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Future Missions to Titan:
Scientific and Engineering Challenges

Low-Temperature Electronics: Opportunities for Titan Science

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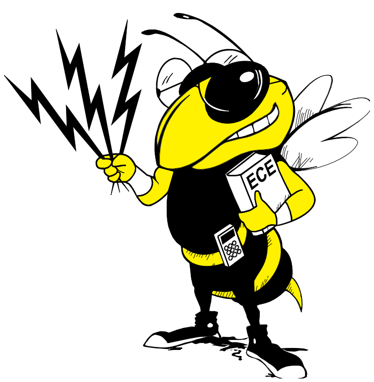

KISS, Titan Study, Cal Tech, May 2010

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A Reminder …

Remember …

There is No Such Thing as Doing Interesting Science on Titan (Physics, Chemistry, Geology Biology, etc.) ...

Without a Robust Electronics Infrastructure!

A Personal Mandate:

We Need to Get Rid of That Darn Warm Box!

HOW?!

Low-T Operation

- **Pro's for Cooling Electronic Devices and Circuits:**
  - mobility increases (depends on doping)
  - current drive increases
  - saturation velocity increases
  - latchup in CMOS improves (BJT gain drops)
  - thermally-activated failure mechanisms improve (e.g., electromigration)
  - subthreshold swing and transconductance improve

- **Con's for Cooling Electronic Devices and Circuits:**
  - carrier freeze-out can become an issue (depends on doping)
  - breakdown voltages degrade
  - hot carrier effects much stronger and can lead to major reliability issues
  - heavy ion induced latchup in CMOS looks like a possibility (2010)
  - TCAD simulation and compact modeling is a real challenge
  - testing is painful
  - cycling presents issues for electronic packaging

Technology Options

Assumptions:

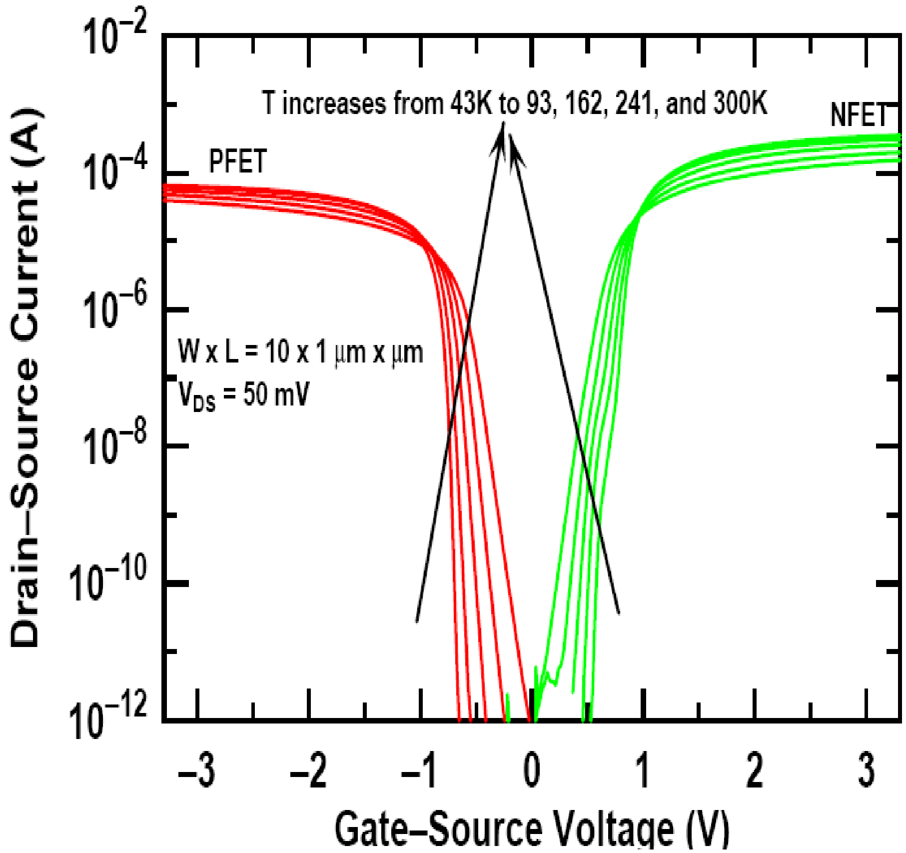
- foundry supported (commercially available via MPW)
- low cost
- must support high levels of integration (e.g., mixed-signal SoC)
- can enable robust operation of complex electronics at 93K

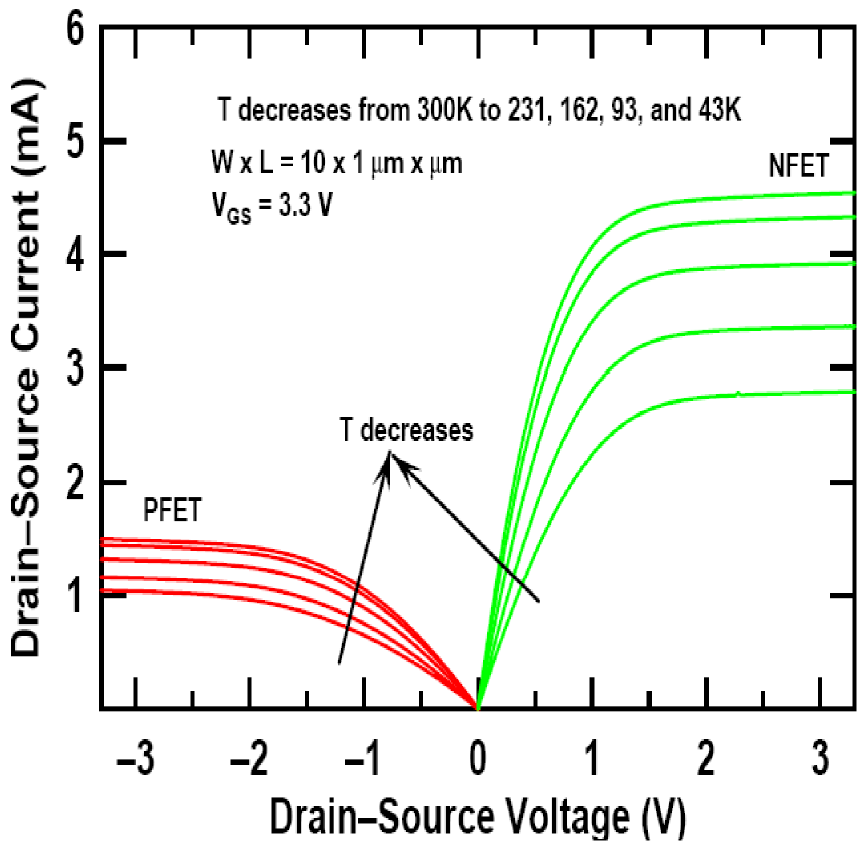
Technology Options / Comments:

