Final Report

“Radiation Effects and Analysis of SiGe HBT Devices and Circuits”
NASA **NNX10AB19G**

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John D. Cressler's SiGe Devices and Circuits Research Team

Major Accomplishments this Quarter (FY10 Q1)

Publications and Presentations

[1] K. A. Moen and J. D. Cressler, "Measurement and Modeling of Carrier Transport Parameters Applicable to SiGe BiCMOS Technology Operating in Extreme Environments," to appear in March 2010 issue of IEEE Trans. Electron Devices.

Radiation Experiments

- **Two-Photon Laser – (11/09 Naval Research Laboratory)**
  - VCO circuits

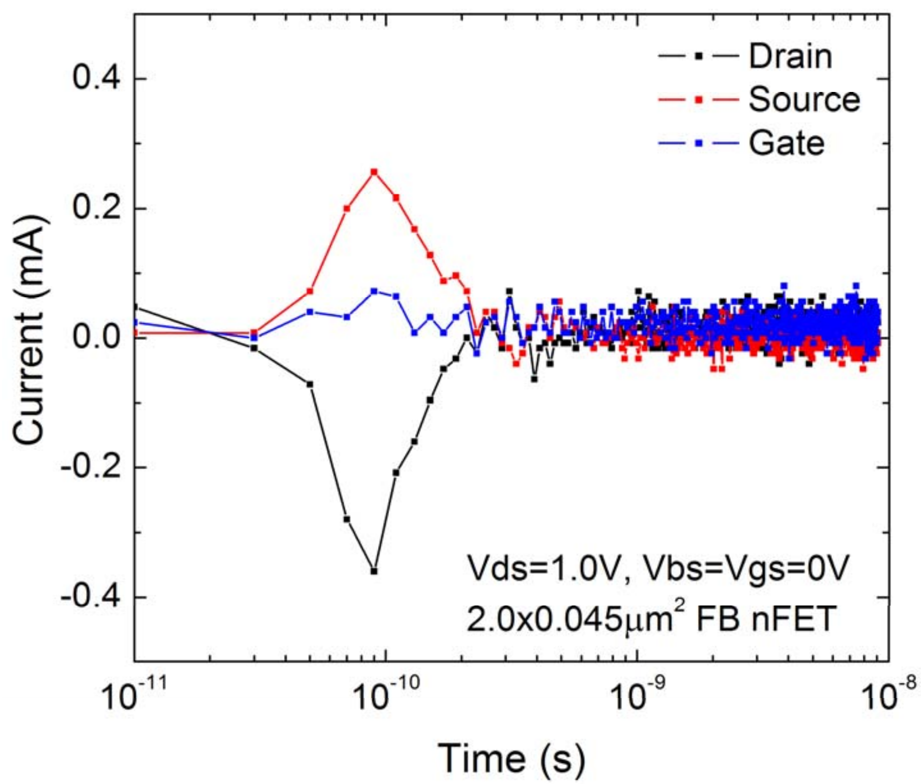
- **36 MeV ^{16}O Microbeam – (12/09 Sandia National Lab)**
  All studies performed were TRIBIC studies
  -IBM SiGe n-MODFET
  -5AM Standard and NRING devices irradiated under various biases
  -BICOM3X SOI Complementary HBTs
  -BICOM3XL Bulk Complementary HBTs
  -8HP no-DT SiGe HBTs

TECHNICAL HIGHLIGHTS

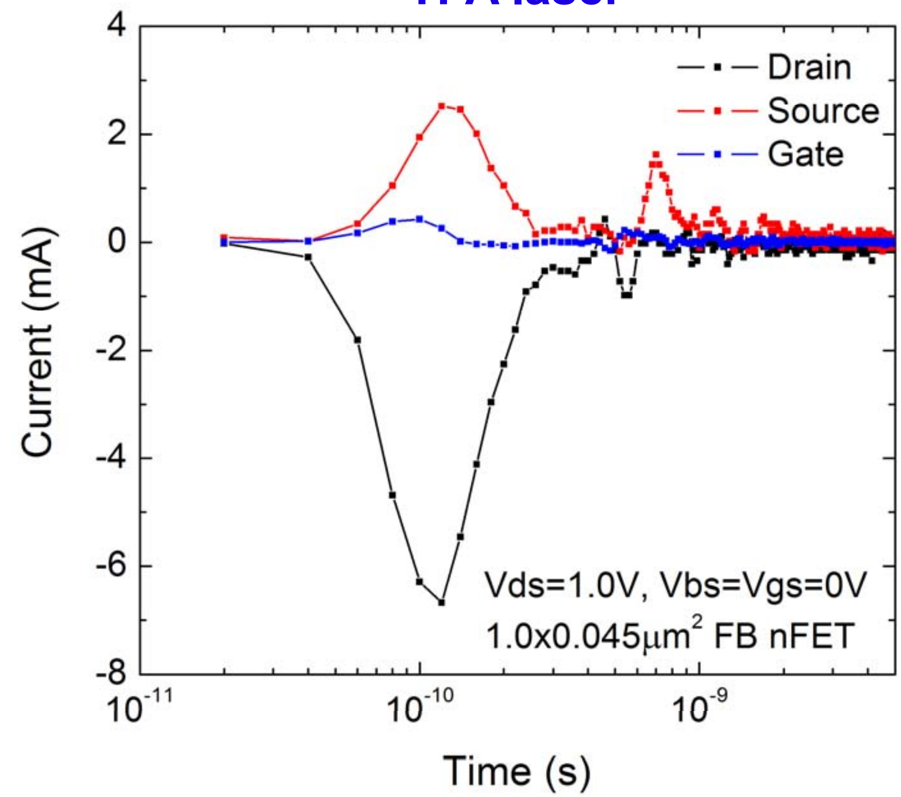
Microbeam + Laser: Transients in 45nm SOI CMOS

- **45 nm multi-finger floating-body nFET**
  - short initial measured transient at worst case bias of V_{DS} = 1V
  - laser and microbeam transients agree in duration
  - microbeam: low magnitude due to small volume (t_{body} = 80nm)

Microbeam



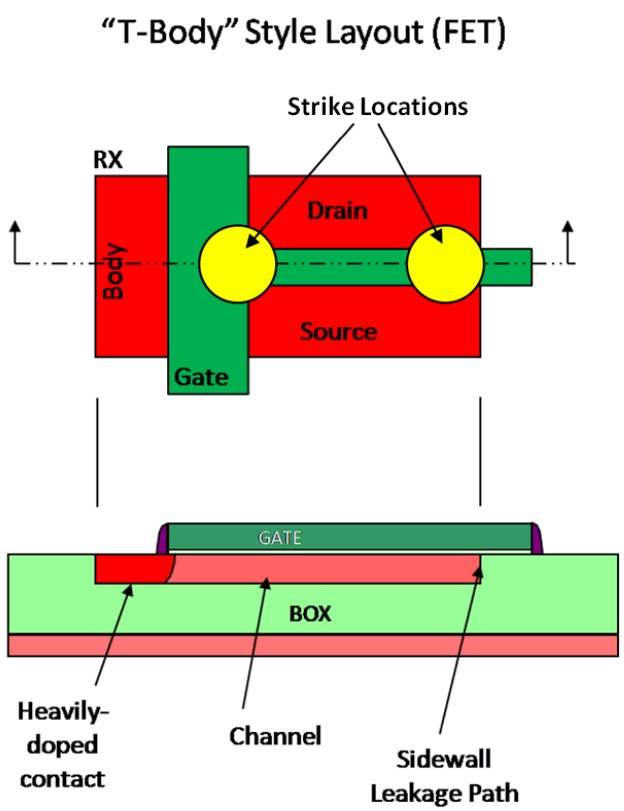
TPA laser

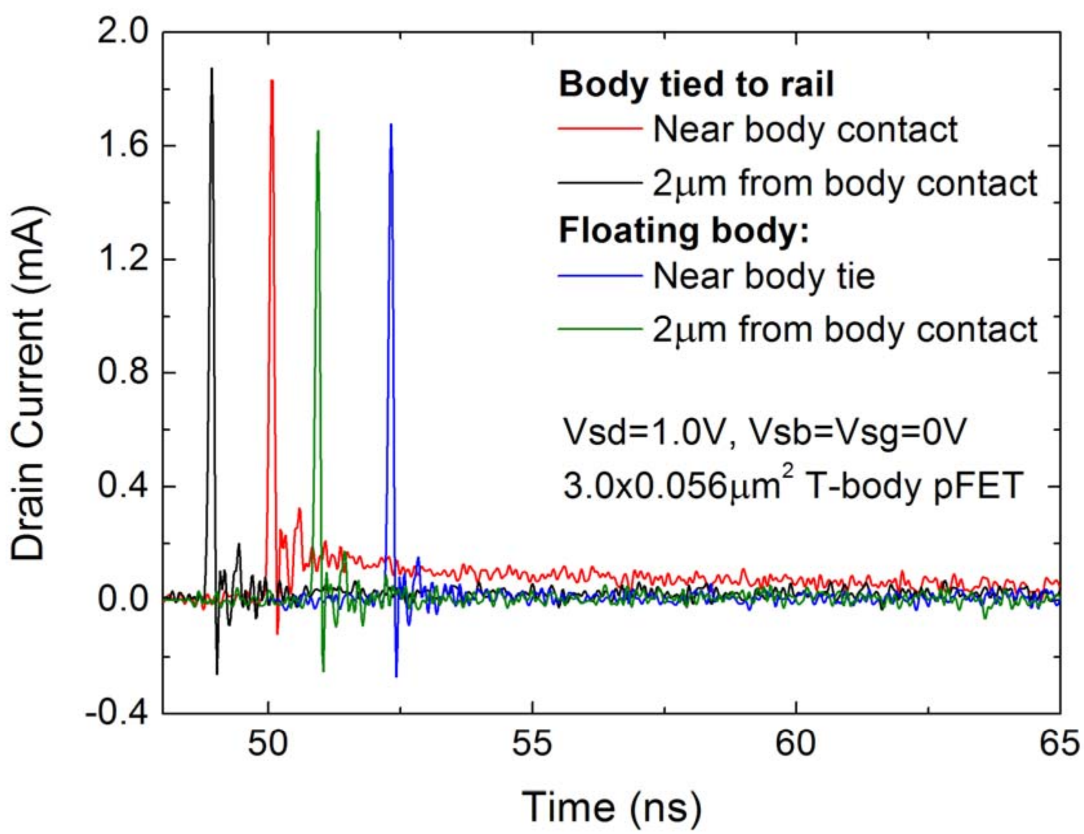


TECHNICAL HIGHLIGHTS

NRL TPA Laser: Transients in 45nm SOI CMOS

- **56 nm single-finger PFET with T-body topology**
  - body-grounded device shows significant lateral variation
  - caused by junction of S/D wells with heavily doped body contact



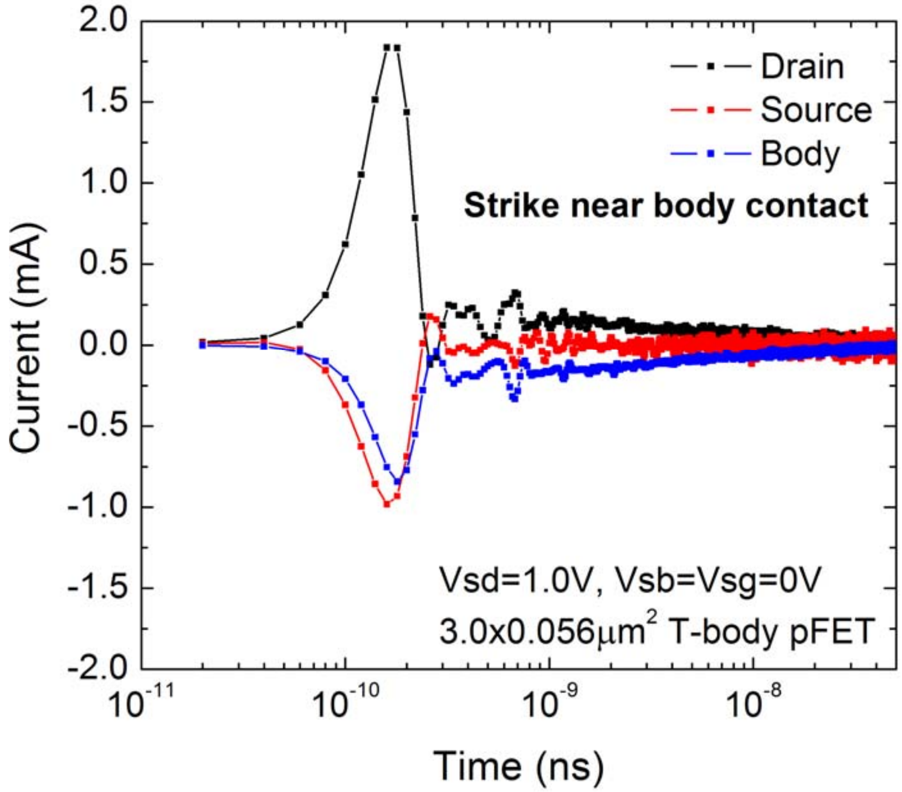


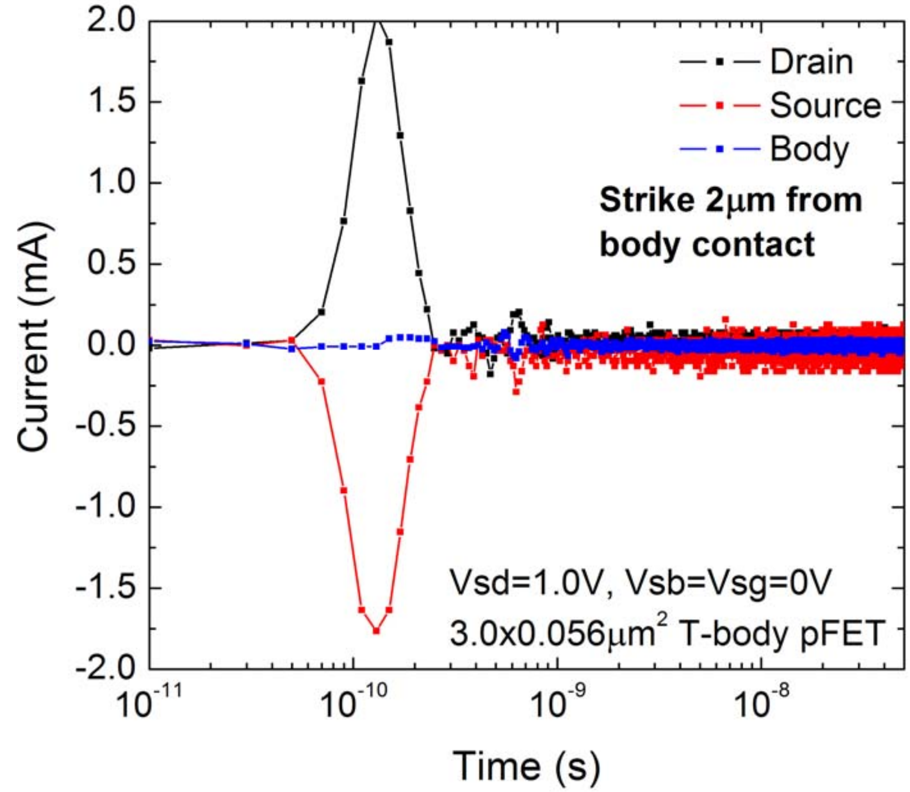
TECHNICAL HIGHLIGHTS

NRL TPA Laser: Transients in 45nm SOI CMOS

- **Increased SEE sensitivity near body-tie**
  - reduced STI (T-Body) & edgeless (H-body) mitigate TID sensitivity
  - increased parasitics degrade RF performance

Trade-off between RF performance + SEE + TID!





