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# Flexible Low-power SiGe HBT Amplifier Circuits for Fast Single-shot Spin Readout

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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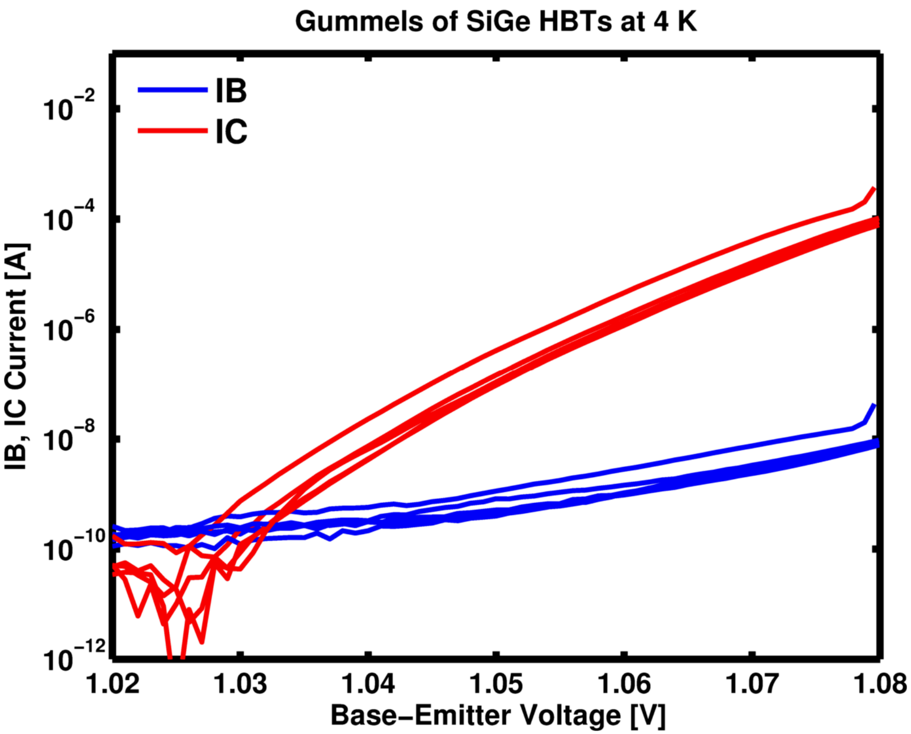
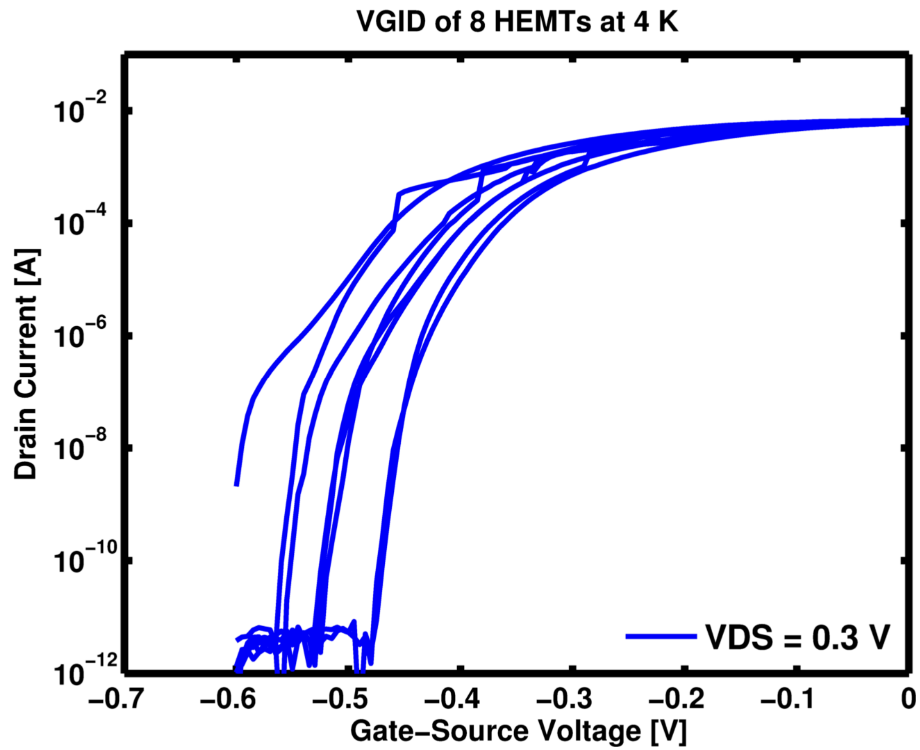
# Fast Single Shot Spin Readout

- We want fast, high-fidelity, single-shot spin readout
- Stand-alone SETs' SNR is too low at wide bandwidths
- RF SETs require complex systems and extensive tuning

- We continue to investigate cryogenic pre-amplification
- Predictable, linear gain with low experiment overhead
- Discrete COTS SiGe heterojunction bipolar transistors
- **New amplifier provides power-efficient, reliable gain**

