SAND2017-2666C

Comparing SiGe HBT Amplifier Circuits for Fast Single-shot Spin Readout

Troy England, Matthew Curry, Steve Carr,
Andrew Mounce, Ryan Jock, Peter Sharma,
Chloe Bureau-Oxton, Martin Rudolph, Terry Hardin,
Malcolm Carroll

March 14, 2017

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

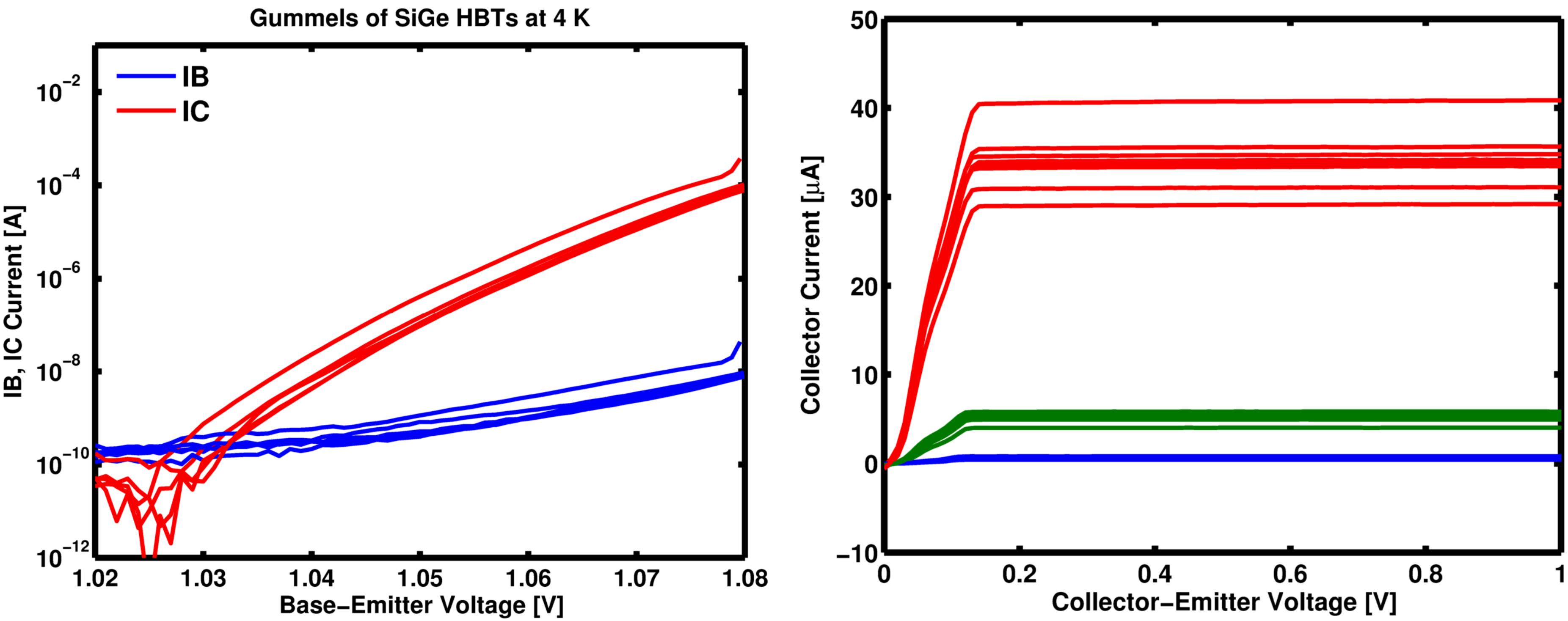
Fast Single Shot Spin Readout

- We want fast, high-fidelity, single-shot spin readout
- SETs by themselves are often not enough
- We continue to investigate cryogenic pre-amplification

- We have developed cryogenic amplifiers with Silicon-germanium (SiGe) heterojunction bipolar transistors (HBTs)
- The most power efficient of these are the **Non-linear HBT** and the **AC-coupled HBT**

- Each amplifier biases the SET fundamentally differently
- Simulation results will show the pros and cons of each circuit
- **Both provide power-efficient, low-noise gain**

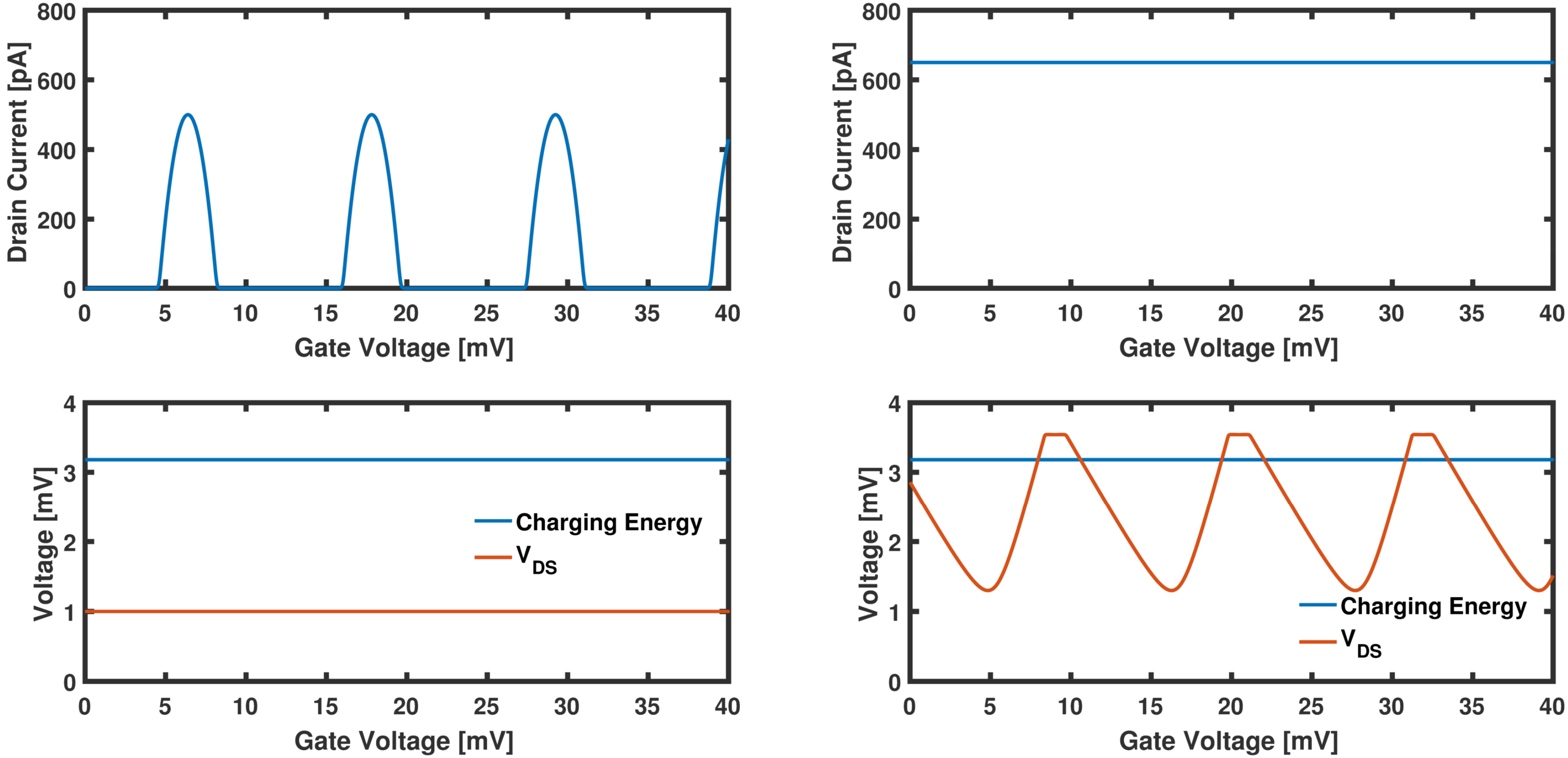
Advantages of SiGe HBTs



- SiGe HBTs have proven reliable cryogenic performance
- Good transconductance gain vs power trade offs
- Output resistance is high and nearly monotonic
- Can be operated with as little as 0.2 V V_{CE} bias, low power