- **Bulk Si CMOS**
  - most performance metrics improve with cooling
  - cryo-T hot carrier lifetime is a serious issue to address
  - best for digital; okay for analog/RF
- **Bulk SiGe BiCMOS**
  - SiGe HBT performance improves with cooling (across board)
  - no issue with SiGe HBT cryo-T reliability
  - CMOS here has the same pro's/con's as for bulk CMOS
  - BiCMOS gives optimal division of labor for analog/RF/digital

Cryo-CMOS Performance

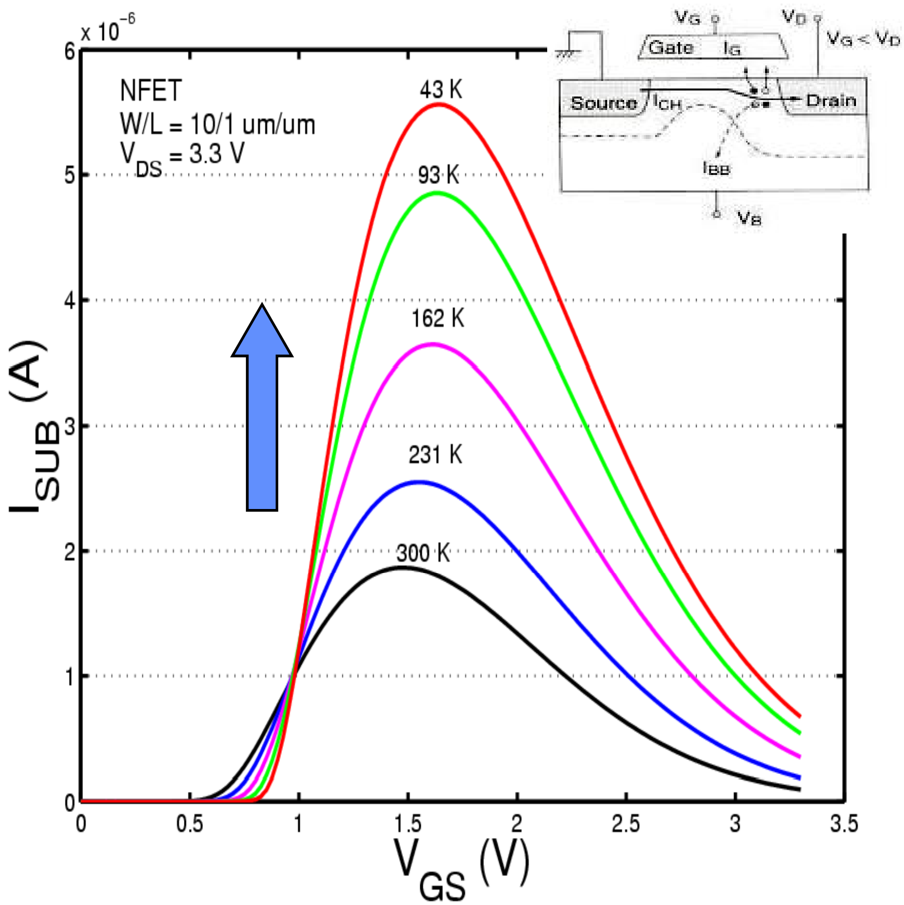
- **CMOS Devices Function Well Down to 43 K**
- **Device Performance Improvement with Cooling (g_m, μ, S)**