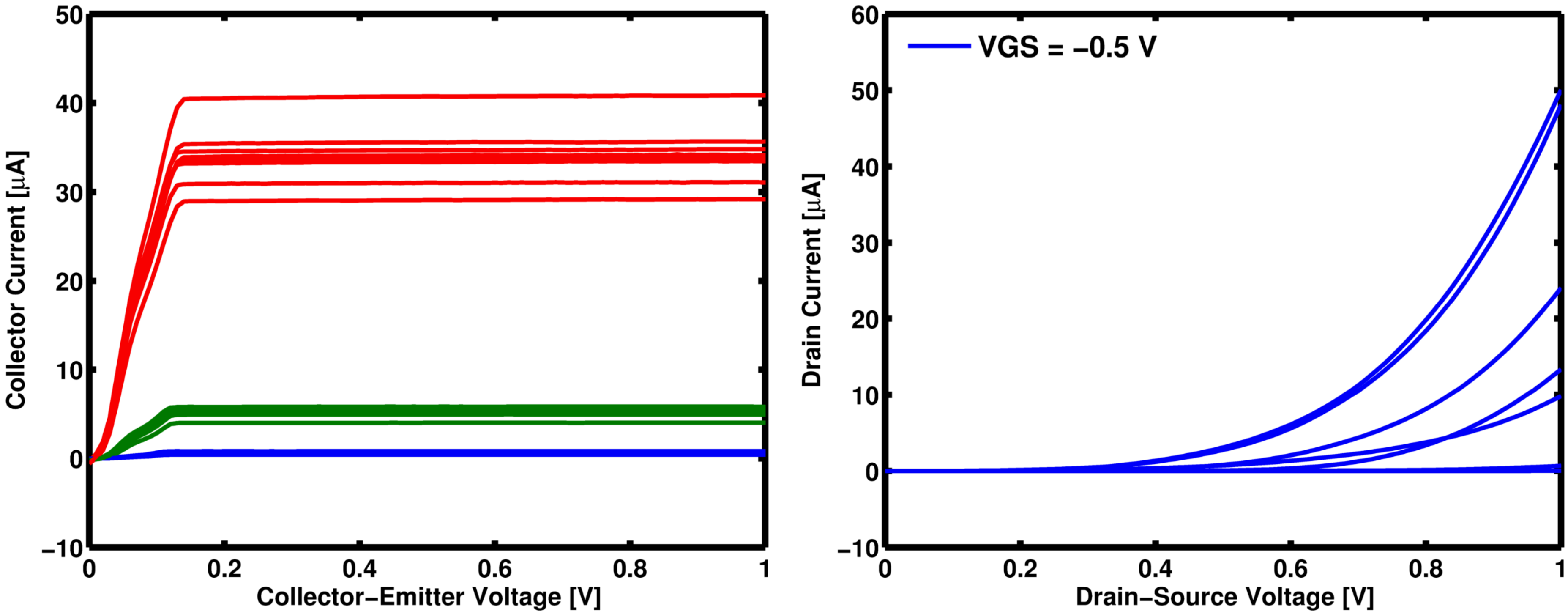
# Why Not HEMTs? Consistency



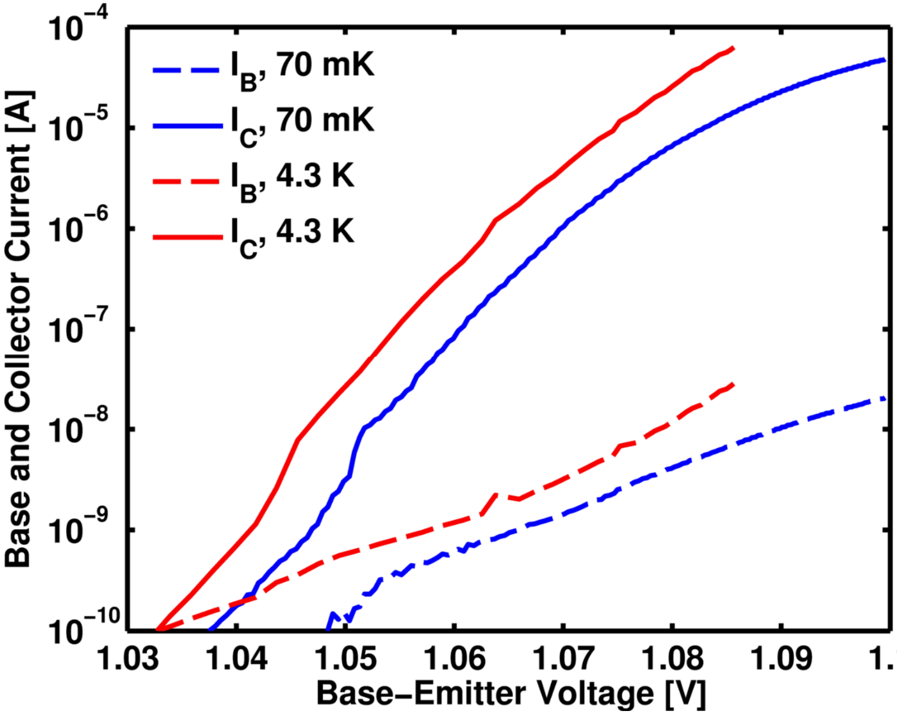

- Variation in current versus input voltage
  - HBT ≈ 5 mV
  - HEMT ≈ 100 mV
- This is an indicator for offsets in TIAs, ADCs, and DACs