Voltage vs Current Biased SETs

Voltage Biased ## Current Biased



- Voltage biased SETs are free to vary current with set voltage conditions
- Current biased SETs are free to vary voltages with set current conduction

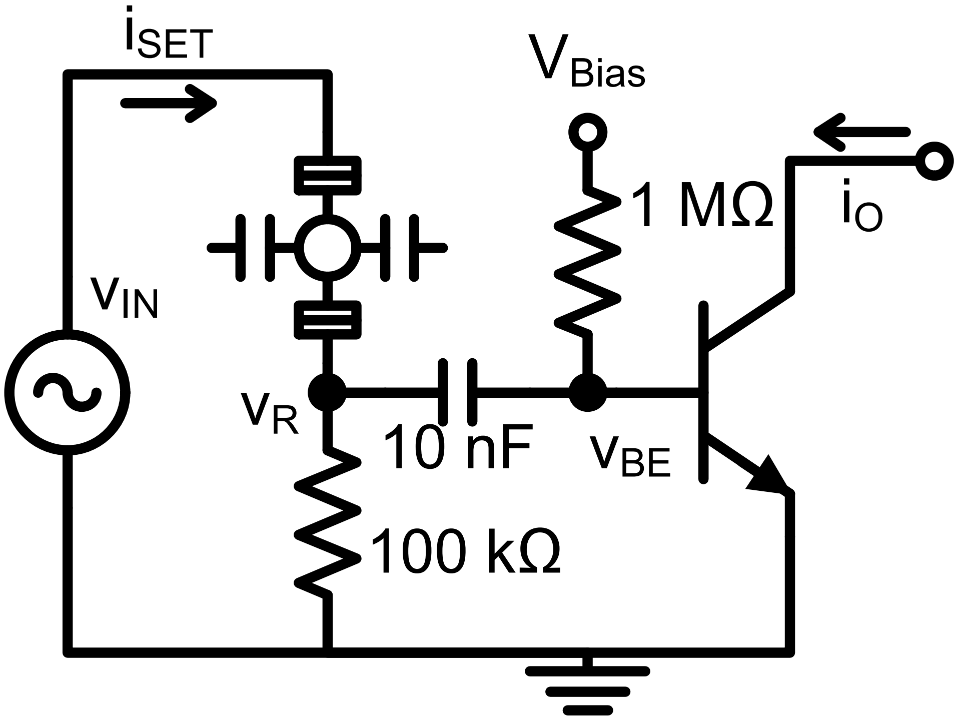
S. Mahapatra, V. Vaish, C. Wasshuber, K. Banerjee, A. M. Ionescu, “Analytical modeling of single electron transistor for hybrid CMOS-SET analog IC design,” *IEEE Trans. Electron Devices,* vol. 51, pp. 1772-1782, Nov. 2004.

AC HBT Background

- DC SET current flows through shunt resistance
- Not as power efficient as the Non-linear HBT
  - Operates between 0.4–50 μW; 23 A/A gain at 1 μW
- Also allows for in situ power vs gain tradeoffs

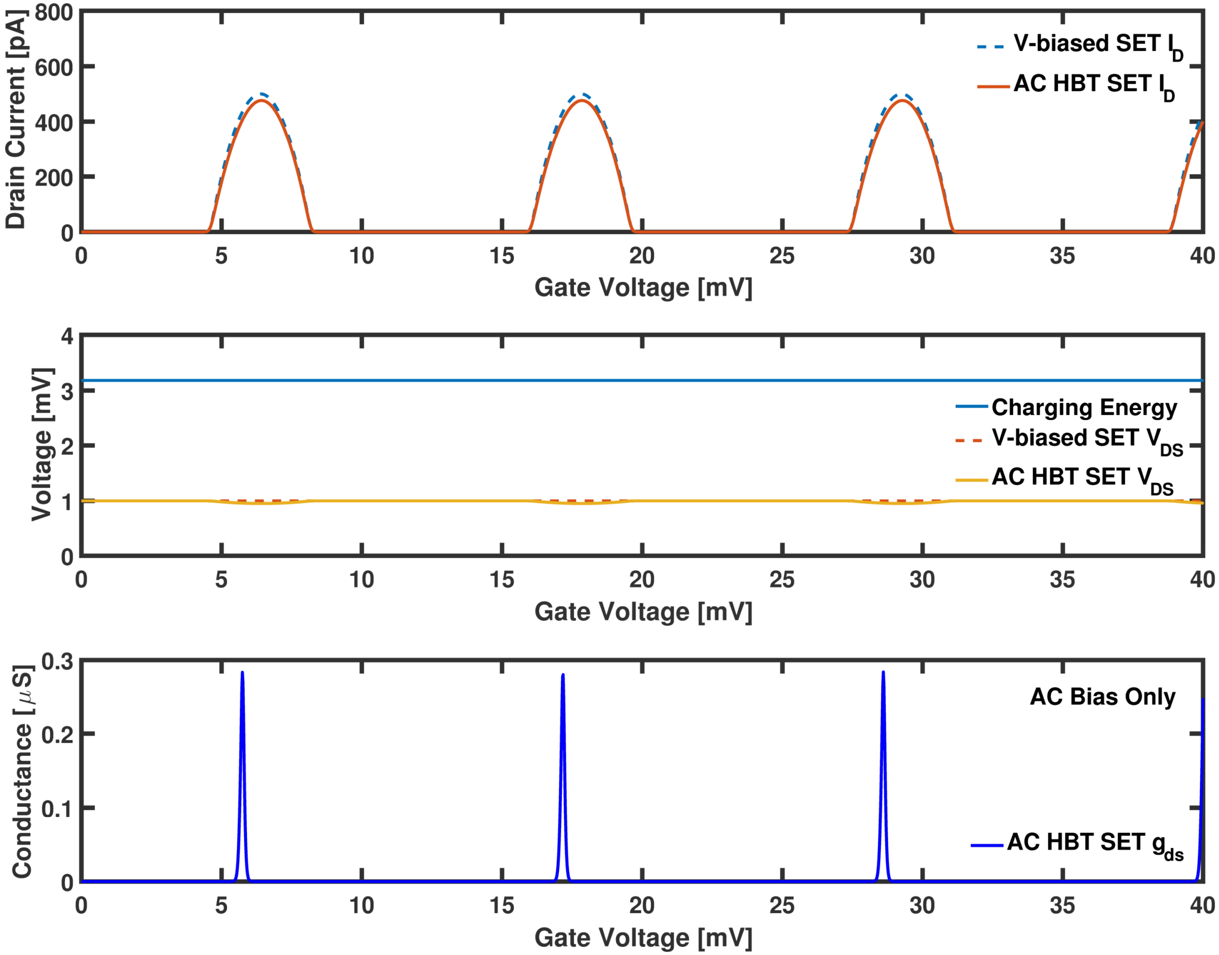
- Where it succeeds:
  - Low power consumption
  - Low noise

- Room for improvement:
  - Saturates if R_{SET} < 100 kΩ
  - Reliant on room-T TIA

