Using SiGe Technology in Extreme Environments

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Outline

- Some Reminders on SiGe
- Using SiGe in a Radiation Environment
- Understanding and Mitigating SEE
- Operation at Cryogenic Temperatures
- Some Thoughts on NASA Apps of SiGe
- Summary

Strain Engineering in Si

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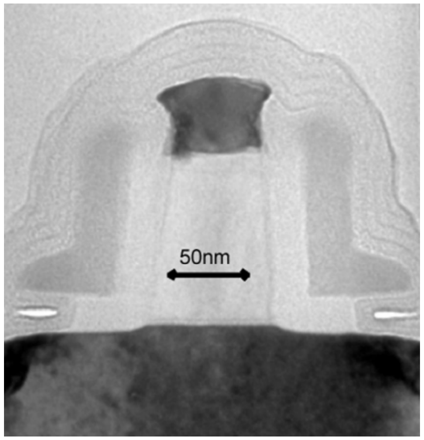
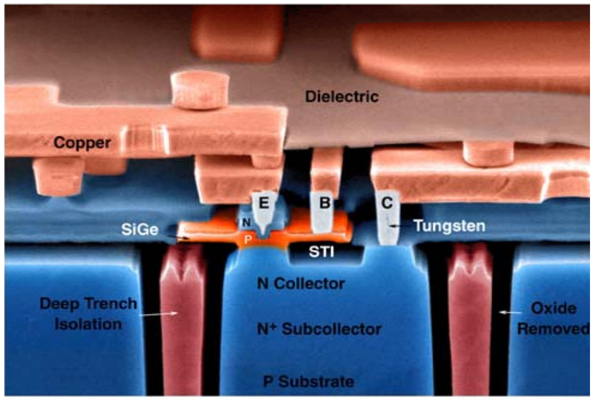
Strained Si CMOS

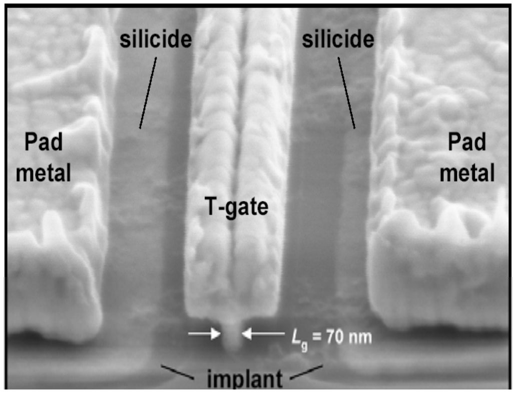


SiGe HBTs



All Are: Strain-Enhanced Si-based Transistors

Close Cousins!

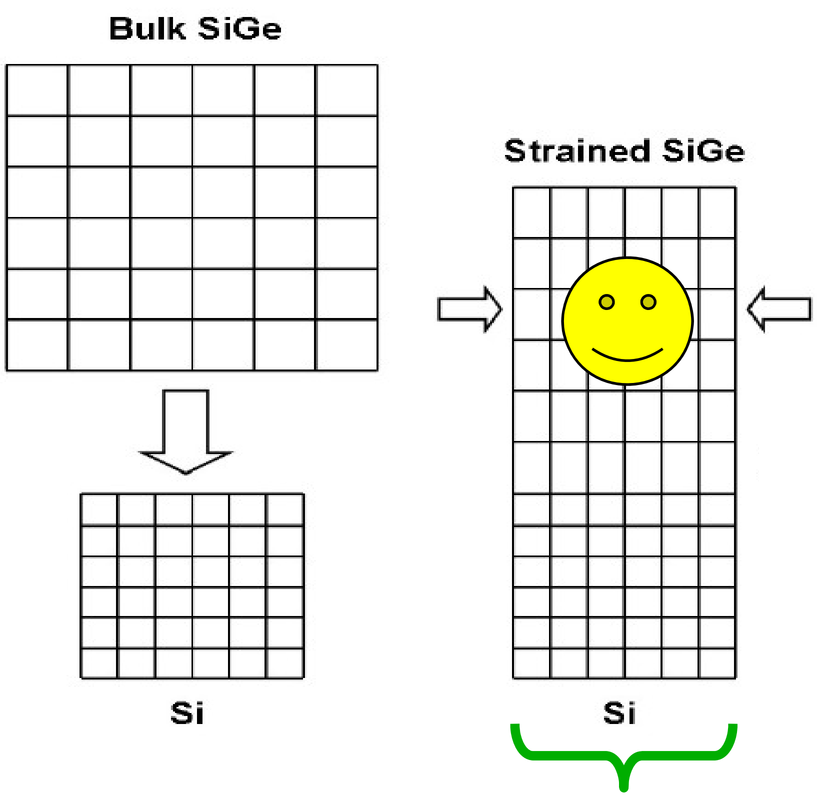


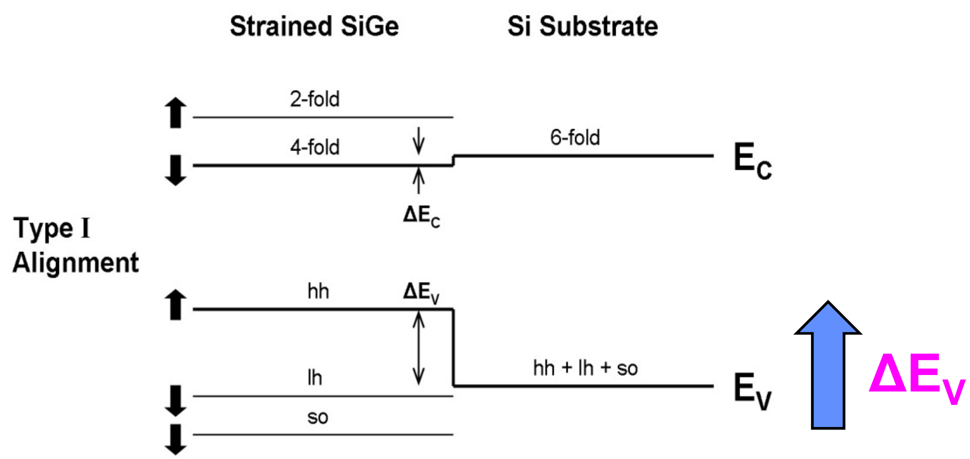
SiGe C-MODFETs / Ge MOSFETs

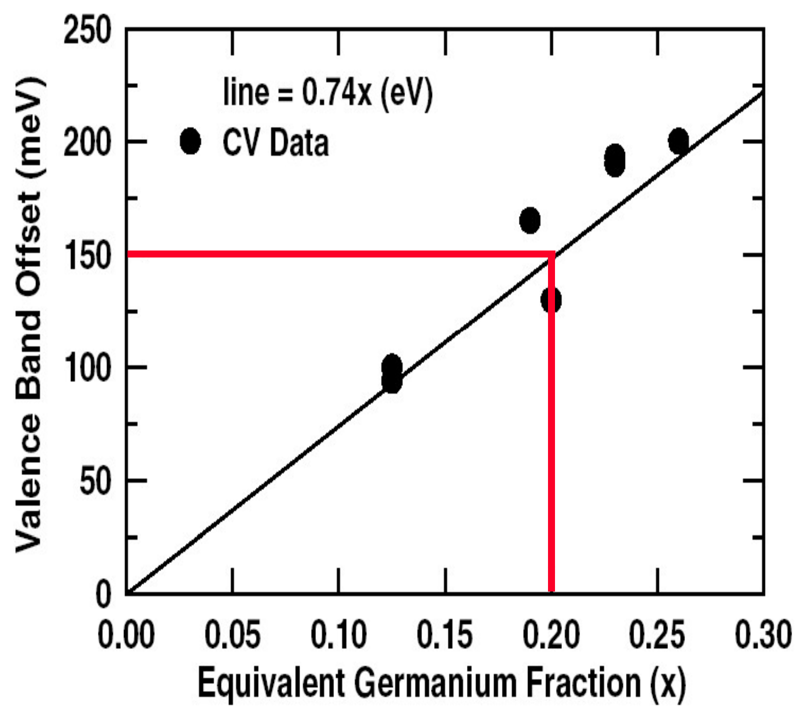
SiGe Strained Layer Epi

The Bright Idea!

Practice Bandgap Engineering
… but do it in Silicon!

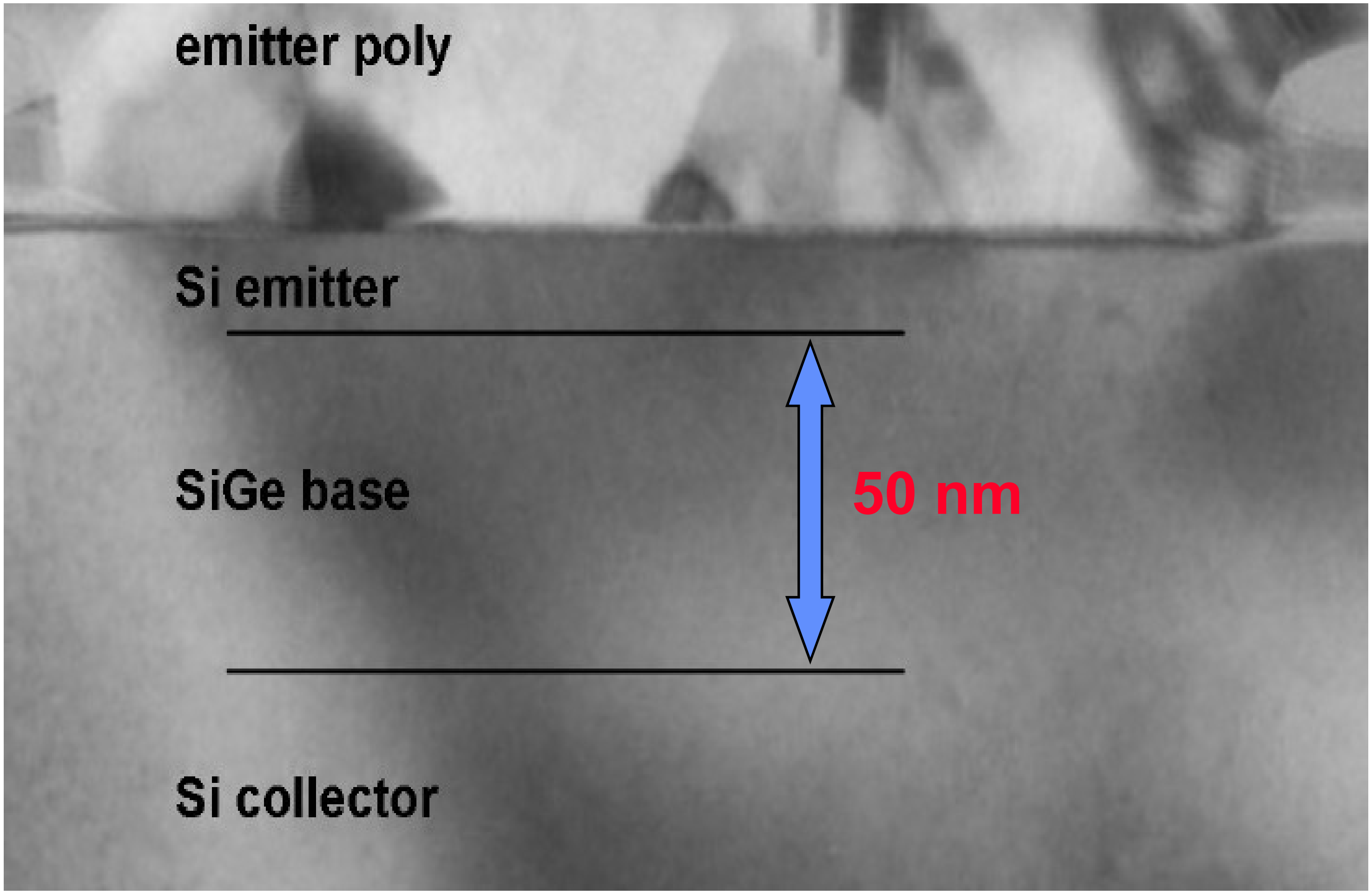






When You Do It Right …

- **Seamless Integration of SiGe into Si**



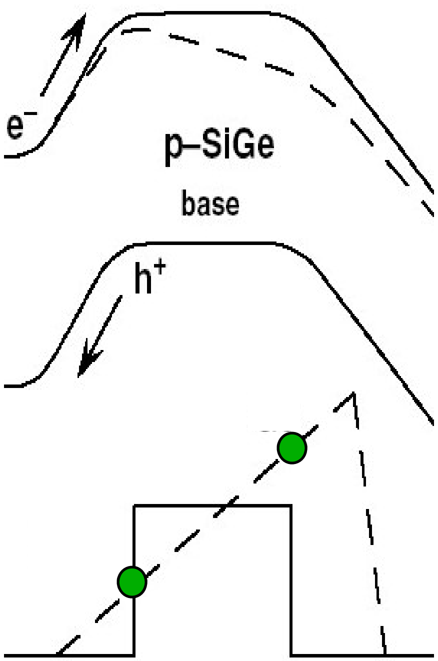
No Evidence of Deposition!

