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Using SiGe Technology for Qubit Readouts

PRESENTED BY

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Takeaways

Silicon-germanium heterojunction bipolar transistors are excellent devices for qubit readout

Inherent device physics results in improved performance at cryogenic temperatures

Basic modeling techniques have enabled numerous circuits

Simple circuits at base temperature have been effective for readout

Increased understanding of device physics in foundry processes can enable circuit improvements

Silicon-Germanium (SiGe) Heterojuction Bipolar Transistors (HBTs)

Diodes to SiGe HBTs in 120 Seconds

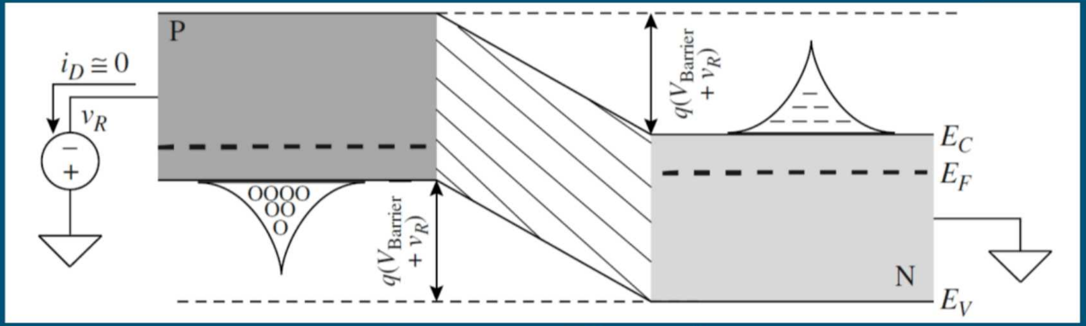
Diodes are diffusion current dominated

Symmetrically doped diodes will have nearly equal electron and hole current

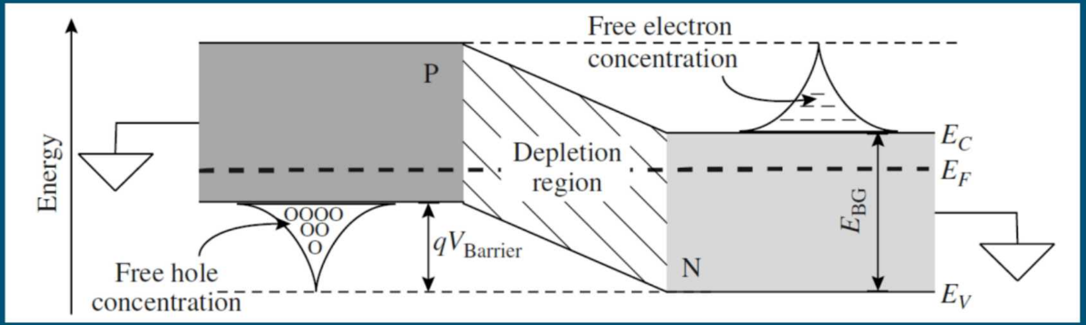
Uneven doping will change the current ratios

Add another n-type area to pull off electrons and make the p-type area very short

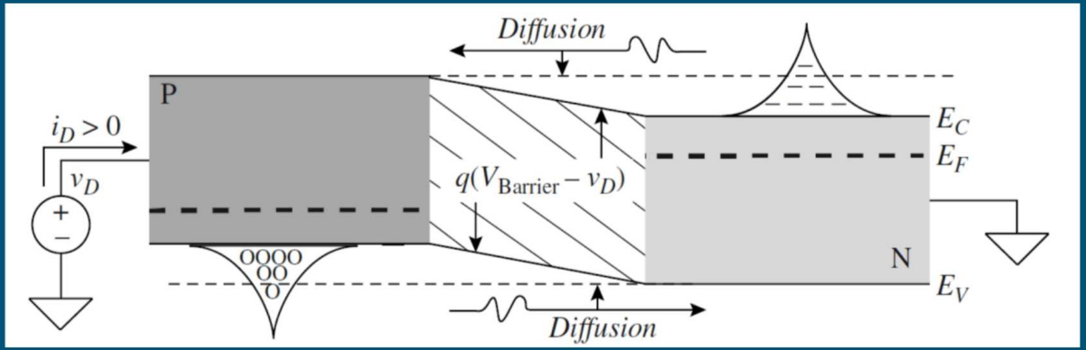
The bipolar junction transistor is created



Reverse Biased



Unbiased



Forward Biased

Rincon-Mora, G., *Analog IC Design with Low-Dropout Regulators*. New York: McGraw-Hill, 2009.

Silicon-Germanium Heterojunction Bipolar Transistors

The BJT reliance on much higher doping in the emitter than in the base adds constraints

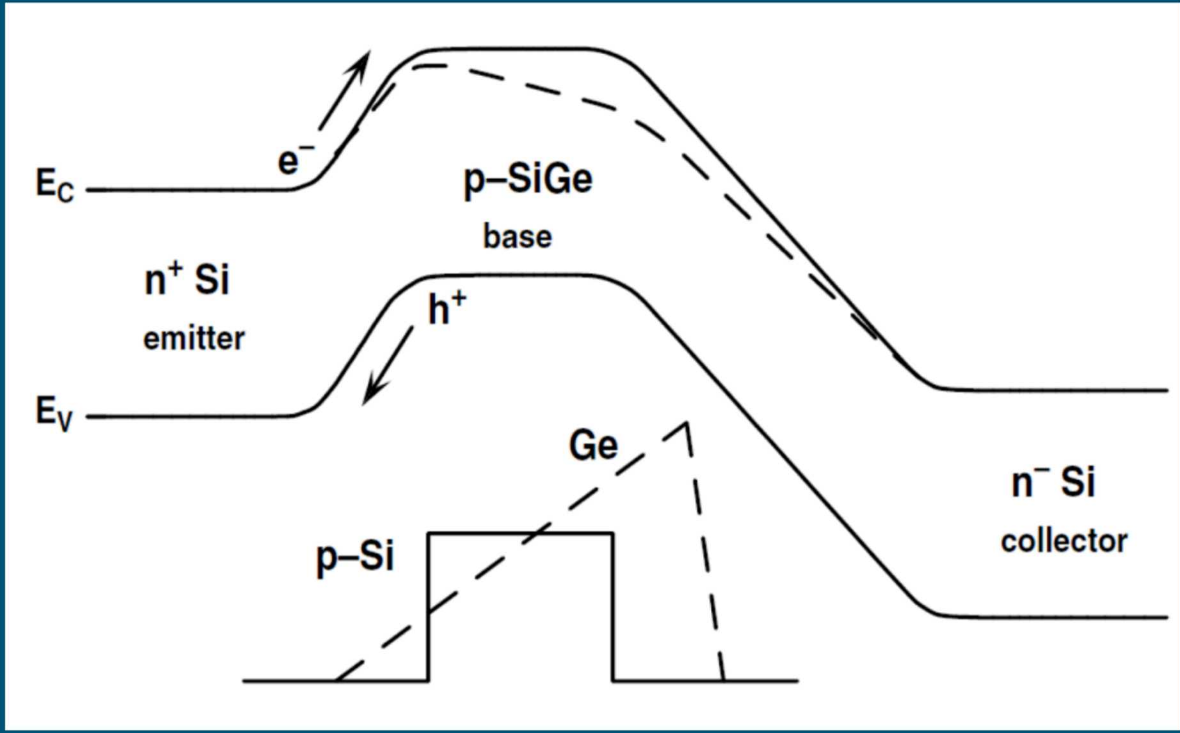
- Resistive base terminal adds noise and slows the transistor
- Higher doping reduces this resistance but lowers current gain

Germanium content in the base lowers the band gap

- Electron current before hole (higher current gain)
- Electric field in base (higher speed)

Increasing both Ge content and base doping keeps current gain high while reducing the base resistance

Consequently, SiGe HBTs are faster and slightly less noisy than Si BJTs



Cressler, J. D. and Niu, G., *Silicon-Germanium Heterojunction Bipolar Transistors*. Boston, MA: Artech House, 2003.

