SAND2015-1378C

Sandia National Laboratories

Measurement, modeling, and simulation of cryogenic SiGe HBT amplifier circuits for fast single spin readout

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March 5, 2015

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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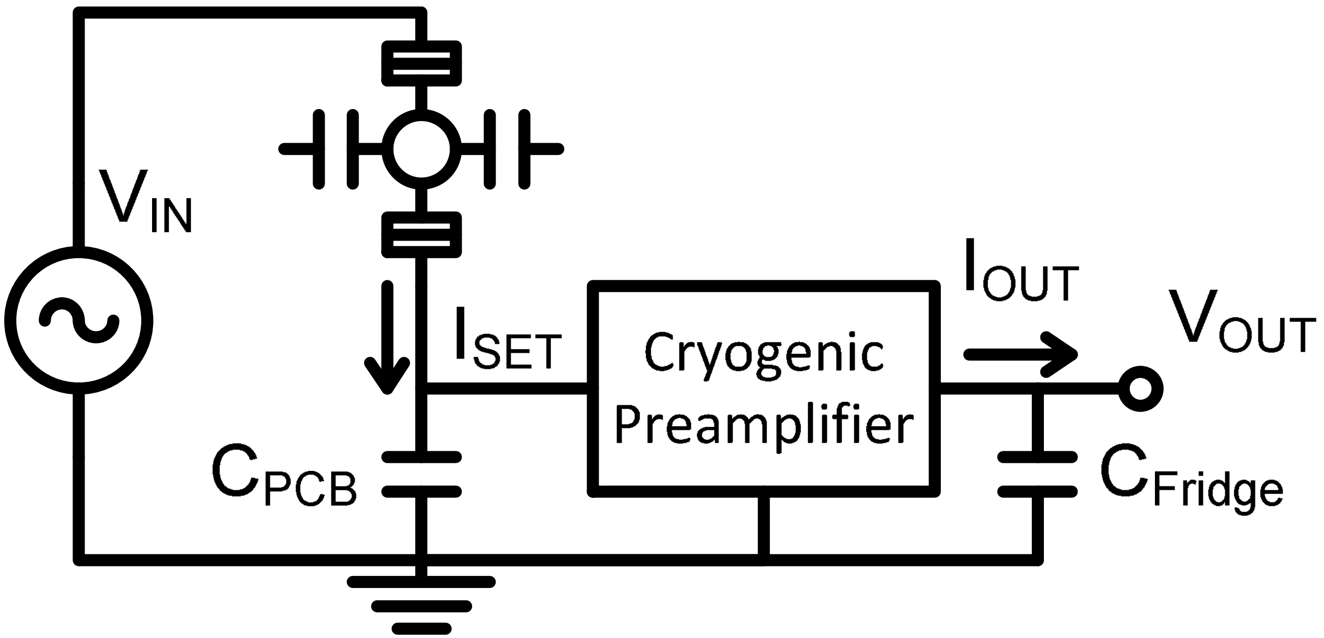
Fast Single Shot Spin Readout

- We Want High Fidelity, Fast Single Shot Spin Readout
- RF SETs are Good at Narrow Bandwidths
- Signal to Noise Ratio is too Low at Wide Bandwidths

- We Investigated Cryogenic Preamplification
- Used Discrete COTS SiGe Heterojunction Bipolar Transistors
- Maintained Low Overhead using PCB Amplifier
- Aiming for 2 MHz Bandwidth, 100 dB Gain, DC Operation