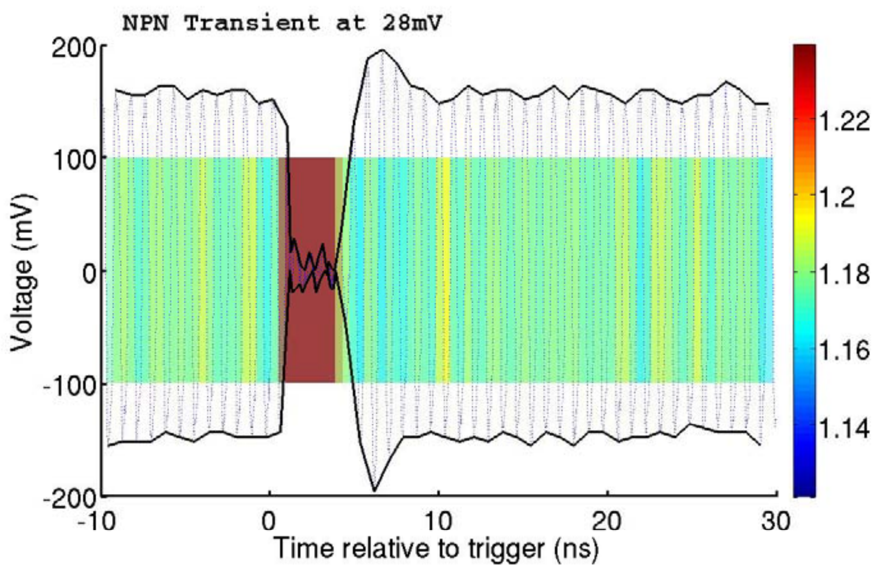
TECHNICAL HIGHLIGHTS

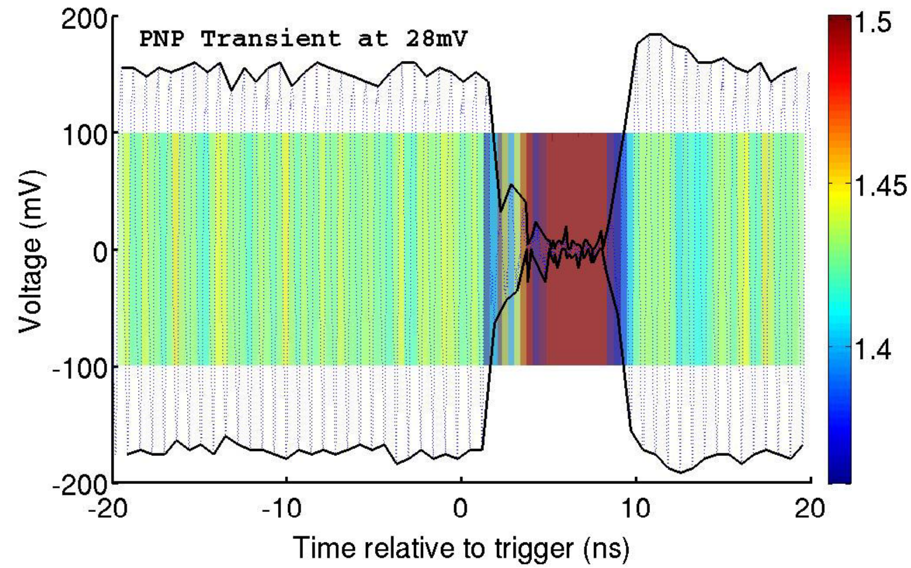
NRL TPA Laser: Transients in Complementary SiGe VCOs

- **Three VCO variants built in IHP's H3 technology platform**
  - full NPN
  - full PNP
  - mixed NPN & PNP
- **Multiple experiments performed on circuits**
  - swept laser energy (10 mV – 30 mV)
  - swept bias current (1 mA – 6 mA)
  - swept control voltage (0 V – 3.3 V)
  - time domain and frequency domain date obtained
- **NPN-only VCOs were extremely sensitive**
  - suffered unrecoverable, catastrophic failure under-beam
  - PNPs operated resiliently under-beam (albeit with transient effects)

TECHNICAL HIGHLIGHTS

NRL TPA Laser: SiGe VCO "Down" Transients



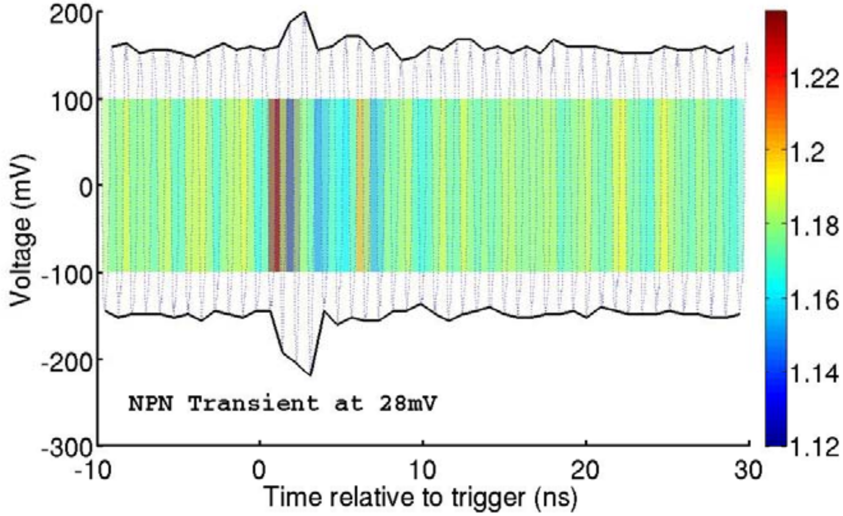


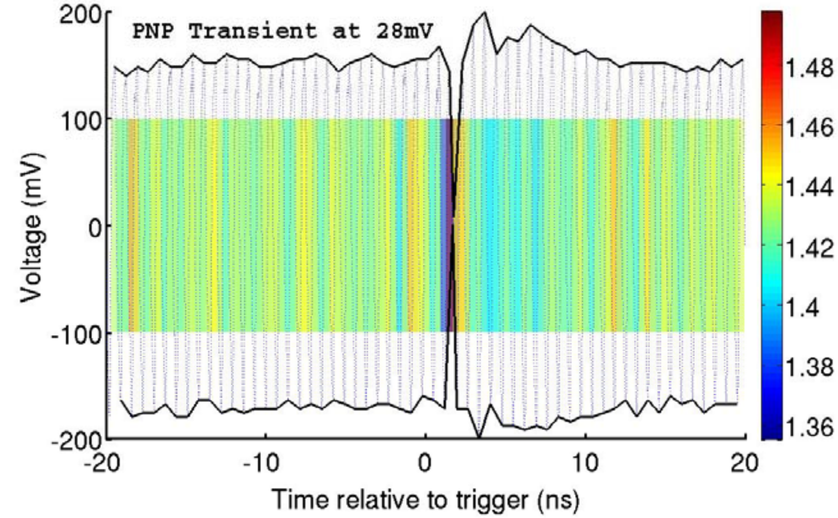
Large transients result in sustained collapse of waveform

- **recovers in time**
- **instantaneous change in oscillating frequency**

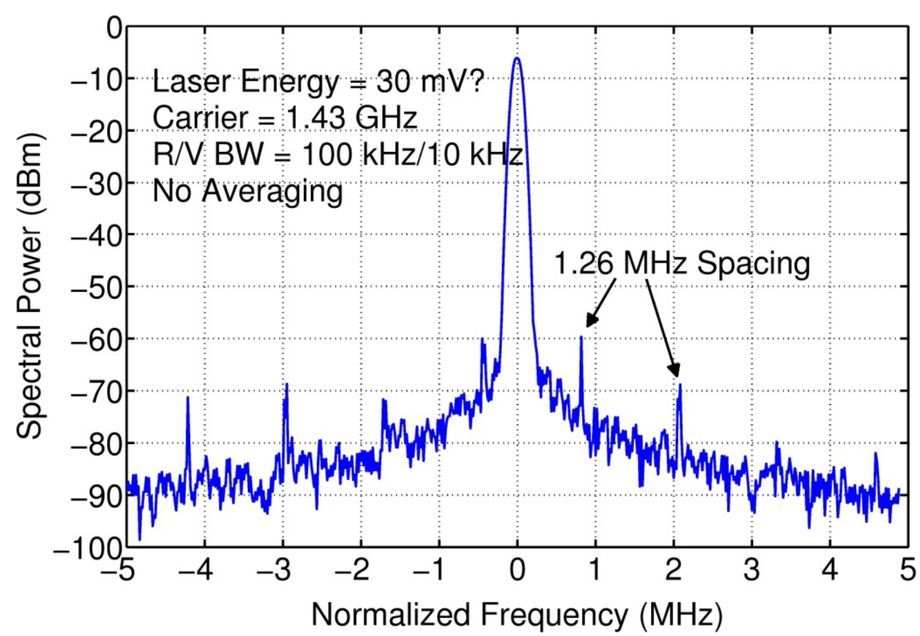
TECHNICAL HIGHLIGHTS

NRL TPA Laser: SiGe VCO "Up" Transients and Frequency Spectrum





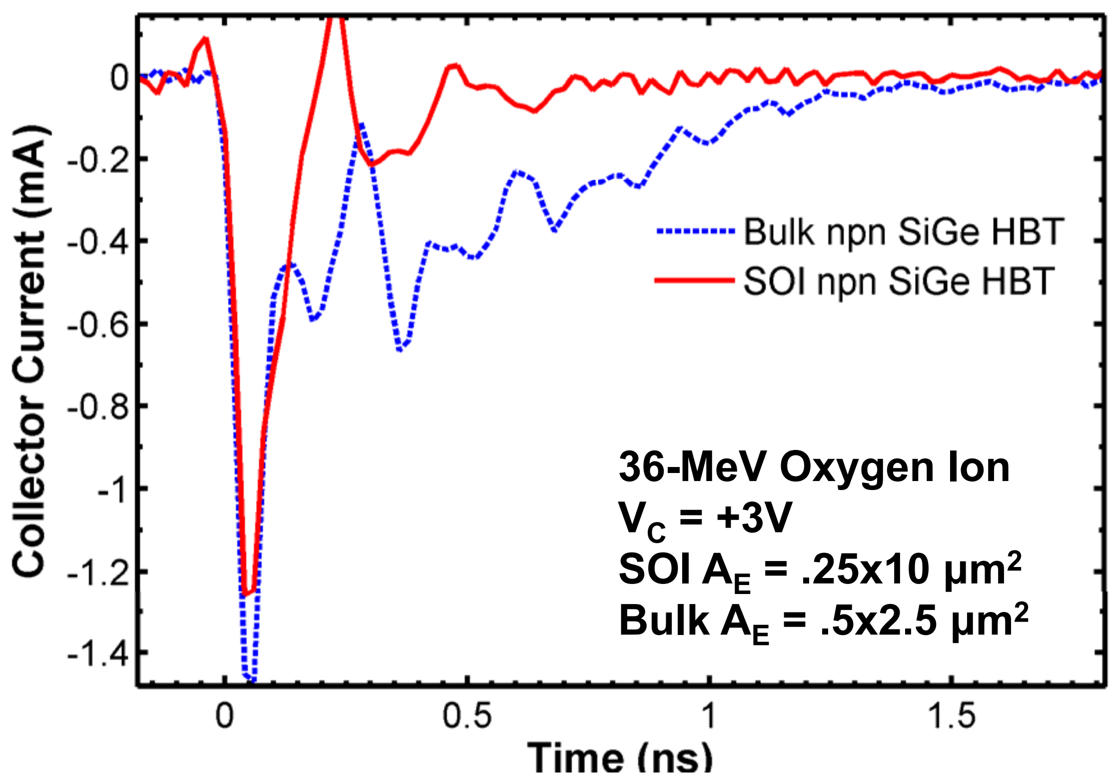
Instantaneous frequency shift of the waveform appears as spurs in the frequency-domain



TECHNICAL HIGHLIGHTS

Sandia Microbeam: Bulk vs SOI Transient Comparsion

- **Transient data obtained from NPN SOI and Bulk HBTs**
  - bulk → 5AM HBT
  - SOI → CBC8 HBT
  - comparison shows similar initial peak
  - very different transient duration



Transient Durations (IC > -.2mA) →

Bulk > 1ns

SOI < .5ns

PLANS FOR NEXT QUARTER

Upcoming Radiation Experiments

- **NRL Two-Photon Pulsed Laser for SET Measurements**
  - IBM 45nm SOI NFETs/PFETs with varied body-tie schemes
  - Inverse mode cascode RHBD devices
- **Vanderbilt x-ray TID studies**
  - IBM 45nm SOI NFETs/PFETs

We will Also Continue to Push on Using NanoTCAD for mixed-mode Simulations of HBT Circuits

PROBLEMS AND CONCERNS

- **None**

John D. Cressler's SiGe Devices and Circuits Research Team

Major Accomplishments this Quarter (FY10 Q2)

Publications and Presentations

[1] M. Turowski, J. A. Pellish, K. A. Moen, A. Raman, J. D. Cressler, and R. Reed, "Reconciling 3-D Mixed-Mode Simulations and Measured Single-Event Transients in SiGe HBTs," (accepted for publication) IEEE Nuclear and Space Radiation Effects Conference, 2010.