Modern SiGe HBT Technology

Graded germanium base profile

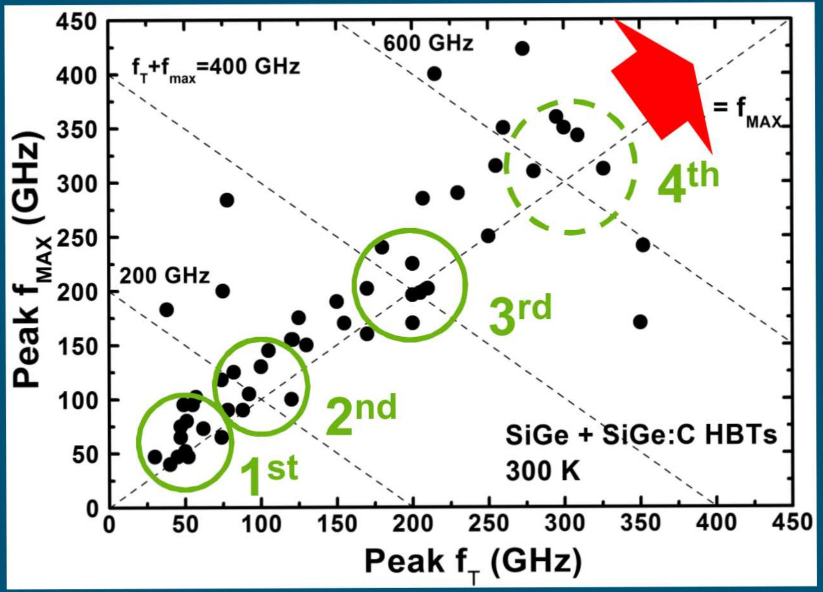
- Tuning knob for device parameters
  - β ↑, f_T ↑, VA ↑, NF ↓

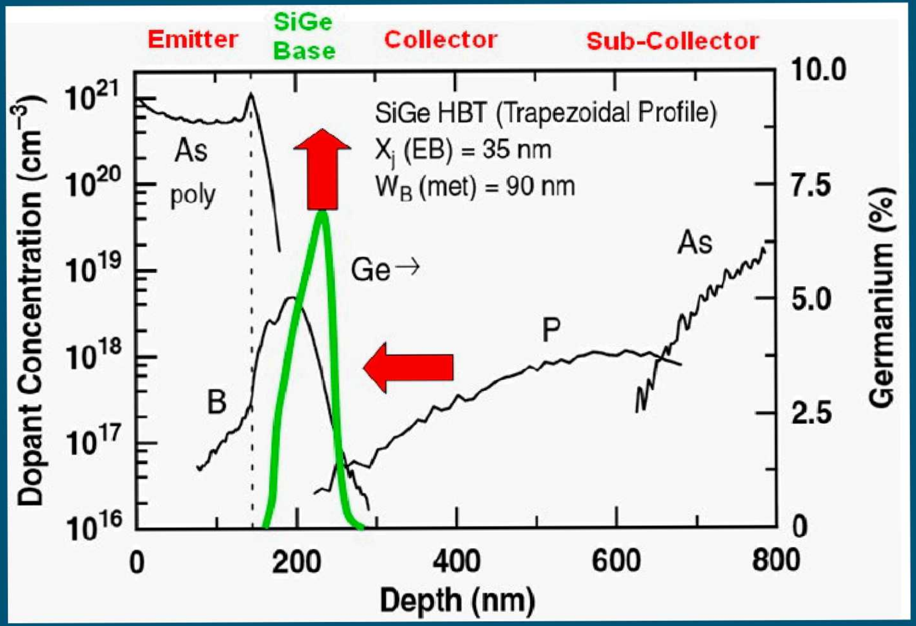
Compatible with standard Si fabs

- Integration with CMOS
  - SiGe BiCMOS available from 0.35 µm down to 90 nm
- Enables system-on-a-chip applications
  - Mixed-signal capability

Rapid scaling & performance trends

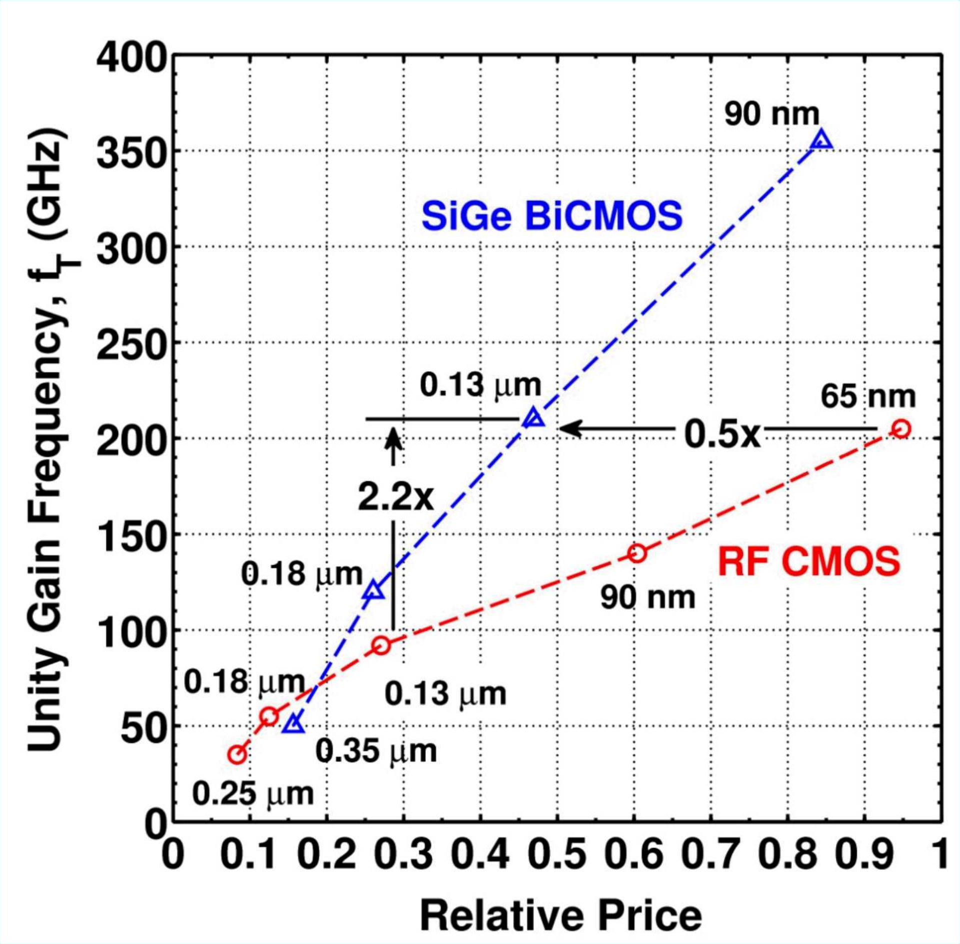
- 4th generation out now
- 500 GHz f_{MAX} devices in silicon





J. D. Cressler

Conventional Performance Niches



A. J. Joseph et al., vol. 93, no. 9. Proc. of the IEEE, 2005, pp. 1539–1558.

Technology Comparison

	MOS	HBT
Speed		✓
Noise		✓
Power Consumption	✓	
Transconductance		✓
Input Impedance	✓	

Low-volume cost per performance favors HBT

HBT outperforms CMOS in speed and noise

If it can be done in silicon,

it will be done in silicon.

