SAND2019-0277C

Improving the Readout of Semiconducting Qubits

1 / 9 / 2019

Matthew J. Curry

Physics and Astronomy Department, University of New Mexico (UNM)

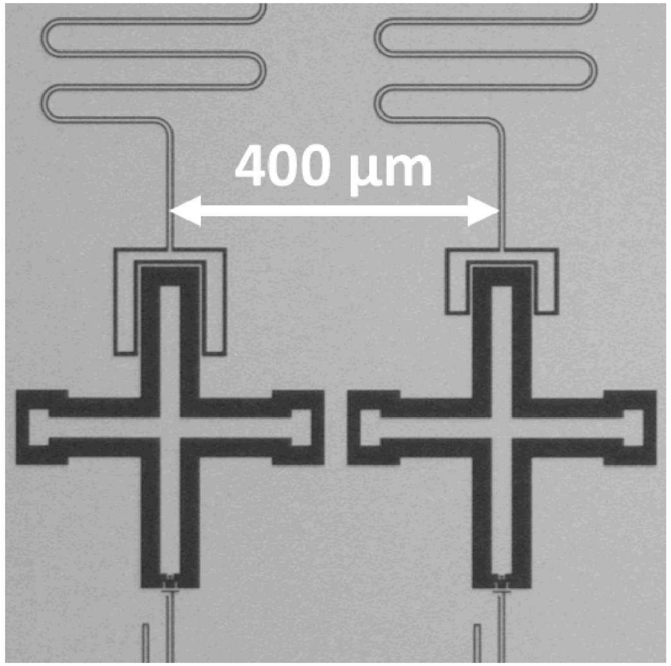
Center for Quantum Information and Control (CQuIC) at UNM

Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

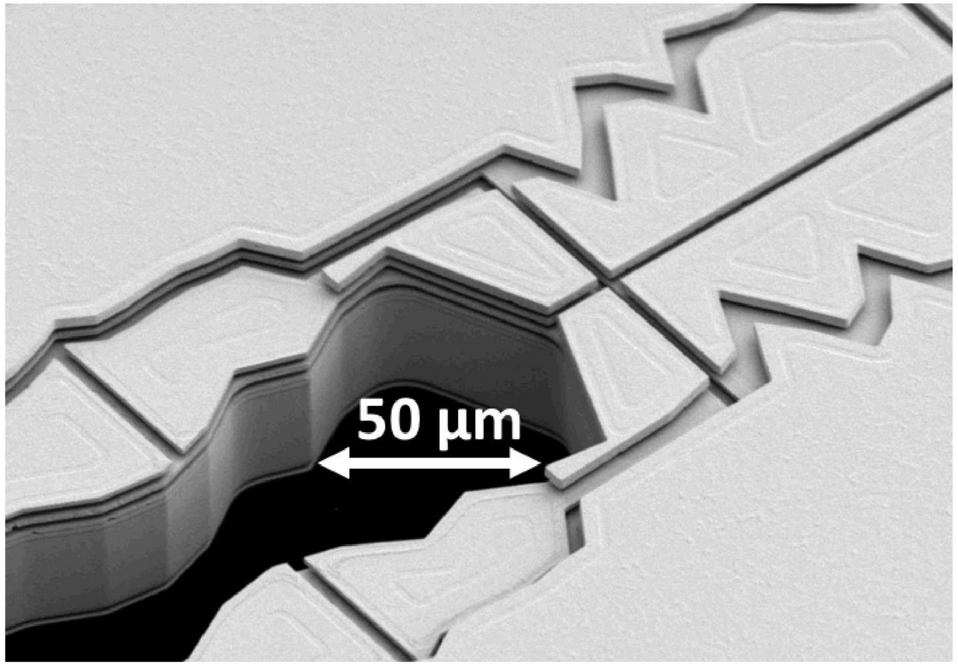
Context

Superconducting



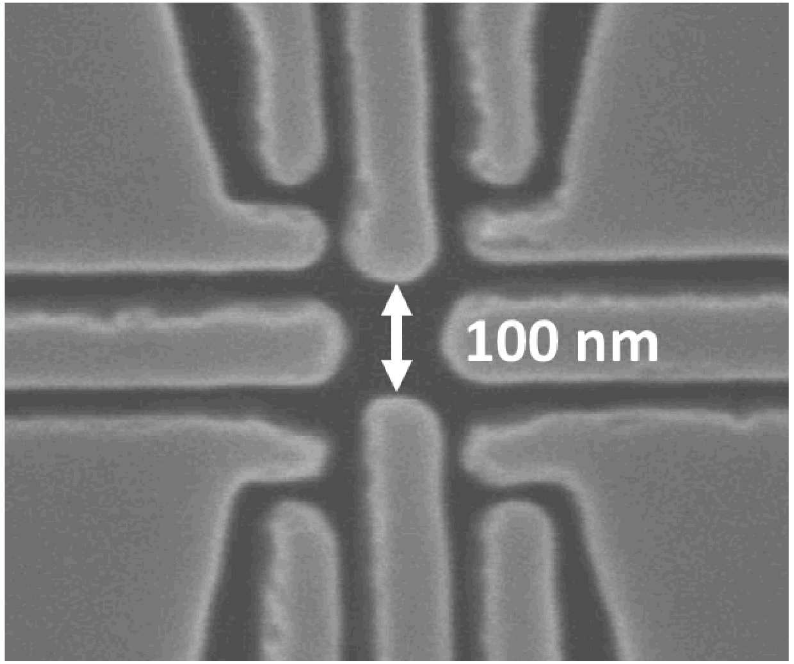
(Google)

Ion Trap



(Sandia)

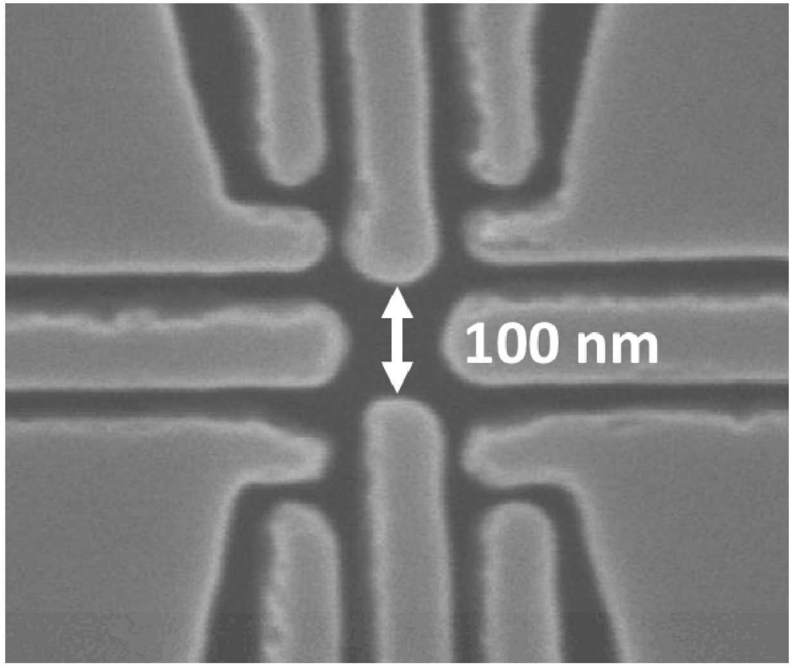
Silicon Spin



(Sandia)

Motivation

Silicon Spin



Qubit Challenges:

- Scalability
- Initialization
- Control
- Coherence Time (Relative)
- ➢ Readout

    Challenges Limiting Fidelity:

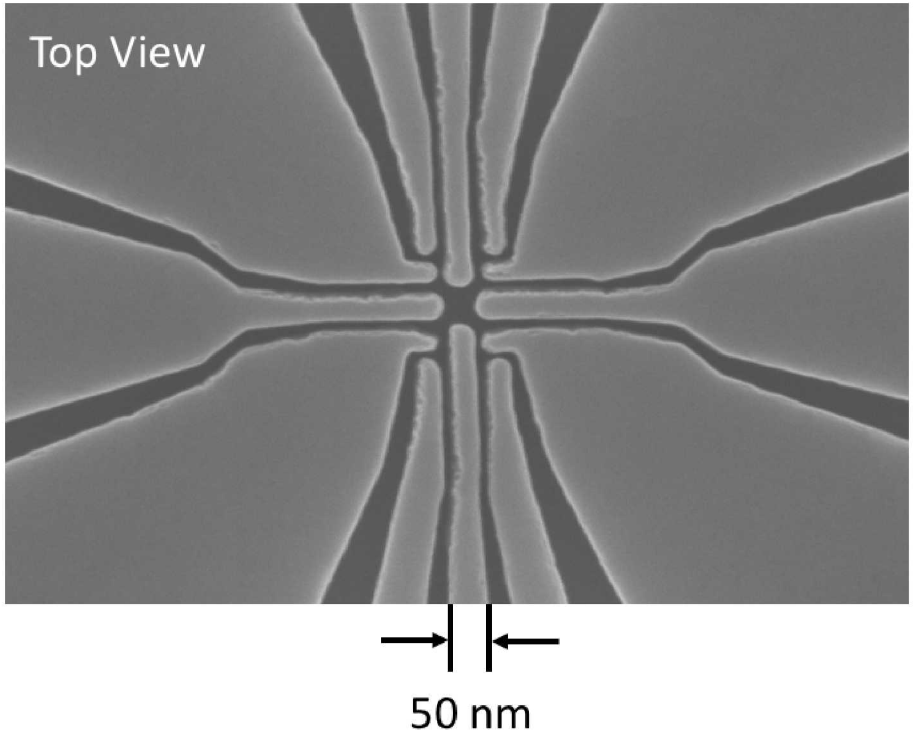
    - Cryogenic Operation
    - Small Signal
    - Noise
    - Parasitic Capacitance

$$error\ rate = 1 - e^{\left(\frac{-t_{meas}}{T_1}\right)} \approx t_{meas}/T_1$$

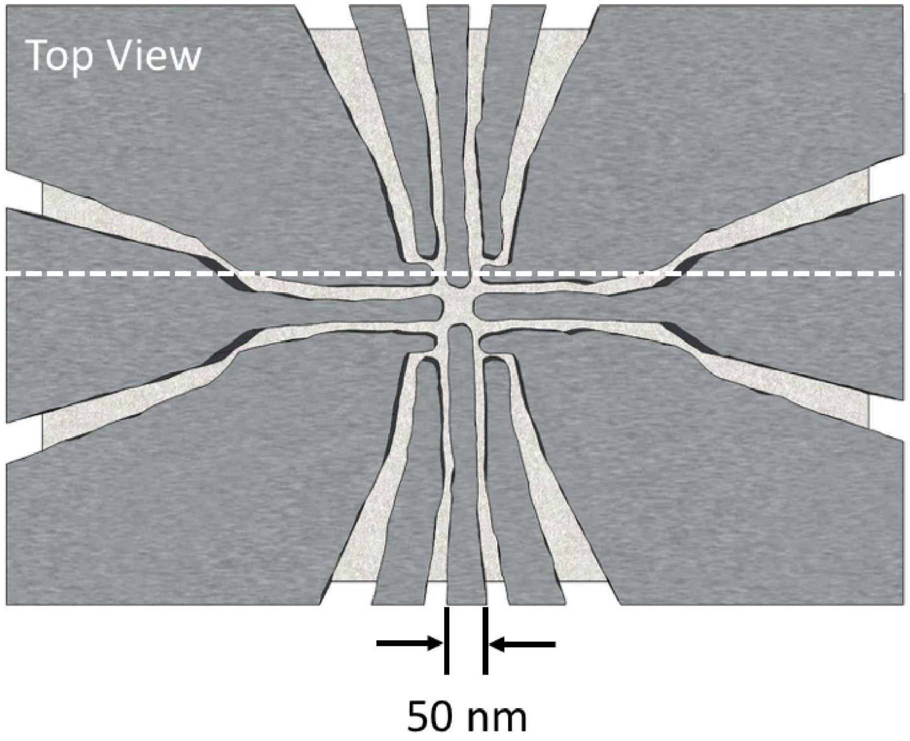
Goal: Increase readout fidelity using heterojunction-bipolar-transistor (HBT) circuits.

Background

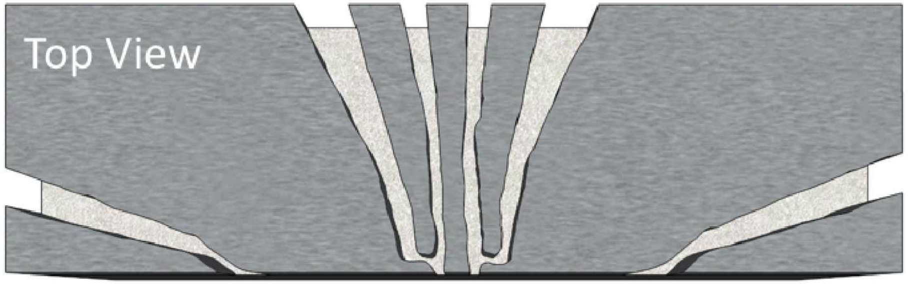
Silicon Metal-Oxide-Semiconductor (MOS) Devices Fabricated at Sandia



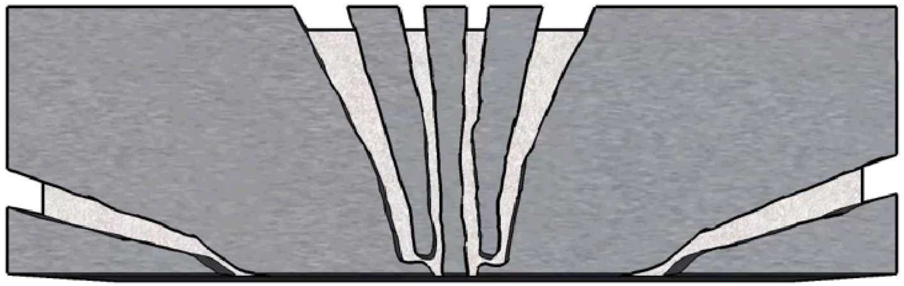
Silicon Metal-Oxide-Semiconductor (MOS) Devices Fabricated at Sandia



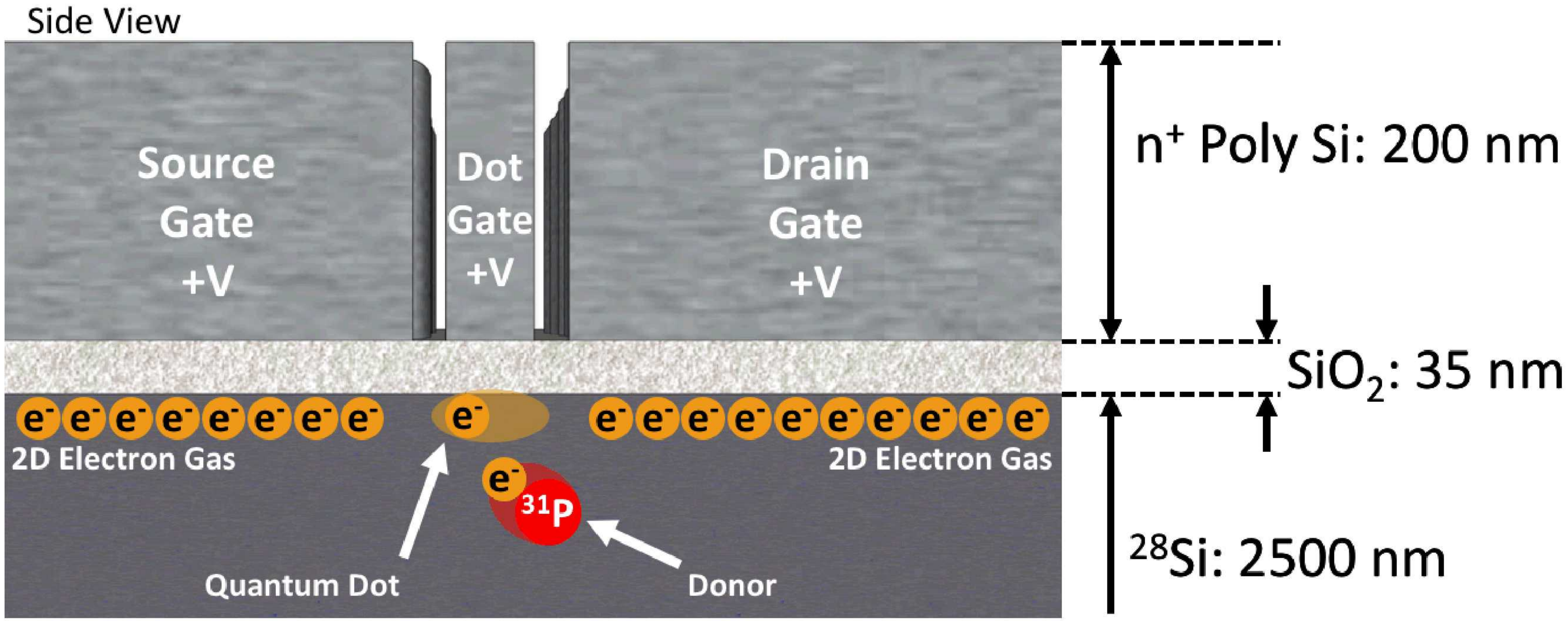
Silicon Metal-Oxide-Semiconductor (MOS) Devices Fabricated at Sandia



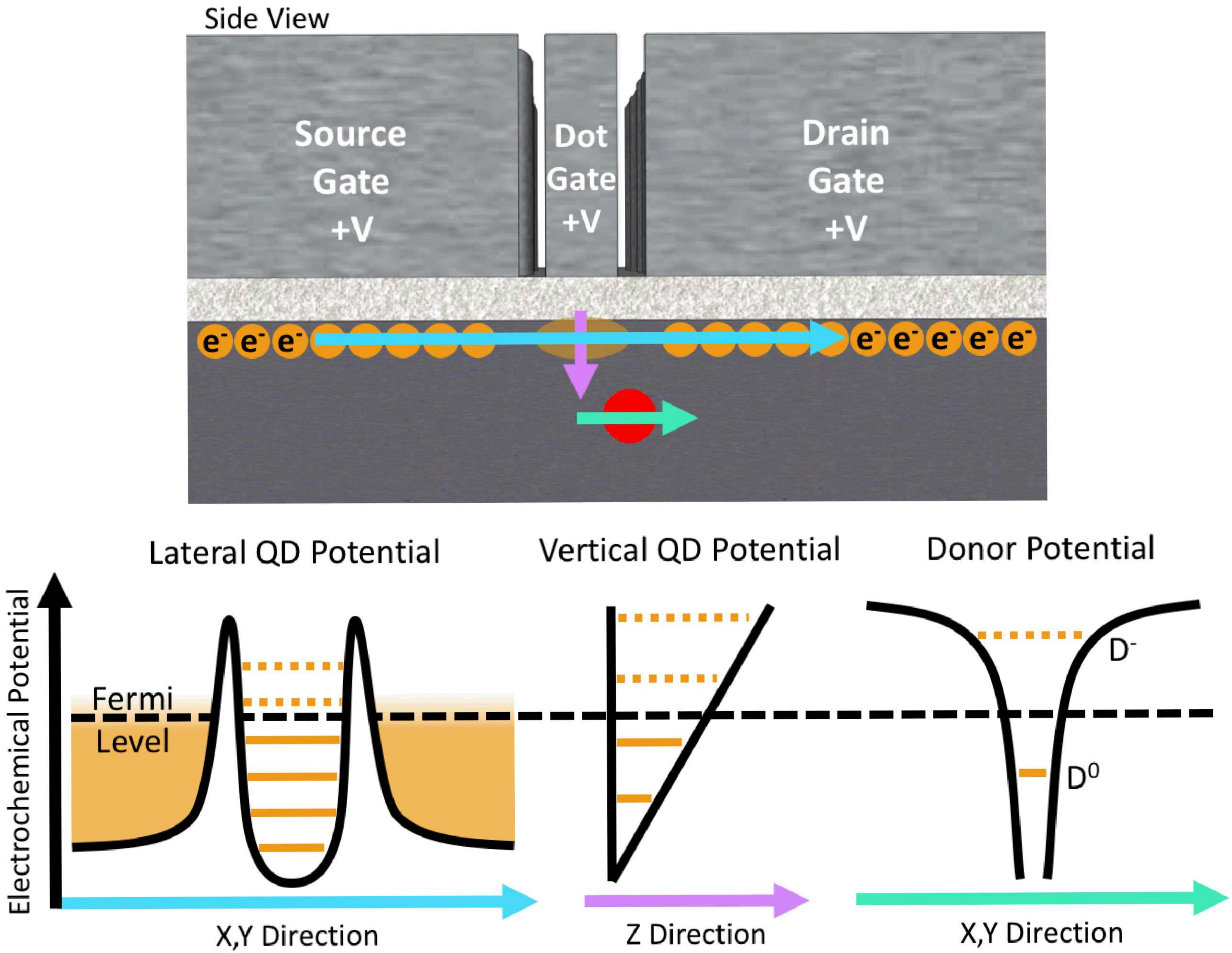
Silicon Metal-Oxide-Semiconductor (MOS) Devices Fabricated at Sandia



