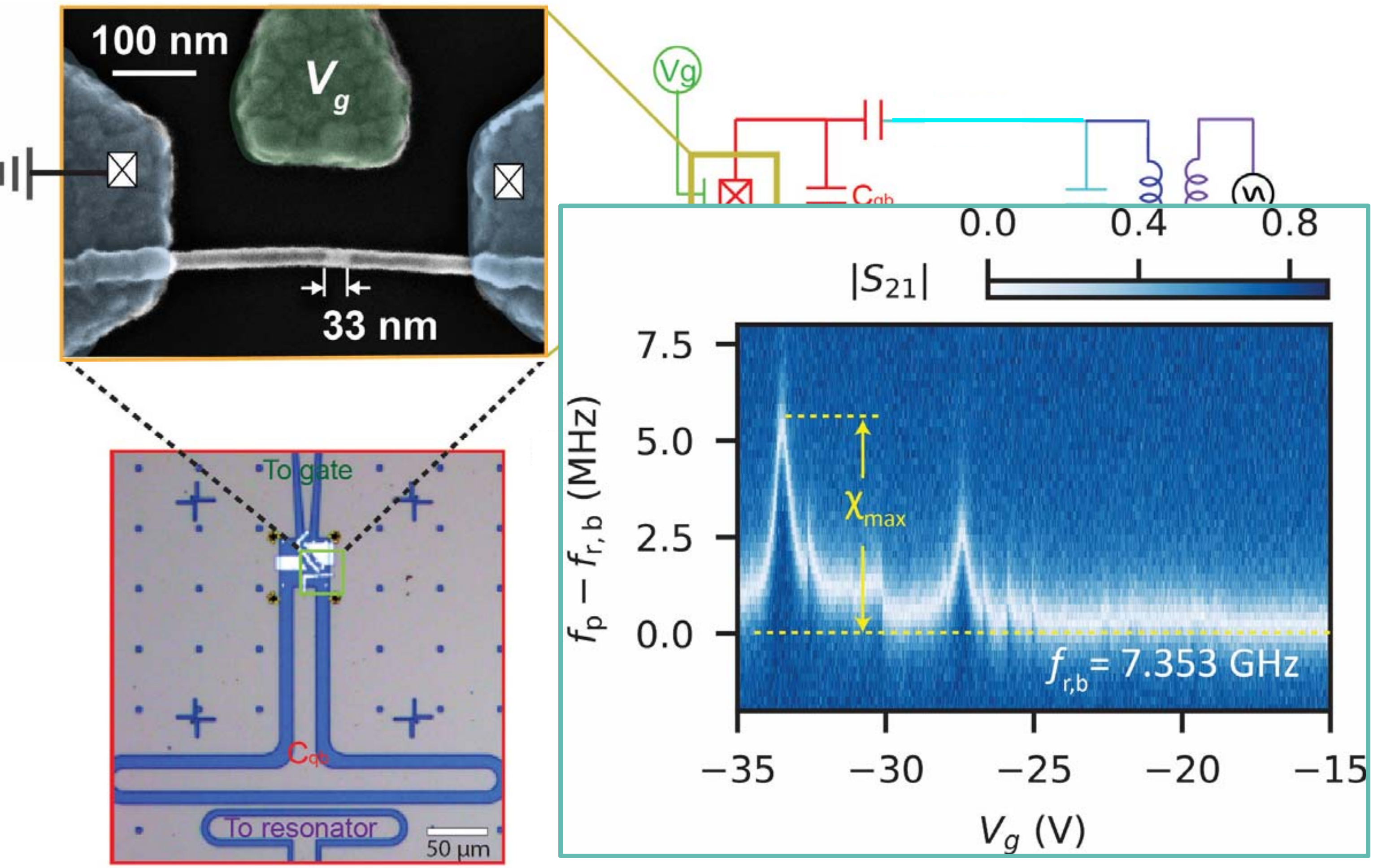


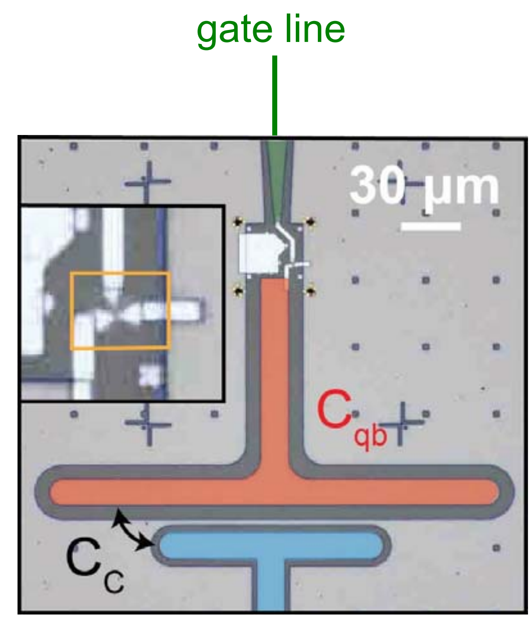


resonator $Q_i > 100'000$ and $Q_c \approx 6'000$

Han Zheng et al. arXiv:2312.06411