The SiGe HBT

The Idea: Put Graded Ge Layer into the Base of a Si BJT

Primary Consequences:

- smaller base bandgap increases electron injection (β ↑)
- field from graded base bandgap decreases base transit time (f_T ↑)
- base bandgap grading produces higher Early voltage (V_A ↑)
- decouples base profile from performance metrics



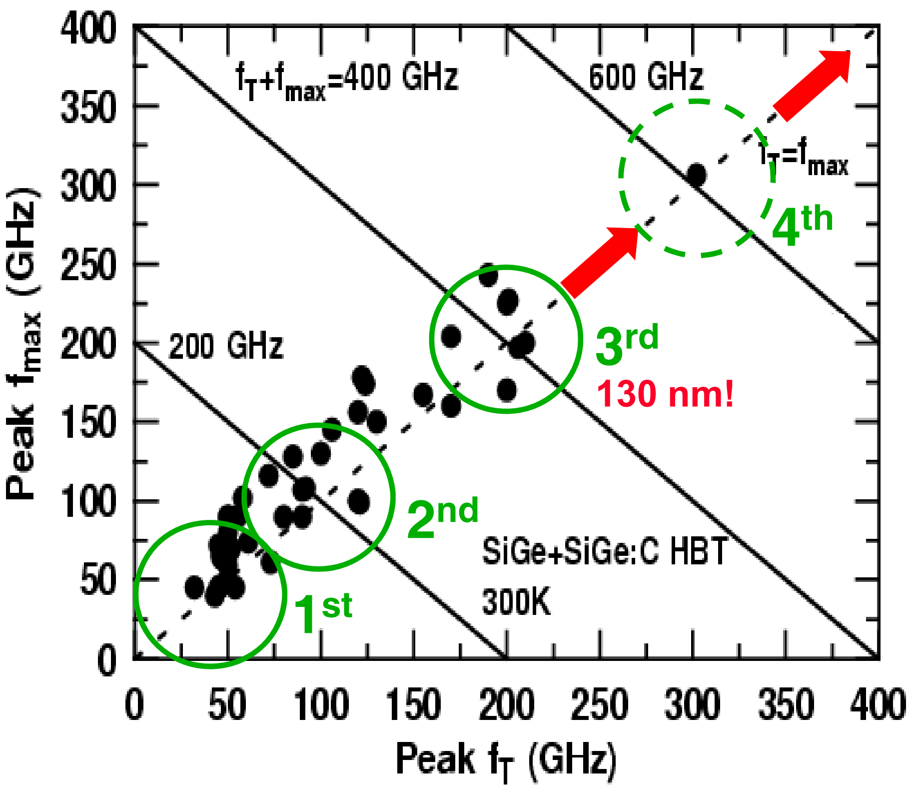
$$\left.\frac{\beta_{SiGe}}{\beta_{si}}\right|_{V_{BE}} \equiv \Xi = \left\{ \frac{\tilde{\gamma}\,\tilde{\eta}\,\Delta E_{g,Ge}(grade)/kT\; e^{\Delta E_{g,Ge}(0)/kT}}{1 - e^{-\Delta E_{g,Ge}(grade)/kT}} \right\}$$

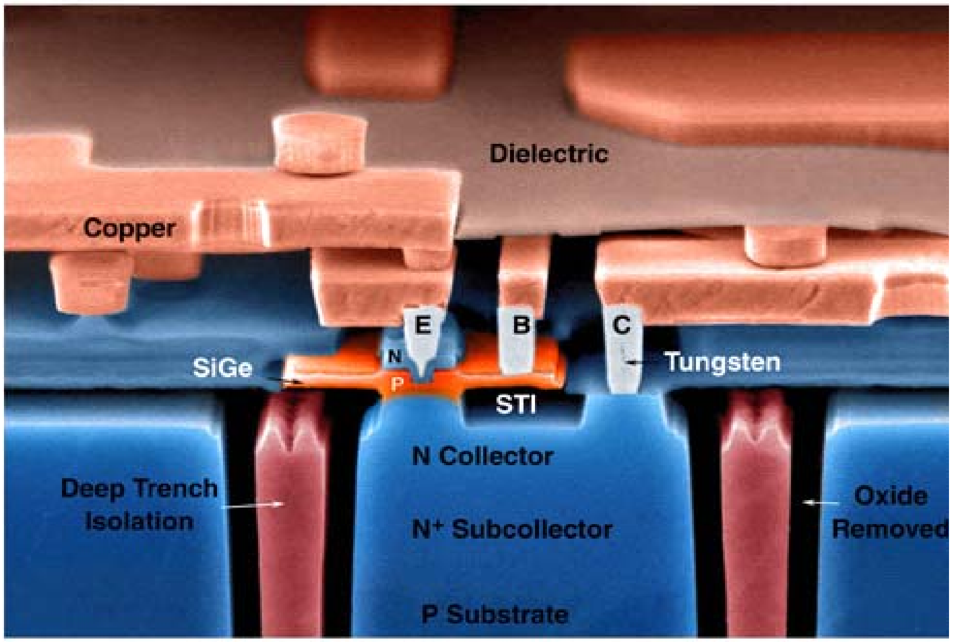
$$\frac{\tau_{b,SiGe}}{\tau_{b,Si}} = \frac{2}{\tilde{\eta}}\,\frac{kT}{\Delta E_{g,Ge}(grade)} \left\{ 1 - \frac{kT}{\Delta E_{g,Ge}(grade)} \left[1 - e^{-\Delta E_{g,Ge}(grade)/kT} \right] \right\}$$

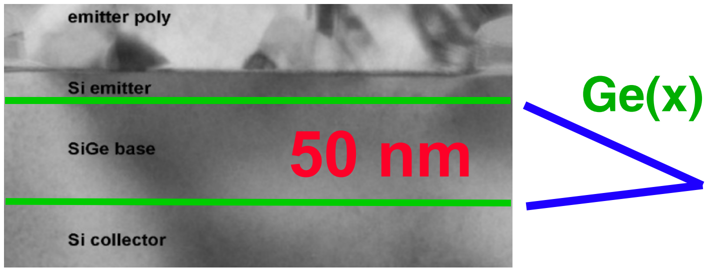
$$\left.\frac{V_{A,SiGe}}{V_{A,Si}}\right|_{V_{BE}} \equiv \Theta \simeq e^{\Delta E_{g,Ge}(grade)/kT} \left[\frac{1 - e^{-\Delta E_{g,Ge}(grade)/kT}}{\Delta E_{g,Ge}(grade)/kT} \right]$$

SiGe Success Story

- SiGe = SiGe HBT + Si CMOS for Highly Integrated Solutions
- Rapid Generational Evolution (full SiGe BiCMOS)
- Significant In-roads in High-speed Communications ICs





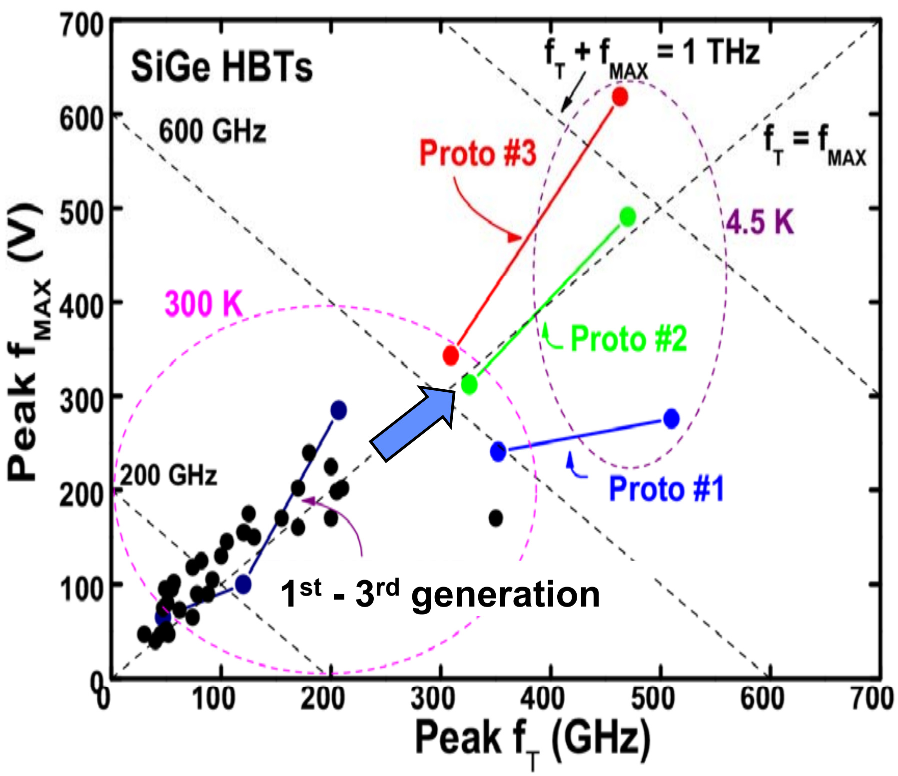


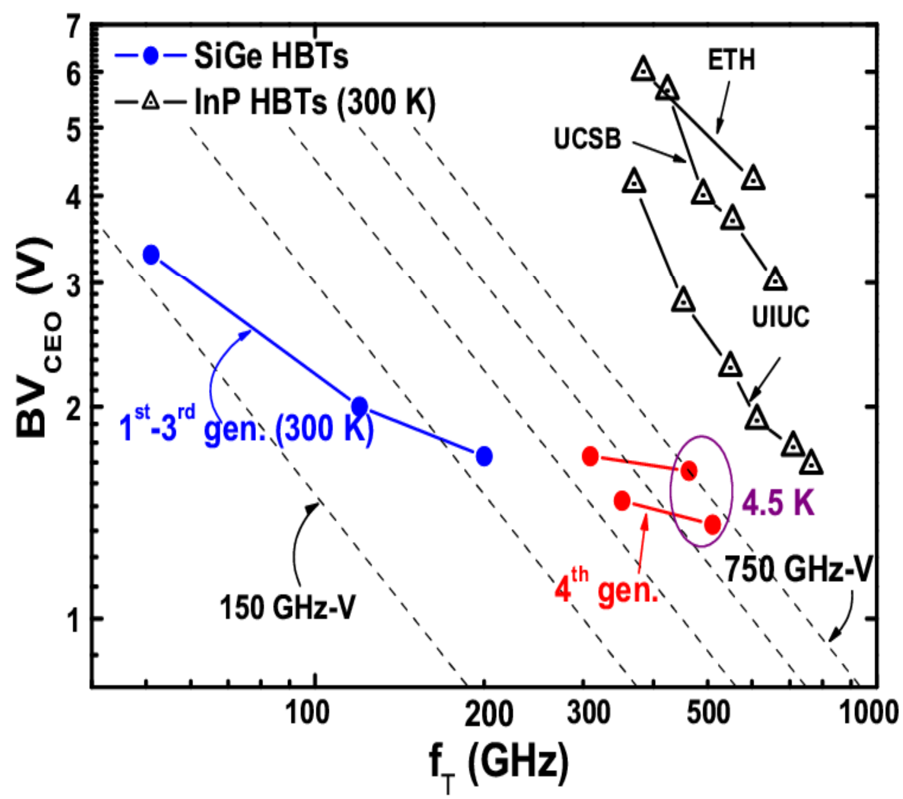
SiGe = III-V Speed + Si Manufacturing

Win-Win!

SiGe Performance Limits

- **Half-TeraHertz SiGe HBTs Are Clearly Possible** (at modest lith)
- **Both f_T and f_{max} above 500 GHz at Cryo-T** (scaling knob)
- **Useful BV @ 500 GHz** ($BV_{CEO} > 1.5$ V + $BV_{CBO} > 5.5$ V)





200-500 GHz @ 130 nm Node!