Dot-Donor System

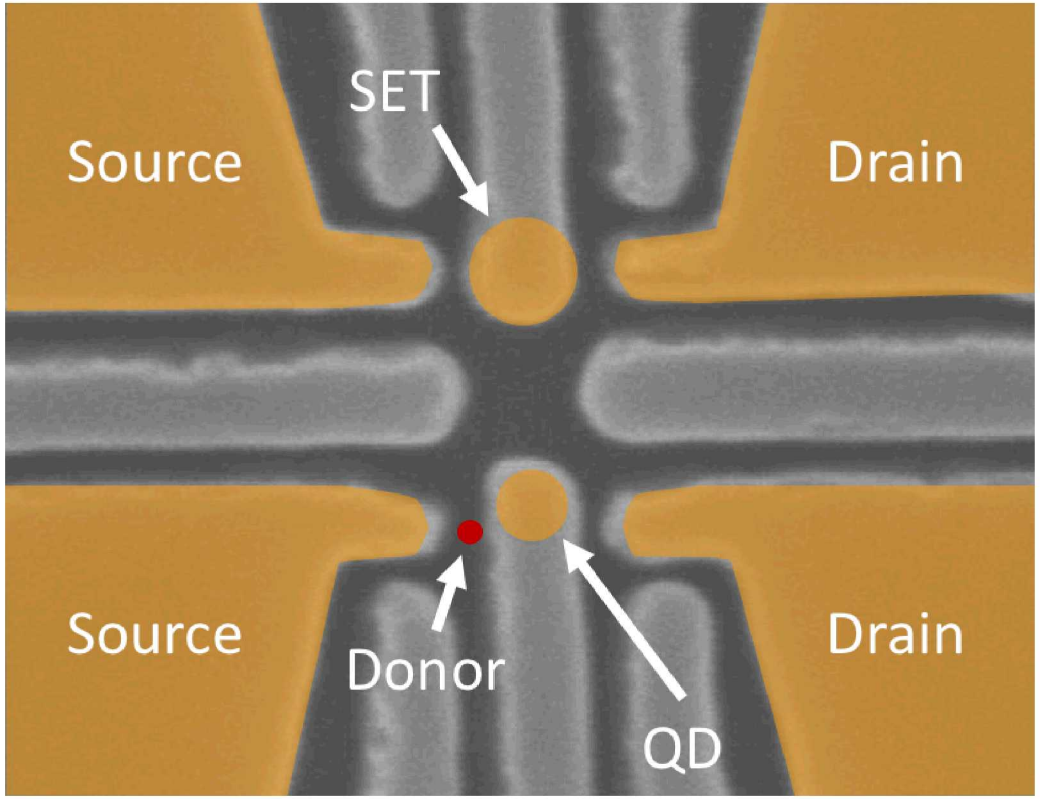


Dot-Donor System

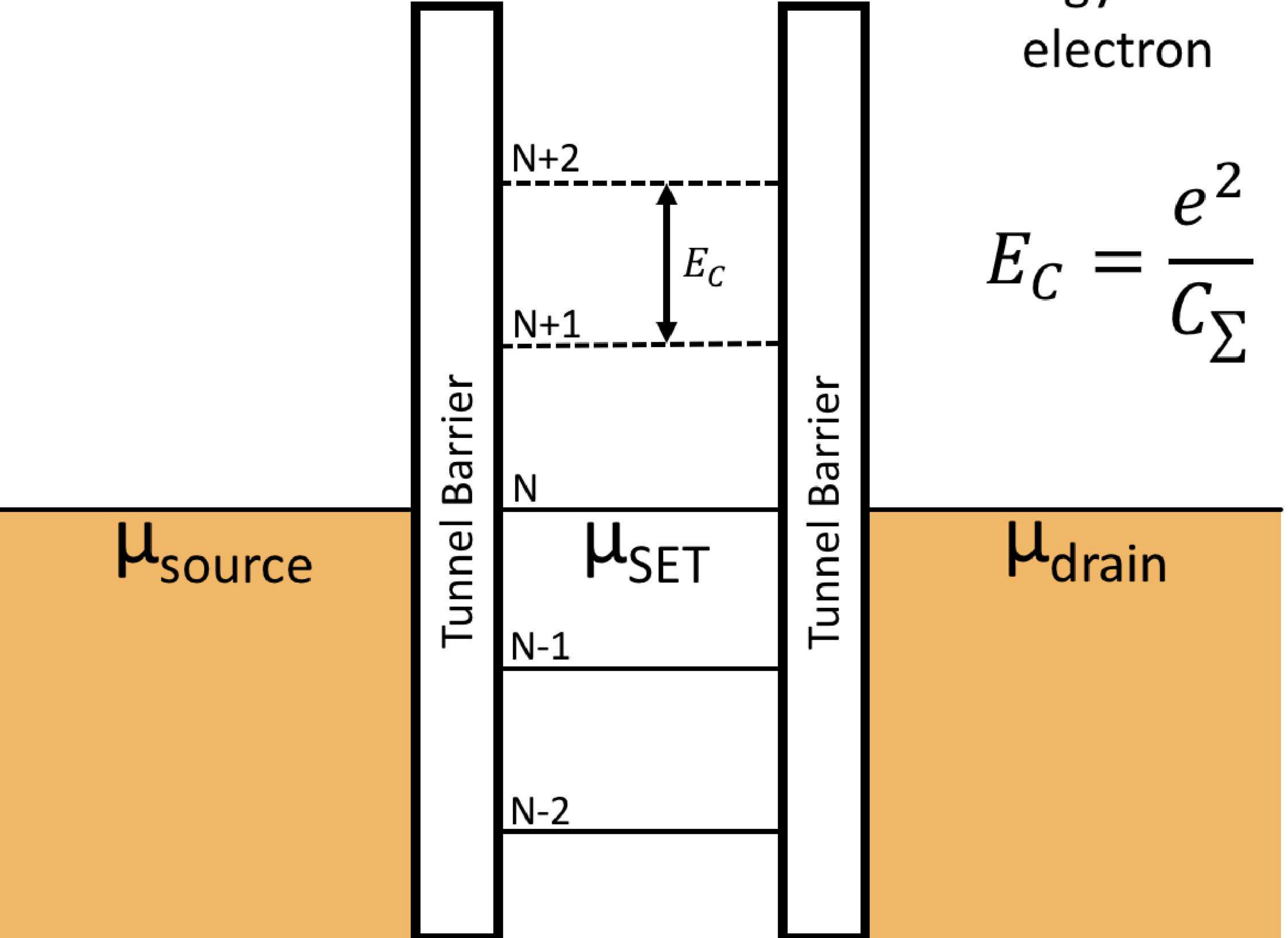


Single Electron Transistor (SET)

