Silicon-Germanium
as an Enabling Technology for Extreme Environment Electronics

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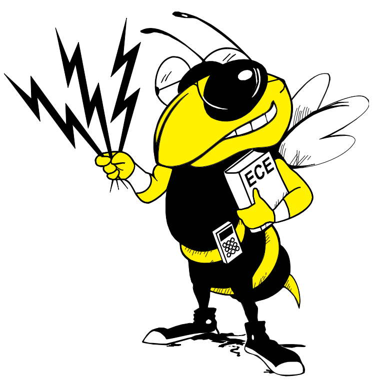

Fermilab, Batavia, IL, June 9, 2009

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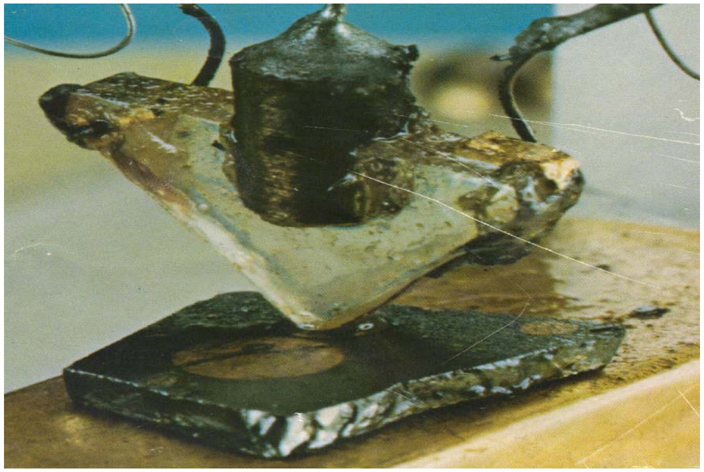
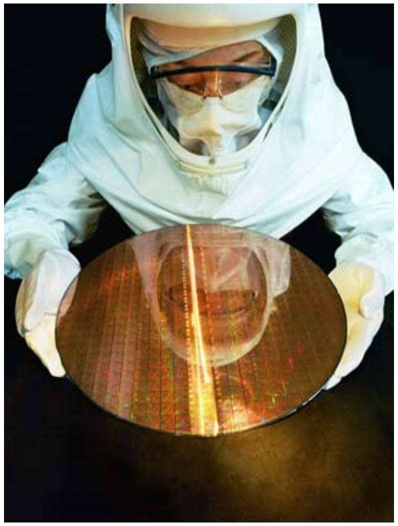
A Level-Set on Miracles

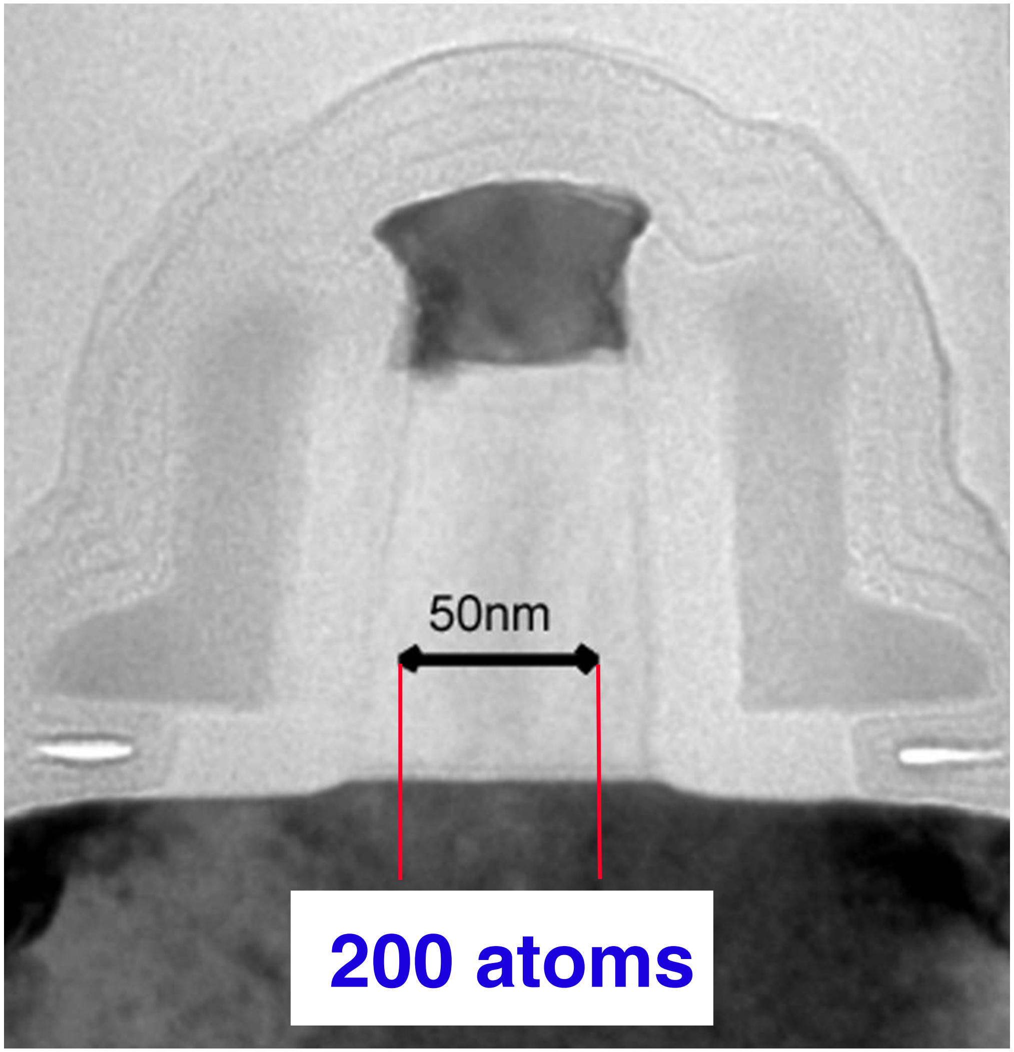
Georgia Institute of Technology

1 Transistor – 1947

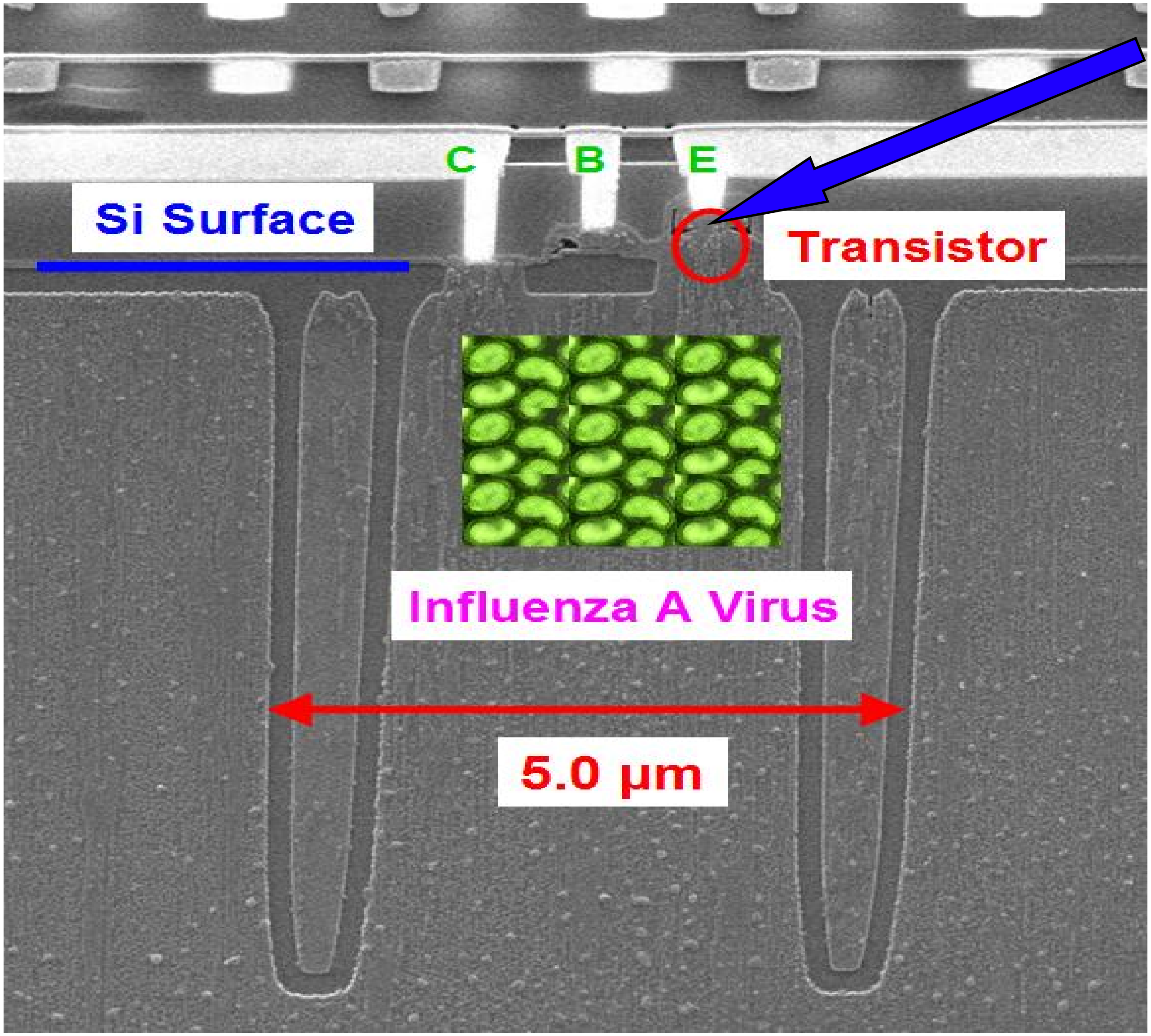




1 Transistor - 2009



A Level-Set on Miracles

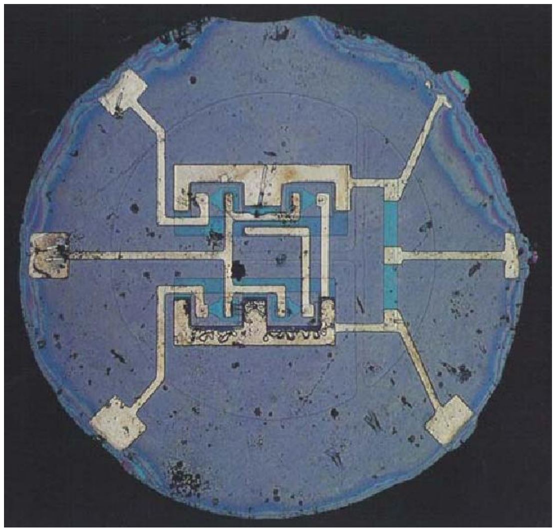


A few atomic layers of SiGe Goes Here … Very Carefully!

A Level-Set on Miracles

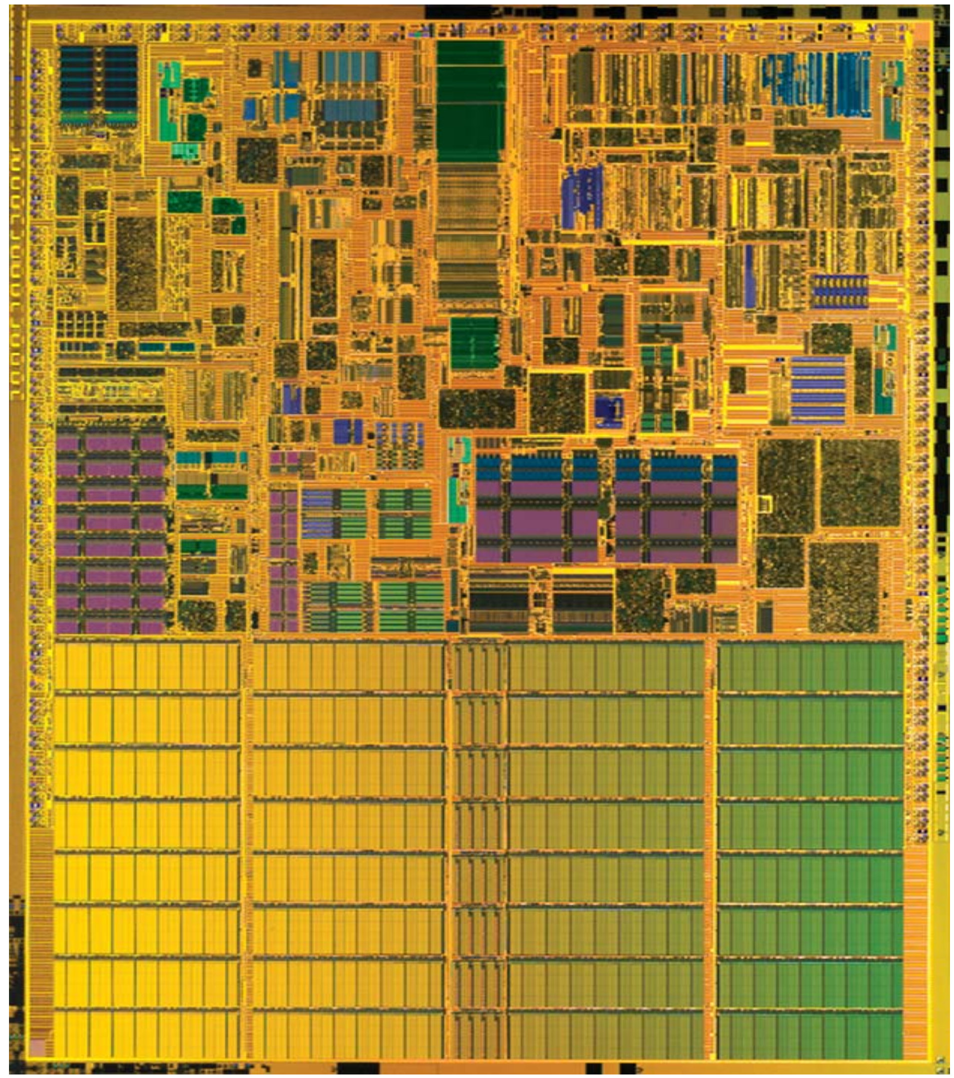
Georgia Institute of Technology

1 IC – 1958



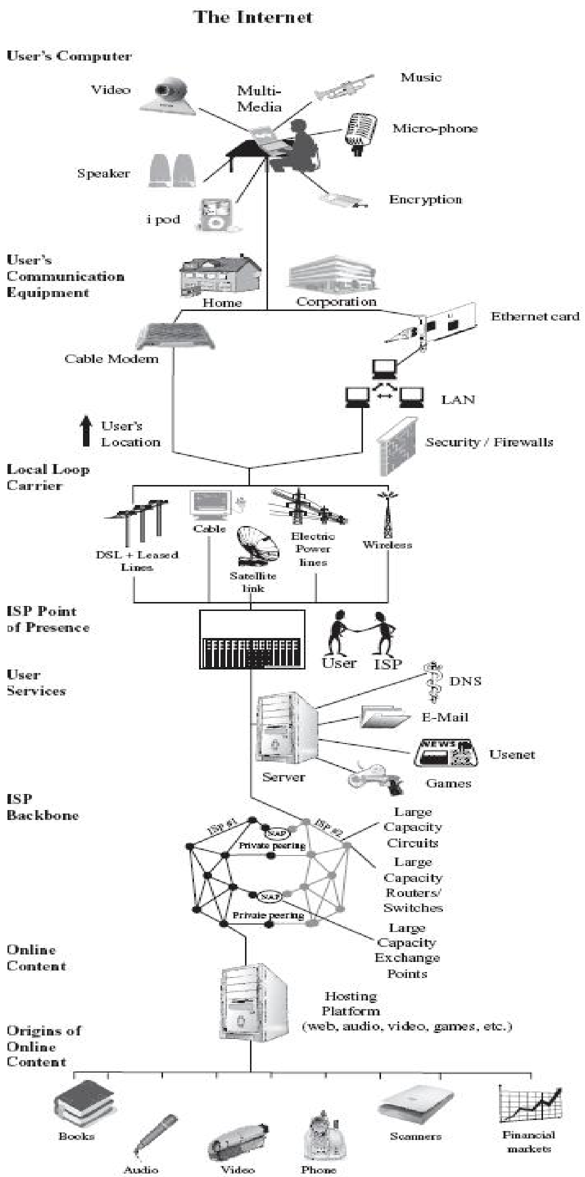
4 Transistors

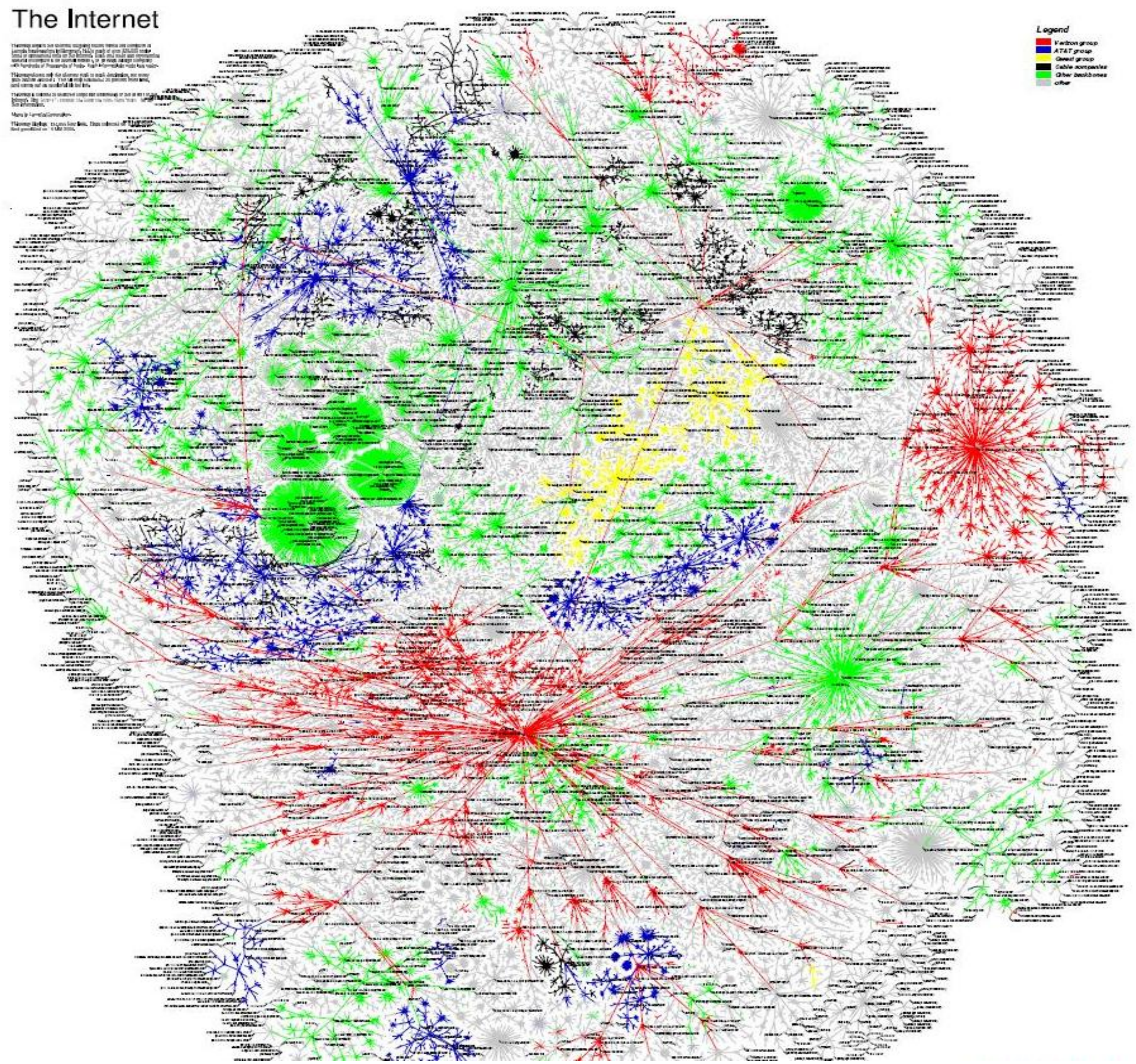
1 IC - 2009



1,000,000,000
Transistors

The Internet



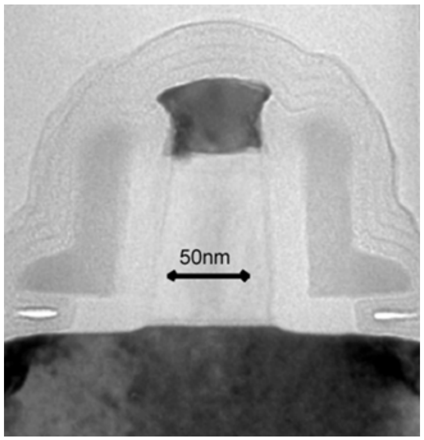


Outline

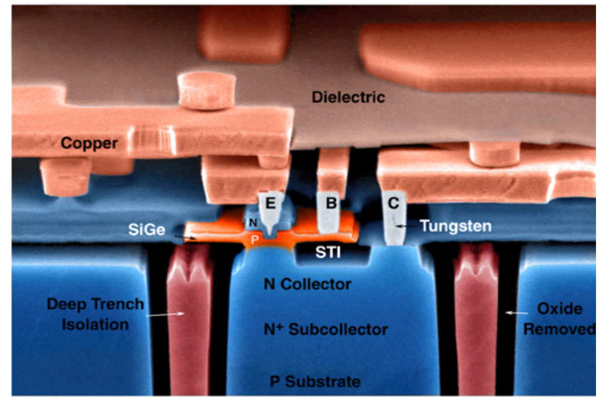
- Some Reminders on SiGe
- Scaling Trends and Performance Limits
- Emerging Application Opportunities for SiGe
- Extreme Environment Electronics
- Using SiGe in a Radiation Context
- Cryogenic Operation of SiGe HBTs
- Cryogenic Operation of CMOS
- Summary

Strain Engineering in Si

Strained Si CMOS

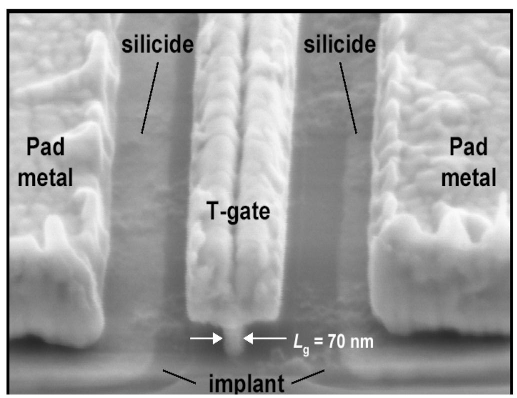


SiGe HBTs



All Are:
Strain-Enhanced
Si-based Transistors

Close Cousins!