New SiGe Opportunities

- **SiGe for Radar Systems**
  - **single chip T/R for phased arrays, space-based radar** (2-10 GHz & up)
  - **automotive radar** (24, 77 GHz)
- **SiGe for Millimeter-wave Communications**
  - **Gb/s short range wireless links** (60, 94 GHz)
  - **cognitive radio / frequency-agile WLAN / 100 Gb Ethernet**
- **SiGe for THz Sensing, Imaging, and Communications**
  - **imaging / radar systems, diagnostics, comm** (94 GHz, 100-300 GHz)
- **SiGe for Analog Applications**
  - **the emerging role of C-SiGe** (npn + pnp) + **data conversion** (ADC limits)
- **SiGe for Extreme Environment Electronics**
  - **extreme temperatures** (4K to 300C) + **radiation** (e.g., space systems)
- **SiGe for Electronic Warfare**
  - **extreme wideband transceivers** (20 MHz – 20 GHz)
  - **dynamic range enhanced receivers**

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SiGe For Space Systems

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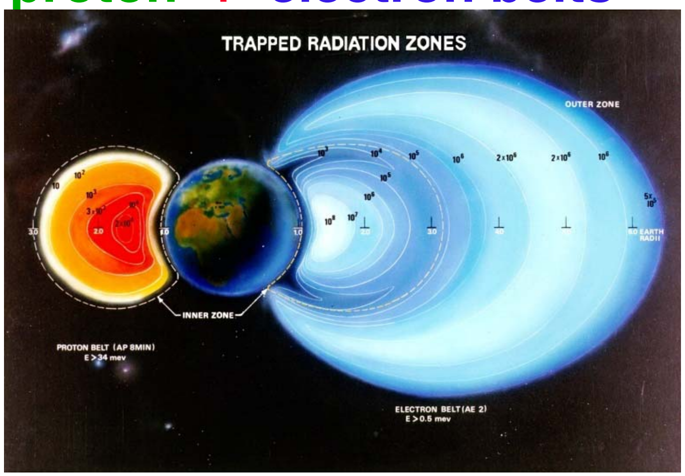
- **The Holy Grail of the Space Community**
  - IC technology space-qualified <u>without</u> additional hardening
  - high integration levels to support SoC / SiP (low cost)

proton + electron belts



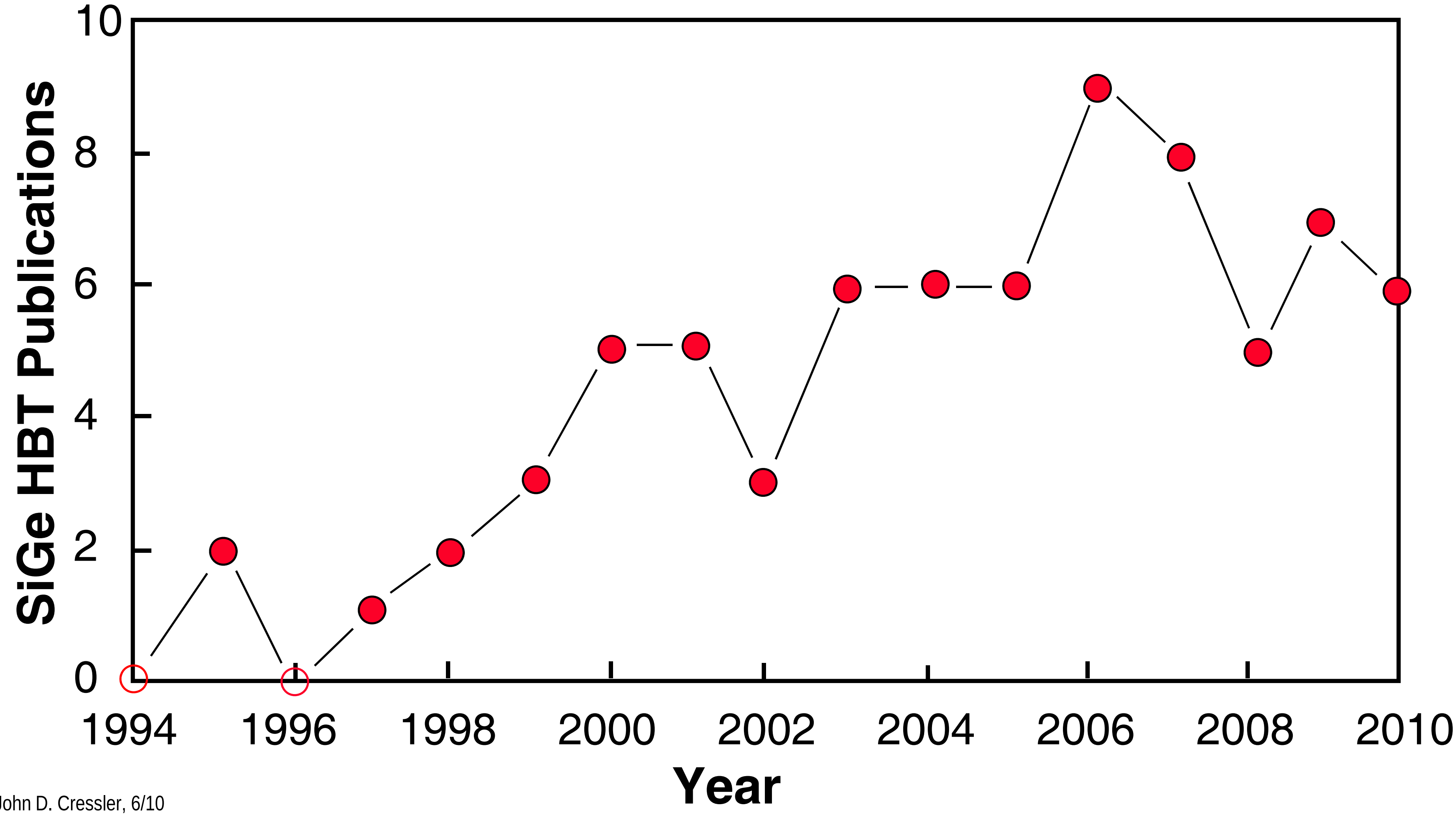
<u>Key Question</u>:
Can SiGe Play a Major Role in Space Systems?

- **Total Ionizing Dose (TID) – ionizing radiation**
  - 100-500 krad(Si) over 10 years for orbit *(300 rad(Si) is lethal to humans!)*
- **Single Event "Stuff"– heavy ions**
  - measure data upset cross-section (σ) vs. Linear Energy Transfer (LET)
  - σ = # errors / particle fluence (ions/cm^2): LET = charge deposition (pC/μm)
  - **<u>Goals</u>:** low cross-section + high LET threshold

YES!

SiGe HBTs at NSREC

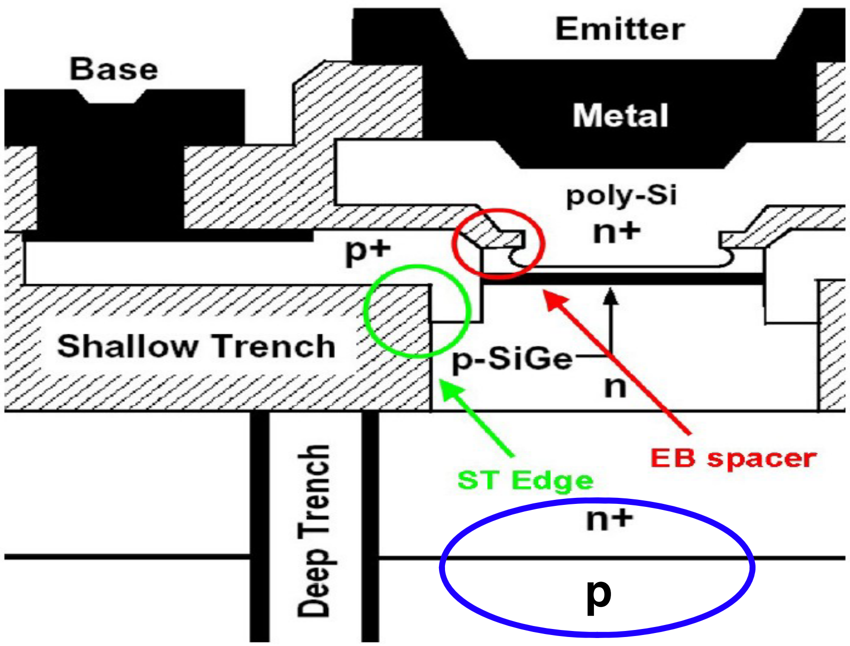
Total SiGe HBT Papers @ NSREC:
1995-2010 = 74



Radiation Experiments

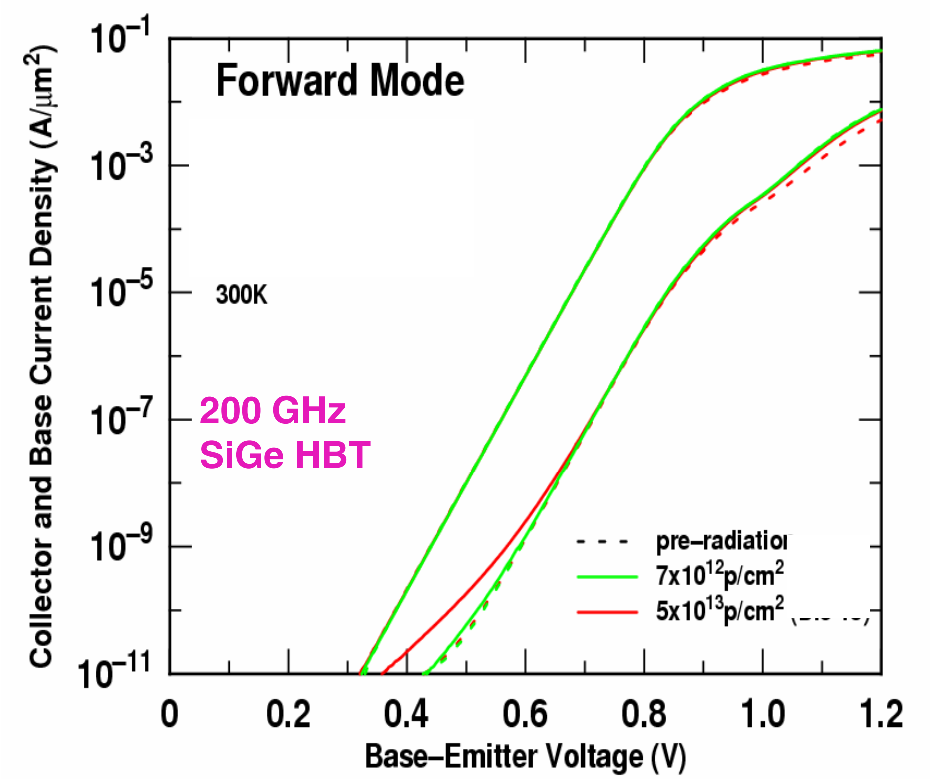
(1995-2010)

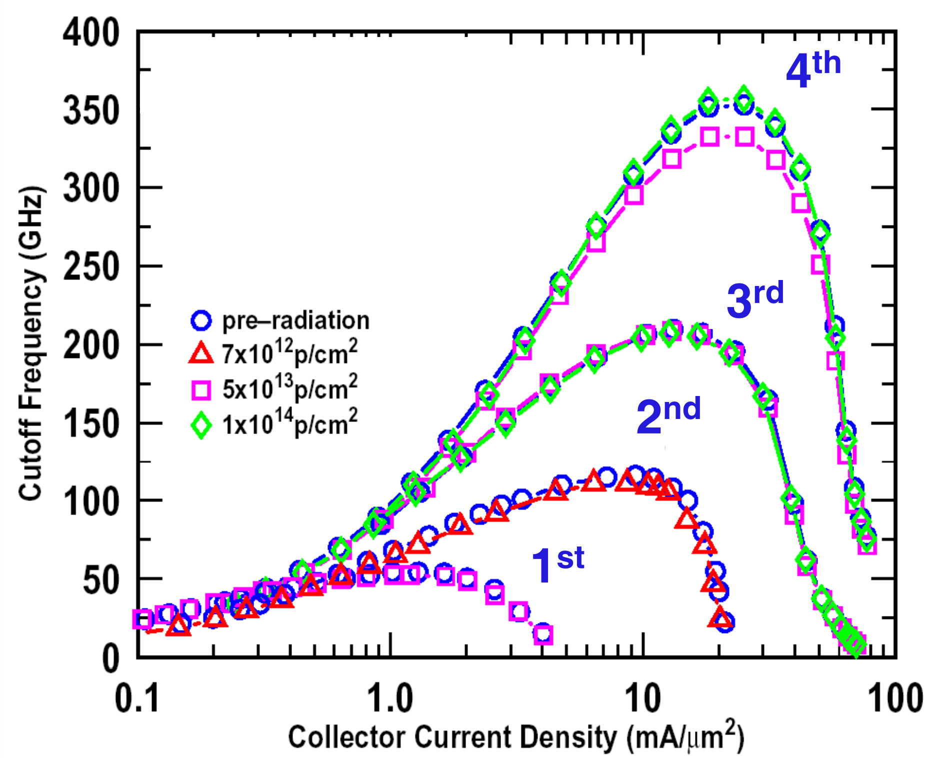
- **SiGe Technology Generations (Devices + Circuits!):**
  - 1st Generation (50 GHz HBT + 0.35 um CMOS)
  - 2rd Generation (100 GHz HBT + 180 nm CMOS)
  - 3rd Generation (200 GHz HBT + 130 nm CMOS)
  - 4th Generation (pre-production 300 GHz HBT)
  - ***many*** **different companies (*npn* + *pnp*; bulk + SOI)**
- **TID Radiation Sources:**
  - gamma ray (>100 Mrad + LDR)
  - proton (1-24,000 MeV + 77K)
  - x-ray
  - neutron
  - prompt dose (krad / nsec)
- **Single Event Effects:**
  - broad beam heavy ion
  - ion microbeam
  - laser (top-side + TPA)



Total-Dose Response

- **Multi-Mrad Total Dose Hardness (with no intentional hardening!)**
  - **ionization + displacement damage very minimal over T; no ELDRS!**
- **Radiation Hardness Due to Epitaxial Base Structure (not Ge)**
  - thin emitter-base spacer + heavily doped extrinsic base + very thin base





63 MeV protons @ $5x10^{13}$ p/cm^2 = 6.7 Mrad TID!

TID Effects: Summary

SiGe HBTs are Inherently Tolerant to TID … as Fabricated!