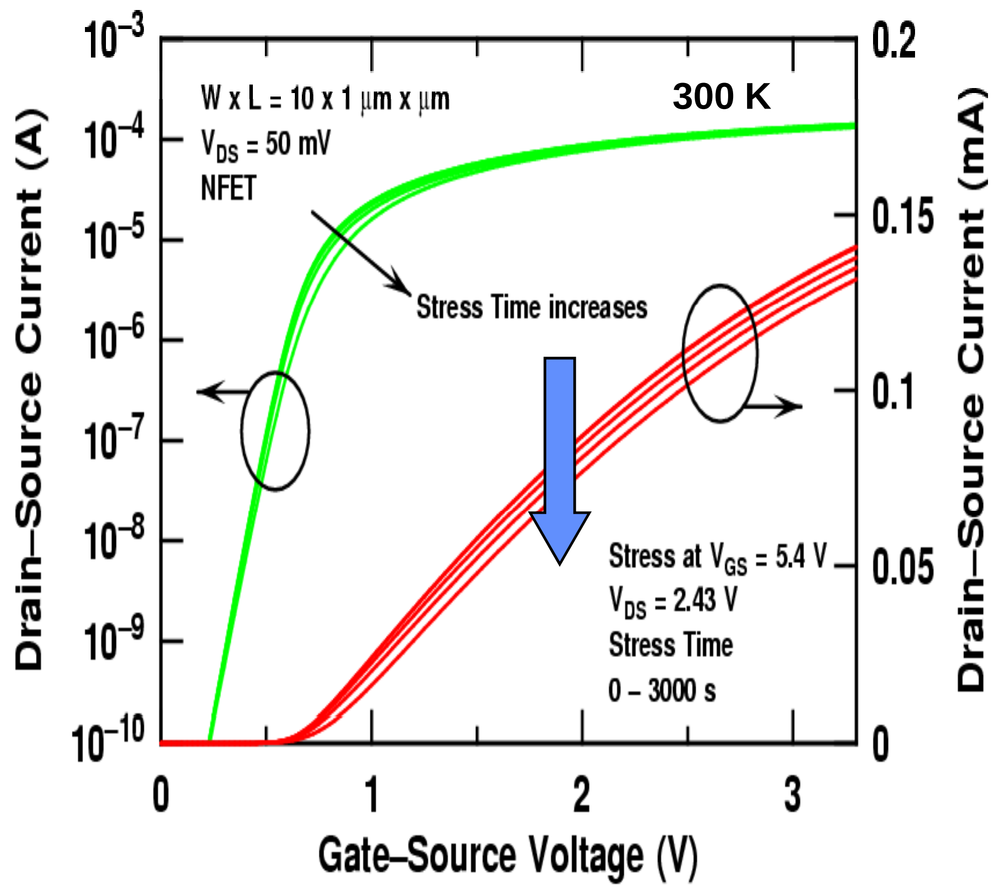




CMOS Reliability

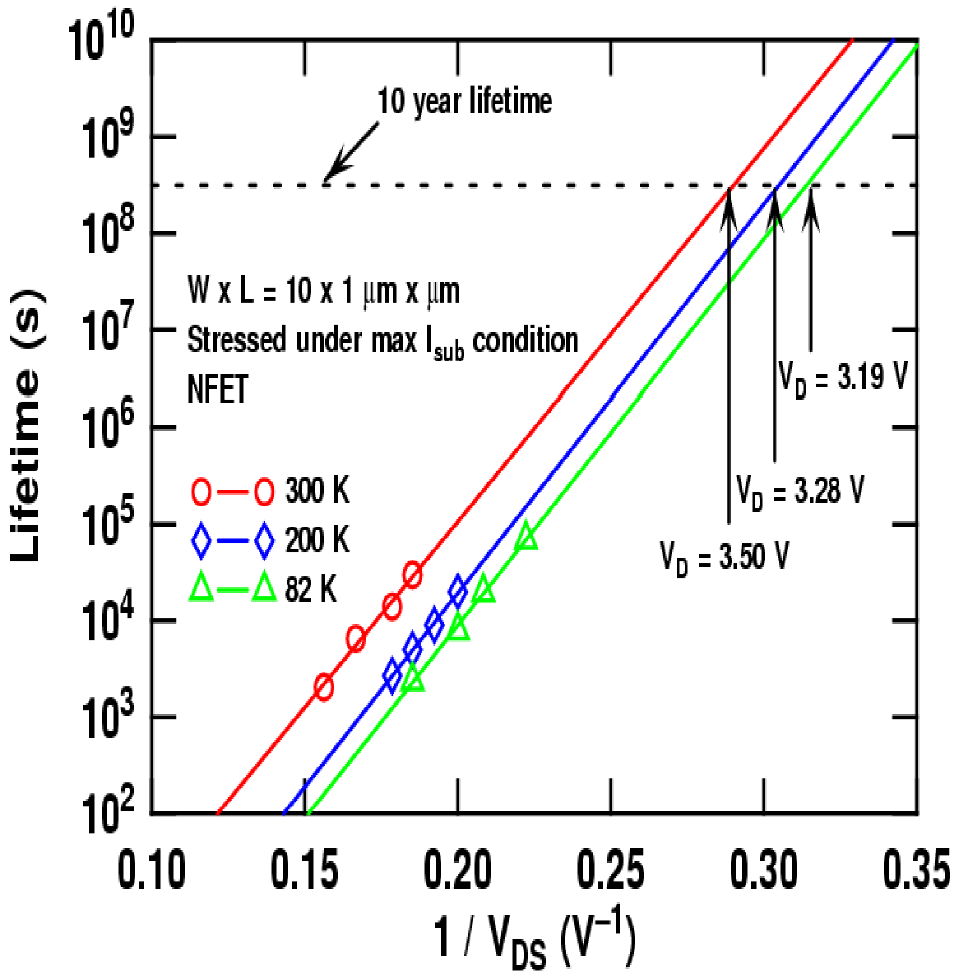
- I_{SUB} is a Good Monitoring Parameter for HCE
- After Stress, I_d and g_m Decrease While V_T and S Increase

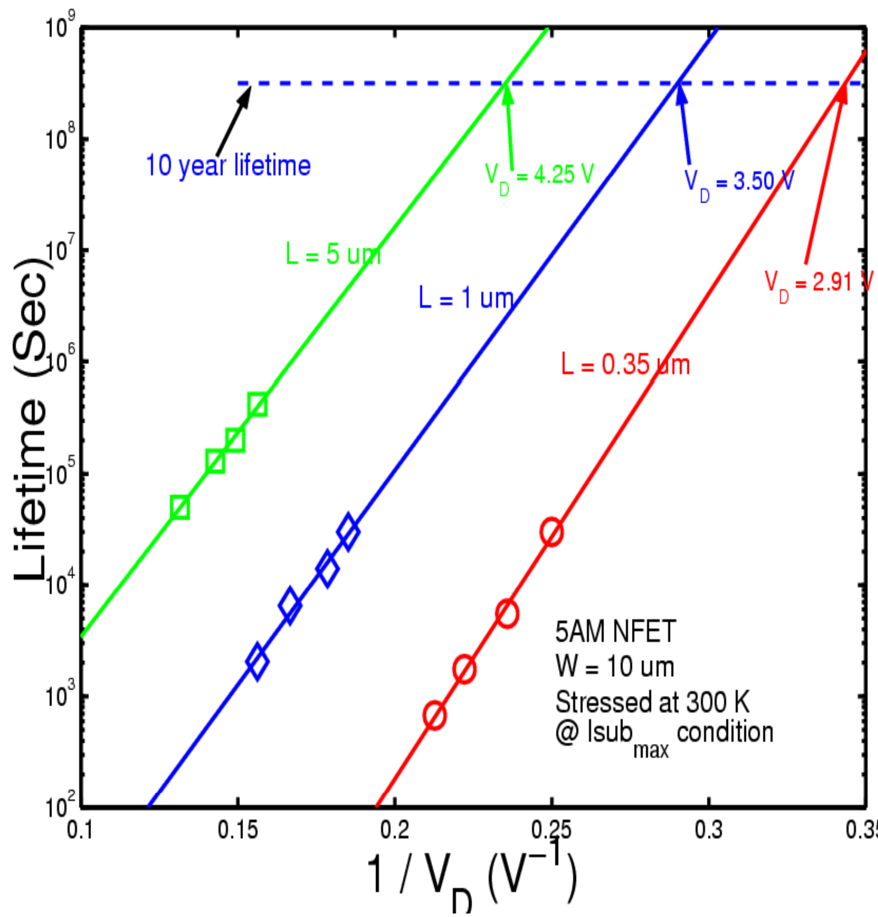




L,T Dependence

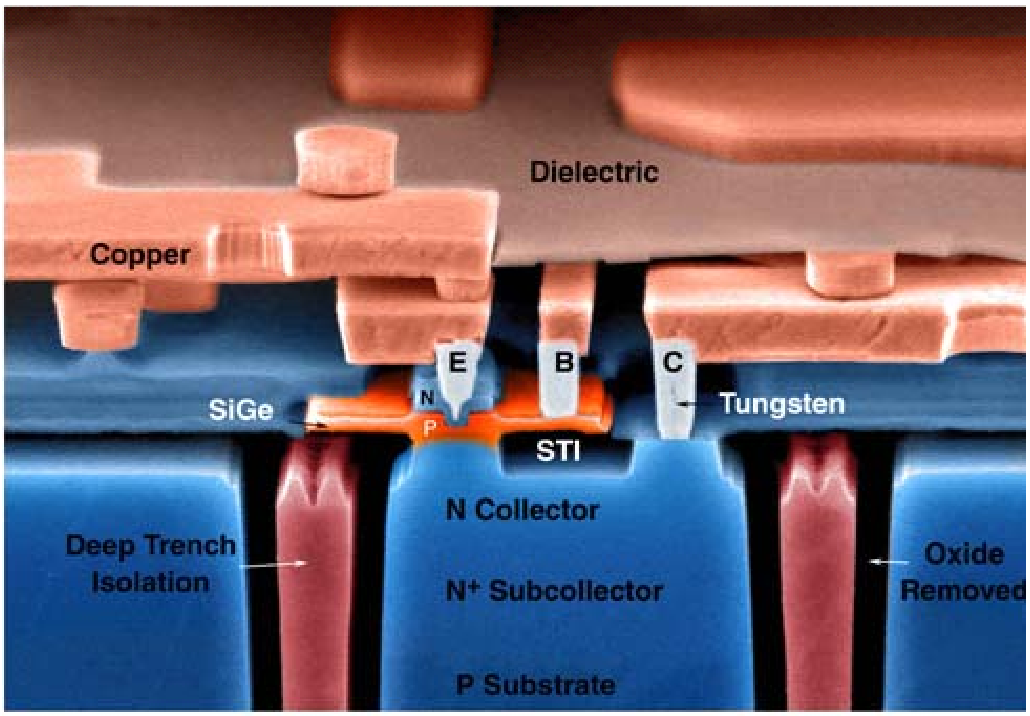
- **Lifetime Decreases with Cooling at Fixed L**
- **Lifetime Decreases With L at Fixed T (Mitigation Path)**