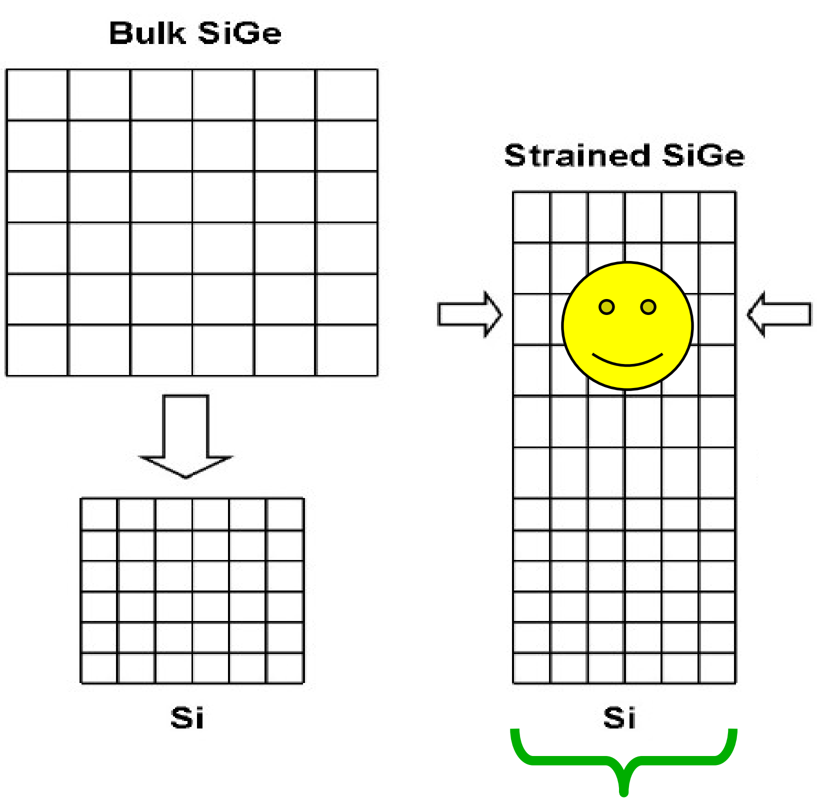


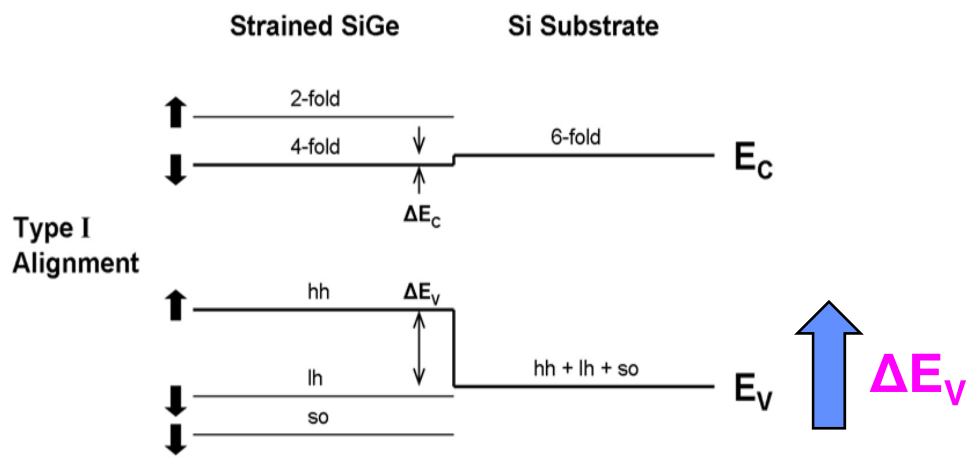
SiGe MODFETs

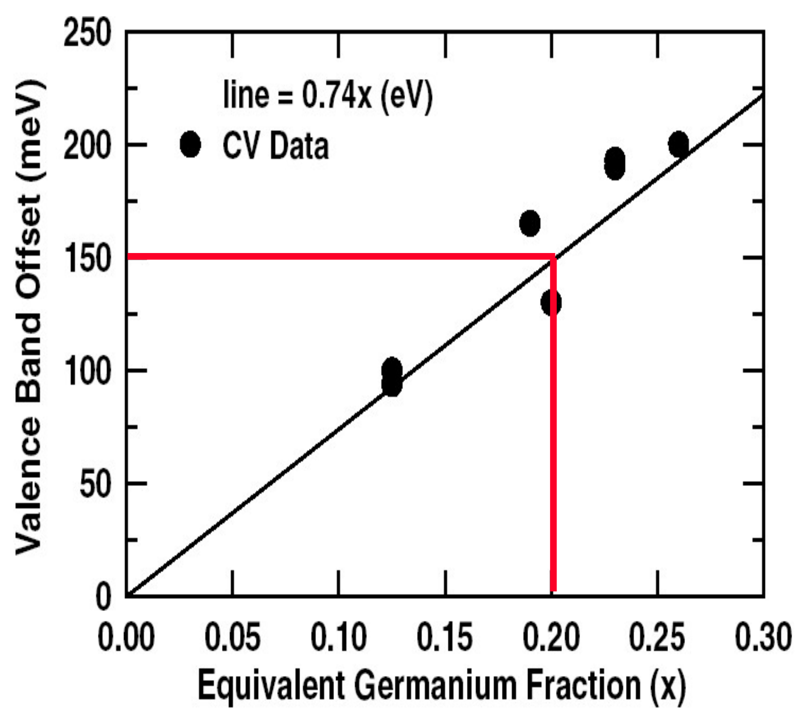
SiGe Strained Layer Epi

The Bright Idea!

Practice Bandgap Engineering
… but do it in Silicon!

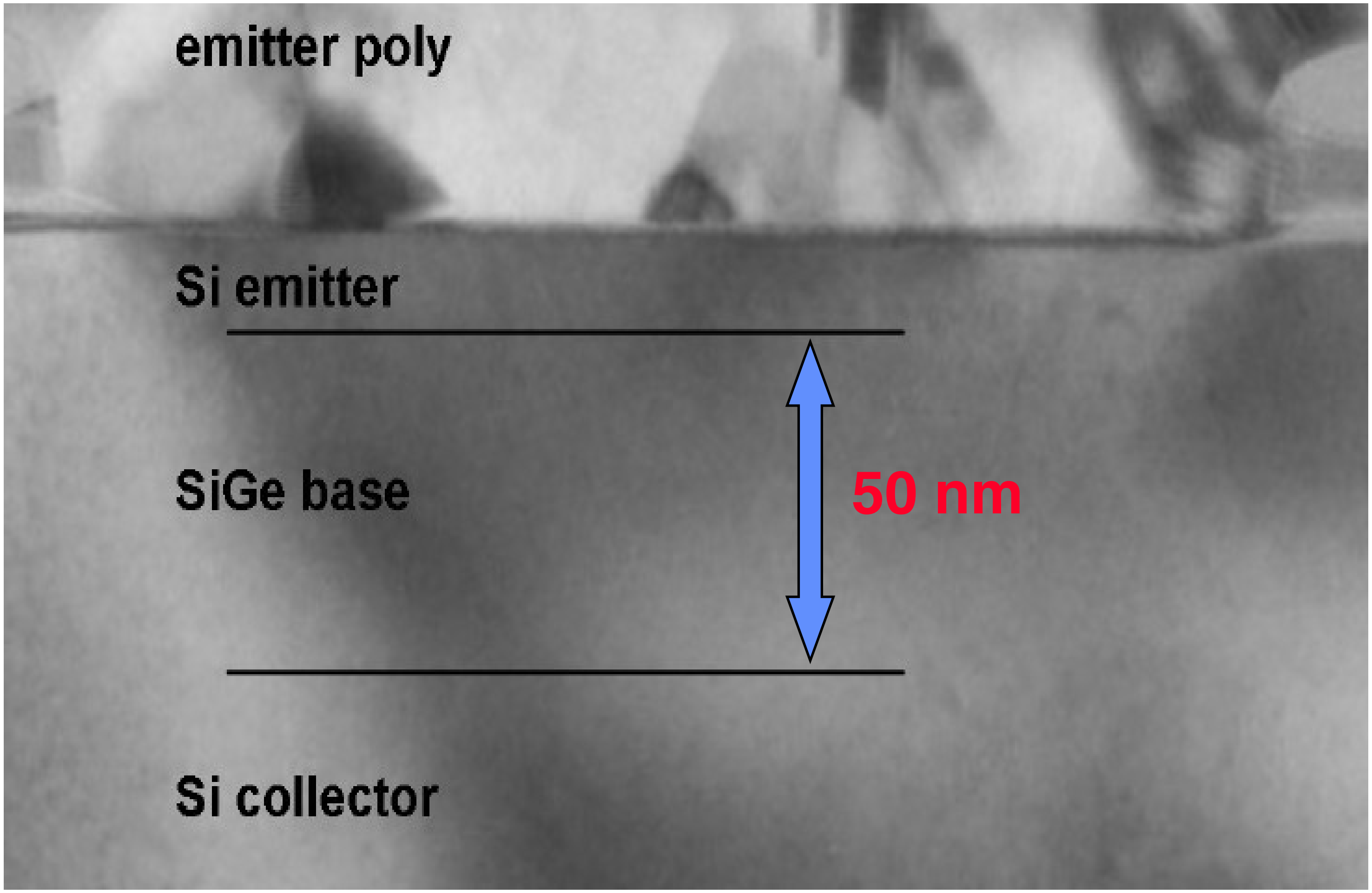






When You Do It Right …

- **Seamless Integration of SiGe into Si**



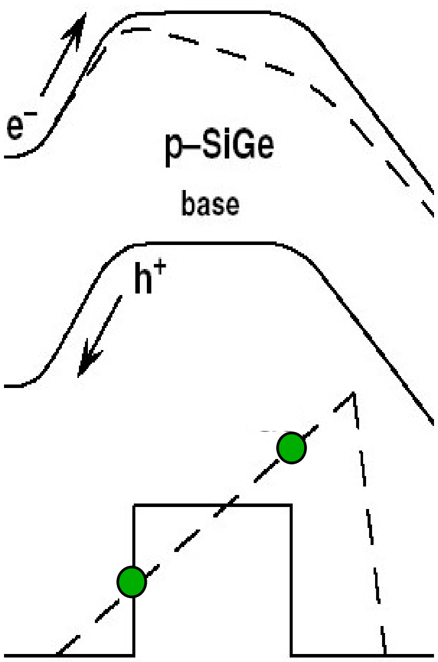
No Evidence of Deposition!

The SiGe HBT

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

Primary Consequences:

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



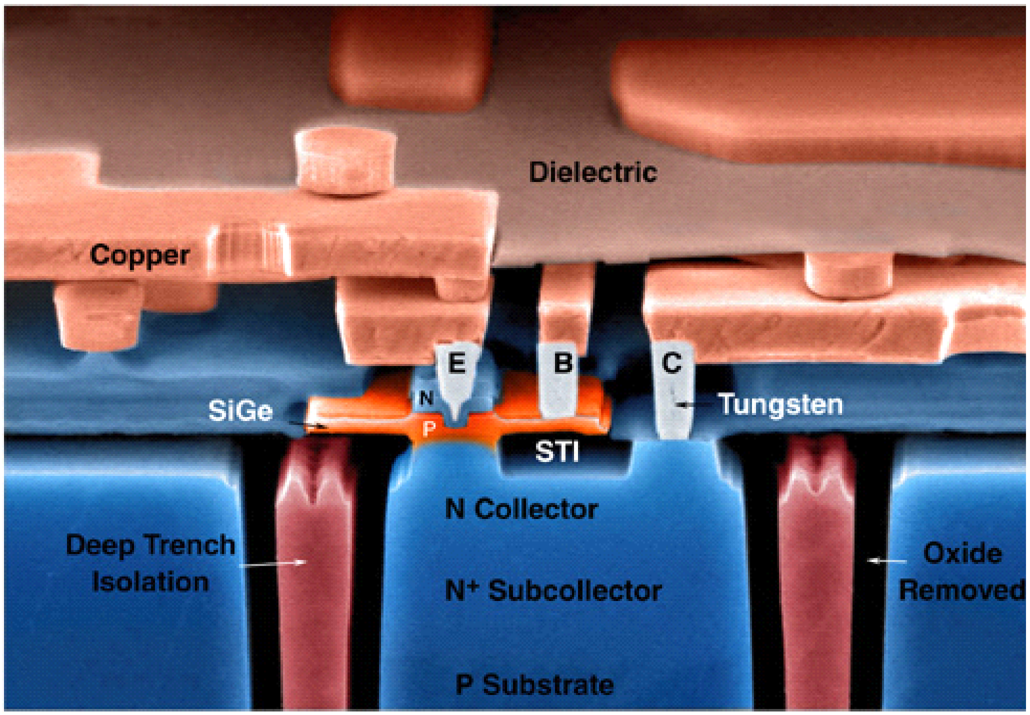
$$\left.\frac{\beta_{SiGe}}{\beta_{Si}}\right|_{V_{BE}} \equiv \Xi = \left\{ \frac{\tilde{\gamma}\,\tilde{\eta}\,\Delta E_{g,Ge}(grade)/kT\; e^{\Delta E_{g,Ge}(0)/kT}}{1 - e^{-\Delta E_{g,Ge}(grade)/kT}} \right\}$$

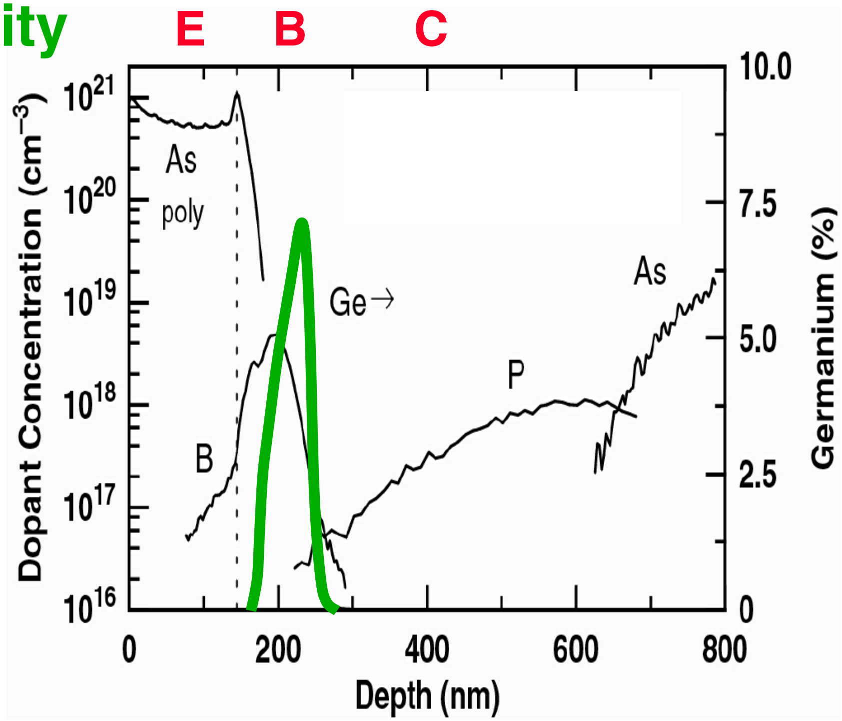
$$\frac{\tau_{b,SiGe}}{\tau_{b,Si}} = \frac{2}{\tilde{\eta}}\,\frac{kT}{\Delta E_{g,Ge}(grade)} \left\{ 1 - \frac{kT}{\Delta E_{g,Ge}(grade)} \left[1 - e^{-\Delta E_{g,Ge}(grade)/kT} \right] \right\}$$

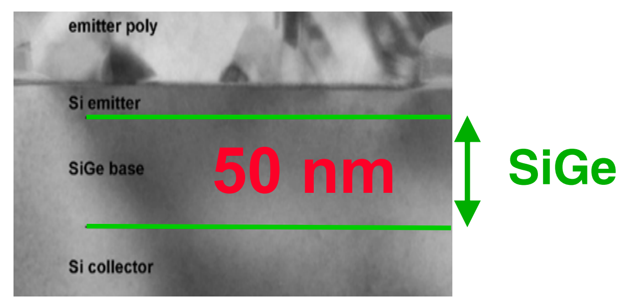
$$\left.\frac{V_{A,SiGe}}{V_{A,Si}}\right|_{V_{BE}} \equiv \Theta \simeq e^{\Delta E_{g,Ge}(grade)/kT} \left[\frac{1 - e^{-\Delta E_{g,Ge}(grade)/kT}}{\Delta E_{g,Ge}(grade)/kT} \right]$$

The SiGe HBT

- Conventional Shallow and Deep Trench Isolation + CMOS BEOL
- Unconditionally Stable, SiGe Epitaxial Base Profile
- 100% Si Manufacturing Compatibility
- SiGe HBT + Si CMOS on wafer





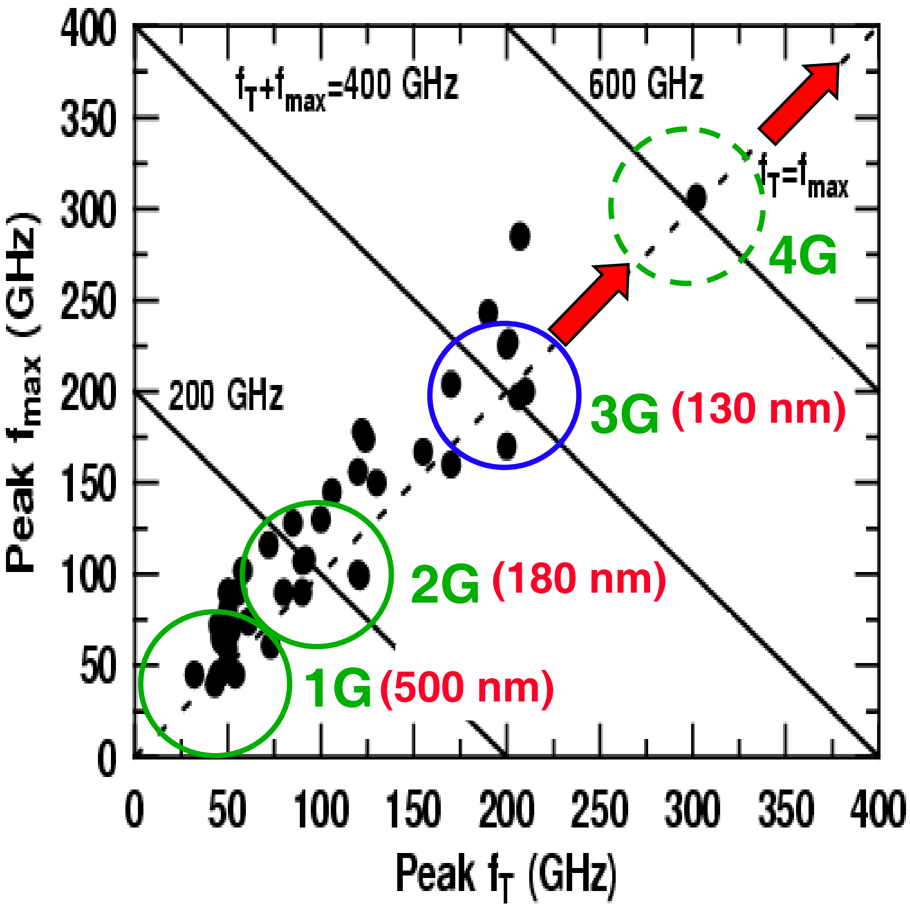


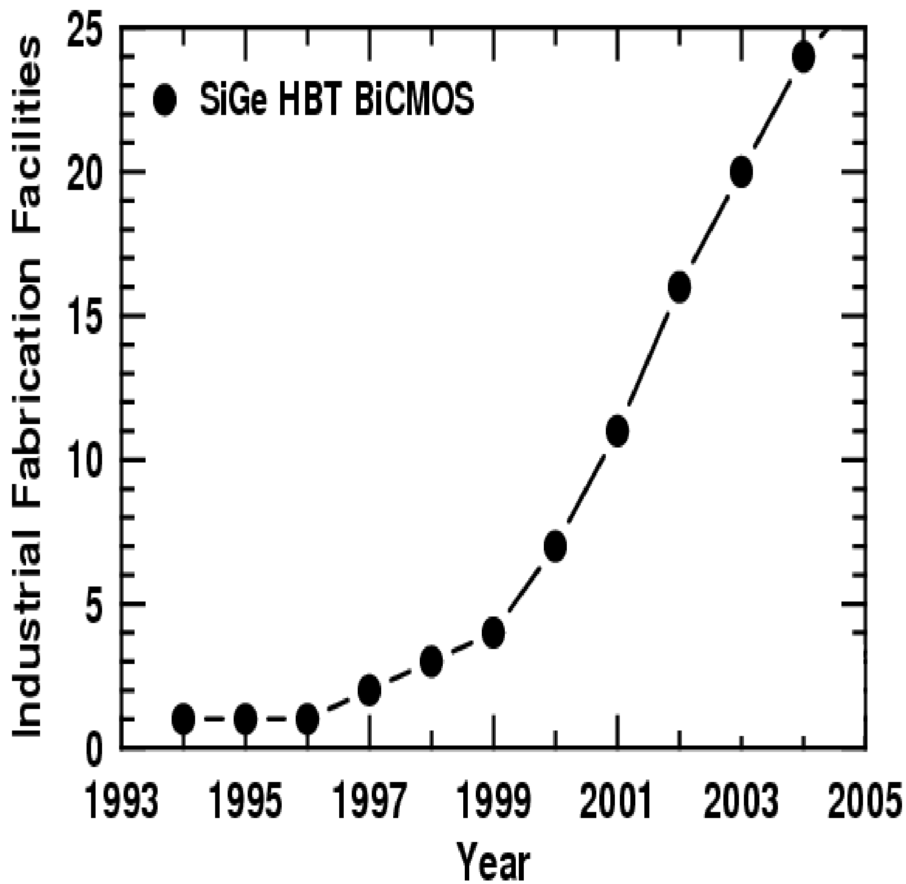
SiGe = III-V Speed + Si Manufacturing

Win-Win!