- **Minimal damage to devices + circuits** (all sources; no ELDRS)
- **Typically multi-Mrad capability, as built**
- **TID-induced damage improves with SiGe technology scaling**
- **No *ac* performance degradation across all SiGe generations**
- **SiGe HBTs much less sensitive to bias effects than CMOS**
- **SiGe HBTs function after 100+ Mrad exposure!**
- **Reduced TID damage at cryogenic temperatures**

Lots of Interesting Physics …

The Story is NOT Over …

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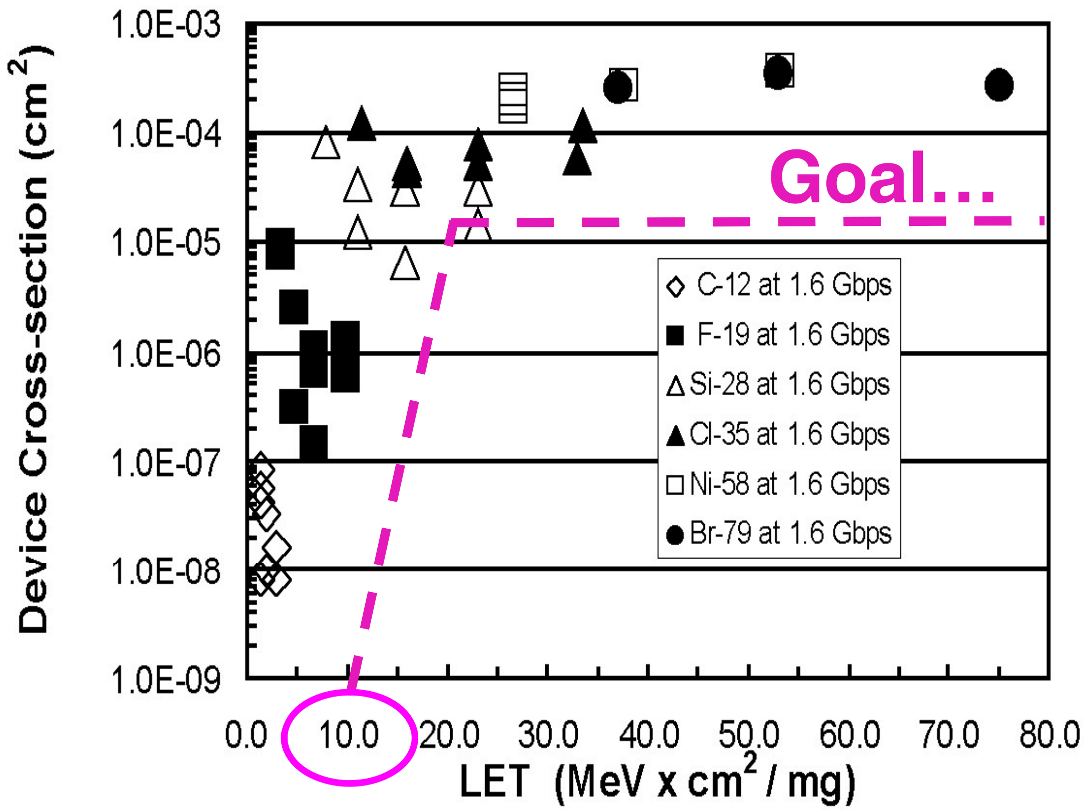
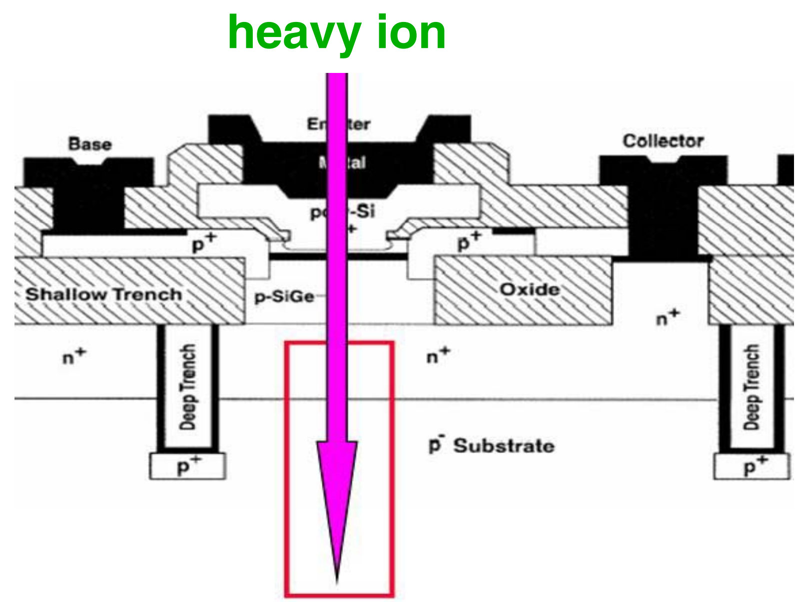
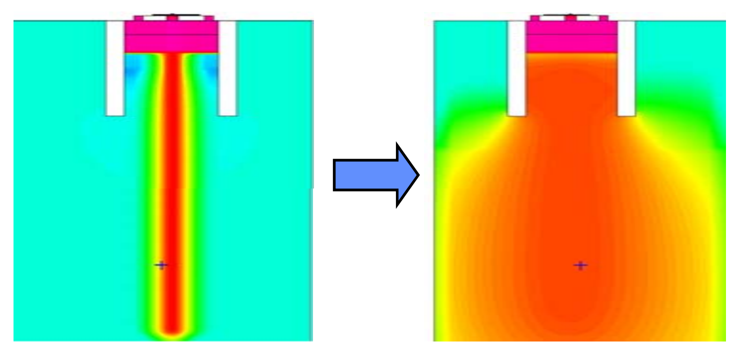
Single Event Effects

- **Observed SEU Sensitivity in SiGe HBT Shift Registers**
  - low LET threshold + high saturated cross-section **(bad news!)**



P. Marshall *et al.*, *IEEE TNS*, 47, p. 2669, 2000





SEU: TCAD to Circuits

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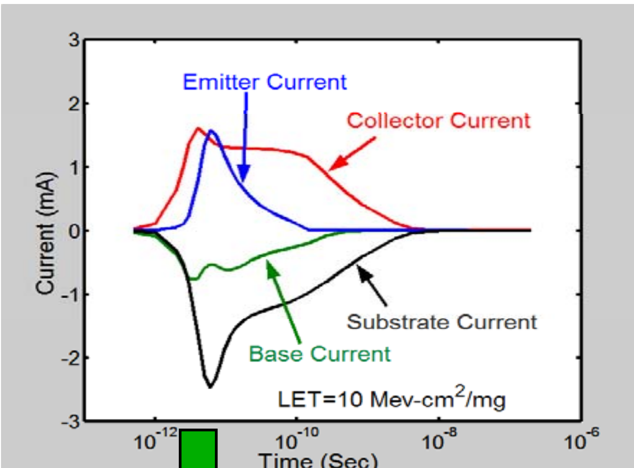
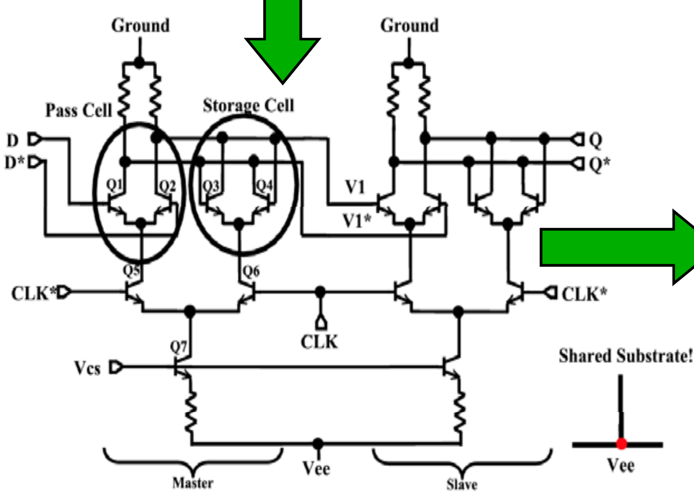
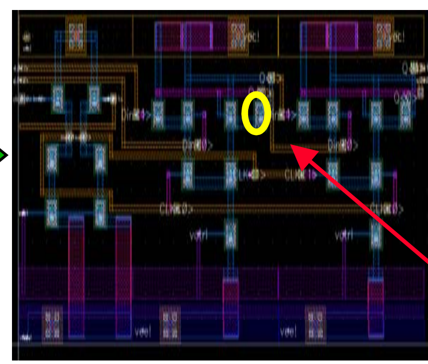
"TCAD Ion Strike"

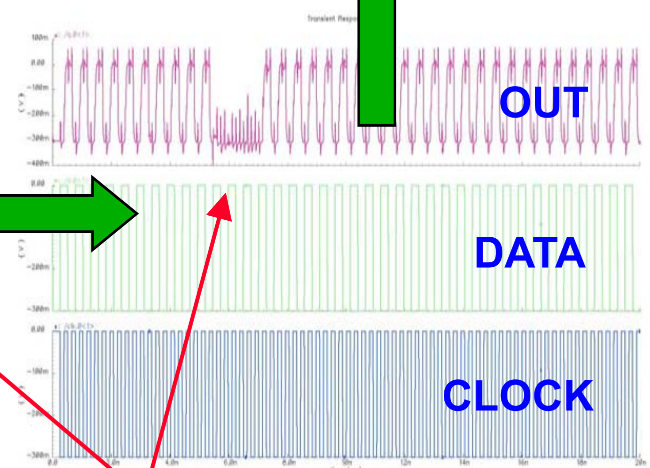




Standard Master Slave Latch

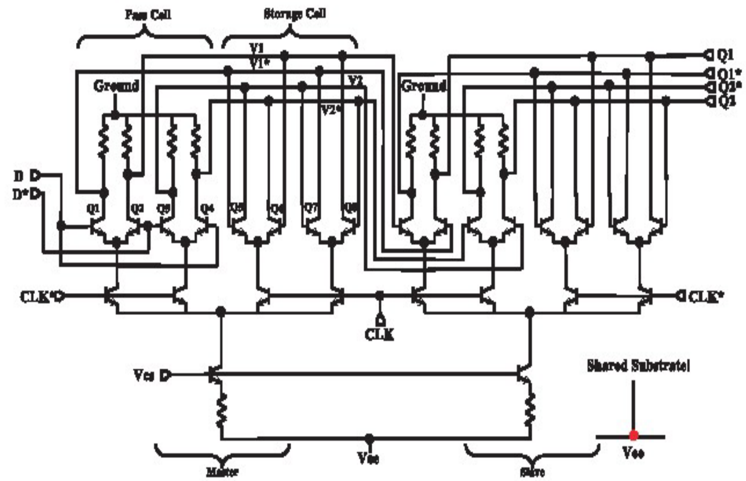
SEU "Soft"