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Radiation Experiments

- **Two-Photon Laser – (01/10 Naval Research Laboratory)**
  - 45 nm RFCMOS
- **10 keV X-ray – (03/10 Vanderbilt University)**
  - IBM 45 nm RF CMOS
  - National complementary HBT
  - Graphene films
  - SiGe HBT LNA's

TECHNICAL HIGHLIGHTS
5AM NRing – Transient Analysis

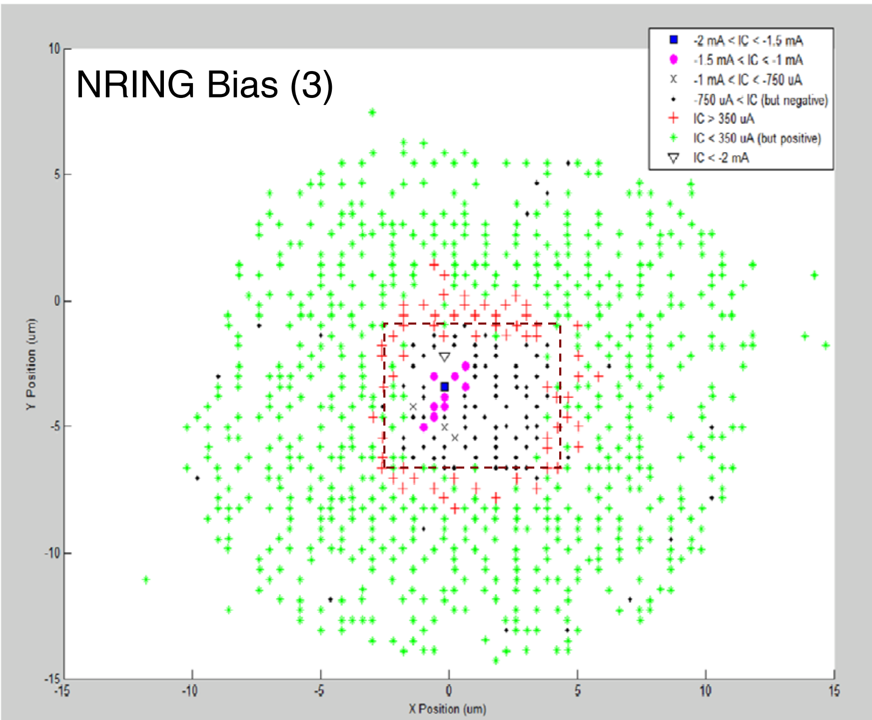
- **NRING originally designed as a mitigation technique for reducing SEE sensitivity for ion strikes outside the deep trench.**
    - Previous measurements have been IBICC
        - Discovered IBIC set-up not compatible with bipolar signals
        - Output of collector transient was found to be bipolar
            - Verified with oscilloscope
    - Transient studies must be performed to evaluate technique

- **Both standard and NRING 5AM HBTs were irradiated with Sandia's 36 MeV ^{16}O heavy-ion microbeam**
    - Three biases for the standard HBT
        1) V_C = 3V all others grounded
        2) V_{SX} = -3V all others grounded
        3) V_C , V_B = 1V all others grounded
    - Two biases for the NRING HBT
        1) V_C , V_B = 1V, V_{NR} = 3V all others grounded
        2) V_{NR} = 3V all others grounded

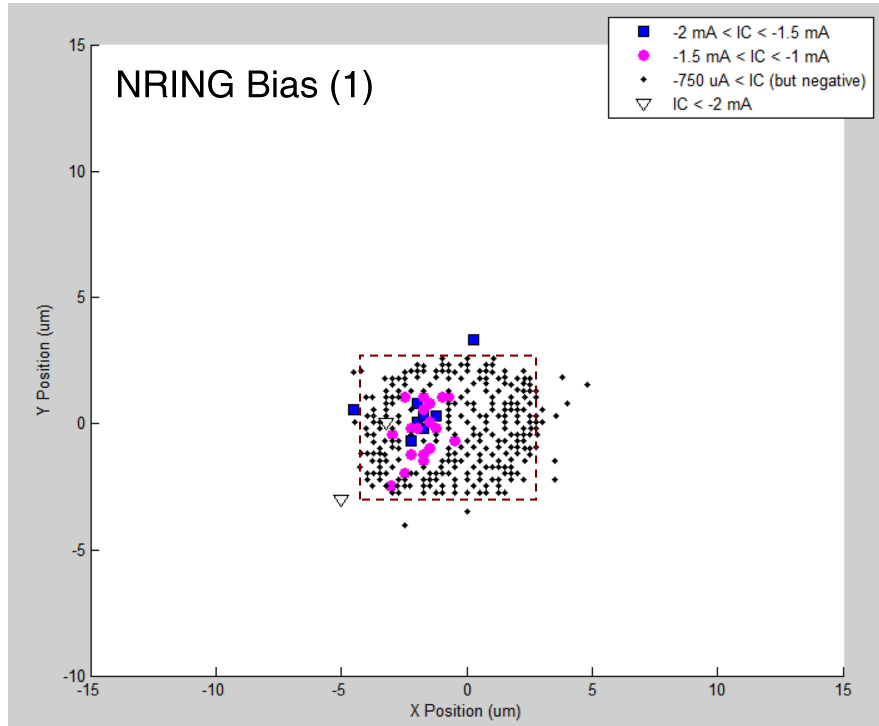
TECHNICAL HIGHLIGHTS

5AM Standard/NRING HBTs – Transient Map

0.5 x 2.5 um^2 NRING HBT



0.5 x 2.5 um^2 Standard HBT

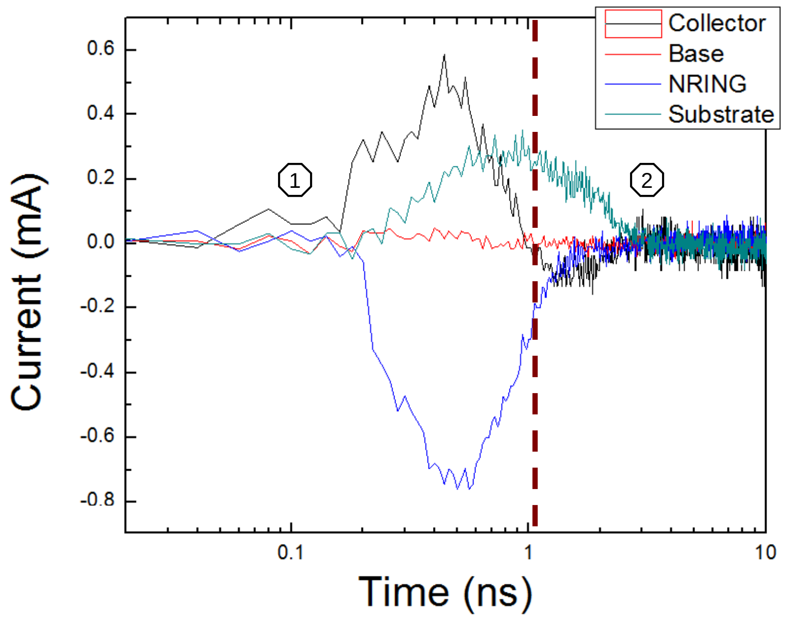


- Internal to Deep Trench response is similar
  - Large negative transients on the collector terminal
- Outside Deep Trench is very different
  - Positive transients induced on collector

TECHNICAL HIGHLIGHTS

5AM NRING HBTs – Waveforms and Conclusions

Transient Currents due to Ion Strike through NRING



1 • Positive collector transient

- Parasitic NPN turning on, C-SX-NR

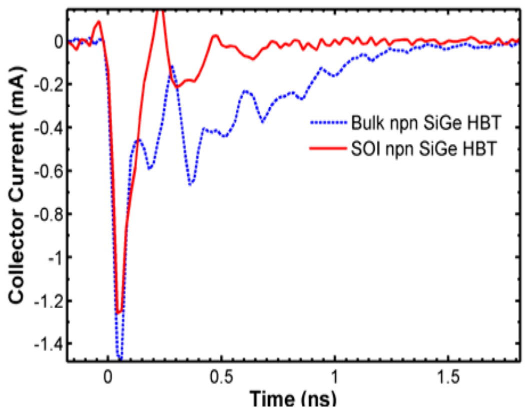
2 • Negative collector transient

- Electrons drifting across C-SX jx

- Adding NRING **increases** the sensitive area of an HBT
  - Standard only sensitive to internal trench strikes
  - Mixed-mode simulations running to determine if sufficient for upset

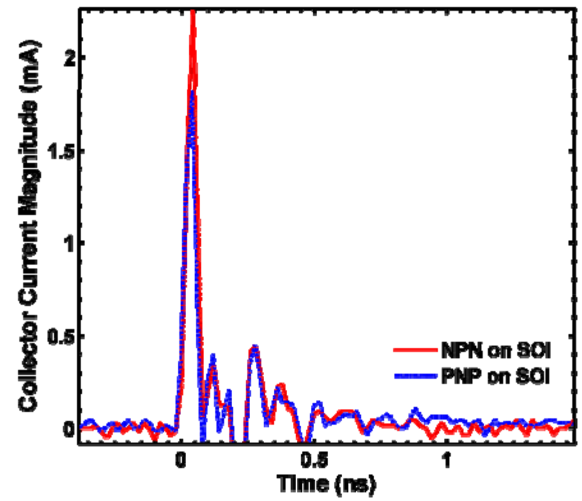
TECHNICAL HIGHLIGHTS

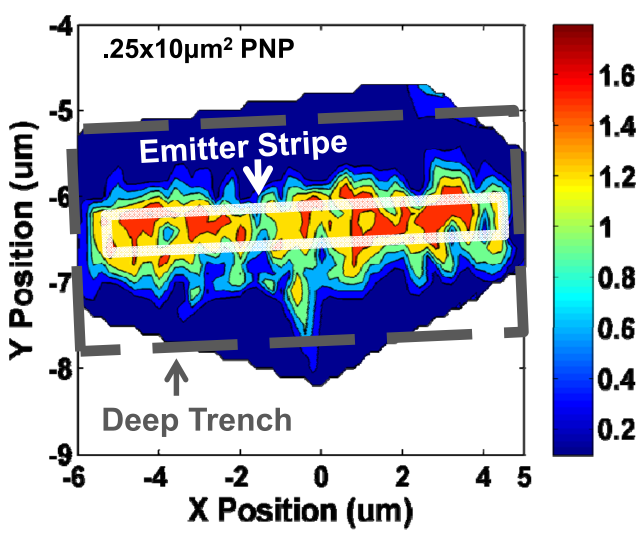
SOI vs. Bulk Transients



- 36 MeV oxygen microbeam at Sandia
- Comparison of bulk SiGe npn (IBM 5AM) and a new complementary SOI platform.
- SOI dramatically shortens transient duration!

Comparison of SOI npn vs. pnp SiGe devices shows similar response



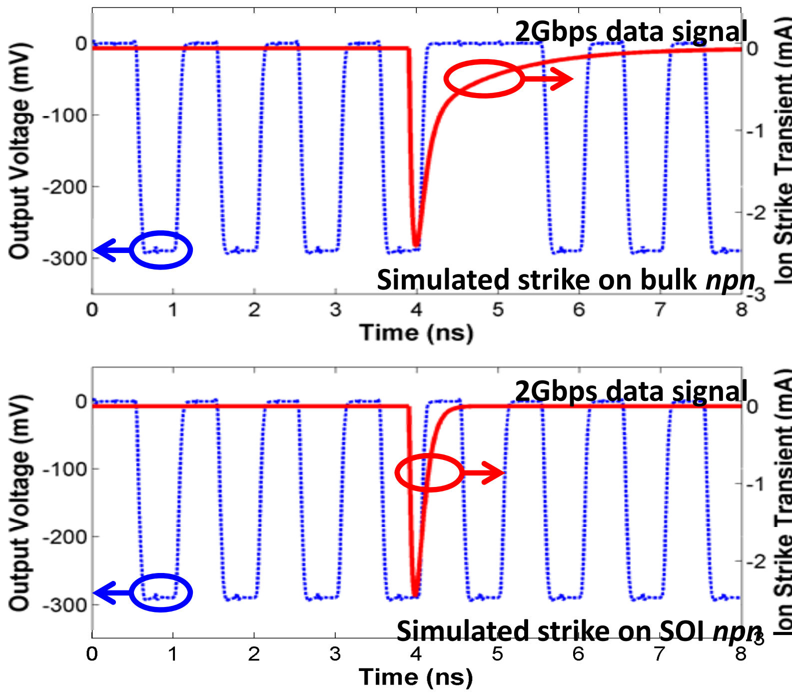


Microbeam scan shows limited sensitive area for the SOI device -- Peak currents heavily concentrated on emitter center and well inside the DT ring

TECHNICAL HIGHLIGHTS

Simulated Strike on SOI

- With shortened transient, SOI may be hardened against SEU → Simulations with microbeam data:

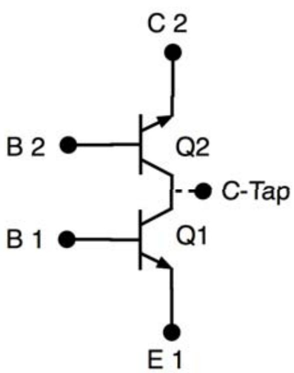


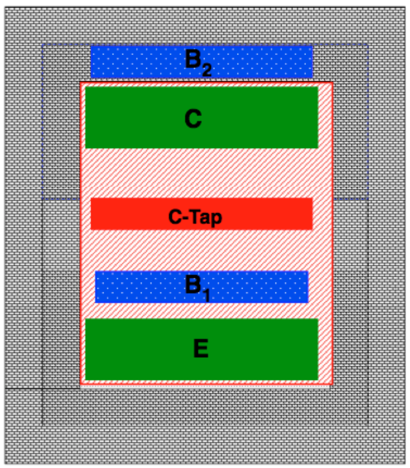
No simulated upsets for shift register using SOI!

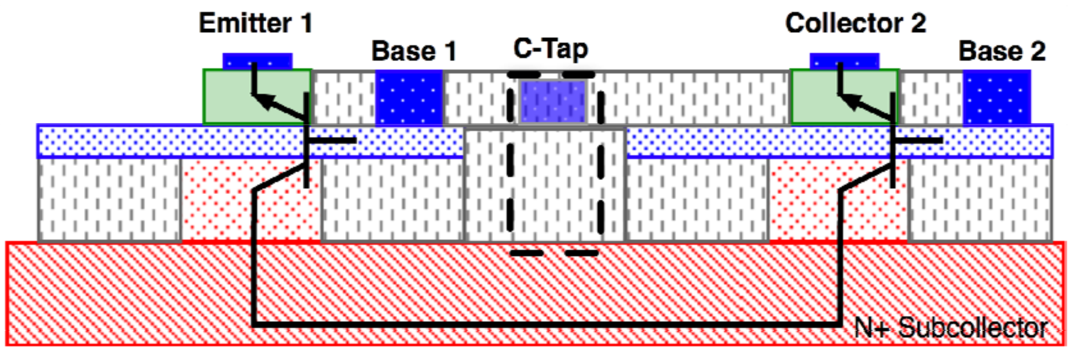
TECHNICAL HIGHLIGHTS

IMC device

- **De-couple sensitive node (Collector) from circuit output**
  - **two transistors operating as one ("cascoded pair")**
  - **use least-sensitive parts of both transistors**
  - **➔ Inverse-Mode Cascode (IMC)**







submitted to NSREC 2010: "Design of Digital Circuits Using Inverse-mode Cascode SiGe HBTs for Single Event Upset Mitigation"