Top View



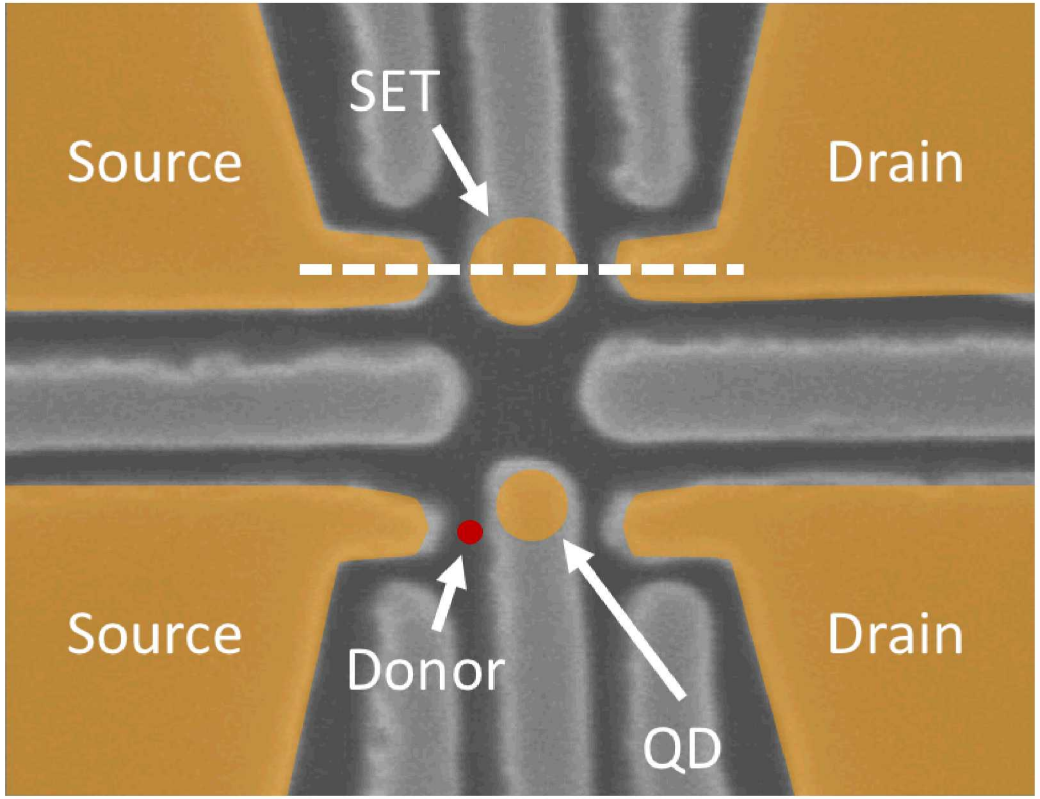
Coulomb Blockade of SET



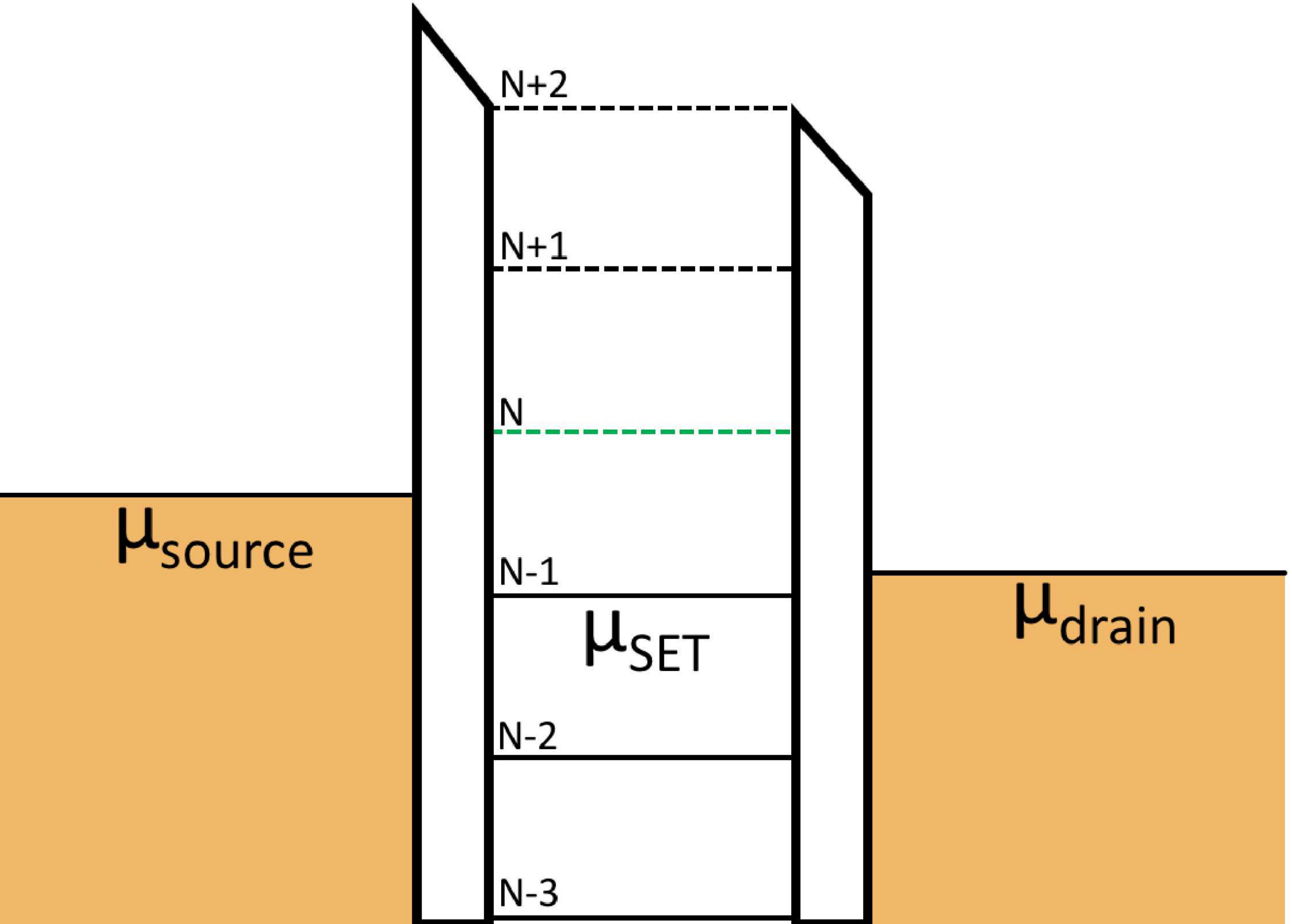
Energy to add electron

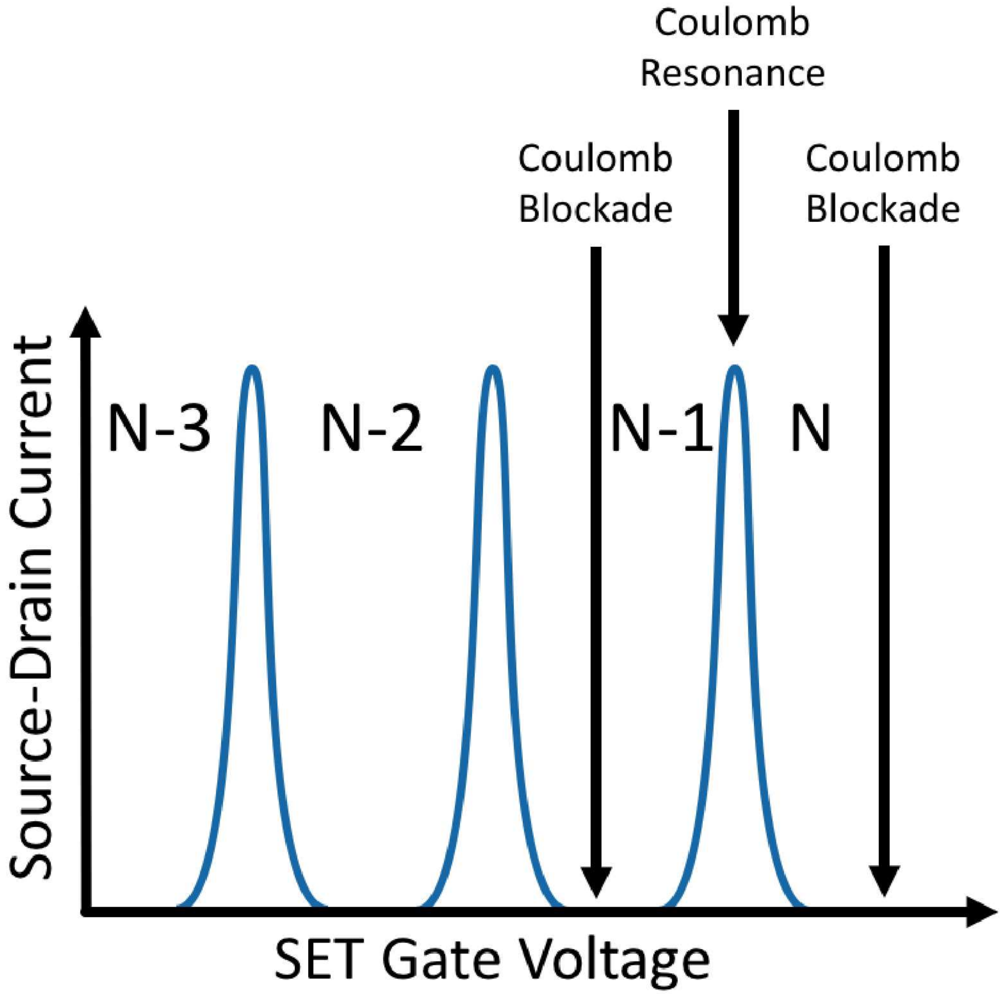
$$E_C = \frac{e^2}{C_\Sigma}$$

Top View

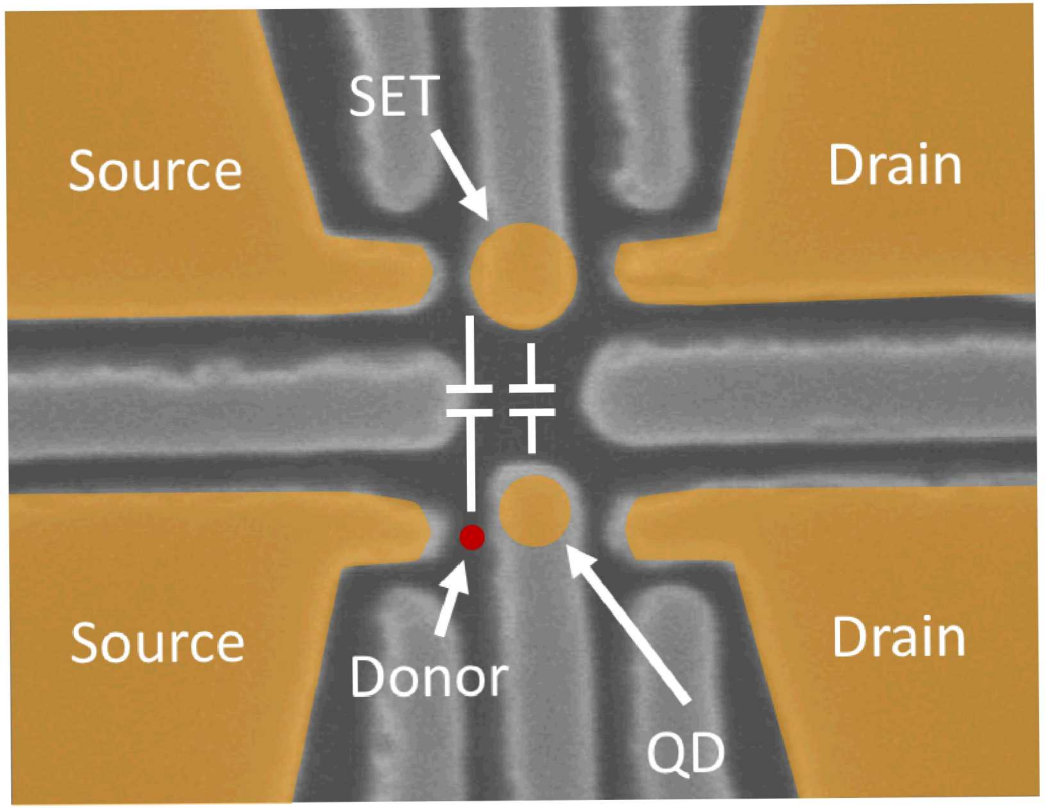


Coulomb Blockade of SET

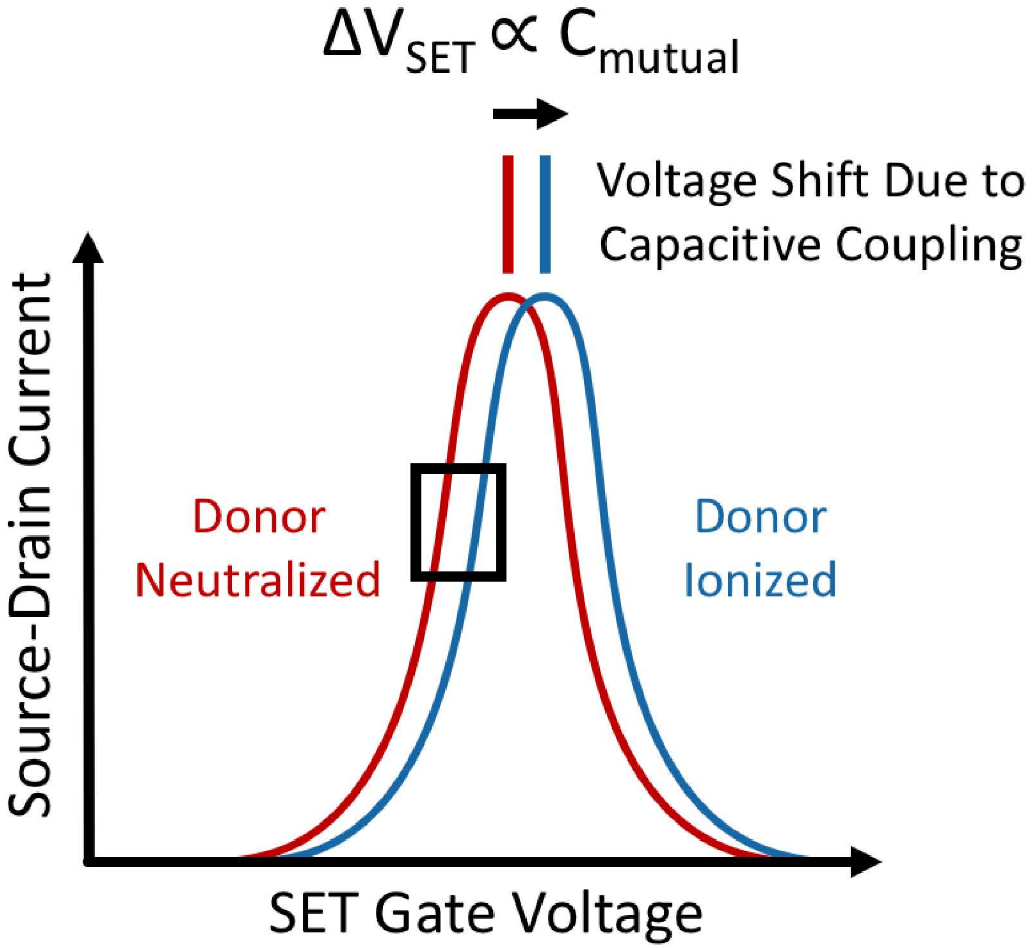


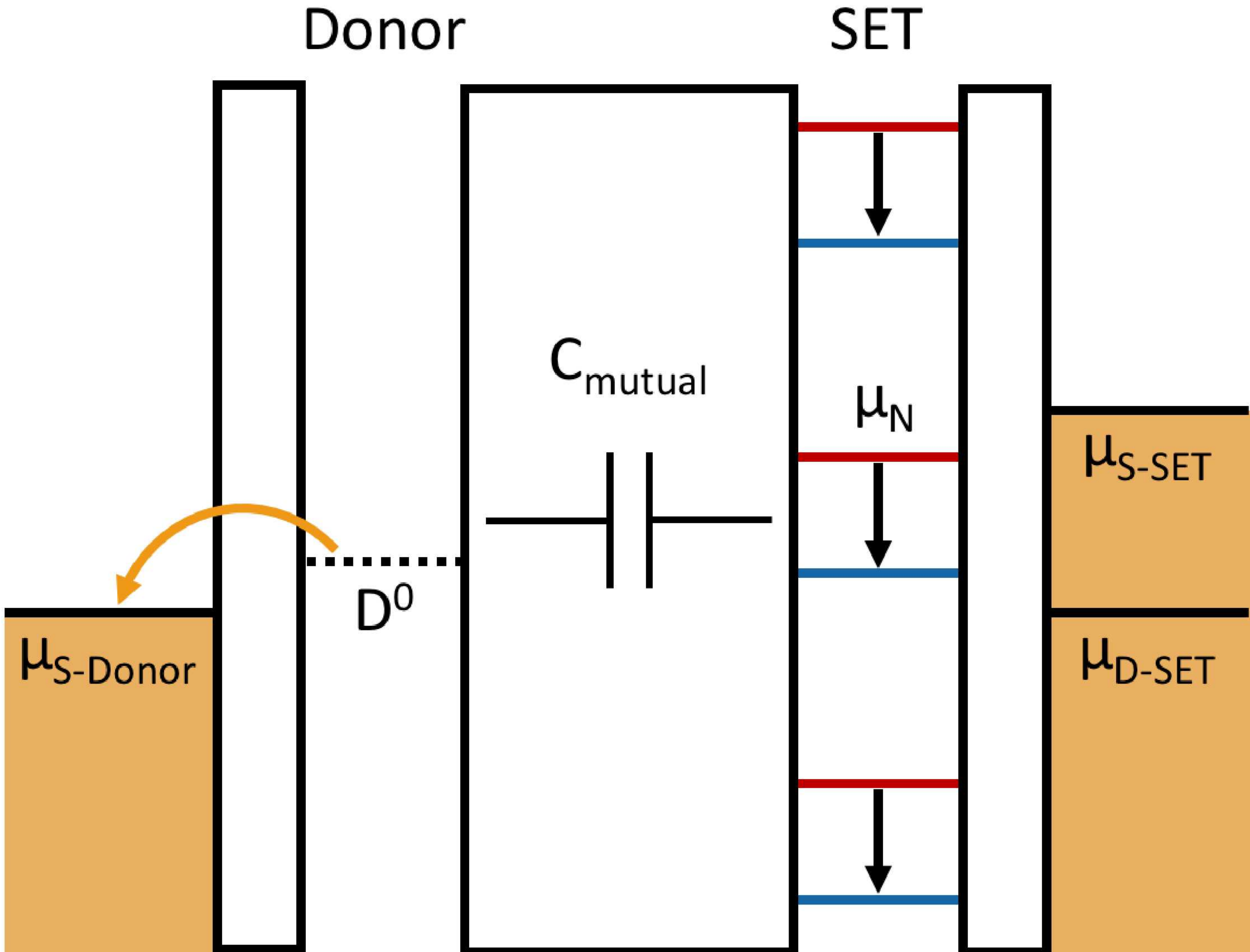


Charge Sensing

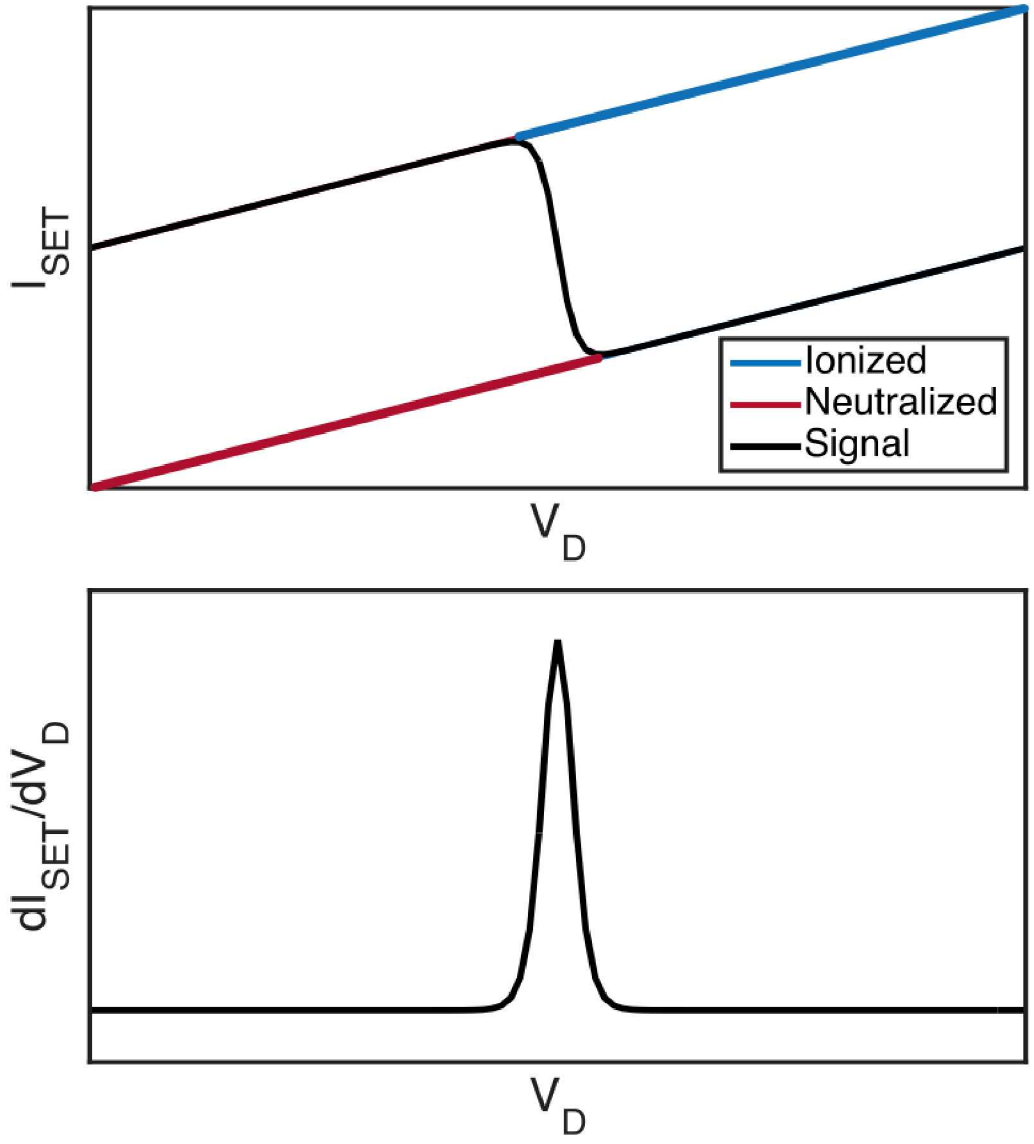


Charge Sensing: Donor Ionization

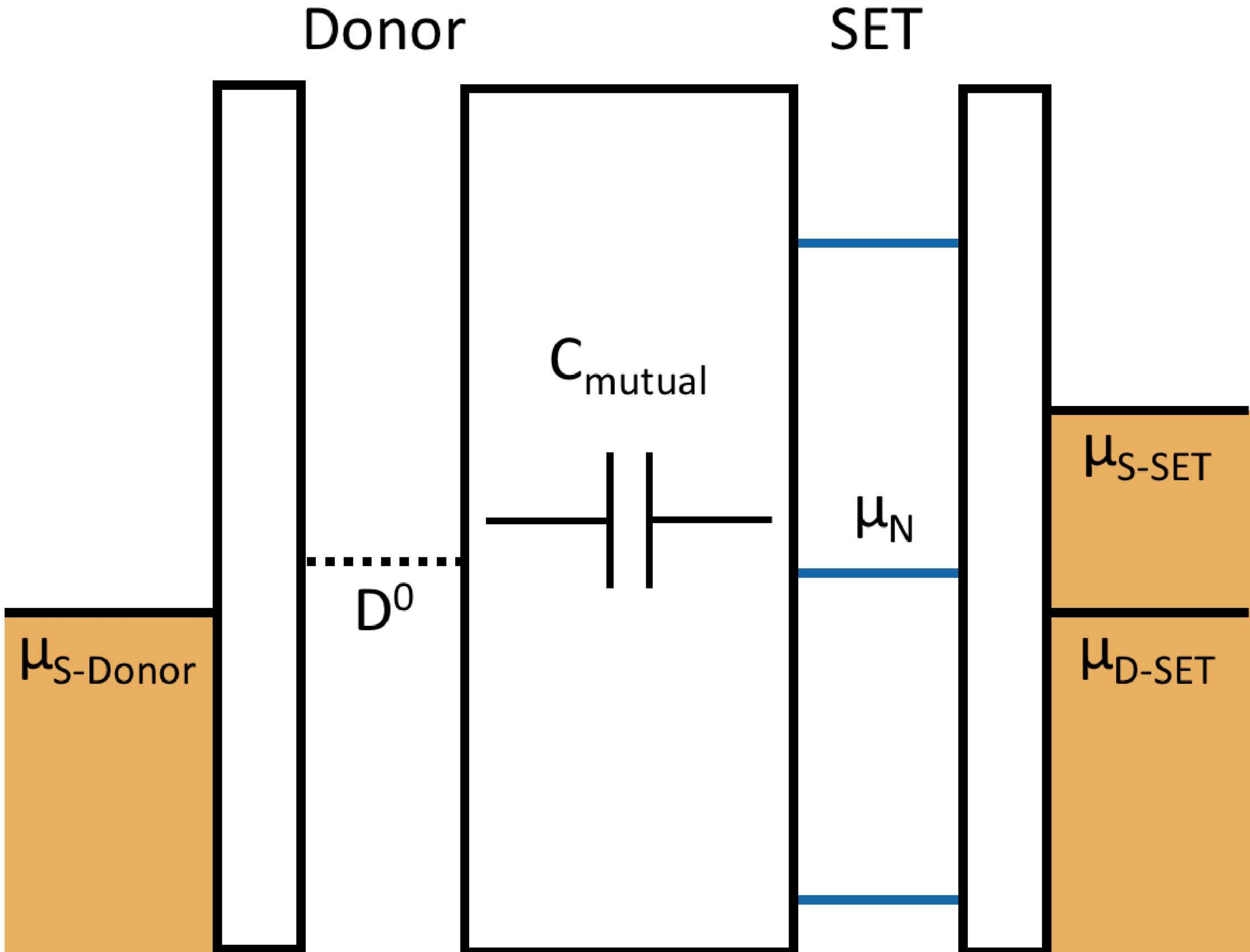




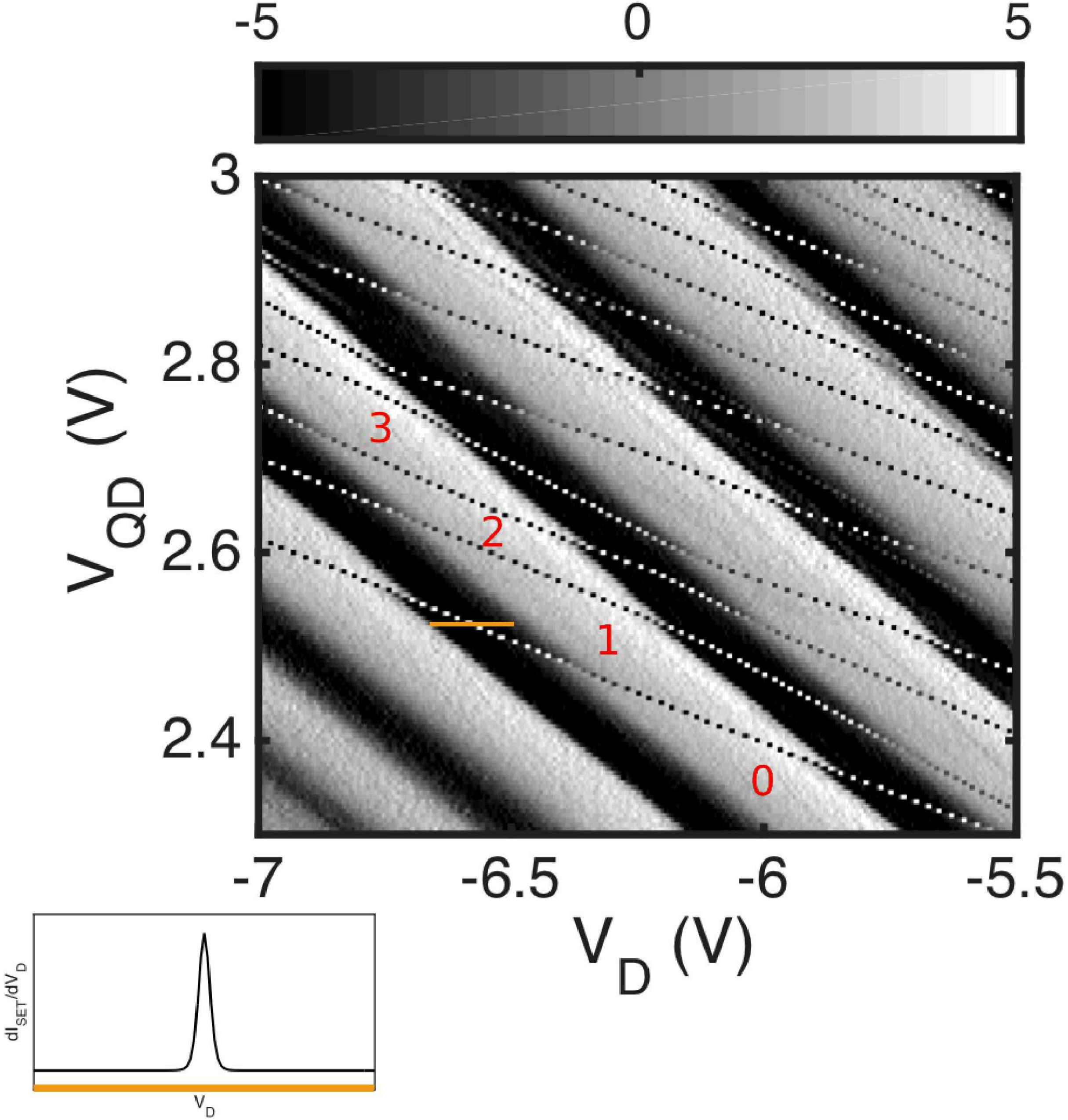
Charge Sensing: Donor Ionization

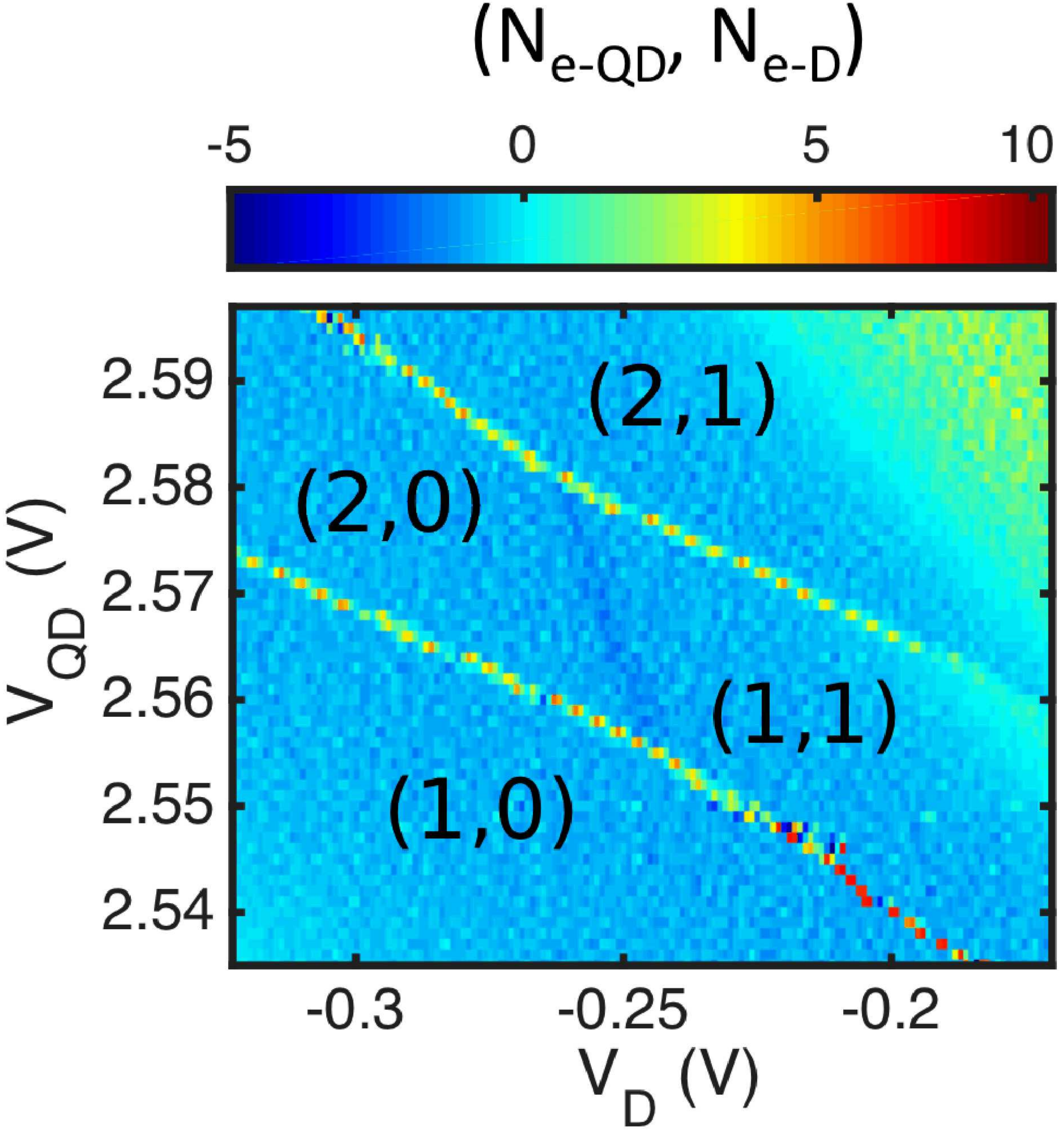


Can sense donor or QD occupancy.

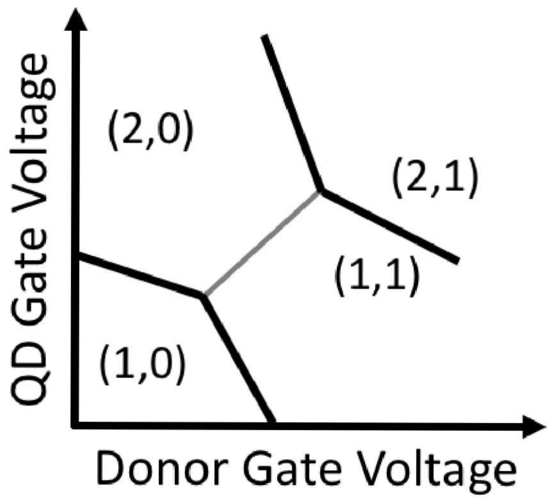


Charge Sensing: Stability Diagrams

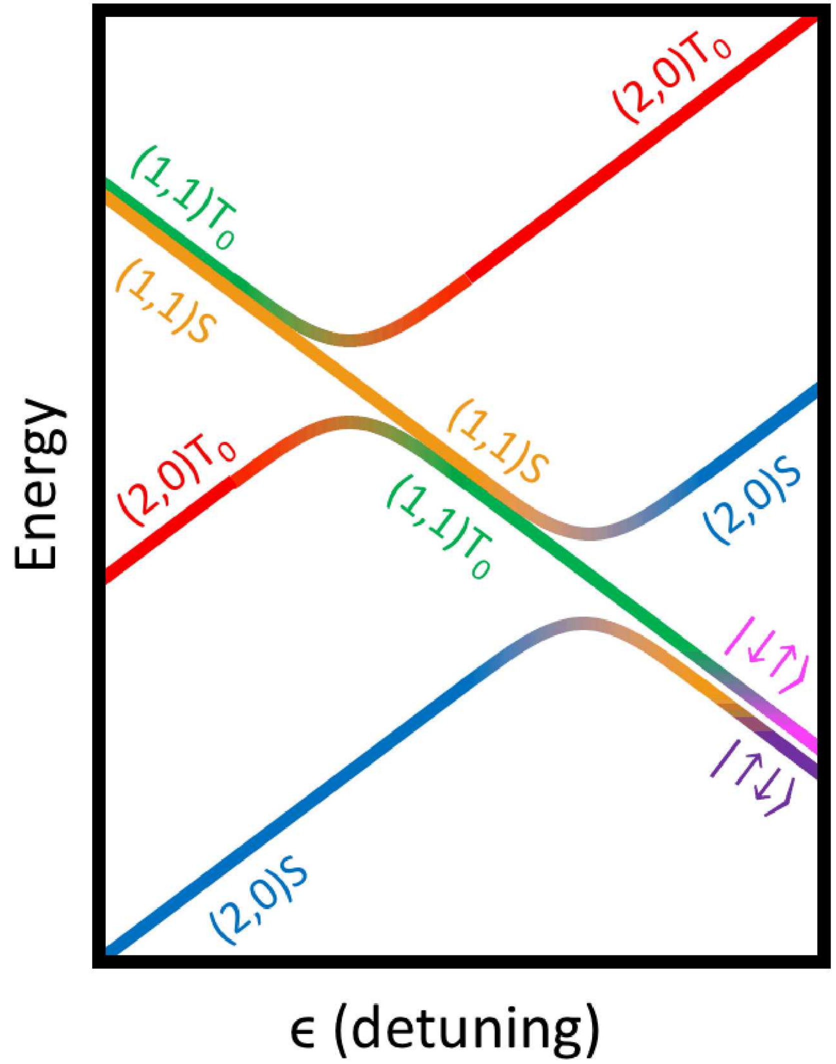


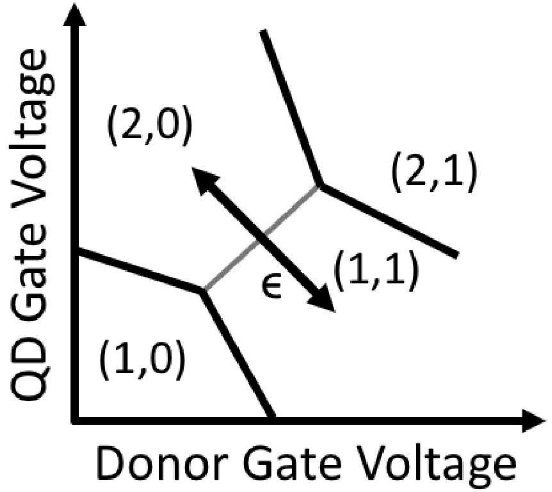


Singlet-Triplet Qubit



Singlet-Triplet Qubit



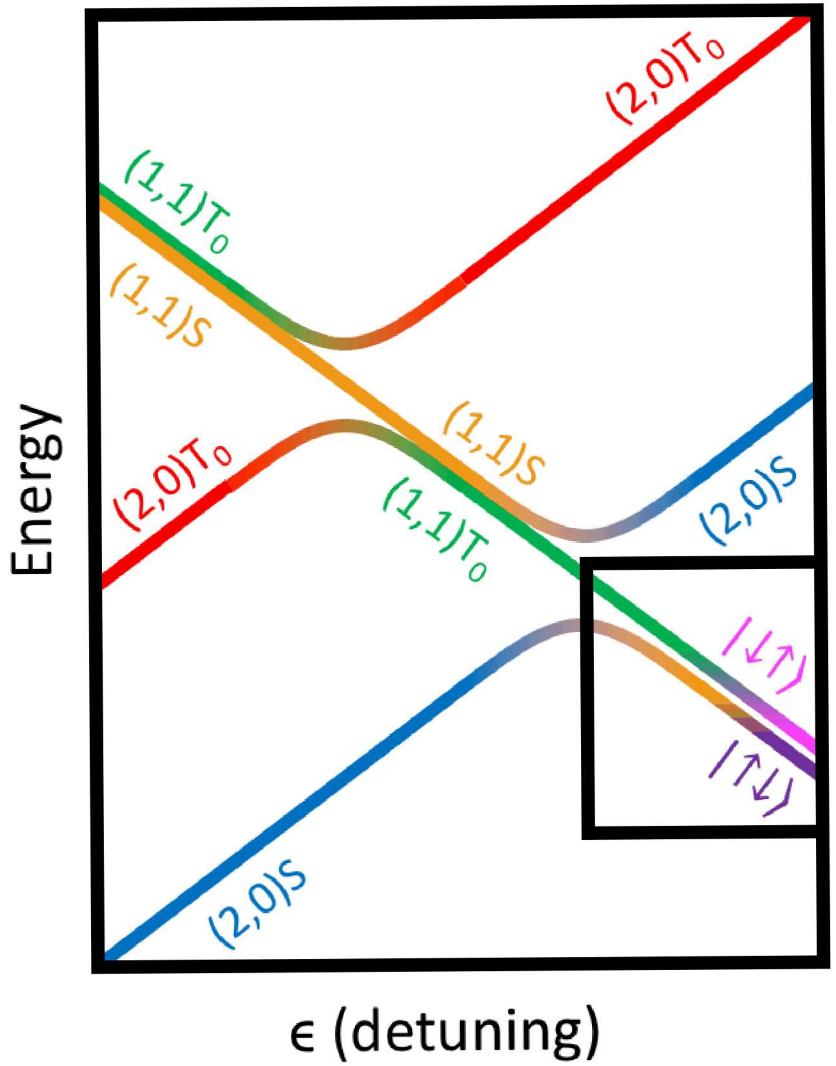


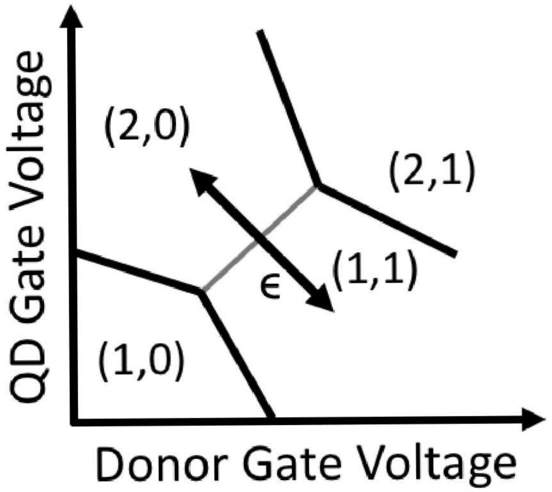
Spin and charge degrees of freedom.

Two electrons → singlets and triplets.

Singlet-Triplet Qubit: Operation

$$\hat{H}_{ST} = J(\epsilon)\hat{\sigma}_Z + \Delta E_Z(\epsilon)\hat{\sigma}_X$$



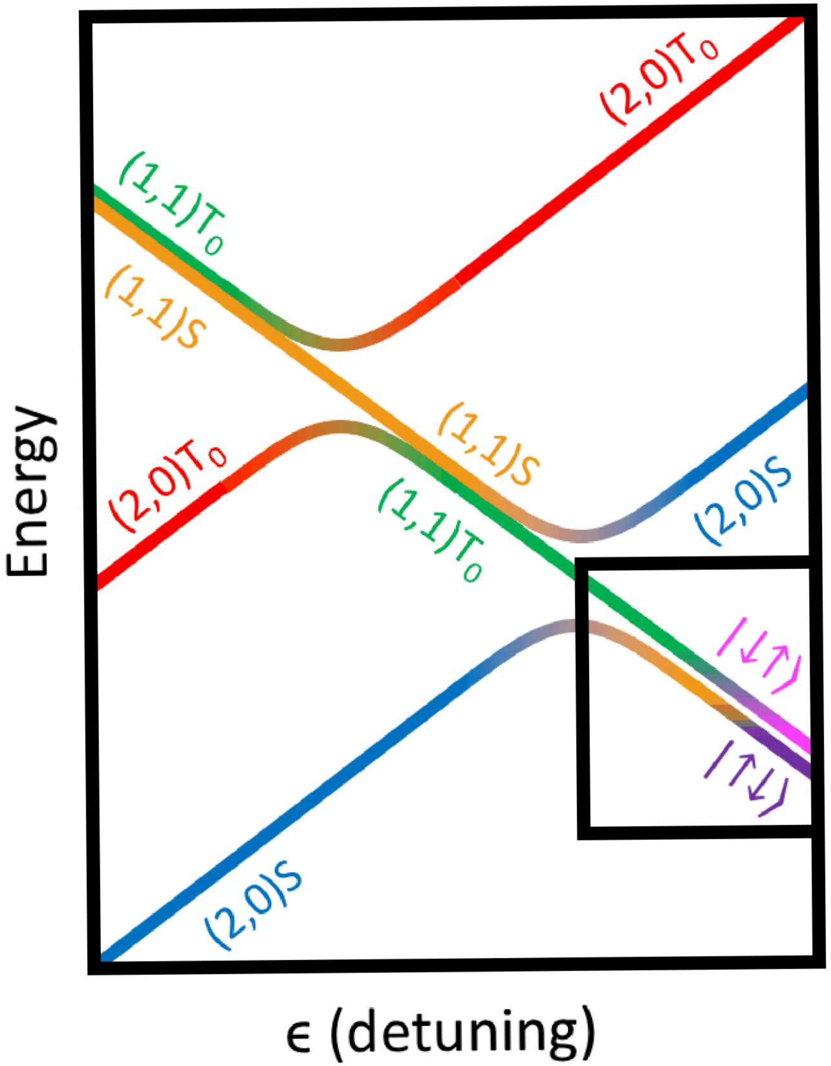


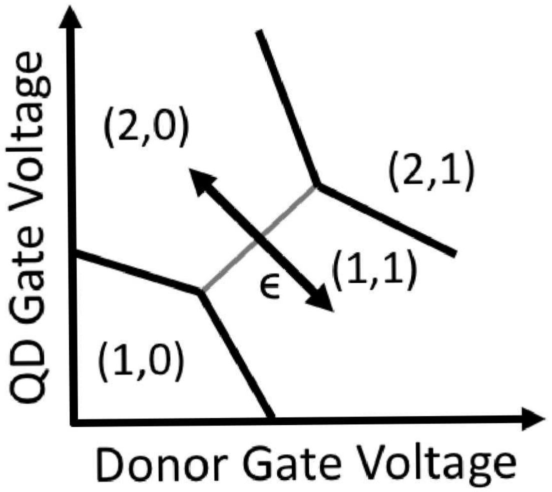
Exchange term depends strongly on detuning.