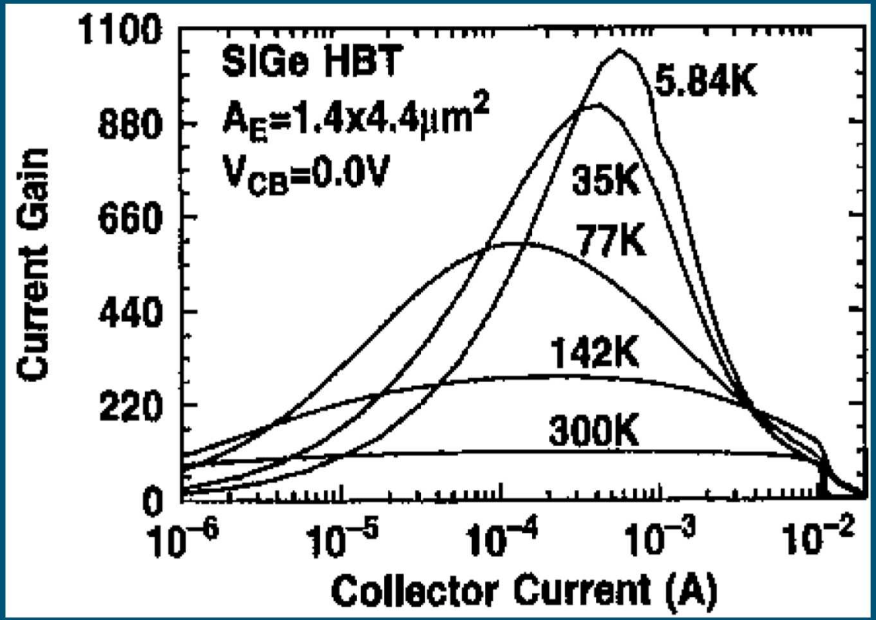
If it can be done in CMOS,

it will be done in CMOS.

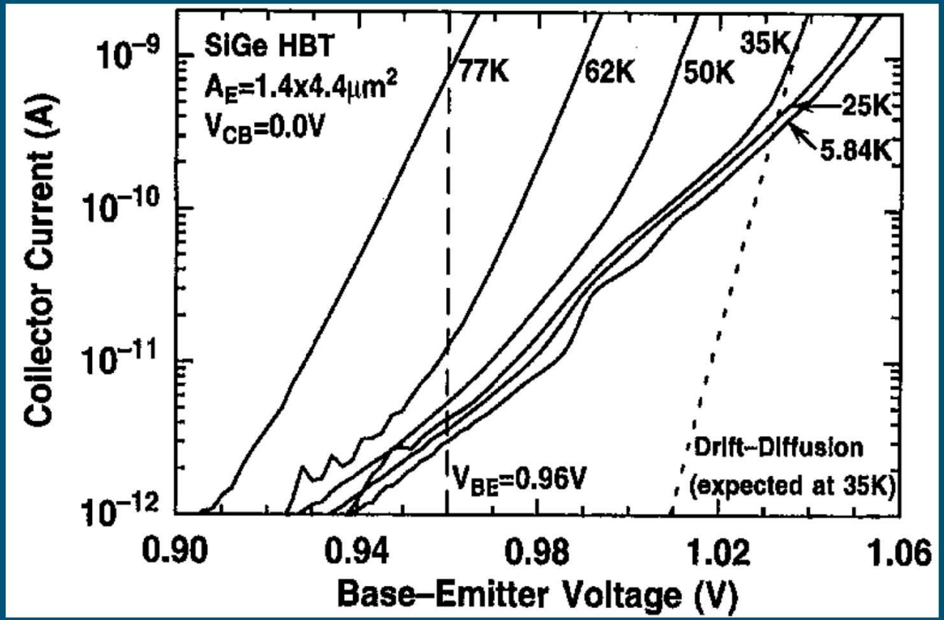
SiGe HBTs at Cryogenic Temperatures

- The physical mechanisms of the band-gap engineering are enhanced at cryogenic temperatures
- The most important device metrics improve: current gain, transconductance, speed, noise, etc.
- Many parameters saturate below 50 K making for a very predictable device with excellent performance

Device current gain increasing down to 5.84 K



Transfer characteristics saturating below 50 K

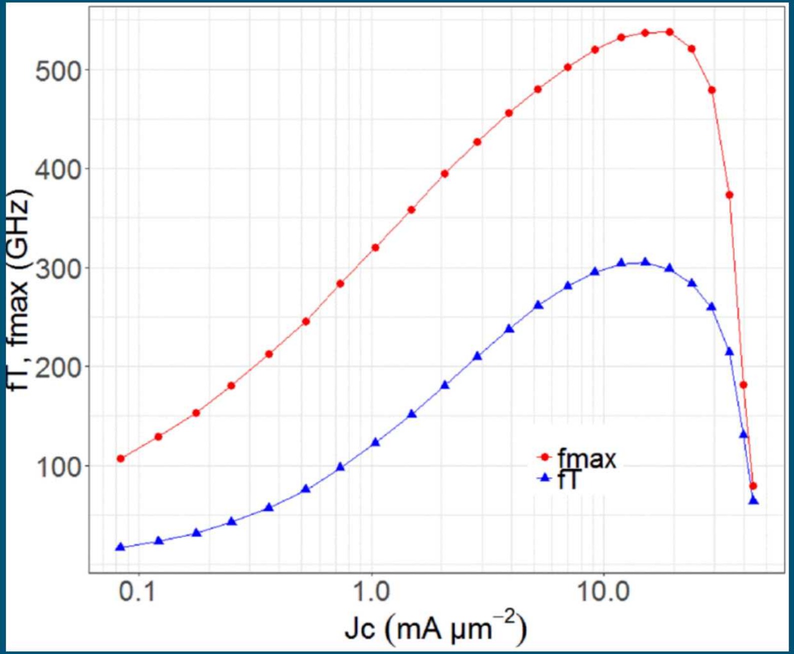


A. J. Joseph et al., “Operation of SiGe heterojunction bipolar transistors in the liquid-helium temperature regime,” *IEEE Electron Device Lett.*, vol. 16, pp. 268–270, June, 1995.

Silicon Speed Records are Held by SiGe HBTs, the Highest at Cryo

Room Temperature BiCMOS Record

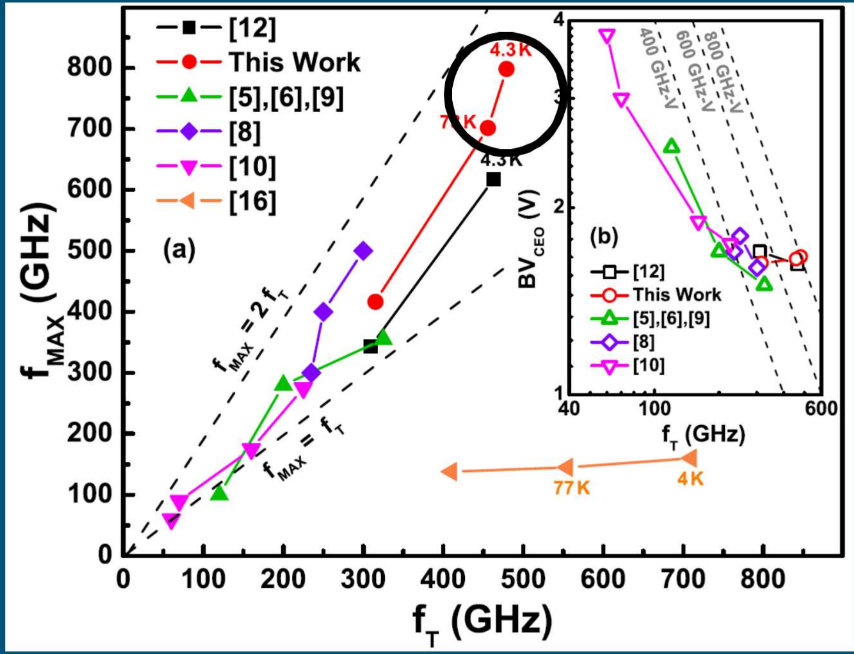
537 GHz f_{MAX}, 305 GHz f_T



D. Manger et al., "Integration of SiGe HBT with f_T=305 GHz, f_{max}=537 GHz in 130nm and 90nm CMOS," 2018 IEEE BiCMOS and Compound Semiconductor Integrated Circuits and Technology Symposium (BCICTS), San Diego, CA, 2018, pp. 76-79.