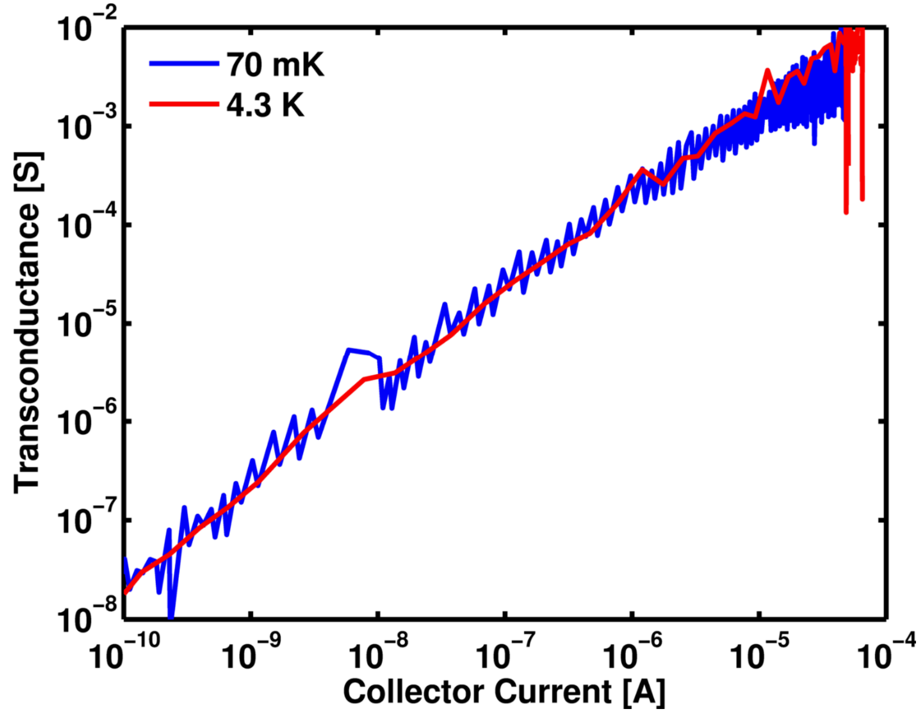
# Why Not HEMTs? Output Current




- 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

# SiGe HBTs working 4 K to 70 mK

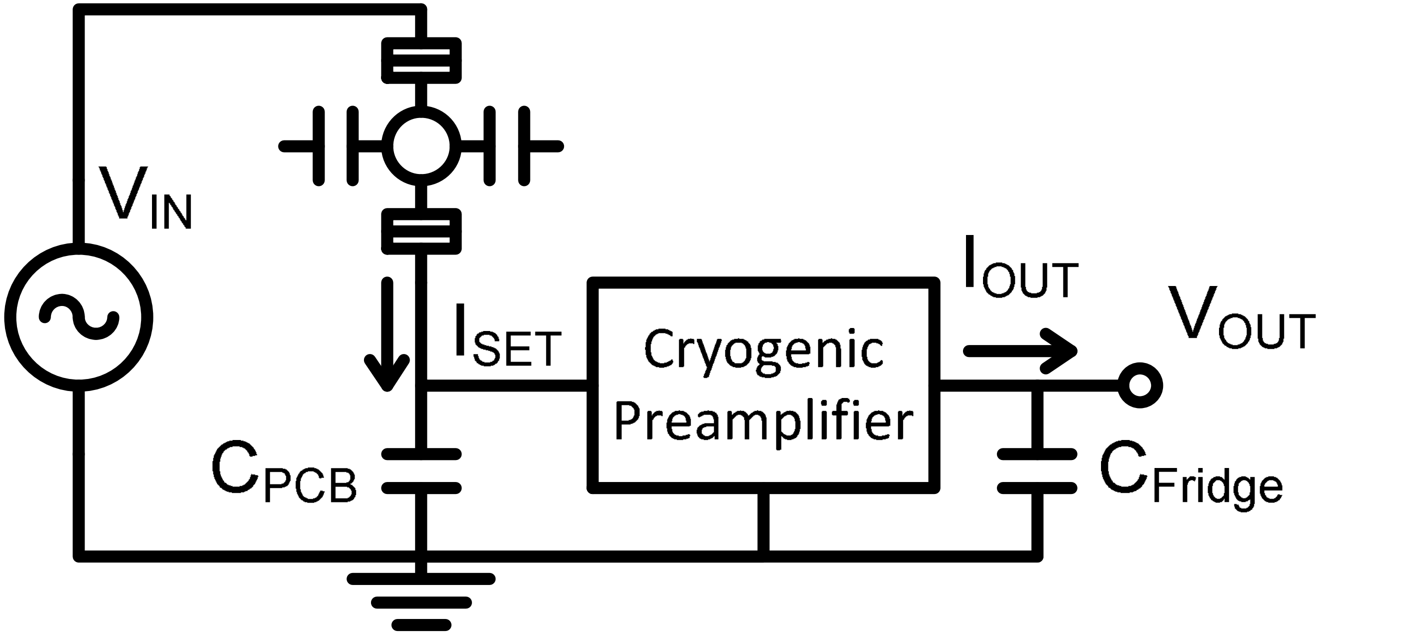



- Increase of turn on voltage of about 10 mV
- First-order performance unchanged down to 70 mK
- Transconductance is $\frac{\partial I_C}{\partial V_{BE}}$ and important for circuit design

