Title: Synthesis of many-body quantum states using group-IV (Ge/Si) quantum devices

Speakers: Joe Salfi

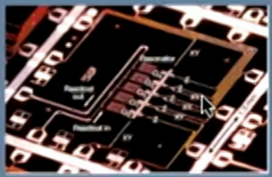
Collection: Quantum Matter Workshop

Date: November 15, 2022 - 11:30 AM

URL: https://pirsa.org/22110071

Abstract: Quantum dot arrays are an emerging system to synthesize controlled many-body quantum states for quantum simulation and computation. When cooled to a low temperature, each quantum dot acts as a site on which the number of half-integer spin particles can be controlled using voltages applied to gates, not unlike the gates on classical transistors. Moreover, the spin can be controlled and measured with the help of patterns of gates. It has recently been shown that tunnel couplings between individual sites can be controlled using the same gates to emulate a Hubbard model (unlike other systems i.e., superconductors, trapped ions, Rydberg atoms, etc), making it possible to program a many-body system using only voltages applied to gates, and that the spin can be initialized, controlled and read out on arrays of 4 to 6 quantum dots like a conventional quantum computer (unlike cold atoms in optical lattices). It has also recently been shown that the coherence times of the spin degree of freedom can be as long as 10 ms in this material system, and that the quantum dots can be proximized to superconductors. In this talk I will describe our efforts towards synthesis of interesting quantum states using this platform, at our lab in University of British Columbia.

Spin Qubits in Quantum Dots: Emerging Few-Body Quantum System

	Ion trap	Superconducting	Spins Qubits
			
Coherence	✓	Noisey	✓
Qubit type	Spin	Anharmonic oscillator	Spinful Fermion
Number of Qubits	44 [1]	53 [2]	6 [3]
Qubit area A	(1 mm)^2	(1 mm)^2	< (1 um)^2

[1] Pagano QST 2018 [2] Arute Nature 2019 [3] Philips Nature 2022

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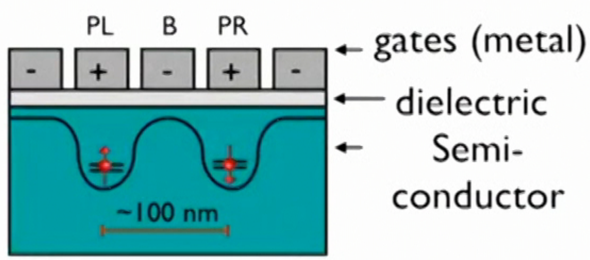
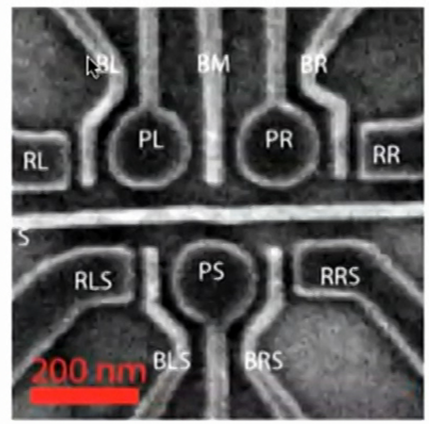
Quantum Dots

Key Idea

- Confine individual carriers in a material
- Accomplished by applying voltages to gates near a reservoir





SEM Image of hole spin qubit device from UBC Nanofab

Spin based quantum computation in QD

Proposal: Loss & DiVincenzo 1998

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Quantum Dots

Frozen out orbital excitation

- No excitation to higher orbitals
- $\delta_s \sim 1$ to 10 meV (QD size dependent)

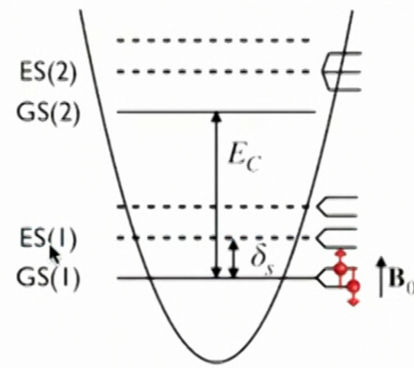
Can freeze out electron number fluctuations

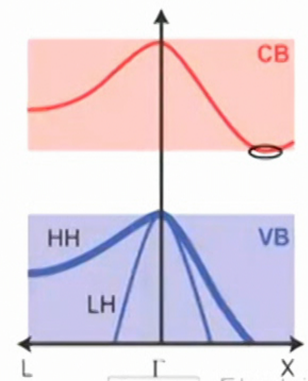
- $E_C = e^2/2C_\Sigma + \delta_s \approx 5$ to 50 meV
- Can control charge # (1,2,3,…)

Applied magnetic field

Takes properties of solid host

- e.g., band
  - CB electrons (S=1/2), VB holes (J=3/2)
- e.g., bath
  - Nuclear bath, phonons, etc





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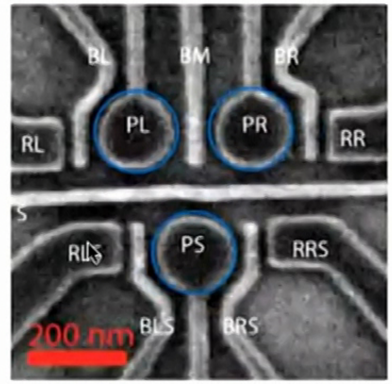
QD Array as Analog Fermionic Simulator

Fermions

- Spin-1/2 particles on a lattice
- Experimental knobs
  - Tunnel couplings t_{ij}, energy levels ϵ_i
  - Tuned by voltages $V_{PL}, V_{BM}, V_{BR}, \dots$
- Fabrication control
  - On-site (U_i) Coulomb repulsion
  - Nearest-neighbour (W_{ij}) Coulomb repulsion
- Note: control coupling to reservoirs
  - $V_{BL}, V_{BR}, V_{BLS}, V_{BRS}$



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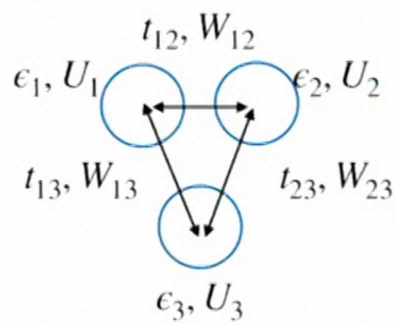

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9:41 AM Tue Jan 9 Salfi_PI 100%

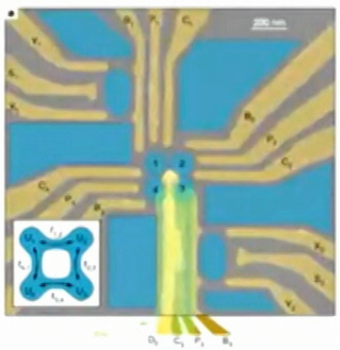
QD Array as Analog Fermionic Simulator

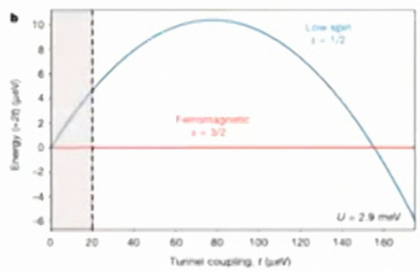
Article

Nagaoka ferromagnetism observed in a quantum dot plaquette

https://doi.org/10.1038/s41586-020-2051-0
Received: 23 May 2019

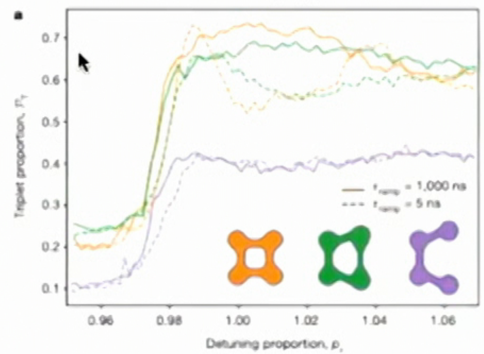
J. P. Dehollain, U. Mukhopadhyay, V. P. Michal, Y. Wang, B. Wunsch, C. Reichl, W. Wegscheider, M. S. Rudner, E. Demler & L. M. K. Vandersypen





This paper

- cross-over from ferro state to anti-ferro state
- Controlled by gate!