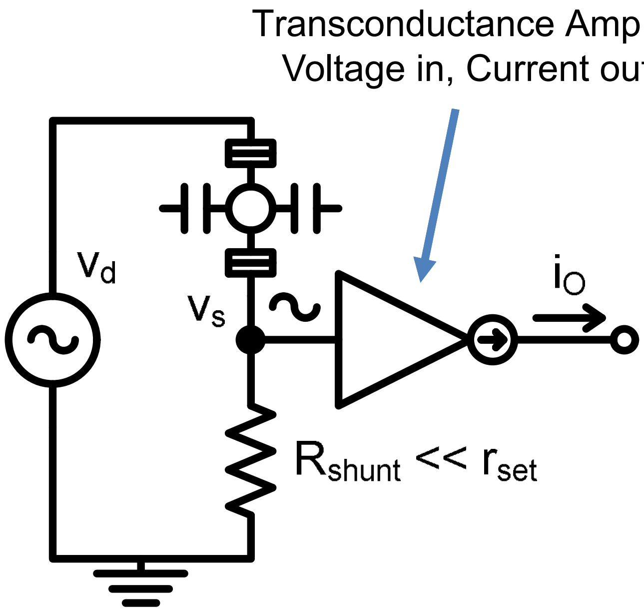


AC HBT vs. Voltage Biased SET

- The shunt resistance of the AC HBT is selected to add minimal disruption to current flow
- It is most similar to a voltage-biased SET
- SET tuning is likely to be intuitive to users



Equivalent Circuit

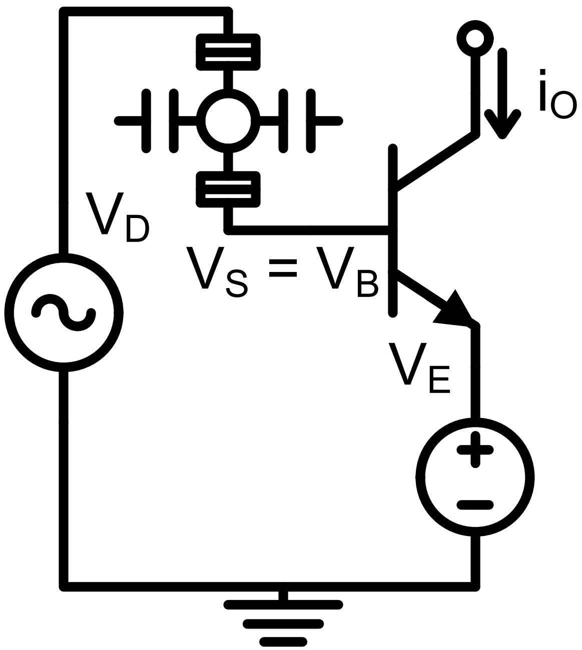


Non-linear HBT Background

- Sometimes referred to as in-line or DC HBT
- The SET is biased through the base of the SiGe HBT
  - Some SiGe HBTs are operable at 100 pA of base current
  - Power dissipation is often in the nW regime
- Allows for in situ power vs gain tradeoffs

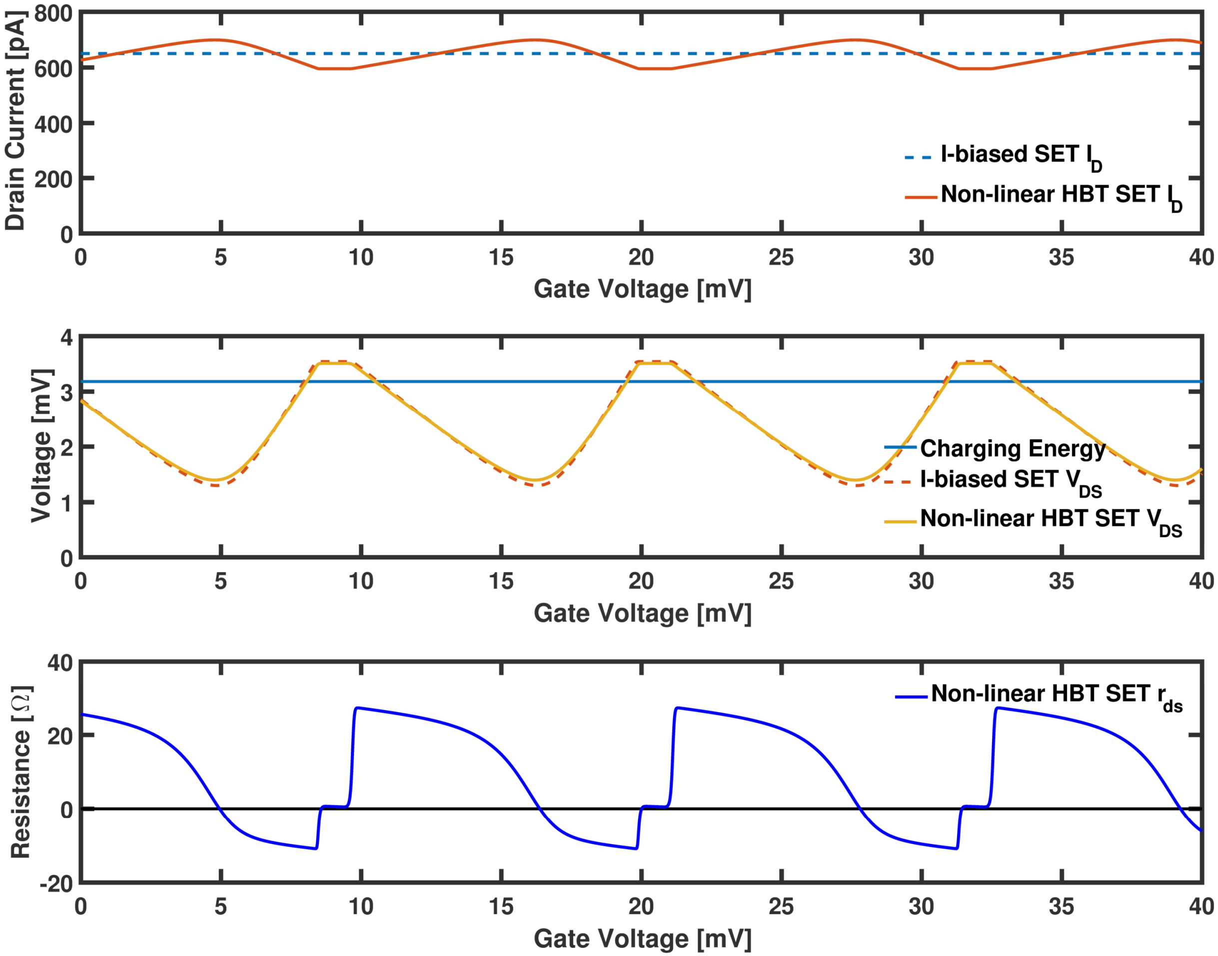
- Where it succeeds:
  - High gain
  - Very low power consumption
  - Low noise

- Room for improvement:
  - Input impedance
  - −3 dB bandwidth
  - Reliant on room-T TIA

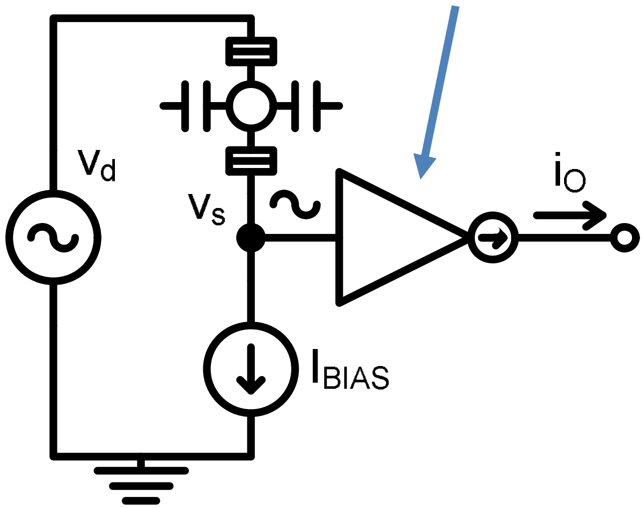


NL HBT vs Current Biased SET

- The exceptionally high impedance of the base terminal results in an effective current bias
- The drain-source voltage varies around the charging energy
- Peaks are spread out, and SET is always sensitive