SiGe Success Story

- **Rapid** Generational Evolution (full SiGe BiCMOS)
- Significant In-roads in Communications / Analog ICs

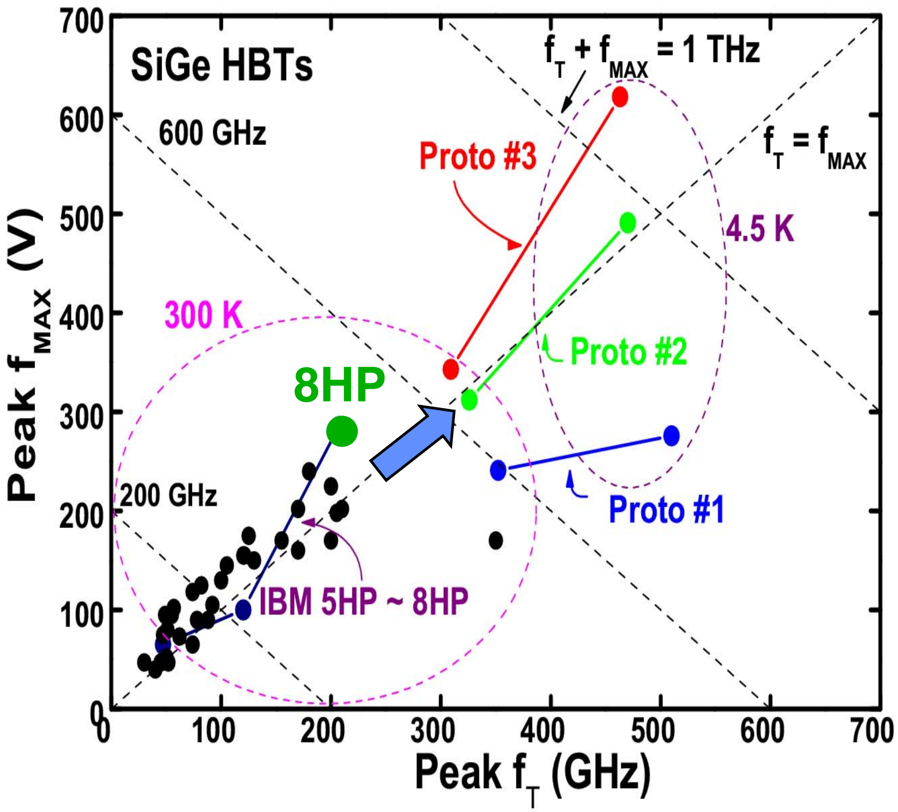


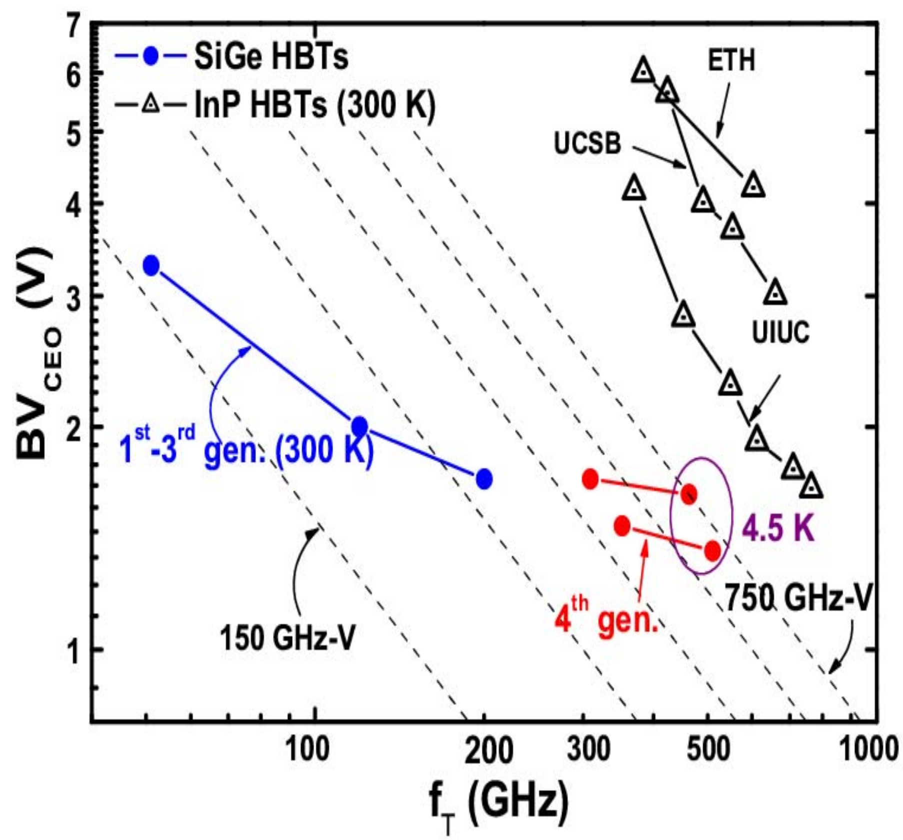


Important Point: 200 GHz @ 130 nm! (2G better than CMOS)

SiGe Performance Limits

- $f_T + f_{max}$ > 1 THz in SiGe Is Clearly Possible (at very modest lith)
- Both f_T and f_{max} above 500 GHz at Cryo-T (T = scaling knob)
- Goal: Useful BV @ 500 GHz (BV_{CEO} > 1.5 V + BV_{CBO} > 5.5 V)

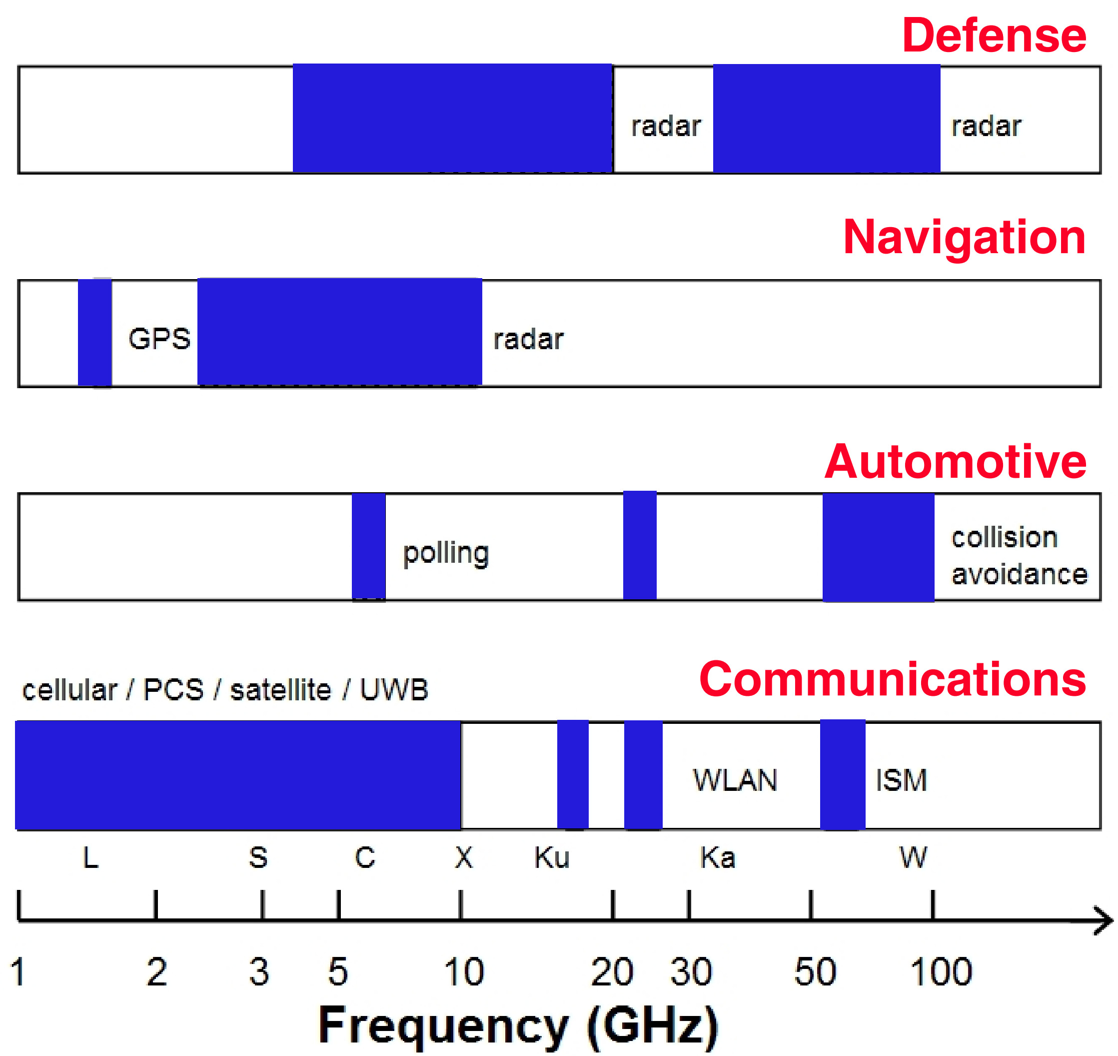


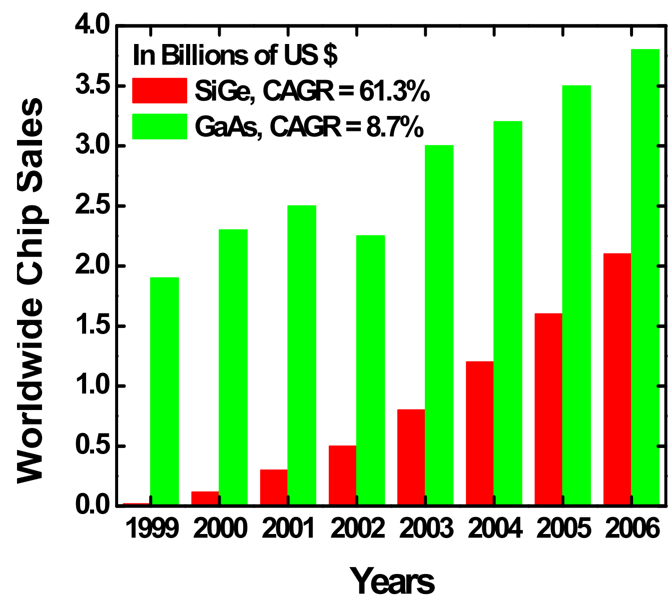


200-500 GHz @ 130 nm Node!

SiGe Apps

Some Application Bands for SiGe IC's





SiGe Analog/MS ICs Are a Major Driver!

Some New Opportunities

Georgia Institute of Technology

- **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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Extreme Environments

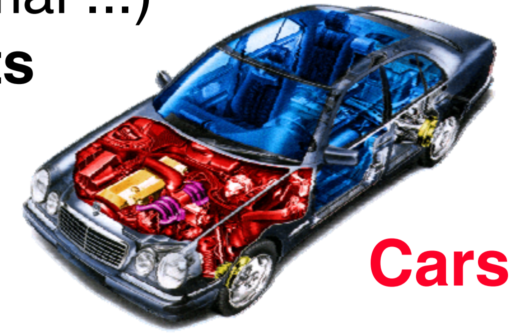
Extreme Environment Electronics:

low-T, high-T, wide-T, radiation, shock, chemical …

- **Aerospace** (aircraft, satellites ...)
- **Space Exploration** (Moon, Mars ...)
- **Automotive** (on-engine electronics …)
- **Drilling** (oil, geothermal ...)
- **Physics Experiments**

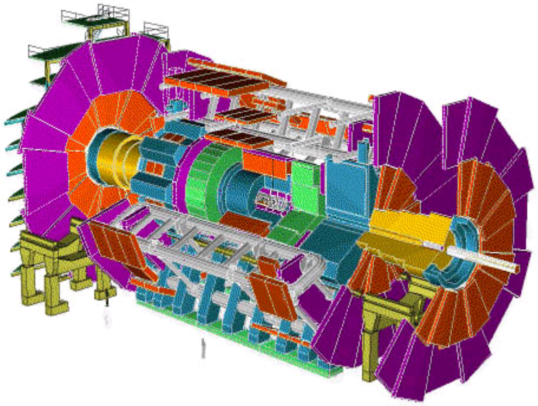
Drilling

Aerospace



Cars

Exploration

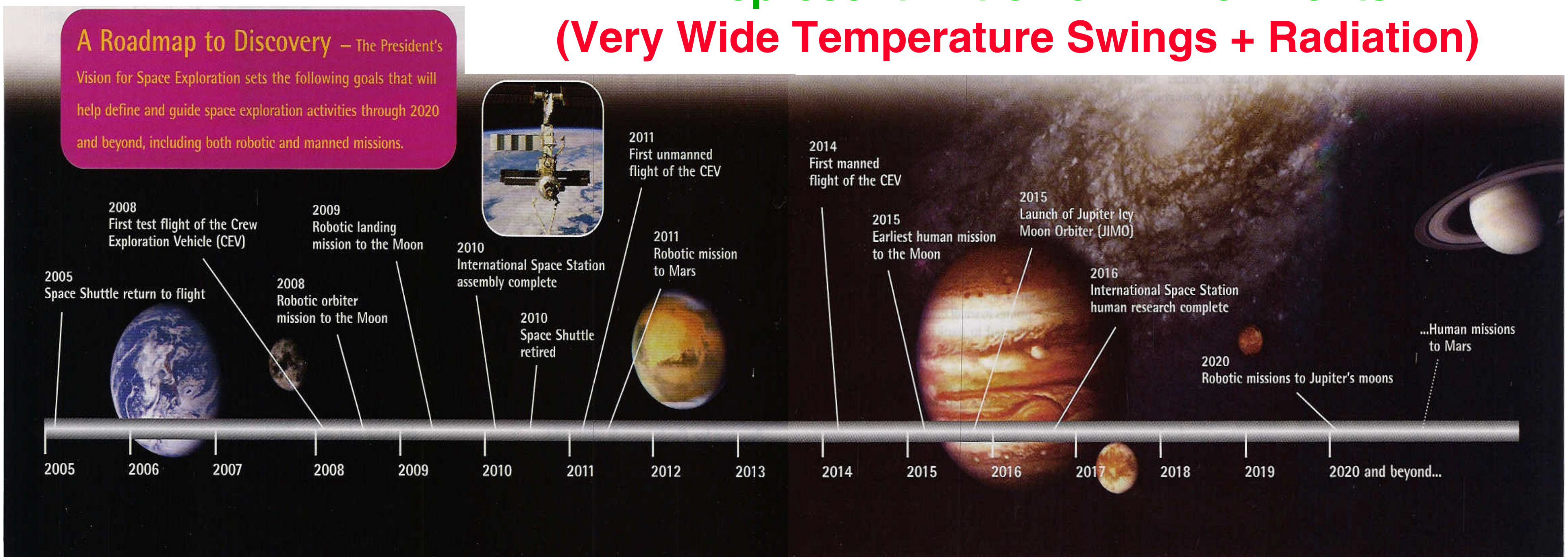


Detectors for Particle Physics

Space Exploration

All Represent Extreme Environments!

(Very Wide Temperature Swings + Radiation)



Moon

Mars

Outer Planets

Planet	$T_{surface}$ (K)	T_{sphere} (K)
Mercury	100-700	445
Venus	740	325
Earth	288-293	277
Mars	140-300	225
Jupiter	165	123
Saturn	134	90
Uranus	76	63
Neptune	72	50
Pluto	40	44

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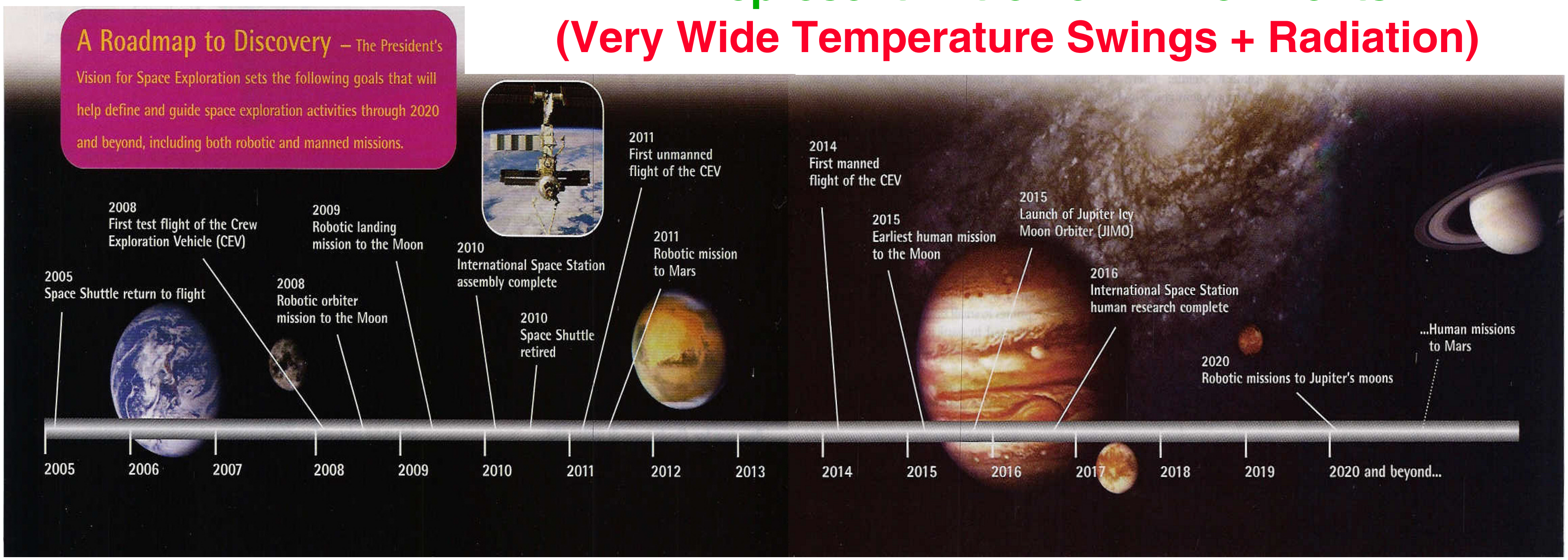

Moon **Mars** **Outer Planets**

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Mars	140-300	225
Jupiter	165	123
Saturn	134	90
Uranus	76	63
Neptune	72	50
~~Pluto~~	~~40~~	~~44~~

The Moon:
A Classic Extreme Environment!

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

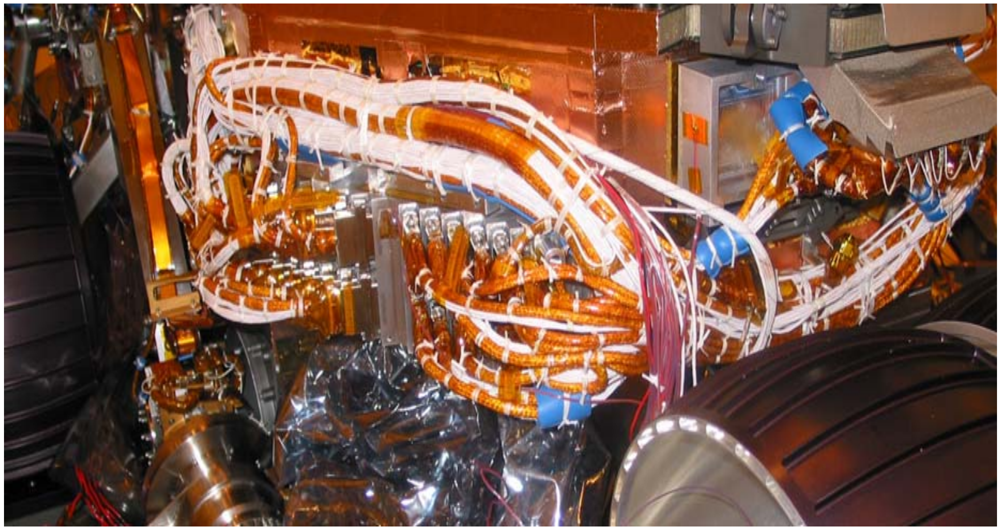
Radiation:
- 100 krad over 10 years
- single event upset (SEU)
- solar events

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

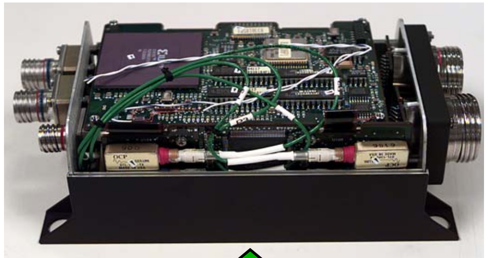
Highly Mixed-Signal Flavor!

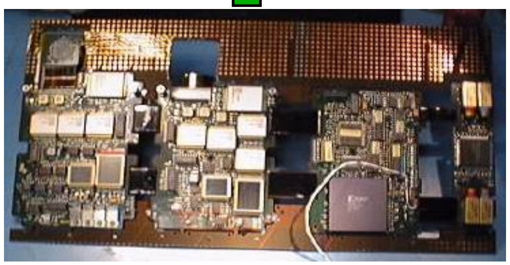
Rovers / Robotics

Requires Centralized "Warm Box"



Remote Electronics Unit

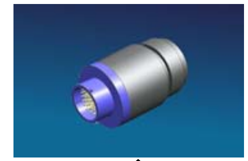




The X-33 Remote Health Unit, circa 1998

SiGe

The ETDP Remote Electronics Unit, circa 2009



REU in connector housing!