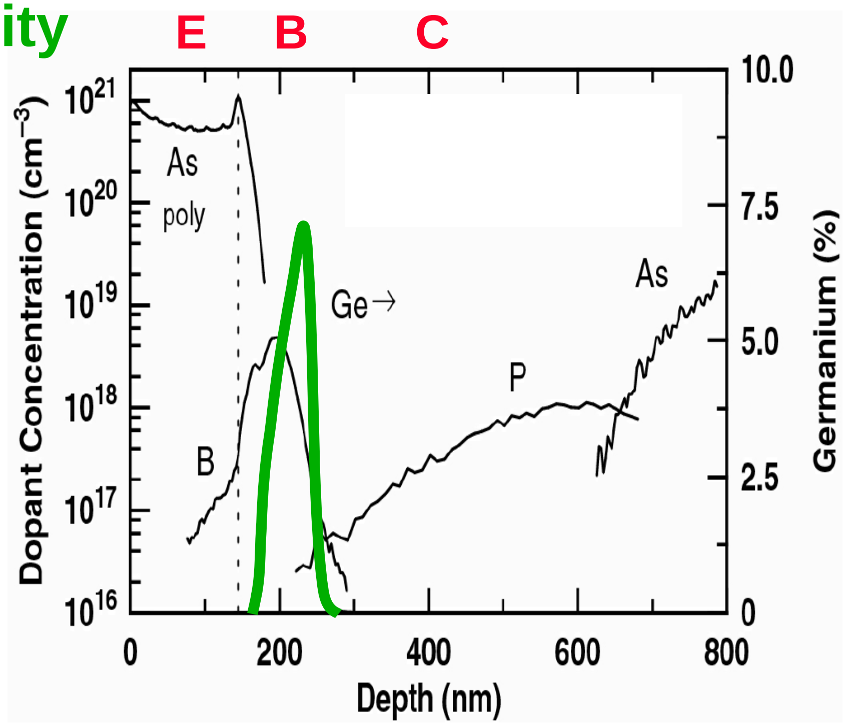


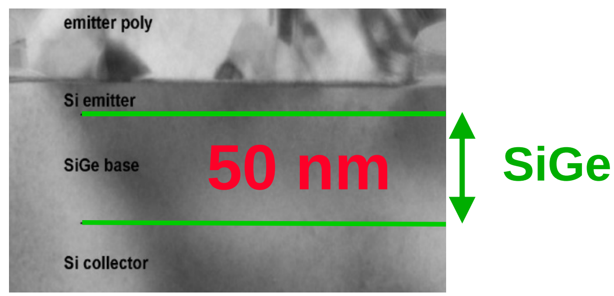


The SiGe HBT

- **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 Performance Limits

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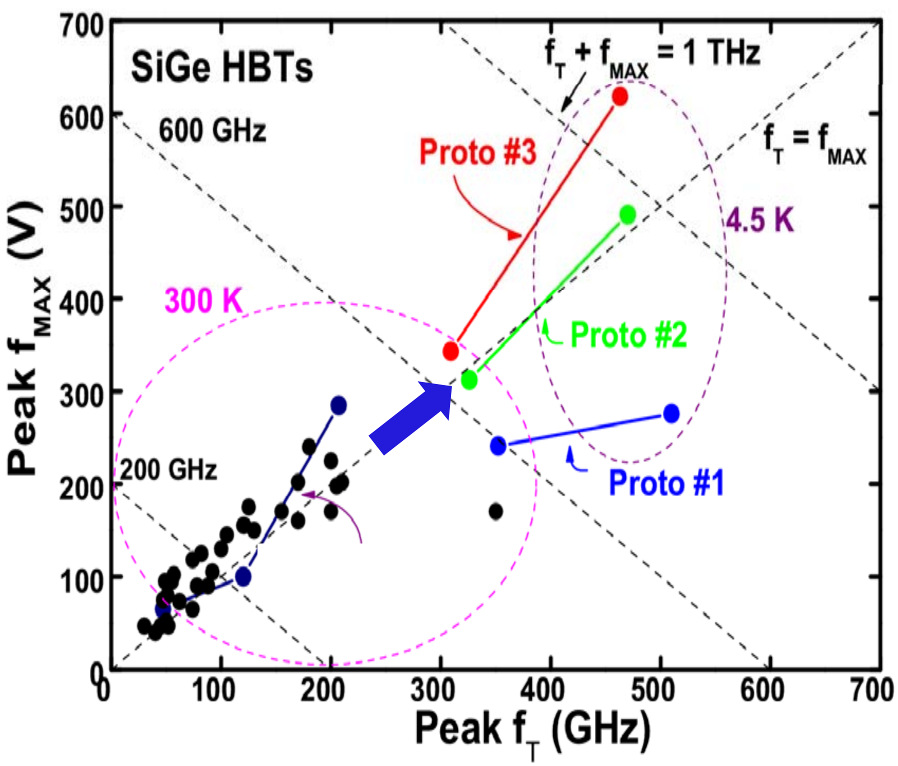
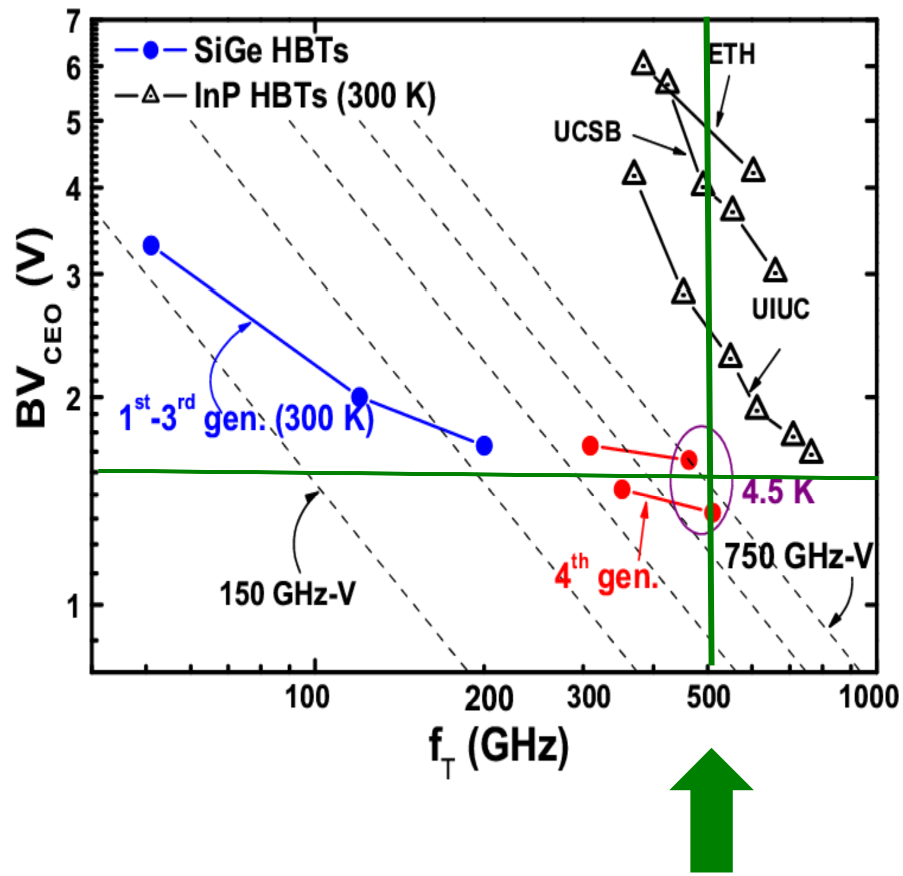
- **Apparent Convergence of SiGe and III-V on Johnson Curve**
- **$f_T + f_{max}$ > 1 THz in SiGe Is Clearly Possible** **(at very modest lith)**
- **Realistic Goal = BV_{CEO} > 1.5 V @ 500 GHz f_T / f_{max}**