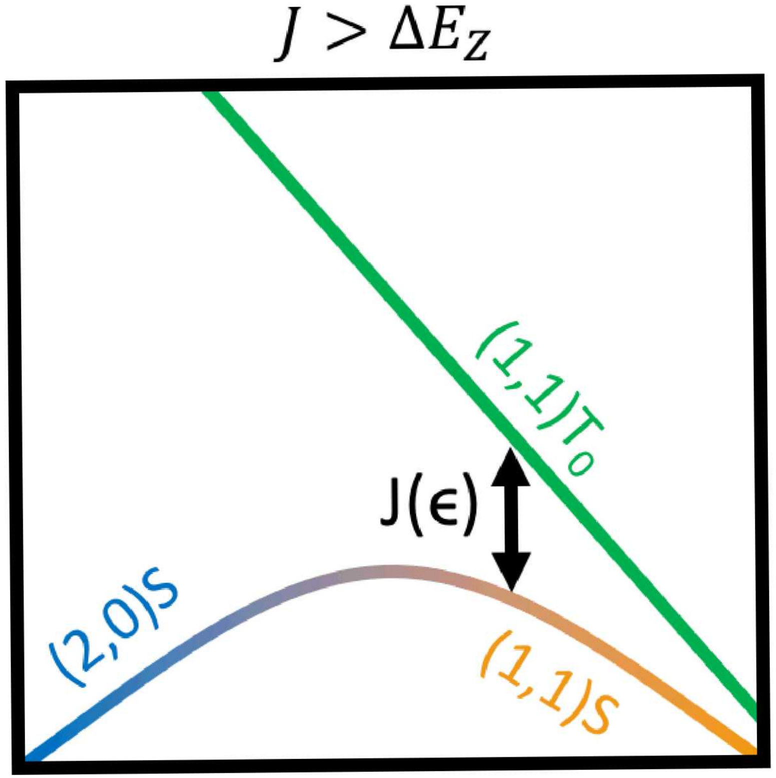
ΔE_Z due to contact hyperfine.

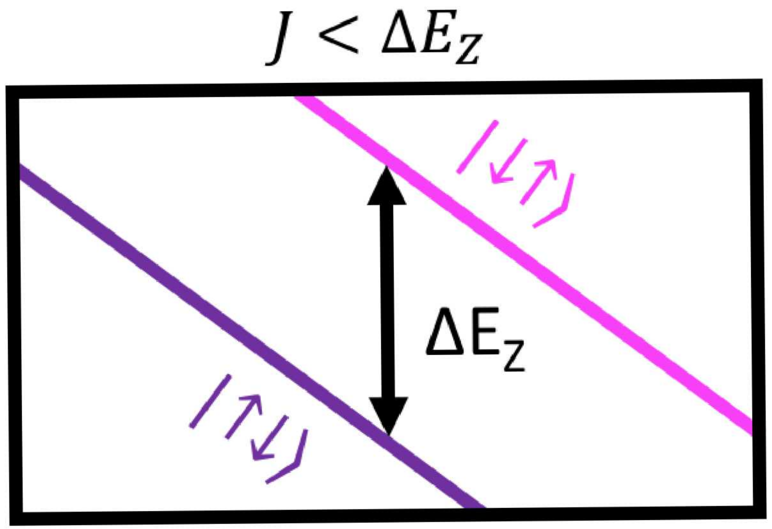
Singlet-Triplet Qubit: Operation

$$\hat{H}_{ST} = J(\epsilon)\hat{\sigma}_Z + \Delta E_Z(\epsilon)\hat{\sigma}_X$$

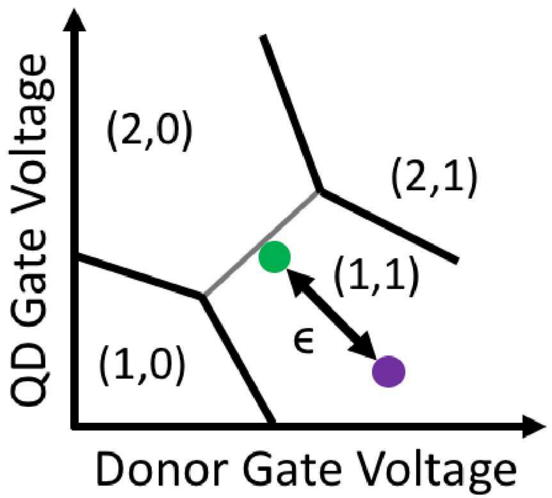


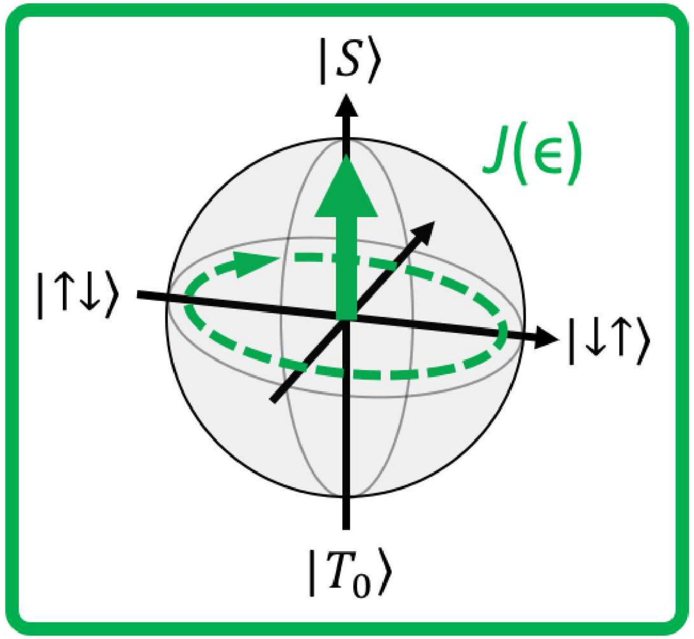


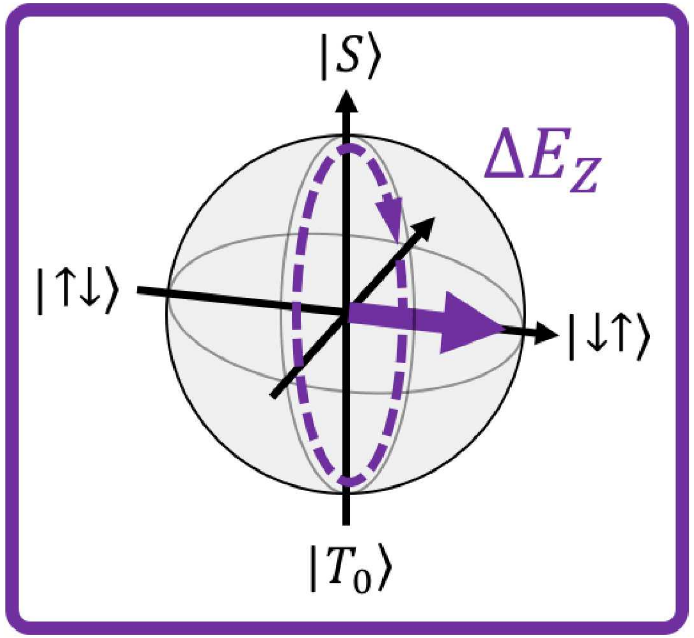




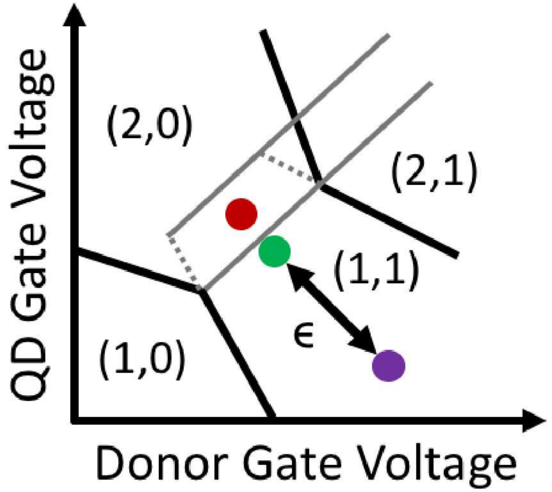
Singlet-Triplet Qubit: Operation

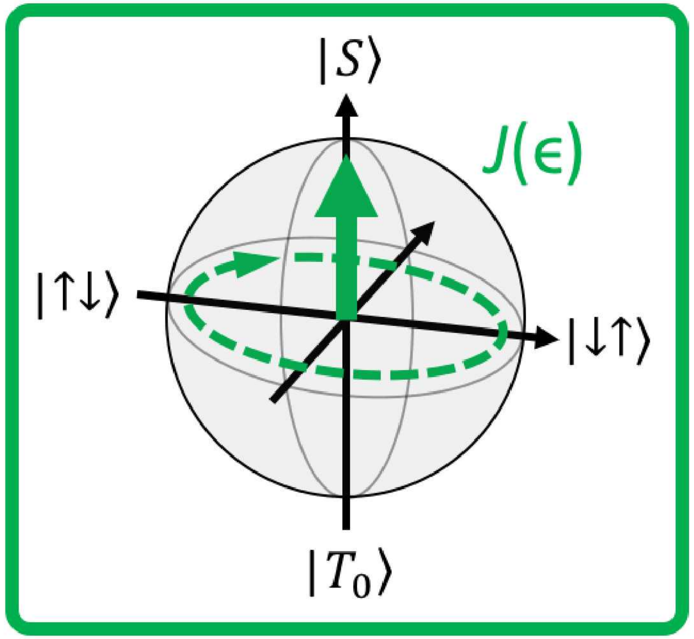




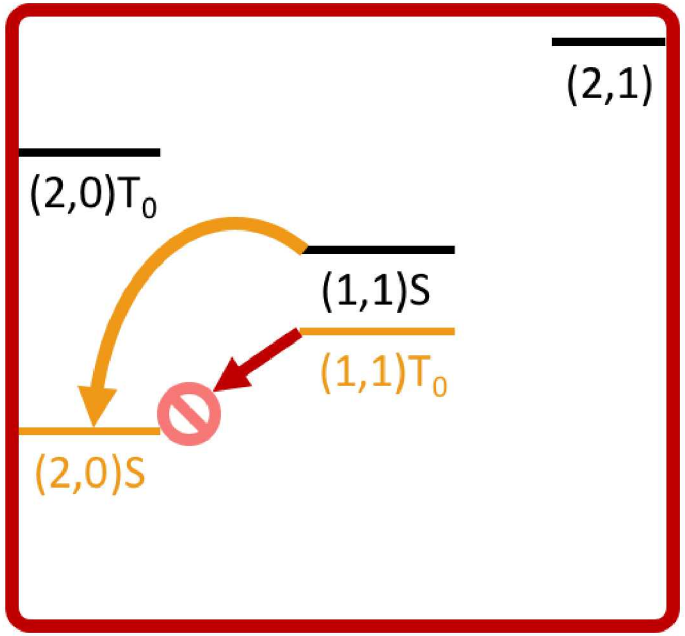


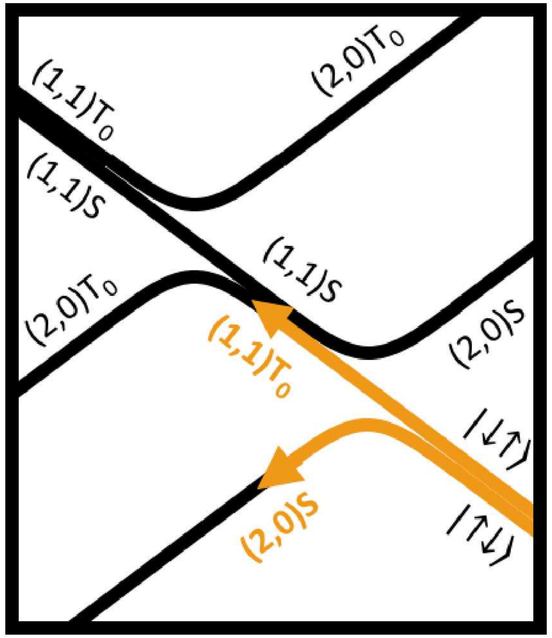
Singlet-Triplet Qubit: Pauli Spin Blockade Readout

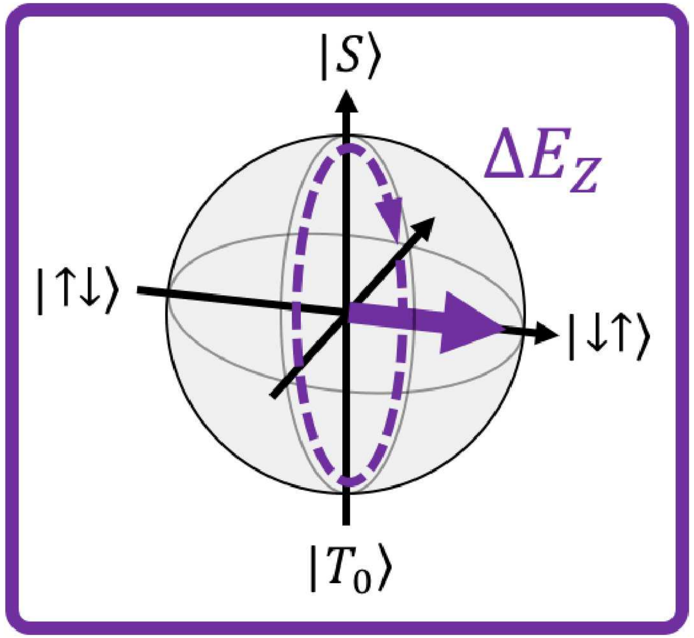




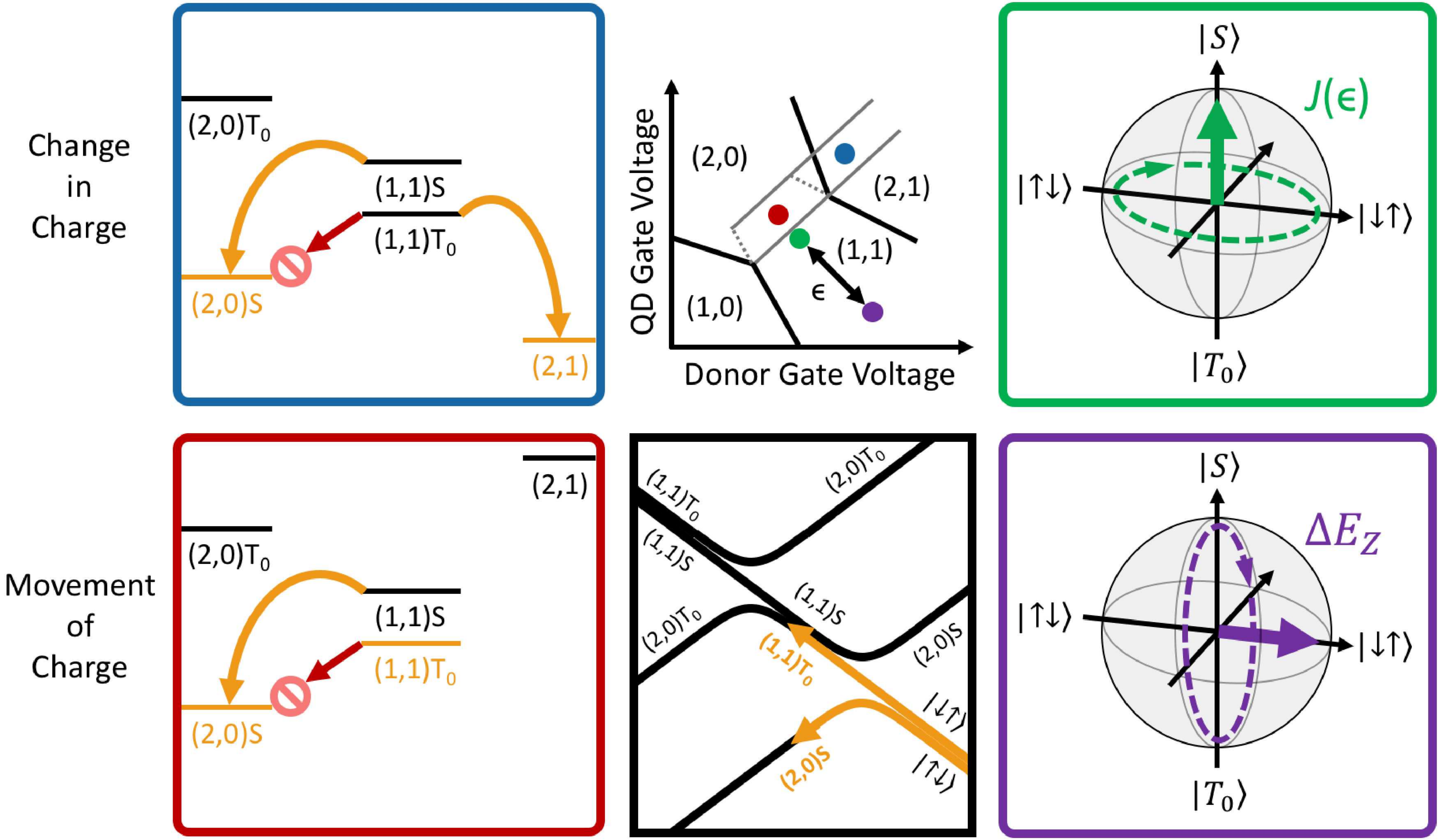
Movement of Charge





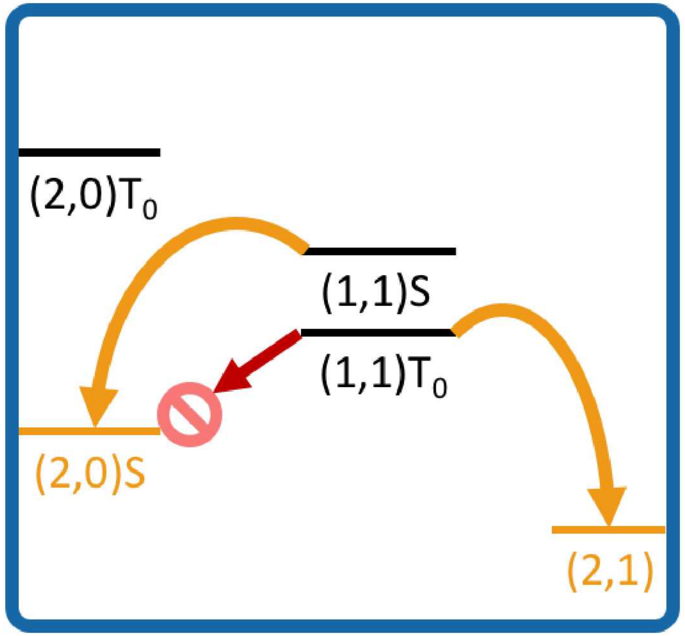


Singlet-Triplet Qubit: Latched Charge Readout



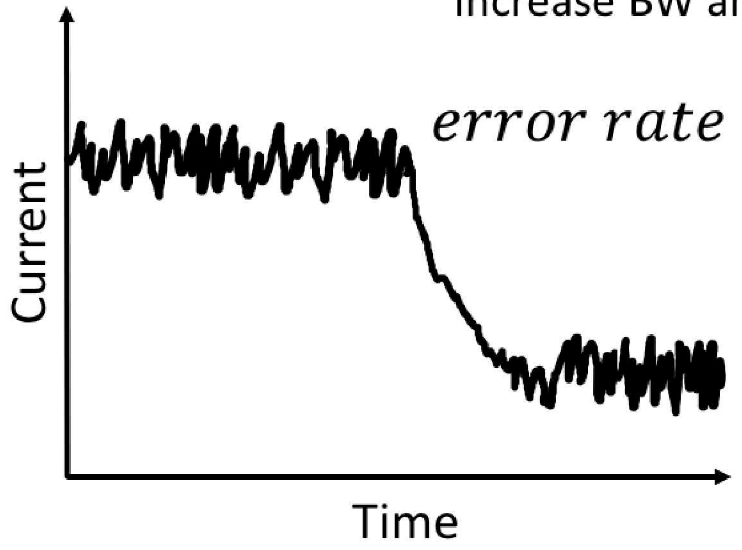
Singlet-Triplet Qubit: Latched Charge Readout

Change in Charge



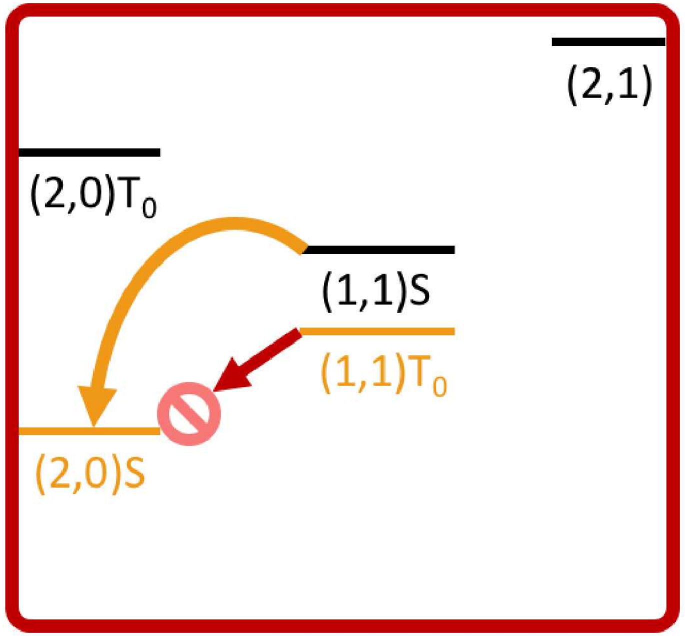
Increase BW and SNR → Readout fast relative to T_1

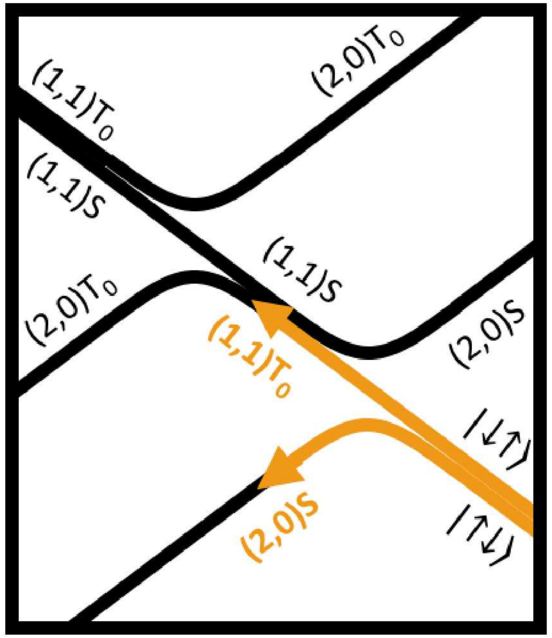
$$error\ rate = 1 - e^{\left(\frac{-t_{meas}}{T_1}\right)} \approx t_{meas}/T_1$$



Goal: Increase readout fidelity using heterojunction-bipolar-transistor (HBT) circuits.