Analog front end die

Digital control die

Conceptual integrated REU system-on-chip SiGe BiCMOS die

Specifications

- 5" x 3" x 6.75" = 101 in^3
- 11 kg
- 17 Watts
- -55°C to +125°C

Goals

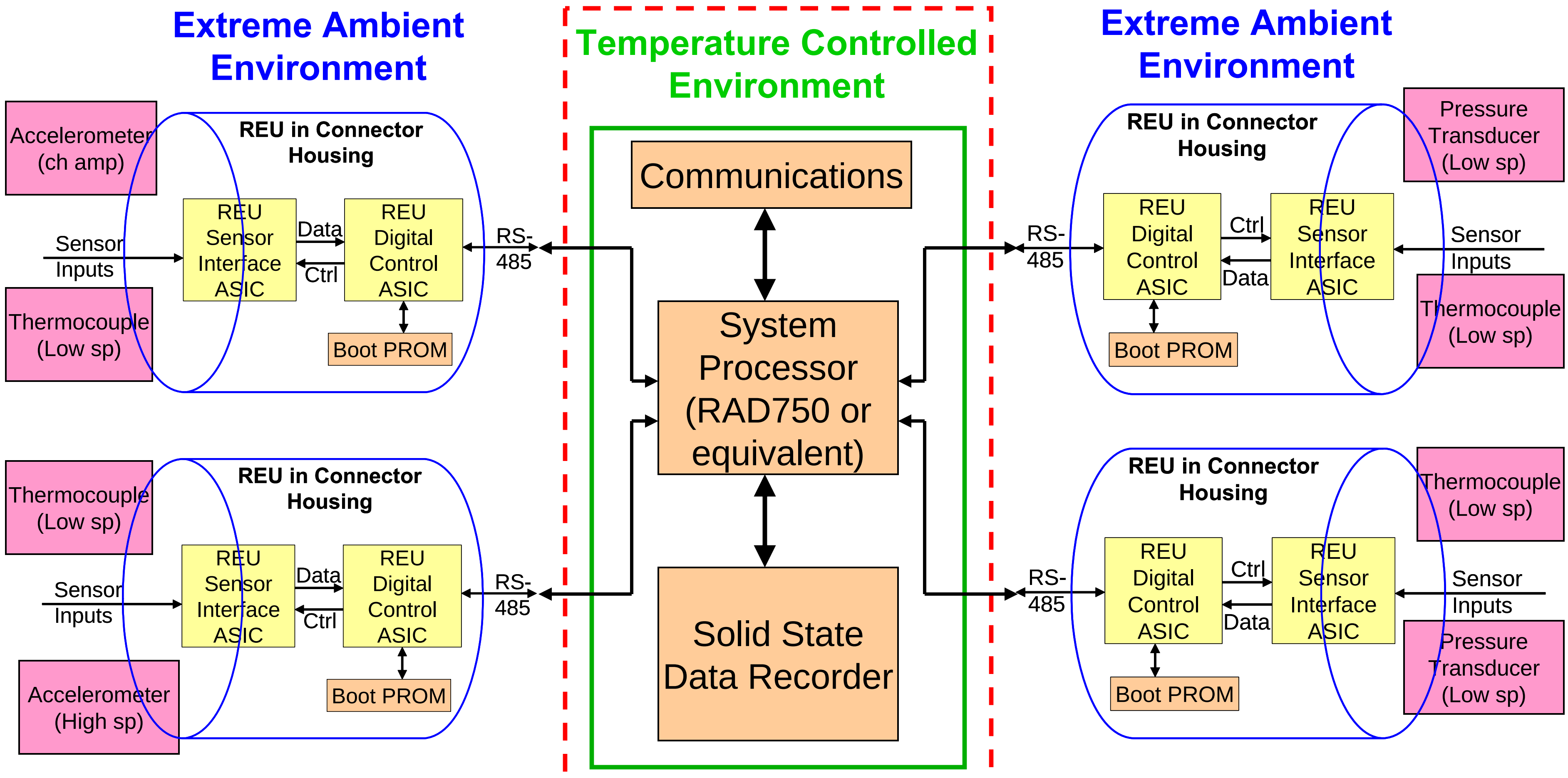
- 1.5" x 1.5" x 0.5" = 1.1 in^3 **(100x)**
- < 1 kg **(10x)**
- < 2 Watts **(10x)**
- **-180°C to +125°C, rad tolerant**

Supports Many Sensor Types:

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

Use This REU as a Remote Vehicle Health Monitoring Node

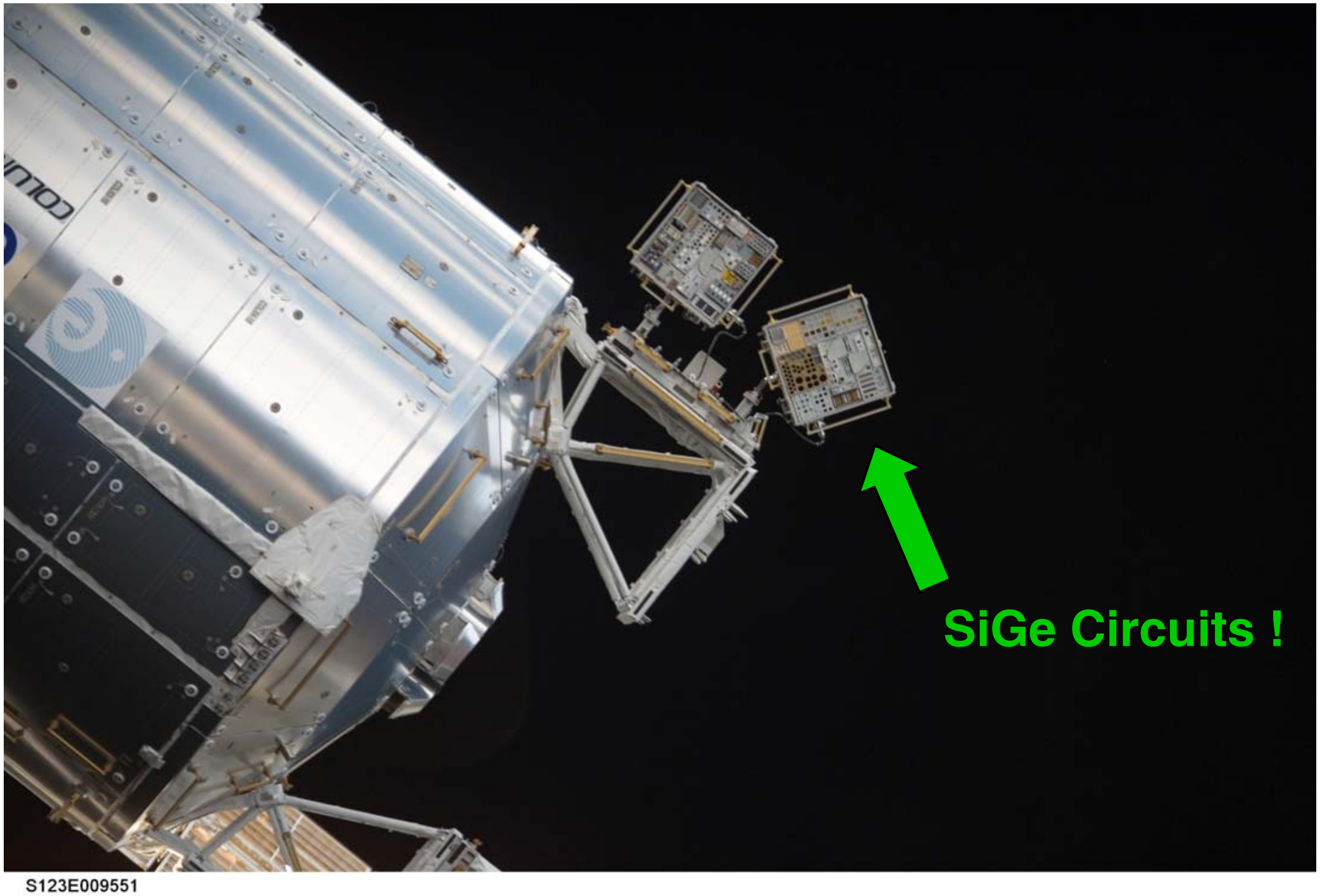
SiGe REU Architecture



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 ISS Mission



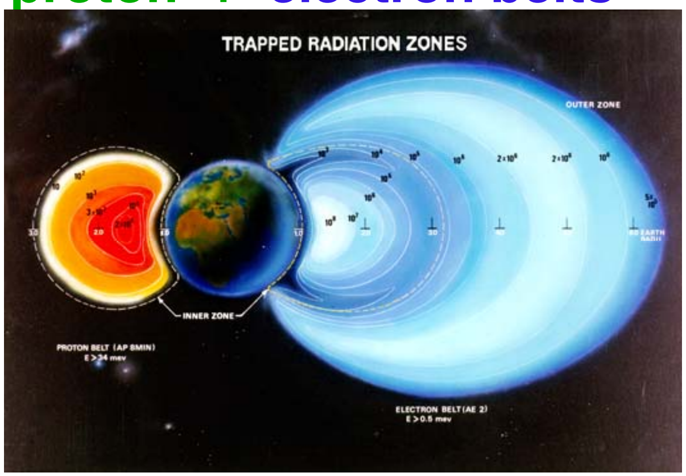
Recent NASA photograph of MISSE-6 after deployment, taken by the Space Shuttle Crew

SiGe For Space Systems

Georgia Institute of Technology

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

proton + electron belts

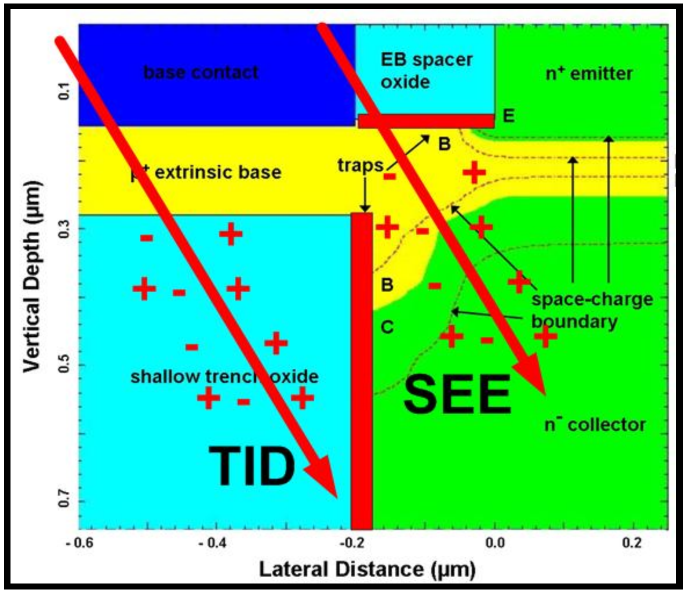


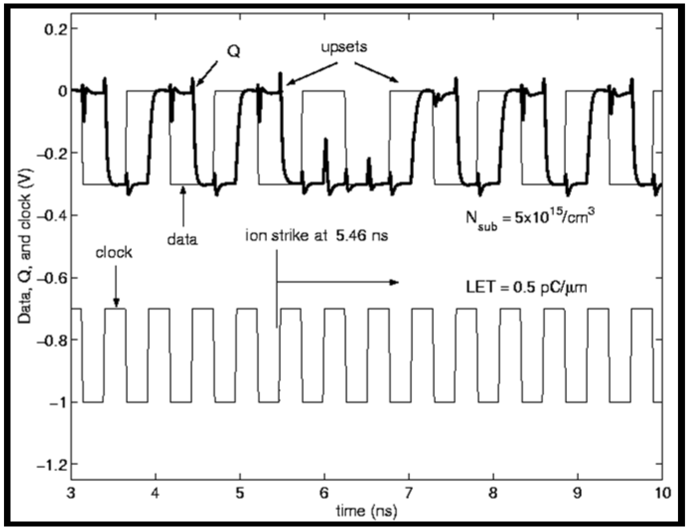
<u>Major Question</u>:
Can SiGe Play a Major Role in Space?

- **Total Ionizing Dose (TID) – ionizing radiation**
  - TID is measured in “rads” (1 rad = 100 ergs per gram of energy absorbed)
  - 100-1000 krad(Si) over 10 years for typical orbit *(300 rad(Si) is lethal to humans!)*
- **Single Event Upset (SEU) – high energy heavy ions**
  - measure data upset cross-section (σ) vs. Linear Energy Transfer (LET)
  - σ = # errors / particle fluence ($ions/cm^2$): LET = charge deposition ($pC/\mu m$)
  - **Goals:** low cross-section + high LET threshold

Radiation Effects

- **Ionization Damage**
  - charged particles + photons
  - oxide charging + interface traps
  - V_T shifts, I_B leakage, circuit bias
- **Displacement Damage**
  - neutral + charged particles
  - vacancies + interstitials
  - dopant de-activation
- **Single-Event Effects**
  - charged particles
  - collection of excess carriers
  - <u>permanent</u>: SEL, SEB, SEGR
  - <u>transient</u>: SET, **<u>SEU</u>**, MBU



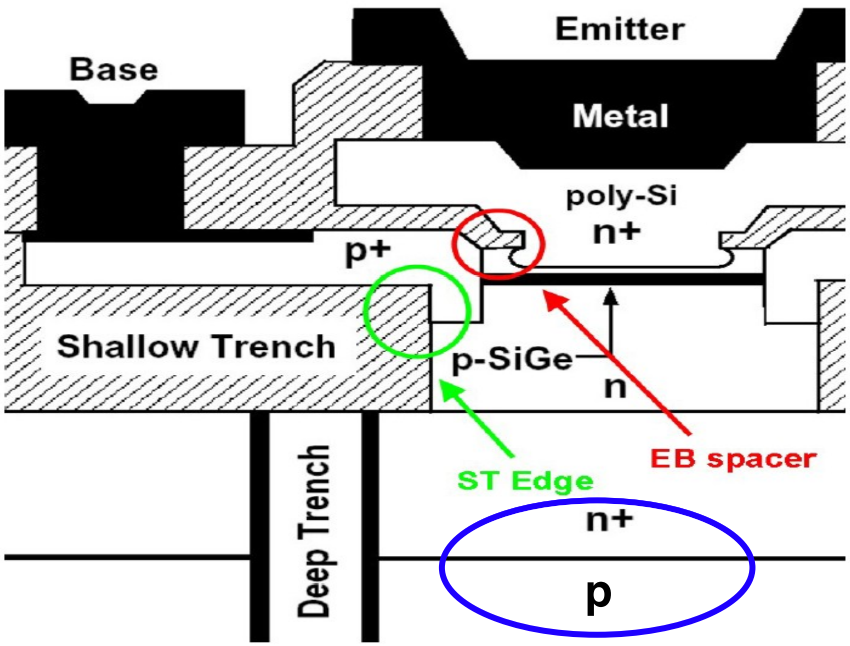


Radiation Experiments

(1995-2009)

Georgia Institute of Technology

- **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

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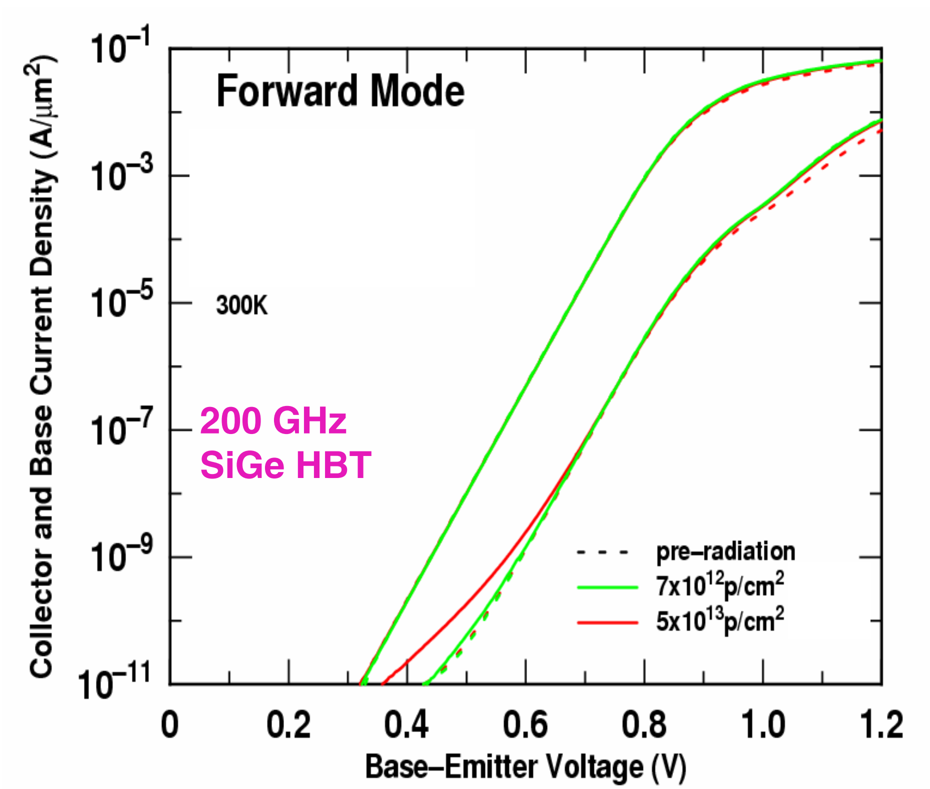
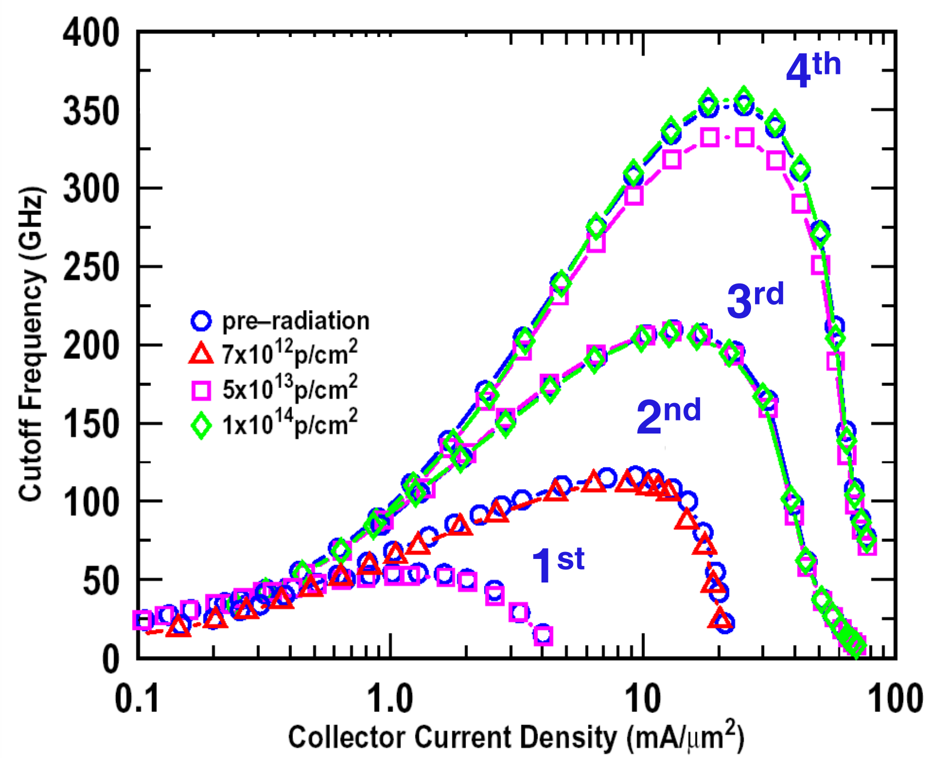
- **Multi-Mrad Total Dose Hardness (with no intentional hardening!)**
  - **- ionization + displacement damage very minimal over T; no ELDRS!**
- **Radiation Hardness Due to Epitaxial Base Structure (not Ge)**
  - - thin emitter-base spacer + heavily doped extrinsic base + very thin base

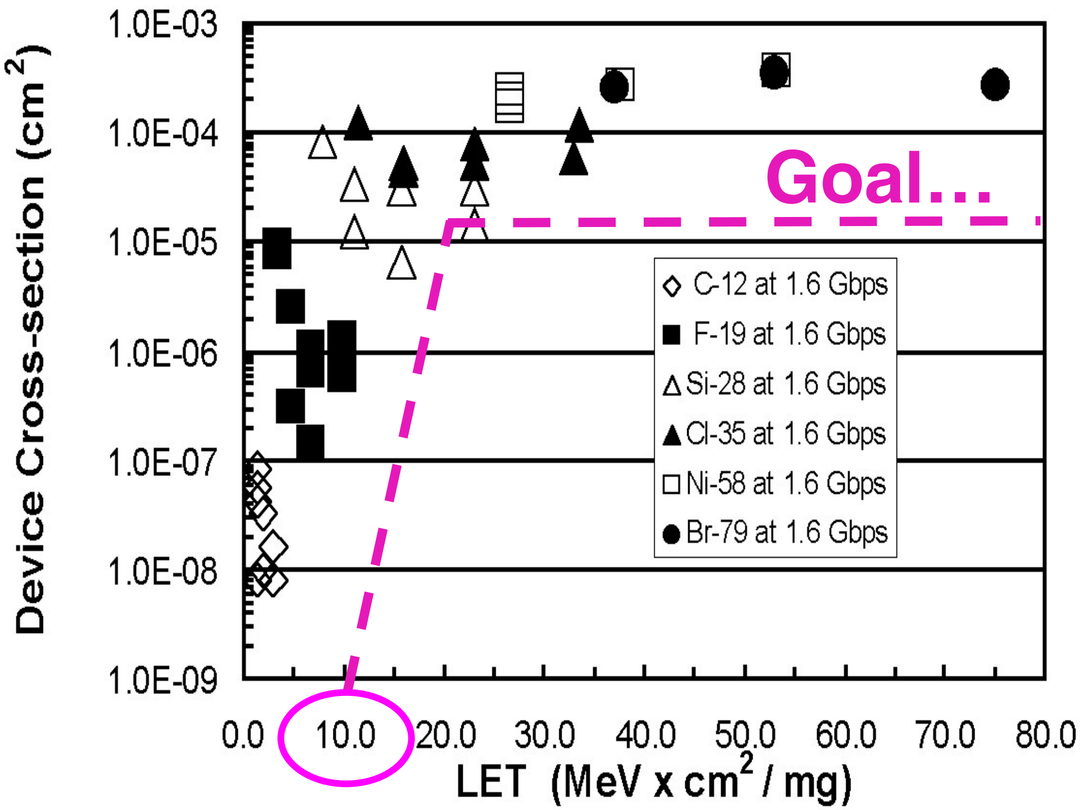




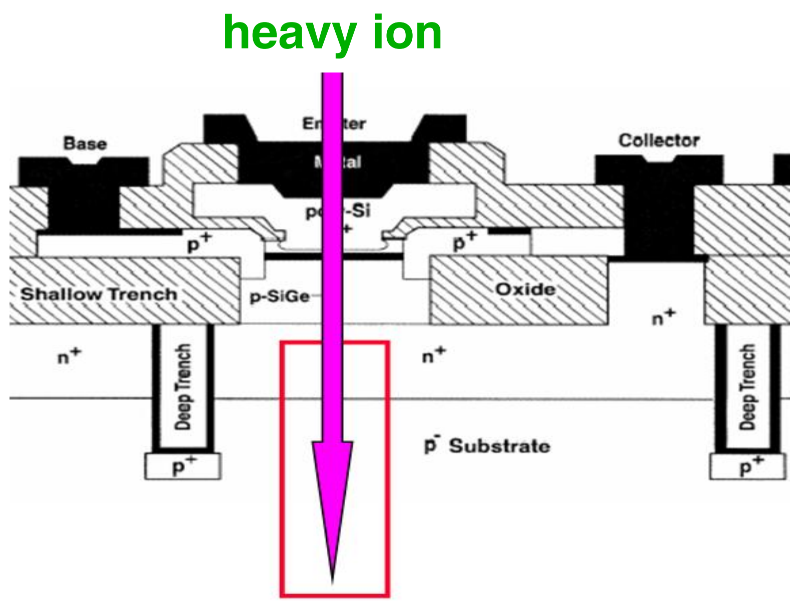
63 MeV protons @ 5×10^{13} p/cm^2 = 6.7 Mrad TID!