SiGe HBTs at Cryo-T

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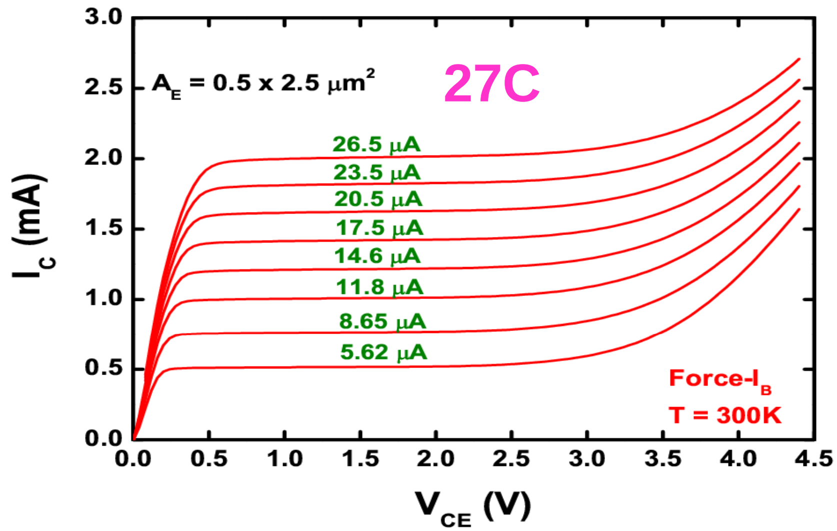
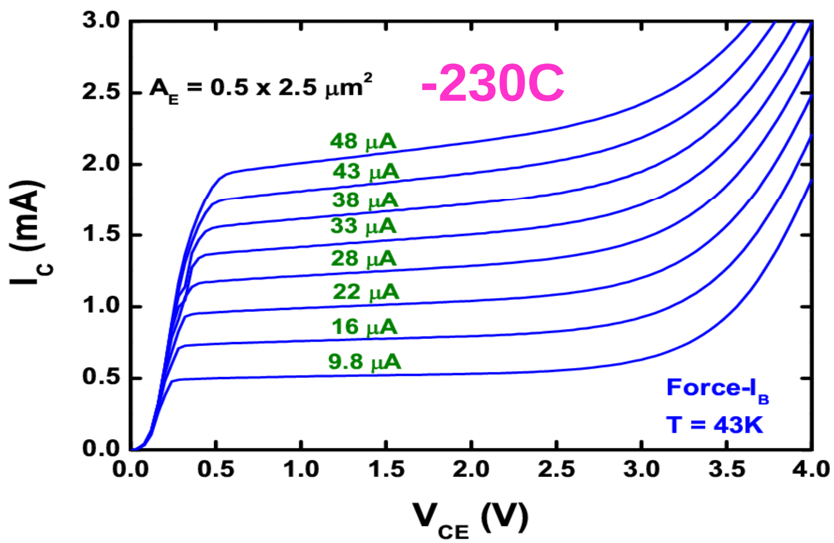
dc





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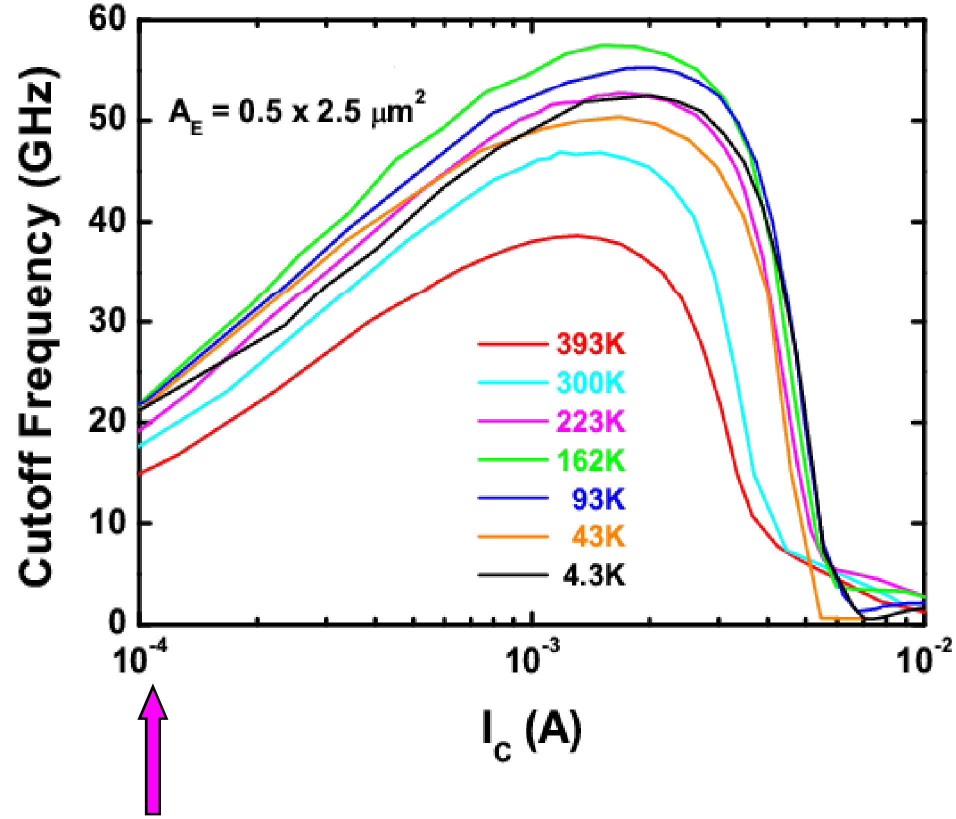

SiGe Exhibits Very High Speed at Very Low Power!