Cryogenic Record

800 GHz f_{MAX}, 500 GHz f_T



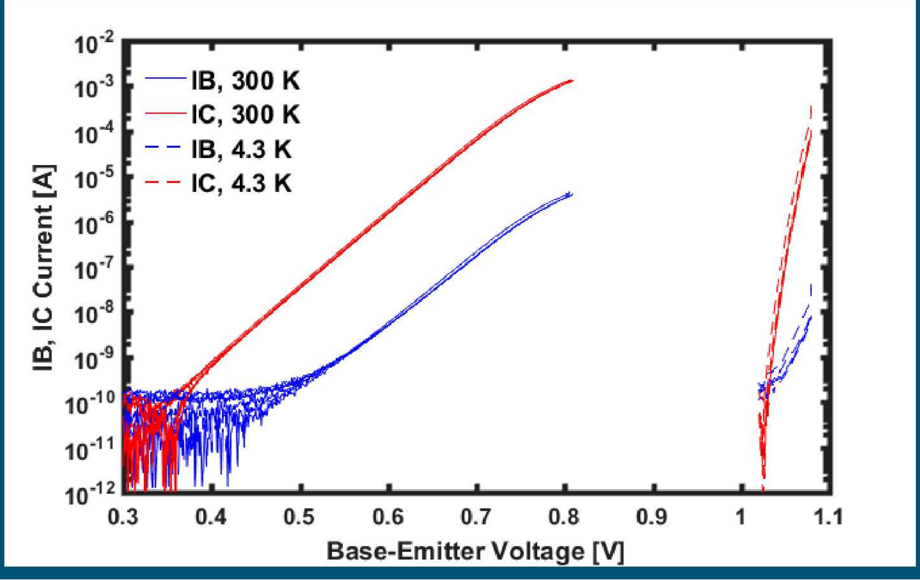
Chakraborty, P.S., et al., "A 0.8 THz SiGe HBT operating at 4.3 K," *Electron Device Letters, IEEE*, vol.35, pp.151,153, Feb. 2014

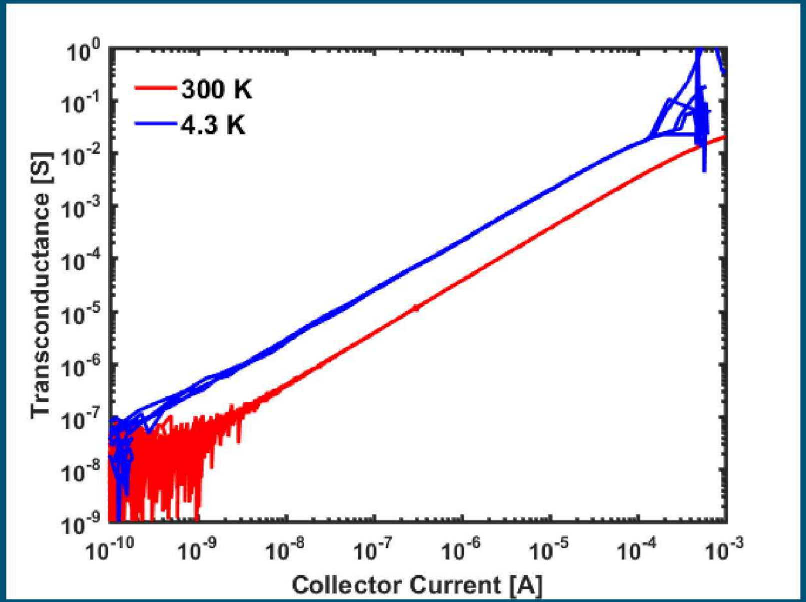
SiGe HBT Metrics at Room Temperature, 4.3 K, and 70 mK

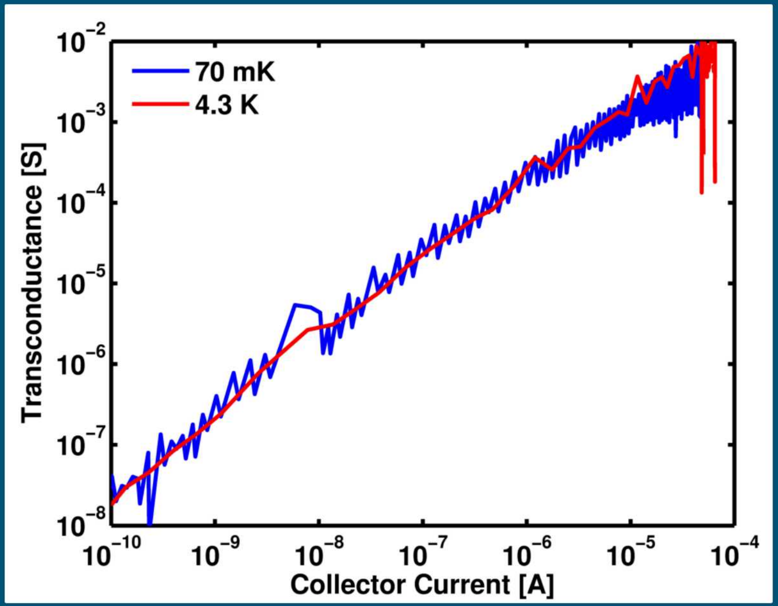
300 K ➔ 4.3 K
- Peak current gain is increased
- Transconductance is increased

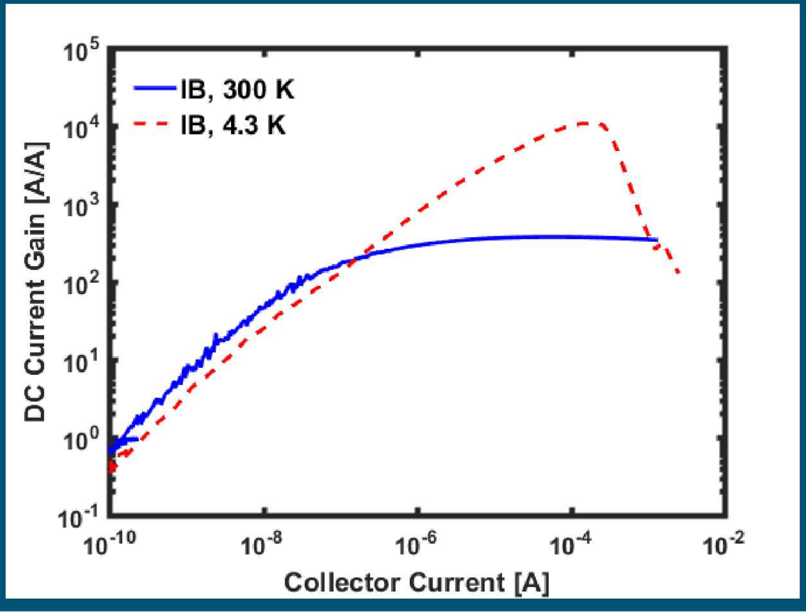
4.3 K ➔ 70 mK
- Increase of V_{BE} of about 10 mV
- First-order performance unchanged down to 70 mK

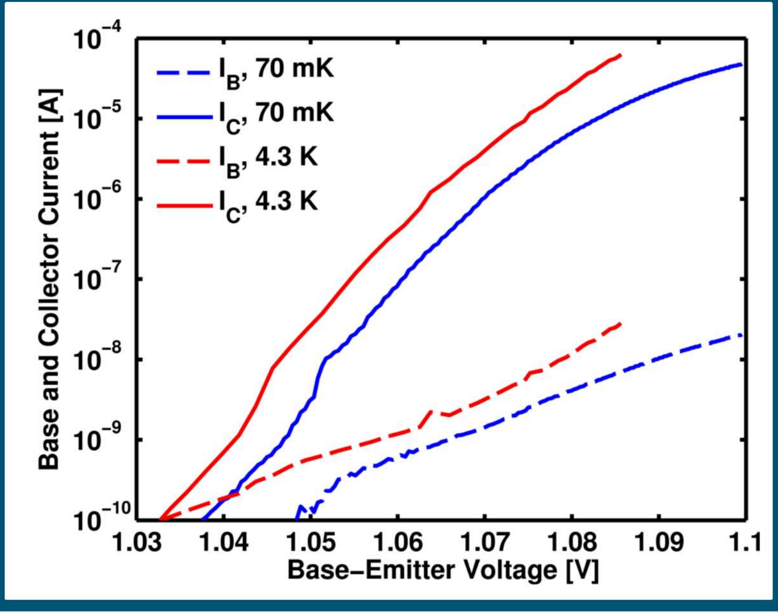
Measurement and modeling at 4.3 K is applicable to 70 mK