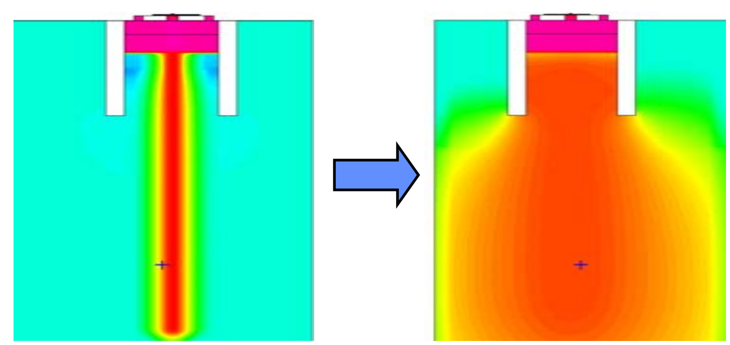
Single Event Effects

- **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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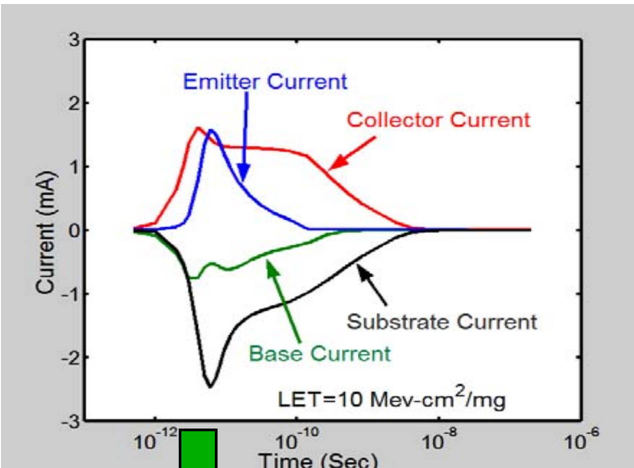
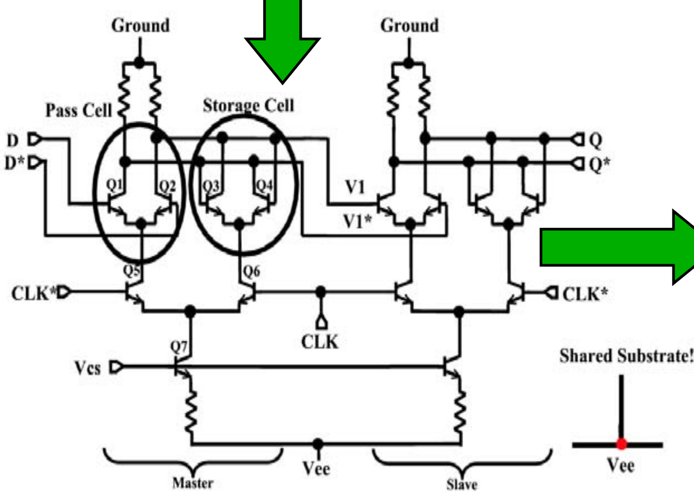
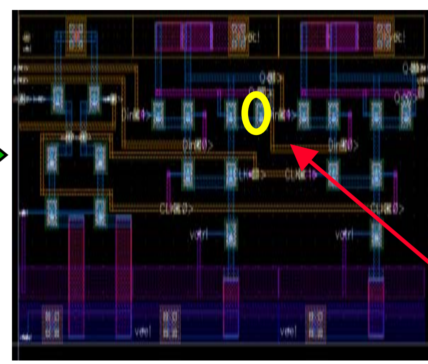
"TCAD Ion Strike"



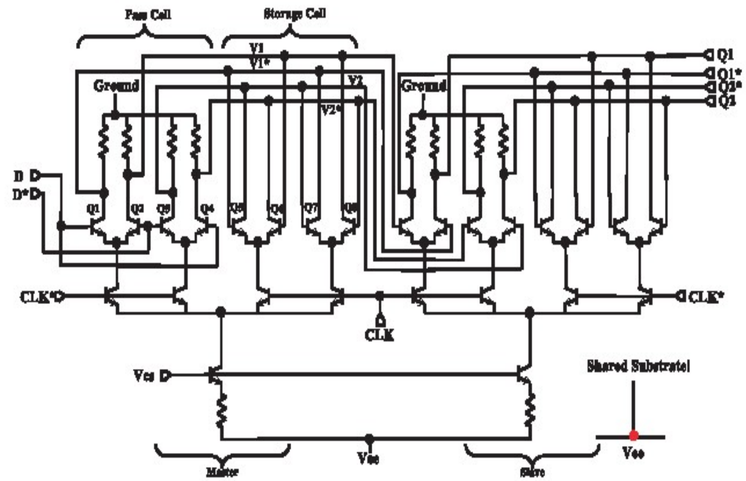


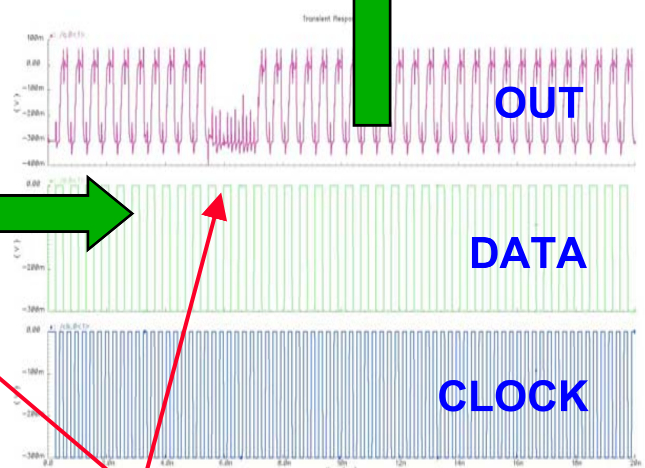
Standard Master Slave Latch

SEU "Soft"



New RHBD SiGe Latch

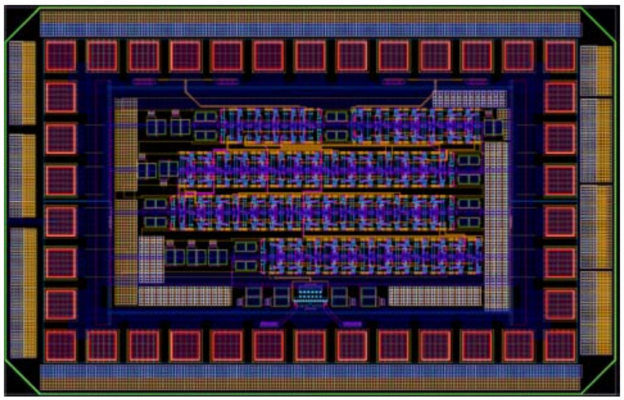


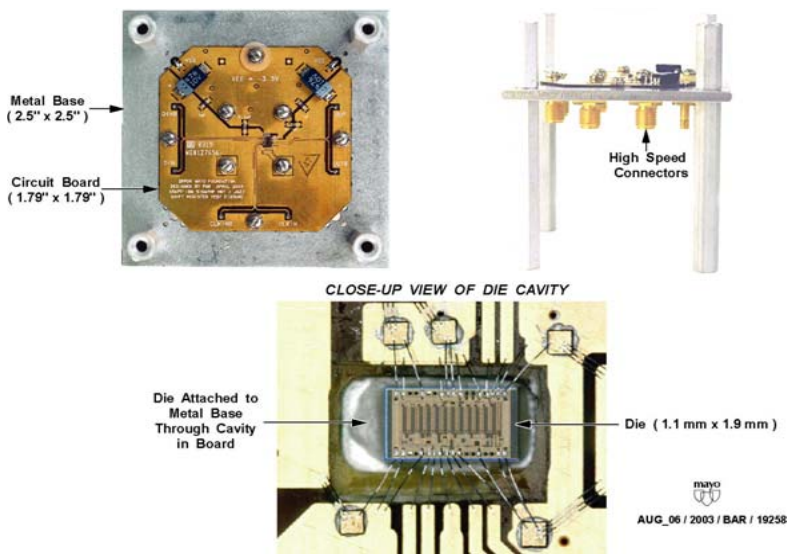


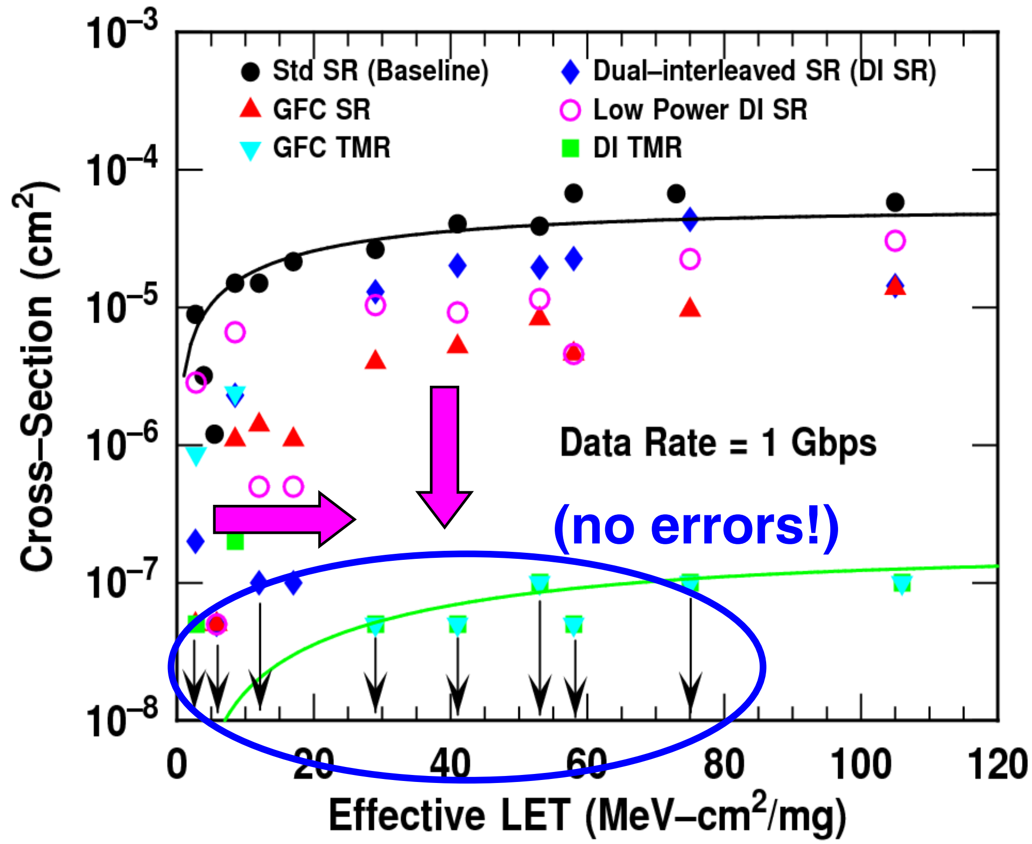
UPSETS

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!

Outline

- Some Reminders on SiGe
- Scaling Trends and Performance Limits
- Emerging Application Opportunities for SiGe
- Extreme Environment Electronics
- Using SiGe in a Radiation Context
- **Cryogenic Operation of SiGe HBTs**
- **Cryogenic Operation of CMOS**
- **Summary**

SiGe HBTs for Cryo-T

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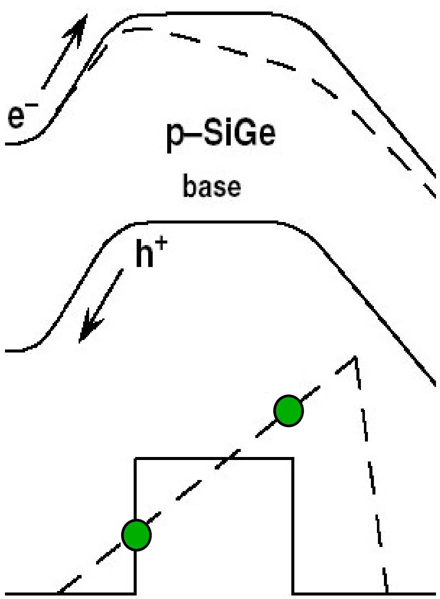
The Idea: **Put Graded Ge Layer into the Base of a Si BJT**

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 ⬆)



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

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

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

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

SiGe HBTs at Cryo-T

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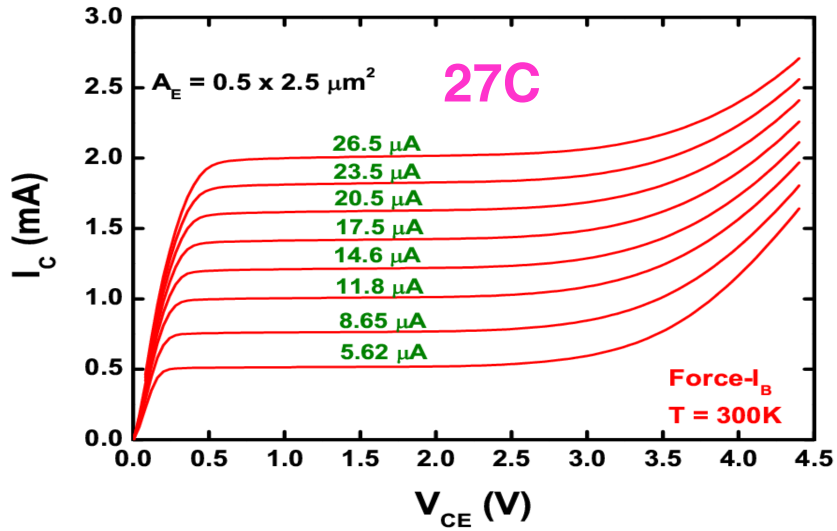
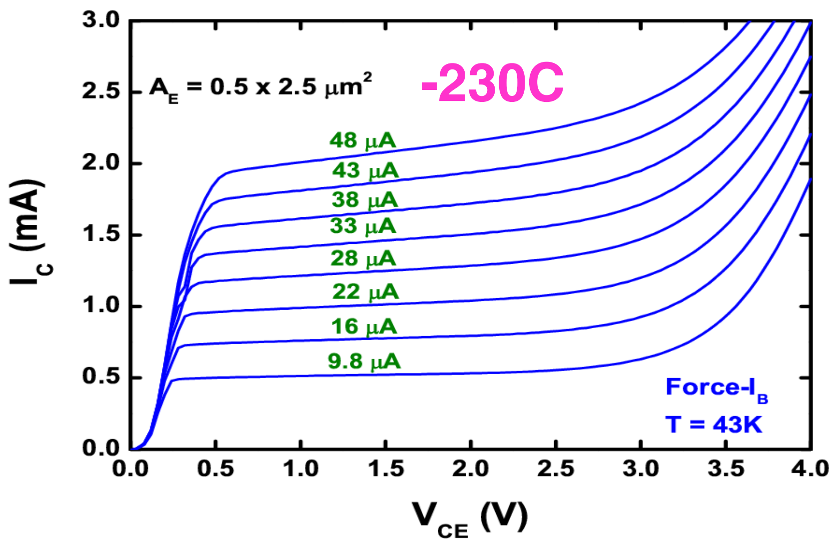
dc





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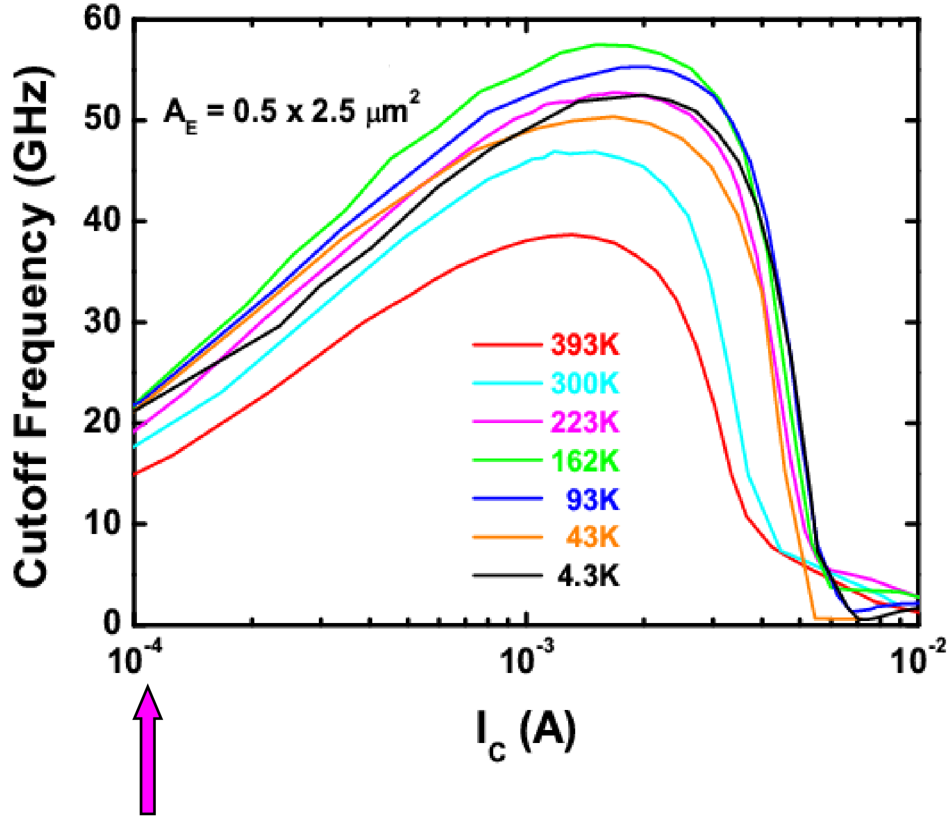


SiGe Exhibits Very High Speed at Very Low Power!