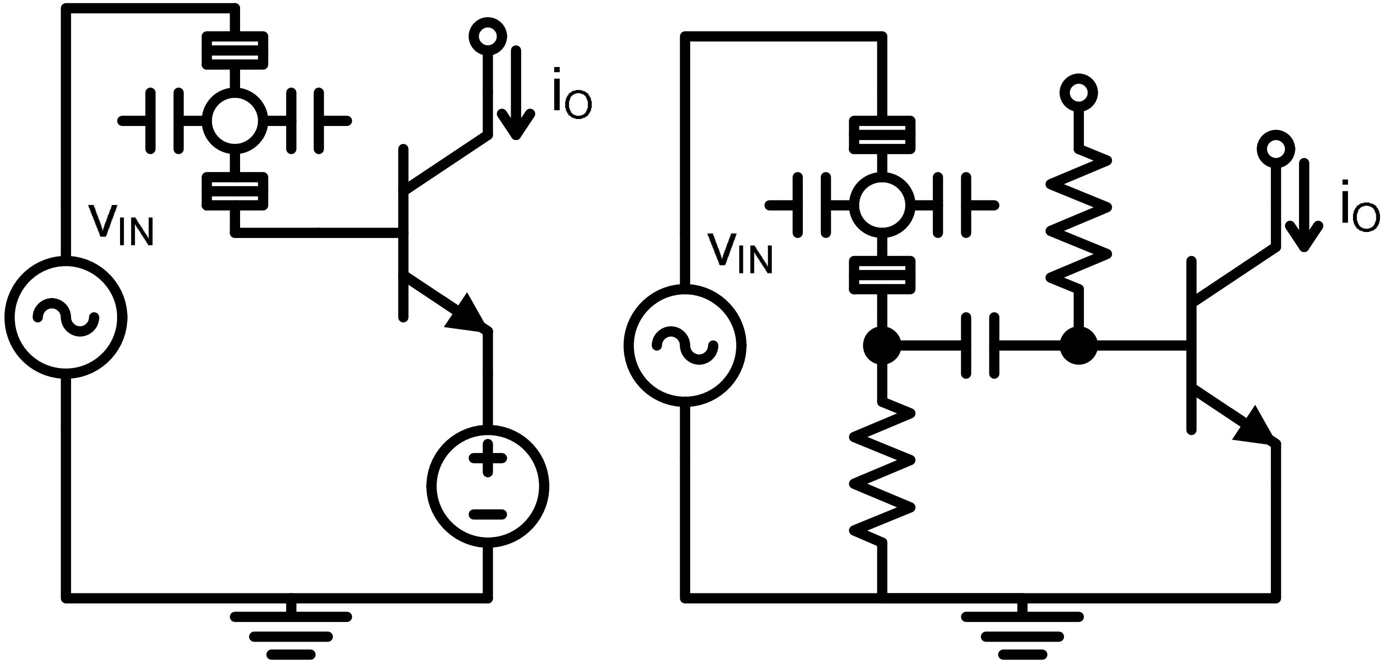


Equivalent Circuit



Comparing the Circuit Performance

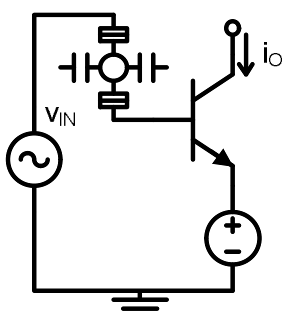
- Direct comparisons are difficult with SETs biased differently
- Using the excitation voltage and output current as basis of comparisons
  - Each circuit has v_{IN} and i_O

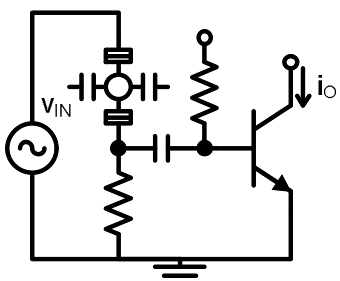


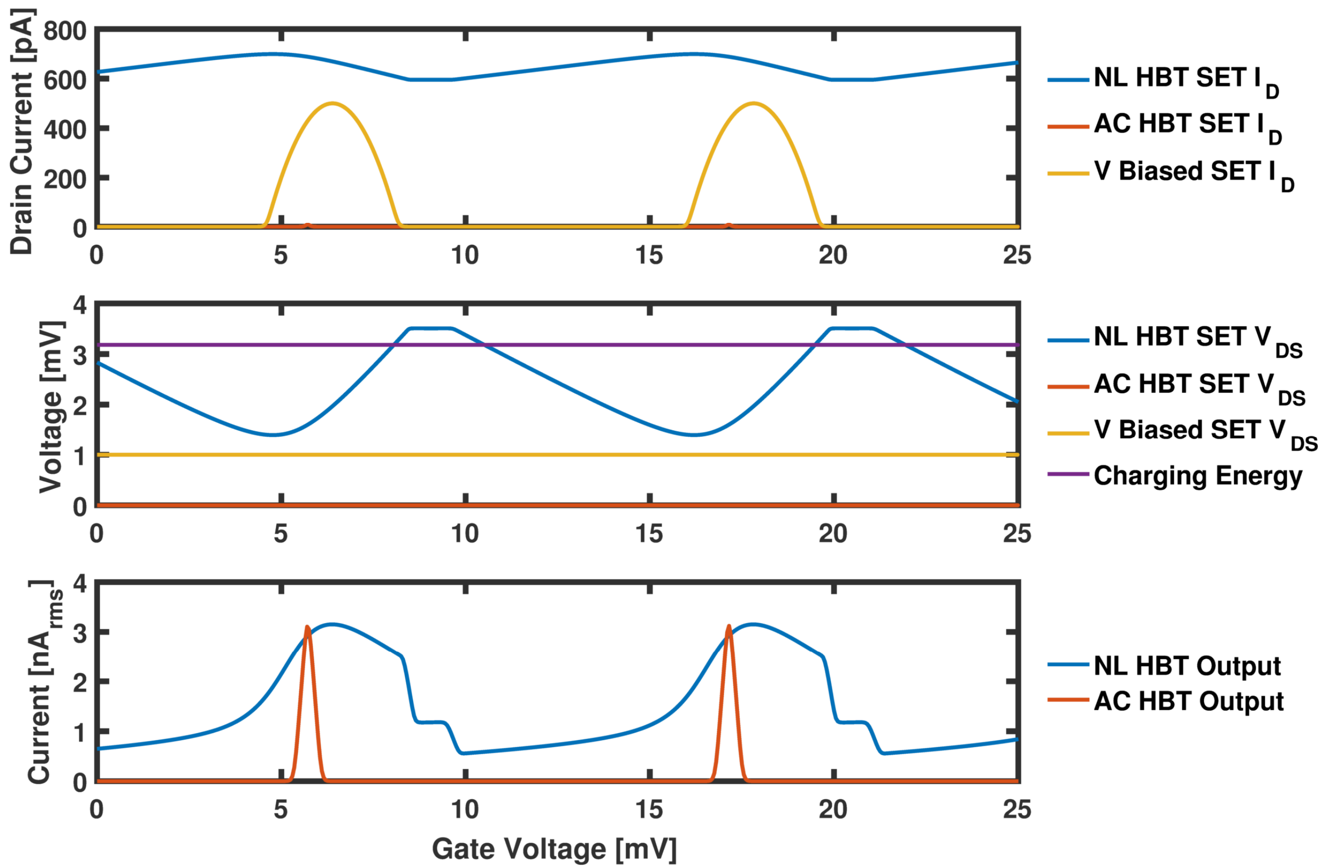
Comparing Gain across Gate Sweep

- Input is 100 μV_{rms} sine
- **The Non-linear HBT output signal is larger in all cases**