GeSi core-shell nanowire Gatemon





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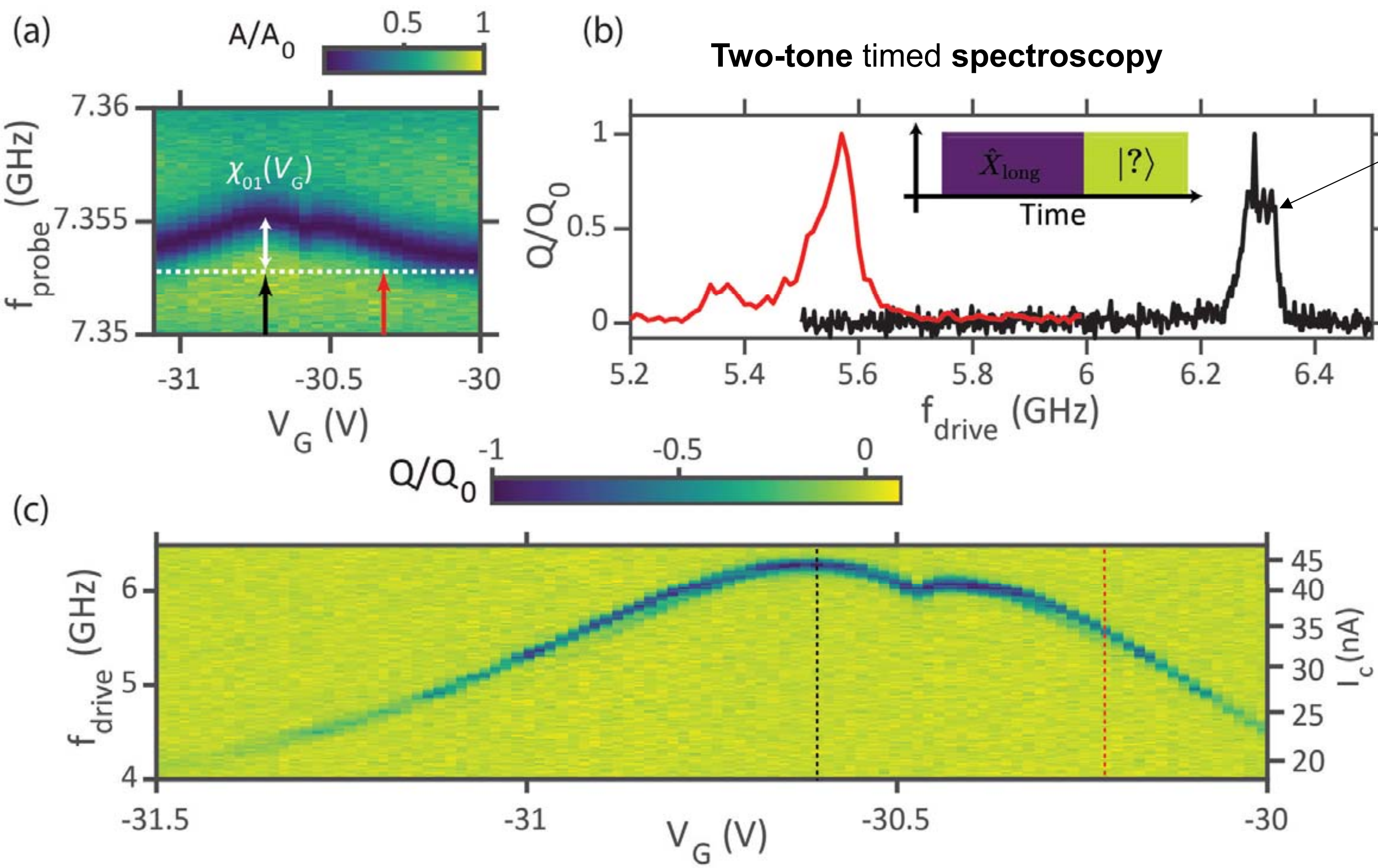
GeSi core-shell nanowire Gatemon