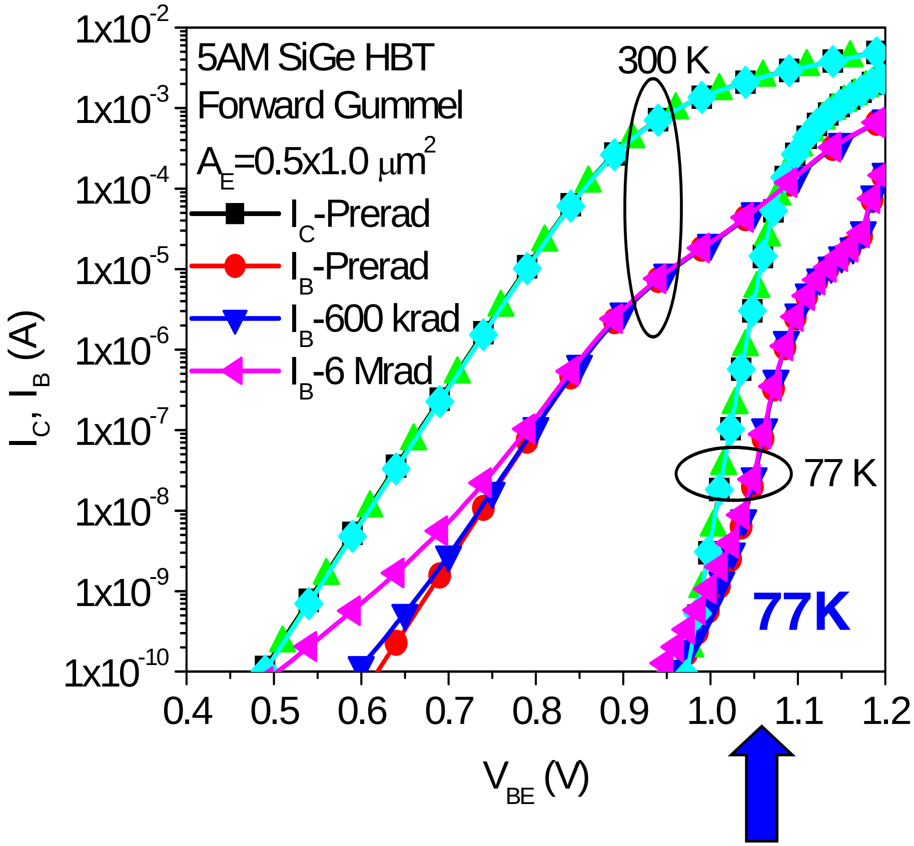
First Generation SiGe HBT

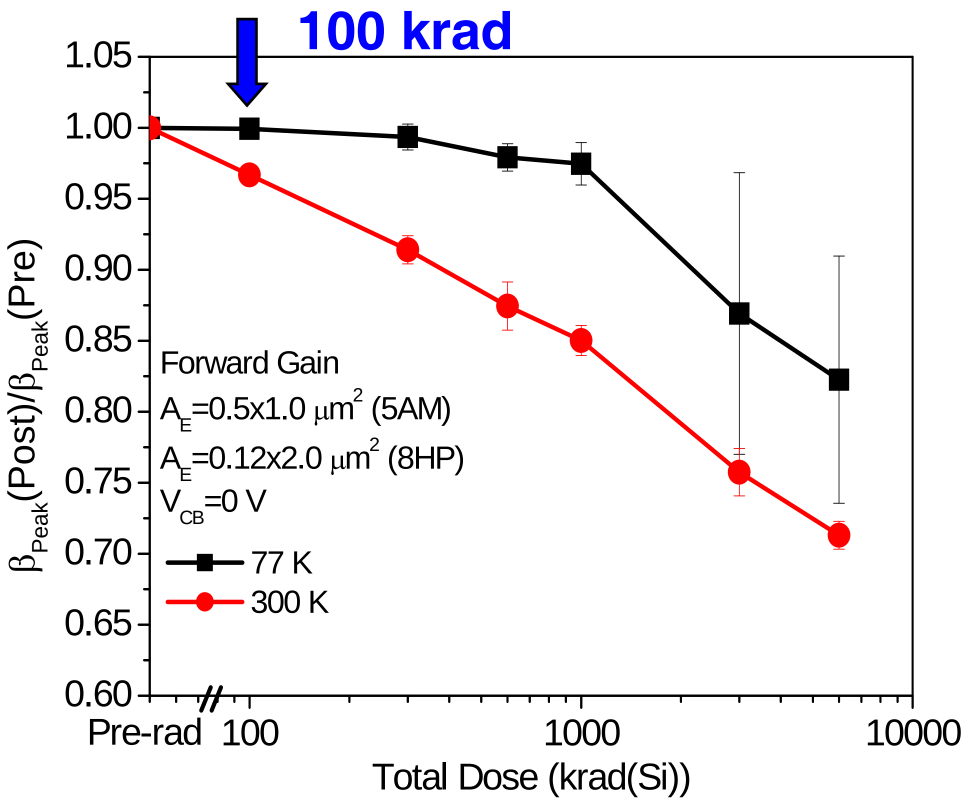
Cryo-T Radiation

First 77K Proton Irradiation Experiment in SiGe Technology

- 63 MeV protons at UC Davis

- **Radiation Damage Smaller at 77K Than at 300K (great news!)**



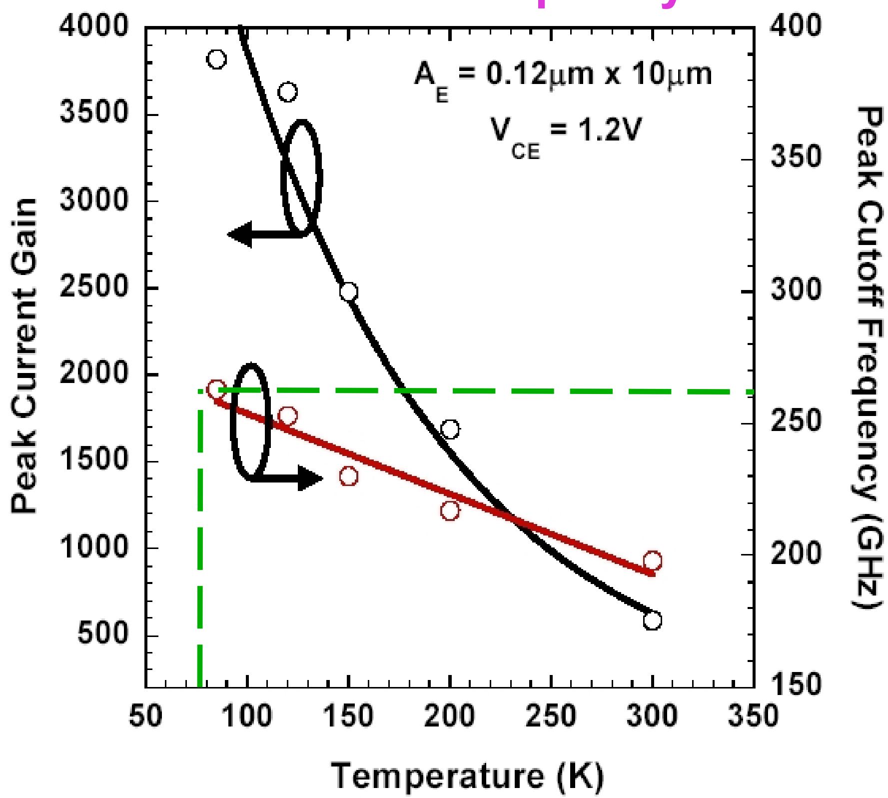


no change in peak β at 100 krad at 77K!

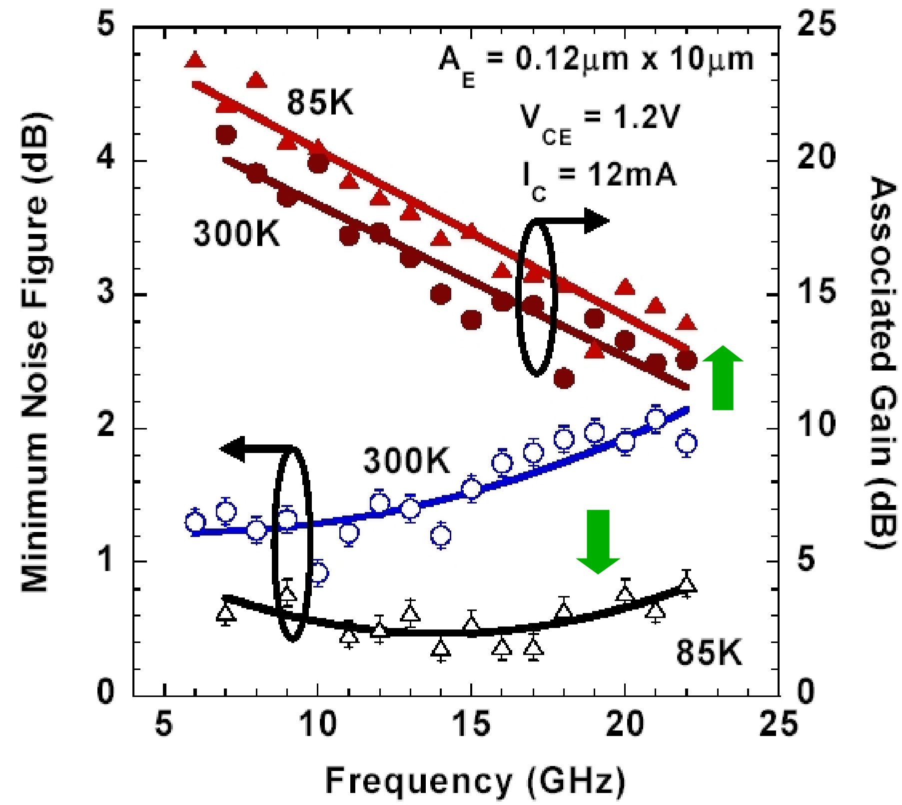
Impact of Scaling

- 200 GHz SiGe Technology Works VERY Well at 77K
- At 85K, f_T > 250 GHz + NF_{min} = 0.30 dB (G_{ass} = 17 dB) at 14 GHz!

Gain and Frequency



Noise

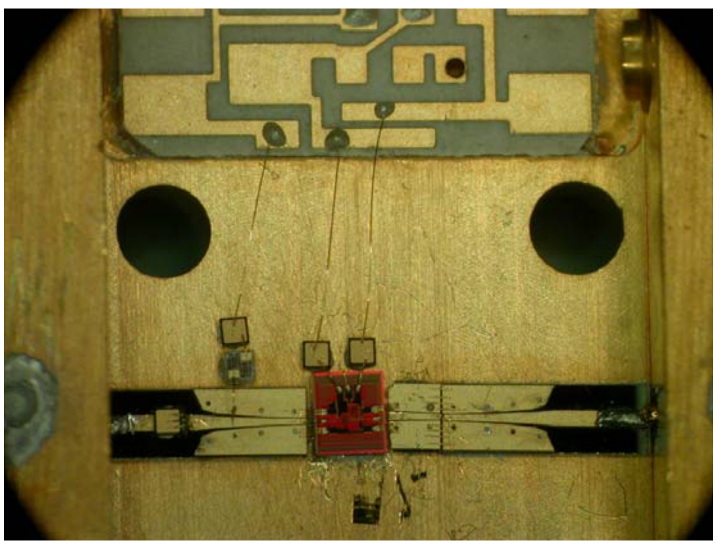


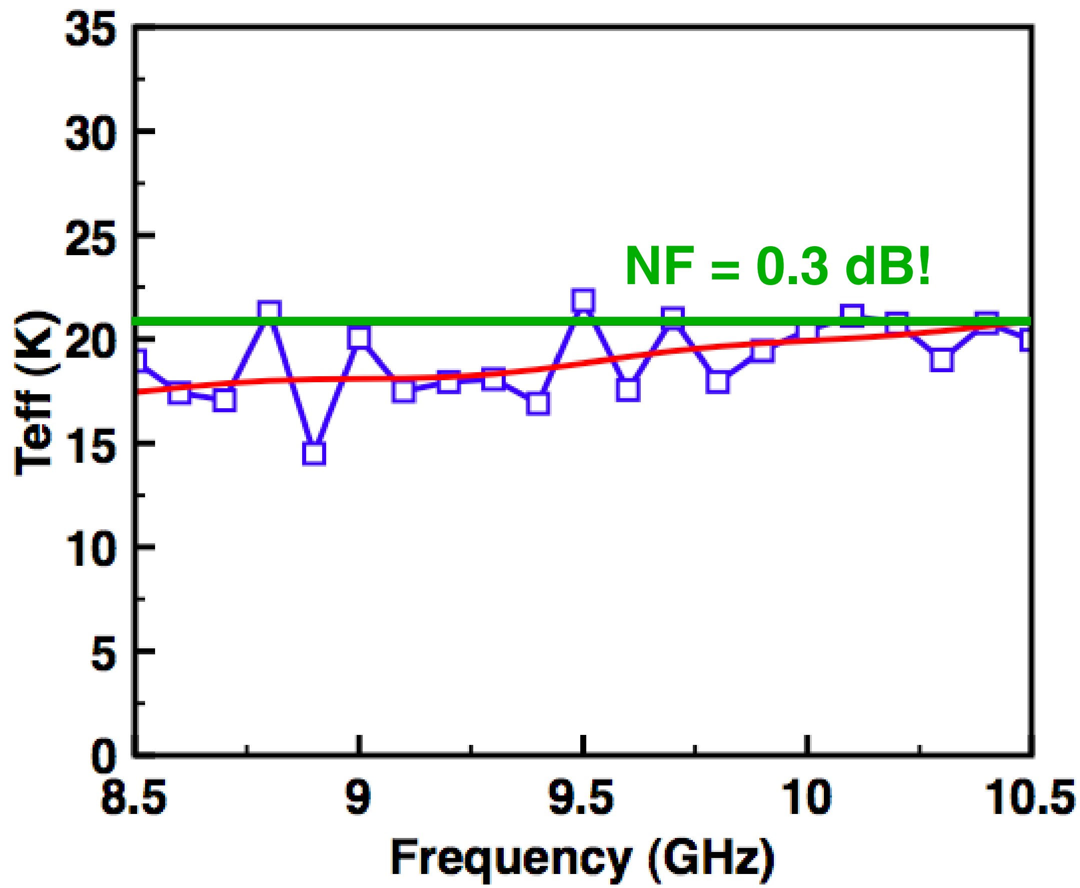
Will Support Cryo-T mm-wave Circuits!

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





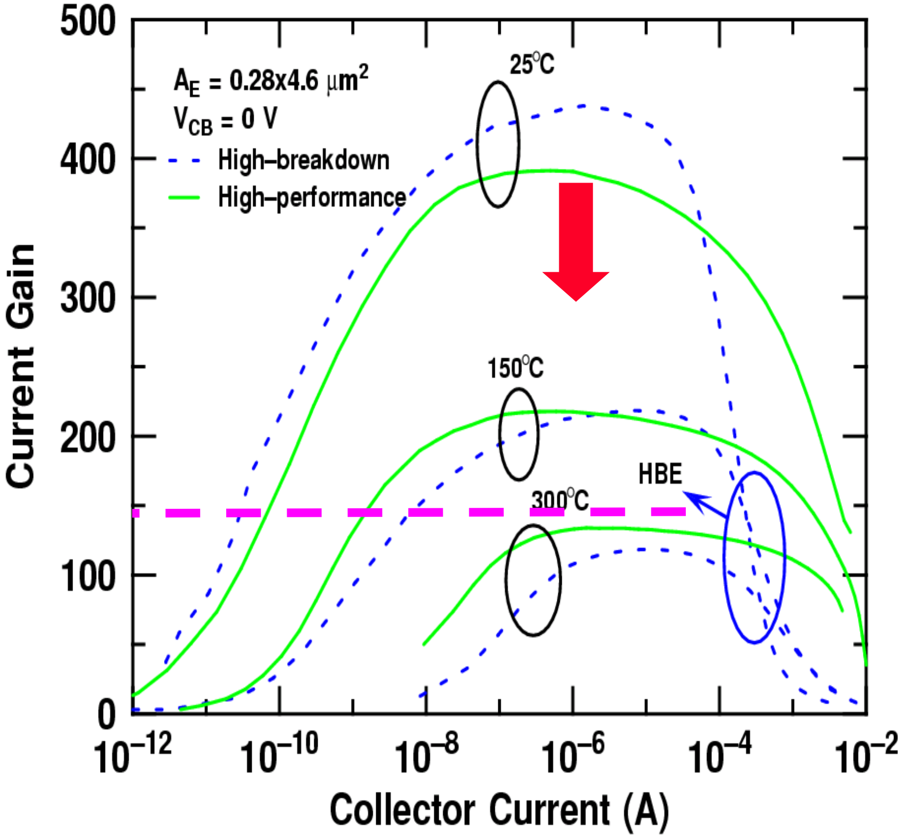
Collaboration with S. Weinreb, Cal Tech

This SiGe LNA is also Rad-Hard!

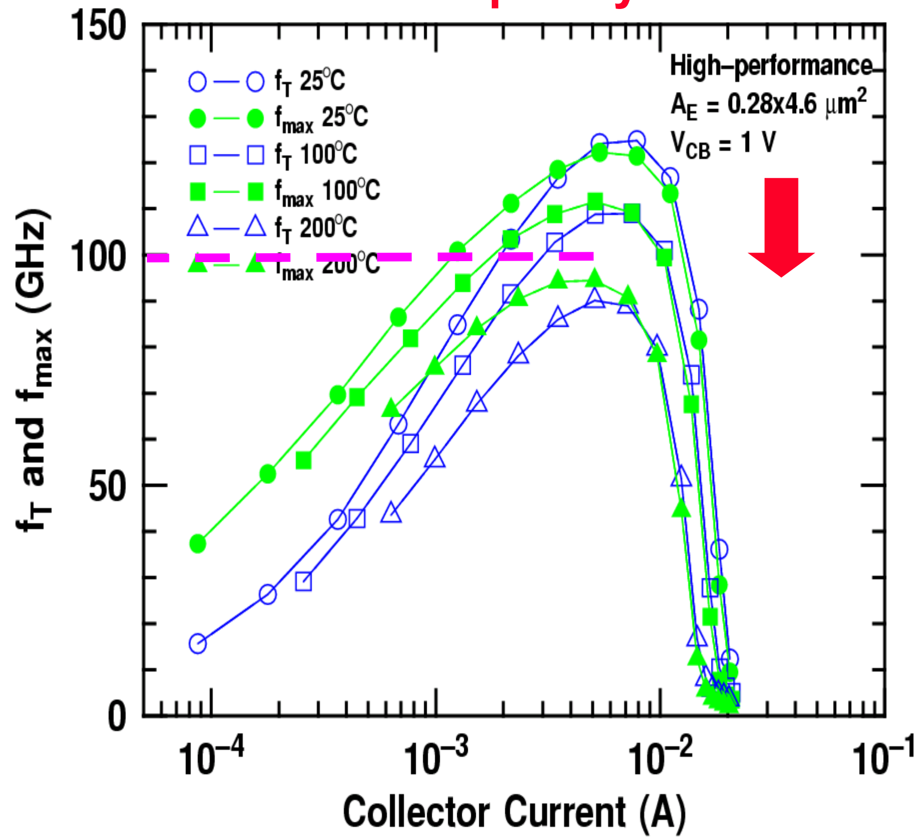
SiGe at High-T? (200-300C)

- Degradation, But Plenty of Performance Left!
- Device Reliability Looks Fine
- <u>Just in</u>: Robust Operation @ 300C for Selected Circuits

Gain



Frequency



Outline

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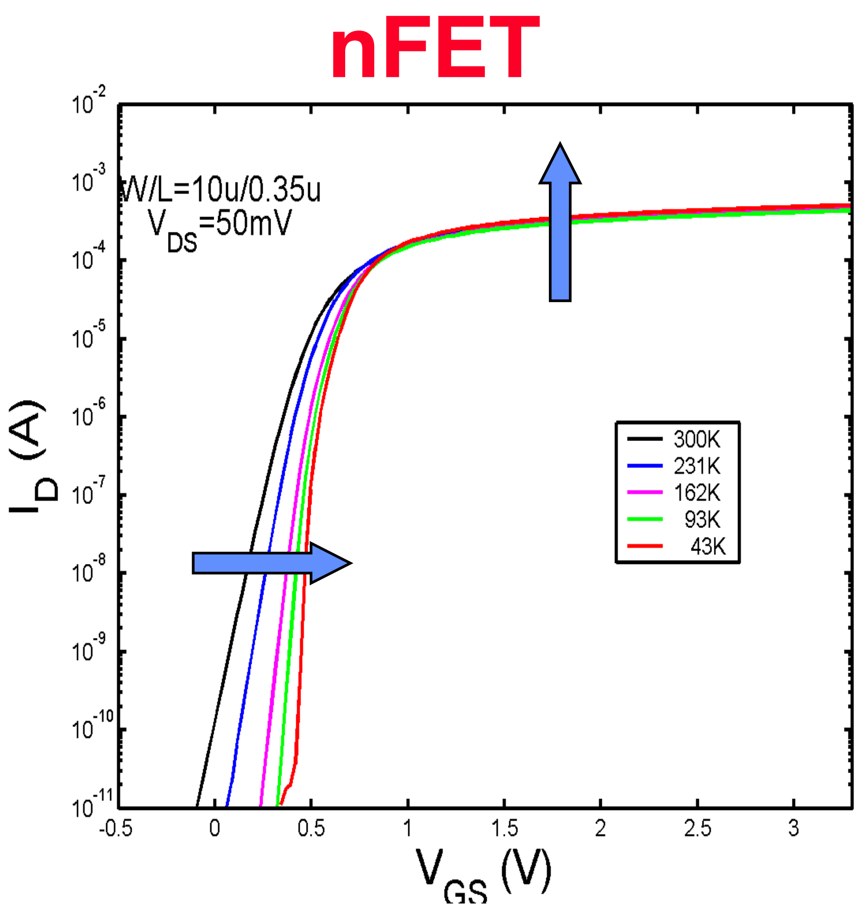
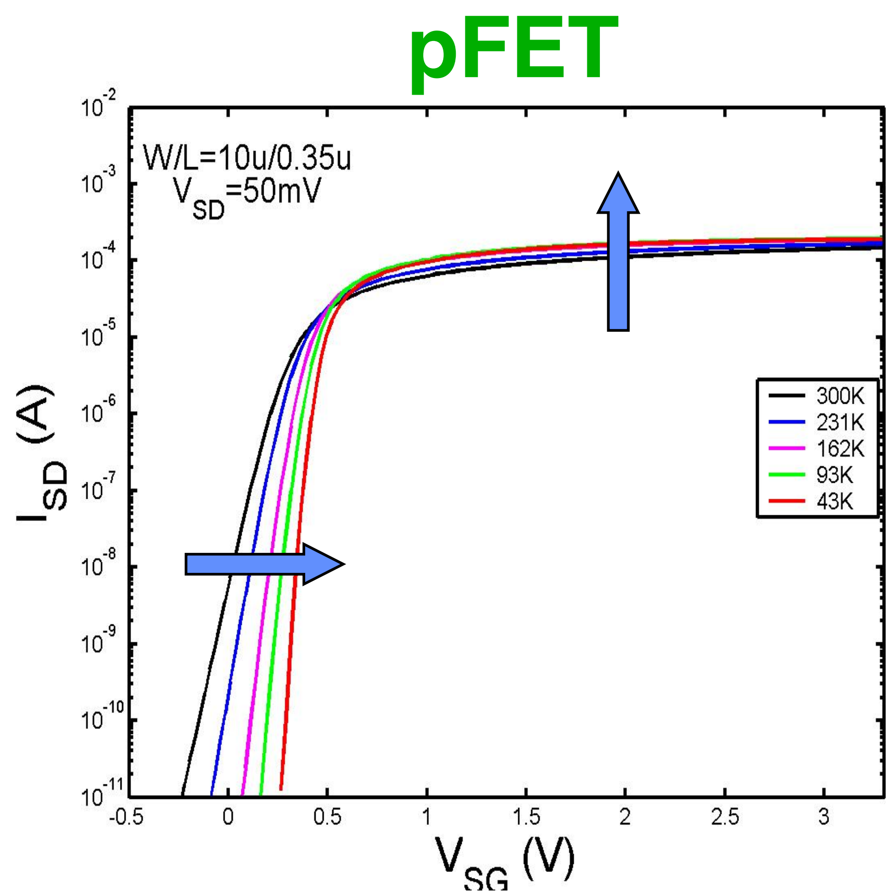
- **Cryogenic Operation of CMOS**
- Summary