Comparison to cold atoms

- Pure state initialisation
- Fewer sites
- Universal control

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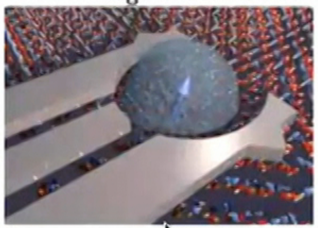
QDs as Conventional Qubits

Image credit: Coish et al PSS 2009



Clean Spin Qubits

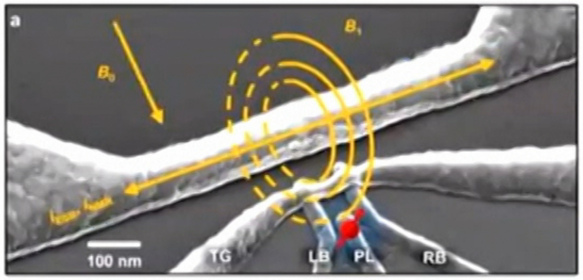
- Long coherence times > 10 ms
  - Eliminate nuclear spins $\mathbf{I}_k$

$$H_c = \sum_k A_k \mathbf{S} \cdot \mathbf{I}_k$$

High Fidelity Single Qubit Gates

e.g., $\Omega_R = g\mu_B B_1/\hbar$

99.9%+ fidelity, 1 microsecond



Pla Nature 2013

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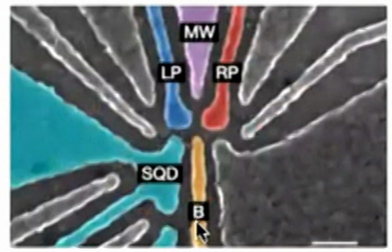
QDs as Conventional Qubits

High Fidelity Two-qubit Gates

e.g., exchange $H = J\mathbf{S}_1 \cdot \mathbf{S}_2$
99%+ fidelity, 100 ns

Xue Nature 2022

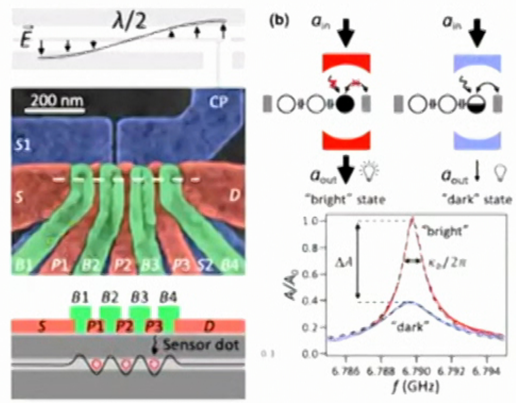


High fidelity measurement

99% fidelity, 1 microsecond

- Co-planar waveguide resonator
- Spin-dependent motion

Borjans Phys. Rev. Applied 2021



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Hybrid analog/digital with QDs?

Aim

- Combine fermionic simulation with measurement & gates
- Half-filling: Heisenberg magnet, away from half-filling: Hubbard
- Starting with small and interesting systems (3-4 sites)

Quantum matter?

- Go beyond traditional condensed matter experiments (e.g., measure correlation functions)
- More control over types of states

Quantum computation?

- Avoid discretization errors in simulation tasks?
- ...
- Avoid fermion-to-spin mappings?

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Quantum Dots

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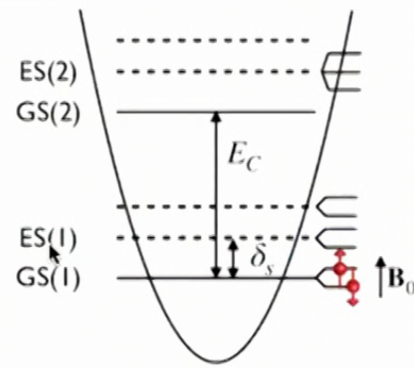

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Applied magnetic field

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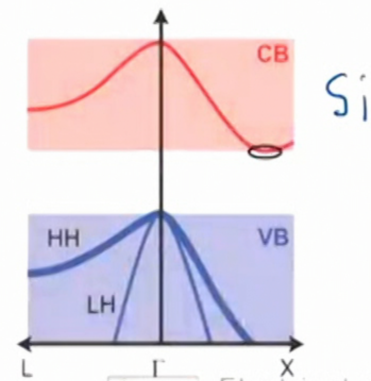

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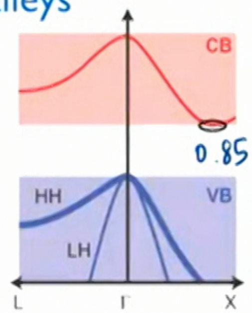
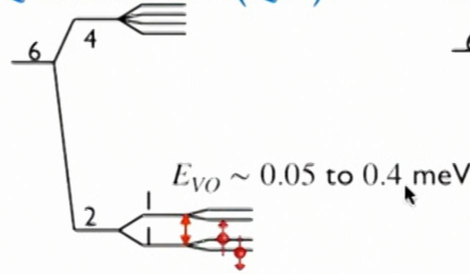
The trouble with electron spin in Si

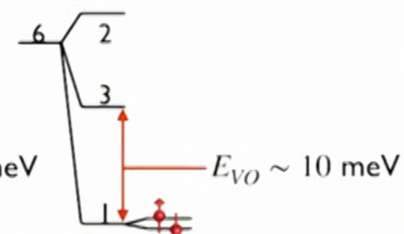
Valleys



Quantum dot (QD)



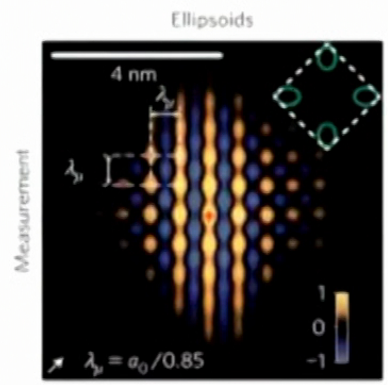
Single donor



6 degenerate minima of CB

Issues

1. Extra states in Hilbert space (QD)
2. Randomizes exchange (QD, donor)
   "Valley interference"
3. Large CB effective mass $m^* \sim m_0$



JS, Mol, Rahman et al Nature Mat 2014

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The Opportunity of Hole Spin Qubits

Keeping the benefits of electrons

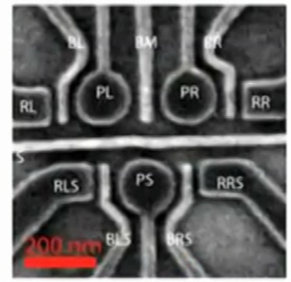
- Small, coherent, transistor-like design

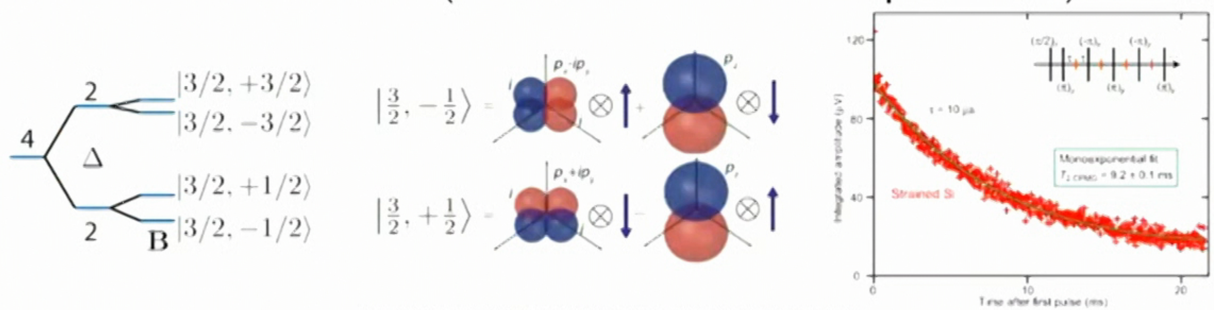
Avoiding weaknesses of electrons

- Electric drive, no valleys

Can even keep the robustness to electric noise

- Electric clock transition (10 ms coherence, 10^4x improvement)





Kobayashi, **JS** et al, Nature Materials (2021)

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Outline

Si-integrated Ge quantum well QDs

- Basic process: single QD
- QD molecules, occupation & tunneling control

High-magnetic field superconducting electronics?

- Can superconducting electronics survive high magnetic fields?
- Yes: Phase sensitive and phase-insensitive gain from para-amp

Computer-aided qubit design

- Connect QD design to qubit properties (optimization?)