Cryogenic Amplification for Semiconducting Qubits

Silicon Quantum Computing Readout

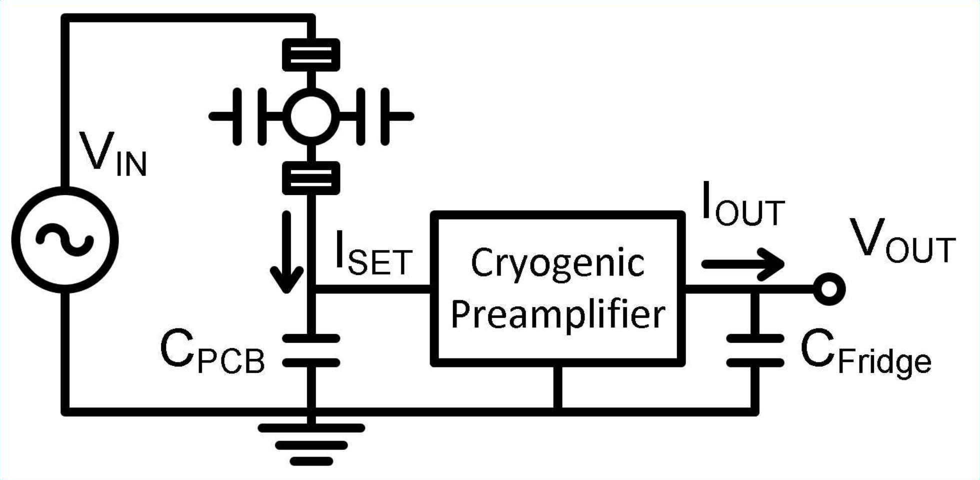
Silicon-based quantum computing readout has a number of challenges

- Single-electron transistors (SETs) are highly sensitive to the environment and have low output signals in the 100 pA range
- Dry dilution refrigerators have low thermal budgets and terrible electromagnetic interference problems
- Cables in and out of fridge are long and highly resistive and capacitive

SiGe HBTs are viable amplifiers for silicon quantum computing readout

- Multiple analog amplifiers have been designed and two topologies are in common use today
- SiGe HBTs can provide the best gain vs. power trade-off of any solid-state solution at base temperature
- Designs to date have used COTS discrete npn transistors, NESG3031 (out of production)

Goal	Requirement
Keep SET Potentials Constant	Low Input Impedance
Keep Temperature Low	Low Power Consumption
Detect Small Signals	Low Added Noise
Mitigate Fridge Noise	High Gain
Fast Response, Bandwidth	Low Input/Output Impedance



Modeling Approach: Single Exponential Fits, Early Voltage, and Shot Noise

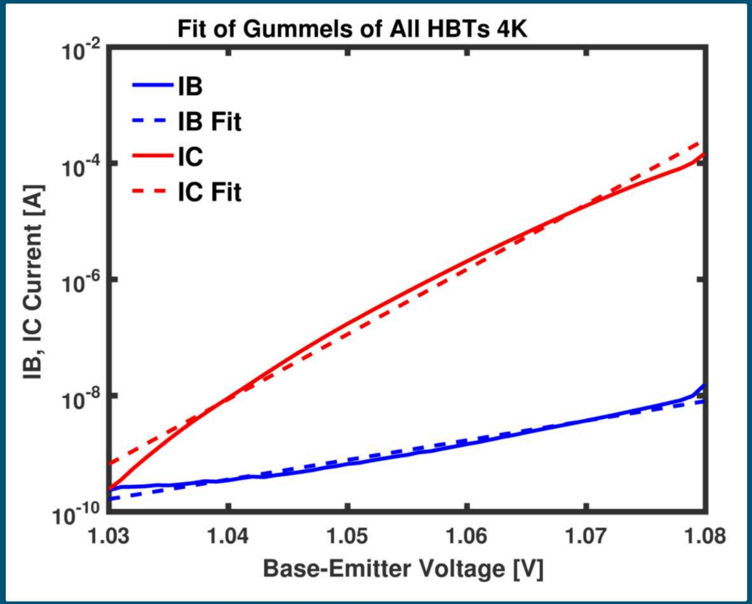
Based on single exponential analytical fits implemented with Verilog-A

$$I_B = e^{b_0 V_{BE} + b_1},\ I_C = e^{c_0 V_{BE} + c_1}$$

Not physically meaningful but effective

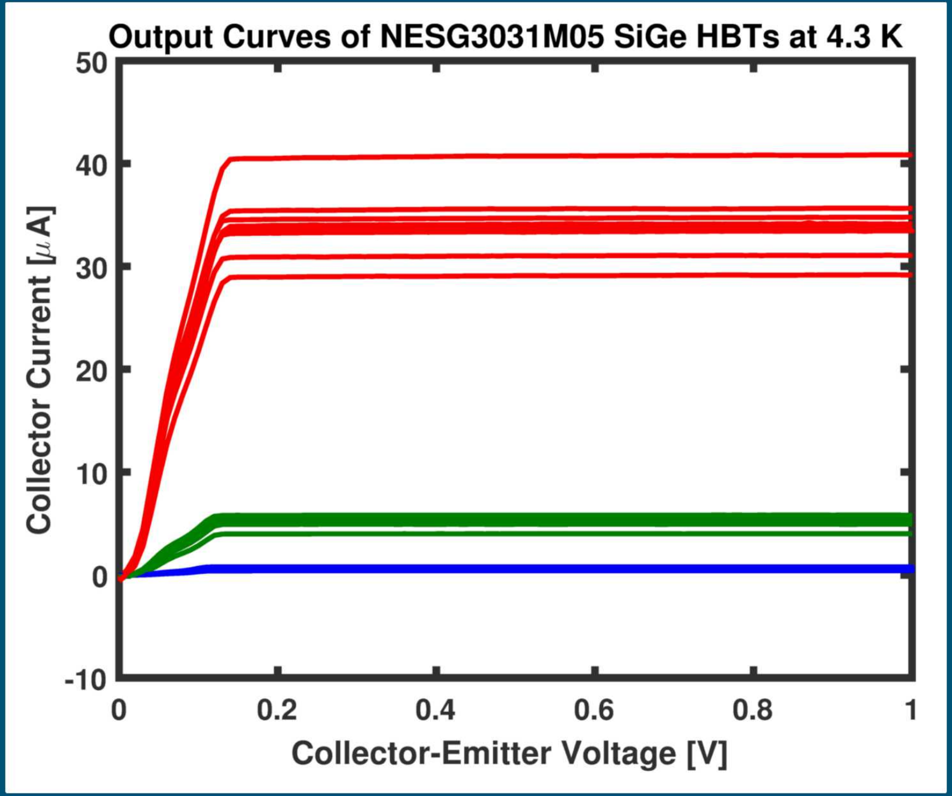
NESG values:

Parameter	Value
b_0	77.7
b_1	-102.6
c_0	257.3
c_1	-286.2



Output conductance is low

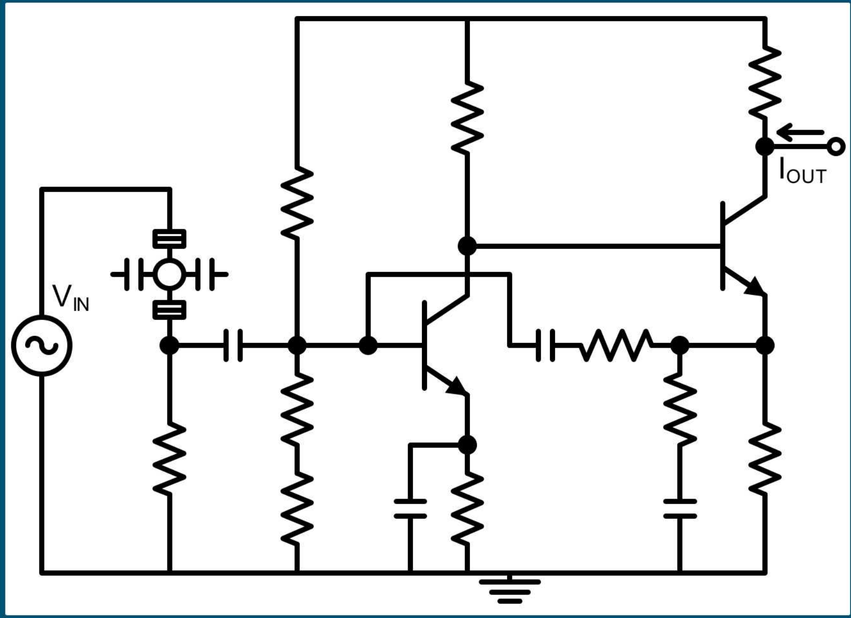
- Often negligible because lack of pnp often means resistive loading