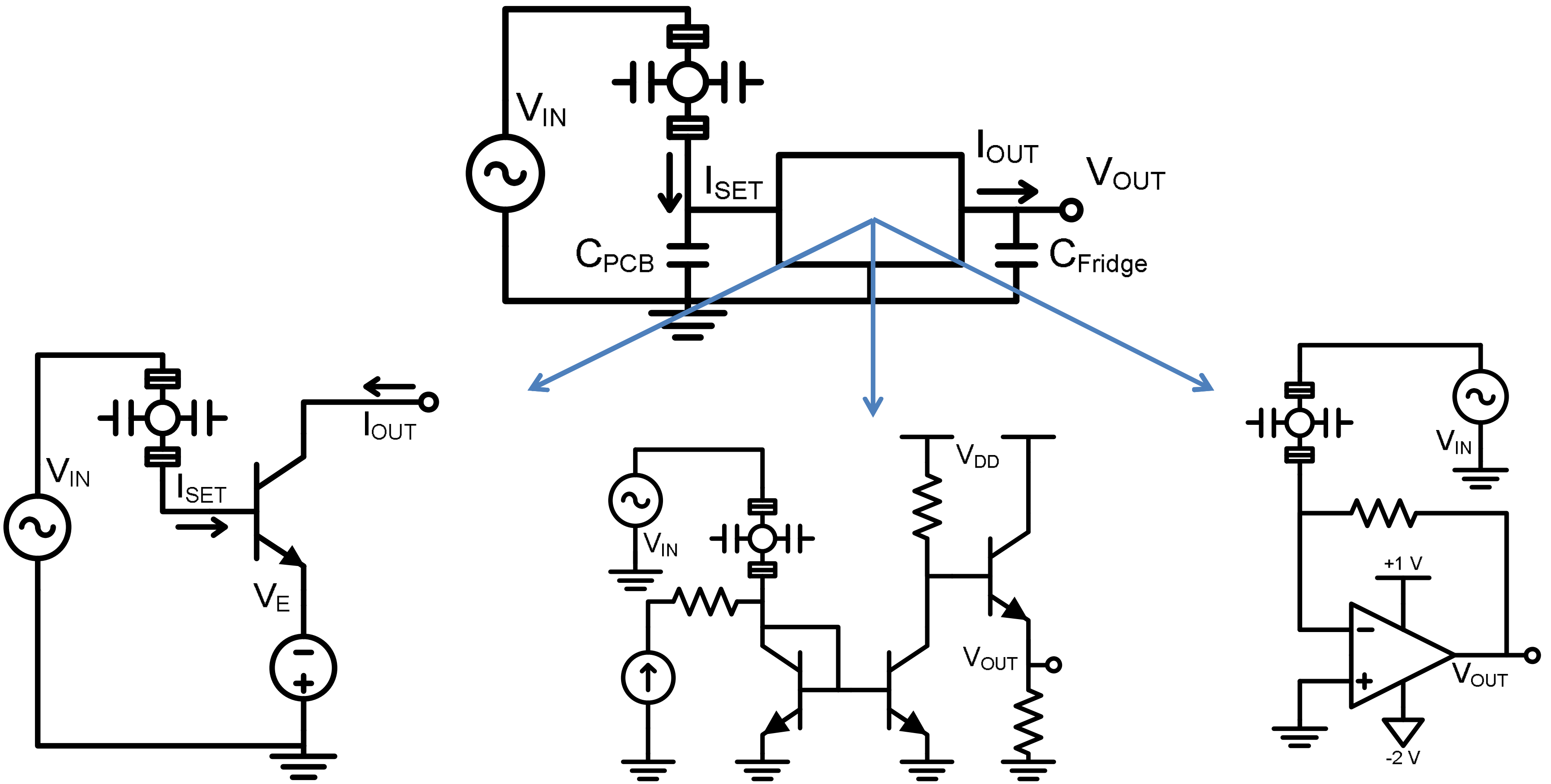
Preamplifier Considerations

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



Implementation

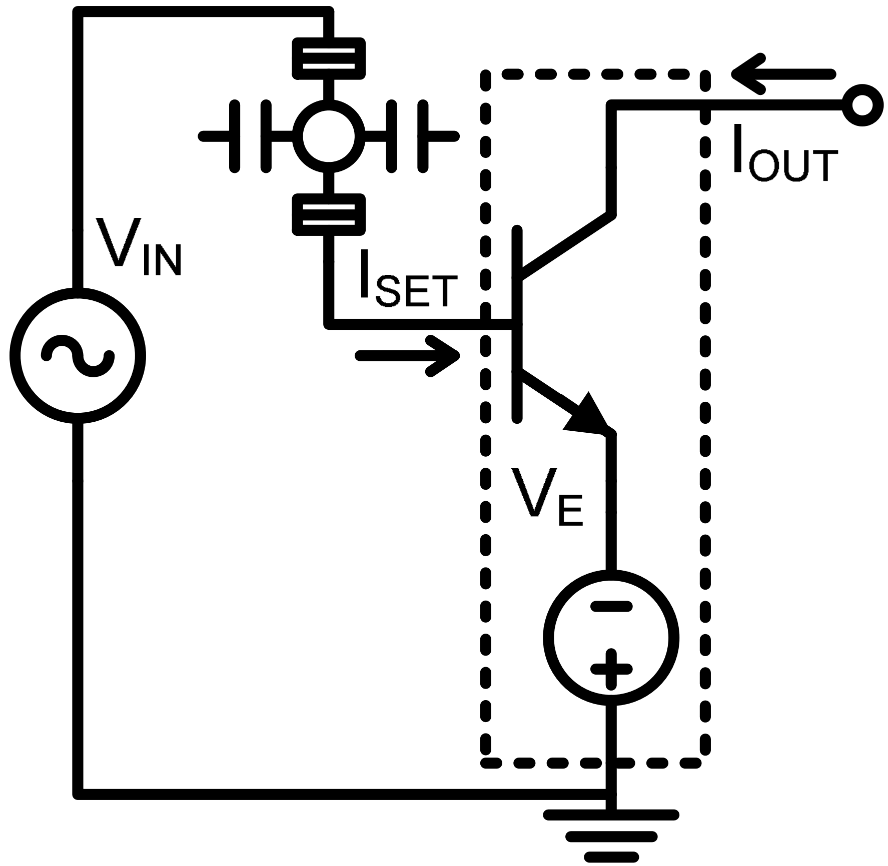
- We Explored Three Designs With Different Trade-offs