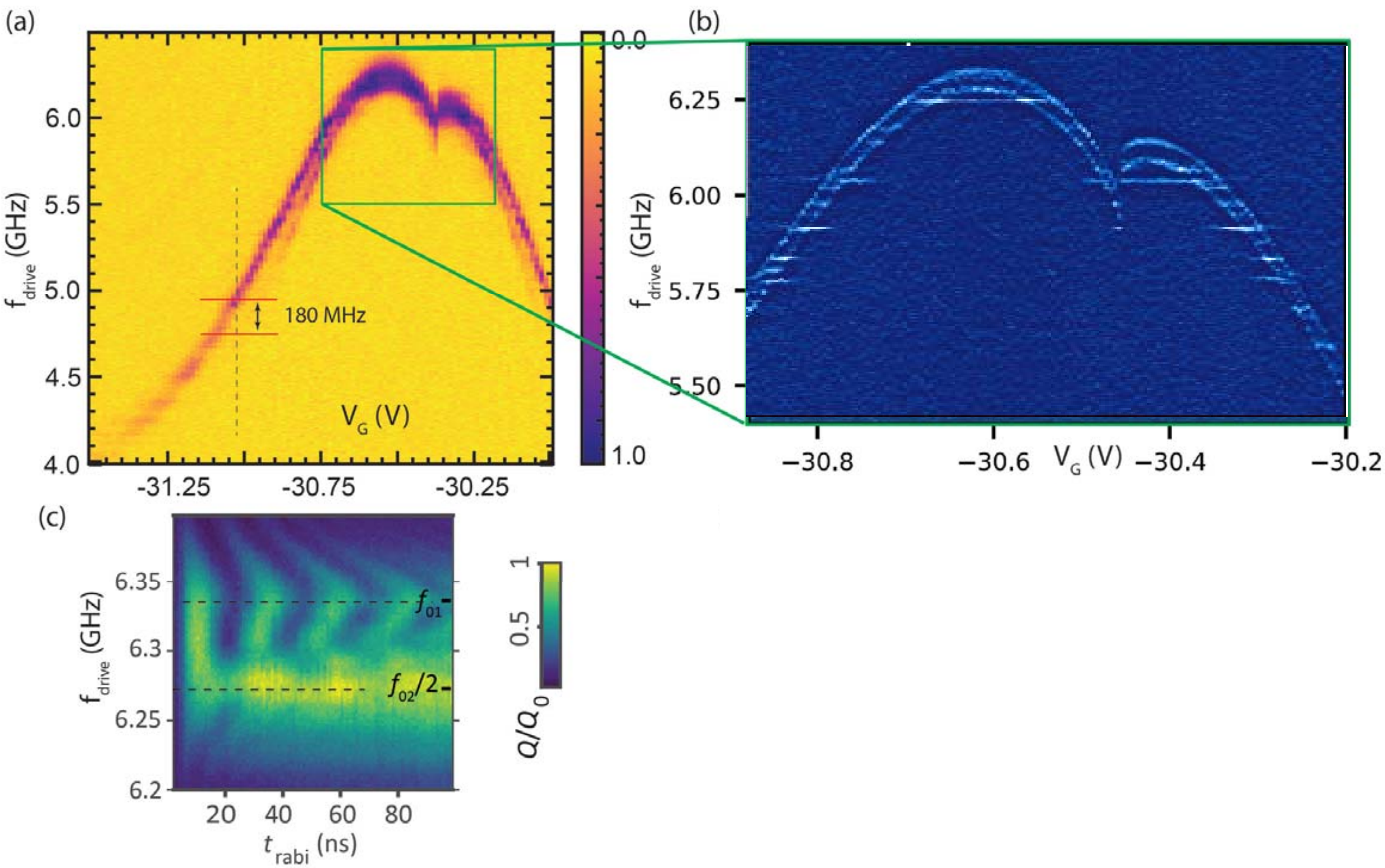
not a single Lorentzian

from dispersive shift χ and detuning we obtain:

$g/2\pi \cong 47$ MHz

Han Zheng et al. arXiv:2312.06411

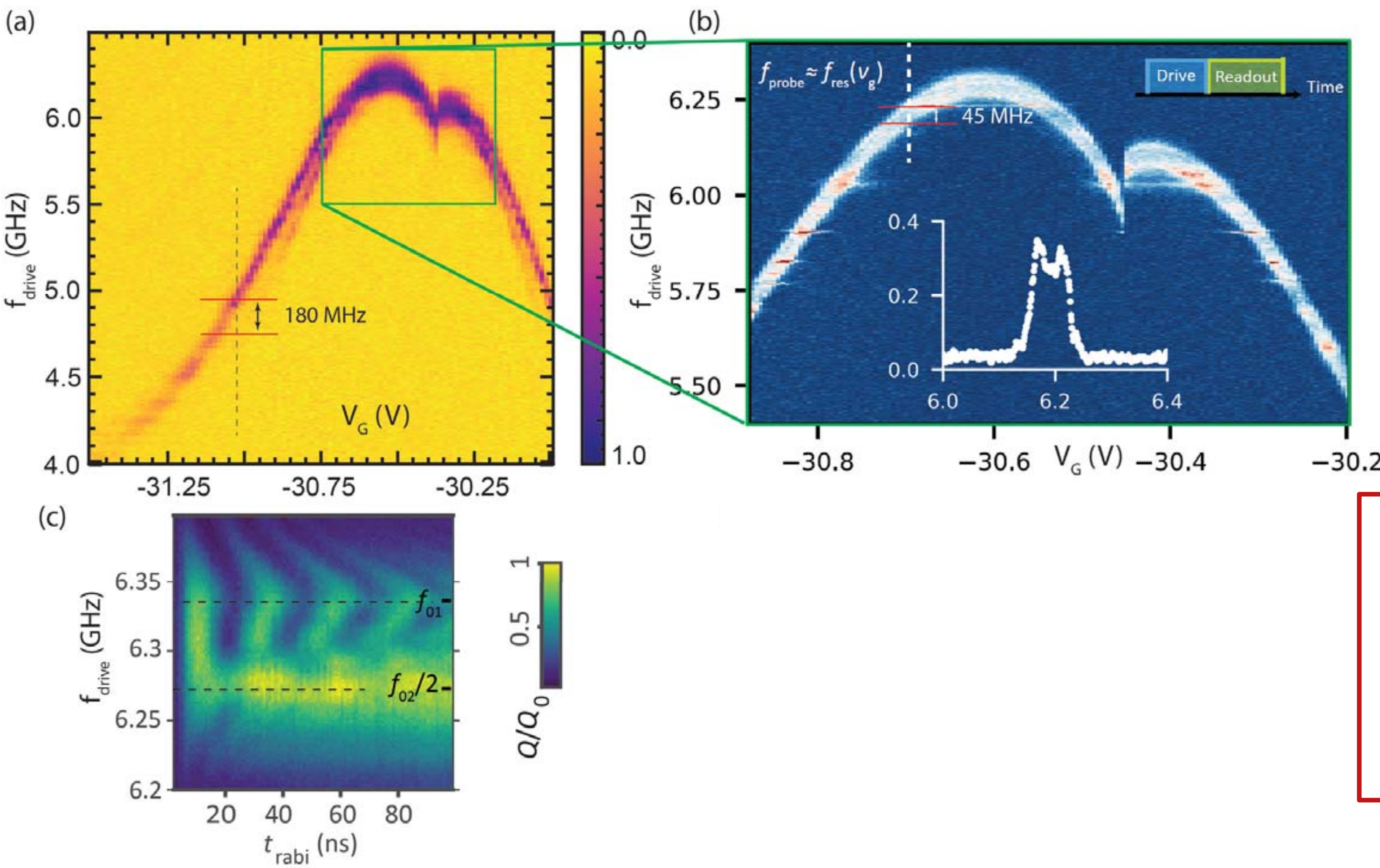
GeSi core-shell nanowire Gatemon



Extracted the **anharmonicity** α from second peak in **two-tone spectroscopy**; supported by additional signal in Rabi measurements

Han Zheng et al. arXiv:2312.06411

GeSi core-shell nanowire Gatemon



Extracted the **anharmonicity α** from second peak in **two-tone spectroscopy**; supported by additional signal in Rabi measurements

Using measured values of f_q and α, we can make some predictions, shown in (d):

Josephson junction is in the QPC limit with N=2 channel of which one channel has (close to) unit transmission

Han Zheng et al. arXiv:2312.06411

GeSi core-shell nanowire Gatemon

A. Kringhoj et al., Anharmonicity of a superconducting qubit with a few-mode Josephson junction, Phys. Rev. B 97, 060508 (2018).

Effective Hamiltonian *PRB* **97**, 060508(R) (2018)

JJ potential in short-junction limit

$$\hat{H} = 4E_C\hat{n}^2 + \sum_i \Delta\sqrt{1 - T_i \sin^2(\hat{\varphi}/2)}$$

$$(f_{12} - f_{01})/h = \alpha \approx -E_C\left(1 - \frac{3\sum_i T_i^2}{4\sum_i T_i}\right)$$

simulation → $E_C/h \cong 250\ MHz$

$$hf_{01} \cong \sqrt{8E_C E_J}$$

$$E_J = \frac{\Delta}{4}\Sigma T_i$$

experiment yields f_{01} (and α)