	I_B	I_C	$i_{o,max}$	$i_{o,min}$
NL HBT	$0.6\ nA$	$0.6\ \mu A$	$3.2\ nA_{rms}$	$0.6\ nA_{rms}$
AC HBT	$2.1\ nA$	$3.3\ \mu A$	$3.1\ nA_{rms}$	≈ 0



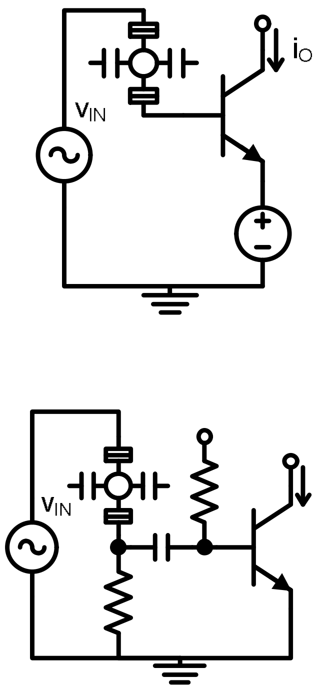


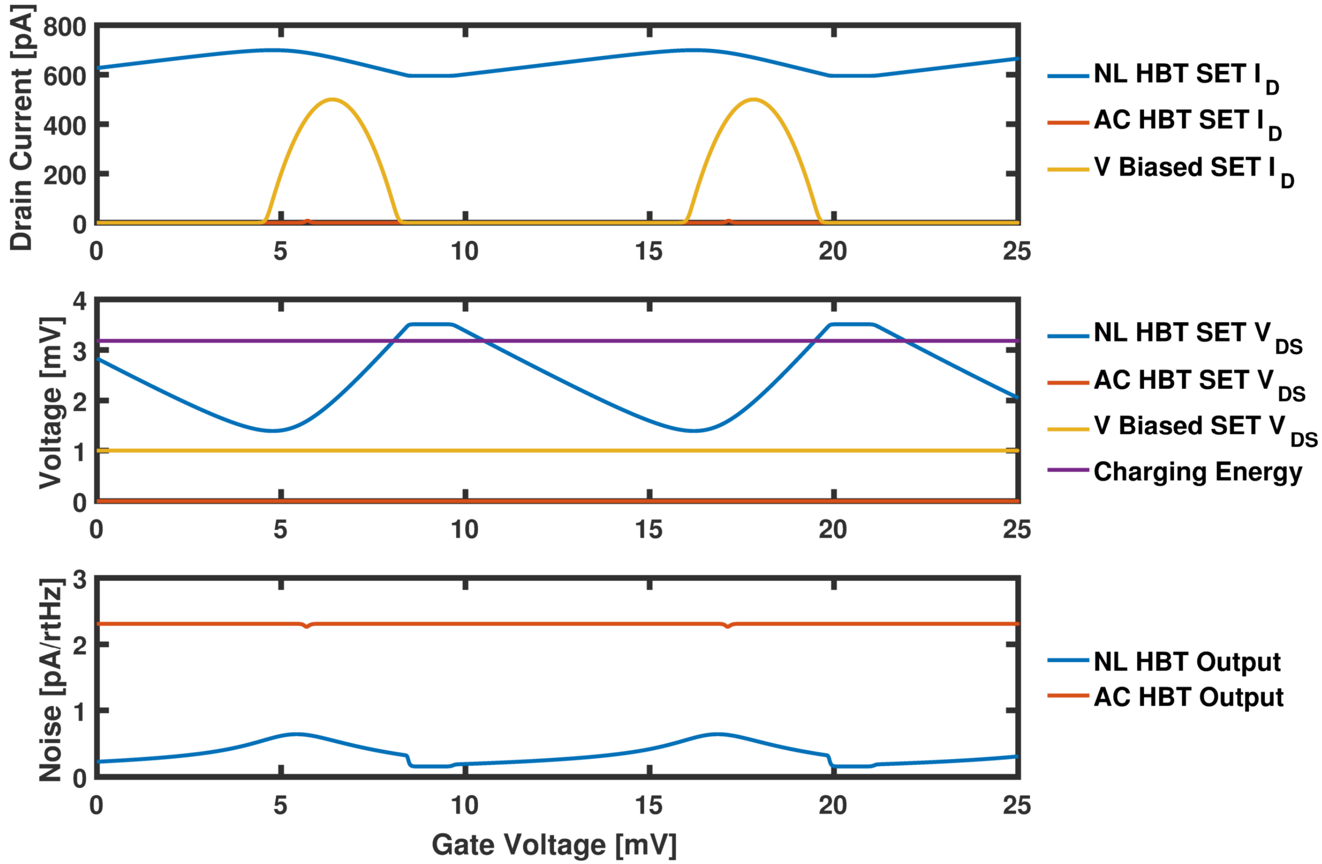


Comparing Noise across Gate Sweep

- Output spot current noise at 1 kHz
- **The Non-linear HBT noise varies but is lower for all gate voltages**

	$i_{no,max}$	$i_{no,min}$
NL HBT	$0.6\ \frac{pA}{\sqrt{Hz}}$	$0.2\ \frac{pA}{\sqrt{Hz}}$
AC HBT	$2.3\ \frac{pA}{\sqrt{Hz}}$	$2.3\ \frac{pA}{\sqrt{Hz}}$