- Using Commercial Parts and PCB Keeps Costs Low
- Initial Testing at 4 K for Modeling and Verification



Single HBT Amplifier

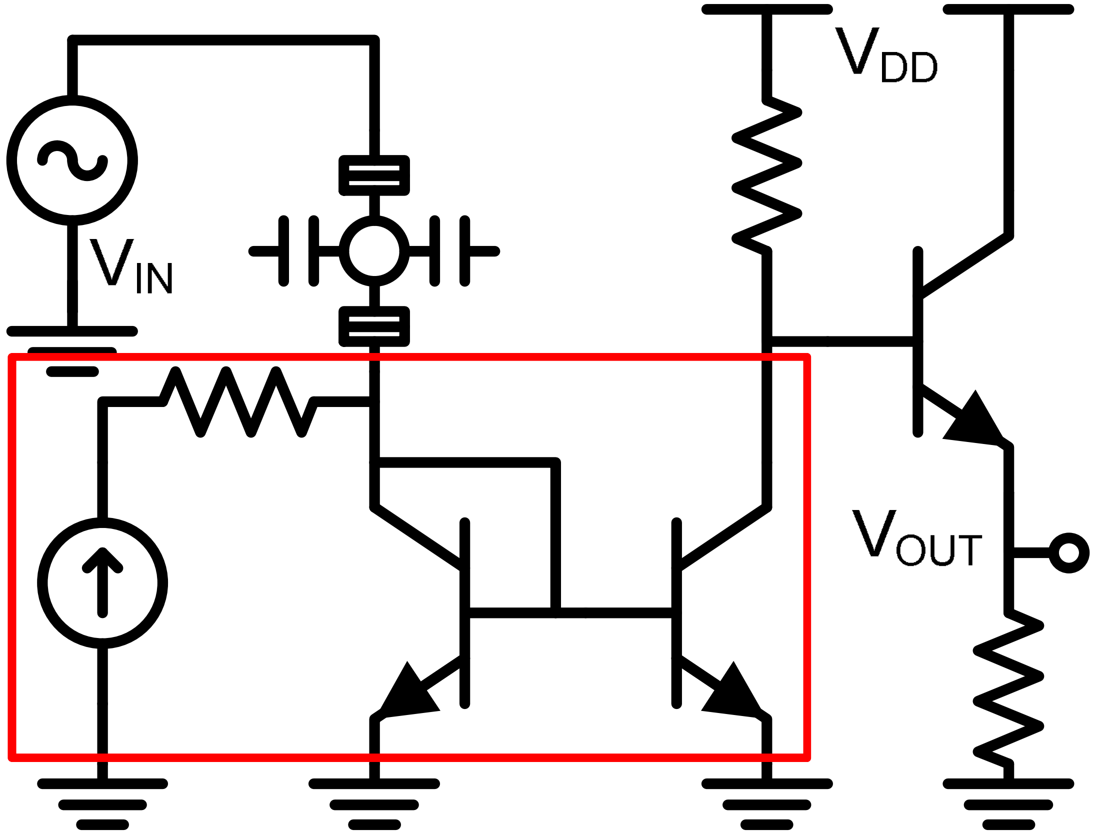
- Goals Accomplished
  - Keeps SET Temperature Low
  - Preserves Small Signals
  - Detects Small Signals