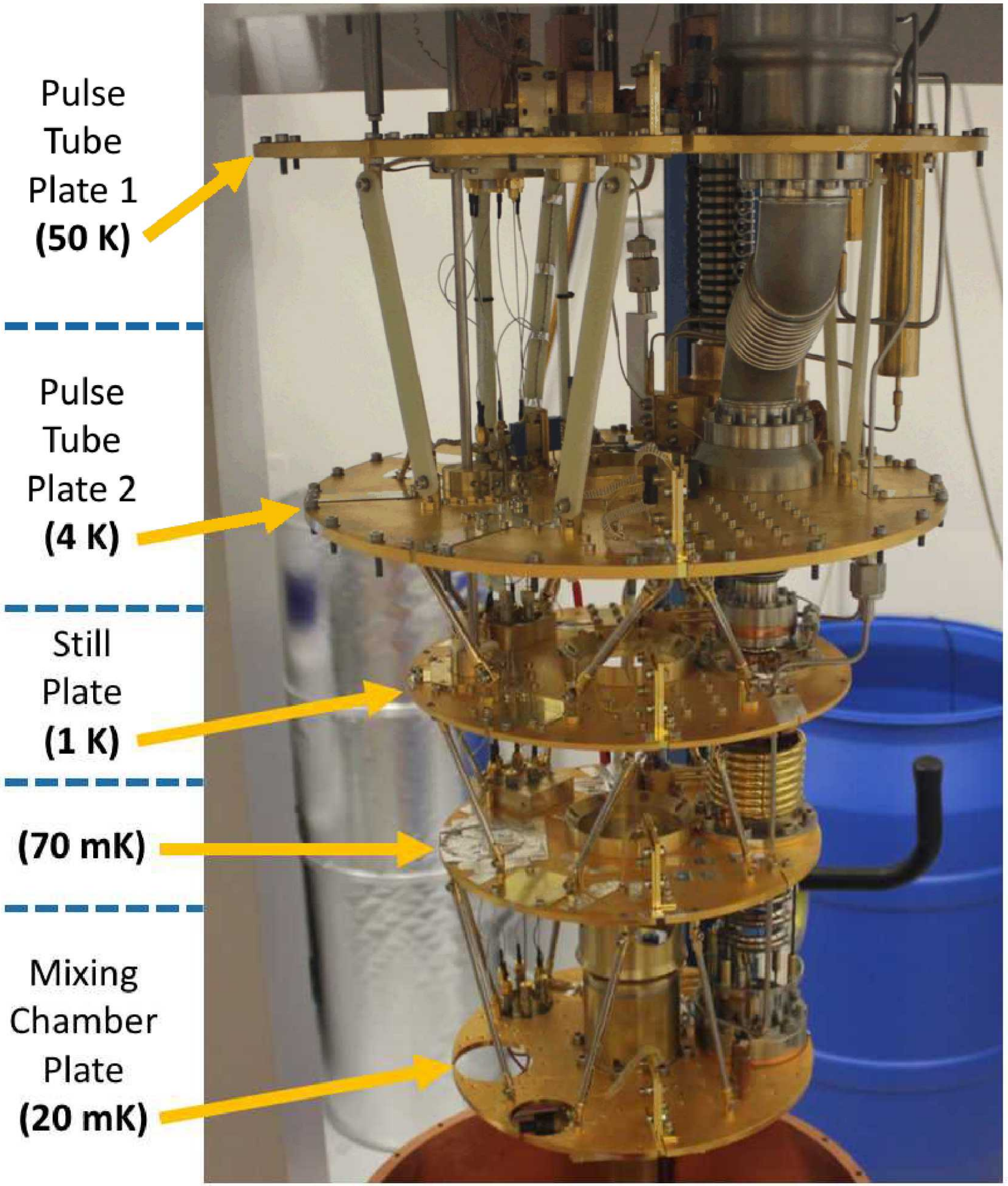
Movement of Charge

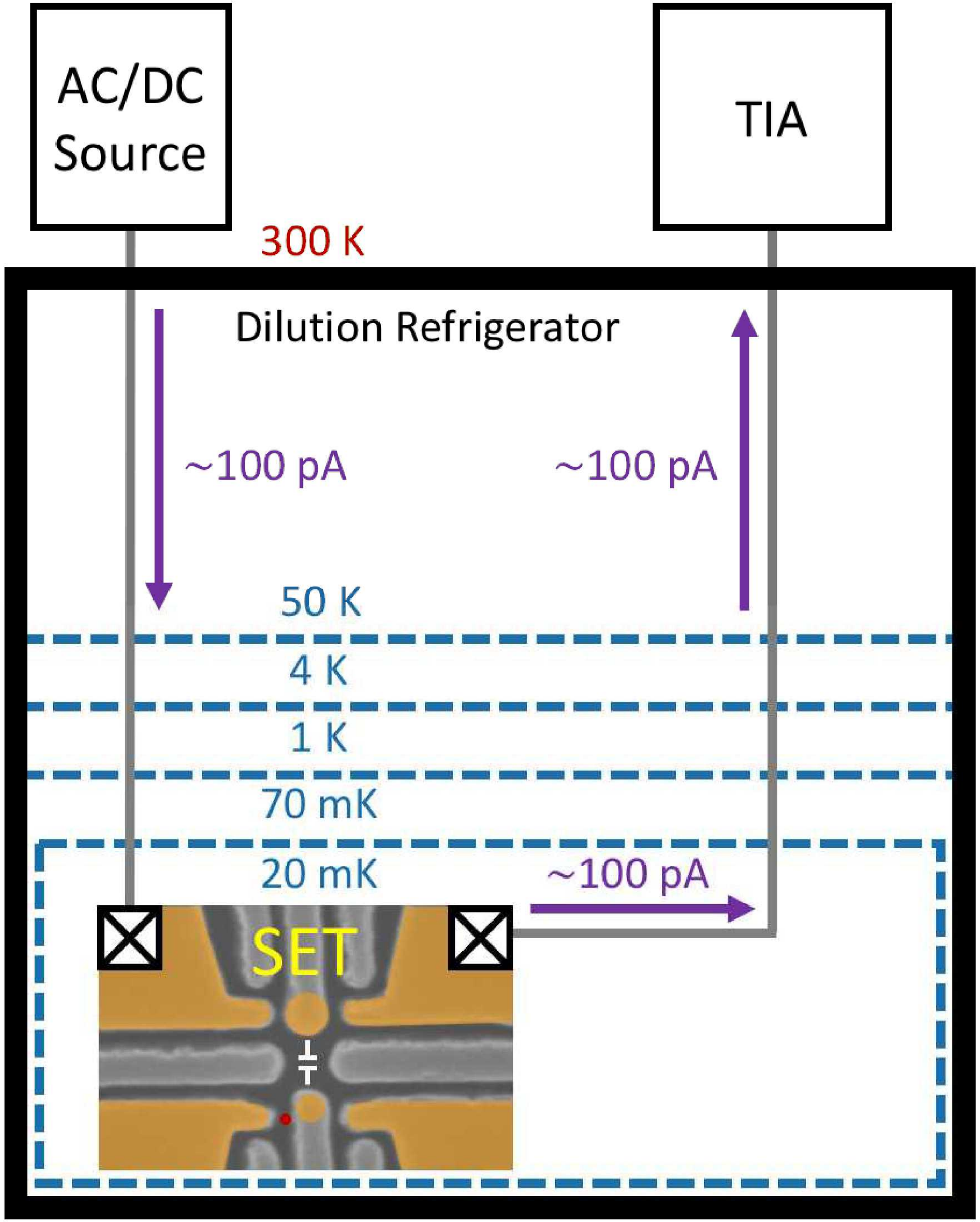




Amplification Background + Results

Basic Measurement Setup

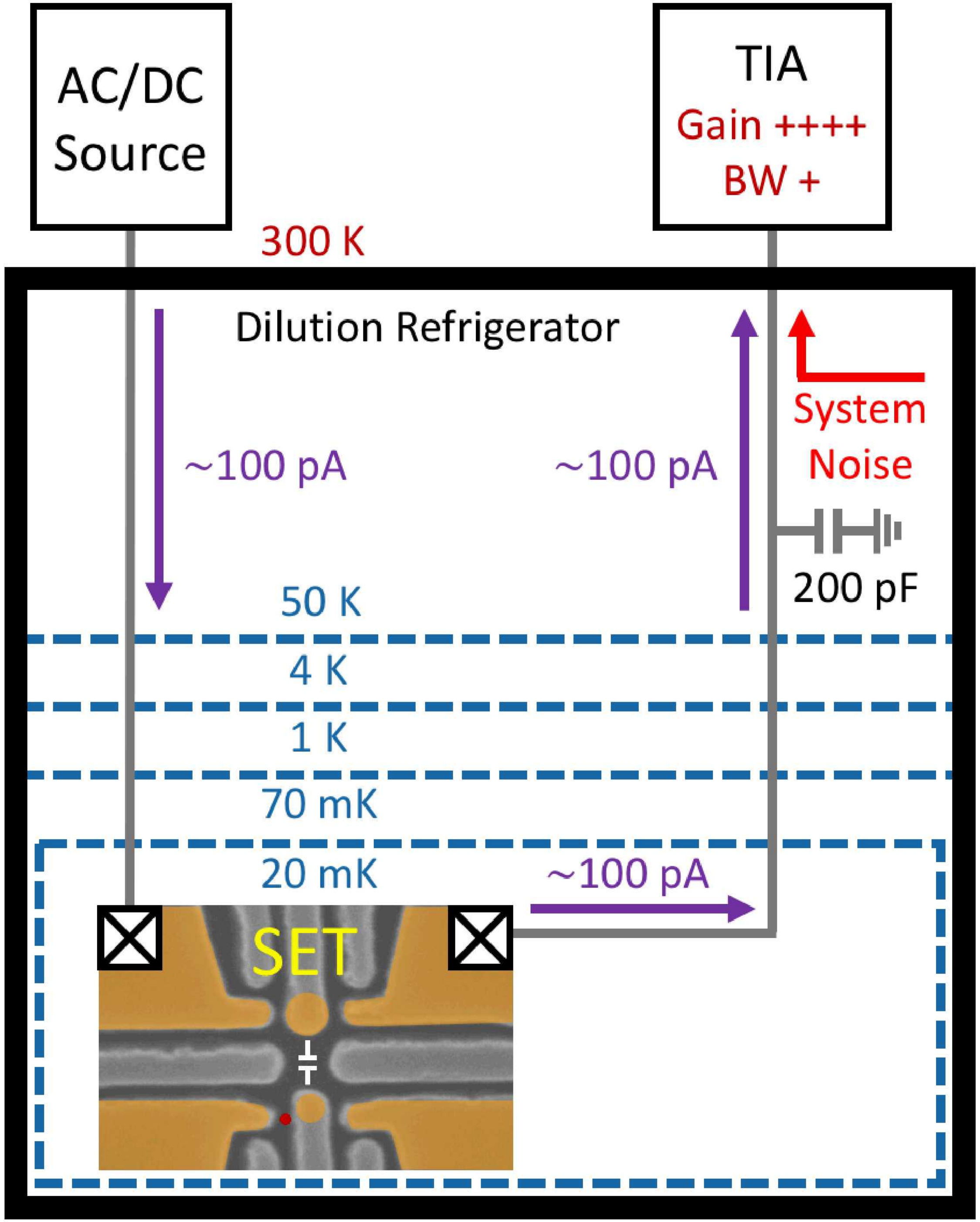




Basic Measurement Setup

Two Limitations:

1. System introduces relatively large amounts of noise.
2. Current-to-voltage amplifier gain limits bandwidth.

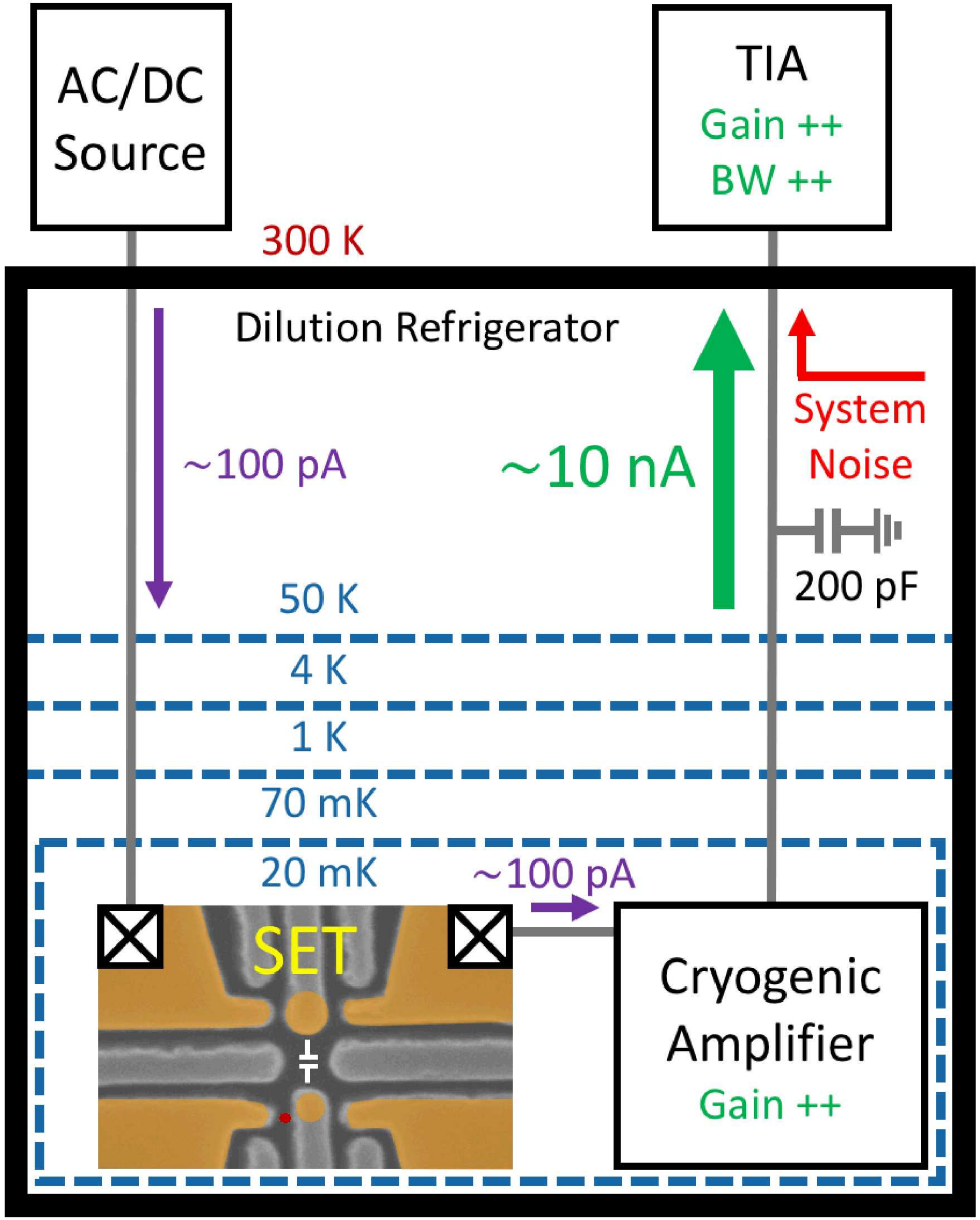


Cryogenic Amplification

Advantages:

1. Cryogenic amplifier increases signal before system noise is introduced.
   - Increases Signal-to-Noise.

2. Lower current-to-voltage amplifier gain.
   - Increases bandwidth.

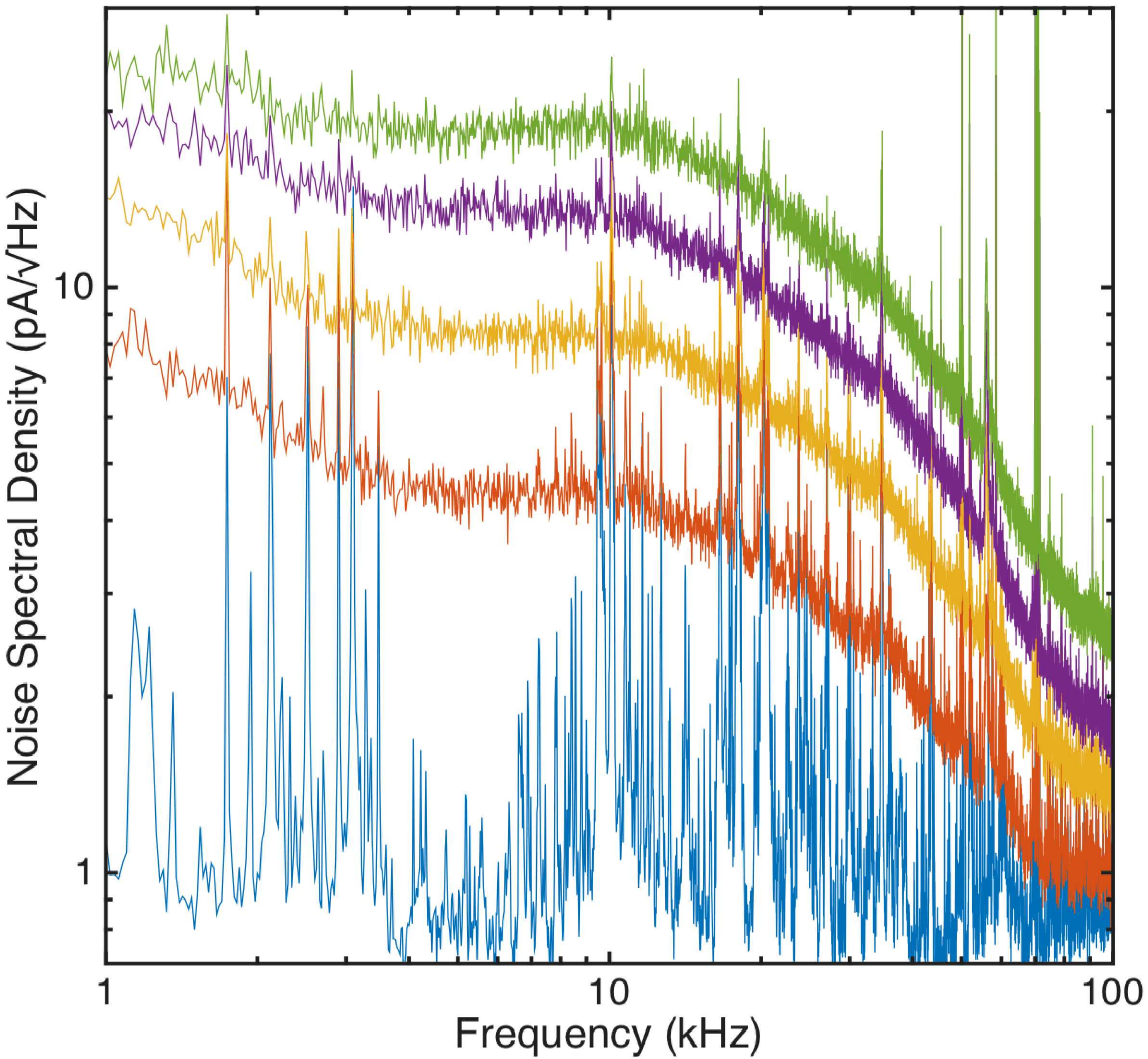


Cryogenic Amplification

Advantages:

1. Cryogenic amplifier increases signal before system noise is introduced.
   - Increases Signal-to-Noise.

2. Lower current-to-voltage amplifier gain.
   - Increases bandwidth.

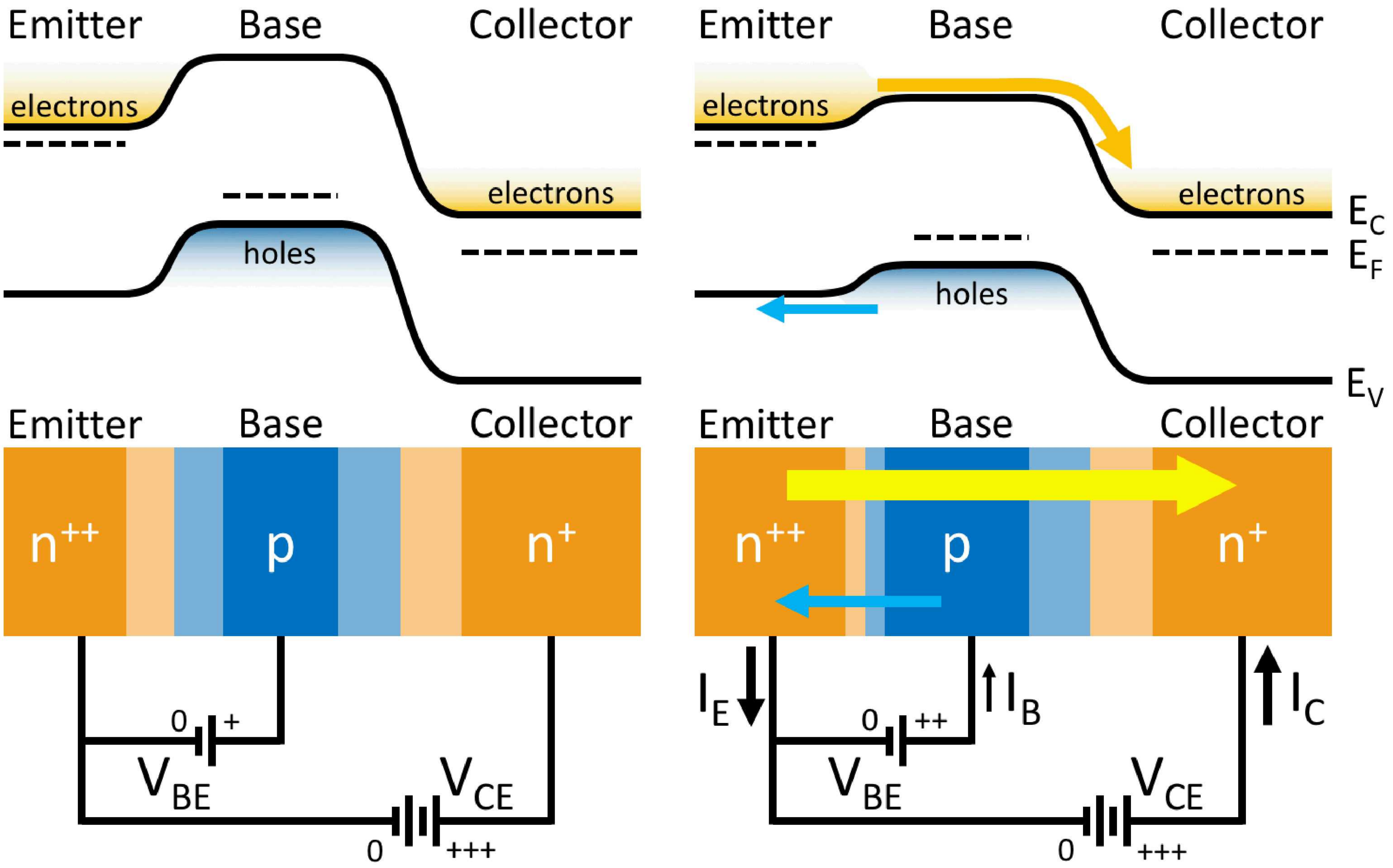


BJT Operation

Base-Emitter forward biased.

Collector-Base reverse biased.

Small voltage fluctuations on Base-Emitter result in large current fluctuations on Collector-Emitter.