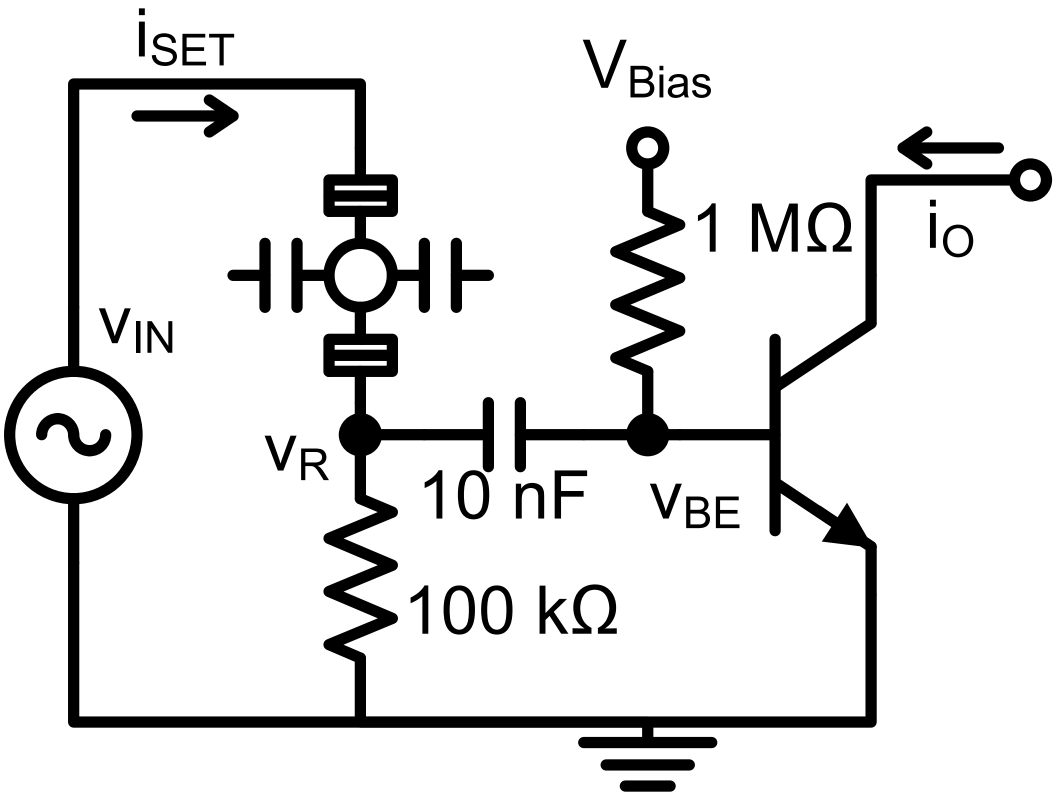
# Preamplifier Considerations

| Goal | Requirement |
|---|---|
| Keep SET Potentials Constant | Low Input Impedance |
| Keep Temperature Low | Low Power Consumption |
| Preserve Small Signals | Low Added Noise |
| Detect Small Signals | High Gain |
| Wide Signal Bandwidth | Low Input/Output Impedance |



# AC HBT Design

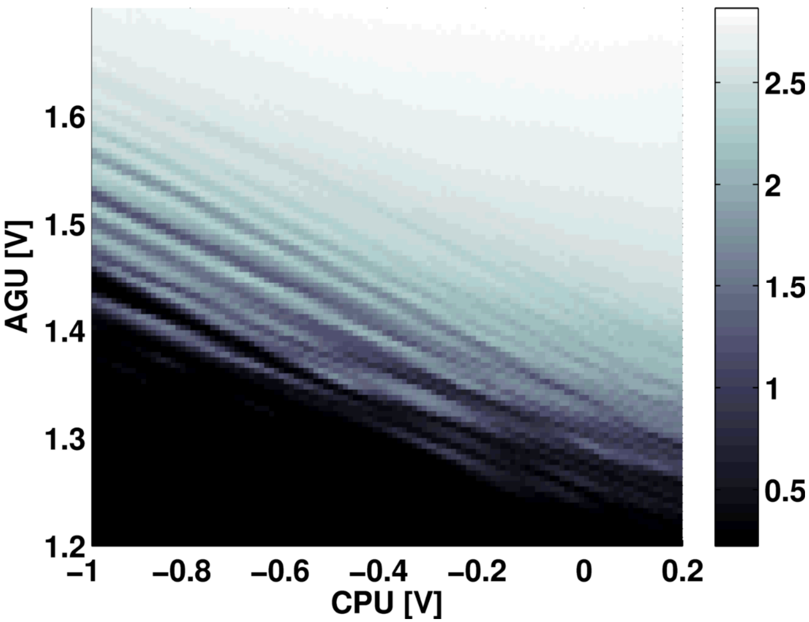
- Incredibly power efficient design
- Allows for in situ power vs gain tradeoffs
- Where it succeeds:
  - Low power consumption
  - Low noise
- Room for improvement:
  - Input impedance
    - Saturates if $R_{SET}$ < 100k
  - Output impedance
    - Reliant on room-T TIA