- Challenges Remaining
  - Keep SET Potentials Constant
  - Wide Signal Bandwidth



Read-out Circuit Design

- Current Mirror Provides Low-impedance Input
  - Biased by separate input current
- Mirrored Current Drives a Resistor for Transimpedance Gain
- Emitter Follower Ensures a Low-impedance Output



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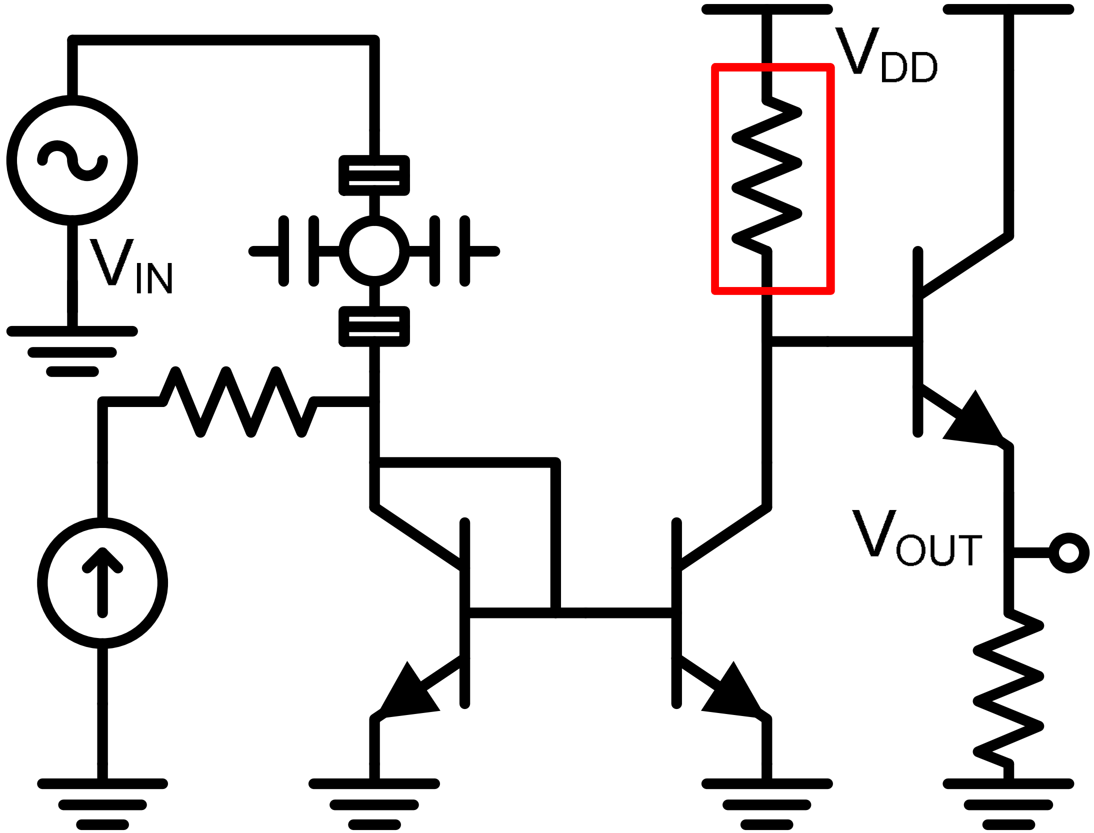