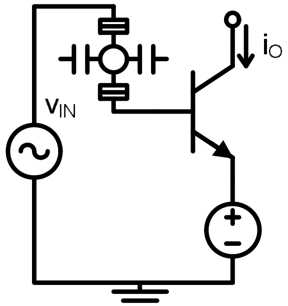


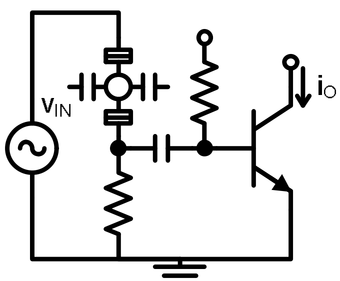


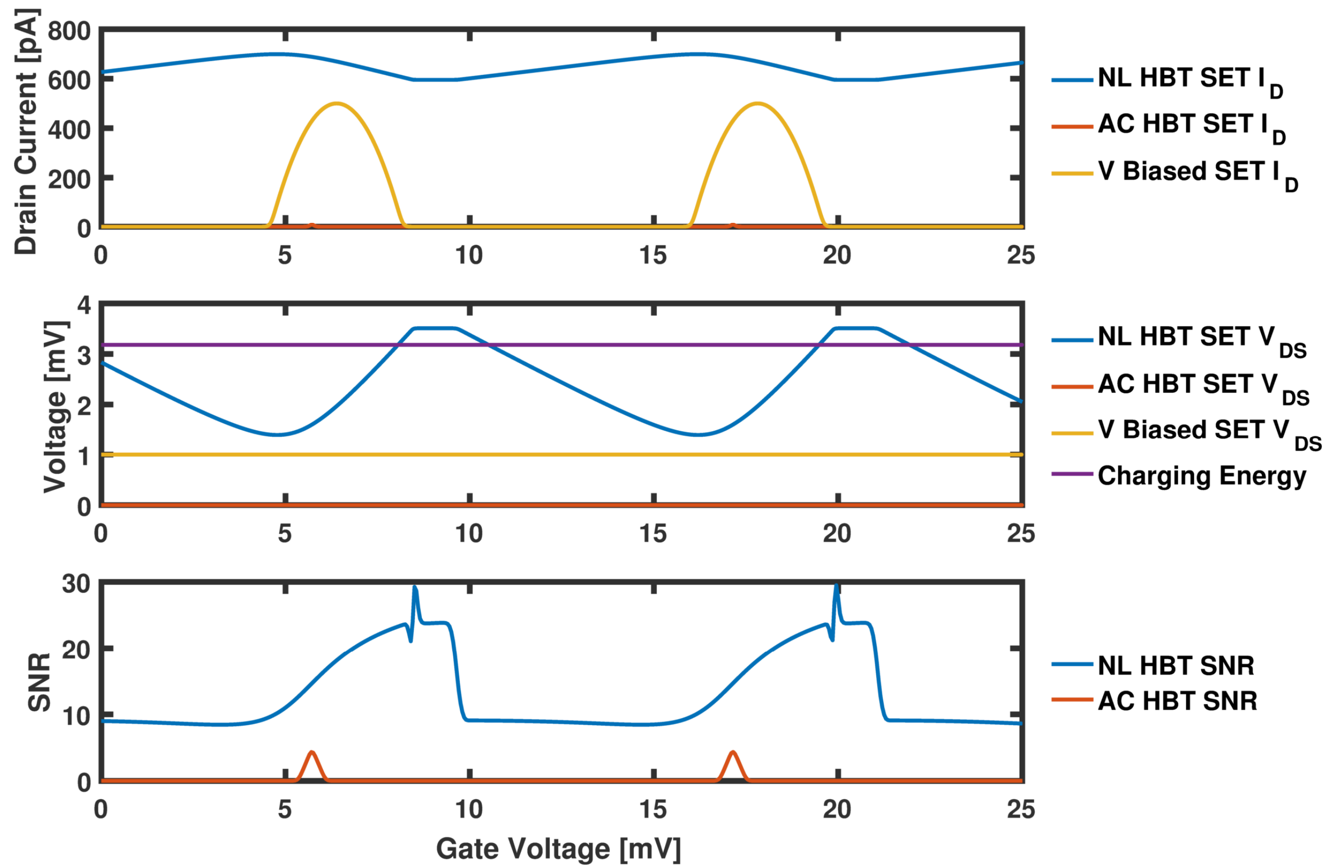
Comparing SNR across Gate Sweep

- SNR for an effective 100 kHz bandwidth
- Because the AC HBT signal approaches 0, SNR approaches 0 in nulls
- **The Non-linear HBT SNR is higher in all cases**

SNR	Max	Min
NL HBT	29.5	8.44
AC HBT	4.35	≈ 0



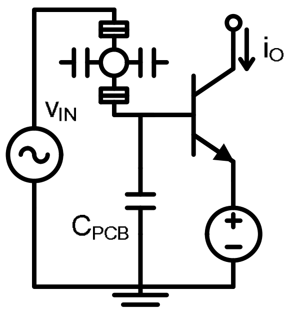


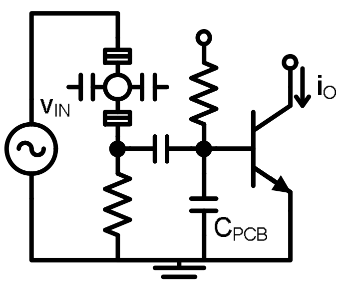


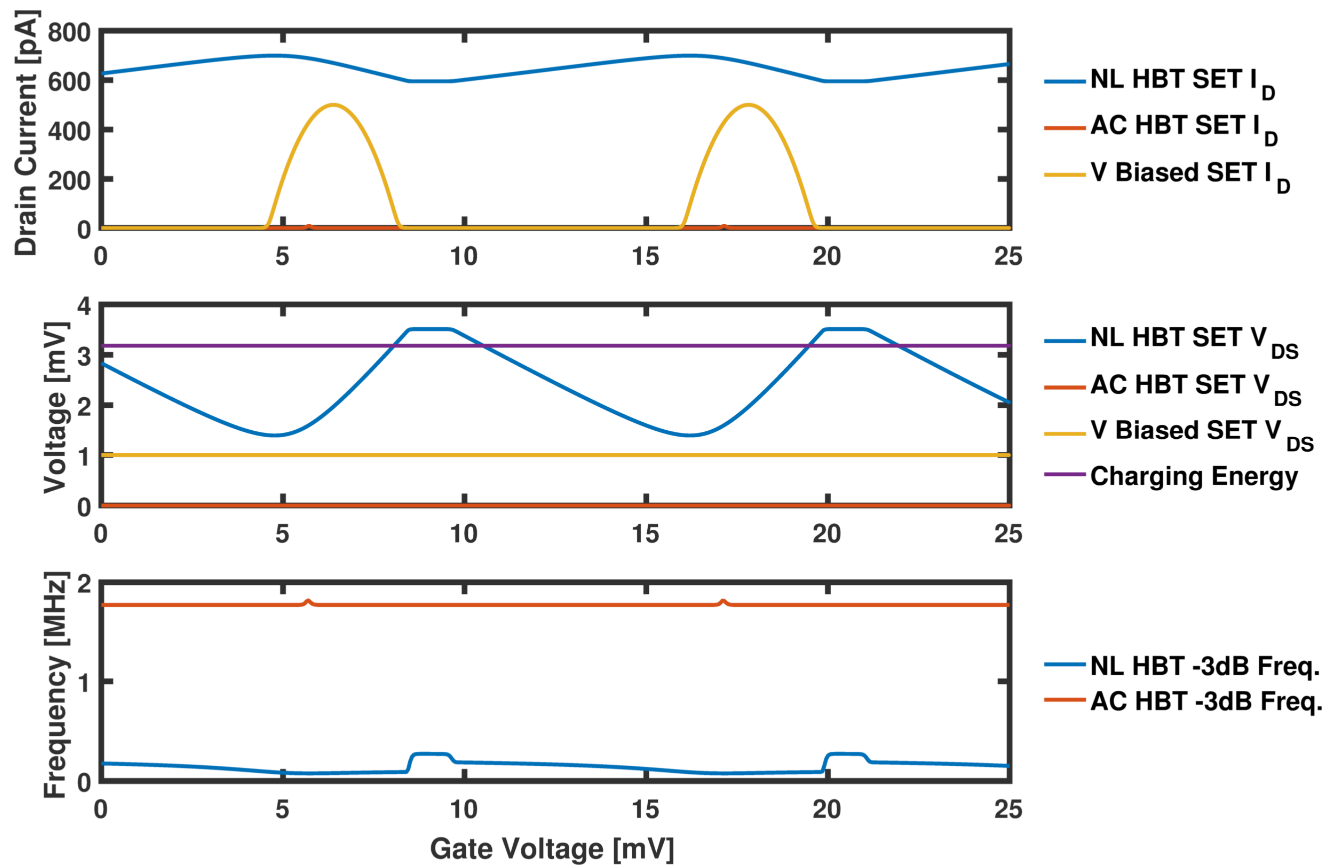
Comparing Bandwidth

- Assuming conservative 1 pF PCB capacitance
- The −3 dB frequency of the NL HBT is set by high, variable impedance of the SET and C_{PCB}
- The −3 dB frequency of the AC HBT is set by the 100 kΩ shunt resistor and C_{PCB}
- **The AC HBT bandwidth is higher in all cases**