Sub-Threshold Behavior

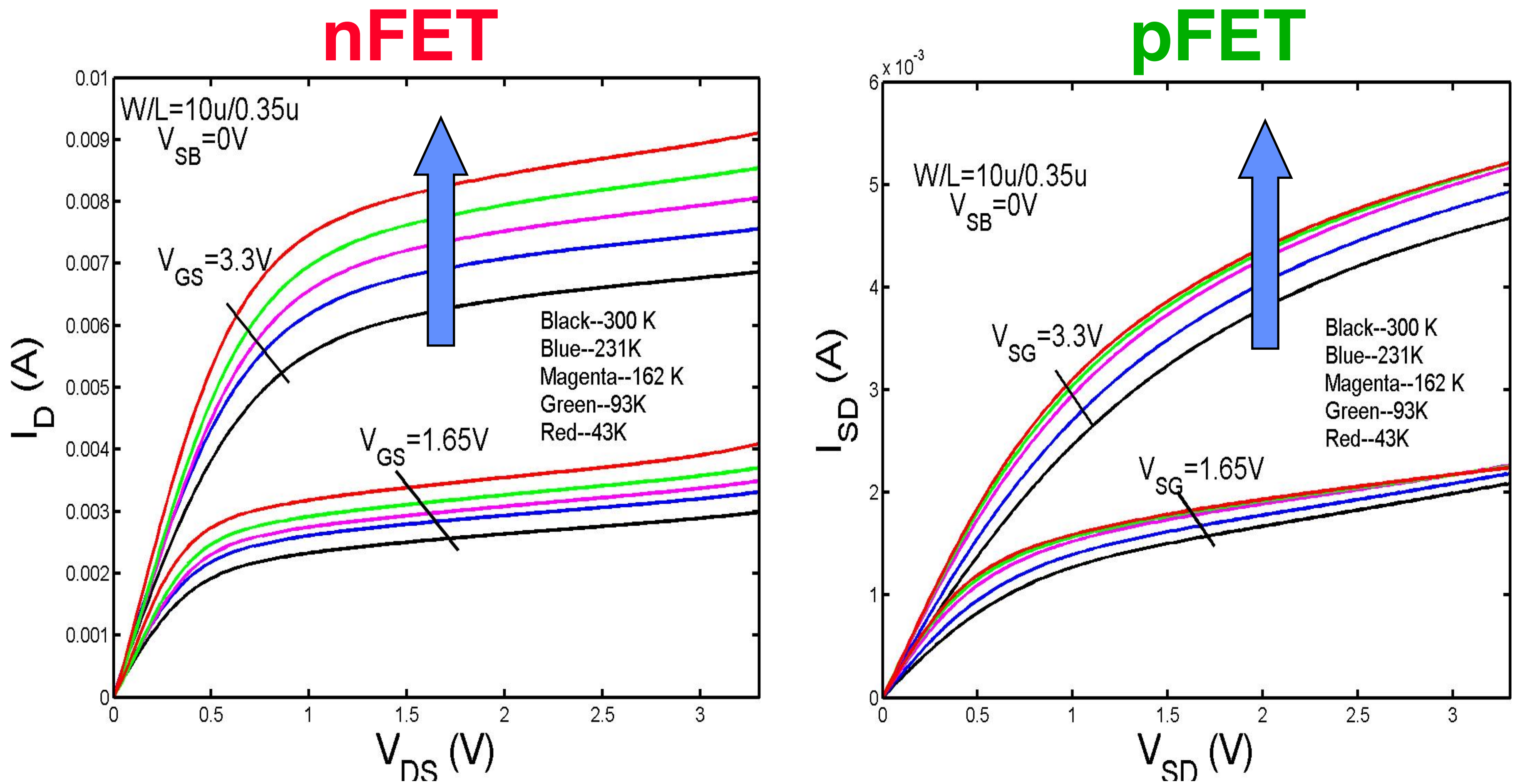
- First Generation SiGe BiCMOS (0.35 um L_{eff})
- V_T and Subthreshold Swing Increase with Cooling
- Output Drive Improves with Cooling





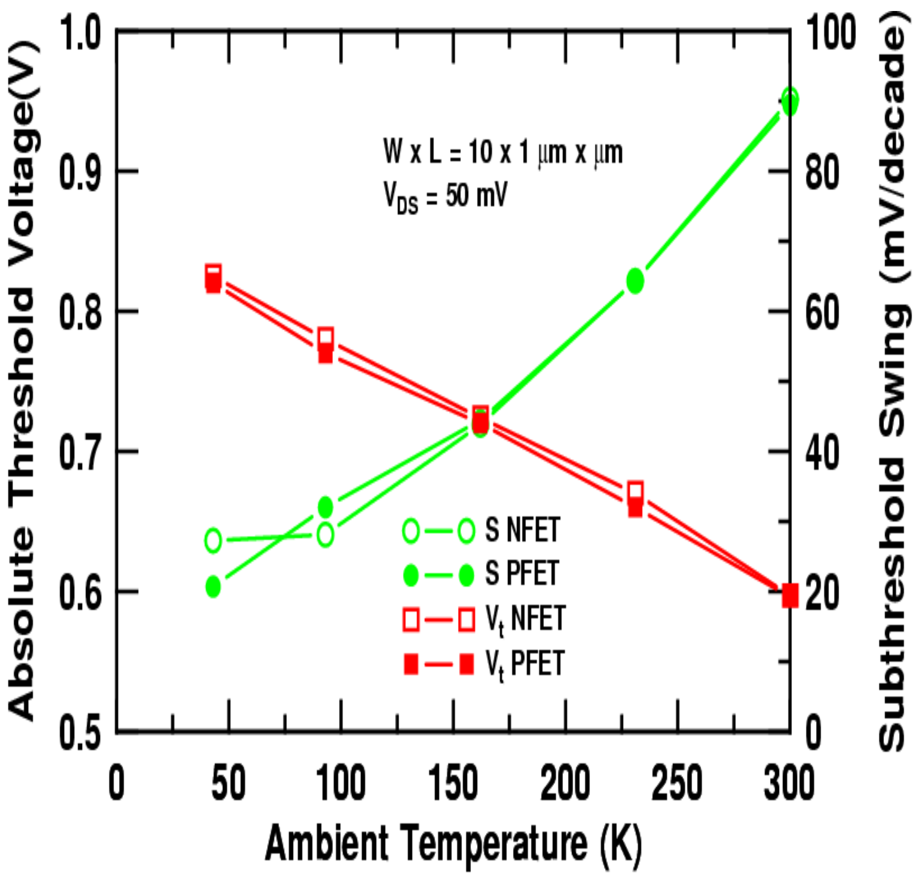
Output Characteristics

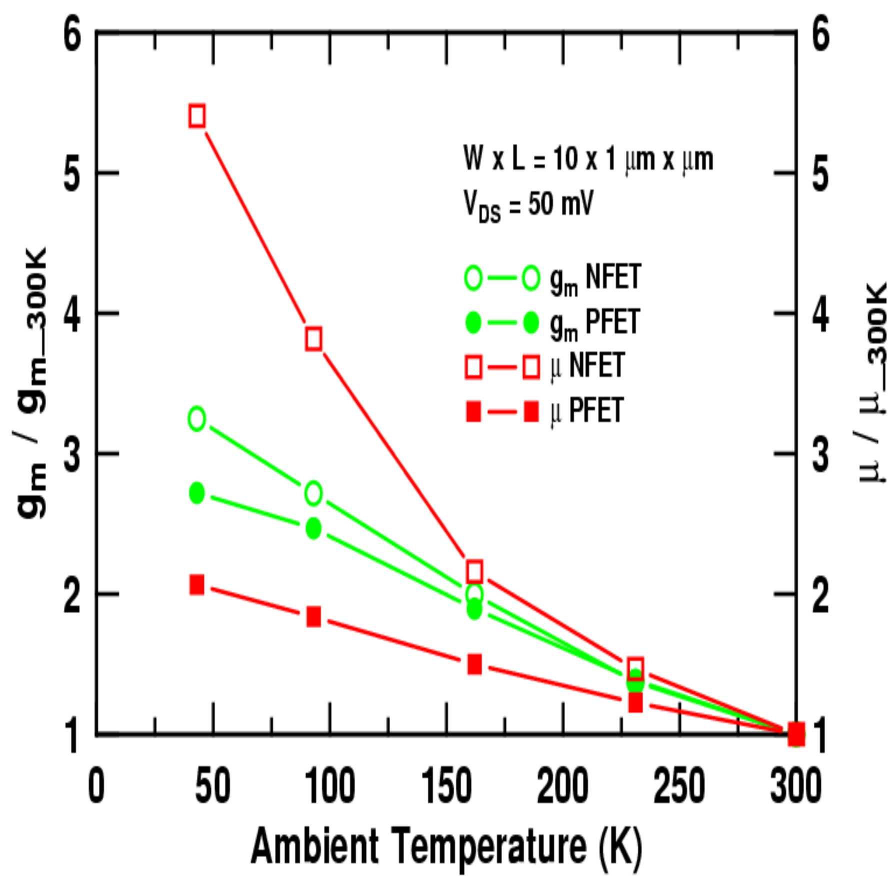
- **Improved Current Drive With Cooling**
- **Modest Degradation in Output Conductance**



T Dependence

- V_T Increases with Cooling / S Decreases with Cooling
- g_m Increases with Cooling / μ Increases with Cooling

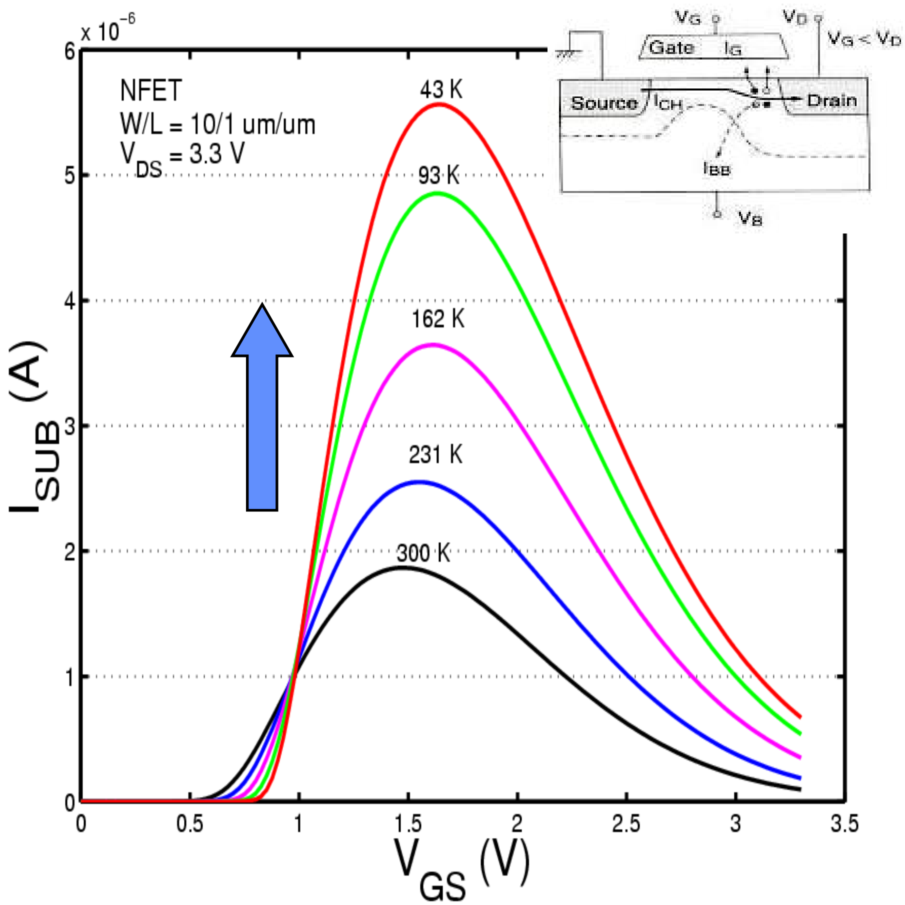


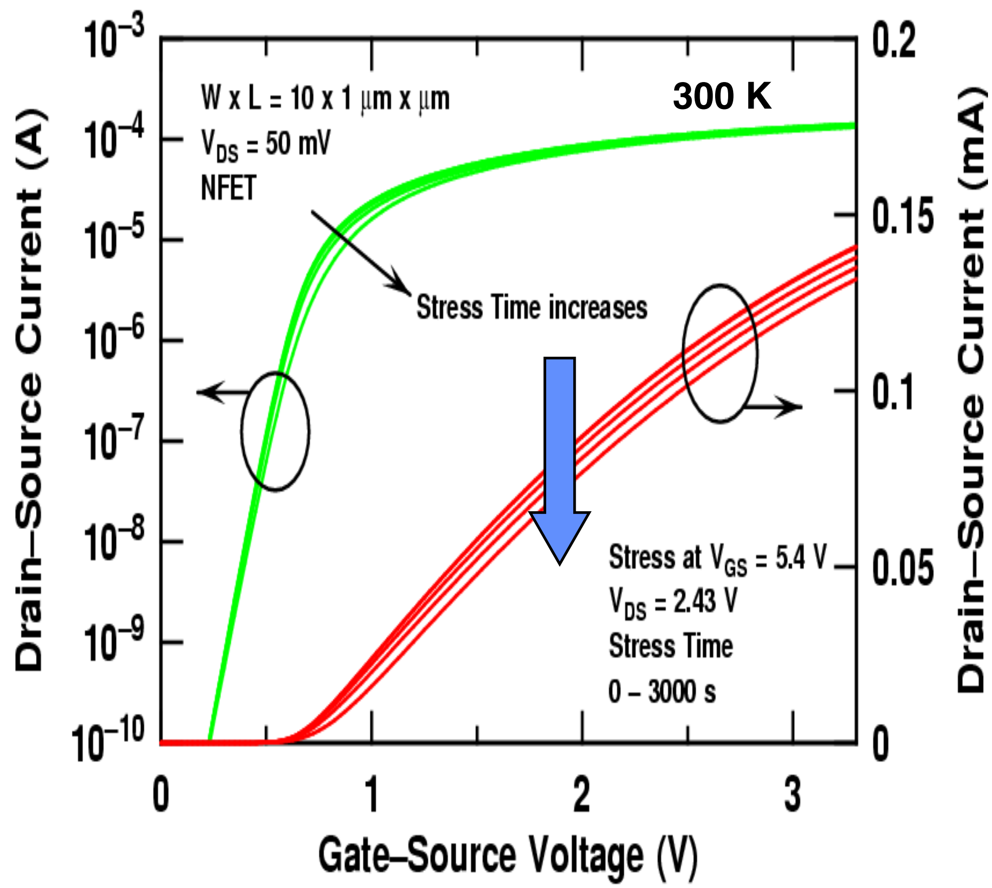


How About Reliability?

Device Reliability

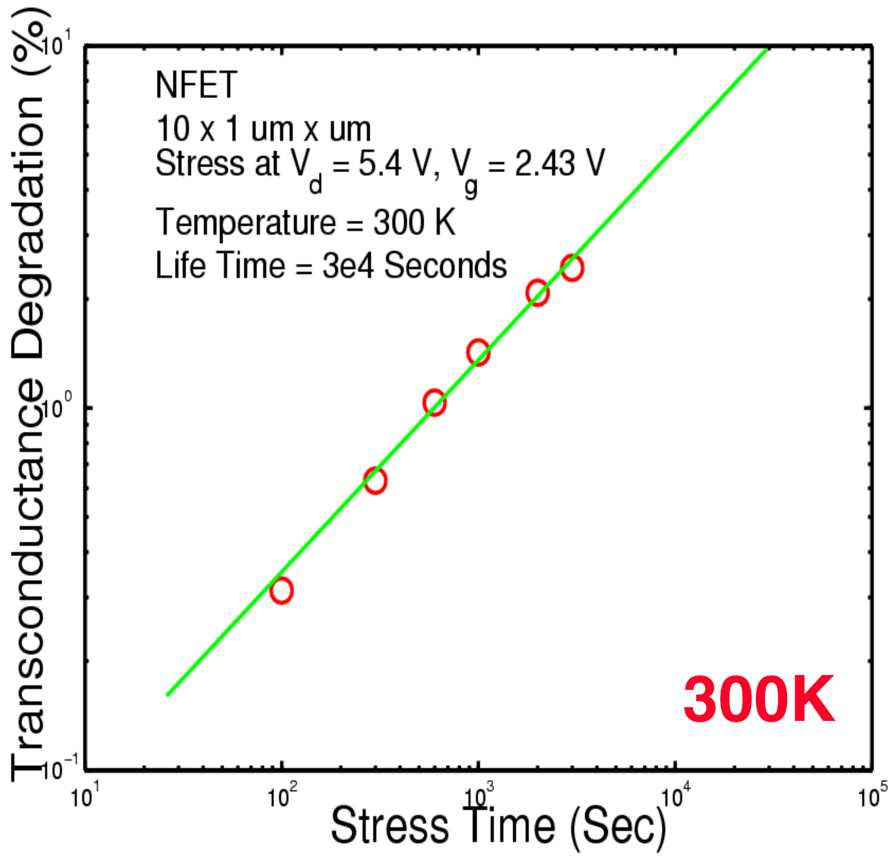
- I_{SUB} is a Good Monitoring Parameter for HCE
- After Stress, I_d and g_m Decrease While V_T and S Increase

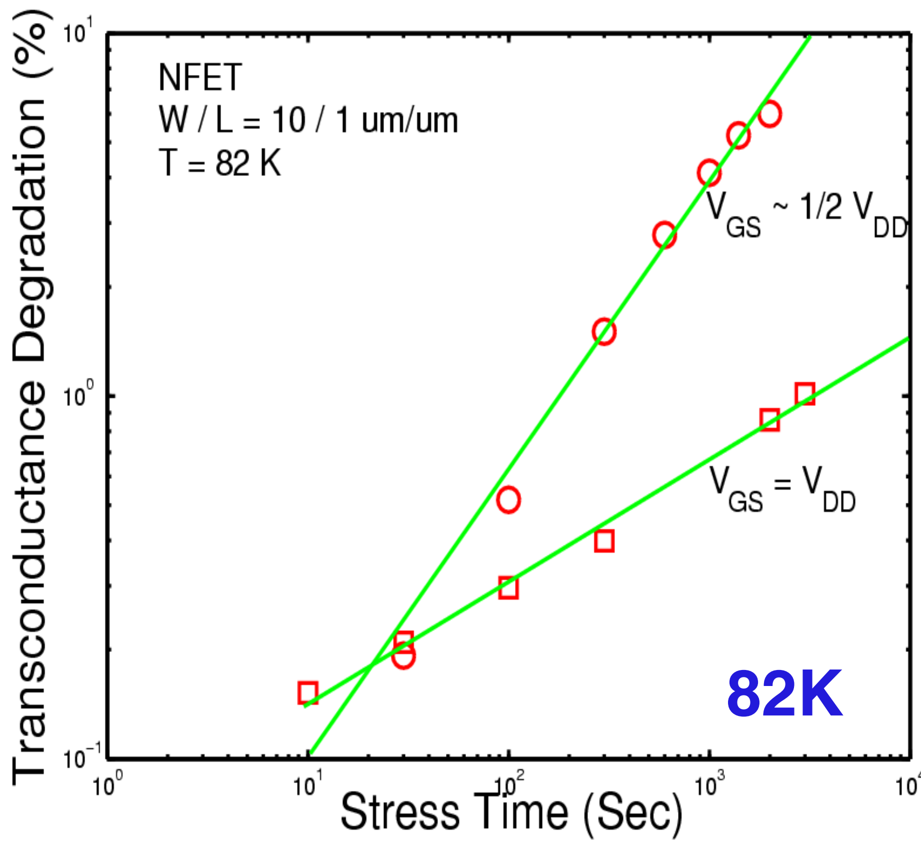




Lifetime Extraction

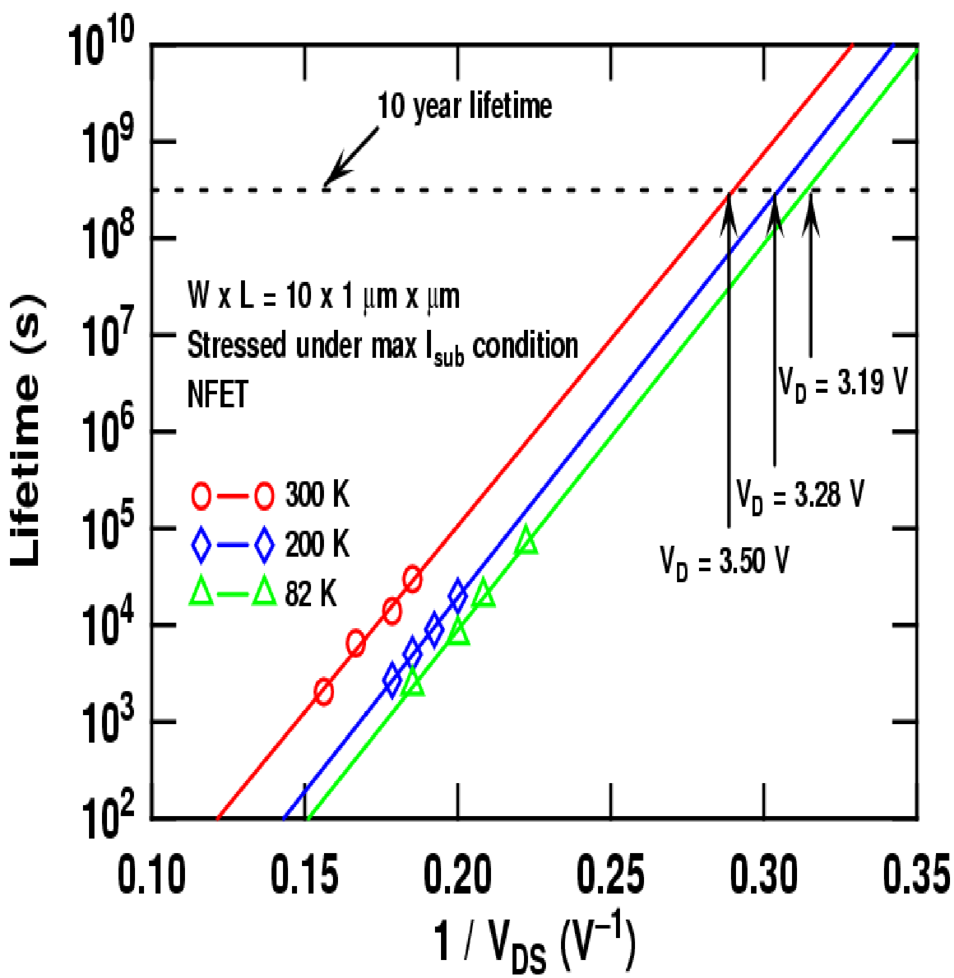
- Both Post-Stress Δg_m and ΔI_{DS} Are Linear With Stress Time
- Extracted Lifetime are the Same for Both Δg_m and ΔI_{DS}
- Max I_{SUB} Remains the Worst Stress Condition for Cryo-T