from E_J one gets $\sum T_i$

N=2

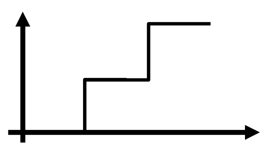
N=3

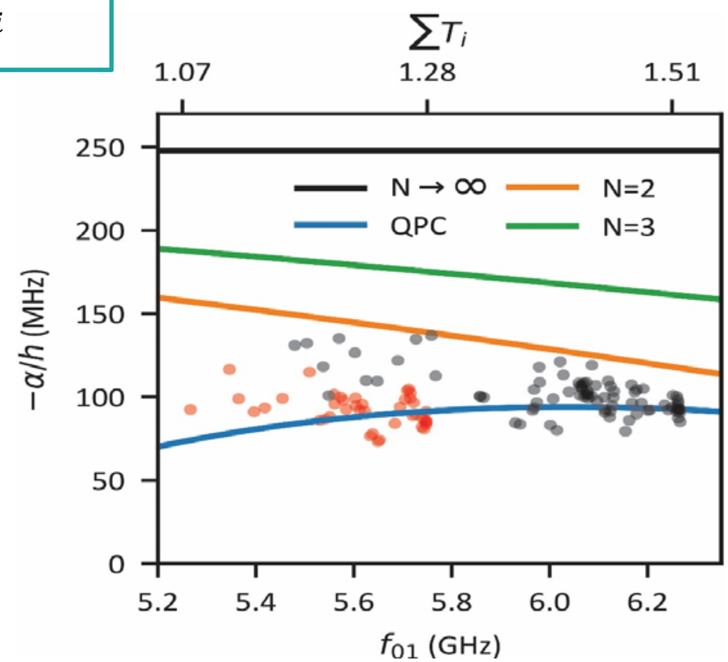
Assuming N channels with equal transmission:

$$E_J = \frac{\Delta}{4}N \cdot \bar{T}$$

QPC

Assuming steplike channels:

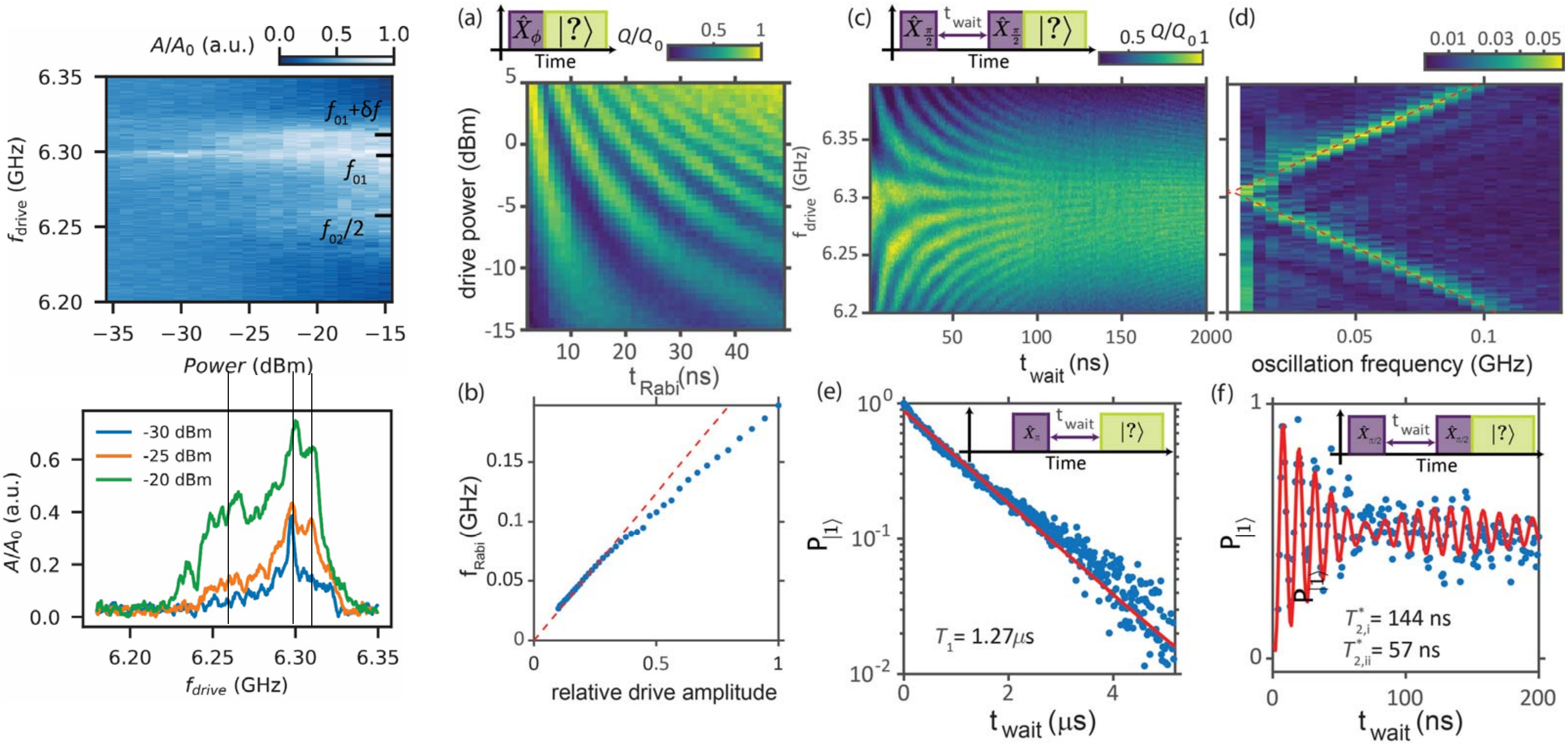




conventional transmon Low transparent many channels ⟷ Ge/Si NW gatemon High transparent 1-2 channels