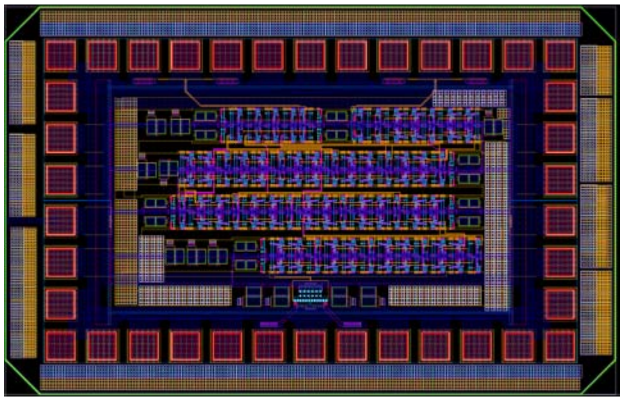
UPSETS

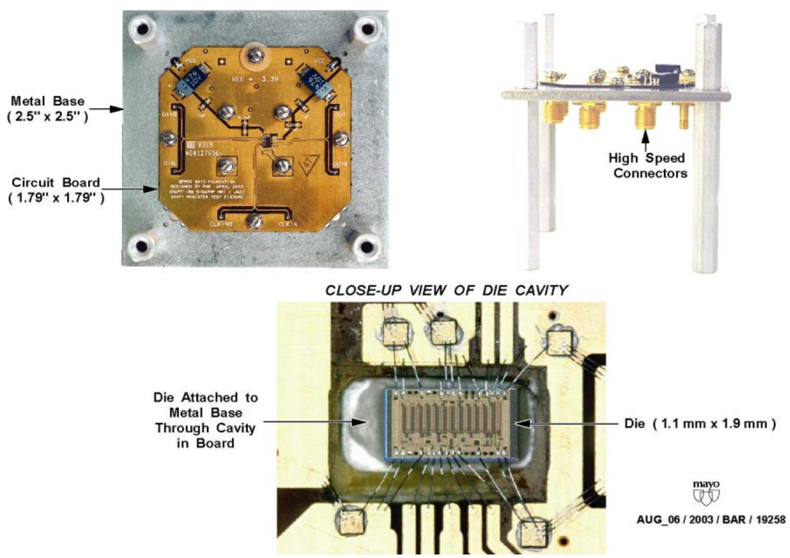
New RHBD SiGe Latch

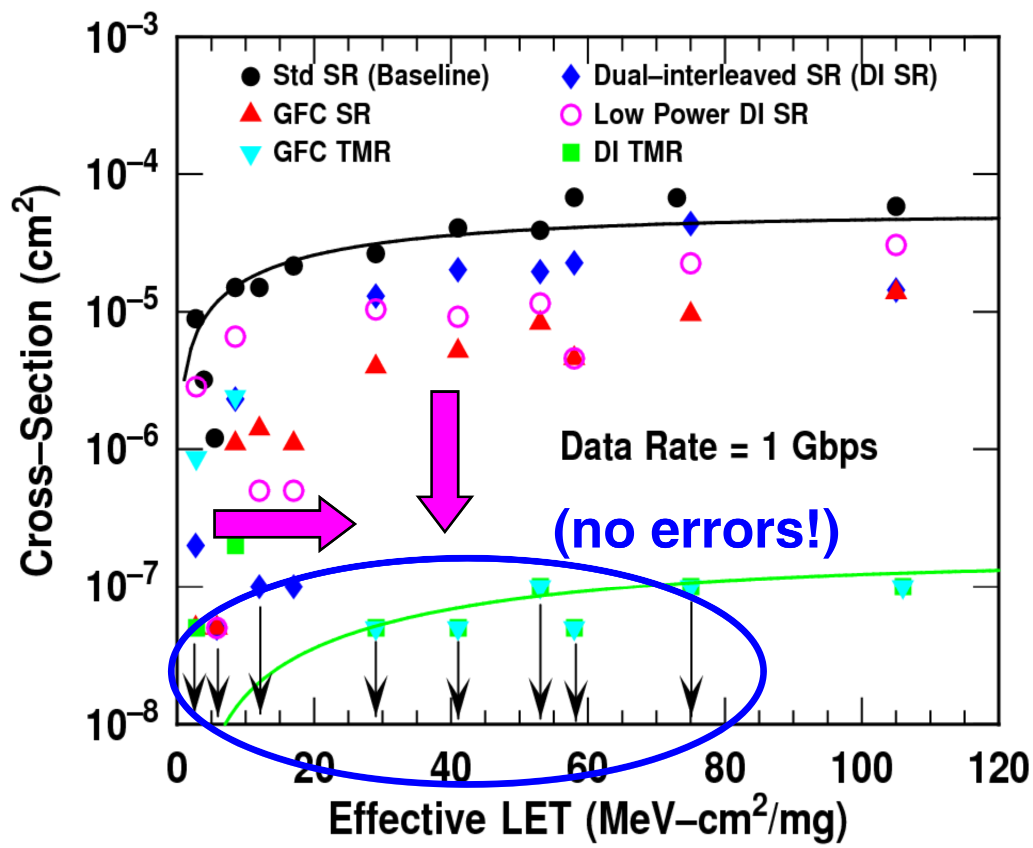


SiGe RHBD Success!

- **Reduce Tx-Tx Feedback Coupling Internal to the Latch**
- **Circuit Architecture Changes + Transistor Layout Changes**





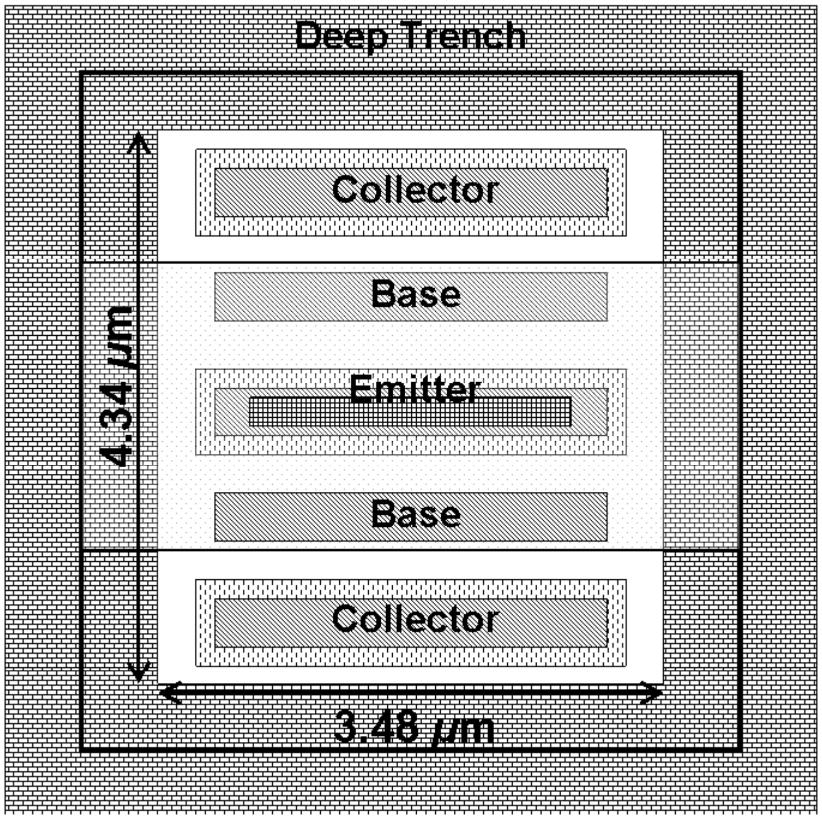


No SEU to LET's of 70!

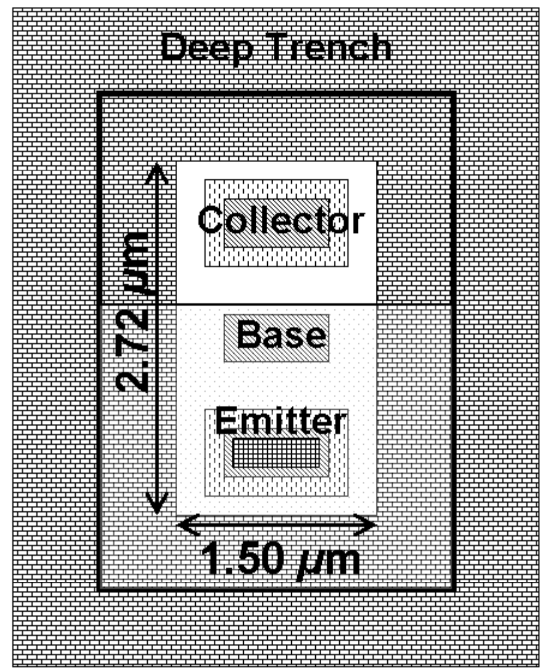
Device-Level RHBD

- **Reduced Deep-trench Area ⇒ Improved Cross-section**
- **Trench Area in CBE (RHBD) Device Reduced by 73%**

$A_E = 0.12 \times 2.50\ \mu m^2$ (CBEBC)



$A_E = 0.12 \times 0.52\ \mu m^2$ (CBE)

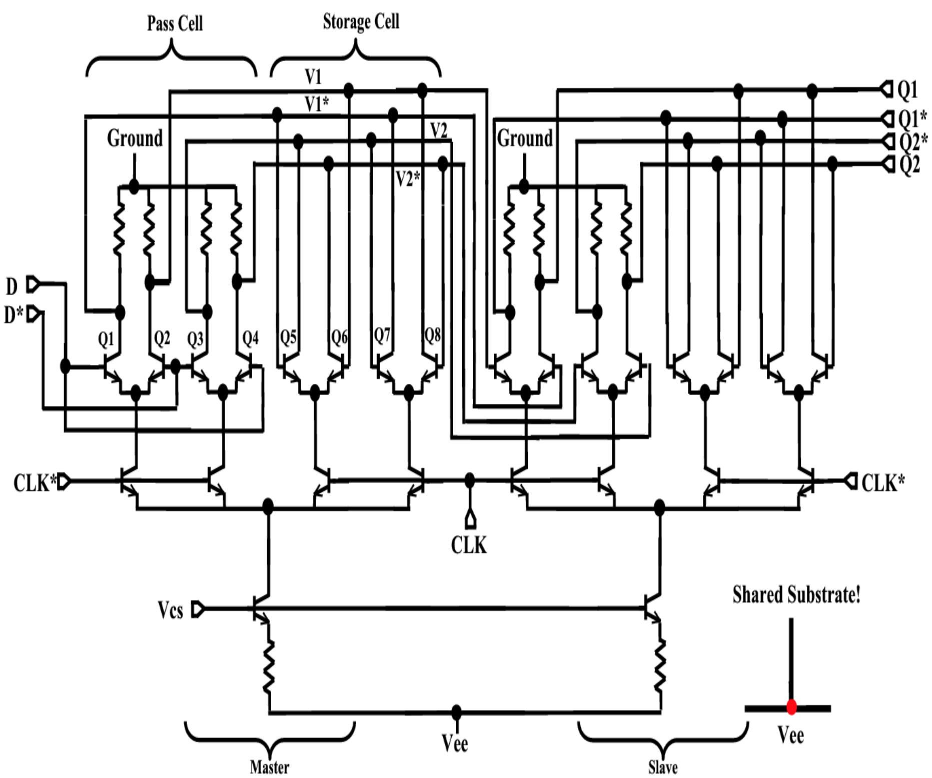


RHBD SiGe HBT

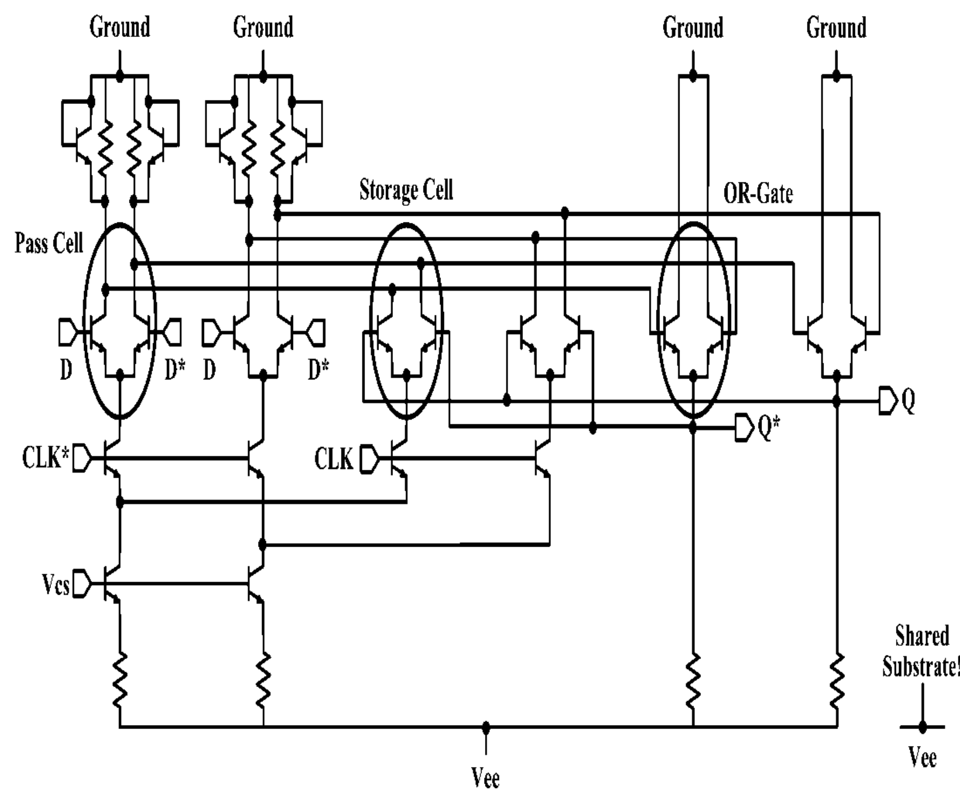
Circuit-Level RHBD

- DI DFF: Limited Transistor-level Decoupling in Storage Cell
- GFC DFF: OR-gate Logic Correction and Load Diode Clamps