BW	Max	Min
NL HBT	$272\ kHz$	$77\ kHz$
AC HBT	$1.8\ MHz$	$1.8\ MHz$

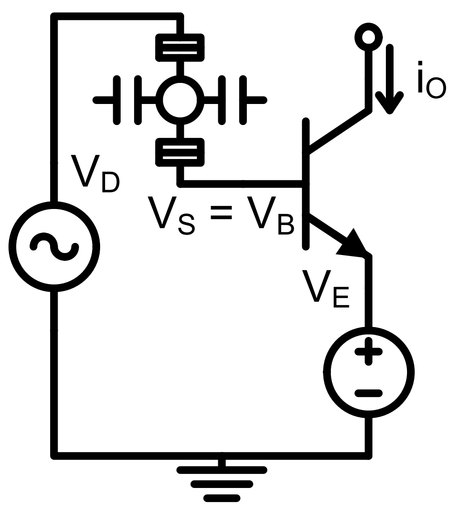




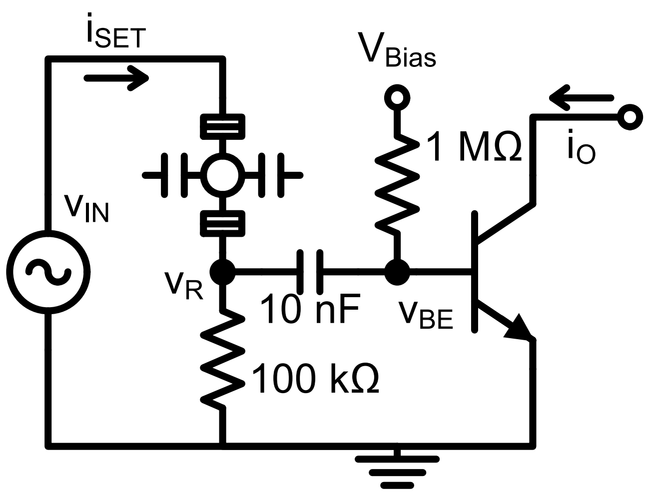


Trade-offs

- **Non-linear HBT**
- Pros
  - Gain
  - Noise
  - Simplicity
- Cons
  - −3 dB Bandwidth
- Consideration
  - V_{DS} Variation



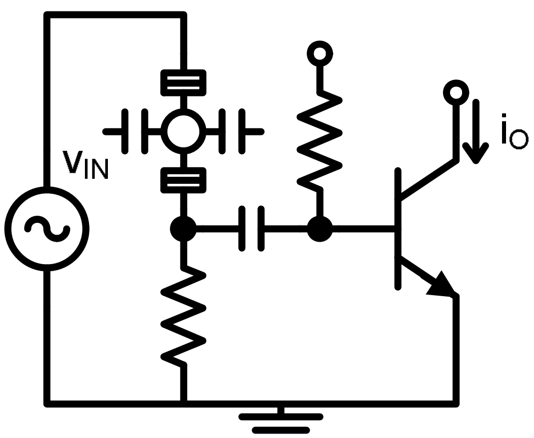
- **AC HBT**
- Pros
  - Intuitive SET Operation
  - −3 dB Bandwidth
- Cons
  - Gain
  - Noise
  - Additional Passives

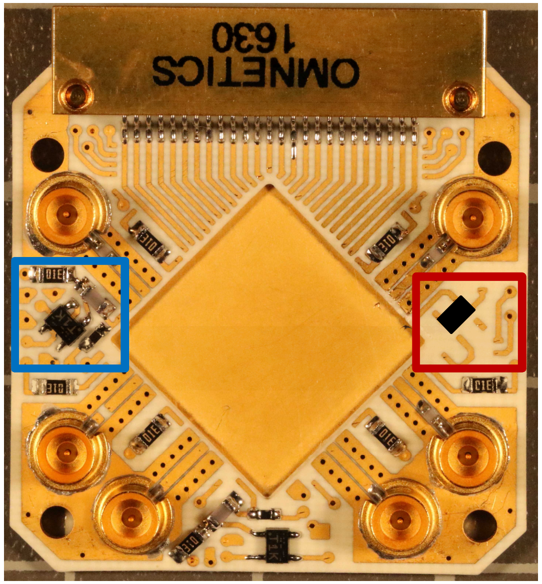


Conclusions

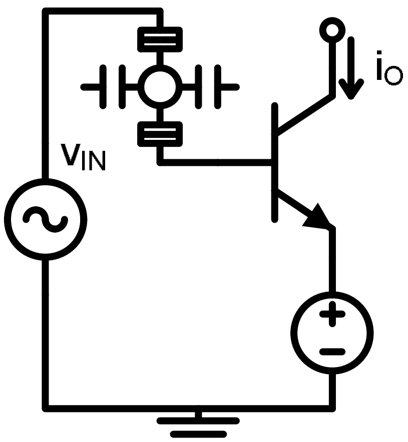
- The Non-linear and AC HBT both provide power-efficient gain
- The Non-linear HBT effectively current biased the SET and provides the best SNR up to 100s of kHz
- The AC HBT largely preserves the SET voltage bias and can be operated in the 1 MHz range
- Both circuits easily integrate with devices on PCB