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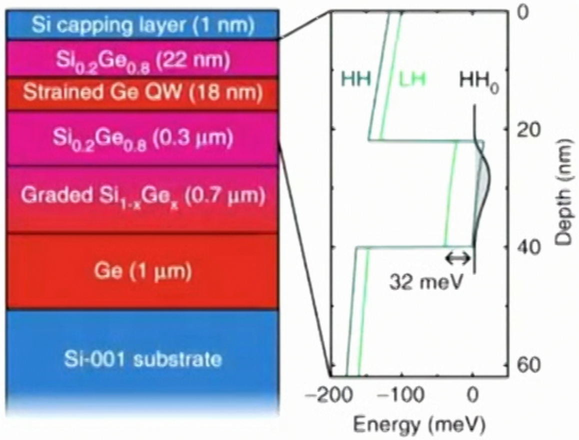
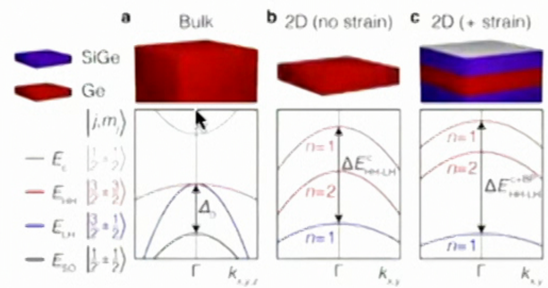
Si-integrated Ge QD devices

Ge QW features





Hendrickx et al Nature Comms (2018)

- Small effective mass (larger devices!) $m^* \sim 0.04 m_0$
- Quasi two-dimensional system w strong spin-orbit coupling
- Valence band degeneracies lifted by confinement and strain

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Si-integrated Ge QD devices
Bond pad
Gates
Bond pad
Bond pad
Ohmic
Gate Dielectric
Ohmic
Bond pad
GeSi
Ge
GeSi
Si
Dr. Ebrahim Sajadi
Mukhlasur Tanvir
Device components (UBC)
Ohmic contacts
Gate Dielectric
Nanoscale top gates
Large gates to bond pads
Simplified architecture
c.f. Hendrickx 2019, 2021
Single gate layer
Accumulated reservoir
Question?
Control down to last hole?
Tunnel coupling control?
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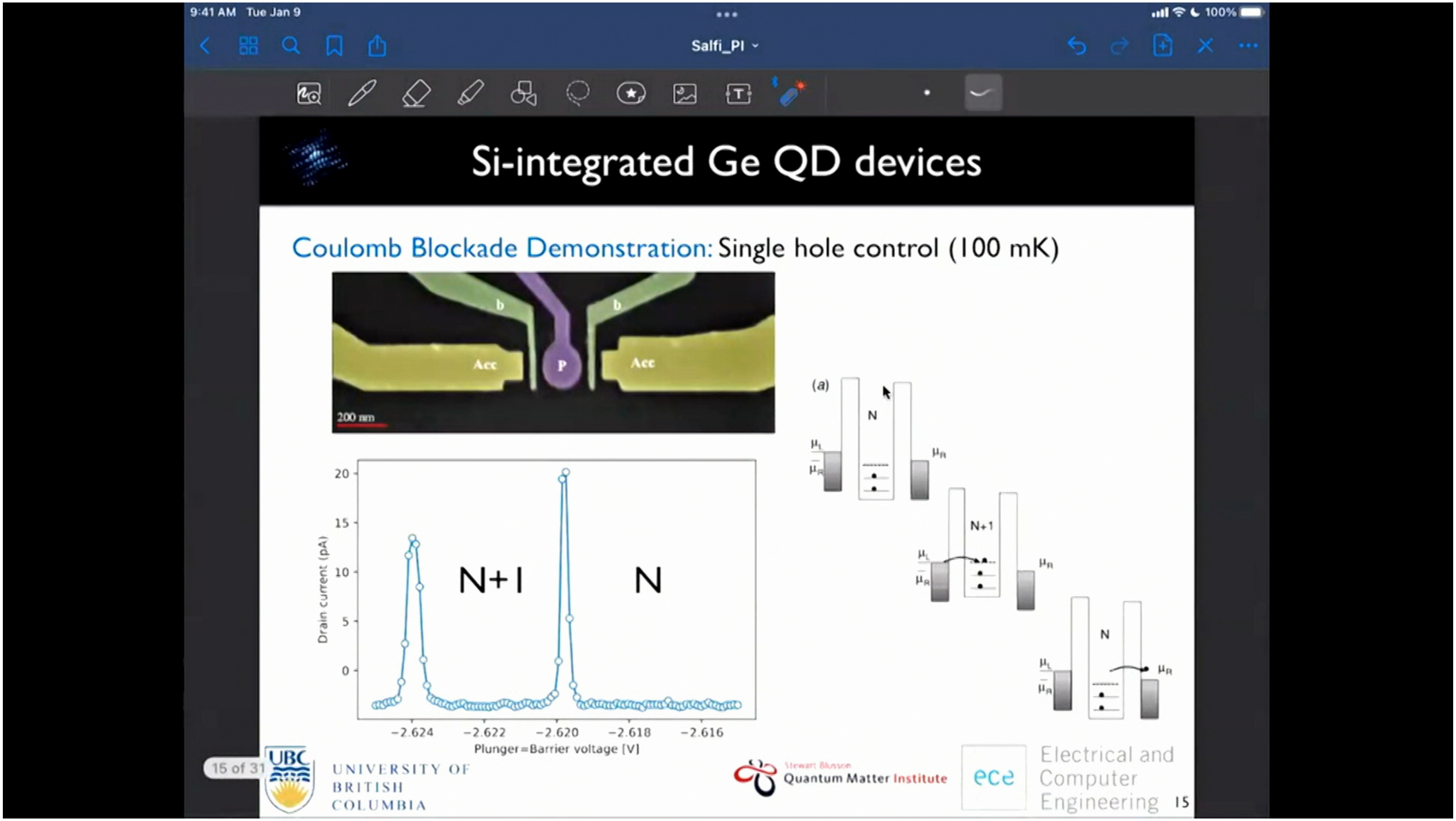
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Si-integrated Ge QD devices
Coulomb Blockade Demonstration: Single hole control (100 mK)
b
b
Acc
P
Acc
200 nm
Drain current (pA)
20
15
10
5
0
N+1
N
−2.624
−2.622
−2.620
−2.618
−2.616
Plunger=Barrier voltage [V]
(a)
N
N+1
N
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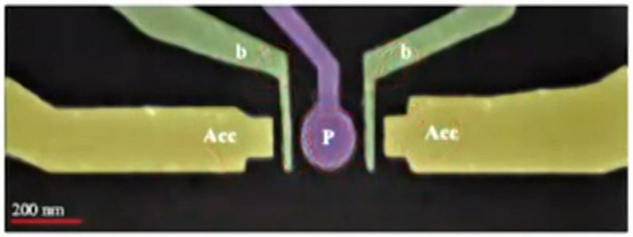
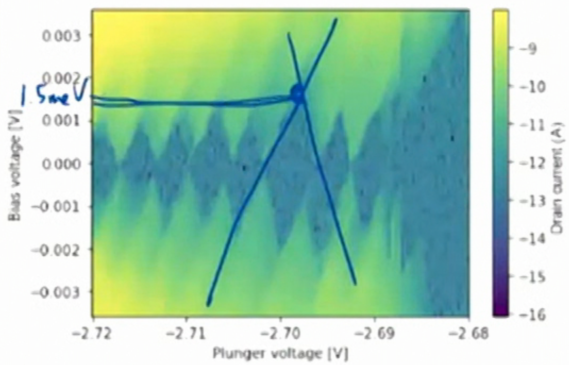
Si-integrated Ge QD devices

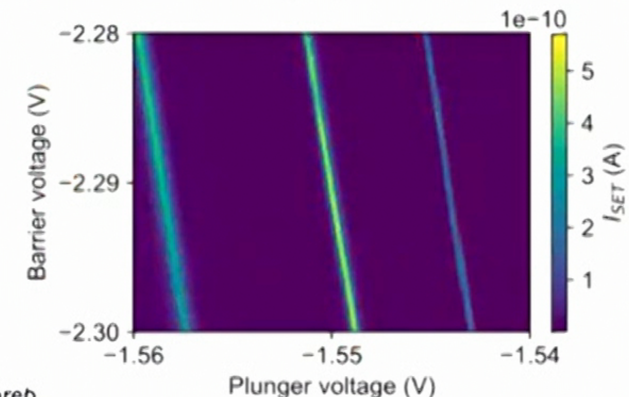
Coulomb Blockade Demonstration





Basic results

- Addition energy $U \sim 1.5$ meV
- Coupling QD energy to gate
  - $\alpha_P = d(q\epsilon_i)/dV_{P_i} \sim 0.3$
- Coupling QD energy to barrier $\alpha_B/\alpha_P \sim 1/10$