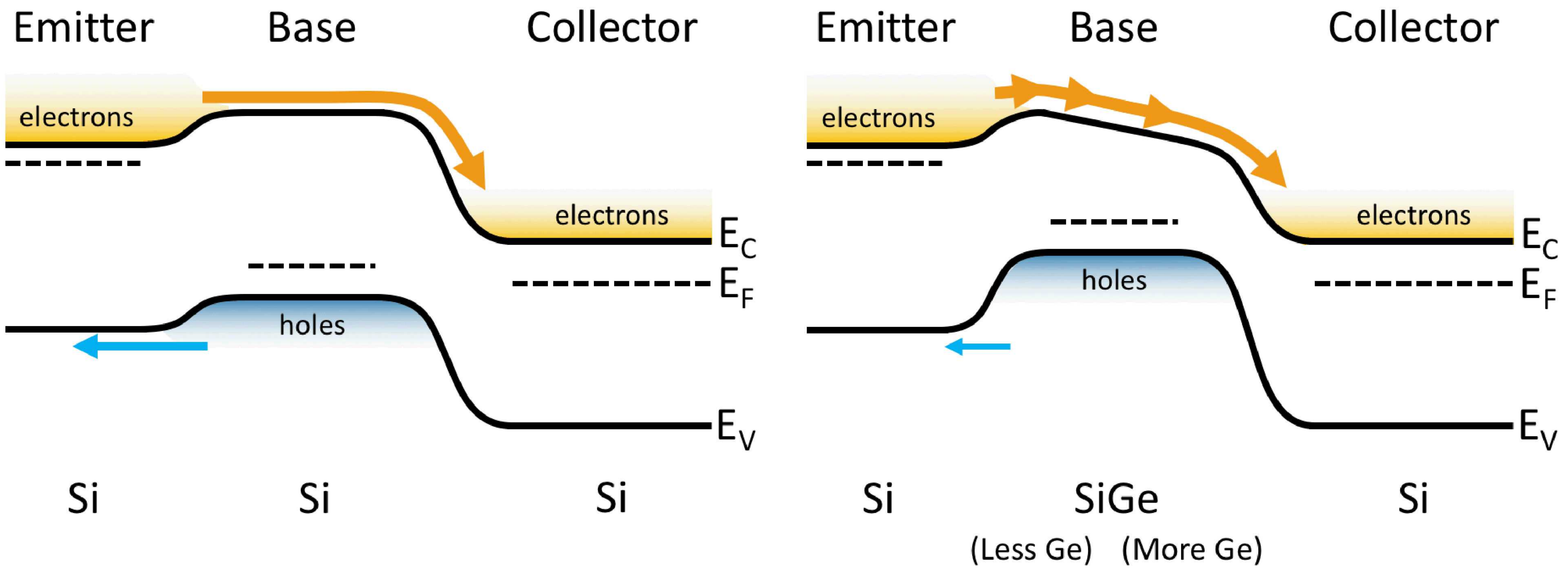


BJT vs. HBT

HBT Advantages:

1. Faster frequency response.
2. Higher base doping.
3. Higher gain.
4. Cryogenic operation.

BJT



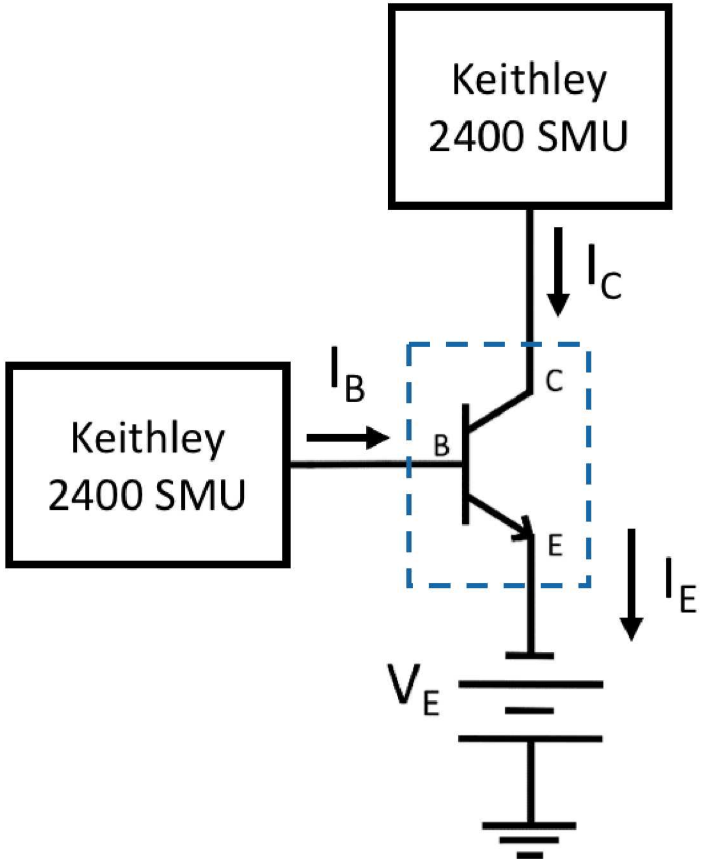
HBT DC Characterization

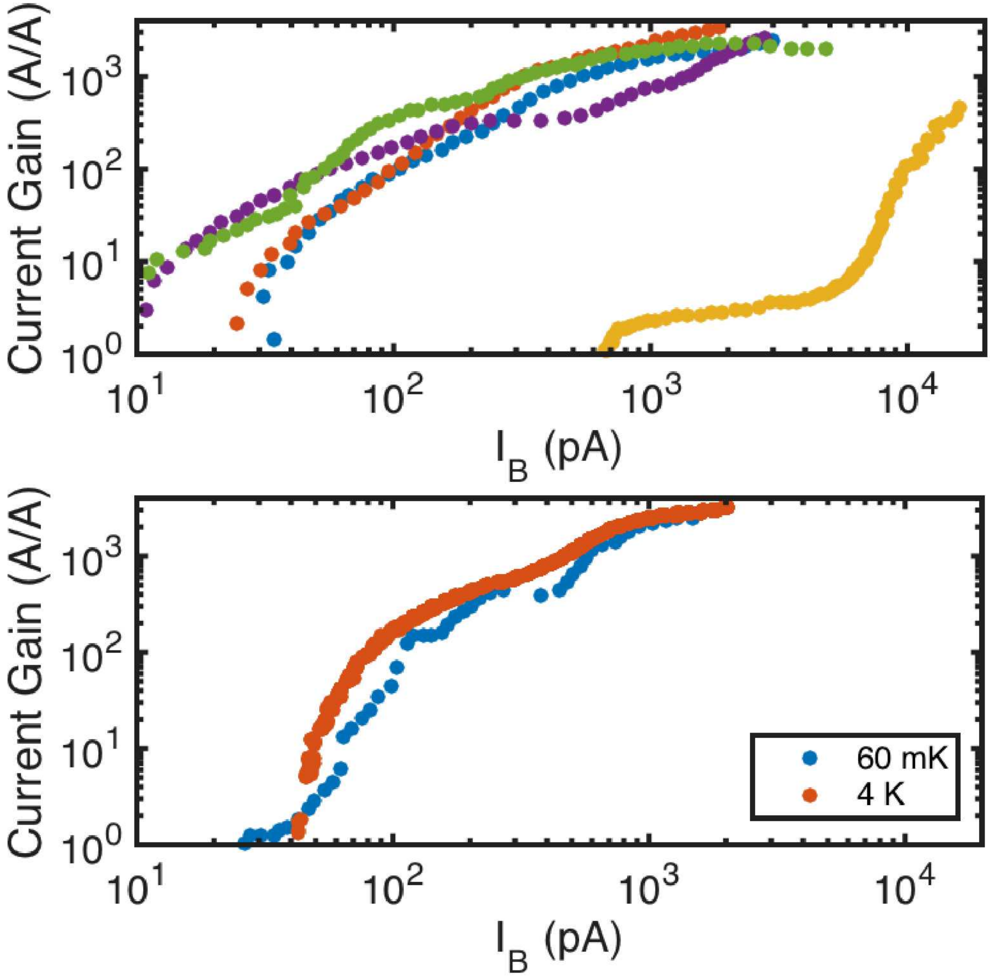
HBTs initially characterized at 4 K.

80%+ of HBTs operate at 4 K.

20% of HBTs operate at 4 K with high current gain and low bias current.

HBTs operate similarly at 4 K and 60 mK (tunneling transport mechanism).





HBT Amplifier Circuits

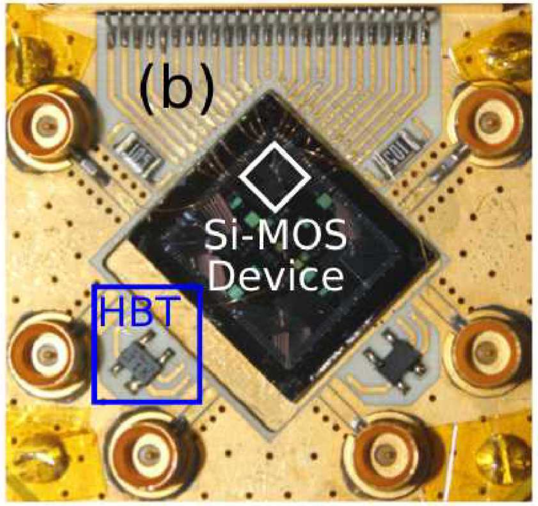
Two Circuits Characterized:

Current-Biased HBT Circuit (CB-HBT).

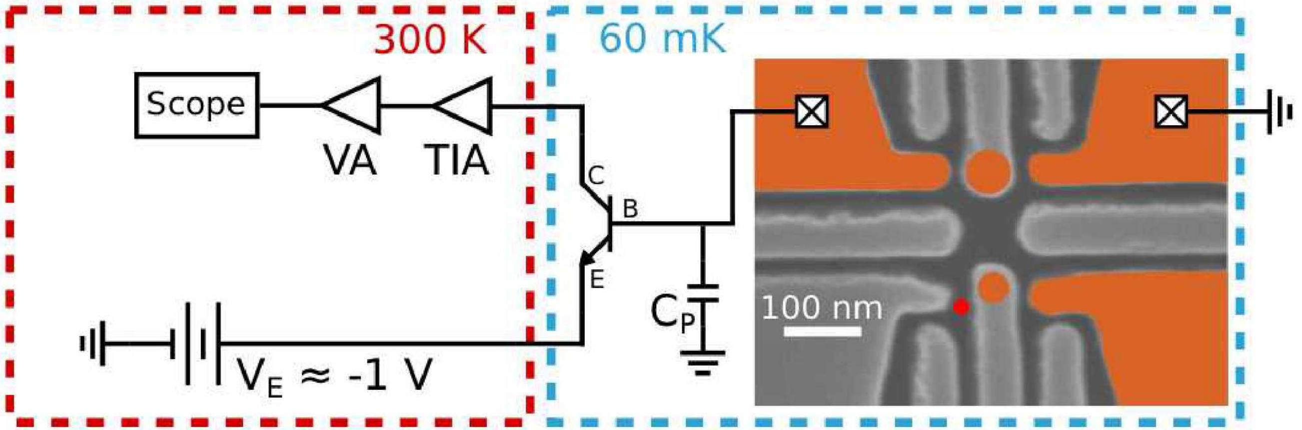
AC-Coupled HBT Circuit (AC-HBT).

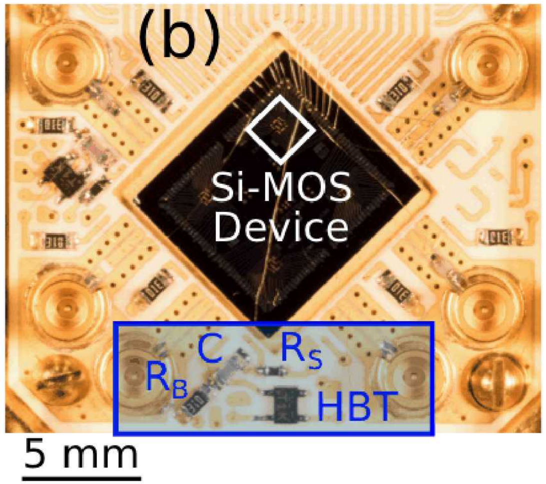
Additional elements for AC-HBT shown with blue shading.

AC coupling motivated by Lisa's HEMT work [Tracy, et. al. APL 2016].

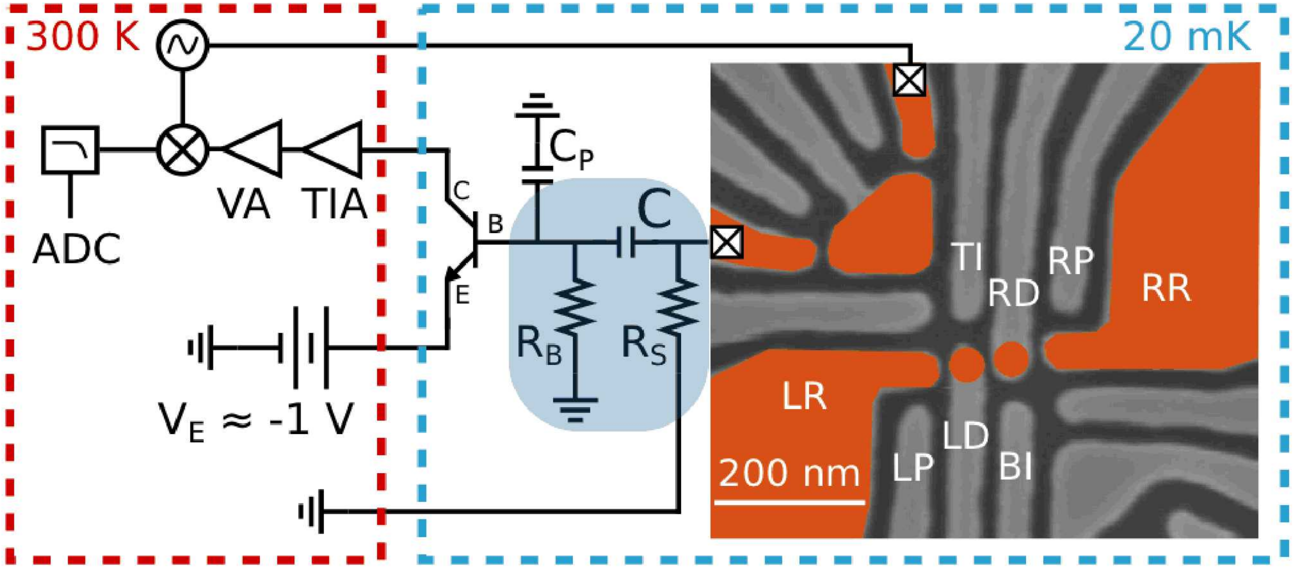


CB-HBT





AC-HBT

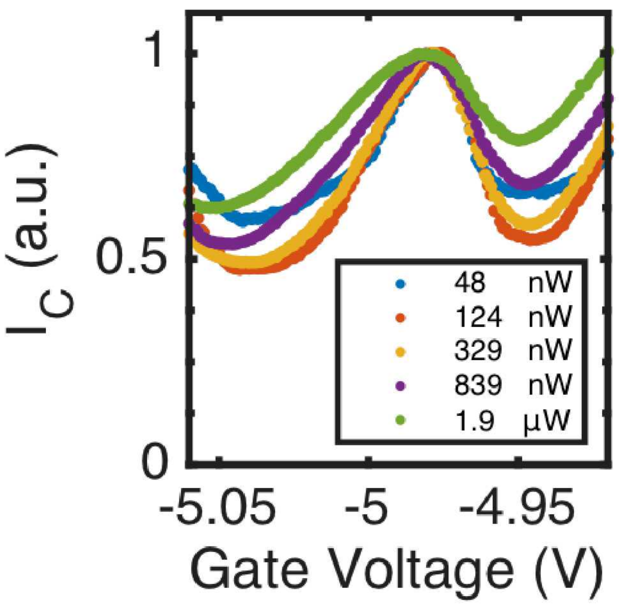


SET Biasing Difference

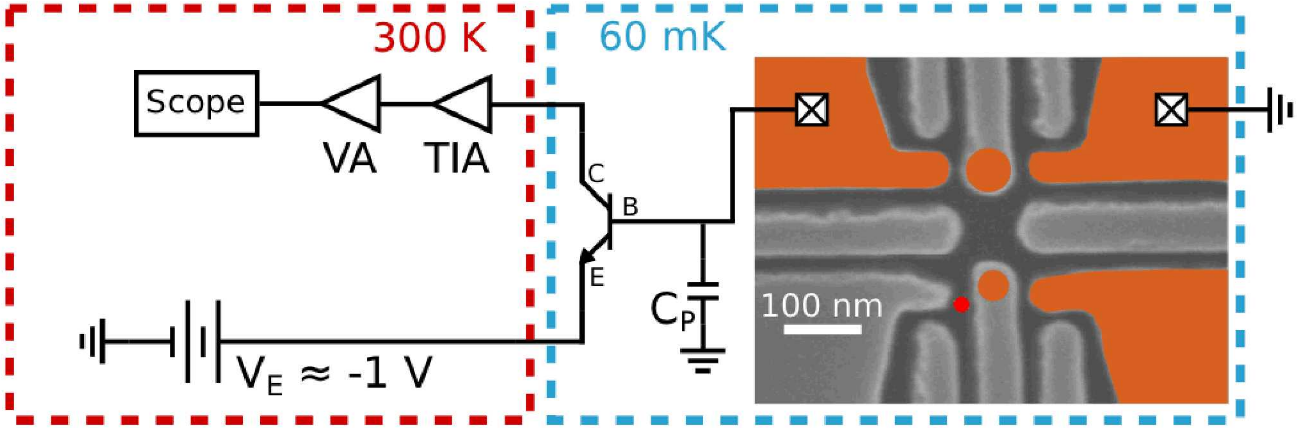
Coulomb blockade peak shown for either circuit (normalized current).

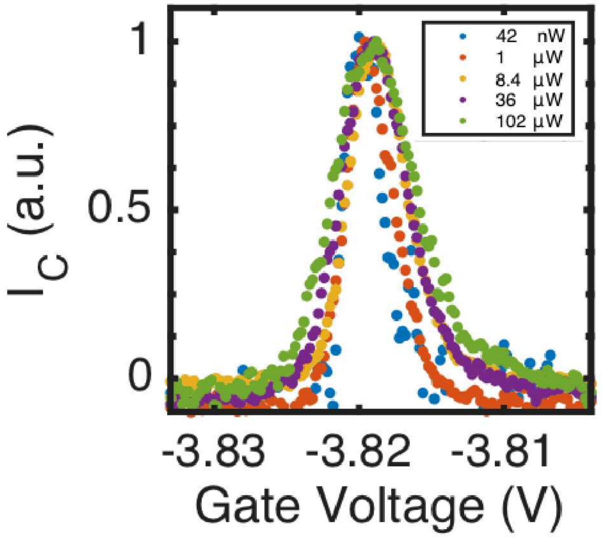
CB-HBT peak does not go to zero current.

AC-HBT peak behavior is similar to voltage-biased SET peak.

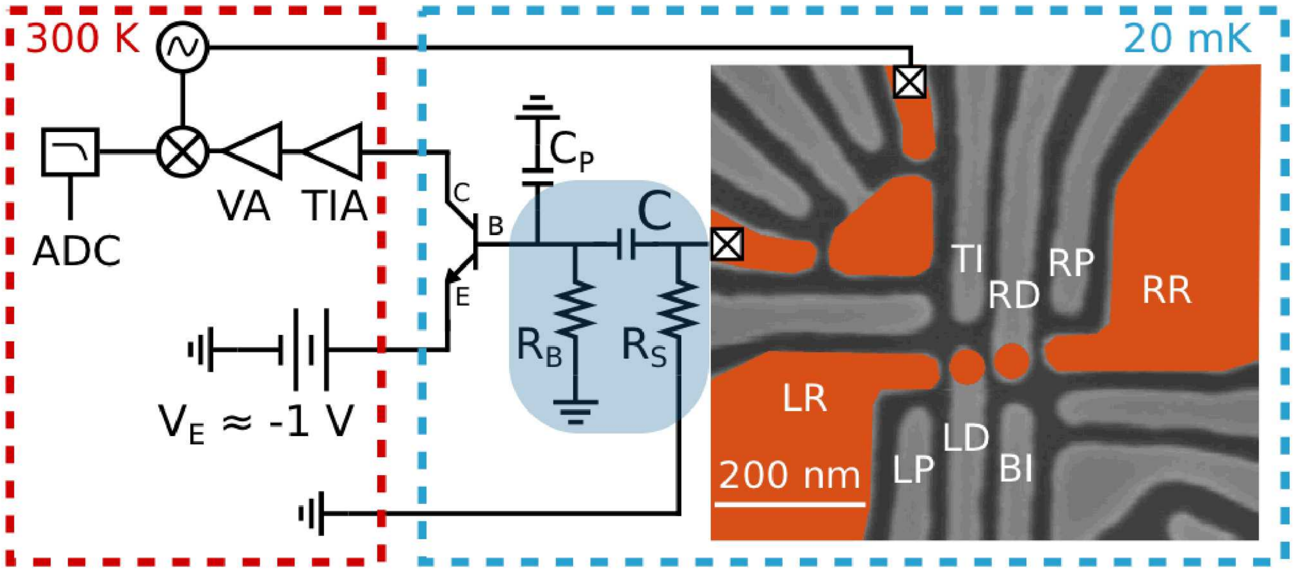


CB-HBT





AC-HBT



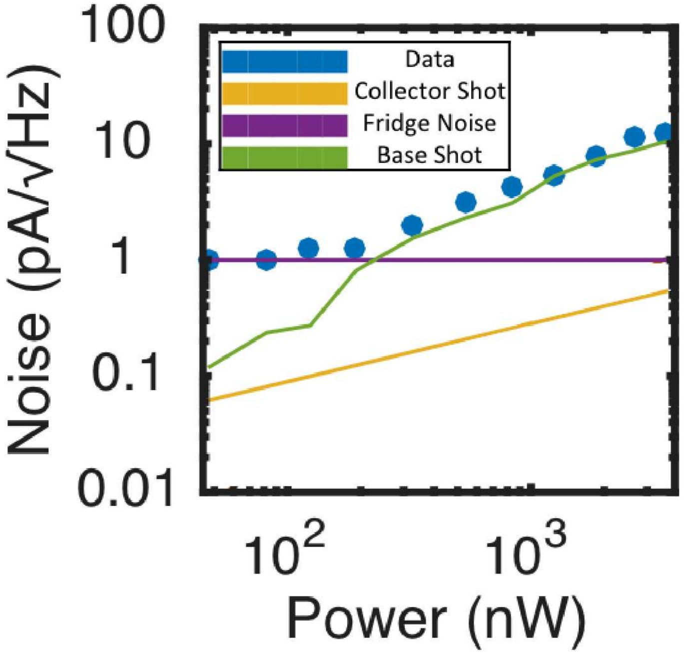
CB-HBT Noise Model

Noise model generated using Norton equivalent circuit and BJT small-signal gain model.

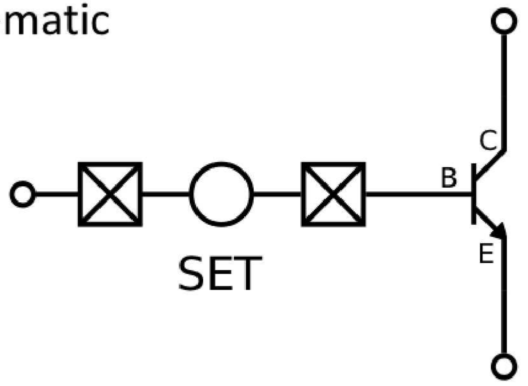
Noise measured at ~7 kHz.

Base shot noise dominates output noise (r_{SET} = 3 MΩ).

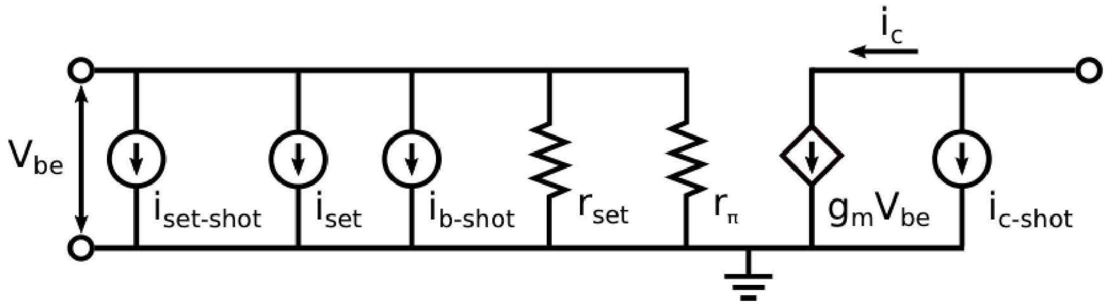
$$i_{b-shot} = \sqrt{2 * e * I_B * \Delta f}$$



Circuit Schematic



Equivalent Circuit



AC-HBT Noise Model

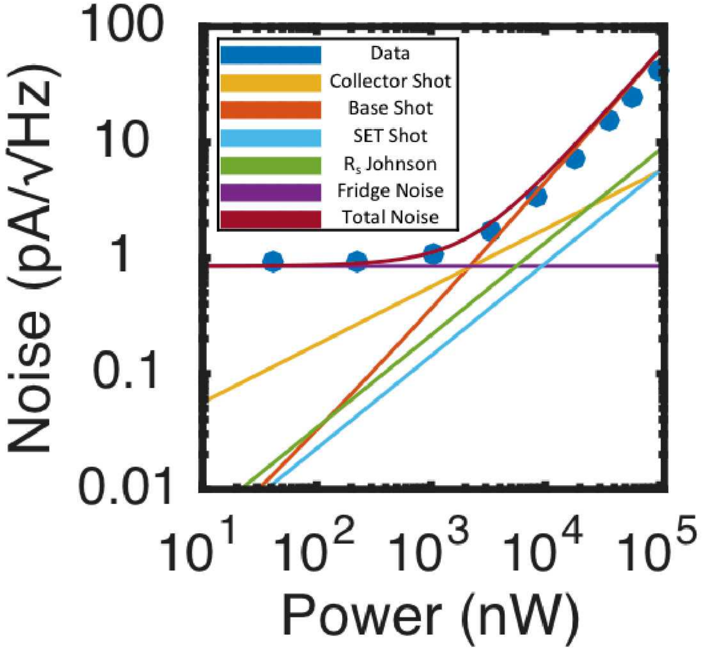
Noise model generated using Norton equivalent circuit and BJT small-signal gain model.