AC HBT





NL HBT



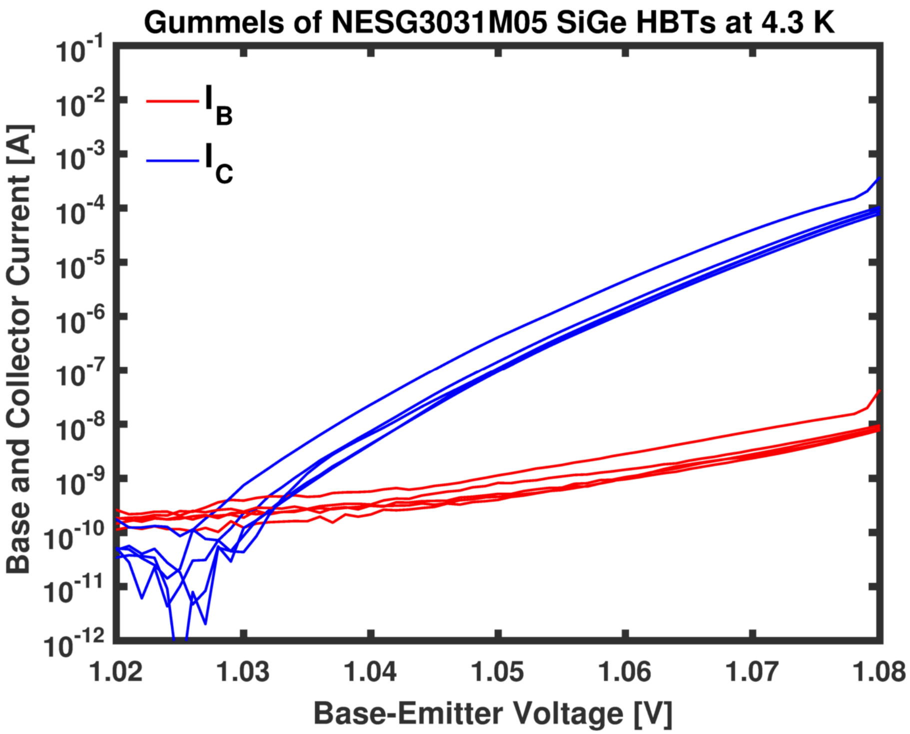
Other Slides

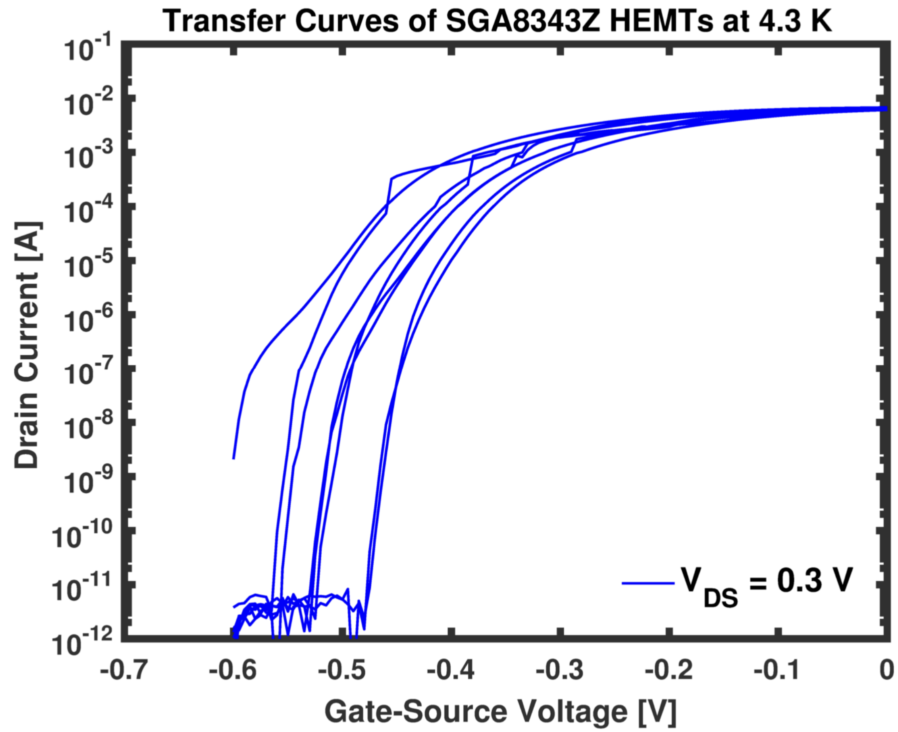
Abstract

Fast, low-power quantum state readout is one of many challenges facing quantum information processing. Single electron transistors (SETs) are potentially fast, sensitive detectors for performing spin readout. From a circuit perspective, however, their output impedance and nonlinear conductance are ill suited to drive the parasitic capacitance of coaxial conductors used in cryogenic environments, necessitating a cryogenic amplification stage.

We will compare two amplifiers based on single-transistor circuits implemented with silicon germanium heterojunction bipolar transistors. Both amplifiers provide gain at low power levels, but the dynamics of each circuit vary significantly. We will explore the gain mechanisms, linearity, and noise of each circuit and explain the situations in which each amplifier is best used.

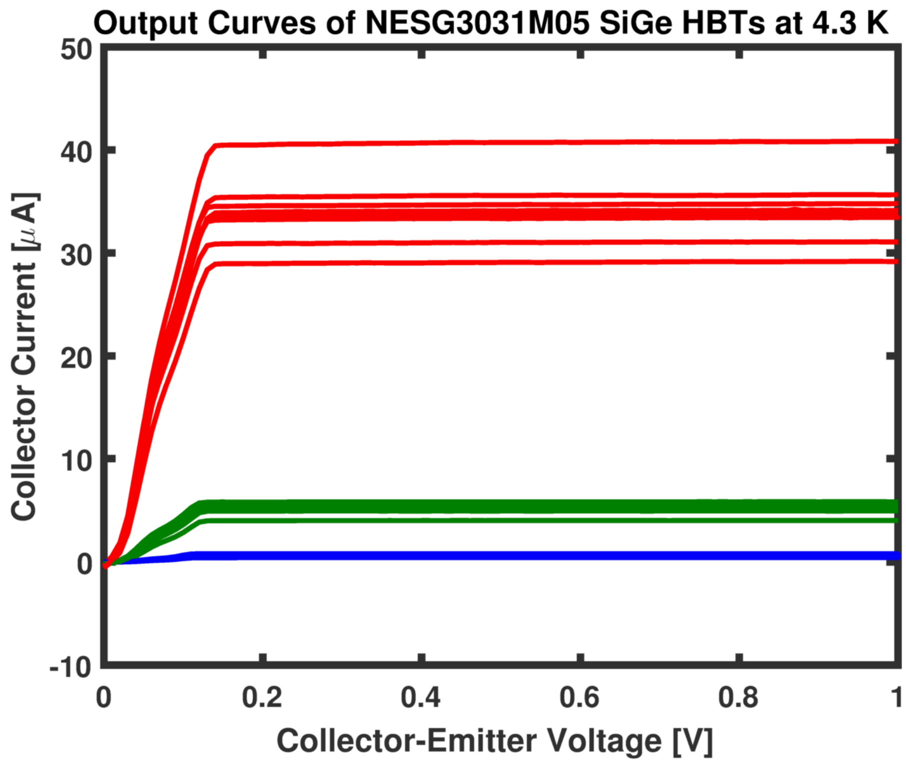
Why Not HEMTs? Consistency

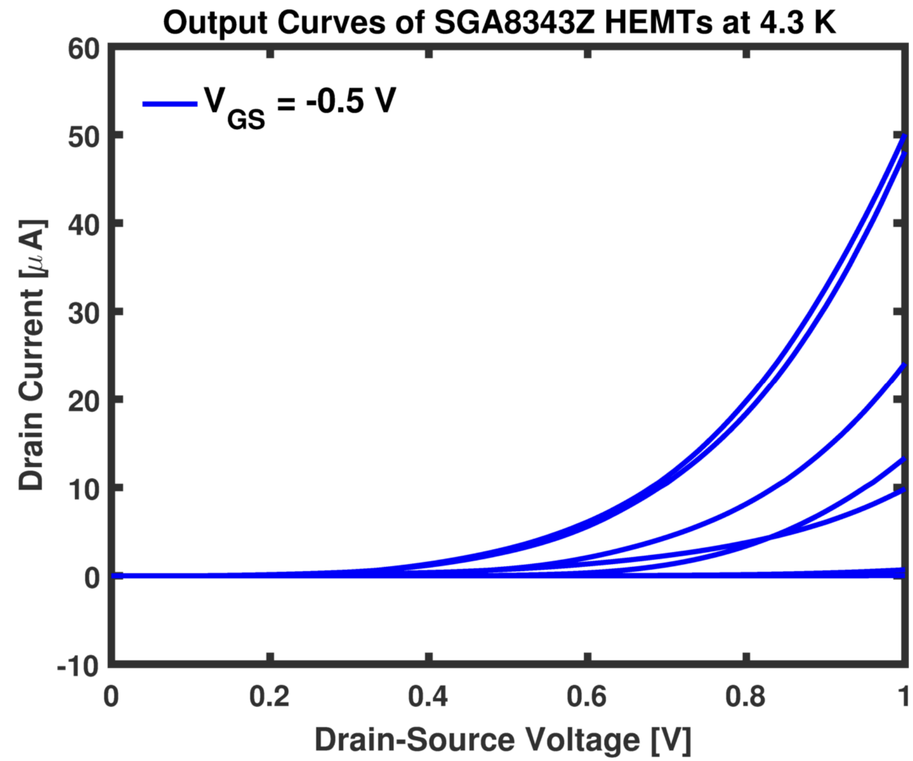




- Variation in current versus input voltage
  - HBT ≈ 5 mV
  - HEMT ≈ 100 mV
- This is an indicator for offsets in TIAs, ADCs, and DACs

Why Not HEMTs? Output Current





- Good design relies on constant current across output voltage
  - Flat lines are the goal
- This is an indicator for maximum gain available in amplifiers
- Unplotted: low frequency noise