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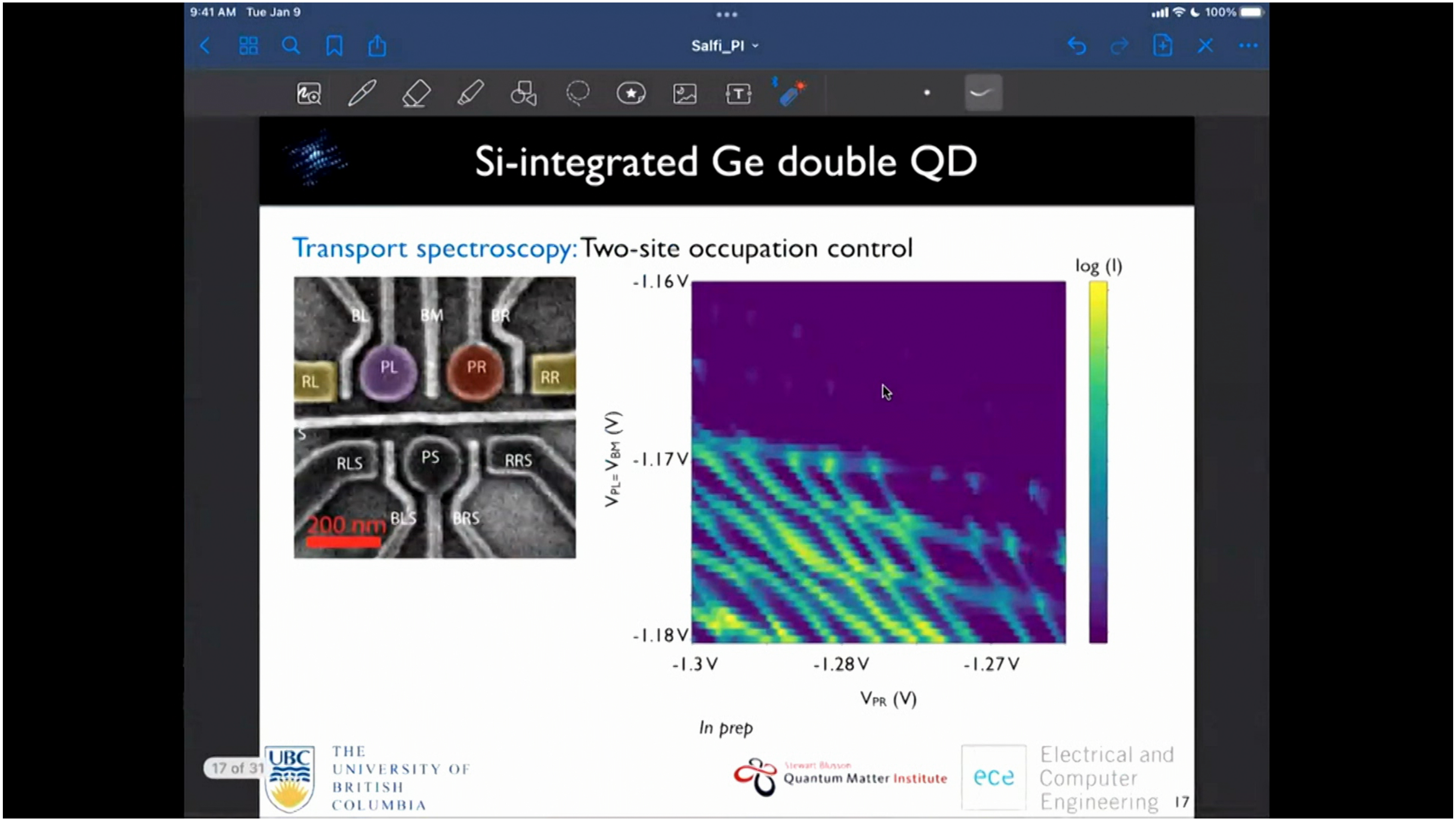
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Si-integrated Ge double QD
Transport spectroscopy: Two-site occupation control
BL
BM
BR
PL
PR
RL
RR
RLS
PS
RRS
BLS
BRS
200 nm
log (I)
-1.16 V
-1.17 V
-1.18 V
V_PL= V_BM (V)
-1.3 V
-1.28 V
-1.27 V
V_PR (V)
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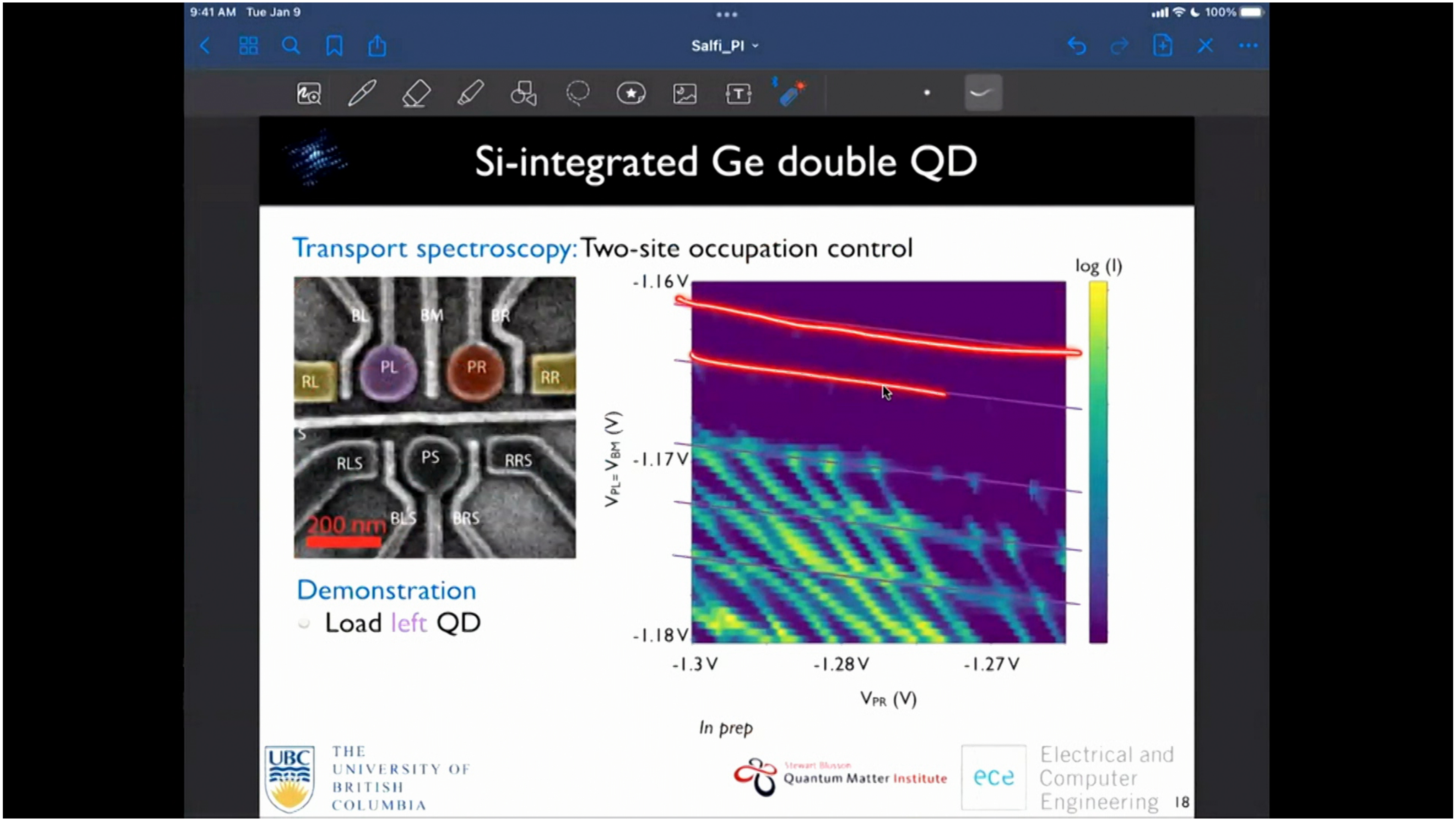
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RLS
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BLS
BRS
200 nm
Demonstration
Load left QD
log (I)
-1.16 V
-1.17 V
-1.18 V
$V_{PL} = V_{BM}$ (V)
-1.3 V
-1.28 V
-1.27 V
V_{PR} (V)
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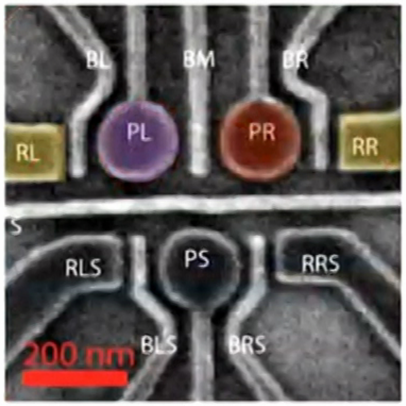
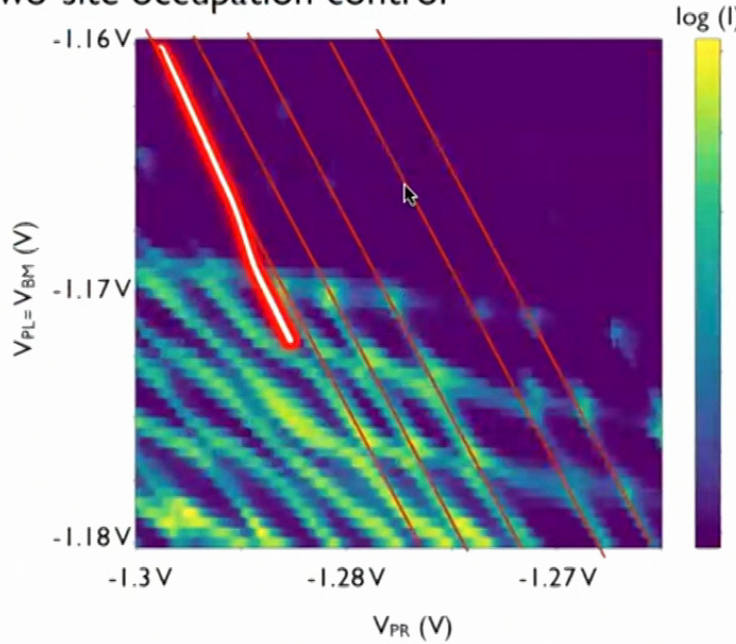
Si-integrated Ge double QD