First Generation SiGe HBT

Cryogenic SiGe LNAs

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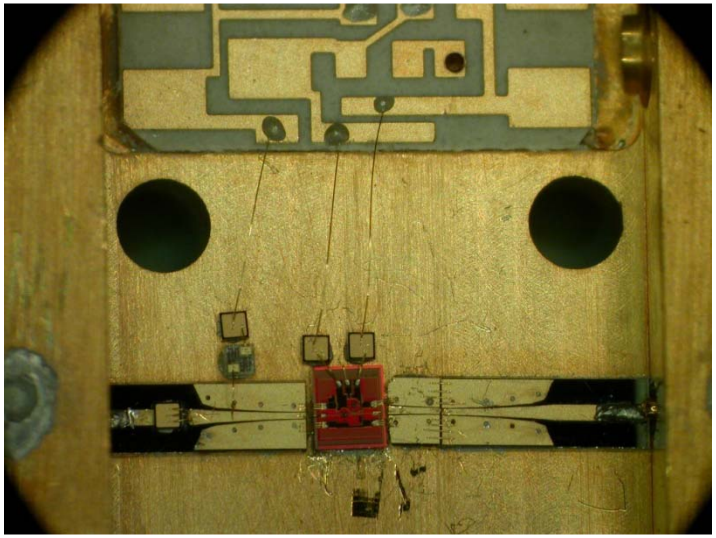
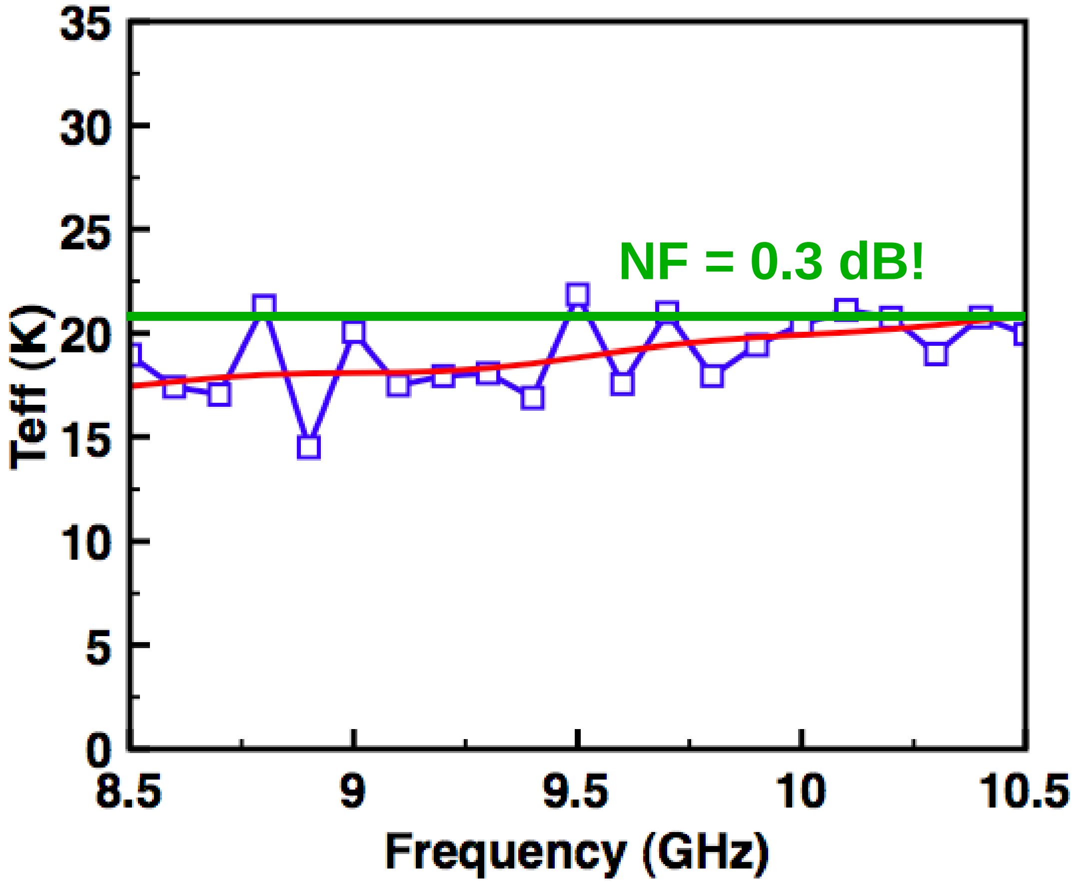
X-band LNA Operation at 15 K (Not Yet Optimized!)