# AC HBT vs Stand-alone SET

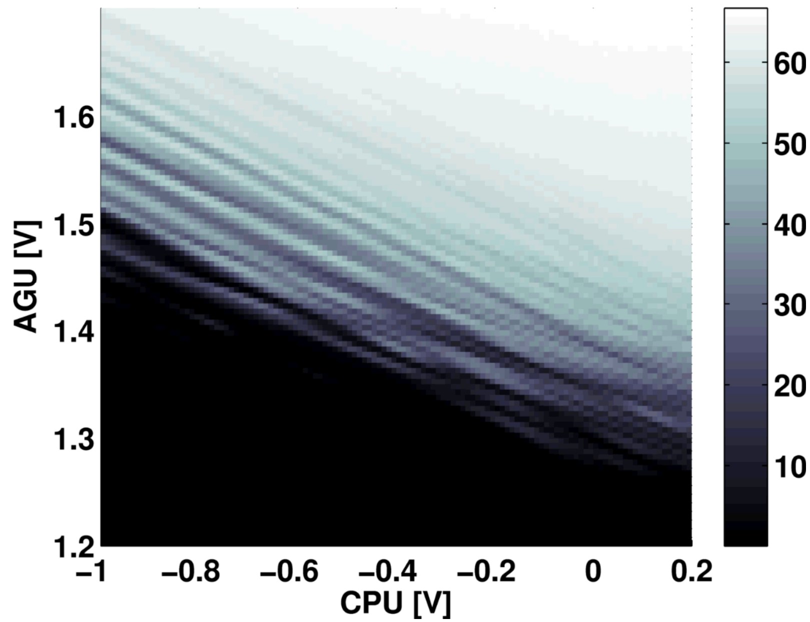
## SET Signal

Magnitude AC Drain Current [$nA_{rms}$]

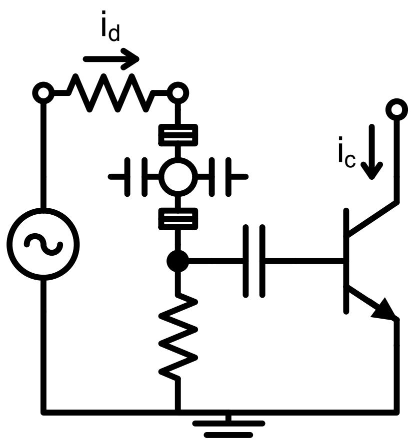



## AC HBT Signal

Magnitude AC Collector Current [$nA_{rms}$]




- 23 A/A gain even at 400 nW
- Very little impact on the SET response



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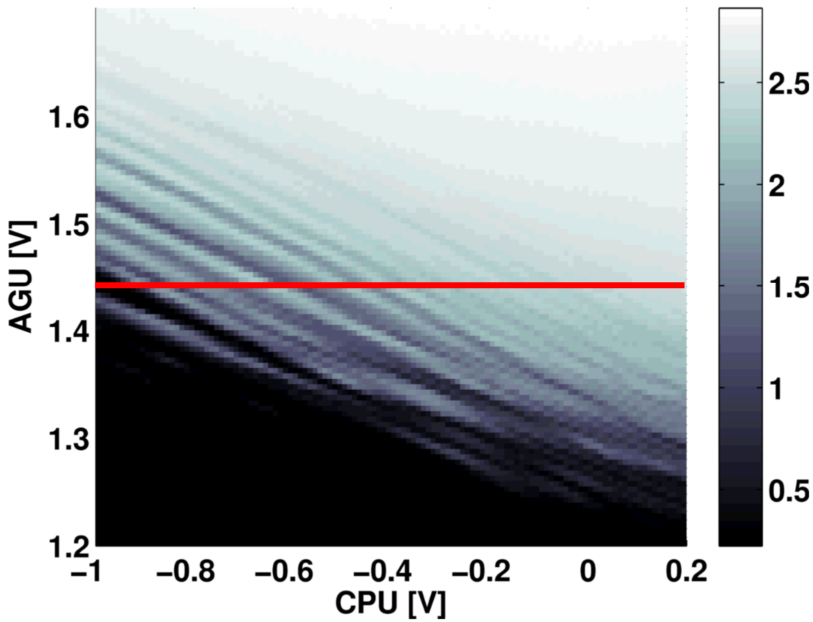
Magnitude AC Drain Current [$nA_{rms}$]