Transport spectroscopy: Two-site occupation control





Demonstration

- Load left QD
- Load right QD

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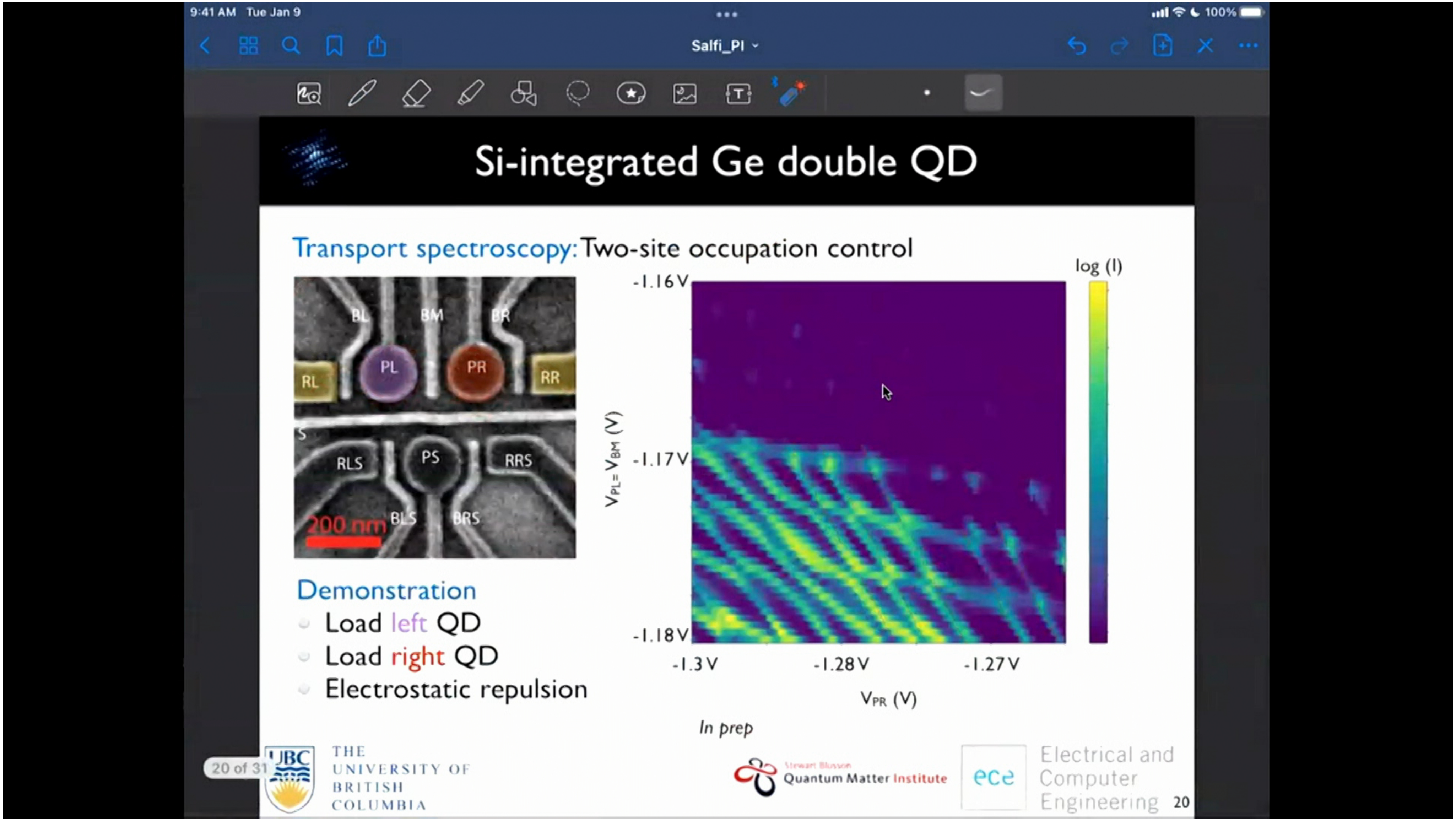
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BLS
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200 nm
Demonstration
Load left QD
Load right QD
Electrostatic repulsion
log (I)
-1.16 V
-1.17 V
-1.18 V
$V_{PL} = V_{BM}$ (V)
-1.3 V
-1.28 V
-1.27 V
V_{PR} (V)
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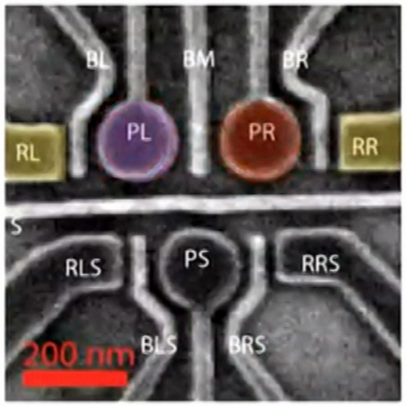
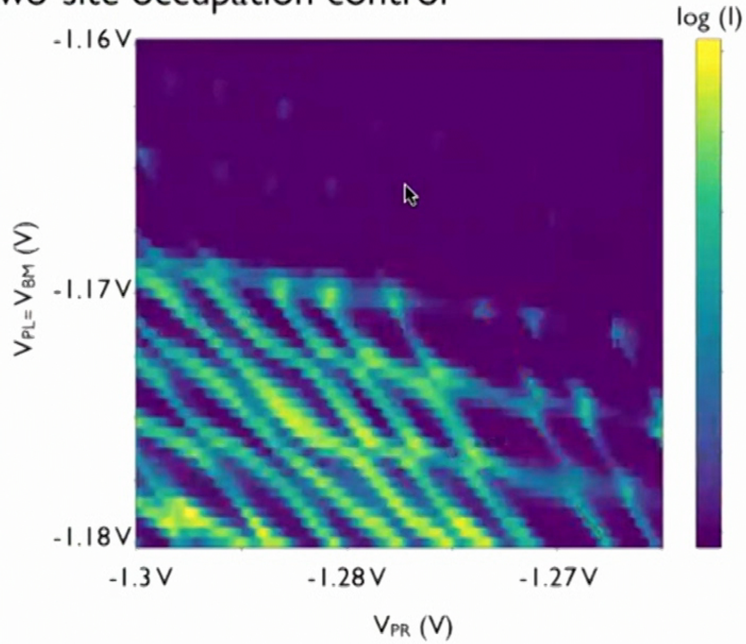
Si-integrated Ge double QD