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



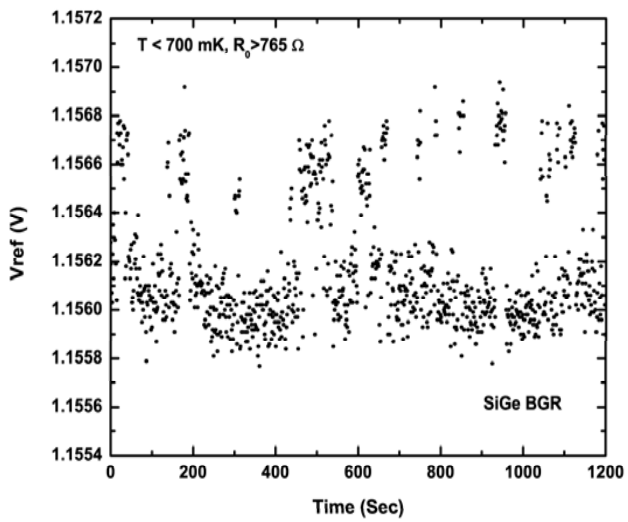


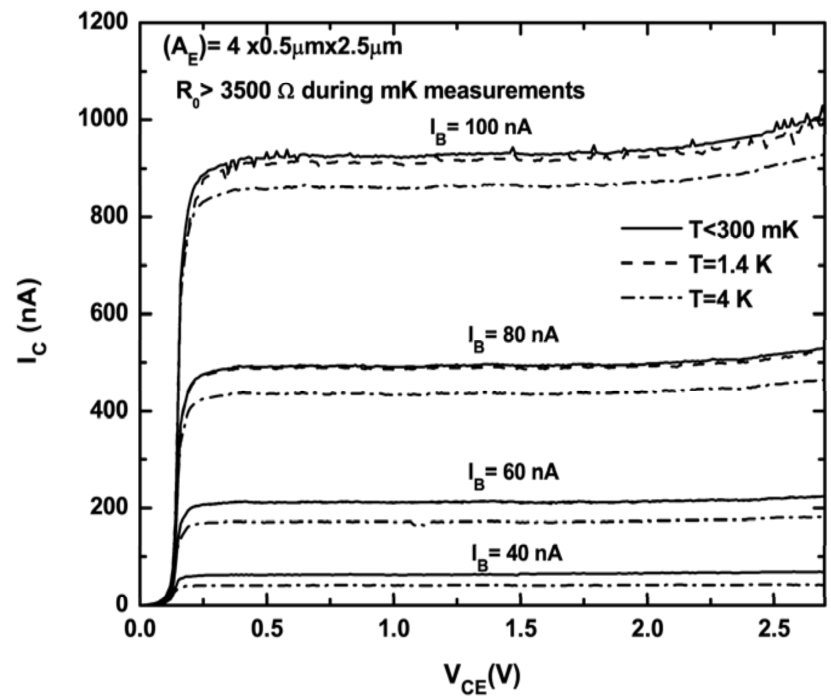
Collaboration with S. Weinreb, Cal Tech

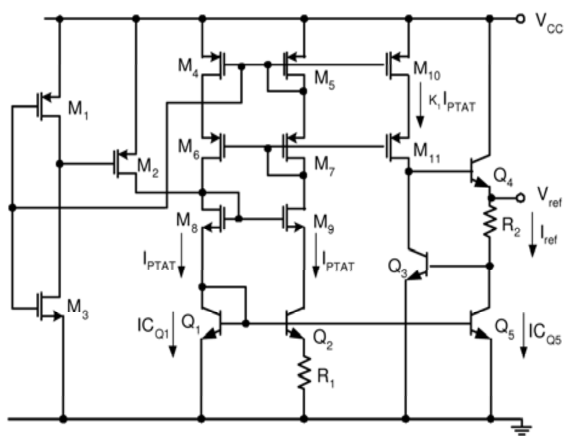
This SiGe LNA is Also Rad-Hard!

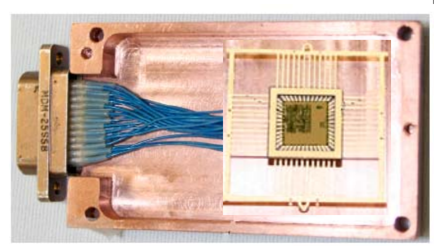
Operation at Sub-1K!

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



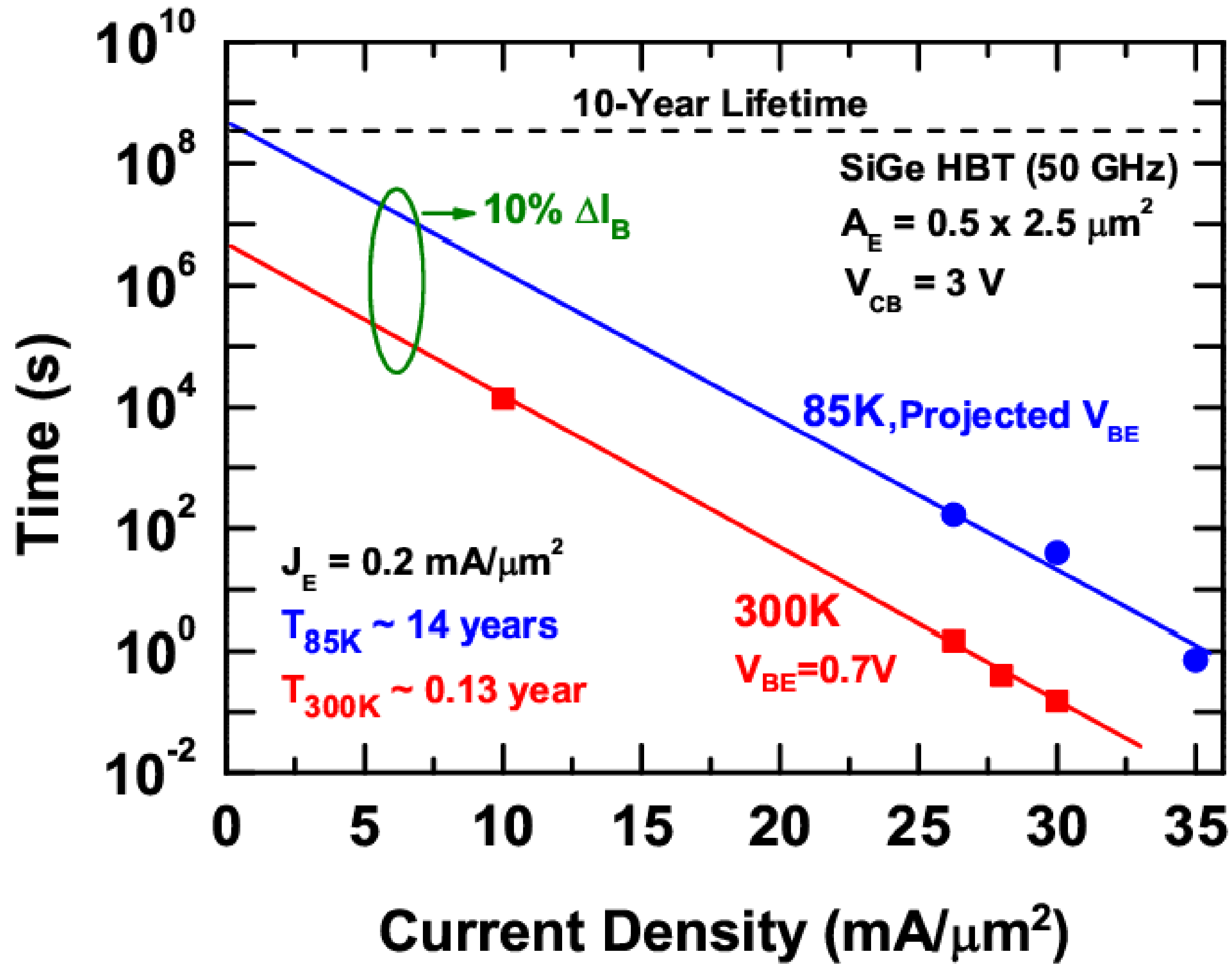




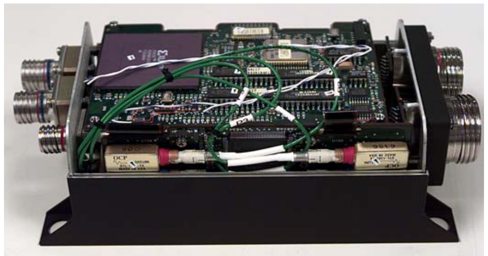


SiGe HBT Reliability

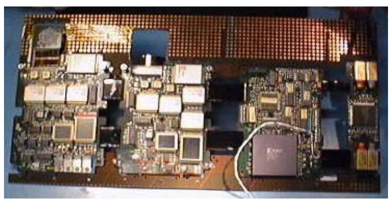
- **SiGe HBT Reliability Fine at Cryo-T**