Noise is based on base and collector shot noise only

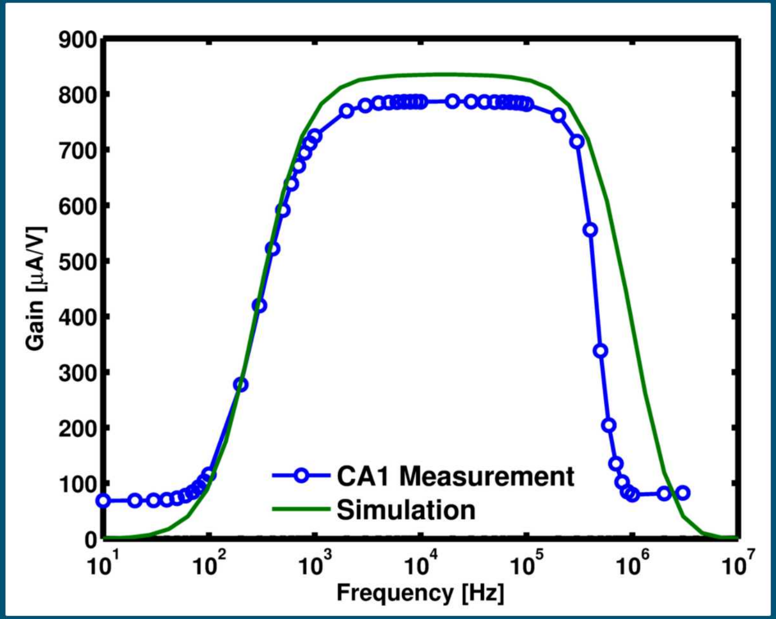
Cadence Spectre natively linearizes models for AC and noise analysis

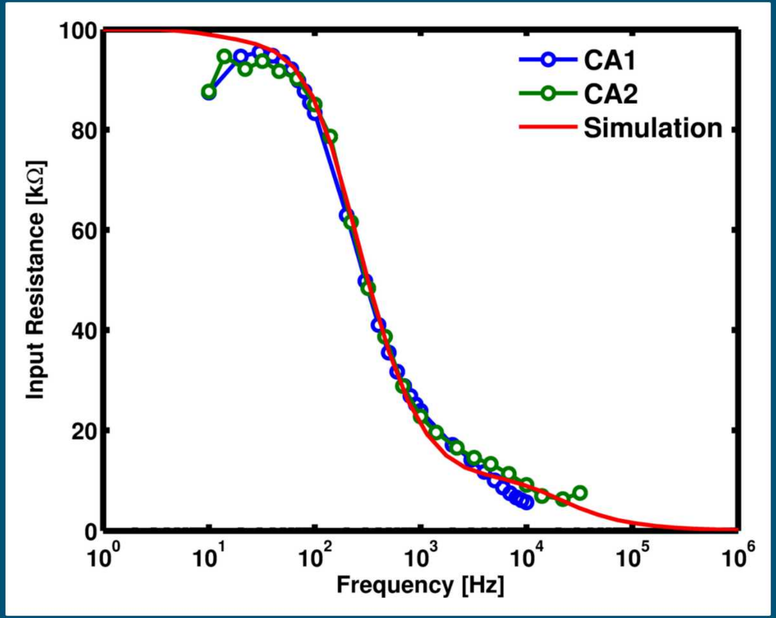
Design Flow Proof of Concept: Current Amplifier



The current amplifier validated the design flow
- Acceptable model to circuit correlation

Performance
- High gain and low noise
- Higher than desired power
- Room temperature TIA required to mitigate capacitance of cabling



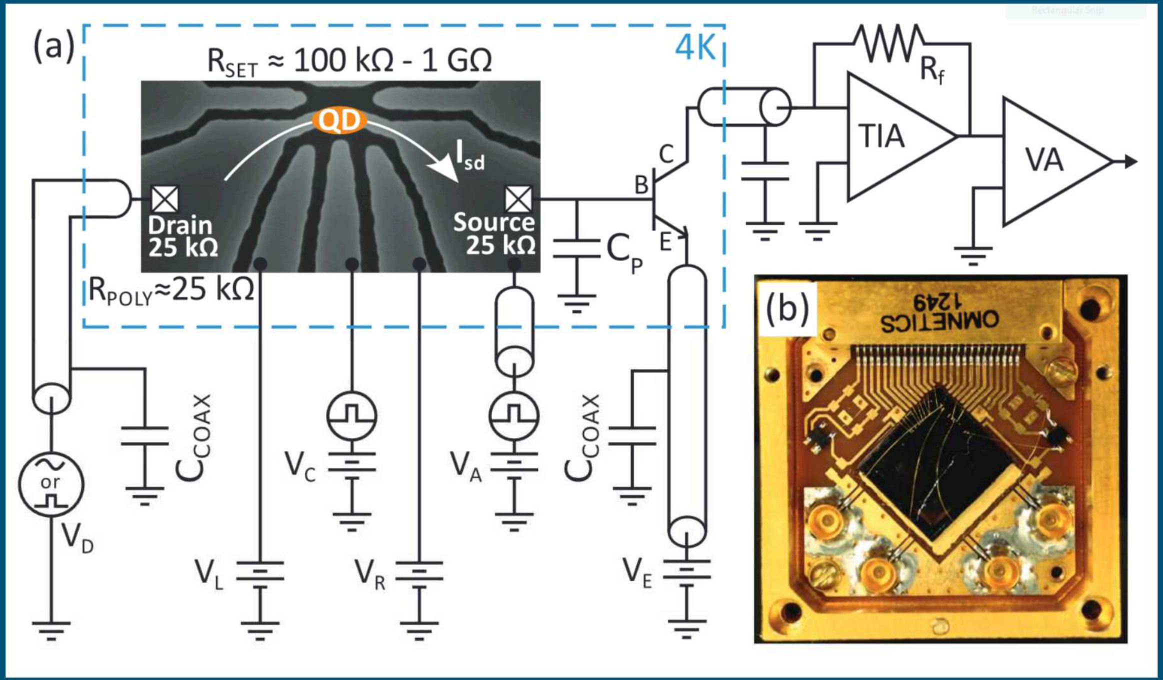


	V_{DD} [V]	I_{DD} [μA]	Power [μW]	Output Noise [nA_{rms}]
Expected	2.0	19.68	39.36	16.8
Actual	2.0	21.5	43	19.76