Transport spectroscopy: Two-site occupation control





Demonstration

- Load left QD
- Load right QD
- Electrostatic repulsion
- Tunnel coupling

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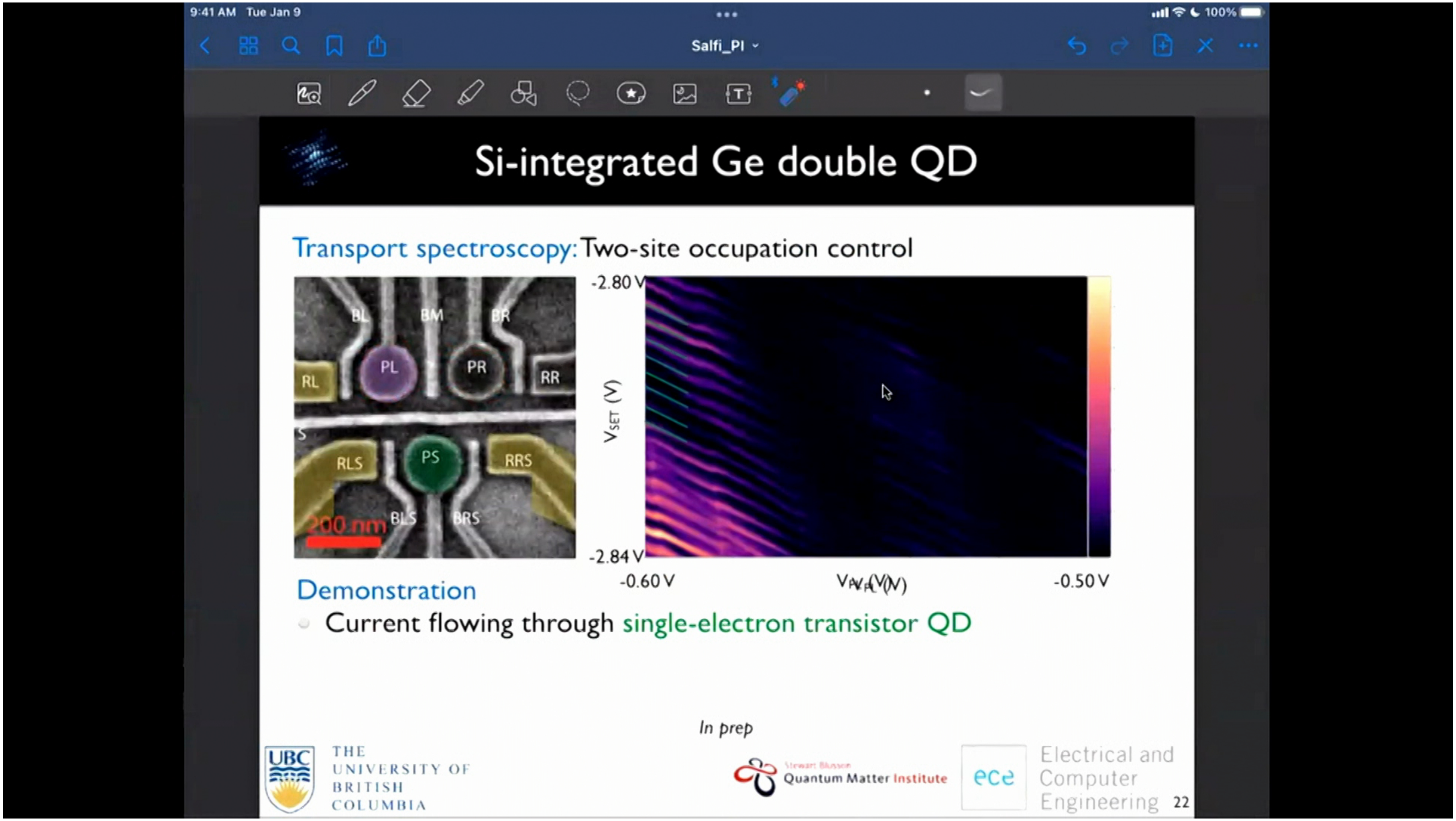
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RL
RR
S
RLS
PS
RRS
200 nm
BLS
BRS
-2.80 V
-2.84 V
V_SET (V)
-0.60 V
-0.50 V
Demonstration
Current flowing through single-electron transistor QD
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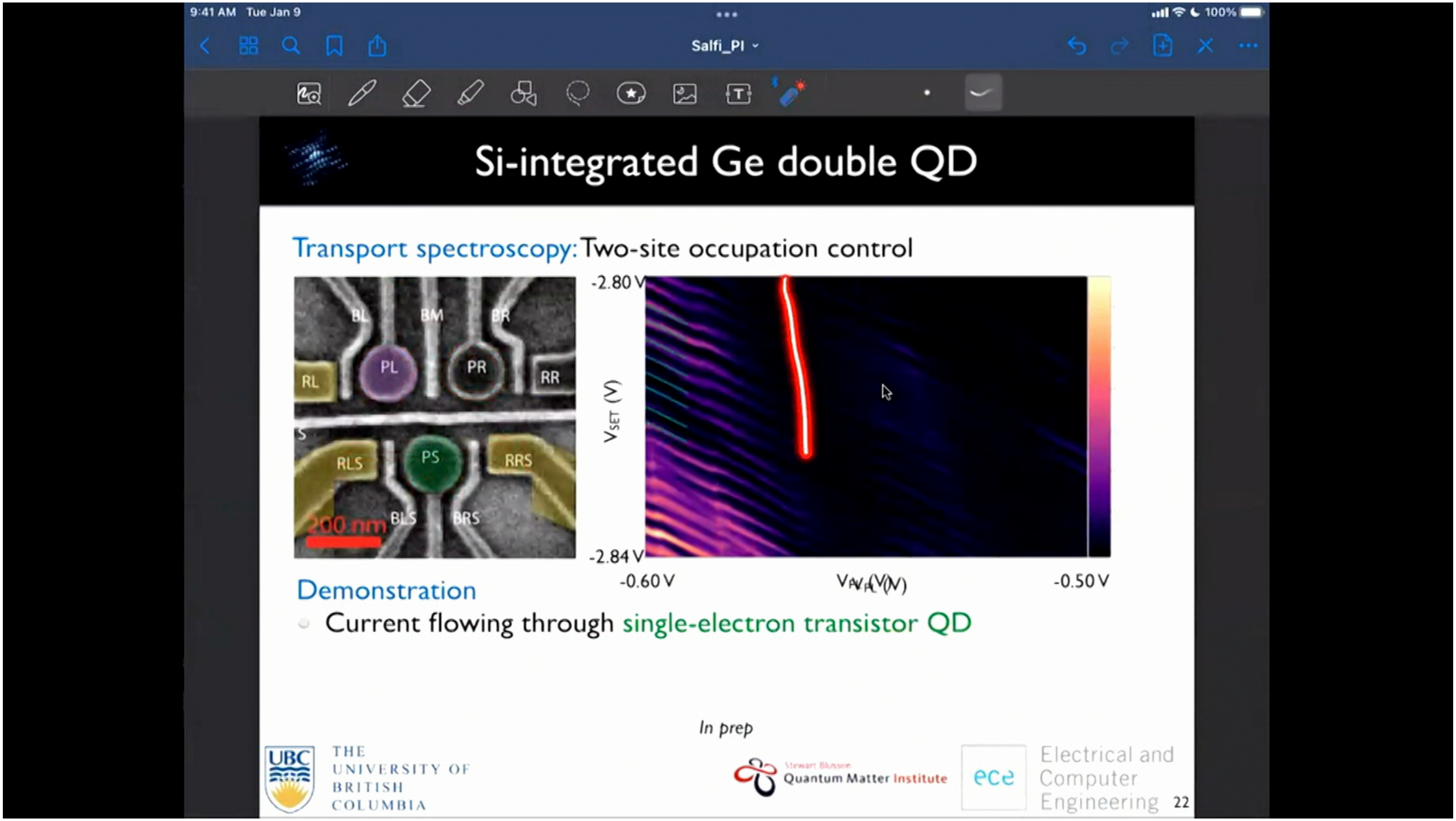
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BLS
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200 nm
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V_{SET} (V)
-0.60 V
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Demonstration
Current flowing through single-electron transistor QD
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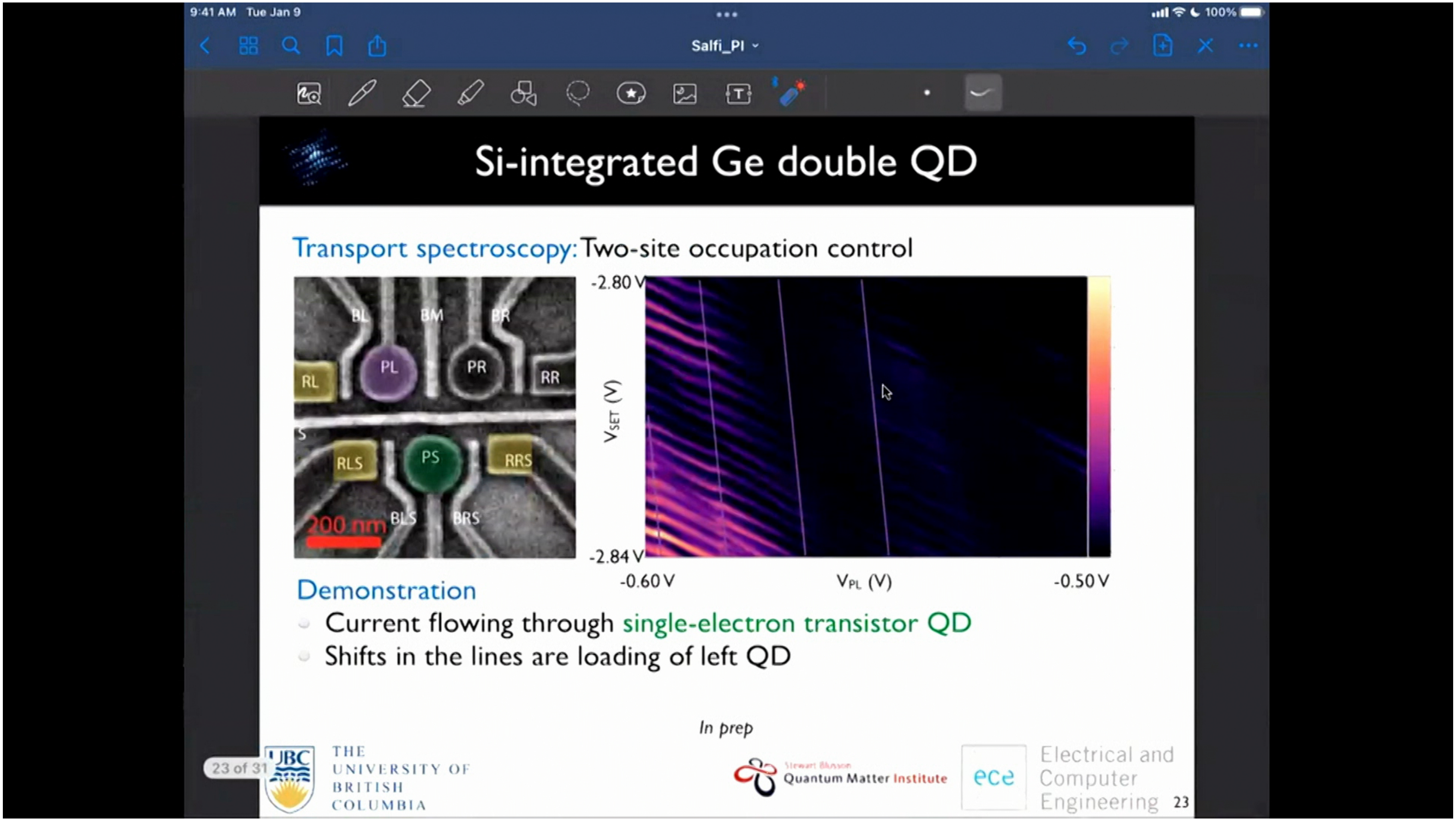
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-0.50 V
Demonstration
Current flowing through single-electron transistor QD
Shifts in the lines are loading of left QD
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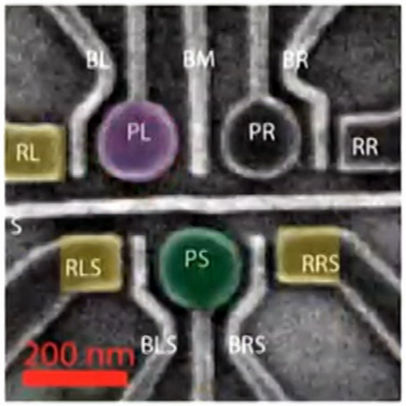
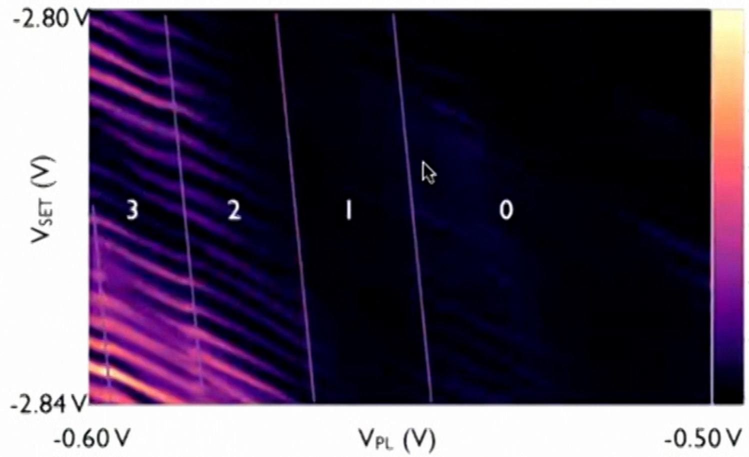
Si-integrated Ge double QD