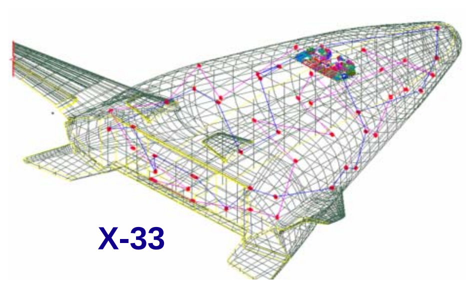


Remote Electronics Unit

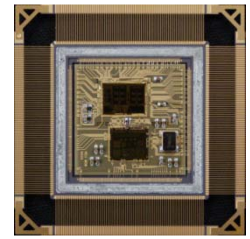


The X-33 Remote Health Unit, BAE Systems, circa 1998



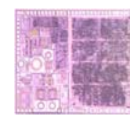


The ETDP SiGe Remote Electronics Unit, 2010

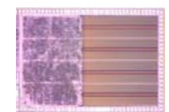


REU in a package!

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

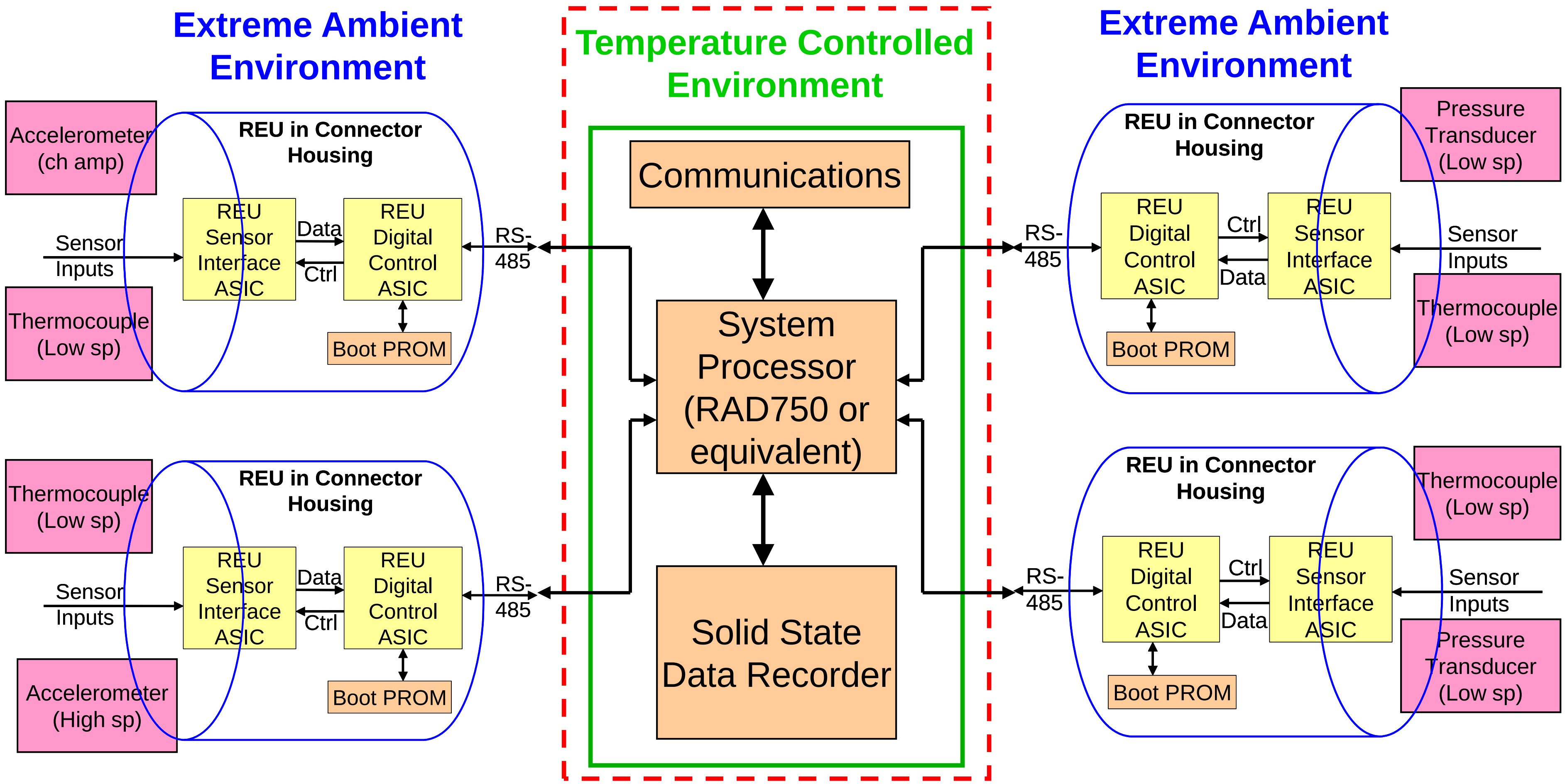
- 1.5" x 1.5" x 0.5" = 1.1 in^3 **(100x)**
- < 1 kg **(10x)**
- < 2 Watts **(10x)**
- **-180^{o}C to +125^{o}C, rad tolerant**

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



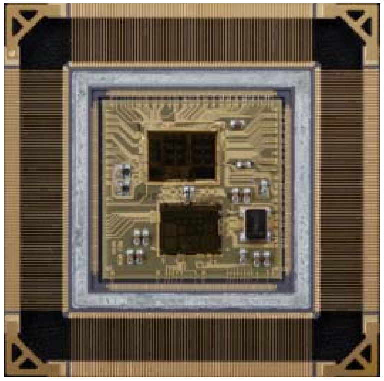
Major Advantages:

- **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)

Some Thoughts / Ideas

- **We now know how to build robust, reliable, complex mixed-signal (analog, digital, RF) electronics to operate at Titan temperatures**

- **We can provide warm-box free "electronic suites" for a wide class of instrument / sensor / control / comm needs that can provide dramatic reductions in SWAP**



Complex On-Surface Electronics

analog, digital, RF, power, etc.

< 1.0 in^2

< 100 g

< 1-2 W for electronics SYSTEMS

Read: Environmental Invariance (e.g., 90 K)

Some Thoughts / Ideas

- **Old Idea: one big, heavy, power hungry science package with lots of instruments drops to the surface**

- **New Idea: identify a "few" (or lots!) target science sensor/instruments (e.g., lab on a chip) that can be packaged at <u>small</u> size and <u>low</u> power and then deploy a "platoon" of such small <u>environmentally invariant</u> science packages by parachute to the surface (land and lake - boat with a sail?), each of which have <u>low-power</u> RF links (operating at ambient) for comm from package-to-package or package-to-balloon or package-to-orbiter**

- **Design small science packages to run off batteries for "long" duration operation, and perhaps even enabled to scavenge energy if desperate (beam RF from orbiter?)**