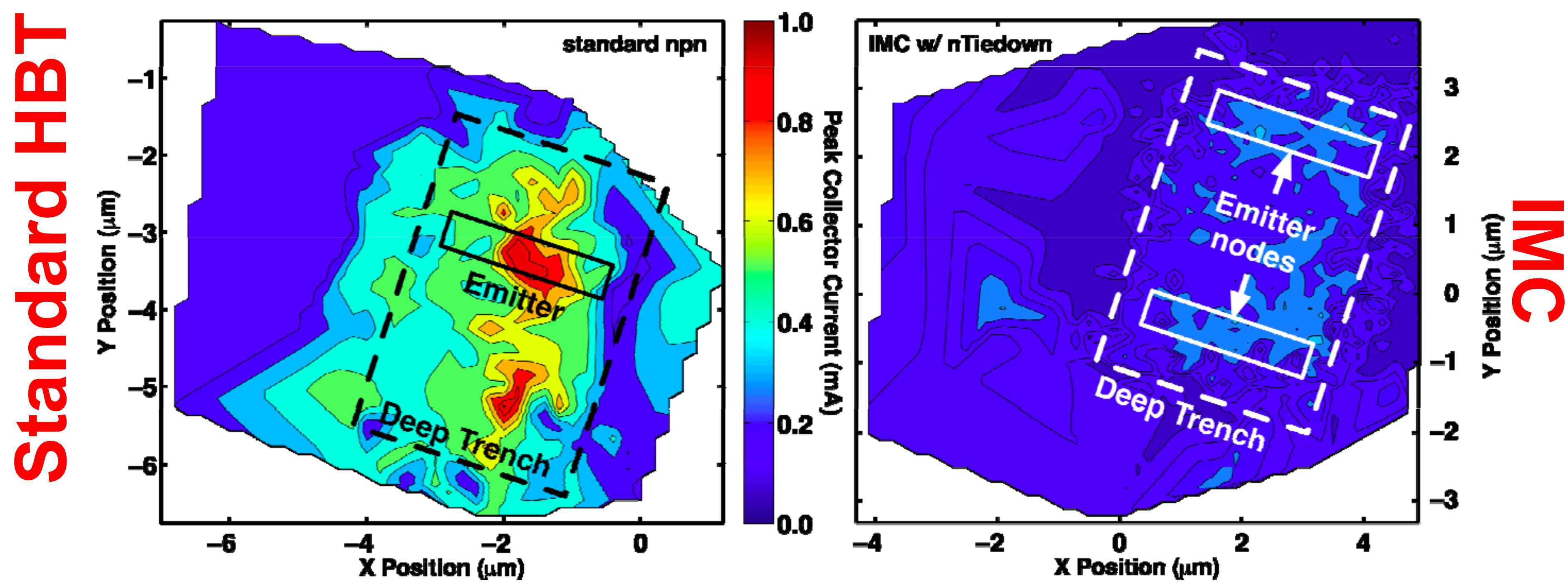
patent pending: US 2009/0231034 A1

TECHNICAL HIGHLIGHTS

μm beam results

- With 100 fF capacitor tied to c-tap node

Peak transient amplitude vs. strike location



TECHNICAL HIGHLIGHTS

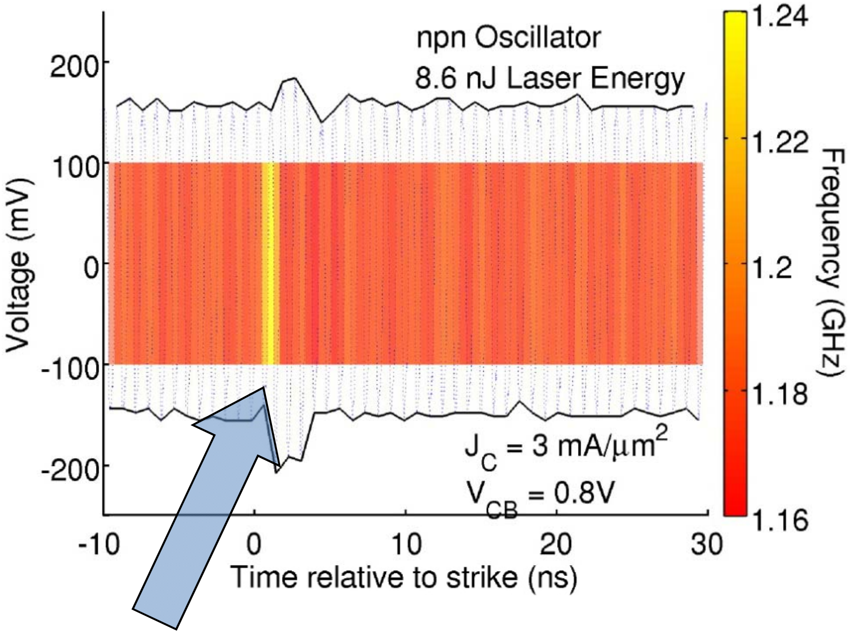
NRL TPA Laser: Transients in Complementary SiGe VCOs

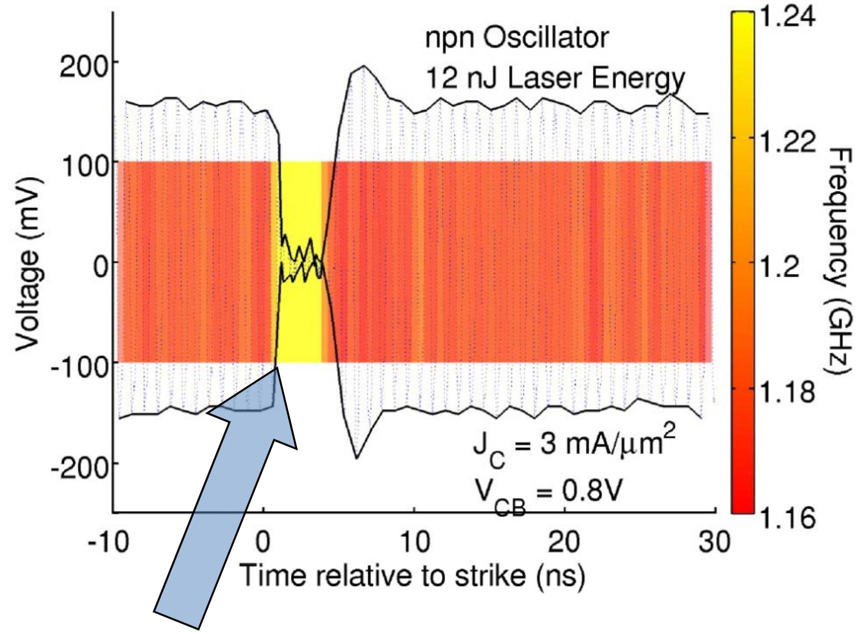
- **Two VCO variants tested in IHP's H3 technology platform**
  - NPN-only negative resistance oscillator
  - PNP-only negative resistance oscillator
- **Multiple experiments performed on circuits**
  - swept laser energy (3 nJ – 13 nJ)
  - swept bias current (1 mA – 6 mA)
  - swept control voltage (0 V – 3.3 V)
  - time domain and frequency domain date obtained
- **NPN-only VCOs were extremely sensitive**
  - suffered unrecoverable, catastrophic failure under-beam
  - PNPs operated resiliently under-beam (albeit with transient effects)

Accepted for oral presentation at NSREC 2010

TECHNICAL HIGHLIGHTS

NRL TPA Laser: SiGe VCO Transients





Moderate energies result in a phase step of the oscillating waveform

- **Brief change in frequency at strike instant**
- **Followed by a bulge or dip in the amplitude envelope**

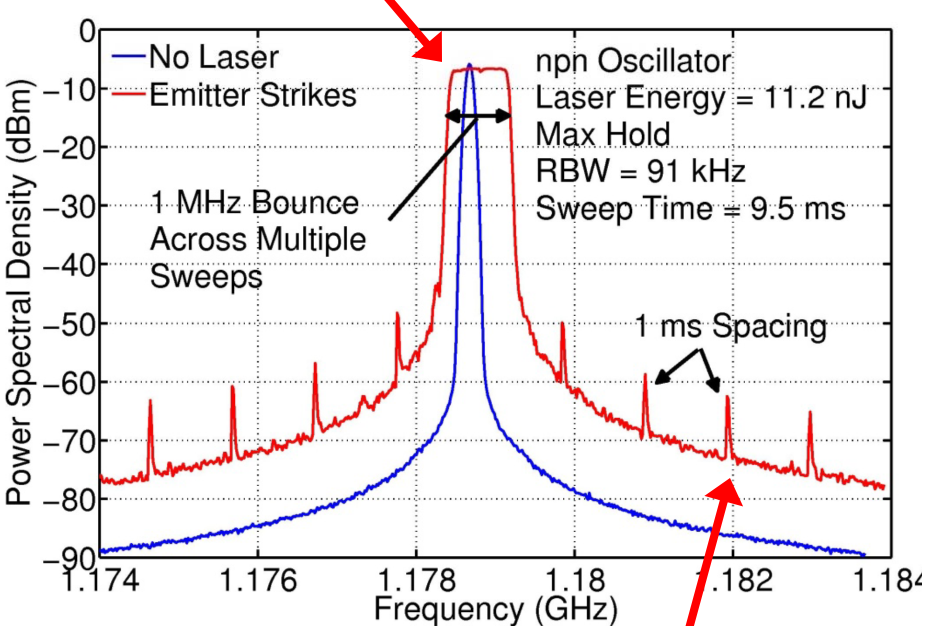
Large energies result in a sustained collapse of the waveform

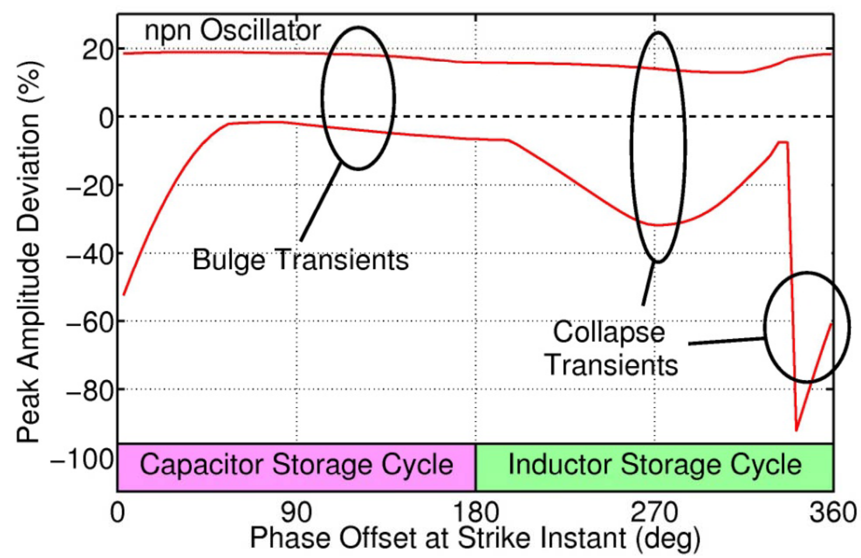
- **Resonant tank overwhelmed by injected charge**

TECHNICAL HIGHLIGHTS

NRL TPA Laser: SiGe VCO Transient Mechanisms

Indicative of pending damage





Normal transients from phase steps

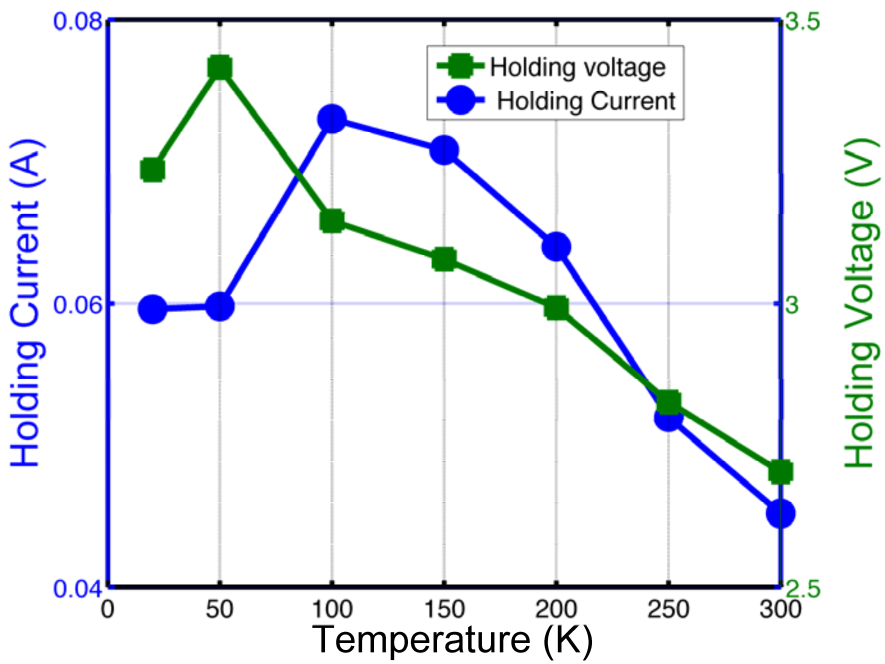
Damage mechanism in NPN oscillator can be separated from “normal” transients by bounce in the frequency spectrum

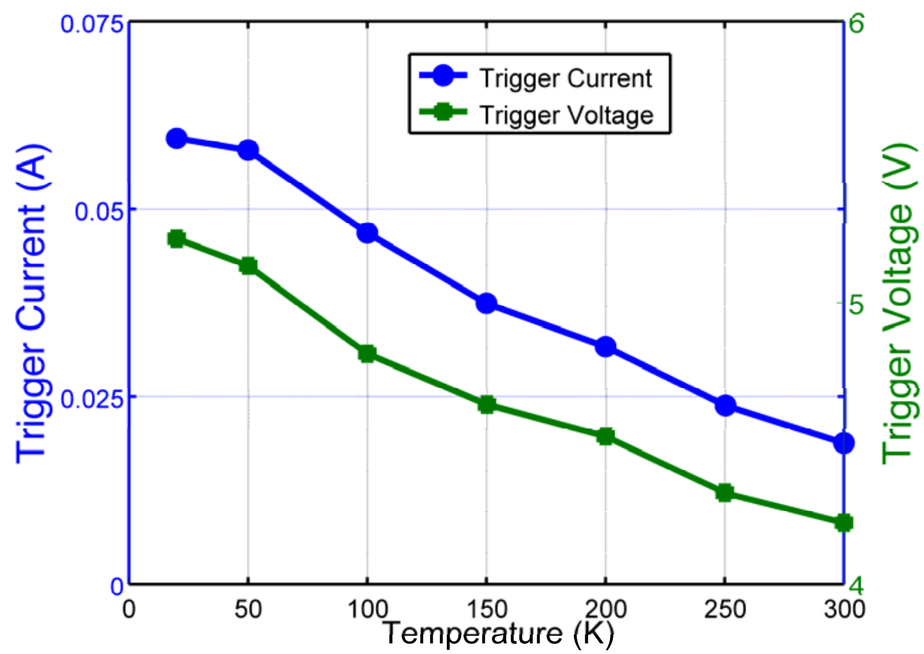
Simulations show envelope transients occur as either a bulge or a collapse dependent on the relative phase of the oscillating signal at the time of the laser strike

TECHNICAL HIGHLIGHTS

Low T Latchup

✧Holding current decreases below ~ 70K.