DI DFF



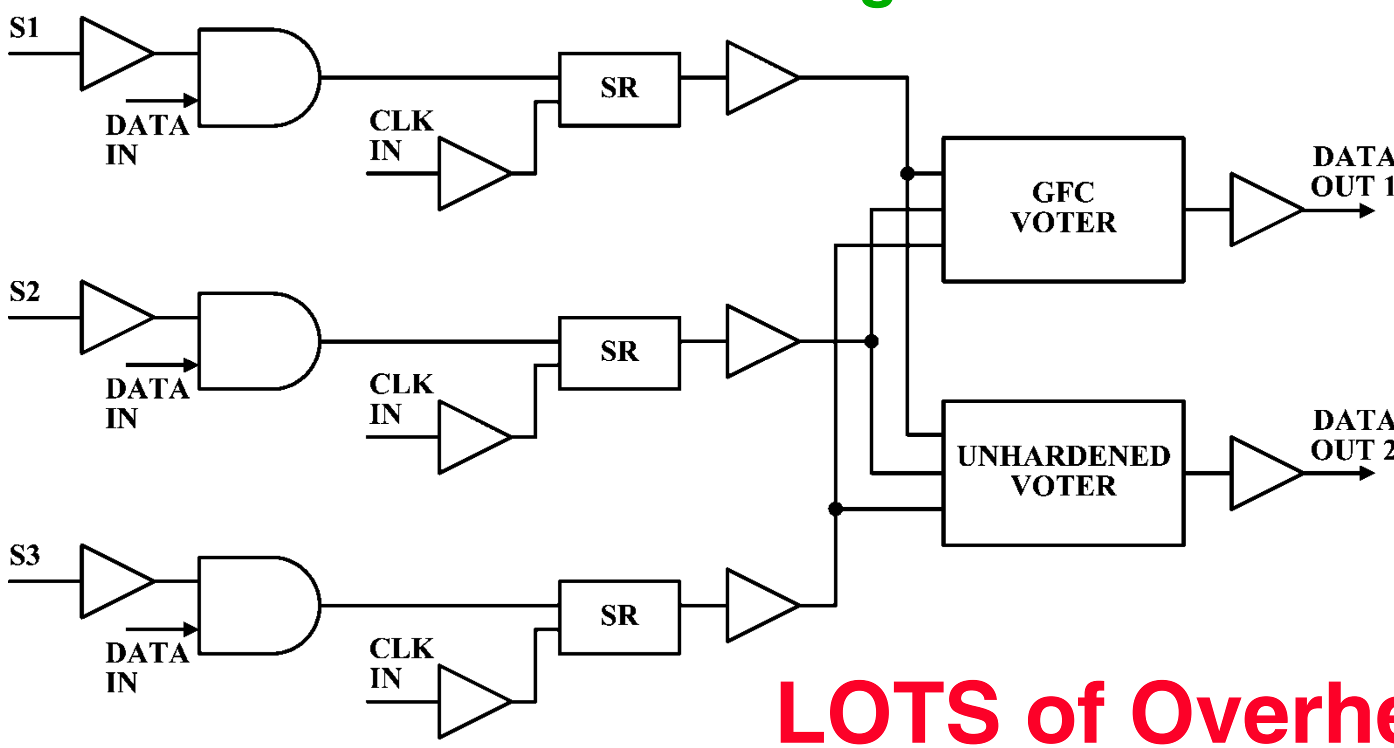
Master Stage of GFC DFF



Register-Level RHBD

- **<u>DI TMR</u>: Triple Modular Redundancy in DI SR**
- **<u>GFC TMR</u>: Triple Modular Redundancy in GFC SR**
- **GFC-Hardened Clocks**
- **Voting Performed Using Parallel GFC/Unhardened Voters**

TMR Block Diagram

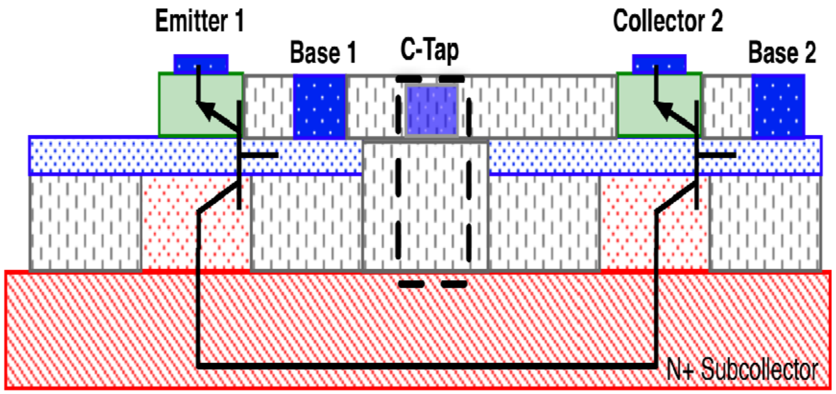


LOTS of Overhead!

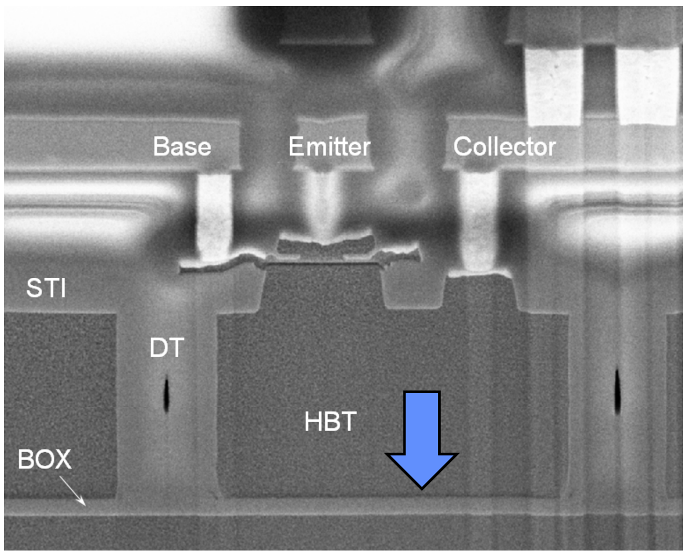
Can We Eliminate TMR and Still SEE-Harden SiGe?

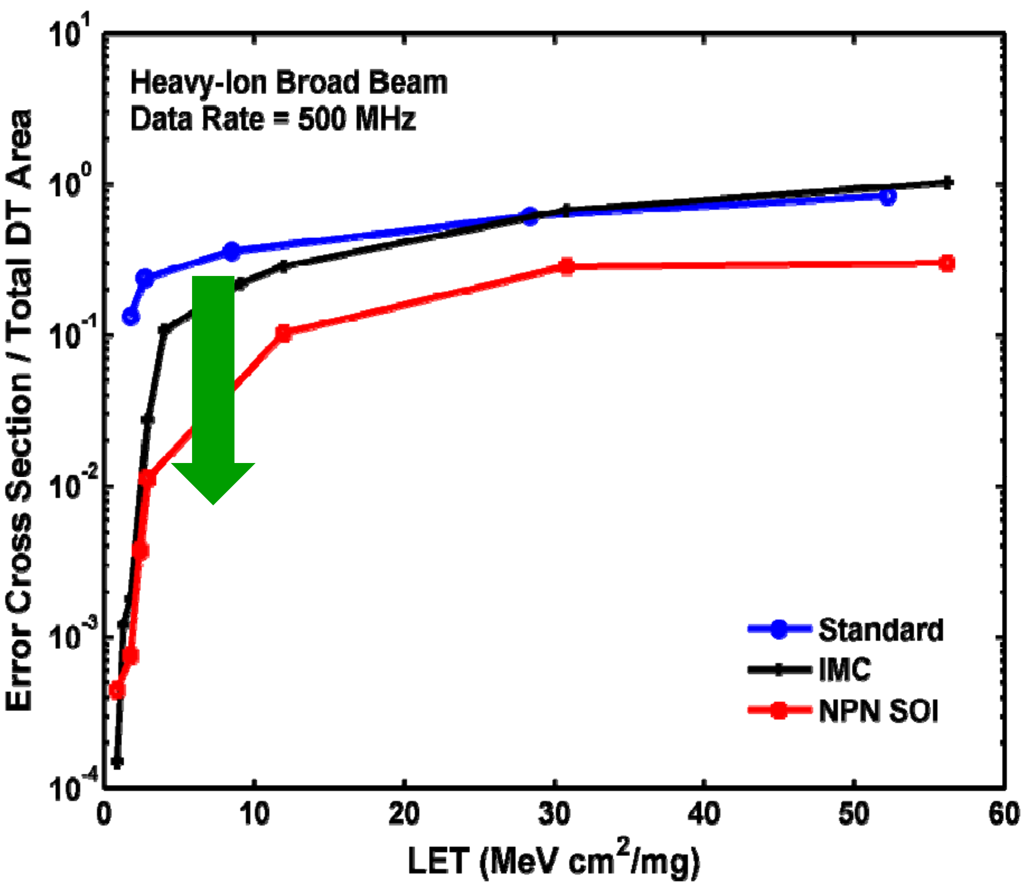
New RHBD Approaches

Inverse-mode Cascode (IMC) SiGe HBT



SiGe HBT on Thick Film SOI





GFC latch + IMC + SOI = SEU hard?

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The Moon:
A Classic Extreme Environment!

Temperature Ranges:
- +120C to -180C **(300C swings!)**
- 28 day cycles

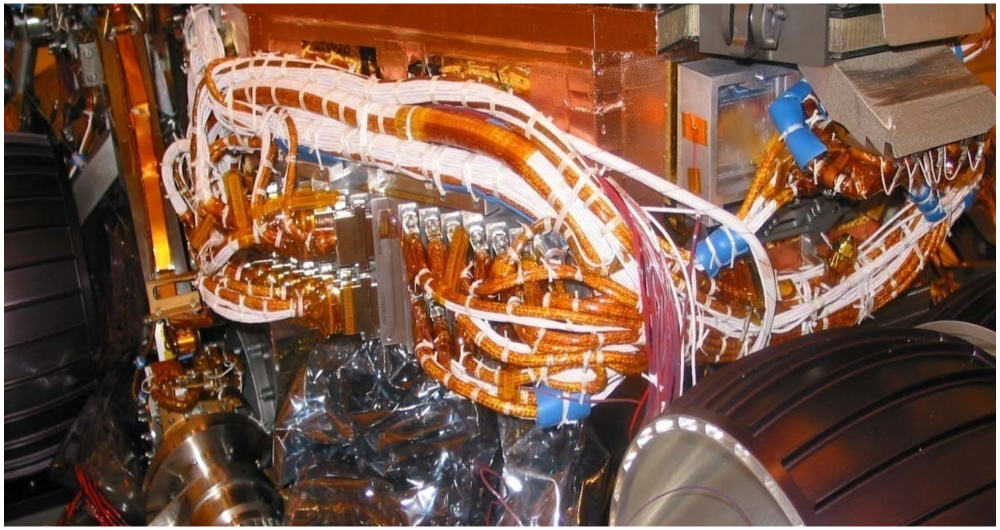
Radiation:
- 100 krad over 10 years
- single event upset (SEU)
- solar events

Many Different Circuit Needs:
- digital building blocks
- analog building blocks
- data conversion (ADC/DAC)
- RF communications
- power conditioning
- actuation and control
- switches
- sensors / sensor interfaces

Highly Mixed-Signal Flavor!

Rovers / Robotics

Requires Centralized "Warm Box"



SiGe HBTs for Cryo-T

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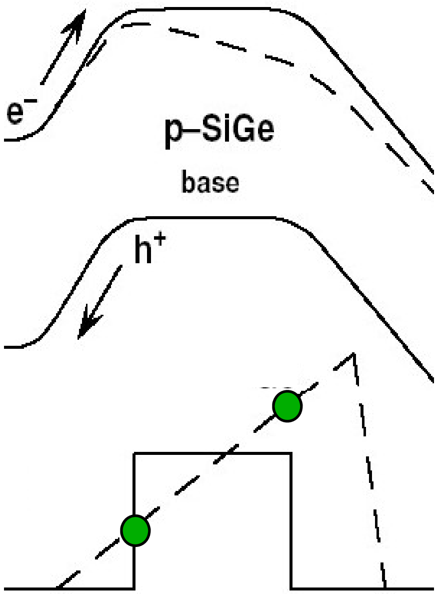
The Idea: **Put Graded Ge Layer into the Base of a Si BJT**

Primary Consequences:

- **smaller base bandgap increases electron injection** **(β⬆)**
- **field from graded base bandgap decreases base transit time** **(f_T⬆)**
- **base bandgap grading produces higher Early voltage** **(V_A⬆)**



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➡ **All kT Factors Are Arranged to Help at Cryo-T!**

SiGe HBTs at Cryo-T

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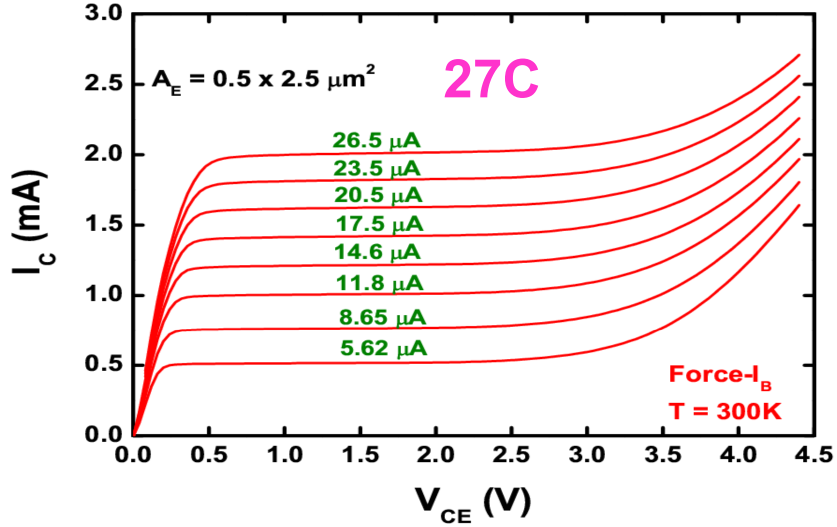