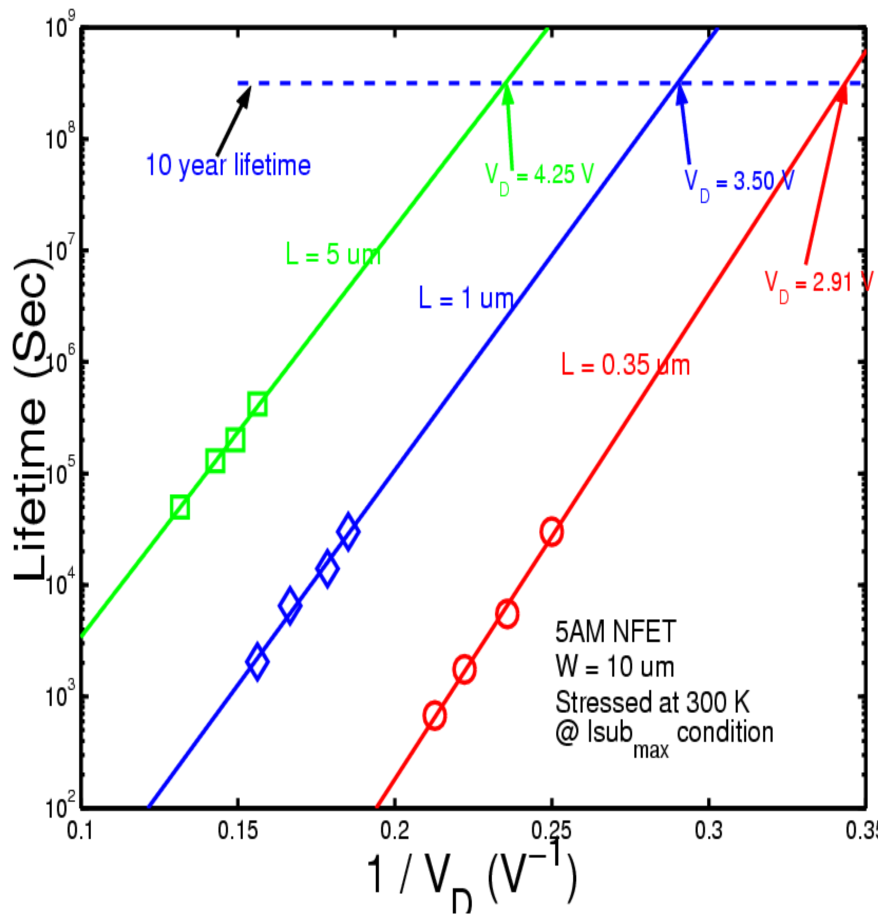




L,T Dependence

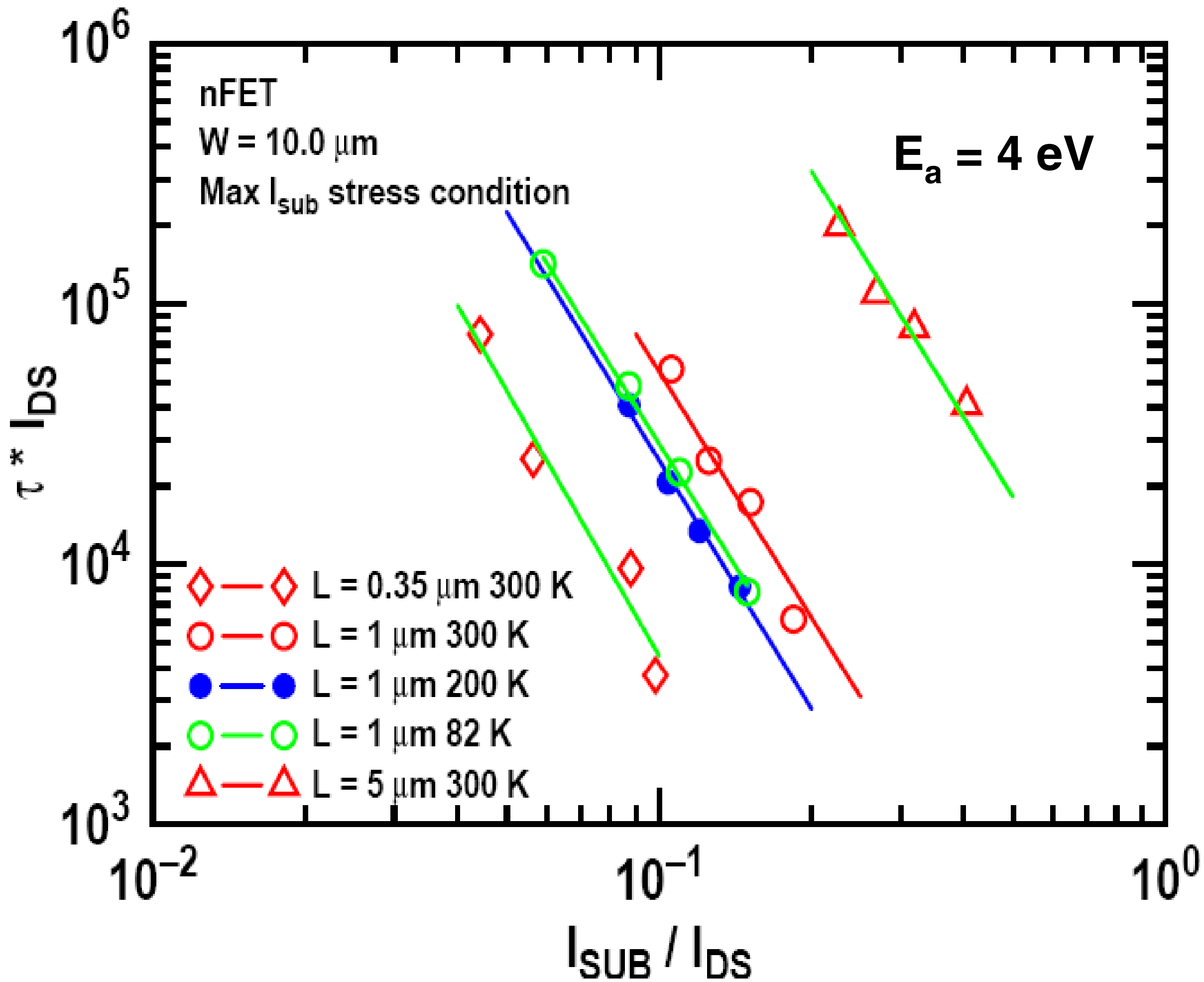
- **Lifetime Decreases with Cooling at Fixed L**
- **Lifetime Decreases With L at Fixed T (Mitigation Path)**





Damage Mechanisms

- **Calculated E_a Values Agree Well With Literature Data**
- **Same Degradation Mechanism Across all the T and all L**



90 nm CMOS at Cryo-T

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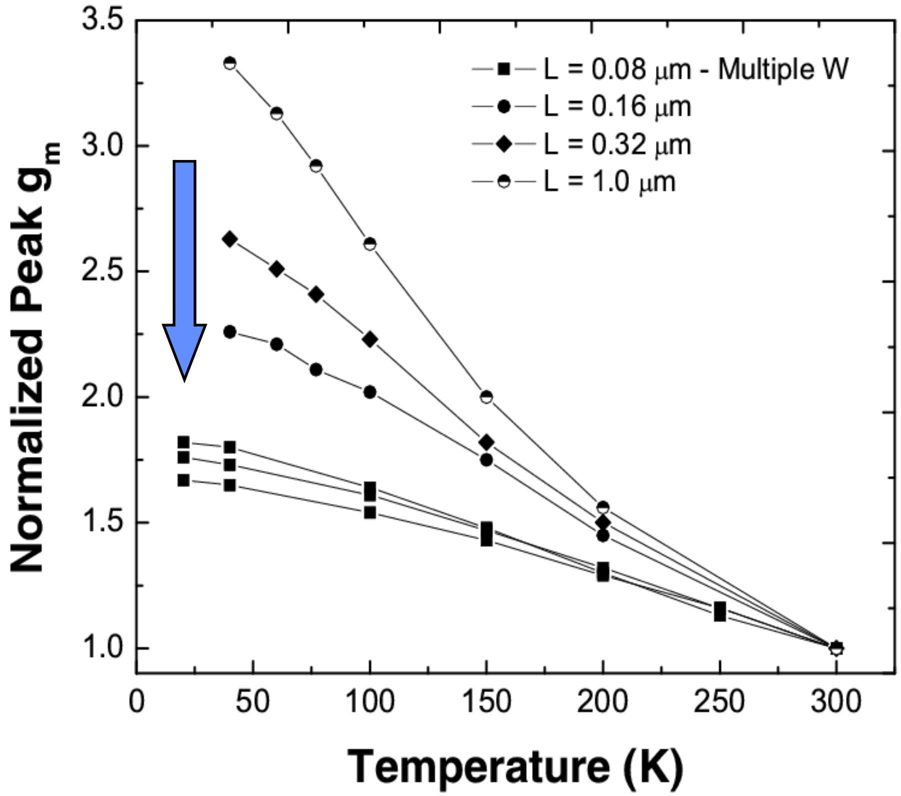
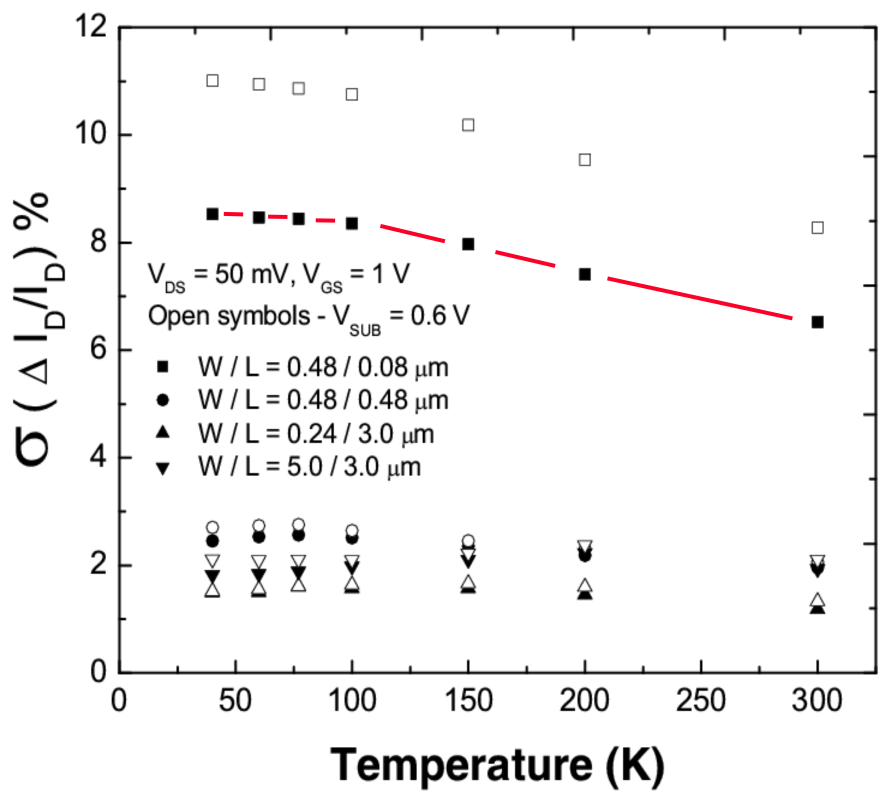
- 90 nm Bulk CMOS (IBM)
- Improvement in Peak g_m With Cooling
- Less Improvement for Minimum L_g
- Device-to-Device Mismatch Worsens With Cooling





BSIM4 Modeling (77K)

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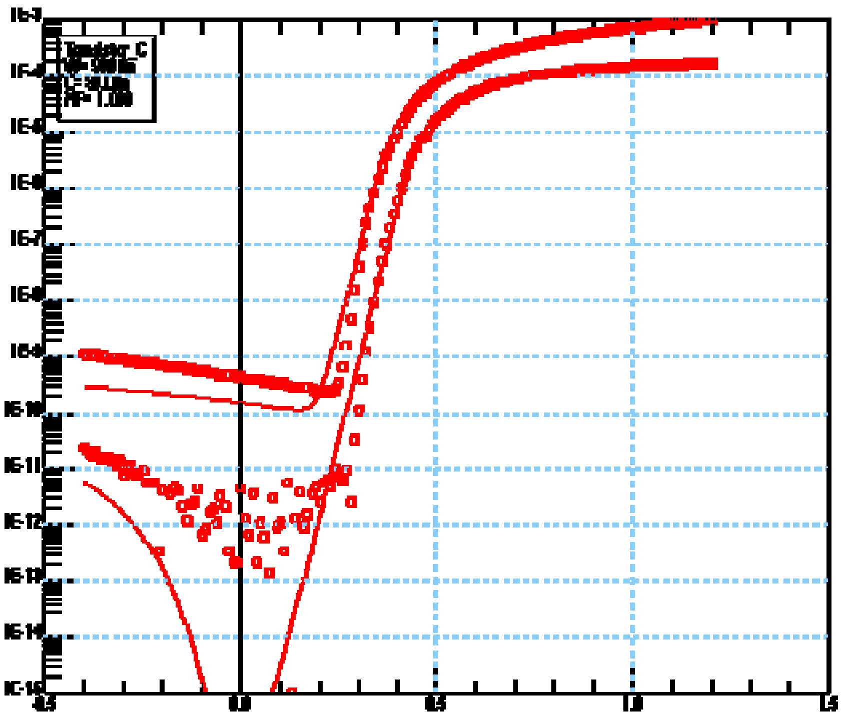
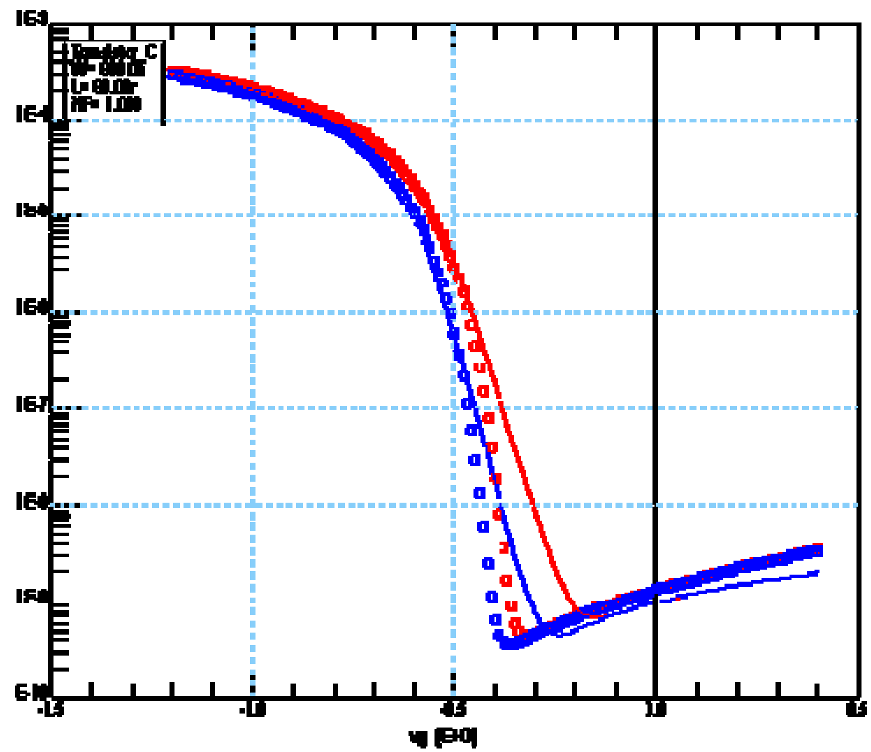
- Design Kit Models Are Only Rated From -55C to 125C
- Models AT T are MUCH Easier Than Models OVER T
- Significant Effort Needed To Develop Calibrated Models

nFET at 77K

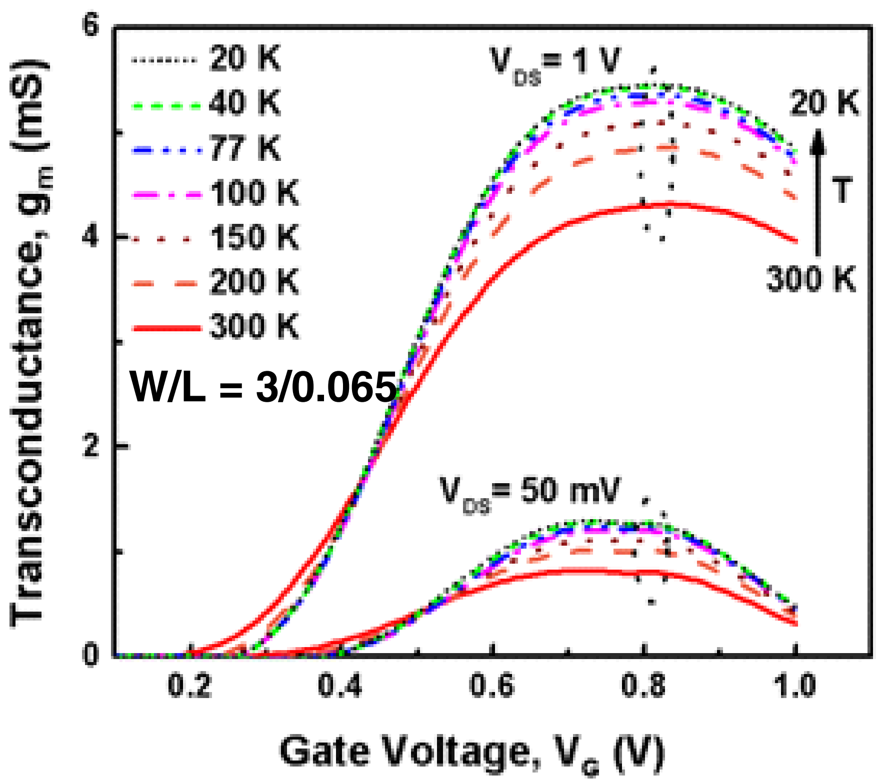


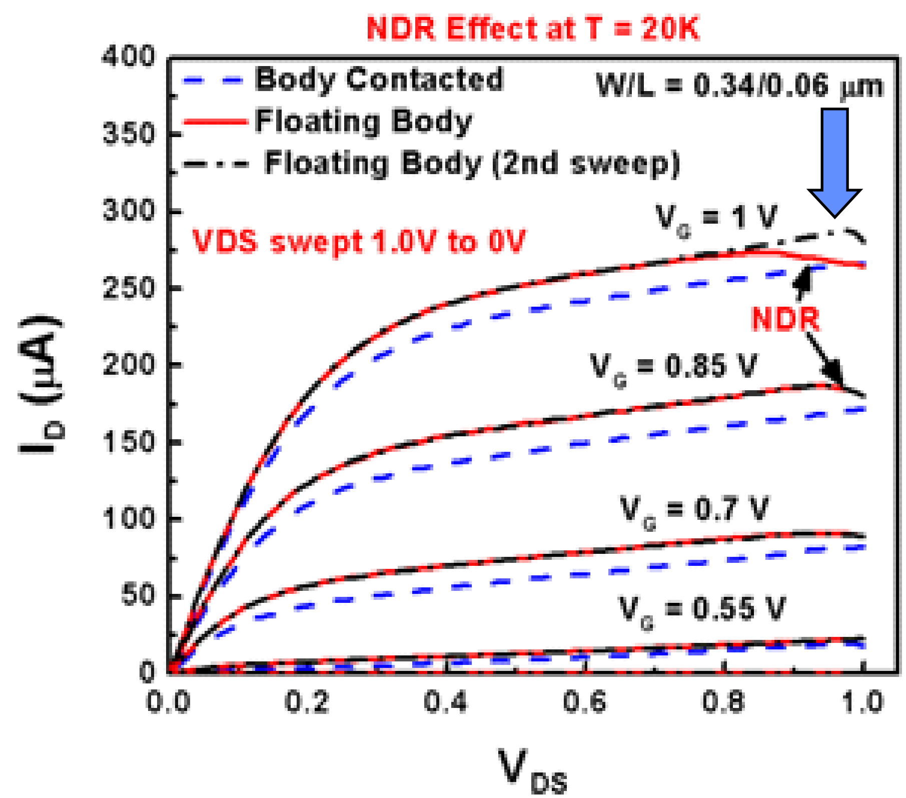
pFET at 77K



65nm CMOS on SOI

- 65 nm CMOS on SOI (IBM) (Uses Strain Engineering)
- Improvement in Peak g_m Down to 20K
- NDR Effect Observed at Cryo-T Due to Floating-body Effects





65 nm Strained Si CMOS

Summary

The Global Landscape:

- **The Emerging Communications Infrastructure**
  - frequency bands pushing upward over time (stresses device design)
  - integration of RF + digital + analog + passives increasingly important
  - SiGe HBT BiCMOS is well-positioned to address this market

SiGe HBT BiCMOS Technology:

- **The SiGe HBT is the First Practical Bandgap Engineered Device in Si**
- **Compared to Si BJTs, SiGe HBTs Offer Better:**
  - $\boldsymbol{\beta}$ + V_A + $\boldsymbol{\beta V_A}$ + f_T + f_{max} + 1/f + NF_{min} + cryo-T performance…
- **Compared to CMOS, SiGe HBTs Offer Better:**
  - f_T/f_{max}/NF at fixed scaling node + matching + g_m/area + 1/f noise, + …
- **Still Room for Lots of Performance Improvement** (f_T / f_{max} = 500 GHz)
- **Still Lots to Learn About the Physics of These Interesting Devices**
- **MANY Interesting Application Possibilities and New Opportunities!**

SiGe Technology is Here to Stay!

My Gang at Georgia Tech

Georgia Institute of Technology