✧ Latchup due to heavy ions observed below 50K
✧ Our data shows enhanced sensitivity to latchup below 50K
✧ NASA GSFC Single event experiment coming up in May

PLANS FOR NEXT QUARTER

Upcoming Radiation Experiments

Naval Research Laboratory – April 26th – 30th 2010

- **Two-Photon Pulsed Laser for SET Measurements**
  - VCOs fabricated with IHP's bulk H3 process
  - VCOs fabricated with NSC's SOI CBC8 process
  - Full PLLs incorporating the above VCOs
  - Low energy laser studies of 45 nm devices and body contacts
- **Single-Photon Front-side Laser Illumination for SET Measurements**
  - Phase Shifter's built in IBM's 8HP technology

We will Also Continue to Push on Using NanoTCAD for mixed-mode Simulations of HBT Circuits

PROBLEMS AND CONCERNS

- **None**

John D. Cressler'sSiGe Devices and Circuits Research Team

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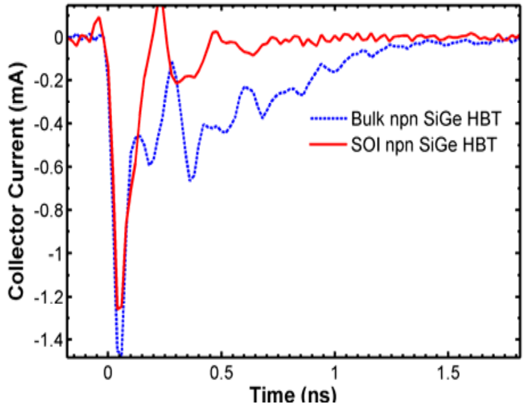
Radiation Experiments

- **NRL Two-Photon Pulsed Laser (04/10)**
  - PLL and VCO devices tested for SEE (TBD)
- **Heavy-ion Broadbeam – (05/10 Texas A&M)**
  - 5AM Inverse Mode Cascode
  - Complementary SOI

TECHNICAL HIGHLIGHTS

Recap of SOI Transient Measurements



- 36 MeV oxygen microbeam at Sandia
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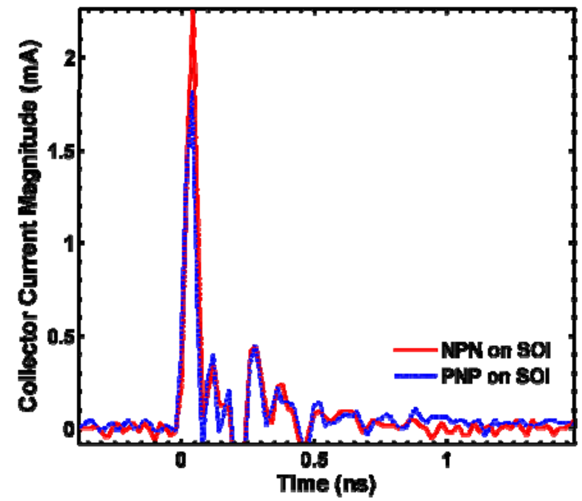
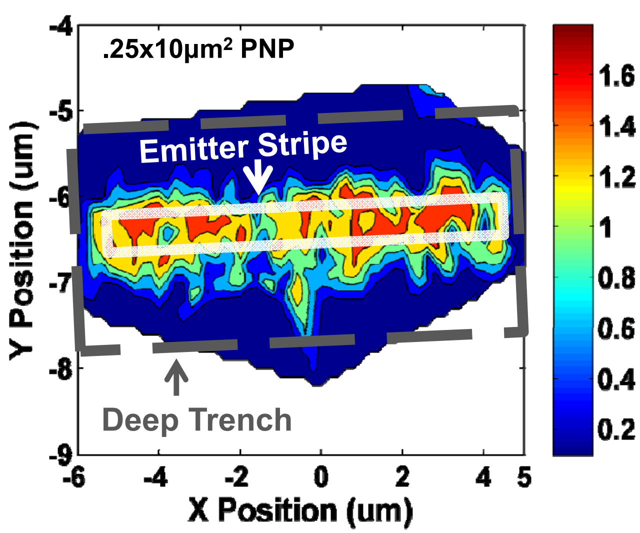
- SOI dramatically shortens transient duration!

Comparison of SOI npn vs. pnp SiGe devices shows similar response





Microbeam scan shows limited sensitive area for the SOI device -- Peak currents heavily concentrated on emitter center and well inside the DT ring

TECHNICAL HIGHLIGHTS

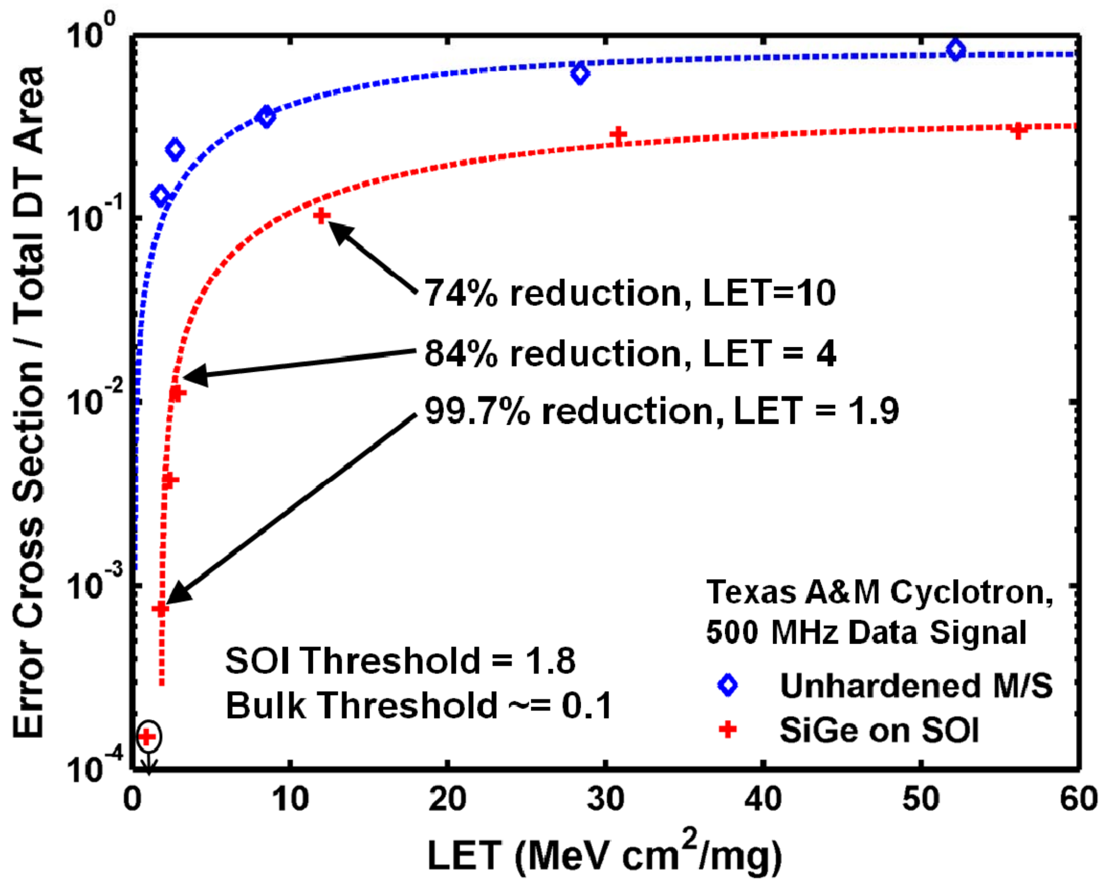
Broadbeam SEU Results for SiGe on SOI

Texas A&M – May 2010

National Semiconductor, 50-GHz complementary thick-film SiGe on SOI

16-bit shift registers operated at 500 MHz

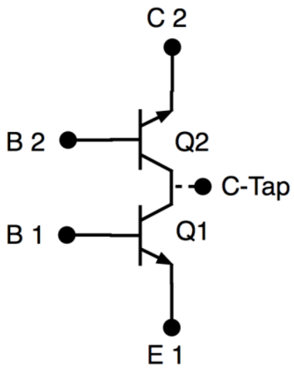
Compared to unhardened, bulk 5AM data

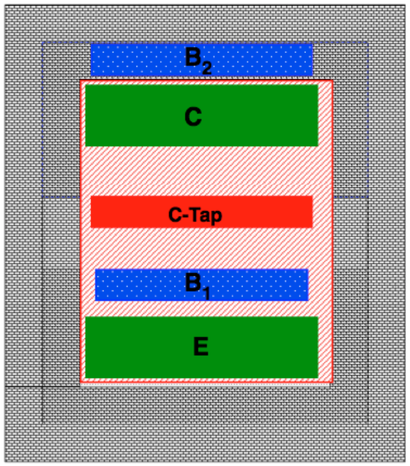


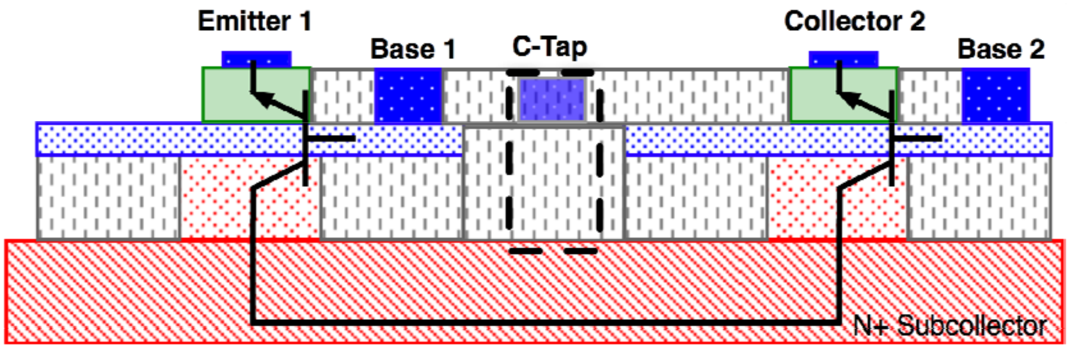
TECHNICAL HIGHLIGHTS

Summary of IMC device

- **De-couple sensitive node (Collector) from circuit output**
  - **two transistors operating as one ("cascoded pair")**
  - **use least-sensitive parts of both transistors**
  - **➔ Inverse-Mode Cascode (IMC)**







submitted to NSREC 2010: "Design of Digital Circuits Using Inverse-mode CascodeSiGeHBTs for Single Event Upset Mitigation"

patent pending: US 2009/0231034 A1

TECHNICAL HIGHLIGHTS

Inverse Mode Cascode Broadbeam Results

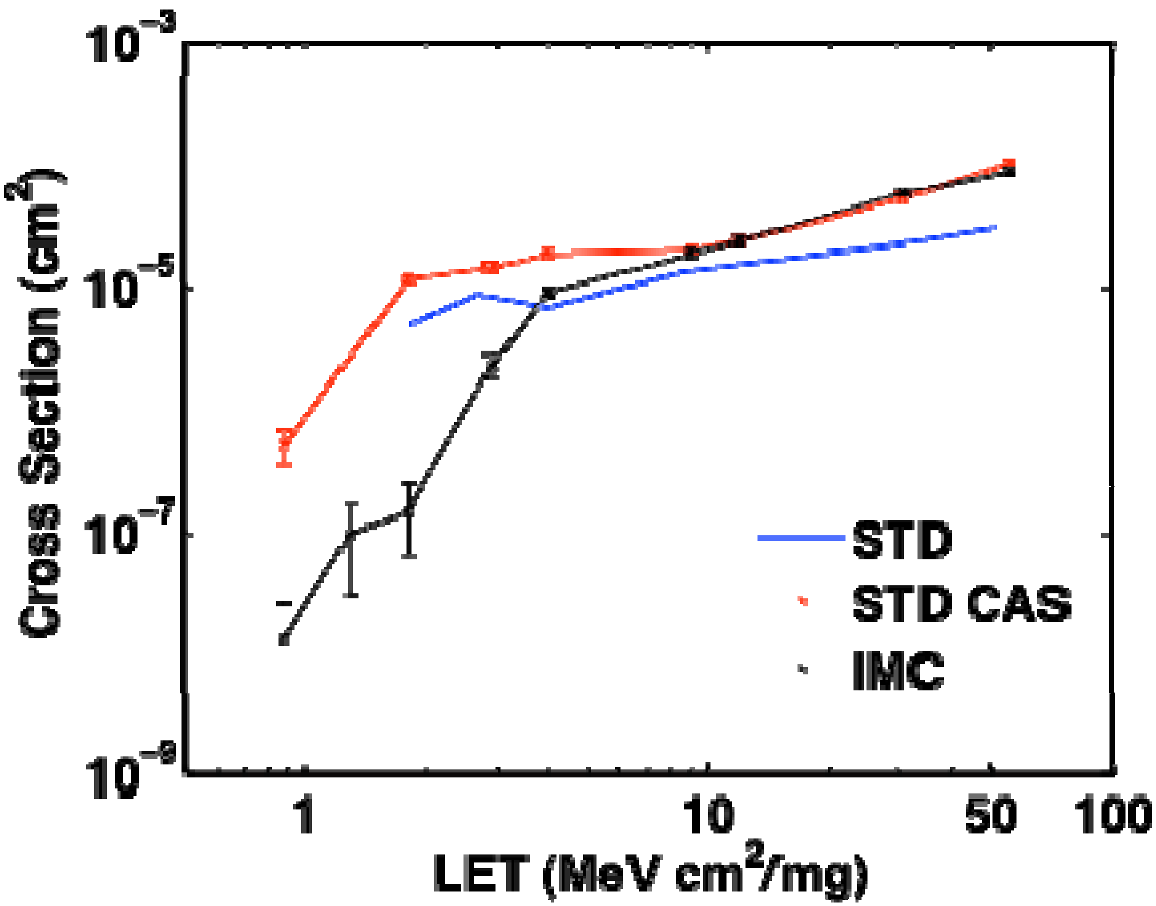
Texas A&M – May 2010

IBM 5AM Bulk SiGe

IMC device features 100fF capacitor tied to common subcollector.

16-bit shift registers operated at 500 MHz

Species	LET
25 MeV N2	0.885, 1.3, 1.8
15 MeV Ne	2.9
15 MeVAr	4
15 MeV Kr	30.8
15 MeVXe	56.2

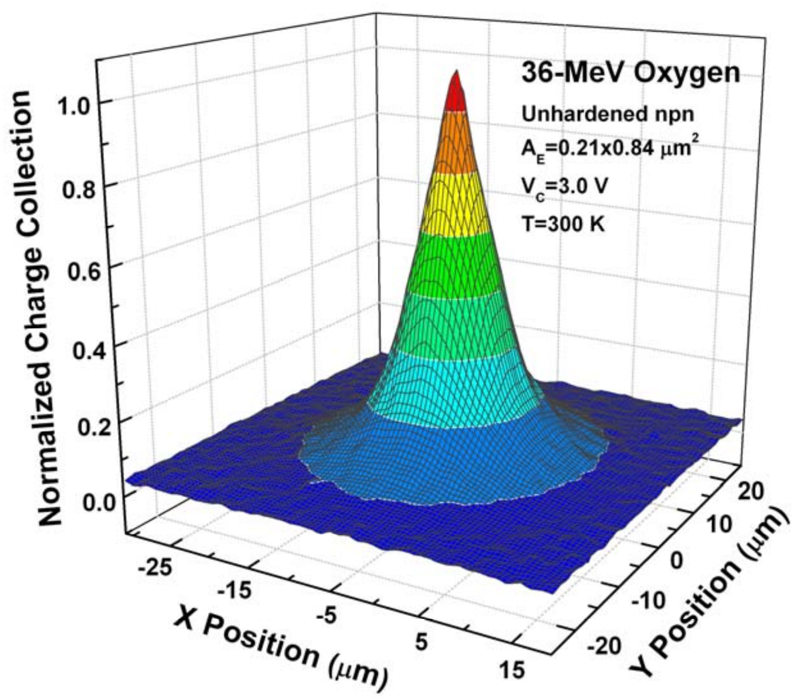


TECHNICAL HIGHLIGHTS

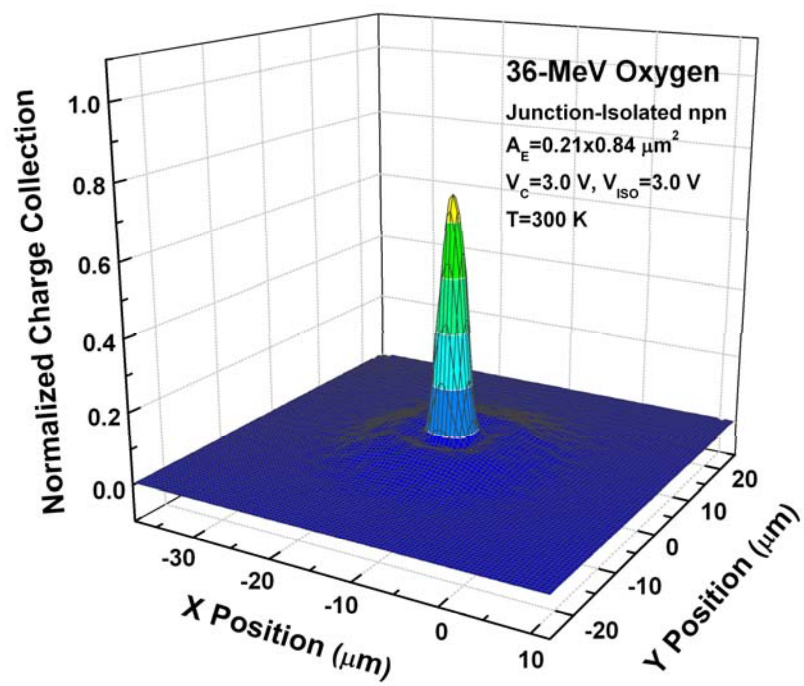
NRING IBICC Results

- **Charge Collection Contours**
  - significant reduction in total charge collection (peak and sensitive area)