Transport spectroscopy: Two-site occupation control





Demonstration

- Current flowing through single-electron transistor
- Shifts in the lines are loading of left quantum dot
- Last shift indicates emptying of QD (log scale of current confirms)

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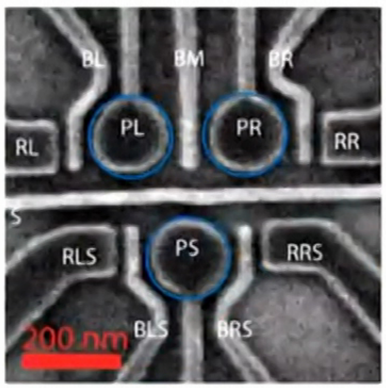
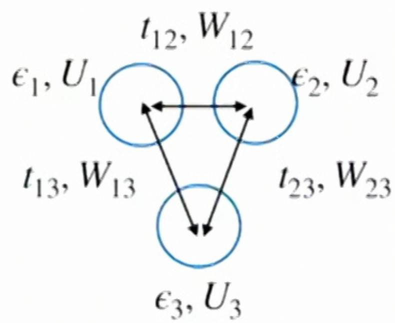
Si-integrated Ge double QD

Conclusions: (Sept 2022) Single-layer device functionality
- Control of single hole at a time (on-site Coulomb repulsion) by gate
- Control of adjacent QDs by adjacent gates (to last hole)
- Tunnel coupling (and coupling control) by gates
- Nearest-neighbour Coulomb (and charge sensing)





Next steps: Small devices
- 2-QD + charge sensor
  - Fast spin readout
- 3-QD + charge sensor
  - Triplet GS (2 or 4 fermions)
  - Dynamics (driven system)

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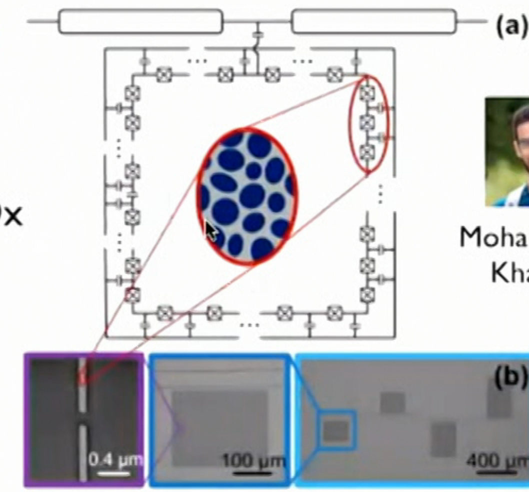
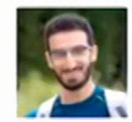
Qubit readout: First stage amp

First-stage amp: quantum limited amp

- Function: amplify readout signal adding smallest amount of noise (Caves PRL)
- NL: typ. Josephson Junctions Al/AlOx





Mohammad Khalifa

Our approach

- Spin qubits need B-fields
- Kinetic inductance (KI) nanowire
  - High-Q in B-field is known (e.g., Samkharadze 2016)
  - Suppresses formation of vortices (maintain Q)

NL of KI device in B-field?: Totally unexplored: we built a para-amp

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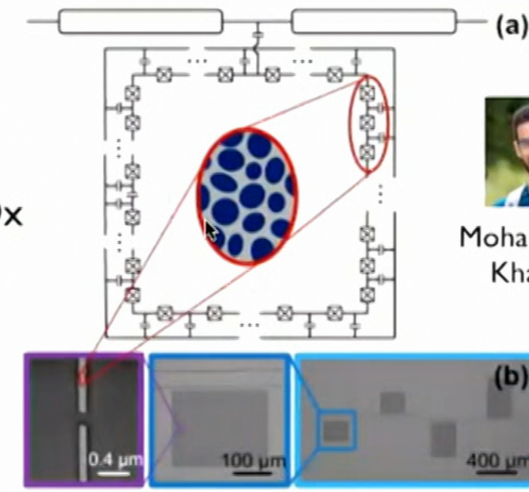

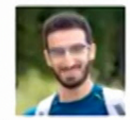

Mohammad Khalifa

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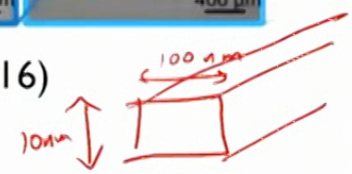

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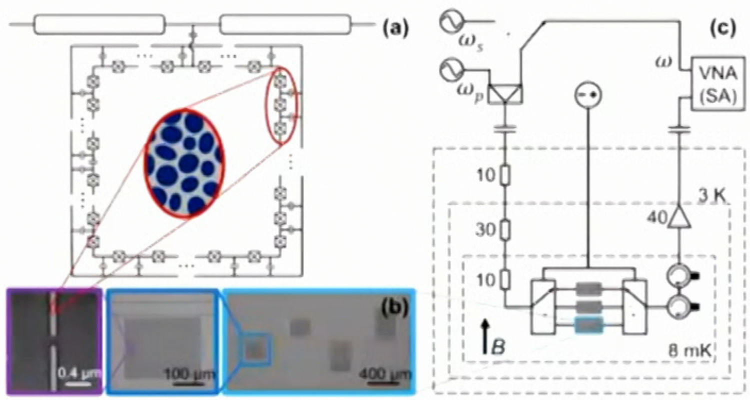
Superconducting Nano-Devices



Nanowire
- Thickness: 10 nm (cal.)
- Width: 100 nm (meas.)