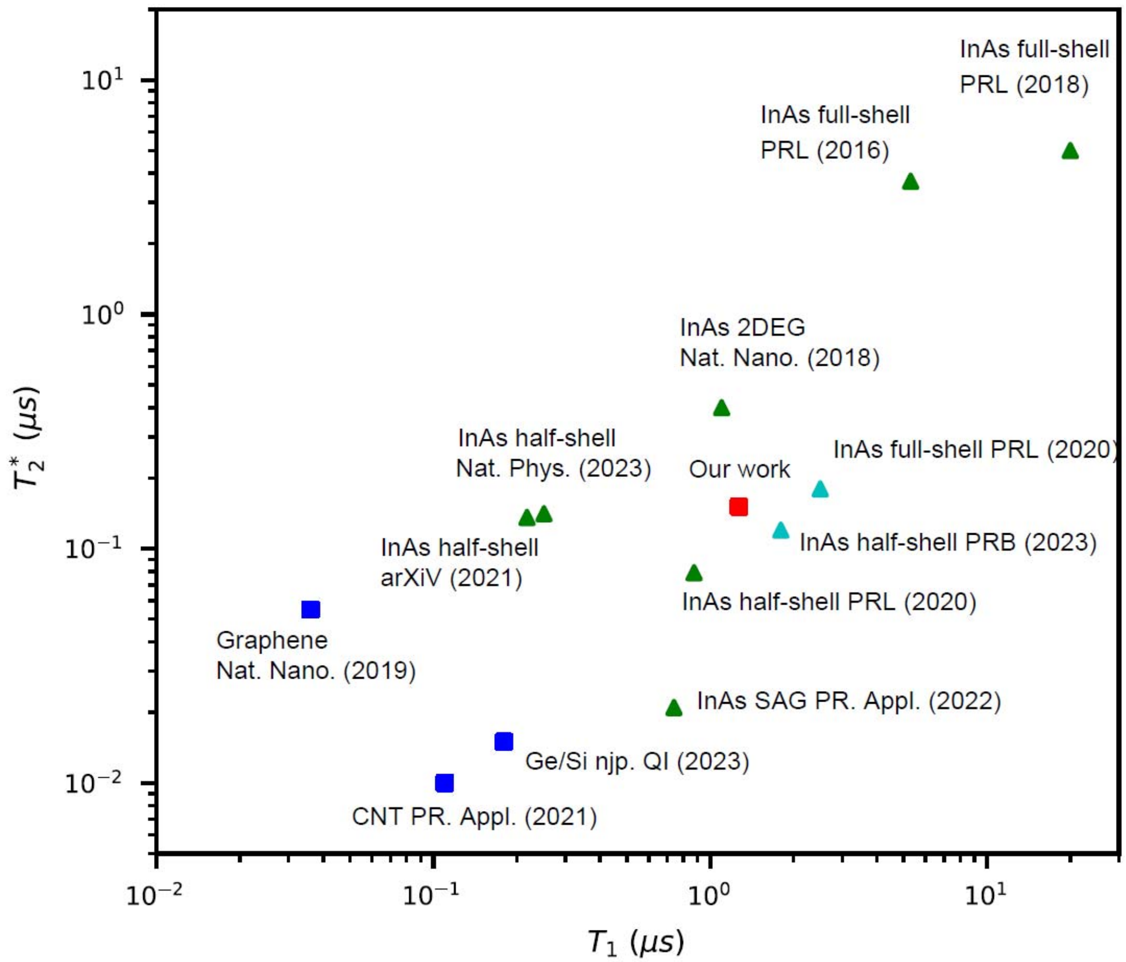
Han Zheng et al. arXiv:2312.06411

GeSi core-shell nanowire Gatemon



Han Zheng et al. arXiv:2312.06411

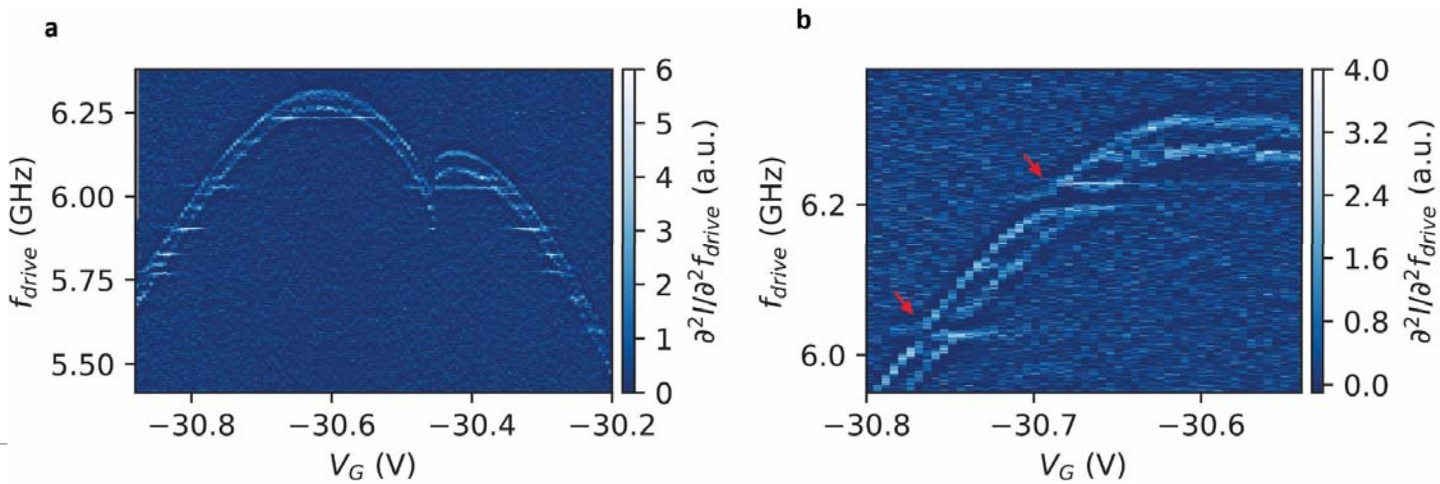
GeSi core-shell nanowire Gatemon



GeSi core-shell nanowire Gatemon

Conclusions:

- gatemon in short strained Ge channel
- at most 2 channels (most likely one that dominates the physics)
- interface from **Al to Ge channel is highly transmissive**
- up to a factor four **reduced anharmonicity**
- relaxation and coherence comparable to state-of-the-art III-V gatemons
- **ideal for Andreev spin qubits**
- two-level fluctuators; needs cleaner processing and etching of Si-oxide



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Thank you

for your attention.