Use of SiGe HBTs for Silicon Quantum Computing Readout

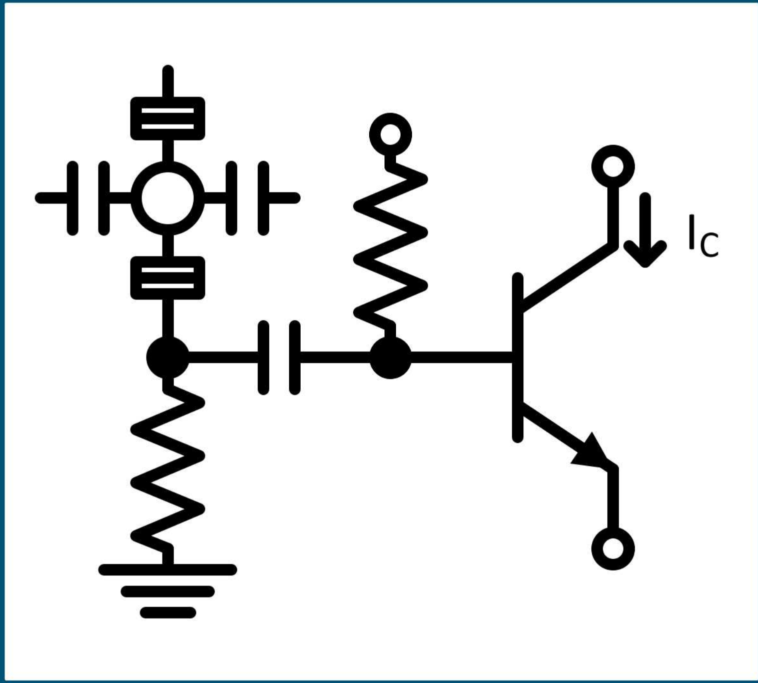
- Simple common-emitter amplifiers provide exceptional power to gain tradeoff at base temperature
- The DC Coupled HBT effectively current biased the SET and provides the best SNR up to 100s of kHz
- The AC Coupled HBT largely preserves the SET voltage bias and can be operated in the 1 MHz range
- Both circuits easily integrate with quantum devices on PCB
- Matthew Curry will present on the experimental results of these amplifiers with quantum devices

DC Coupled HBT Amplifier



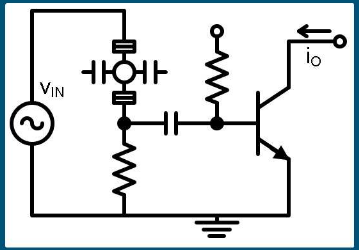
M. J. Curry et al, App. Phys. Lett. 106, 203505 (2015)
Also, APS March Meeting 2015-2018

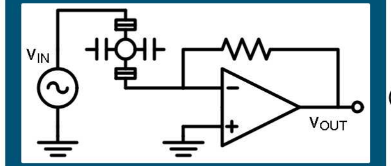
AC Coupled HBT Amplifier

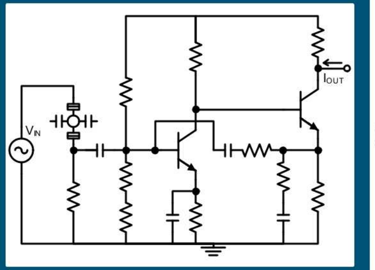


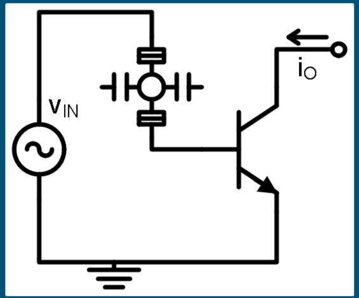
APS March Meeting 2015-2017

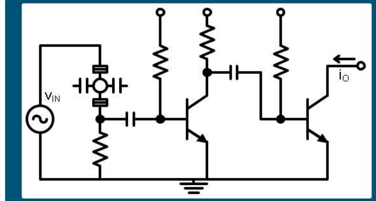
A Wide Variety of Circuits are Available











Specification	AC HBT ($3\ \mu A\ I_C$)	TIA	Current Amplifier	DC HBT	Two Stage AC HBT
Gain	**70 A/A***	100k V/A	800 A/A	4000 A/A	5400 A/A
-3 dB Carrier Bandwidth	20 Hz – 1 MHz	DC – 1 MHz	800 Hz - 500 kHz	20 kHz	20 Hz – 1 MHz
Input Resistance	100 kΩ	30 kΩ	10 kΩ	10 MΩ	100 kΩ
Power	**1.2 μW***	91 μW	40 μW	800 nW	6 μW
Input Referred Noise	Measured < 40 fA/√Hz	Simulated < 40 fA/√Hz	Simulated < 100 fA/√Hz	Measured < 30 fA/√Hz	Simulated < 100 fA/√Hz

All discrete devices on PCB

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

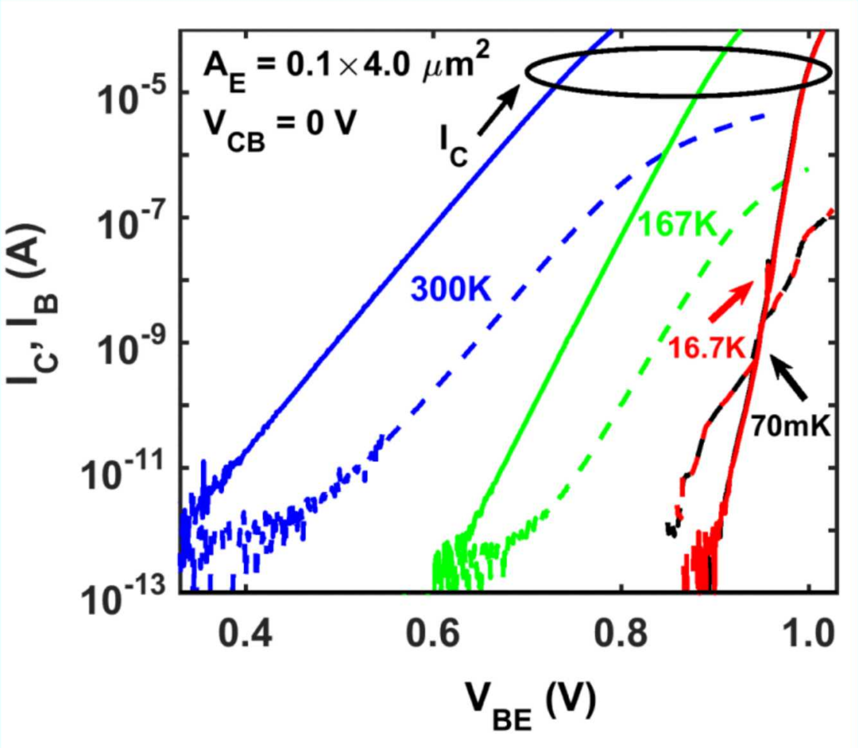
Device and Technology Research for Future Circuit Improvements

Work by John Cressler’s team at Georgia Tech funded by Sandia Labs’ Laboratory Directed Research & Development program and Academic Alliance program

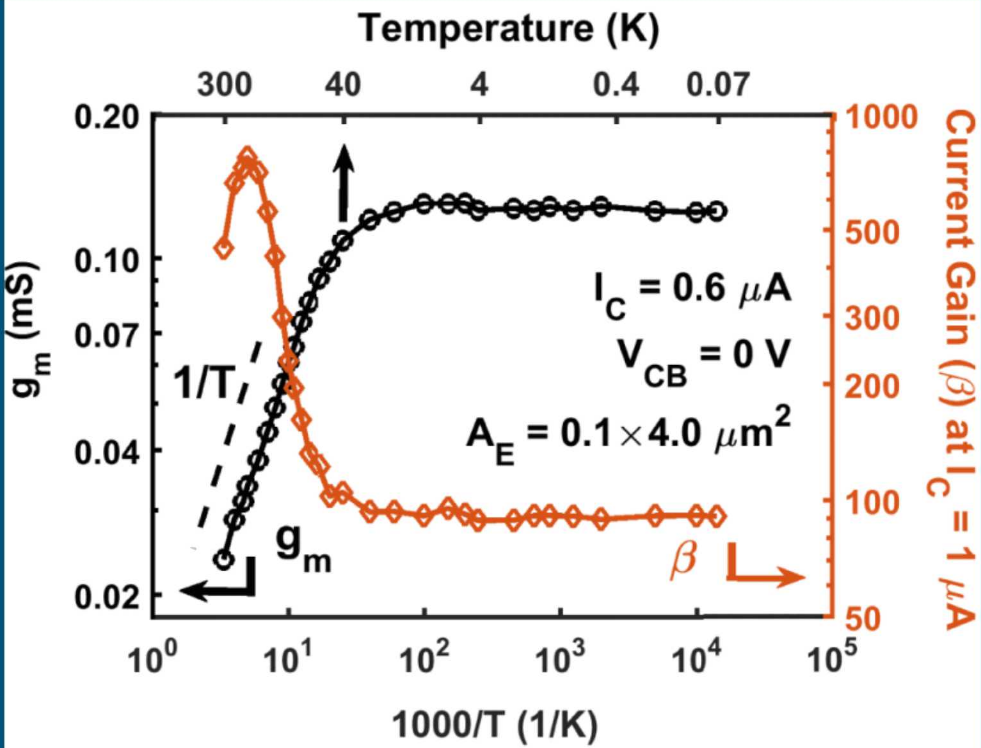
Process Investigation

- The path to better circuits is through better devices and device understanding
- A number of commercial processes are showing promise for future development
- Global Foundries 9HP, 90 nm BiCMOS, exhibits similar behavior to the discrete devices in use today