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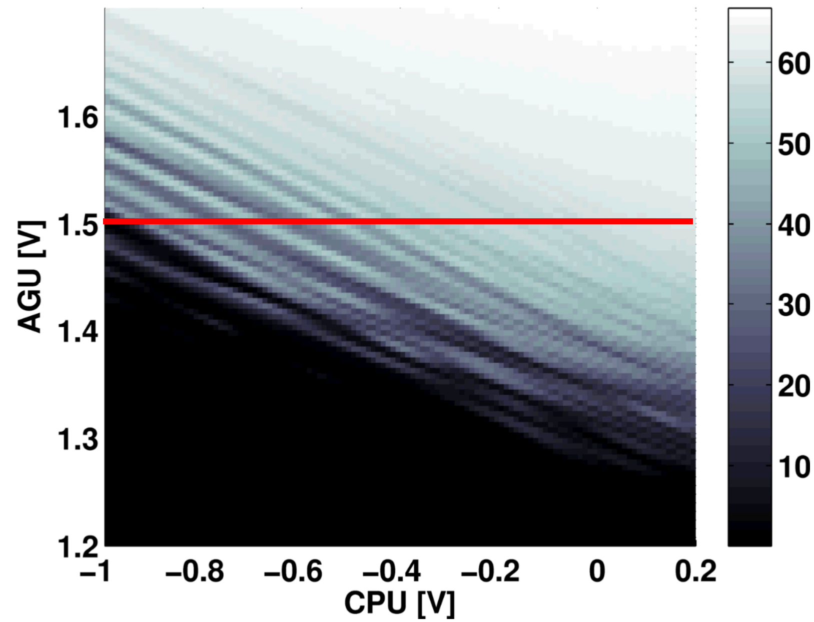
Magnitude AC Collector Current [$nA_{rms}$]

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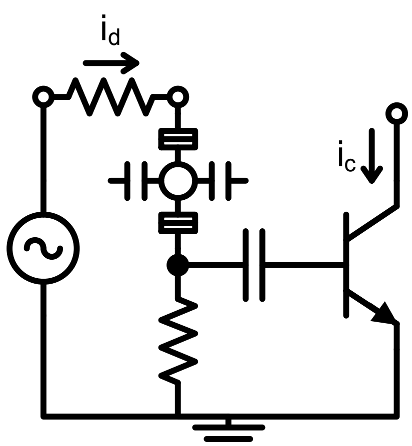
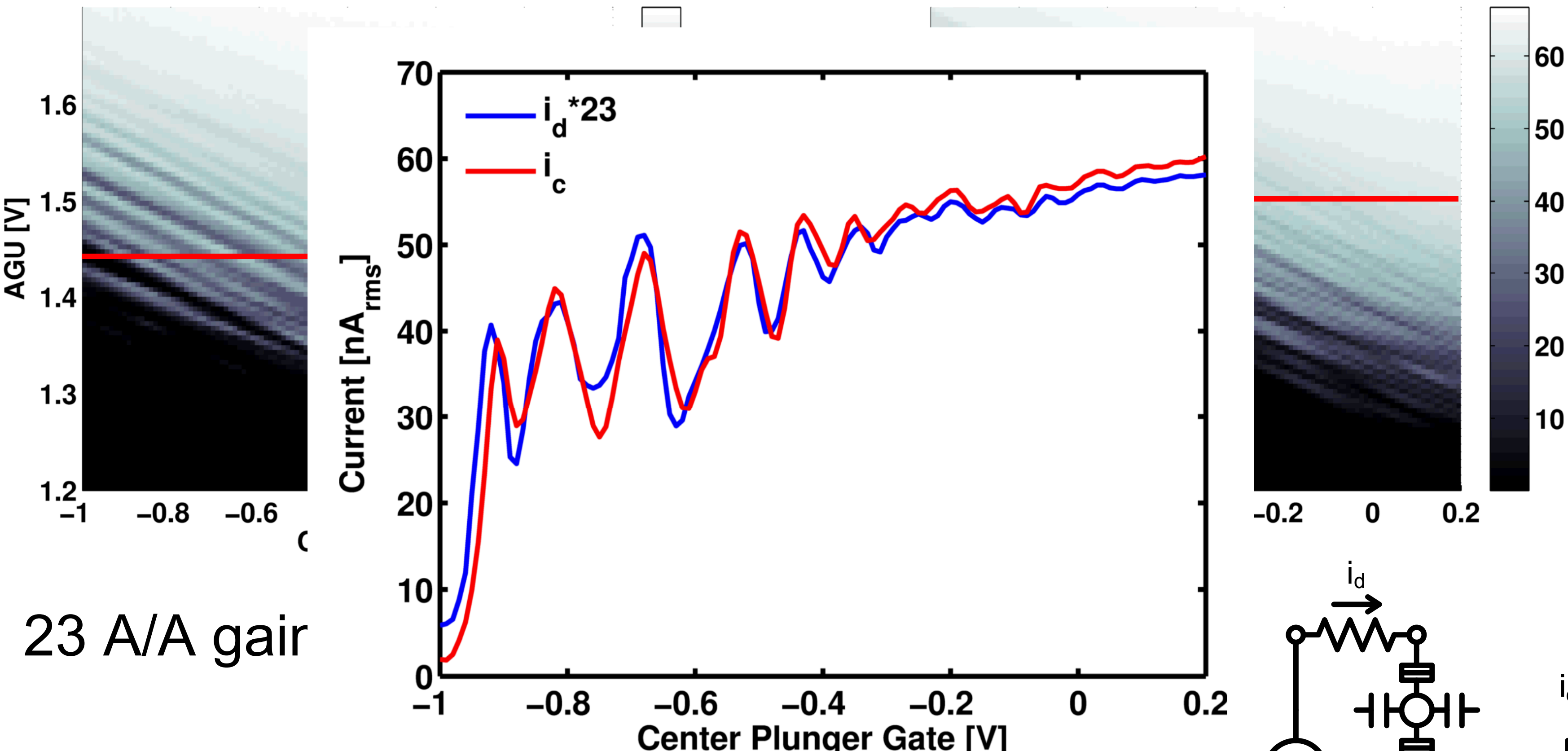