Standard HBT



NRING HBT



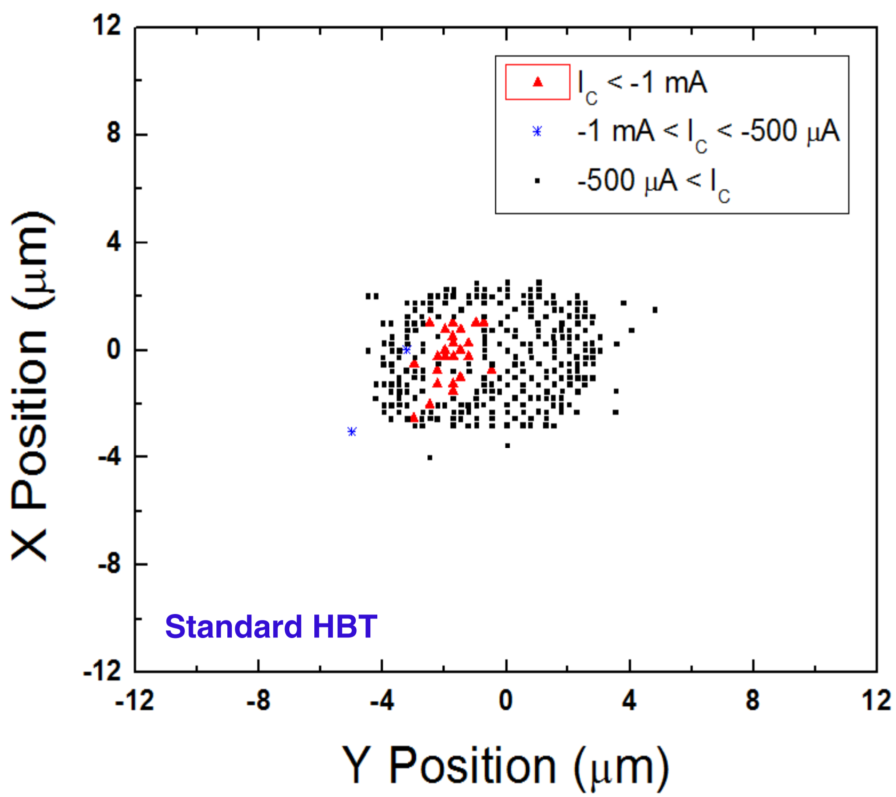
Q: Are these IBICC results real?

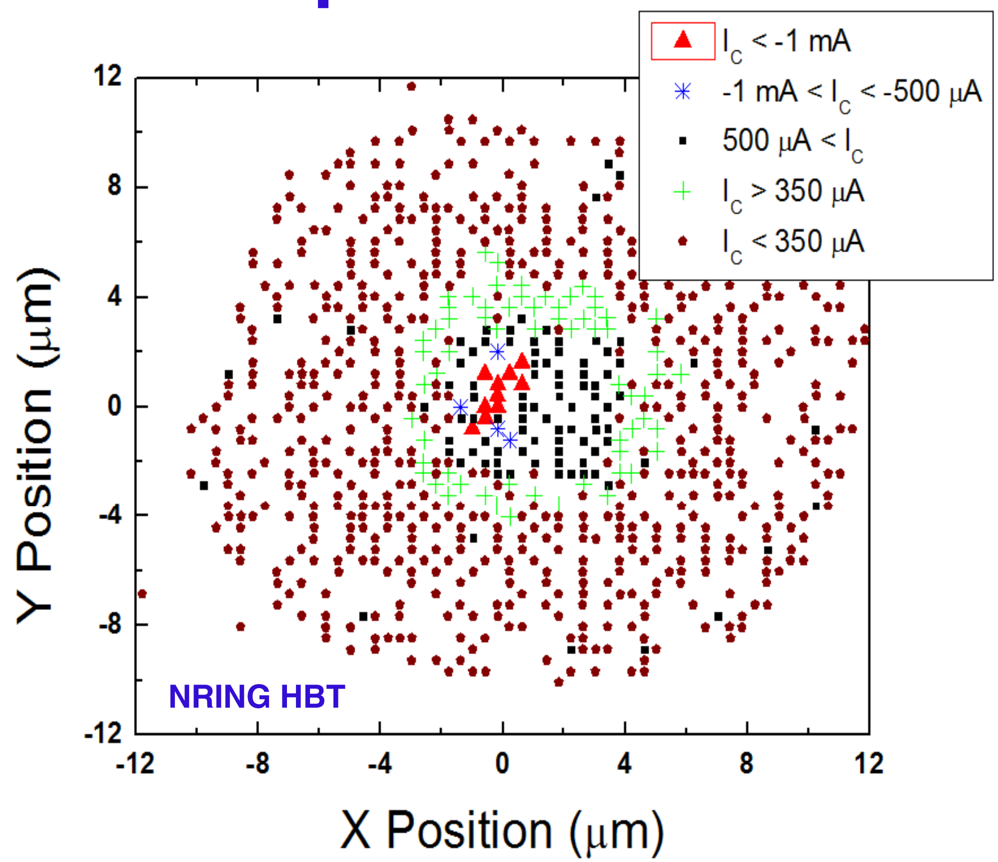
TECHNICAL HIGHLIGHTS

NRING TRIBICC Results

- **TRIBICC Shows Strikingly Different Results From IBICC**
  - NRING device has **large** increase in sensitive area
  - Positive transients exist outside the deep trench

Collector Transient Peak Amplitude

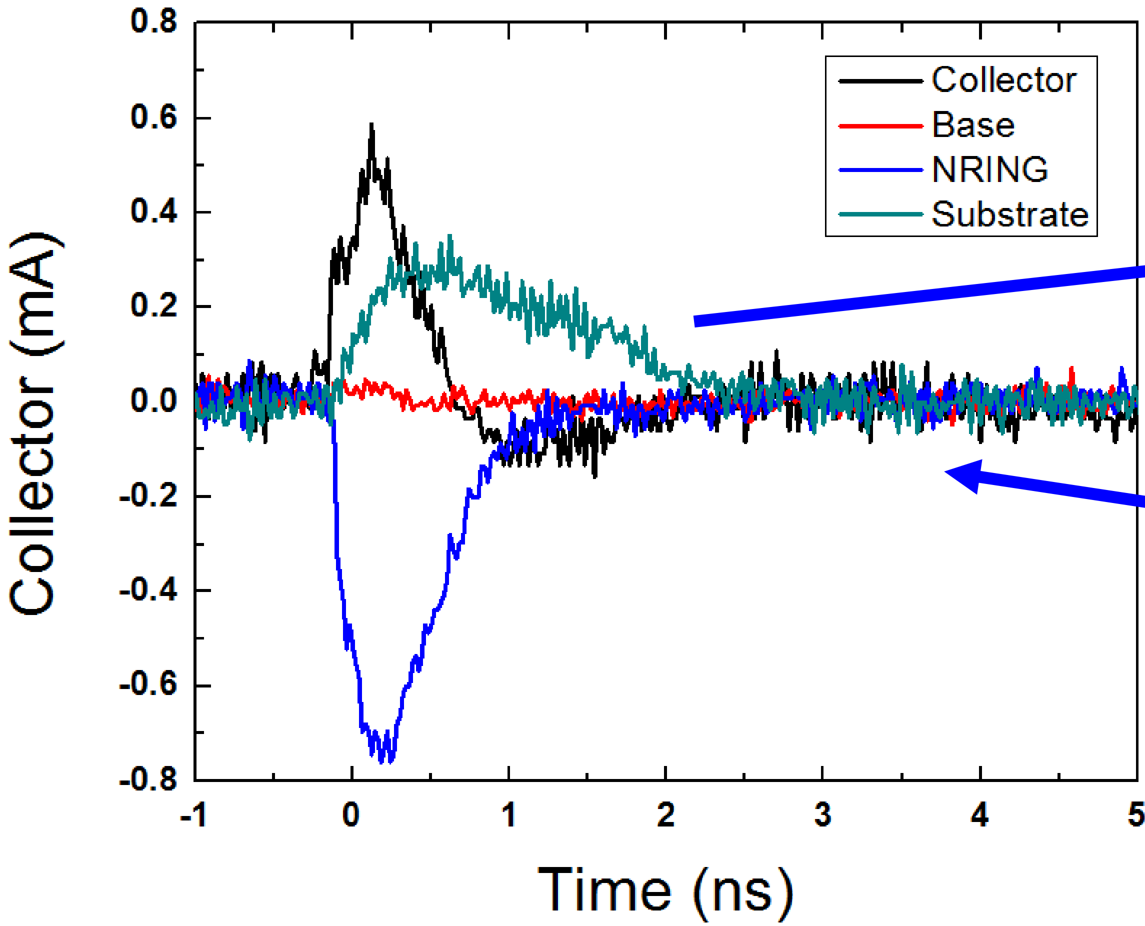


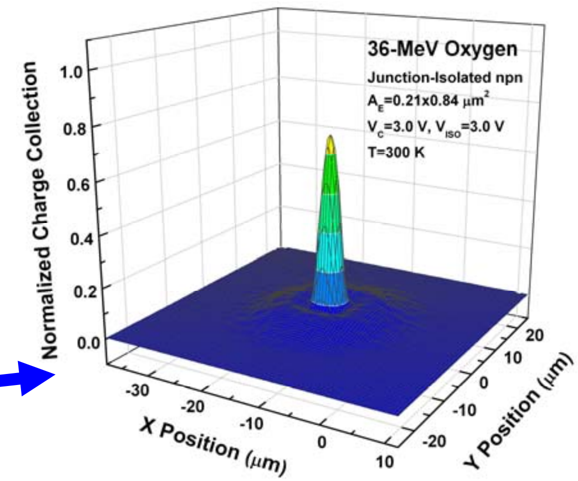


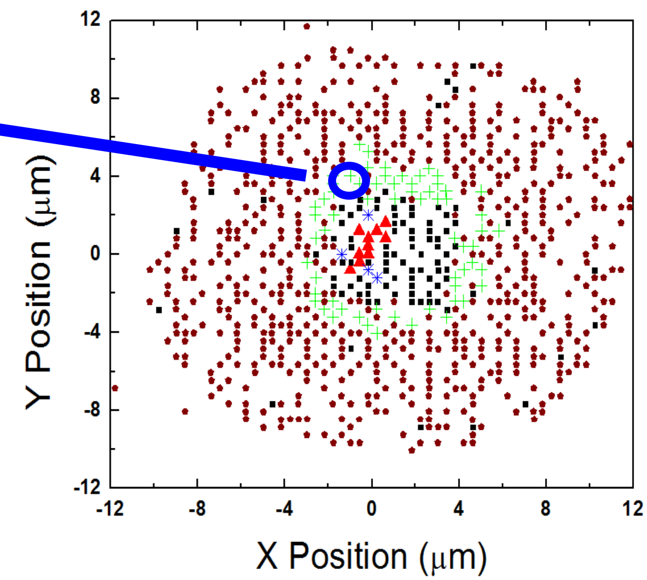
TECHNICAL HIGHLIGHTS

Exterior Transients

- **Transients Induced Outside the Deep Trench Are Bipolar**
  - Integrating will cause cancellation





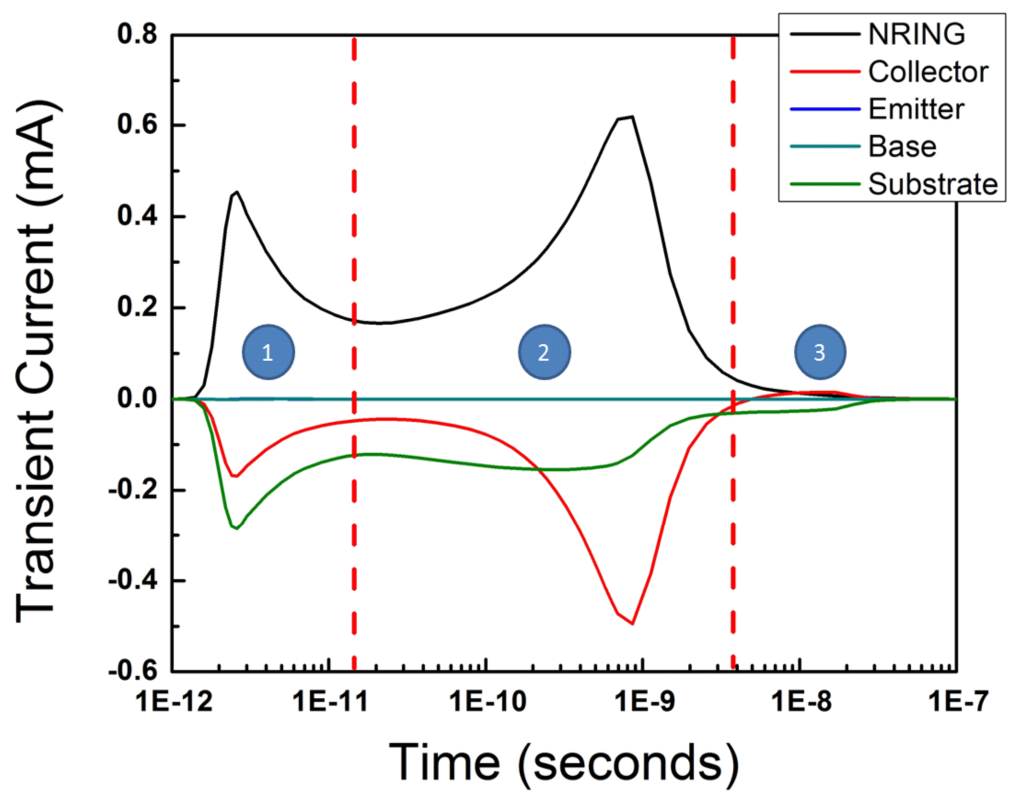


TECHNICAL HIGHLIGHTS

3D TCAD Simulations

- **Ion strike simulations through NRING**
  - Collector transient is bipolar → matches measurement!
  - Transient broken into three regions of different phenomena

1. Capacitive coupling between substrate and collector
2. Parasitic NPN turns on as a result of potential modulation in the substrate
3. Classical collection of electrons through the subcollector-substrate junction