Gummel Characteristics



Saturation of β and g_m below 40 K

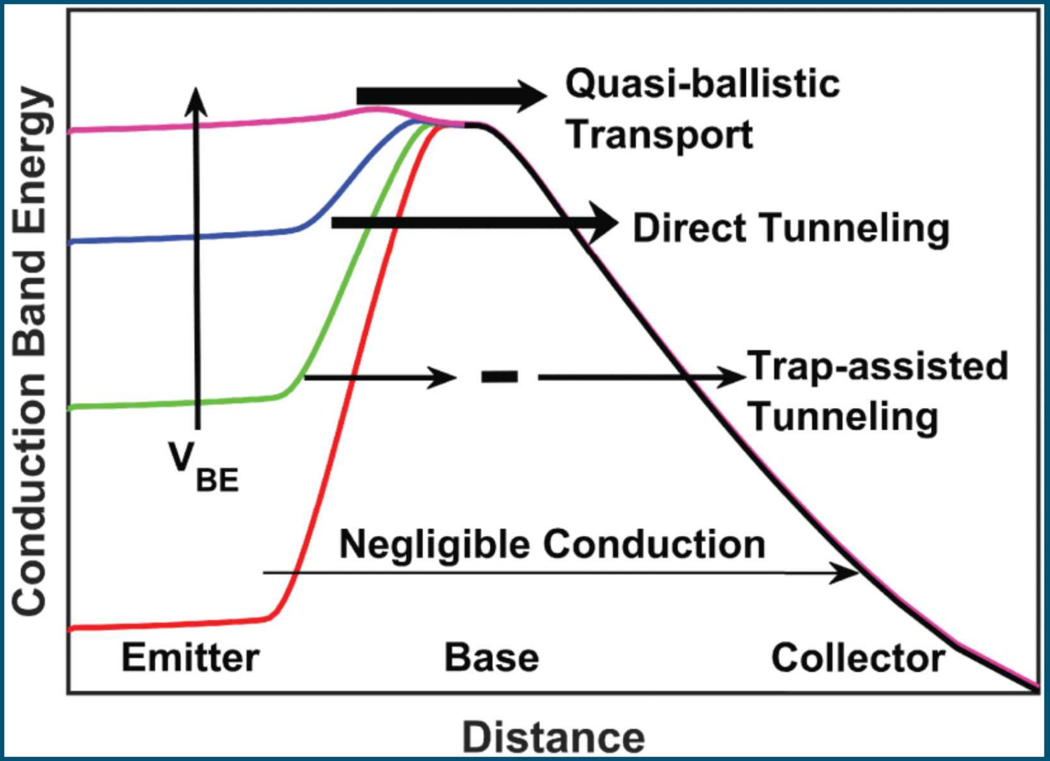


Ying, H., et al., "Operation of SiGe HBTs Down to 70 mK," *Electron Devices Letters, IEEE*, pp. 12-15, Jan. 2017

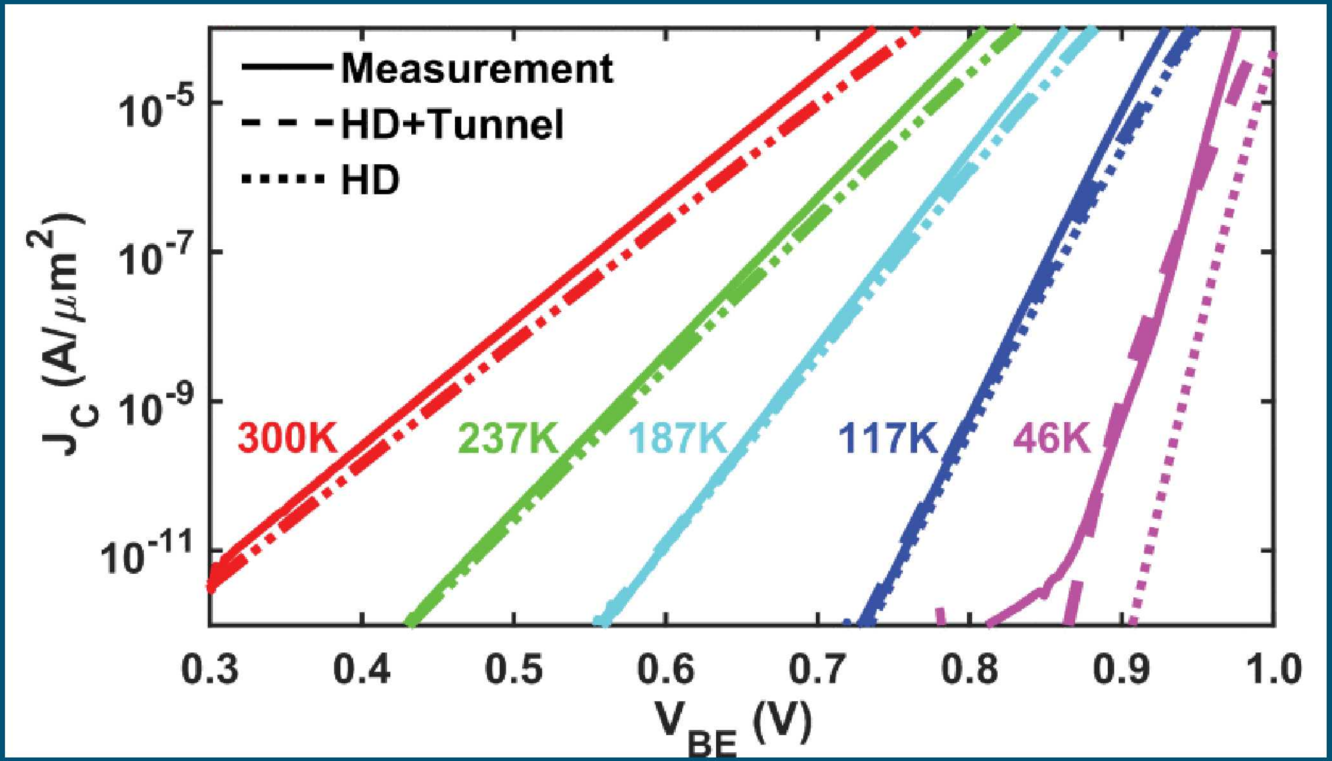
Greater Understanding of Collector Current Transport

- Standard current modeling is no longer sufficient below 50 K
- Tunneling current becomes dominant transport mechanism

Qualitative Transport Mechanisms



TCAD Simulation of Tunneling Transport



Ying, H., et al., "Operation of SiGe HBTs Down to 70 mK," *Electron Devices Letters, IEEE*, pp. 12-15, Jan. 2017

Thanks for Listening!

Thanks to all those who have provided insight into SETs and been willing to take on amplifier testing!

SNL Collaborators: Matthew Curry, Andy Mounce, Lisa Tracy, Michael Lilly, Dwight Luhman, Steve Carr, and many others

Georgia Tech Team: Hanbin Ying, Jeffrey W. Teng, Anup Omprakash, Brian Wier, Uppili Raghunathan, Nelson Lourenco, Jason Dark, Luwei Ge, Dragomir Davidovic, Martin P. Mourigal, and John D. Cressler