# AC HBT vs Stand-alone SET

**SET Signal**
Magnitude AC Drain Current [$nA_{rms}$]

**AC HBT Signal**
Magnitude AC Collector Current [$nA_{rms}$]

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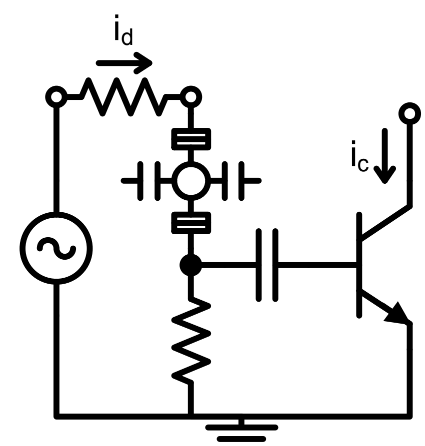
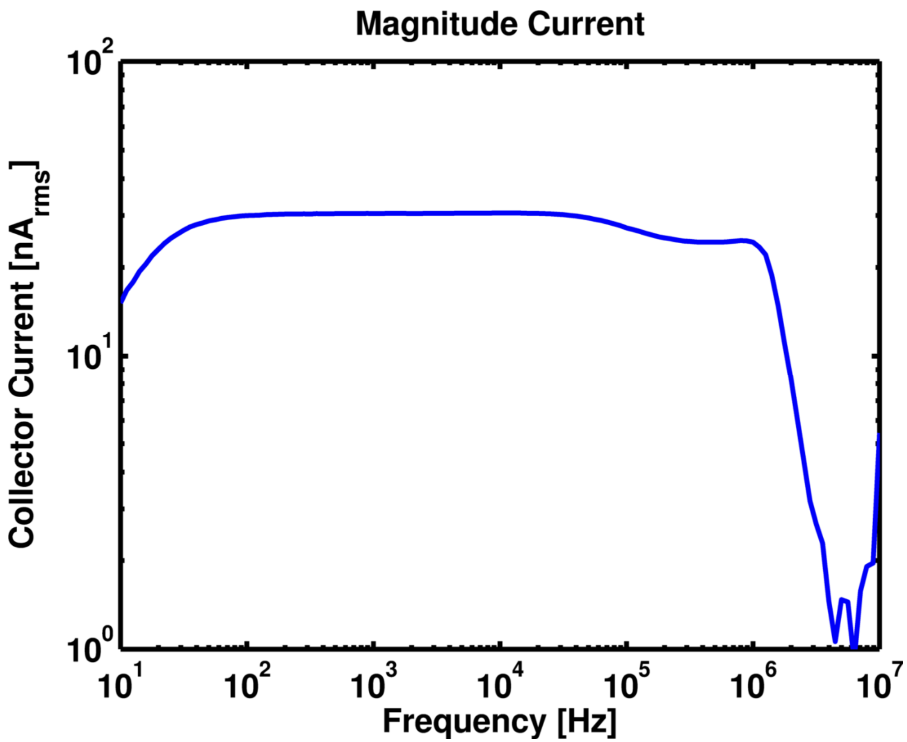
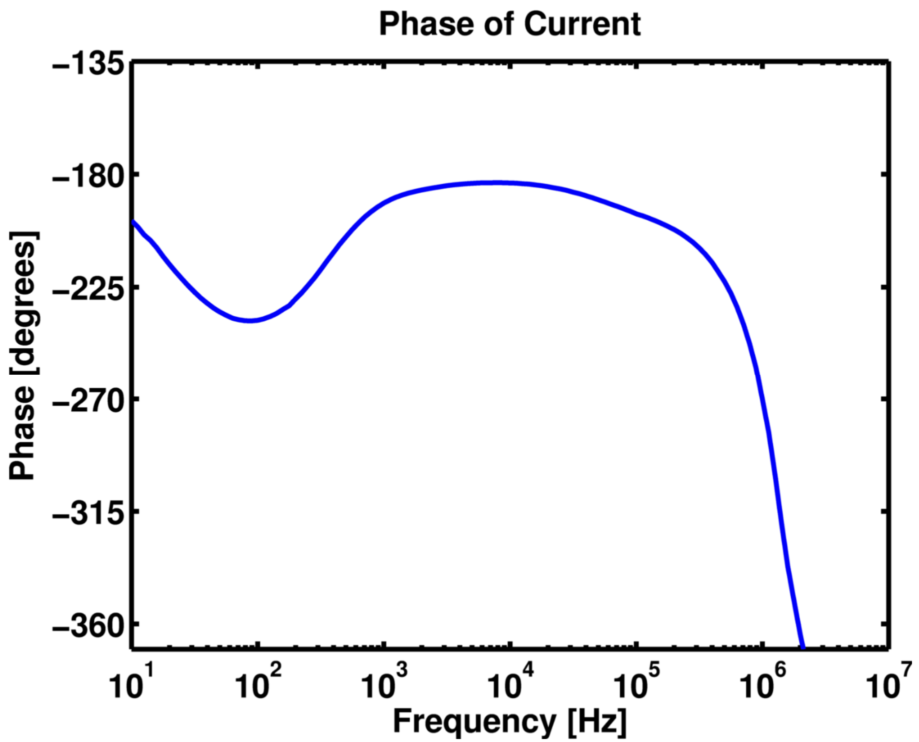