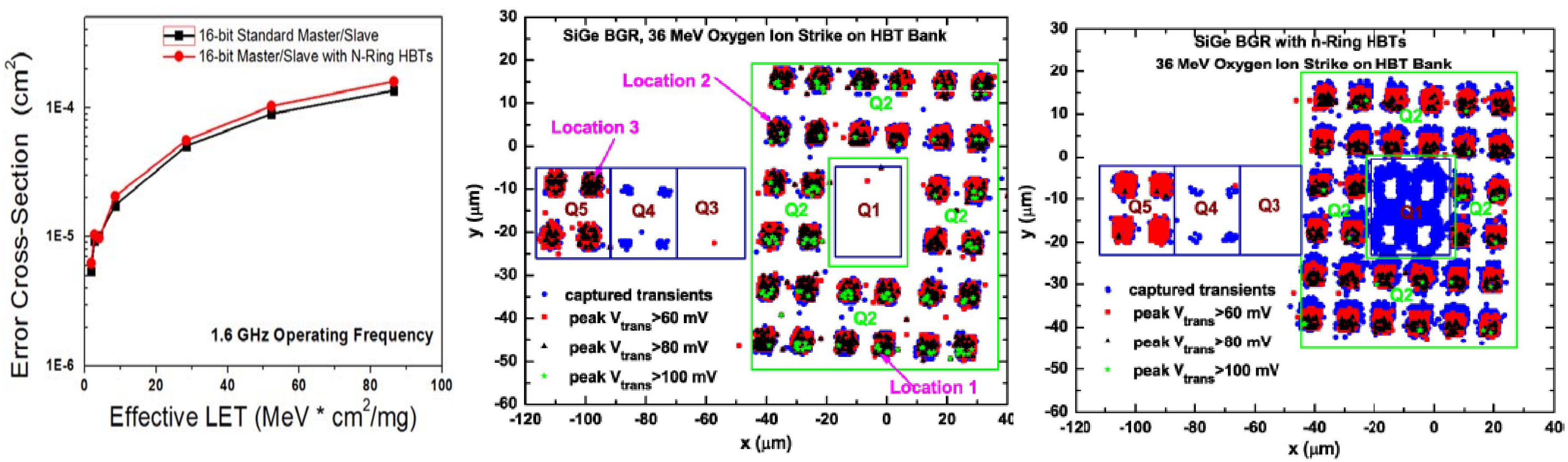


TECHNICAL HIGHLIGHTS

Circuit Implications

- **NRing affect is strongly application dependent**
  - Analog vs. Digital

- Digital shift registers show elevated error cross-section curves when built with NRing HBTs
- Analog voltage references show reductions in large output disturbances, but additional sensitivities for some HBTs



PLANS FOR NEXT QUARTER

Upcoming Radiation Experiments

Texas A&M – Week of July 24

- **NASA ETDP Cryogenic SEU Experiment**
- **Inverse Mode Cascode Shift Registers on Jazz 120 Bulk SiGe**

PROBLEMS AND CONCERNS

- **None**

John D. Cressler's SiGe Devices and Circuits Research Team

Major Accomplishments this Quarter (FY10 Q4)

Journal Publications

[1] M. Turowski, J. A. Pellish, K. A. Moen, A. Raman, J. D. Cressler, and R. Reed, "Reconciling 3-D Mixed-Mode Simulations and Measured Single-Event Transients in SiGeHBTs," (accepted for publication) Transactions on Nuclear Science, Decemeber 2010.

[2] E. P. Wilcox, S. D. Phillips, J. D. Cressler, G. Vizkelethy, P. W. Marshall, J. A. Babcock, K. Kruckmeyer, R. Eddy, G. Cestra, and B. Zhang, "Single Event Transient Hardness of a New Complementary (npn + pnp) SiGe HBT Technology on Thick-film SOI," Transactions on Nuclear Science, December 2010.

[3] S. J. Horst, S. D. Phillips, P. Saha, J. D. Cressler, D. McMorrow, P. Marshall, H. Gustat, B. Heinemann, G. G. Fisher, D. Knoll, and B. Tillack, "An Investigation of Single-Event Transients in Complementary SiGeBiCMOS Resonant Tank Oscillators," (accepted for publication) Transactions on Nuclear Science, December 2010.

[4] T. Thrivikraman, E. P. Wilcox, S. D. Phillips, J. D. Cressler, G. Vizkelethy, P. Dodd, and P. Marshall, "Design of Digital Circuits Using Inverse-mode Cascode SiGe HBTs for Single Event Upset Mitigation," (accepted for publication) Transactions on Nuclear Science, Decemeber 2010.

[5] K. A. Moen, E. P. Wilcox, S. D. Phillips, J. D. Cressler, H. Nayfeh, A. Sutton, D. McMorrow, G. Vizkelethy, and P. Dodd, "Evaluating the Influence of Various Body-Contacting Schemes on Single Event Transients in 45 nm SOI CMOS," (accepted for publication) Transactions on Nuclear Science, December 2010.

[6] Z. Xu, G. Niu, L. Luo, J. D. Cressler, P. Marshall, R. Reed, and M. Alles, "Charge Collection and SEU in SiGe HBT Current Mode Logic Operating at Cryogenic Temperatures," (accepted for publication) Transactions on Nuclear Science, December 2010.

[7] C. J. Marshall, P. W. Marshall, R. L. Ladbury, A. Waczynski, J. A. Pellish, R. D. Foltz, N. A. Dodds, D.M. Kahle, N. Boehm, R. Arora, J.D. Cressler, R.A. Reed, and K.A. LaBel, "Particle-Induced Latchup in a Cryogenic CMOS Readout Integrated Circuit," (accepted for publication) Transactions on Nuclear Science, December 2010.

[8] S. D. Phillips, K. A. Moen, L. Najafizadeh, R. Diestelhorst, A. K. Sutton, J. D. Cressler, G. Vizkelethy, P. Dodd, and P. Marshall, "A Comprehensive Understanding of the Efficacy of N-Ring SEE Hardening Methodologies in SiGe HBTs," (accepted for publication) Transactions on Nuclear Science, December, 2010.

Radiation Experiments

- **Heavy-ion Broadbeam – (07/10 Texas A&M)**

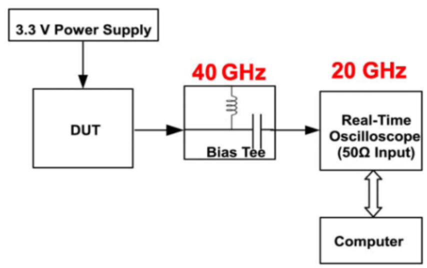
- NASA ETDP Cryogenic SEU Experiment

TECHNICAL HIGHLIGHTS

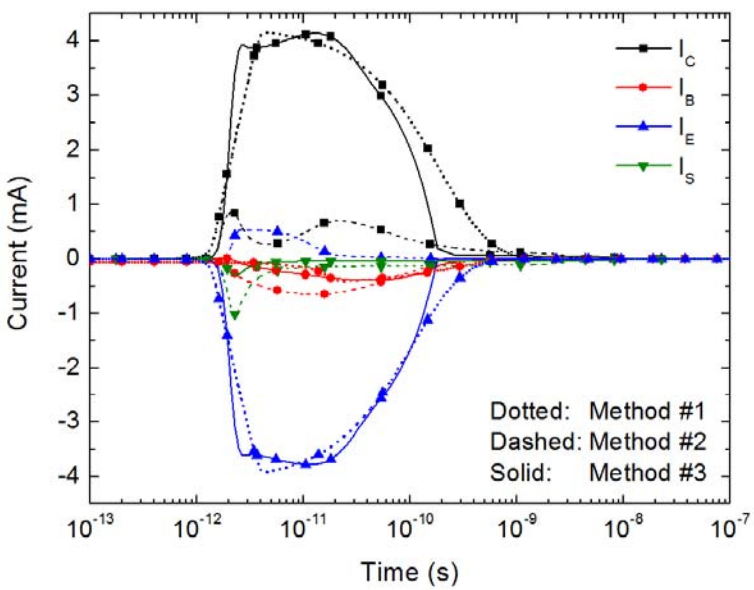
SiGe Voltage Reference Transient Modeling

- **What Are the Best Practices for Circuit SET Modeling?**
  - Compare true mixed-mode vs. Spectre transient current sources
  - Validate against microbeam data measured on SiGe BGR

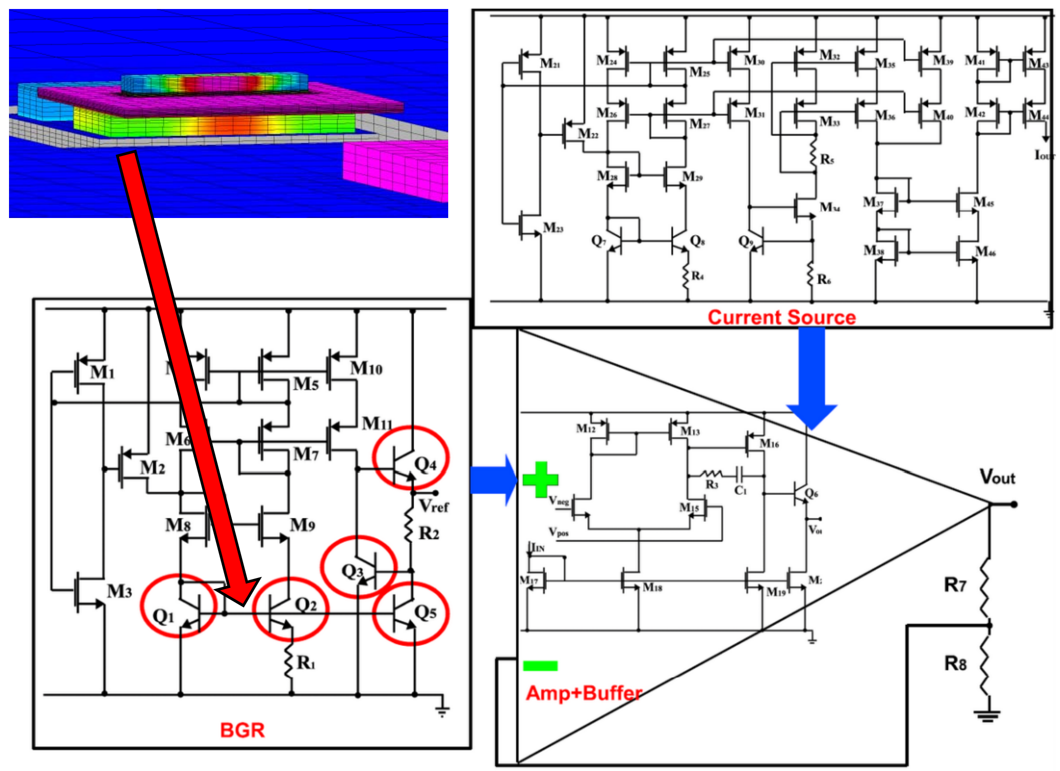
Modeled Experimental Setup



Device SET Within BGR For Each Compact Model Approach



3-D NanoTCAD within Cadence Spectre

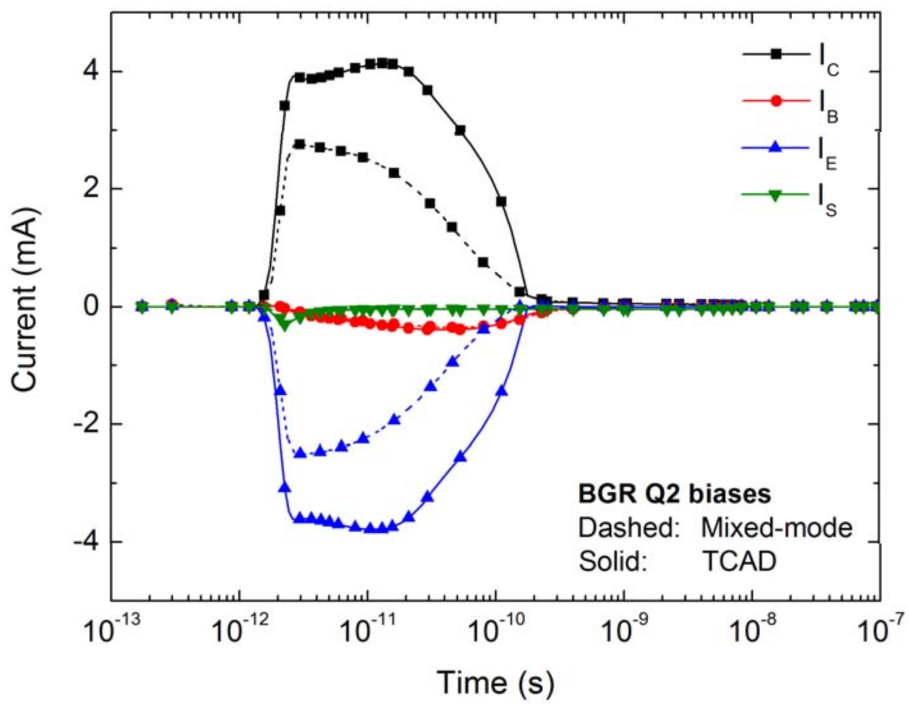


TECHNICAL HIGHLIGHTS

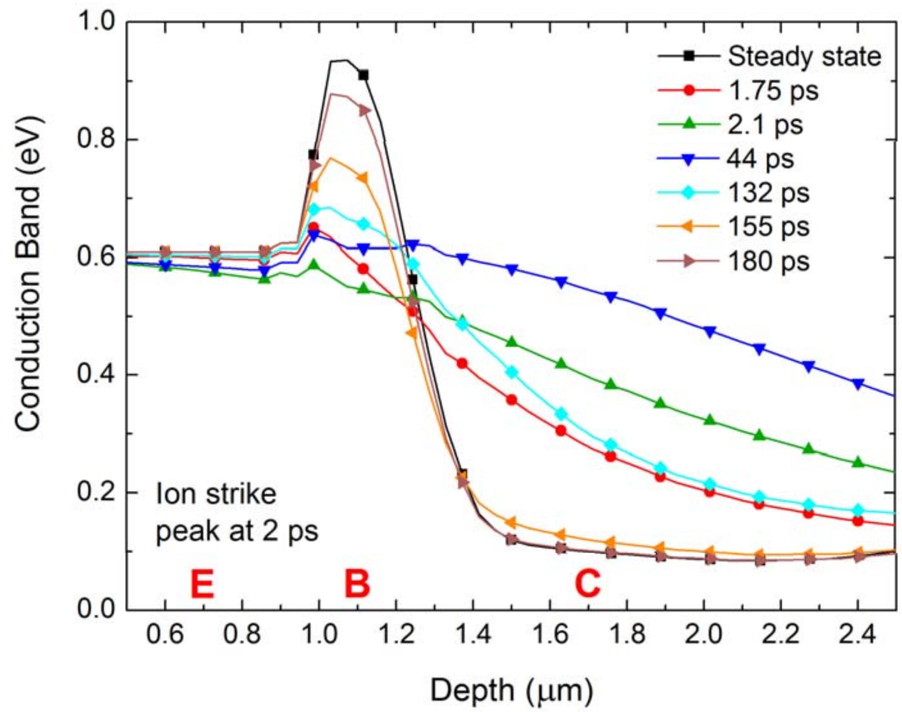
SiGe Voltage Reference Transient Modeling

- **Strong Bias Dependence of Device-Level SET**
  - Large I_C, I_E transients due primarily to ion shunt effect
  - Emitter shorts to collector: nonzero V_{CE} → large I_C + I_E!
  - Mixed mode captures reduced I_C, I_E as V_{CE} decreases during SET

Circuit Loading Effect on Device SET



Ion Shunt Effect (Resistive Current Flow)