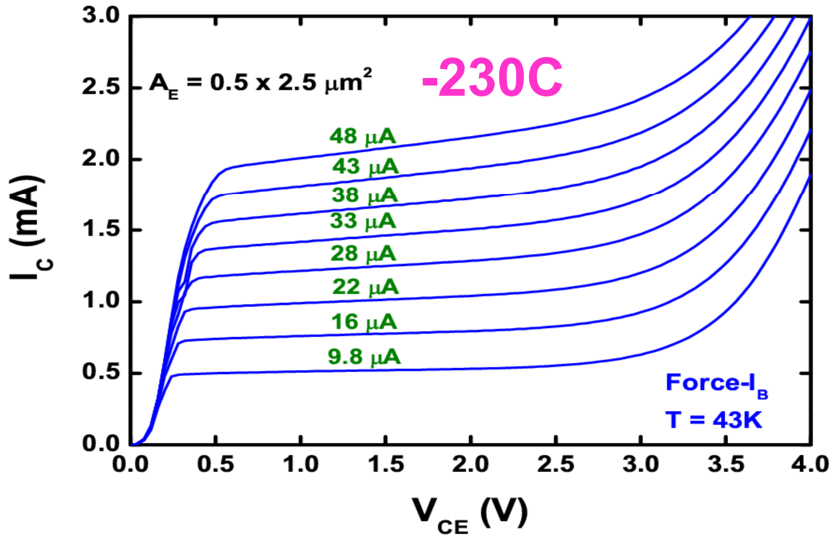

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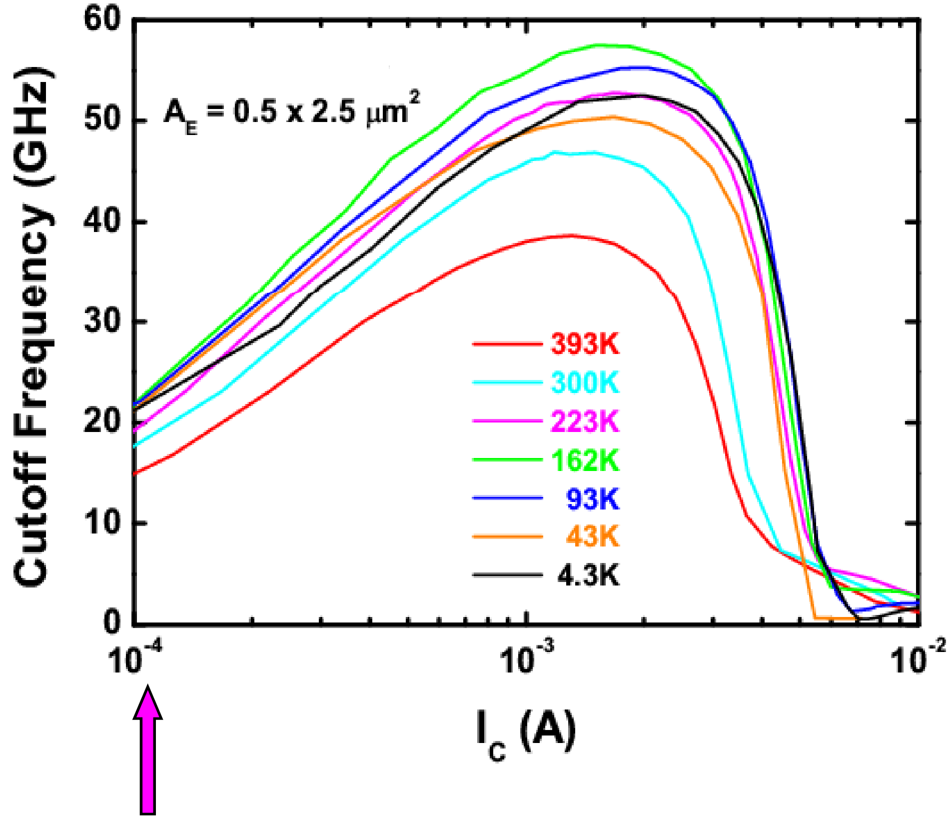

SiGe Exhibits Very High Speed at Very Low Power!

First-Generation SiGe HBT

Remote Electronics Unit

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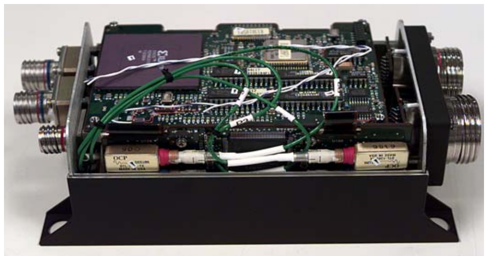
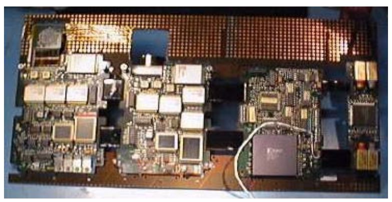
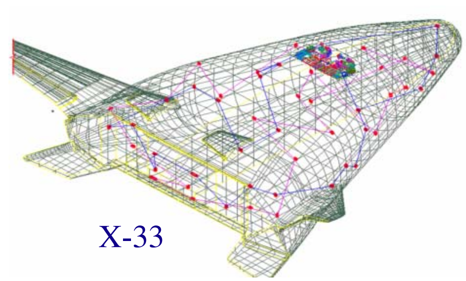
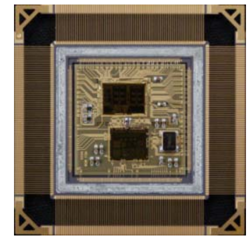


The X-33 Remote Health Unit, BAE Systems, circa 1998



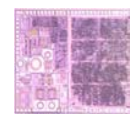


The ETDP SiGe Remote Electronics Unit, 2010

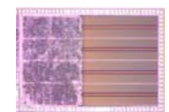


REU in a package!

SiGe Analog front end die



SiGe Digital control die



Specifications

- 5” x 3” x 6.75” = 101 in^3
- 11 kg
- 17 Watts
- -55^{o}C to +125^{o}C

Our SWAP Goals

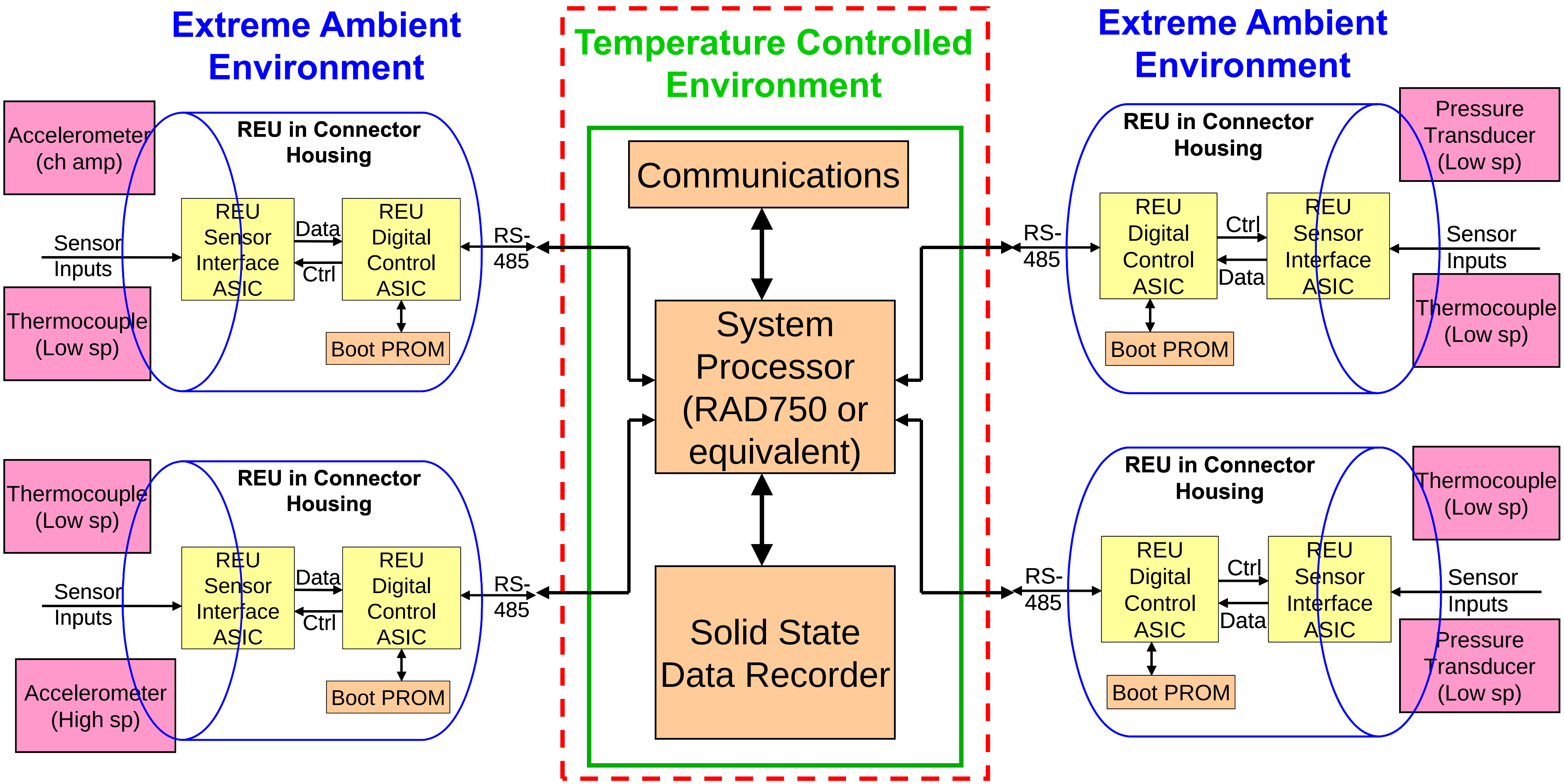
- 1.5” x 1.5” x 0.5” = 1.1 in^3 **(100x)**
- < 1 kg **(10x)**
- < 2 Watts **(10x)**
- **-180^{o}C to +125^{o}C, rad tolerant**

Supports Many Sensor Types:

Temperature, Strain, Pressure, Acceleration, Vibration, Heat Flux, Position, etc.

Use This SiGe REU as a Remote Vehicle Health Monitoring Node

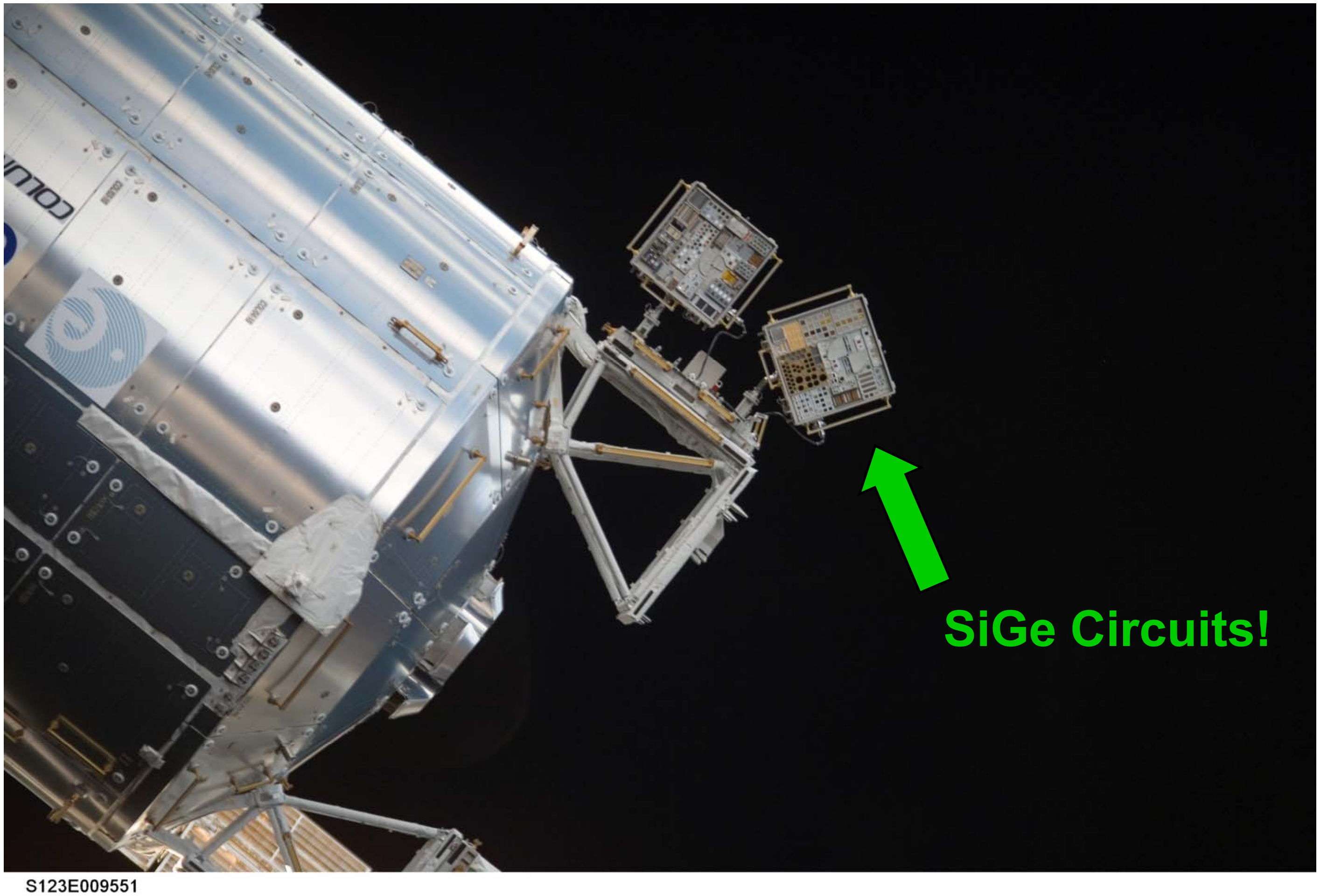
SiGe REU Architecture



Major Advantages:

- **Eliminates Warm Box (size, weight, and power; allows de-centralized architecture)**
- **Significant Wiring Reduction (weight, reliability, simplifies testing & diagnostics)**
- **Commonality (easily adapted from one system to the next)**

MISSE-6,7 ISS Missions

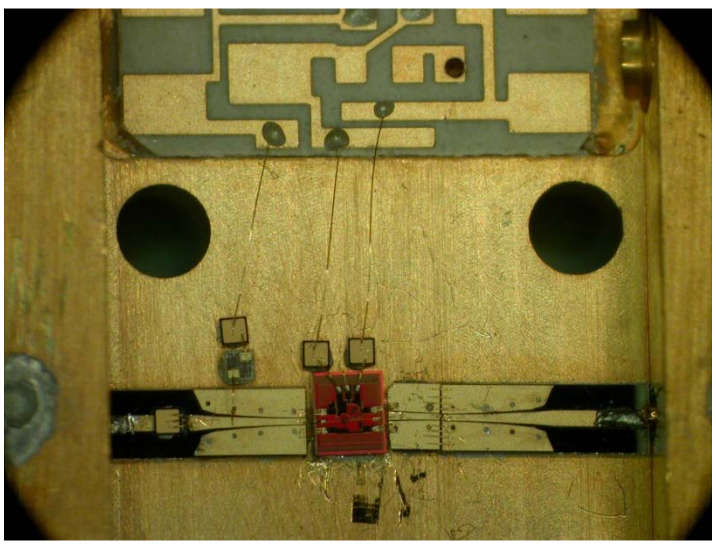


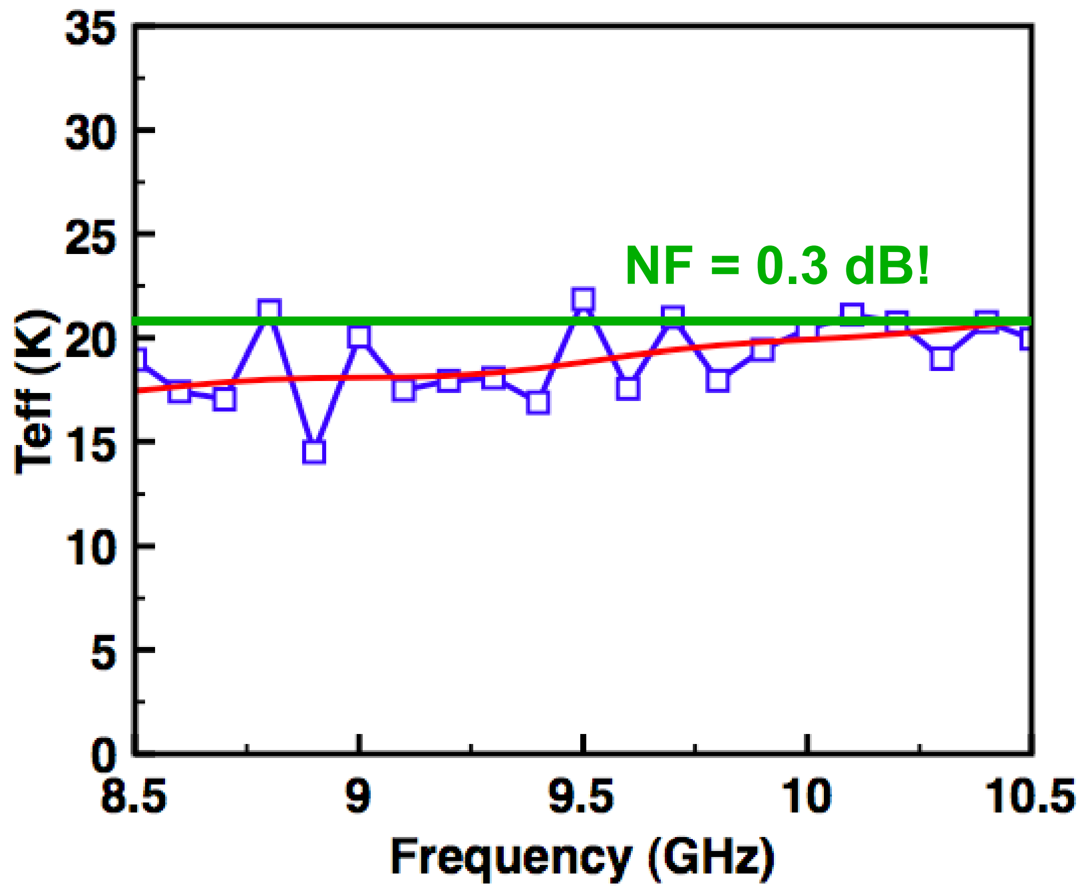
Recent NASA photograph of MISSE-6 after deployment, taken by the Space Shuttle Crew

Cryogenic SiGe LNAs

X-band LNA Operation at 15 K (Not Yet Optimized!)

- T_{eff} < 20 K (noise T)
- NF < 0.3 dB
- Gain > 20 dB
- *dc* power < 2 mW



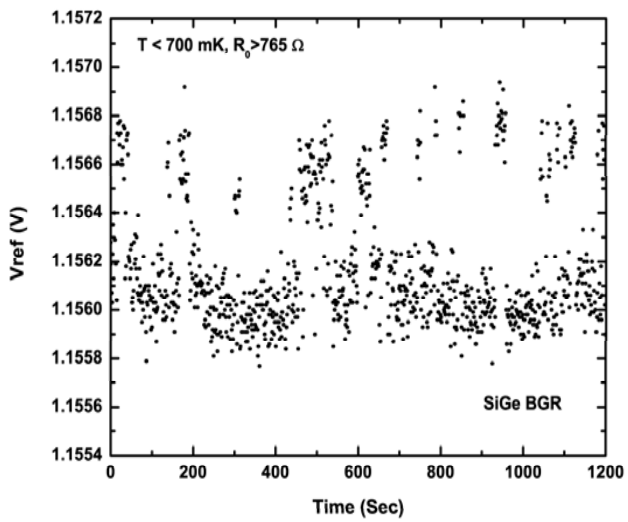


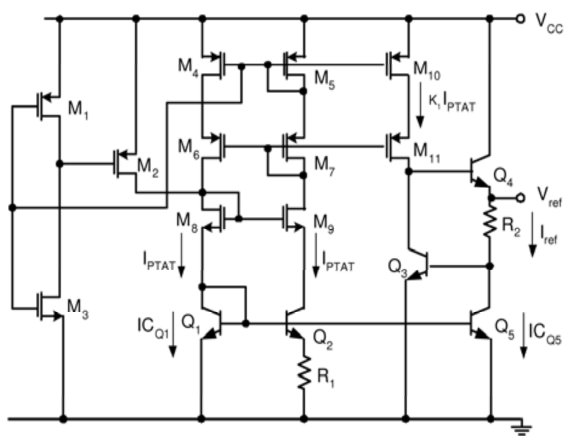
Collaboration with S. Weinreb, Cal Tech

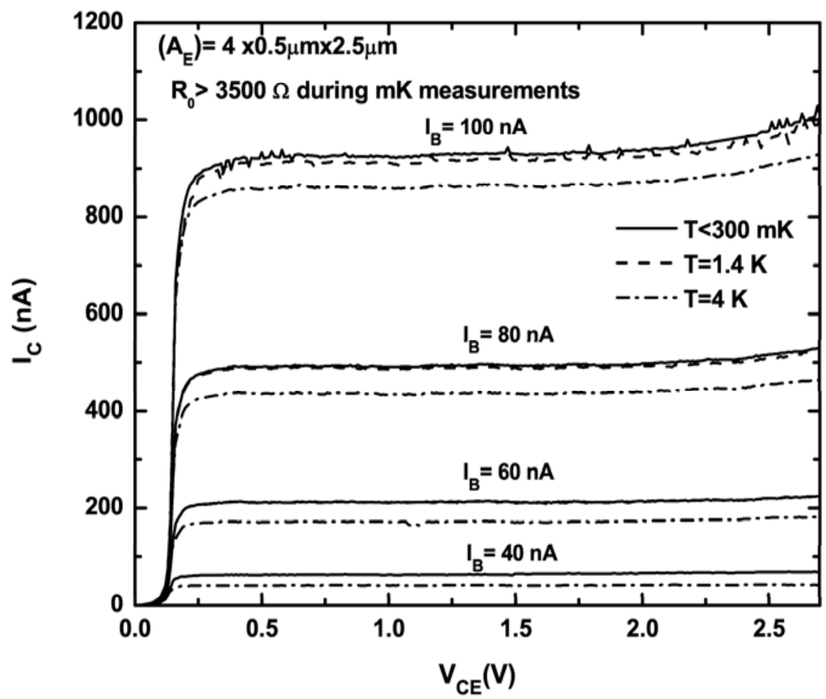
This SiGe LNA is Also Rad-Hard!

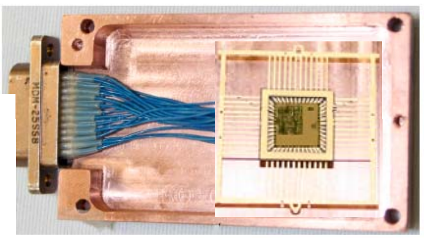
Operation at Sub-1K!

- **SiGe HBT Works Just Fine Down to 300 mK!**
- **SiGe Reference Circuit Also Works! (700 mK)**









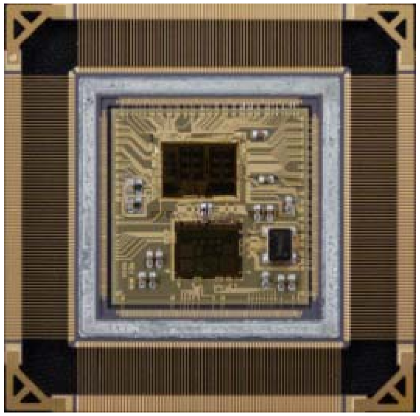
Collaboration with NASA-GSFC:
S. Aslam, T. Stevenson, and B. Meloy

Outline

- Some Reminders on SiGe
- Using SiGe in a Radiation Environment
- Understanding and Mitigating SEE
- Operation at Cryogenic Temperatures
- **Some Thoughts on NASA Apps of SiGe**
- **Summary**

Some Thoughts / Ideas

- We now know how to build robust, reliable, complex mixed-signal (analog, digital, RF) SiGe electronics to operate in Lunar/Martian/Europa/Titan/etc. environments
- We can provide warm-box free SiGe "electronic suites" for a wide class of instrument / sensor / control / comm needs that can provide dramatic reductions in SWAP



Complex on-Surface Electronics

analog, sensors, digital, RF, power, etc.

< 1.0 in^2 (small)
< 100 g (light weight)
< 1-2 W for SYSTEMS (low power)

Key Takeaway: Environmentally Invariant Electronics

Summary

- **SiGe HBT BiCMOS Technology**
  - combines III-V speed with Si manufacturing (win-win)
  - many new apps **(SiGe is a natural for space environments)**
- **Using SiGe HBTs in Radiation Environments**
  - built-in total-dose hardness (multi-Mrad!)
  - SEU is an issue to be reckoned with (fast digital = worst case)
- **SiGe Technology Can Provide Mission Designers With:**
  - **environmentally-invariant** electronic suites
  - warm-box free operation
  - dramatic reductions in SWAP
  - improved reliability
  - commonality of electronic systems

→ **New Ways to Think About NASA Mission Design**

Acknowledgement

- **Akil Sutton, Stan Phillips, Ryan Diestelhorst, Laleh Najafizadeh, Ted Wilcox, Marco Bellini, Kurt Moen, Aravind Appaswamy, Tushar Thrivikraman, and Tom Cheng** (my Georgia Tech team)
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- **George Vizkelethy and Paul Dodd** (Sandia)
- **Dale McMorrow** (NRL)
- **Marek Turowski and team** (CFDRC)
- **The SiGe Teams at IBM, Jazz, IHP, TI, National, and ST Micro**

and many others …