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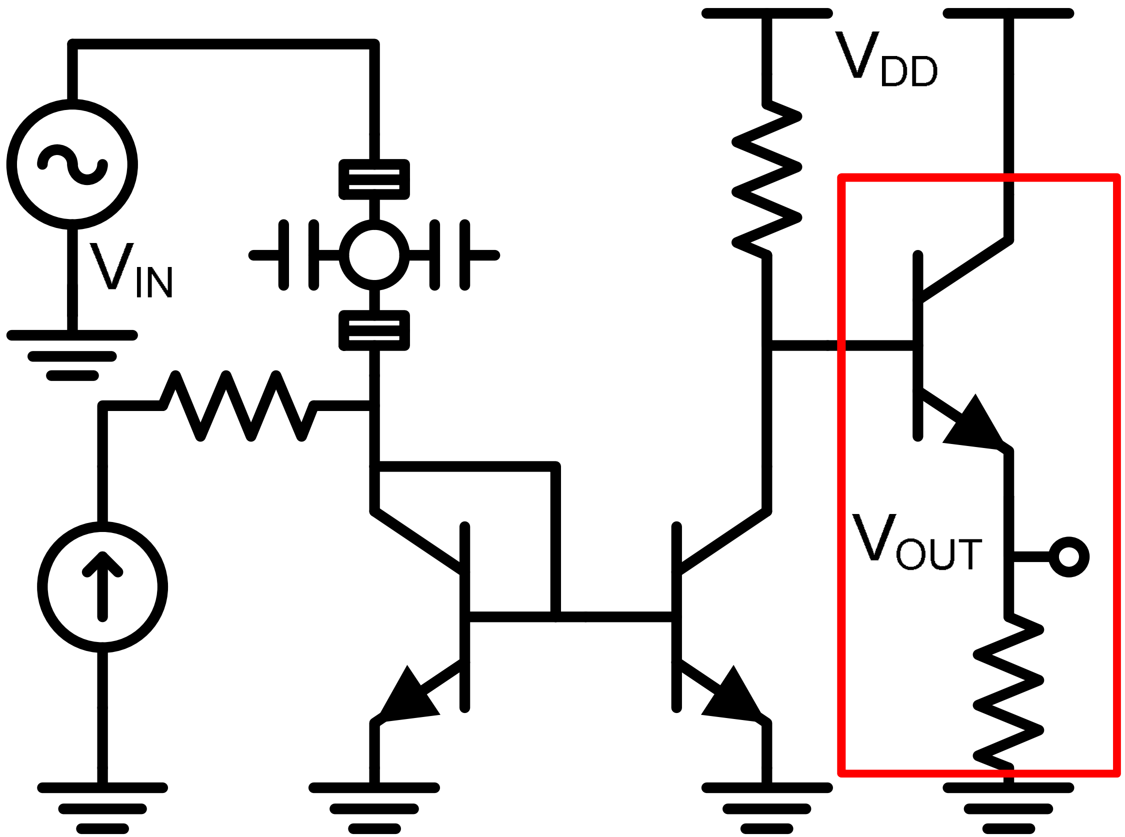
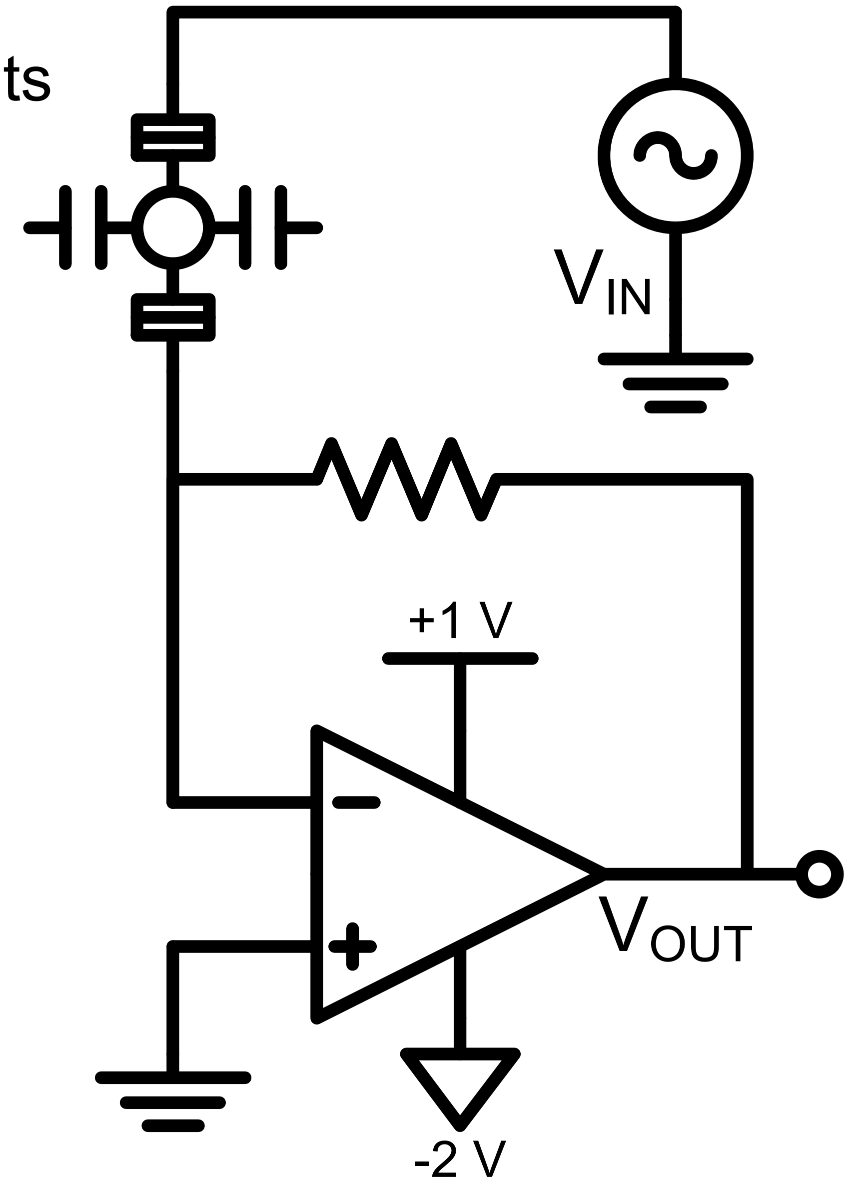