# AC HBT Carrier Bandwidth




- Leverages the room-T TIA to achieve 1 MHz bandwidth

# Performance Comparison to Similar

| Specification | AC HBT (1 μA $I_C$) | TIA 2015 | DC HBT | Two Stage HEMT[1] |
|---|---|---|---|---|
| Gain | **23 A/A*** | 100k V/A | 1000 A/A | 2700 A/A |
| –3 dB Carrier Bandwidth | 20 Hz – 1 MHz | DC – 1 MHz | Under Investigation | 100 Hz – 900 kHz |
| Input Resistance | 100 kΩ | 30 kΩ | 10 MΩ | 100 kΩ |
| Power | **400 nW*** | 91 μW | 1 μW | 13 μW |
| Input Referred Noise | Simulated<br>< 100 fA/√Hz<br>40 Hz – 3 MHz<br>Min: 35 fA/√Hz | Simulated<br>< 40 fA/√Hz<br>DC – 3 MHz<br>Min: 35 fA/√Hz | Measured<br>< 100 fA/√Hz<br>1 kHz – 60 kHz<br>Min: 40 fA/√Hz | Measured<br>< 100 fA/√Hz<br>150 kHz – 1 MHz<br>Min: 50 fA/√Hz |
| Best Case Charge Sensitivity | 175 μe/√Hz# | 175 μe/√Hz# | 100 μe/√Hz | 350 μe/√Hz# |

*tunable gain vs. power tradeoff **57 (A/A)/μW**

#Calculated with a 200 $pA_{rms}$ signal

[1]APL 108, 063101 (2016)

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

# Performance Comparison to Others

| Specification | Reference | –3 dB Carrier Bandwidth | Location | Charge Sensitivity |
|---|---|---|---|---|
| AC HBT (1 μA IC) | This Talk | 20 Hz – 1 MHz | Mixing Chamber | Simulated 175 μe/√Hz[#] |
| HEMT | APL 91, 123512 (2007) | DC – 1 MHz | 1 K Stage | 400 μe/√Hz |
| RF-QPC | Physica E 42, 813 (2010) | 10 MHz around 763 MHz | 1 K Stage | 100 μe/√Hz |
| RF-SET | PRB 81, 161308(R) (2010) | 1.5 MHz around 220 MHz | 1 K Stage | 80 μe/√Hz |
| RF Cavity & JPA | PR Applied 4, 014018 (2015) | 3.8 MHz around 7.88 GHz | Mixing Chamber | 80 μe/√Hz |

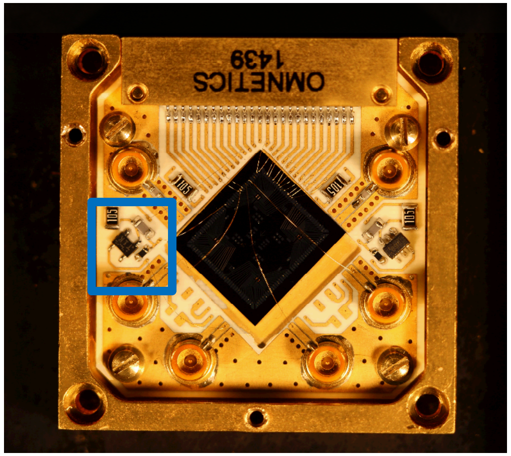
[#]Calculated with a 200 $pA_{rms}$ signal

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

# Conclusions and Future Work

- AC HBT is Incredibly Power Efficient
- Simulated Noise Approaching the Leading Edge
- Circuit Easily Integrated with Devices on PCB

AC HBT




- Noise Model Calibration Needed
- Bandwidth Work is in Progress

- Two Stage Design can Further Improve Gain vs. Power
- An Integrated Circuit Approach is Attractive