Coupling capacitor treated as short for noise frequencies.

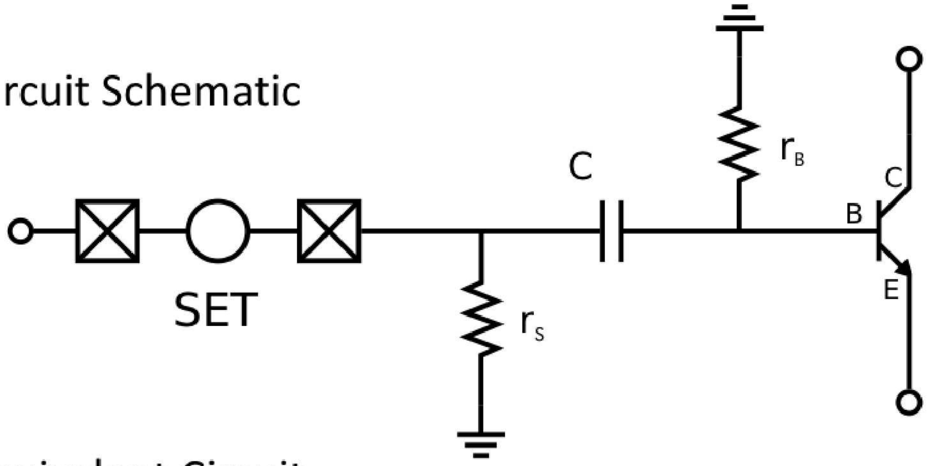
Noise measured at ~70 kHz.

Similarly, base shot noise dominates output noise.

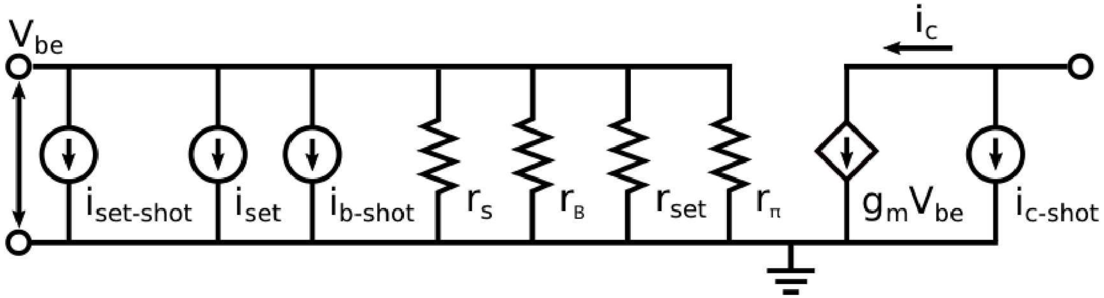
$$v_{s-johnson} = \sqrt{4 * k_B * T * r_S * \Delta f}$$



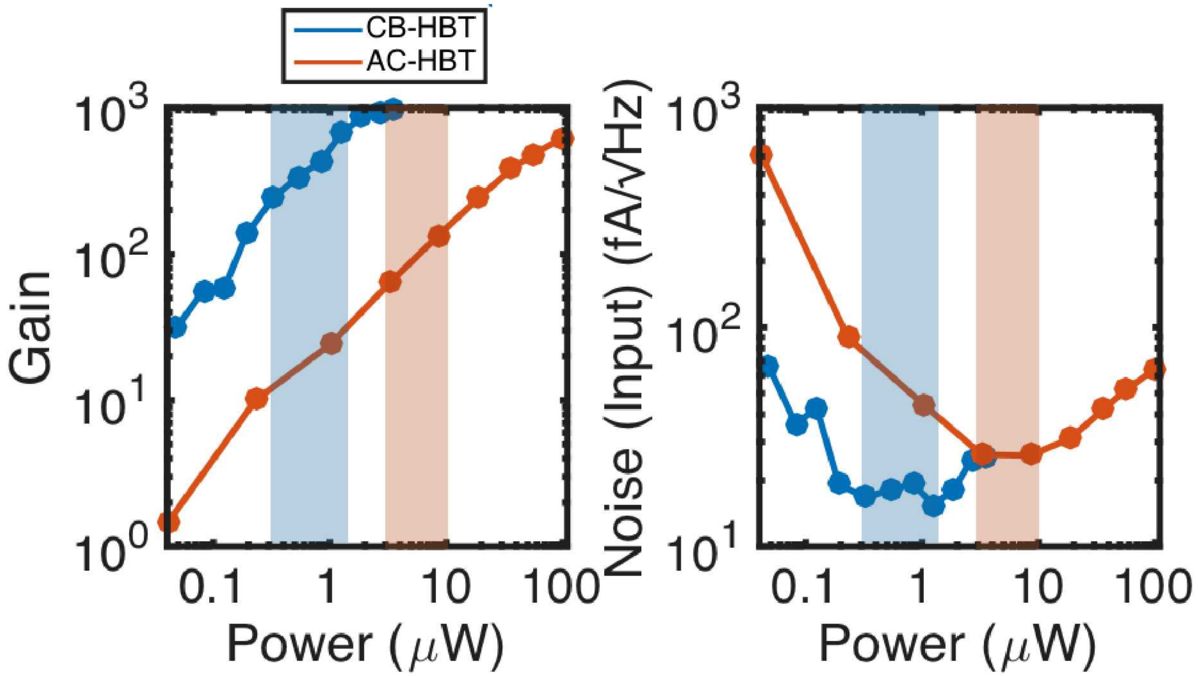
Circuit Schematic

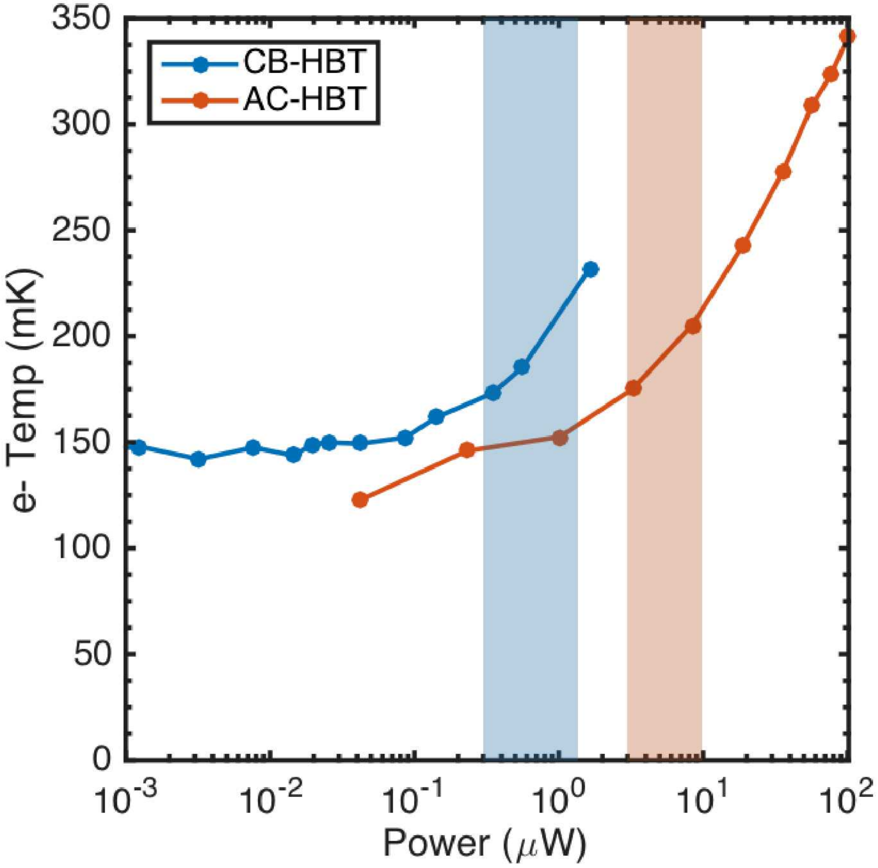


Equivalent Circuit



Amplifier Performance Comparison



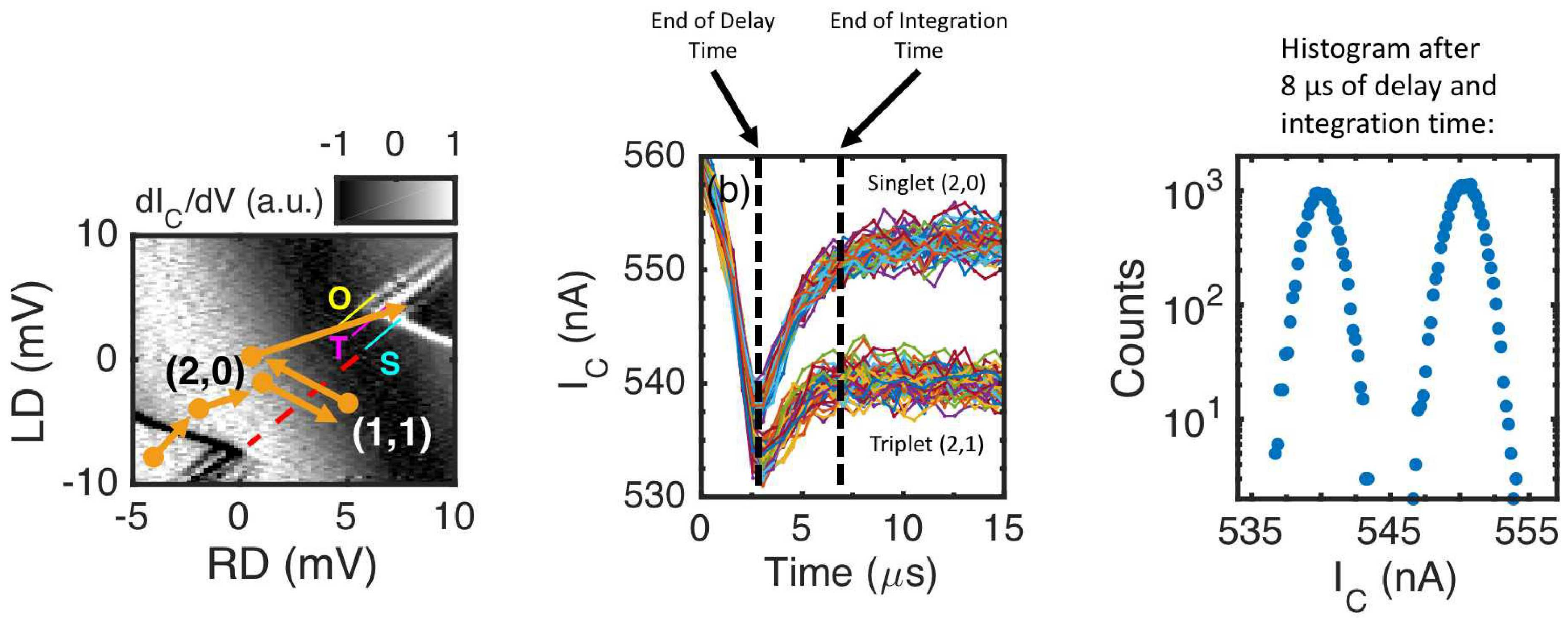


Gain of CB-HBT is greater at lower powers.

Minimum noise of CB-HBT is lower at lower powers.

Electron temperatures are comparable (160 – 200 mK).

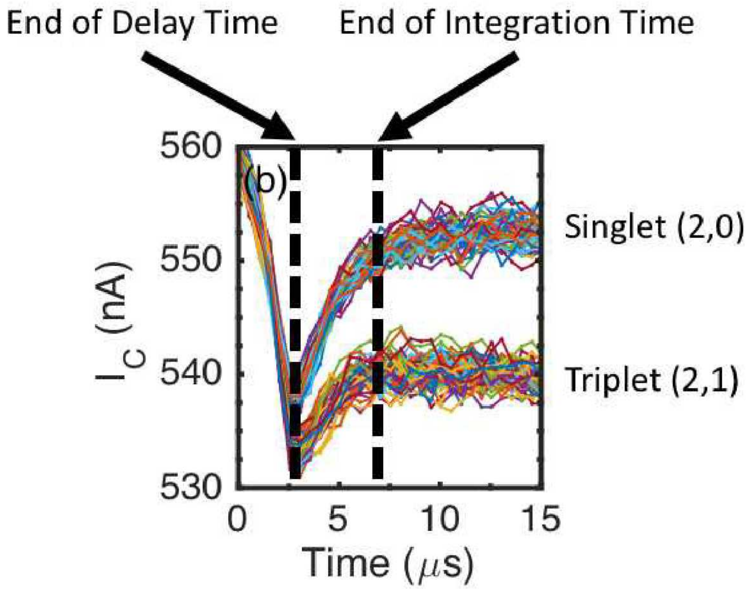
Single-Shot Readout



Latched readout of charge states performed.
(load singlet, evolve mixture, readout in latched region)

$\text{SNR} = \frac{\text{separation}}{\text{average width}}$ of peaks in histogram.

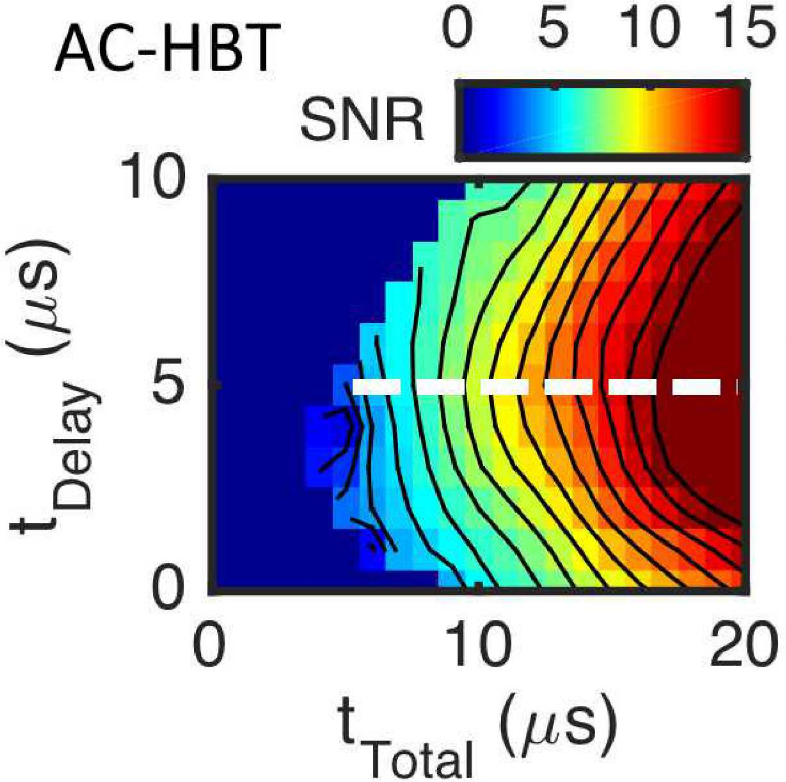
Single-Shot Readout Comparison

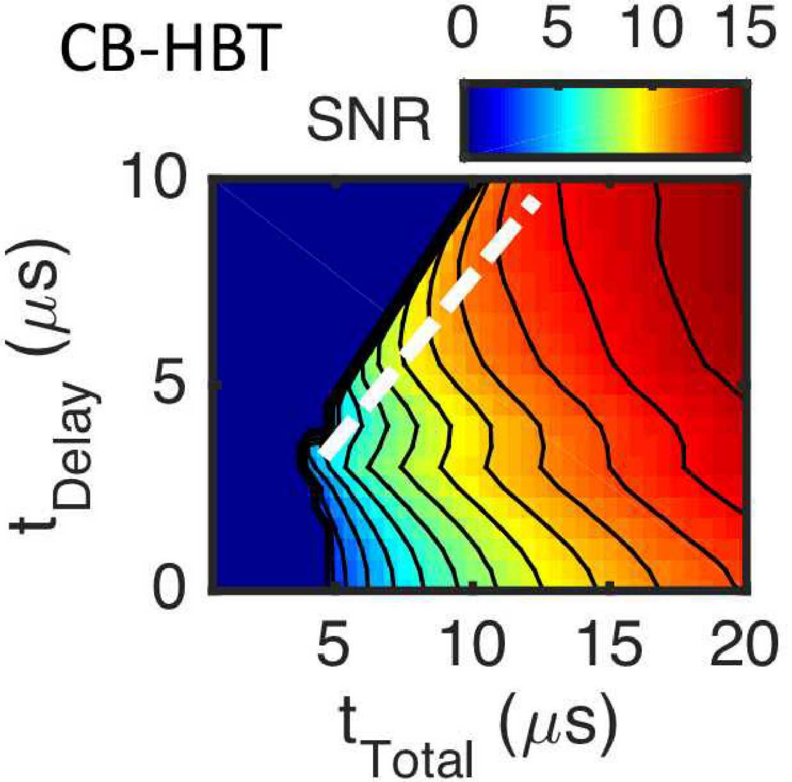


SNR extracted from histograms for different delay and integration times.

White dashed line shows minimum total time for maximum SNR.

AC-HBT has horizontal dashed line due to faster response.





Conclusion

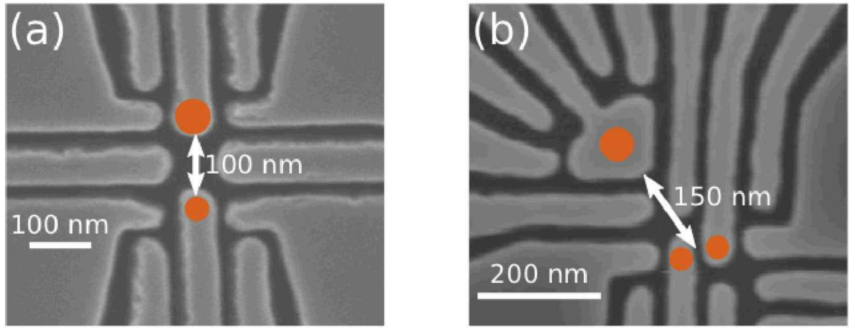
AC-HBT SNR scaled by sensitivity of CB-HBT SET shows converging performance.

Both circuits achieve SNR > 7 and bit error rate < 10^{-3} in times less than 10 μs.

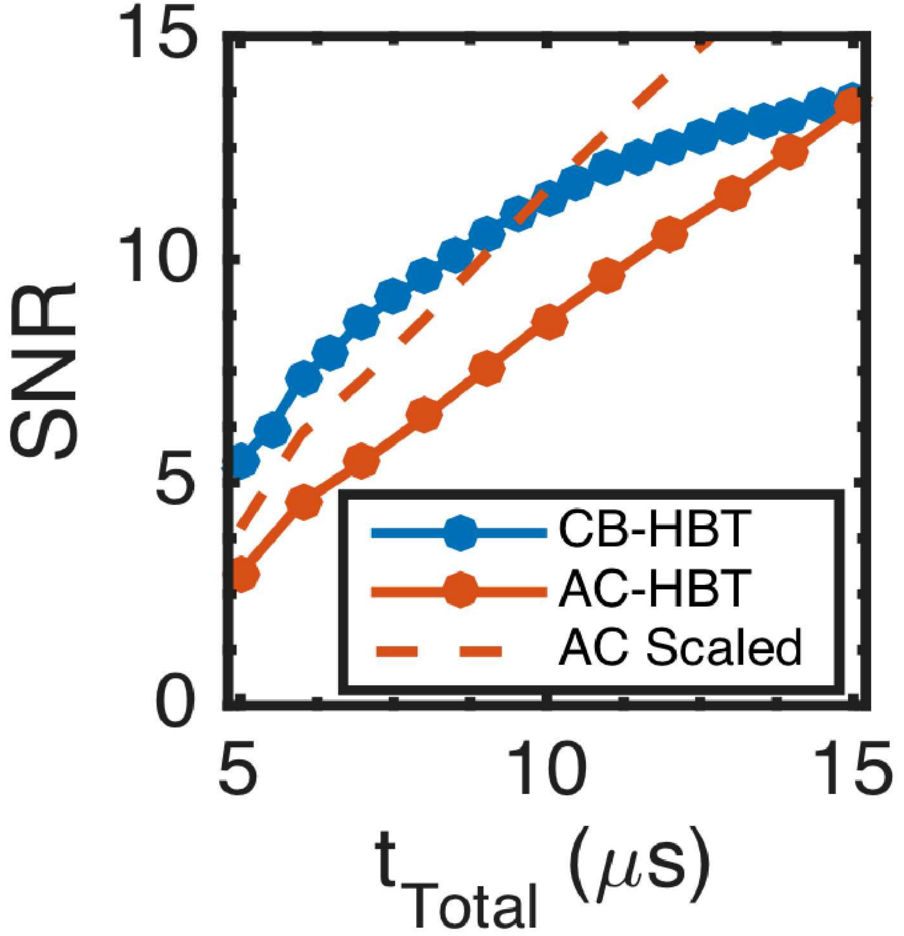
CB-HBT readout is 10 times faster for same SNR than previous high fidelity result [Harvey-Collard 2018].

In general, CB-HBT is lower power and AC-HBT has higher bandwidth.

	AC-HBT	CB-HBT
Input Noise	26 fA/√Hz	16 fA/√Hz
-3 dB Bandwidth	650 kHz	20 kHz
Power	8.4 μW	800 nW
e^- Temperature	160 - 200 mK	160 - 200 mK



CB-HBT AC-HBT



Impact and Future Direction

Collaborations with:

- Dzurak Group (UNSW, Australia)
  - November 2017 invited visit.
  - Working CB-HBT in one week!
- Bluhm Group (RWTH Aachen, Germany)
  - Interested in low-power CB-HBT configuration for scaling up to 1000s of qubits.

Future Directions:

- Characterize new commercial HBTs and other transistors, look for higher transconductance at lower powers and bias currents.
  - At least 65 candidates identified on DigiKey!
- Design and characterize dual-stage AC-HBT to reduce power and maintain bandwidth.