Transimpedance Amplifier Concept

- Similar to DL1211 and Femto Units
- Feedback Has Many Advantages
  - Low input impedance
  - Low output impedance
  - Low added noise
  - Voltage at inputs follow each other
- Other Challenges Remain
  - Low power
  - High gain



Simulation Summary

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Specification	Read-out Circuit	Transimpedance Amp.
Gain	100 dB V/A	100 dB V/A
-3 dB Bandwidth	2 MHz	1.9 MHz
Input Resistance	100 kΩ	5 kΩ
Power	138 μW	91 μW
Input Ref. Noise 1 Hz to 1 MHz	220 pA_{rms}	32 pA_{rms}

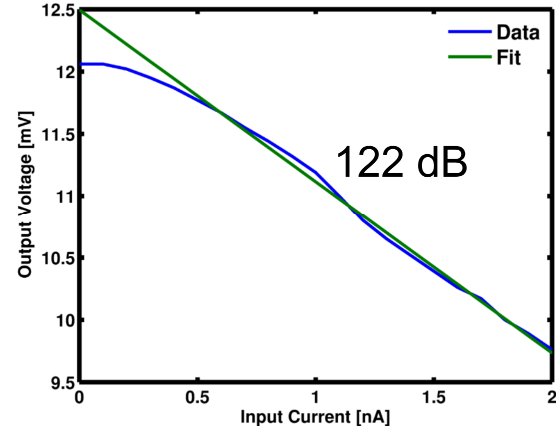
Simple 4 K HBT Models with Shot Noise

Ideal Resistors with Johnson-Nyquist Noise

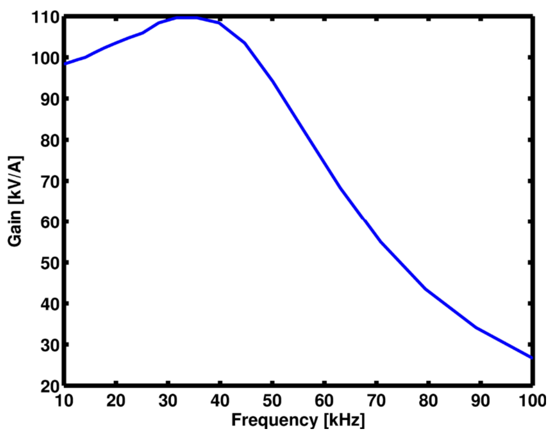
Measurements

- 4 K Functionality Proven
- Initial Setup Limited Bandwidth
- Measurement to Model Fidelity Retained

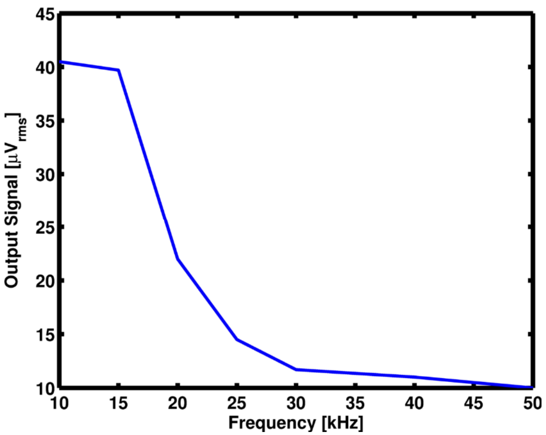
Read-out Circuit Gain



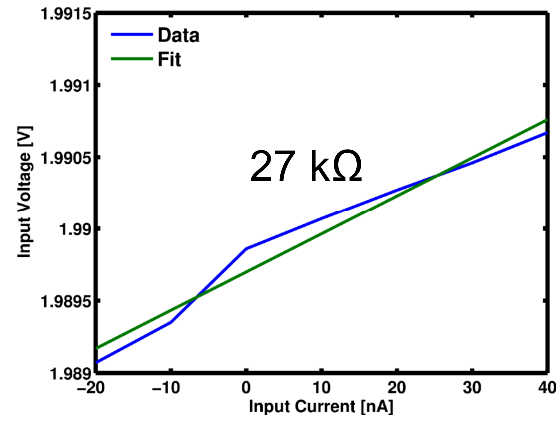
Simulated TIA Bandwidth Limited by Setup



Actual TIA Bandwidth Limited by Setup



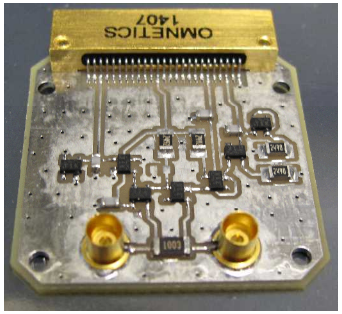
TIA Input Impedance



Conclusions and Future Work

- Simple Models and Basic Assumptions
- Working Amplifiers at 4 K
- Model to Circuit Correlation was Good
- Complete PCB Solution for ≈$1k/board

2 RoCs



TIA

- Accurate Noise Measurement Needed for Model Verification
- Detailed Measurements Needed for Gain Improvements

- An Integrated Circuit Approach is Attractive
- 10x the Cost for 100x the Gain, Lower Noise at Same Power