Small cross-sectional area
- Kinetic inductance ≫ magnetic inductance

Concept: Simple resonator based PA
- Pump tone and signal
- Pump tone amplifies signal
  - 4WM (3WM also possible)
- Measure this at 8 mK in a dilution fridge

$$H=\sum_n \hbar\omega_n\left(a_n^\dagger a_n+\frac{1}{2}\right)+\sum_n \frac{\hbar}{2}K_n\left(a_n^\dagger a_n\right)^2 + \sum_{n,m\neq n}\hbar K_{mn}\left(a_m^\dagger a_m a_n^\dagger a_n\right)$$

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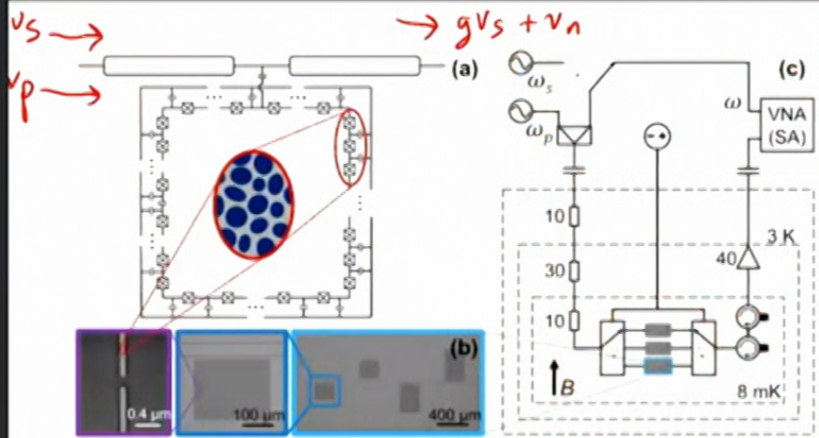
Superconducting Nano-Devices



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Small cross-sectional area
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$E_K = \frac{1}{2} L_K I^2$

$E_B = \frac{1}{2} L_m I^2$

Concept: Simple resonator based PA
- Pump tone and signal
- Pump tone amplifies signal
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$$H = \sum_n \hbar\omega_n \left(a_n^\dagger a_n + \frac{1}{2}\right) + \sum_n \frac{\hbar}{2} K_n \left(a_n^\dagger a_n\right)^2 + \sum_{n,m\neq n} \hbar K_{mn} \left(a_m^\dagger a_m a_n^\dagger a_n\right)$$

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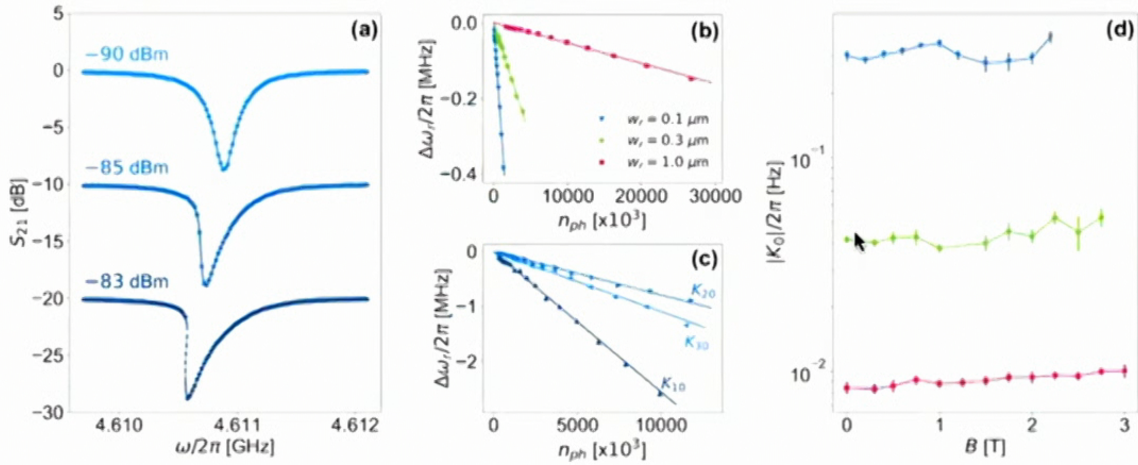
Superconducting Nano-Devices



Power Dependence, Kerr Nonlinearity, B-field dependence Nonlinearity

- Resonance shift, change in line-shape
- Self-Kerr, Cross-Kerr non-linearity increases as W decreases (lower I_c)
- Magnetic field slightly increases K (lower I_c)

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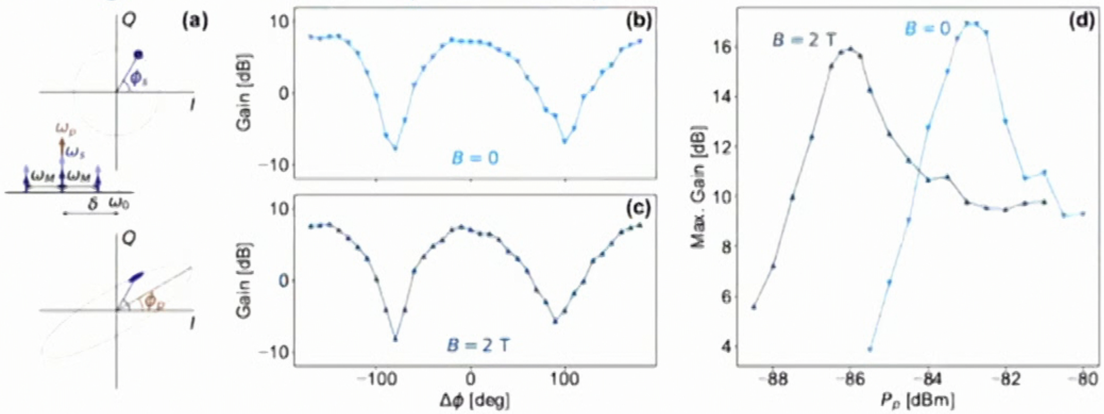
Superconducting Nano-Devices

Degenerate Parametric Amplification

- Feature: Phase-Sensitive Gain
  - Up to 17 dB of amplification at optimum pump power
  - Optimized devices (new) have 30 dB amplification
- The KI nonlinearity is highly robust to B-field for spin qubit devices
- No degradation of SNR (not shown)



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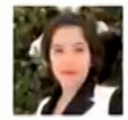
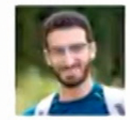
Towards Qubit-CAD





Ana Ciocoiu

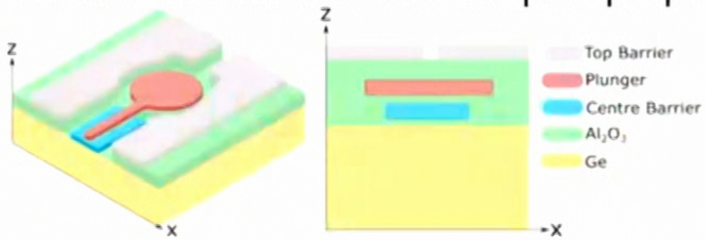
Mohammad Khalifa

Classical transistors, and now superconducting circuits

- Simplified models extracted from device-level sim

Hole spin qubits:

- Realistic description of states, or device, not both
- What is the role of device on qubit properties?



Key findings

- Rashba spin-orbit coupling is not the only physics (this is asymp 2D)
- Hole occupation
- Qubit drive in real devices

$$H_{LK} = \begin{bmatrix} P+Q & 0 & L & M \\ 0 & P+Q & M^* & -L^* \\ L^* & M & P-Q & 0 \\ M^* & -L & 0 & P-Q \end{bmatrix}$$

$$\mathcal{H} = (\hbar\omega + \chi \cdot \delta\mathbf{E})\sigma_z + (\mathbf{v} \cdot \mathbf{E})\sigma_x$$

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Thank you!

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Bill Coish (hyperfine) (McGill)

Australian Government
Australian Research Council

Materials
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Menno Veldhorst

NSERC CRSNG

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