Compare Parts		Image	Digi-Key Part Number	Manufacturer Part Number	Manufacturer	Description	Quantity Available	Unit Price USD	Minimum Quantity	Packaging	Series	Part Status	Transistor Type	Voltage - Collector Emitter Breakdown (Max)	Frequency - Transition	Noise Figure (dB Typ @ f)	Gain
			BFP420H6327XTSA1TR-ND	BFP420H6327XTSA1	Infineon Technologies	TRANS RF NPN 25GHZ 4.5V SOT343	33,000 - Immediate	$0.14787	3,000	Tape & Reel (TR) Alternate Packaging	-	Active	NPN	5V	25GHz	1.1dB @ 1.8GHz	21dB
			BFP420H6327XTSA1CT-ND	BFP420H6327XTSA1	Infineon Technologies	TRANS RF NPN 25GHZ 4.5V SOT343	34,072 - Immediate	$0.43000	1	Cut Tape (CT) Alternate Packaging	-	Active	NPN	5V	25GHz	1.1dB @ 1.8GHz	21dB
			BFP420H6327XTSA1DKR-ND	BFP420H6327XTSA1	Infineon Technologies	TRANS RF NPN 25GHZ 4.5V SOT343	34,072 - Immediate	Digi-Reel®	1	Digi-Reel® Alternate Packaging	-	Active	NPN	5V	25GHz	1.1dB @ 1.8GHz	21dB
			BFP405H6327XTSA1TR-ND	BFP405H6327XTSA1	Infineon Technologies	TRANS RF NPN 4.5V 25MA SOT343	6,000 - Immediate	$0.14493	3,000	Tape & Reel (TR) Alternate Packaging	-	Active	NPN	5V	25GHz	1.25dB @ 1.8GHz	23dB
			BFP405H6327XTSA1CT-ND	BFP405H6327XTSA1	Infineon Technologies	TRANS RF NPN 4.5V 25MA SOT343	6,769 - Immediate	$0.42000	1	Cut Tape (CT) Alternate Packaging	-	Active	NPN	5V	25GHz	1.25dB @ 1.8GHz	23dB
			BFP405H6327XTSA1DKR-ND	BFP405H6327XTSA1	Infineon Technologies	TRANS RF NPN 4.5V 25MA SOT343	6,769 - Immediate	Digi-Reel®	1	Digi-Reel® Alternate Packaging	-	Active	NPN	5V	25GHz	1.25dB @ 1.8GHz	23dB
			BFP840ESDH6327XTSA1TR-ND	BFP840ESDH6327XTSA1	Infineon Technologies	IC TRANSISTOR RF NPN SOT343-4	3,000 - Immediate	$0.16415	3,000	Tape & Reel (TR) Alternate Packaging	-	Active	NPN	2.25V	80GHz	0.85dB @ 5.5GHz	18.5dB
			BFP840ESDH6327XTSA1CT-ND	BFP840ESDH6327XTSA1	Infineon Technologies	IC TRANSISTOR RF NPN SOT343-4	4,616 - Immediate	$0.48000	1	Cut Tape (CT) Alternate Packaging	-	Active	NPN	2.25V	80GHz	0.85dB @ 5.5GHz	18.5dB
			BFP840ESDH6327XTSA1DKR-ND	BFP840ESDH6327XTSA1	Infineon Technologies	IC TRANSISTOR RF NPN SOT343-4	4,616 - Immediate	Digi-Reel®	1	Digi-Reel® Alternate Packaging	-	Active	NPN	2.25V	80GHz	0.85dB @ 5.5GHz	18.5dB
			BFP842ESDH6327XTSA1TR-ND	BFP842ESDH6327XTSA1	Infineon Technologies	IC TRANSISTOR RF NPN SOT343	3,000 - Immediate	$0.16415	3,000	Tape & Reel (TR) Alternate Packaging	-	Active	NPN	3.7V	60GHz	0.65dB @ 3.5GHz	26dB
			BFP842ESDH6327XTSA1CT-ND	BFP842ESDH6327XTSA1	Infineon Technologies	IC TRANSISTOR RF NPN SOT343	4,826 - Immediate	$0.48000	1	Cut Tape (CT) Alternate Packaging	-	Active	NPN	3.7V	60GHz	0.65dB @ 3.5GHz	26dB
			BFP842ESDH6327XTSA1DKR-ND	BFP842ESDH6327XTSA1	Infineon Technologies	IC TRANSISTOR RF NPN SOT343	4,826 - Immediate	Digi-Reel®	1	Digi-Reel® Alternate Packaging	-	Active	NPN	3.7V	60GHz	0.65dB @ 3.5GHz	26dB
			BFP760H6327XTSA1TR-ND	BFP760H6327XTSA1	Infineon Technologies	TRANSISTOR RF NPN AMP SOT-343	3,000 - Immediate	$0.18016	3,000	Tape & Reel (TR) Alternate Packaging	-	Active	NPN	4V	45GHz	0.5dB ~ 0.95dB @ 900MHz ~ 5.5GHz	16.5dB ~ 29dB
			BFP760H6327XTSA1CT-ND	BFP760H6327XTSA1	Infineon Technologies	TRANSISTOR RF NPN AMP SOT-343	5,823 - Immediate	$0.52000	1	Cut Tape (CT) Alternate Packaging	-	Active	NPN	4V	45GHz	0.5dB ~ 0.95dB @ 900MHz ~ 5.5GHz	16.5dB ~ 29dB
			BFP760H6327XTSA1DKR-ND	BFP760H6327XTSA1	Infineon Technologies	TRANSISTOR RF NPN AMP SOT-343	5,823 - Immediate	Digi-Reel®	1	Digi-Reel® Alternate Packaging	-	Active	NPN	4V	45GHz	0.5dB ~ 0.95dB @ 900MHz ~ 5.5GHz	16.5dB ~ 29dB
			BFP640ESDH6327XTSA1TR-ND	BFP640ESDH6327XTSA1	Infineon Technologies	TRANS RF NPN 46GHZ 4.7V SOT343	3,000 - Immediate	$0.20336	3,000	Tape & Reel (TR) Alternate Packaging	-	Active	NPN	4.7V	46GHz	0.6dB ~ 2dB @ 150MHz ~ 10GHz	7dB ~ 30dB

Donor-Dot Singlet-Triplet Qubit Team at SNL

Experiment:

- Malcolm Carroll
- Steve Carr
- Martin Rudolph
- Matt Curry
- Ryan Jock
- Andy Mounce
- Chloe Bureau-Oxton

Theory and Modeling:

- Toby Jacobson
- Andrew Baczewski
- Erik Nielsen
- Kenny Rudinger

Fabrication:

- Dan Ward
- Ron Manginell
- Joel Wendt
- DeAnna Campbell
- John Anderson

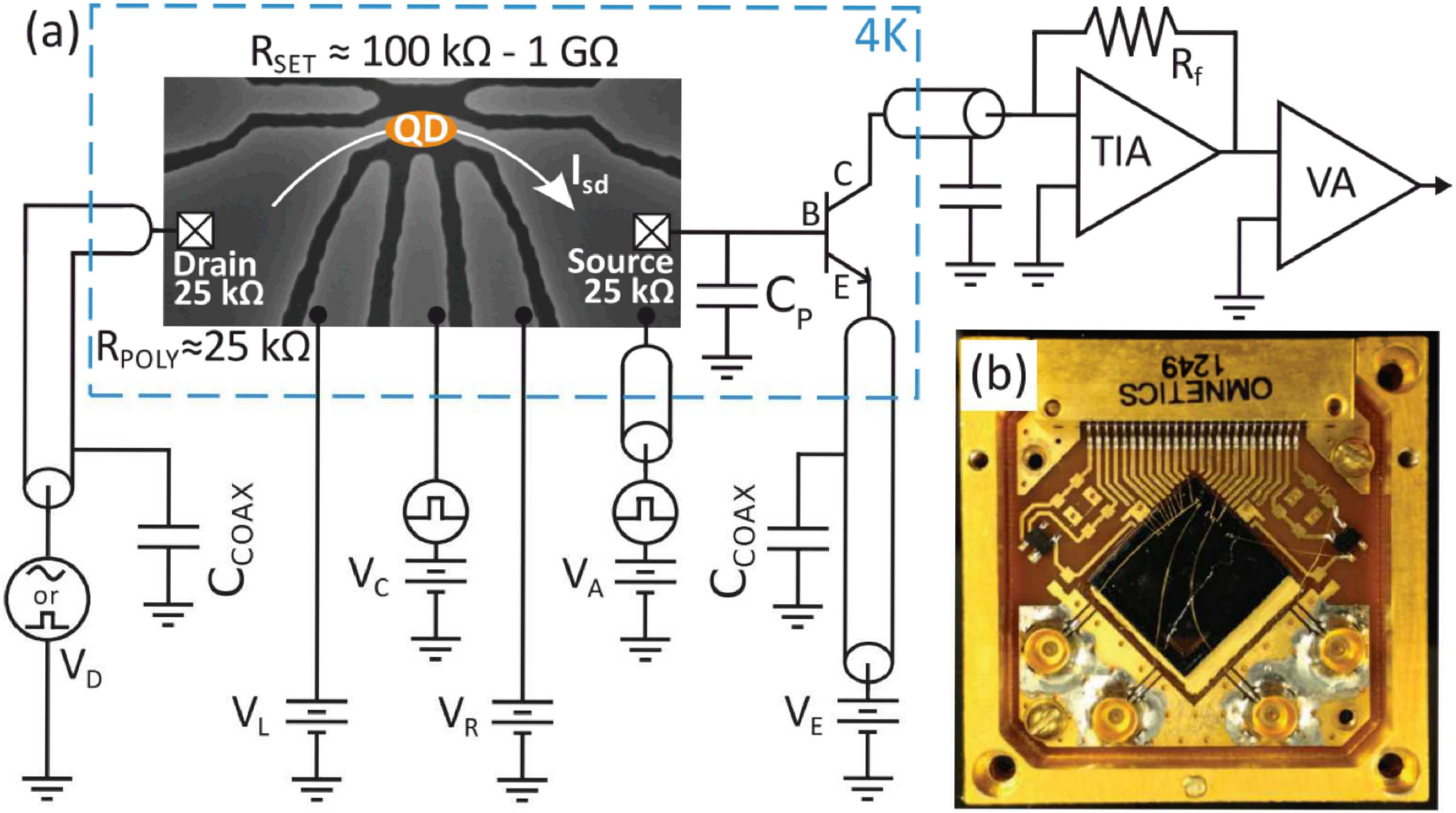
This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the DOE's National Nuclear Security Administration under contract DE-NA0003525.

Questions?

UNM

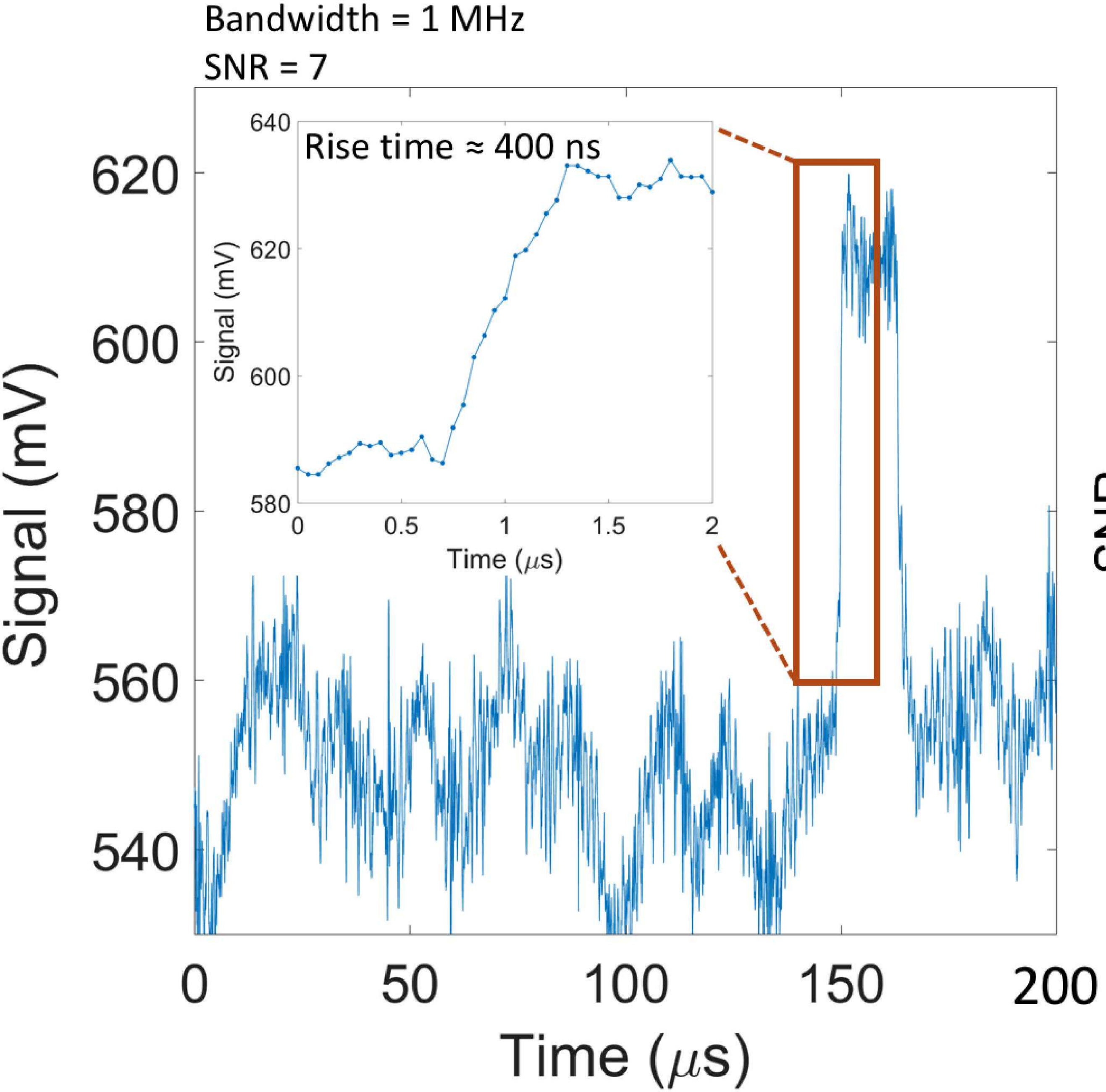
CQuIC
Center for Quantum Information and Control

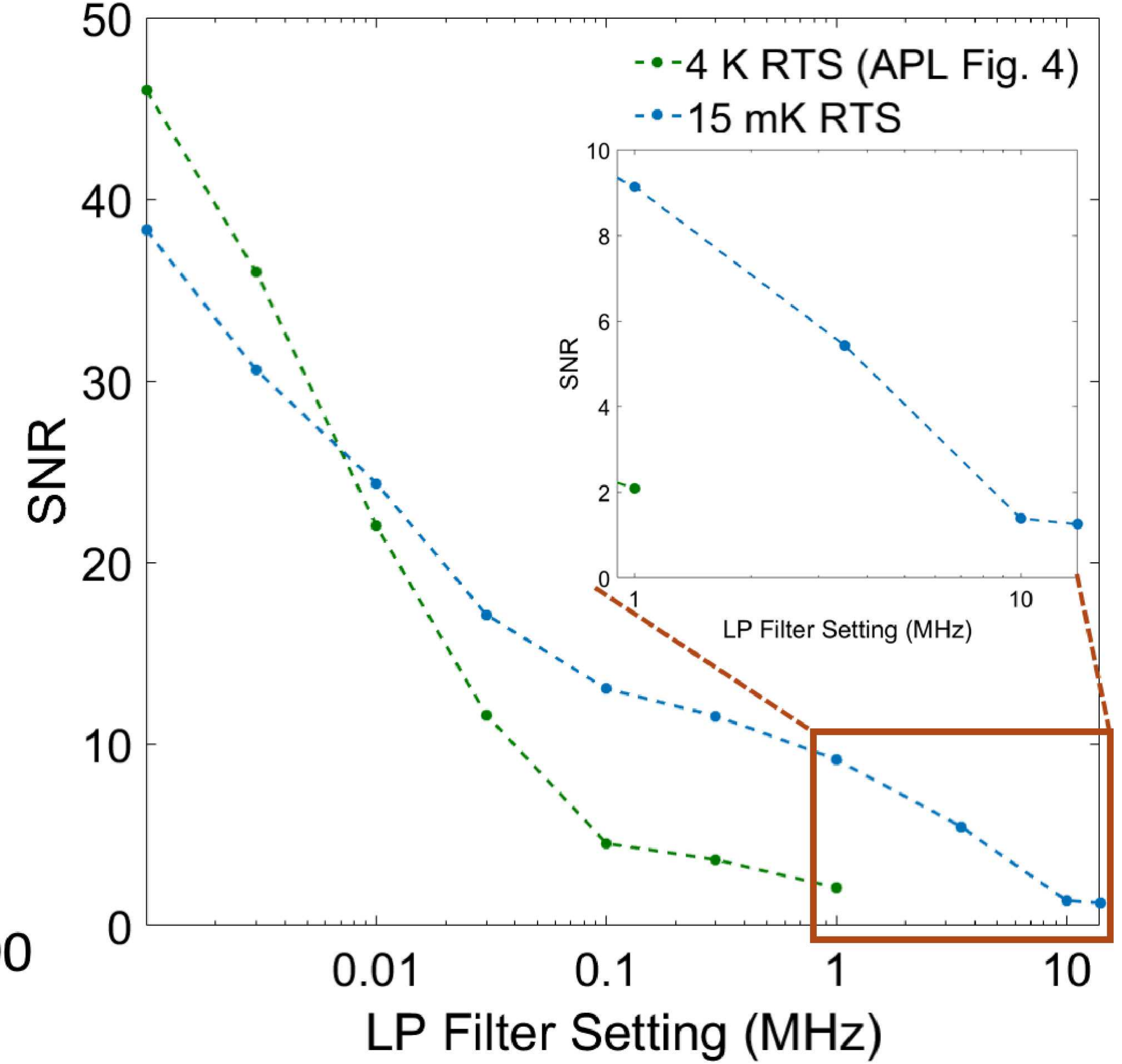
Cryogenic Preamplification Using a Heterojunction Bipolar Transistor (HBT) T = 4 K



M.J. Curry et al., Applied Physics Letters 106 203505 (2015)

RTS Measurements With HBT Inline In Dilution Refrigerator T = 15 mK





Time-Domain Single-Shot Readout: State of the Art

$$\begin{matrix}Charge \\ Sensitivity\end{matrix} \equiv \frac{1}{(SNR)\cdot\sqrt{B}} = \frac{\sqrt{\tau_{int}}}{SNR} \quad \left(\frac{e}{\sqrt{Hz}}\right)$$

Single-Shot Readout Technique	Group	Reference	Carrier Frequency	Time-Domain Bandwidth	Time-Domain SNR	Charge Sensitivity (μe/$\sqrt{Hz}$)
HBT (Single-Stage)	Sandia/UNM/CQuIC	This Presentation Also: APL 106, 203505 (2015)	N/A	30 kHz 100 kHz 1 MHz 3 MHz	13 10 7 4	400 300 100 100
HEMT (Single-Stage)	Delft	APL 91, 123512 (2007)	N/A	800 kHz	3	400
HEMT (Dual-Stage)	Sandia	APL 108, 063101 (2016)	300 kHz	100 kHz	10	300
RF-QPC	Harvard CQC2T NRC Canada	PRB 81, 161308(R) (2010) APL 91, 222104 (2007) Physica E 42, 813 (2010)	220 MHz 332 MHz 763 MHz	5 MHz 500 kHz 1 MHz	2 7 7	200 200 100
RF-SET	Harvard Wisconsin/Dartmouth	PRB 81, 161308(R) (2010) APL 101, 142103 (2012)	220 MHz 936 MHz	10 MHz 2 MHz	4 4	80 100
Gate-Dispersive RF	ARC Sydney	PRL 110, 046805 (2013)	700 MHz	30 kHz	1	6000
RF Transmission SC Cavity + JPA	Princeton	PR Applied 4, 014018 (2015)	7.88 GHz	2.6 MHz	9	80

HBT DC Characterization Circuit

HBTs are characterized at 4 K using the circuit shown to the right.

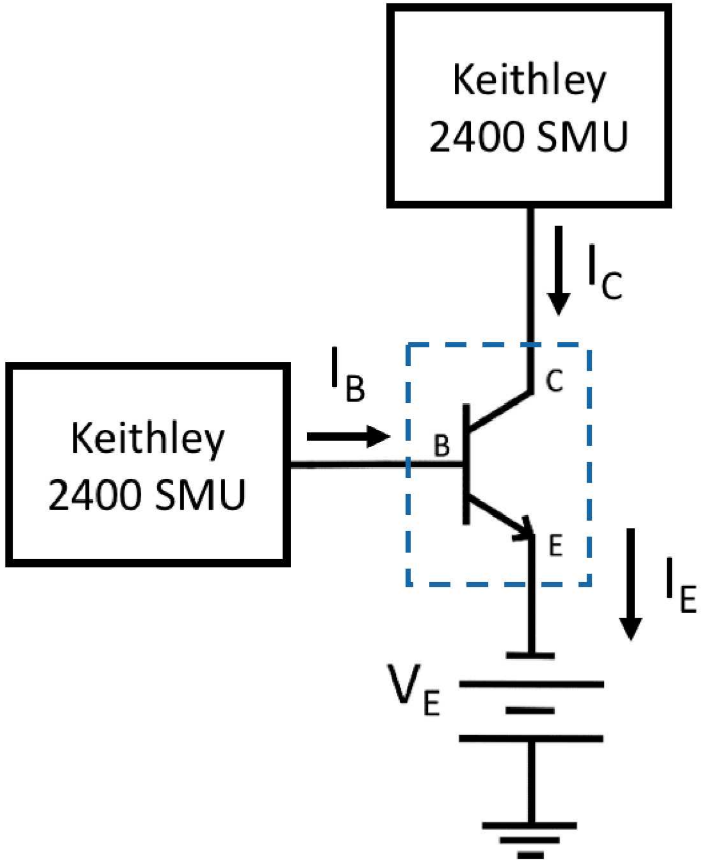
Required instruments: Two source-measure units (SMUs) (e.g. Keithley 2400) and one DC power supply (e.g. SIM928 battery box).

The two SMUs measure the base and collector current.

The DC power supply biases the base-emitter and collector-emitter junctions of the HBT.

The unity-gain crossover point of the HBTs is usually between V_E = -1.02 V and V_E = -1.03 V, so the measurements usually begin at V_E = -1 V to capture some sub-unity behavior.

The current gain of the HBTs usually saturates or is in the thousands when V_E = -1.07 V. The measurements usually end at this emitter bias point.



HBT Characterization Data

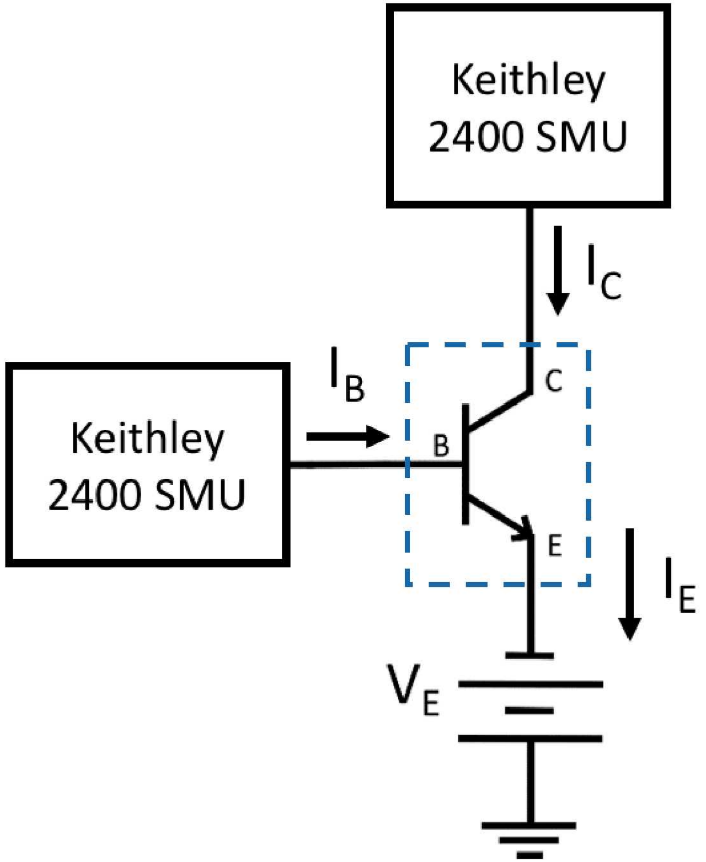
Emitter bias (V_E) is the only parameter swept for a given HBT characterization.

The parameters measured during the sweep should be:

- Emitter bias voltage
- Base current
- Collector current

The parameters calculated during/after the sweep should be:

- Emitter current ($I_C + I_B$)
- DC current gain (I_C/I_B)



HBT Characterization Data

Plotted to the right is DC current gain vs. base current for nine HBTs.

HBTs are selected for use in the non-linear amplification circuit based on how high their current gain is at two base current points: I_B = 100 pA and I_B = 1000 pA (marked by black dashed lines).

Some selection examples:

HBT 10 has the lowest current gain at I_B = 1000 pA, but it has much higher current gain than HBT 18 at I_B = 100 pA, so HBT 10 is selected over HBT 18.

HBT 19 is a top-performer with relatively high current gain at both base current points and a smooth curve in between.