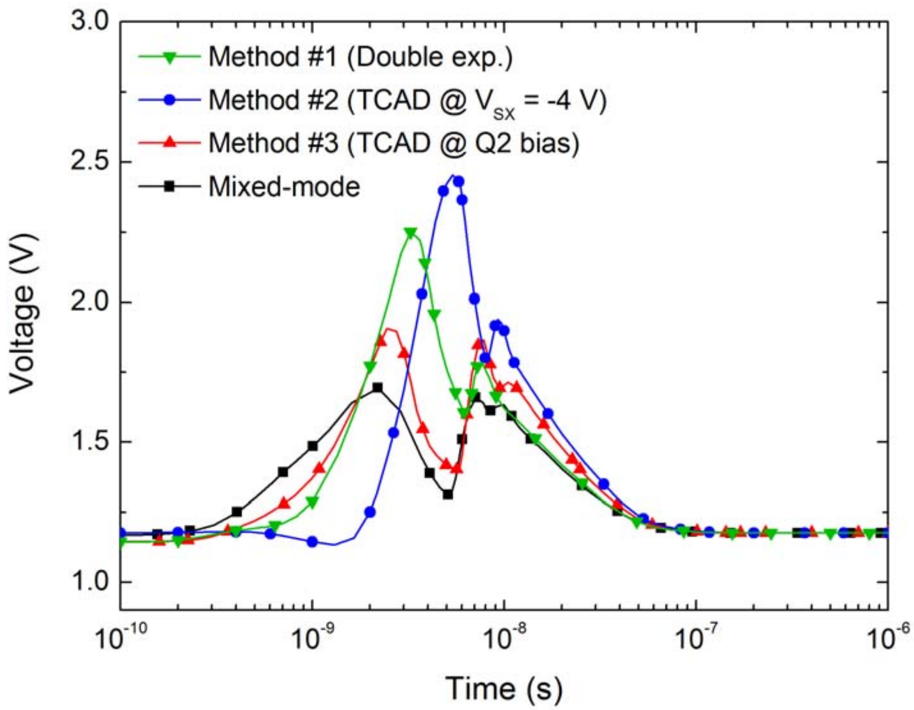


TECHNICAL HIGHLIGHTS

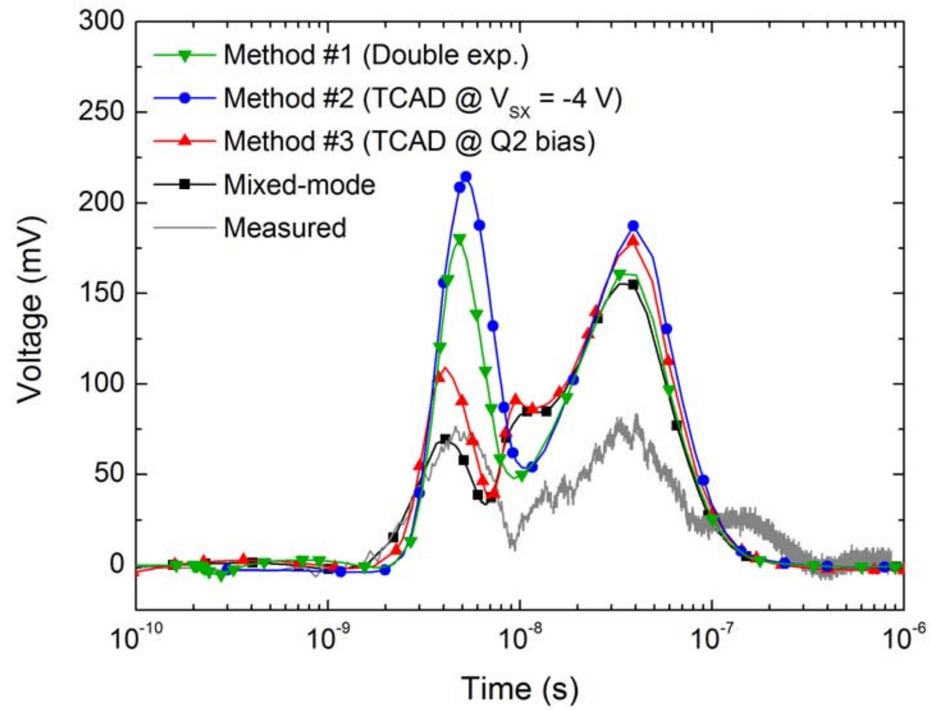
SiGe Voltage Reference Transient Modeling

- **Comparison of Simulated SiGe BGR Output Transients**
  - All approaches show lengthened circuit SET due to similar Q2 I_B
  - True 3-D mixed-mode best captures SET structure
  - Further work required to identify error in second SET peak

Simulated SET at BGR Output



Simulated SET at Oscilloscope

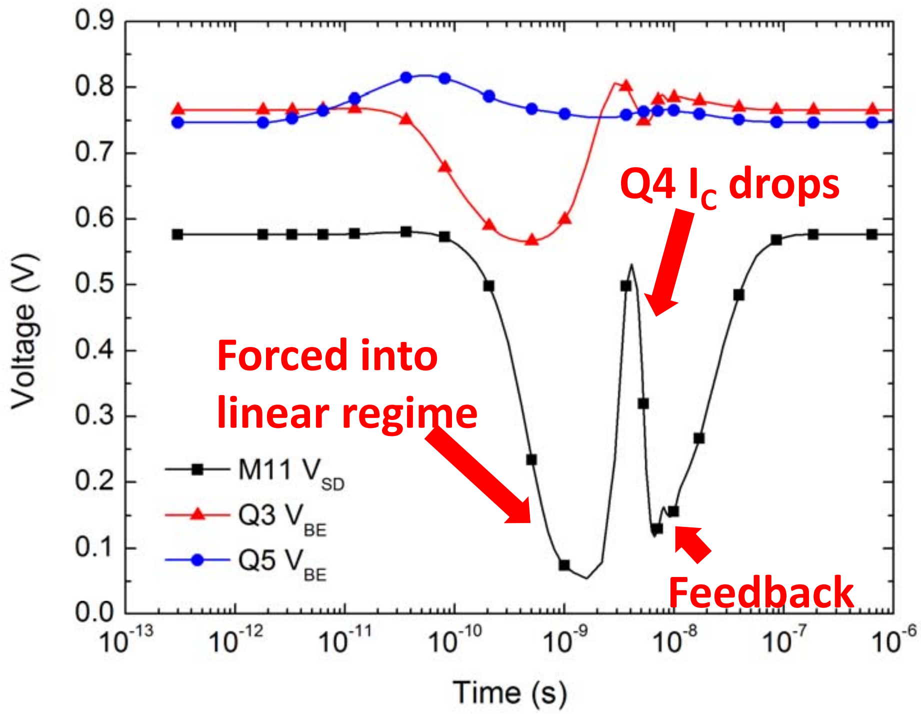


TECHNICAL HIGHLIGHTS

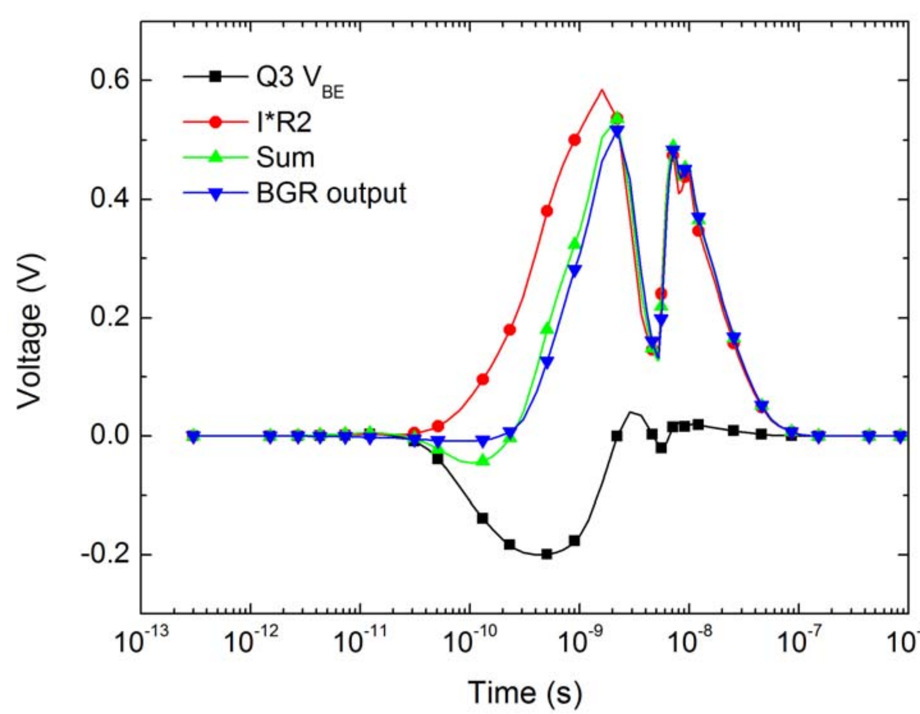
SiGe Voltage Reference Transient Modeling

- **Mixed-Mode Results Illuminate BGR SET mechanisms**
  - Sensitive to Q2 I_B transient! → forces Q5 I_C transient at output
  - Circuit SET shape driven by feedback loop with PFET mirror
  - Results highly dependent on analog circuit topology!

Voltage Bias Transients



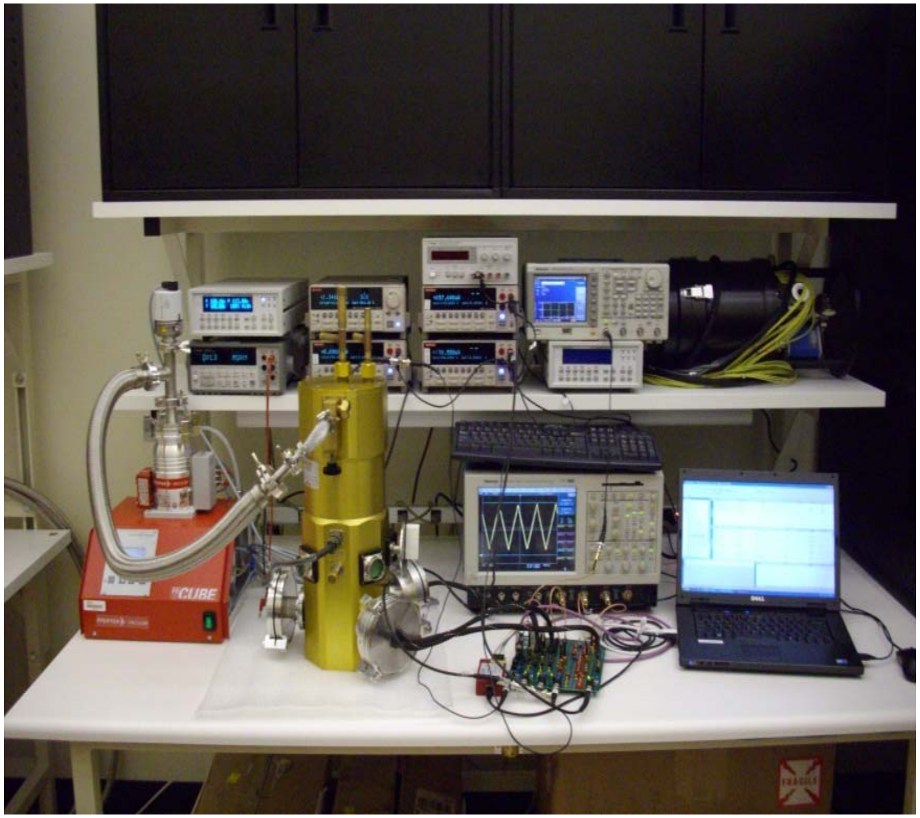
Output Transient Components



TECHNICAL HIGHLIGHTS

REU Measurement Description

- **Over-T Objectives**
  - Channel Resolution
  - Noise Analysis
  - Sensitivity
- **Radiation Test Objectives**
  - Single Event Effects as noise
  - Single Event Latchup immunity



Over Temperature setup at Georgia Tech

TECHNICAL HIGHLIGHTS

REU Measurement Description: Channel Resolution

LSC & HSC: Resistance

- Pick 5 resistances spaced evenly in the full scale range
- Take mean of output samples
- Use linear fit to find resolution

CHC: Charge

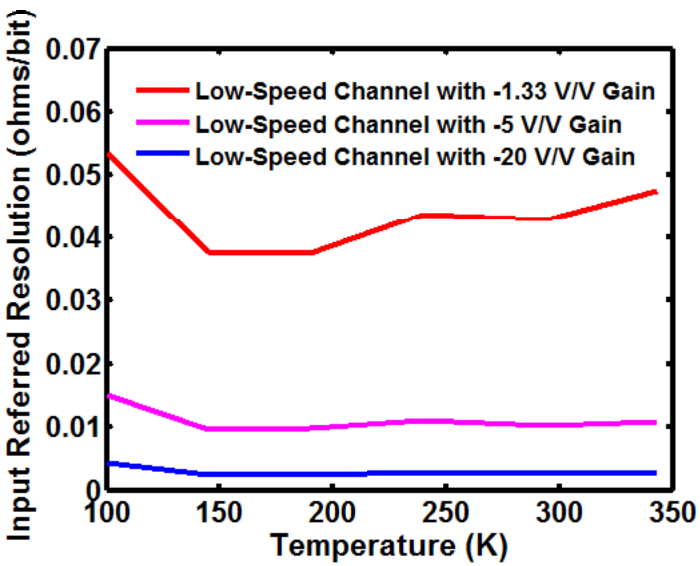
- Hard to know exact charge on input
- Use current source instead
- Sine wave is simple to integrate and sample in digital environment

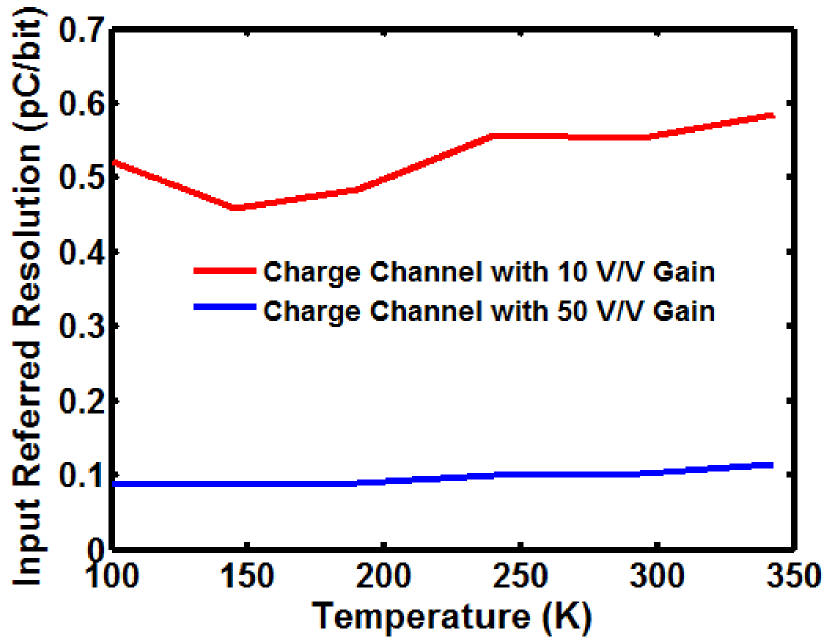
$$Q_{pp} = \int_0^{\frac{1}{2f}} A\sin(2\pi f t)dt = \frac{2A}{2\pi f}$$

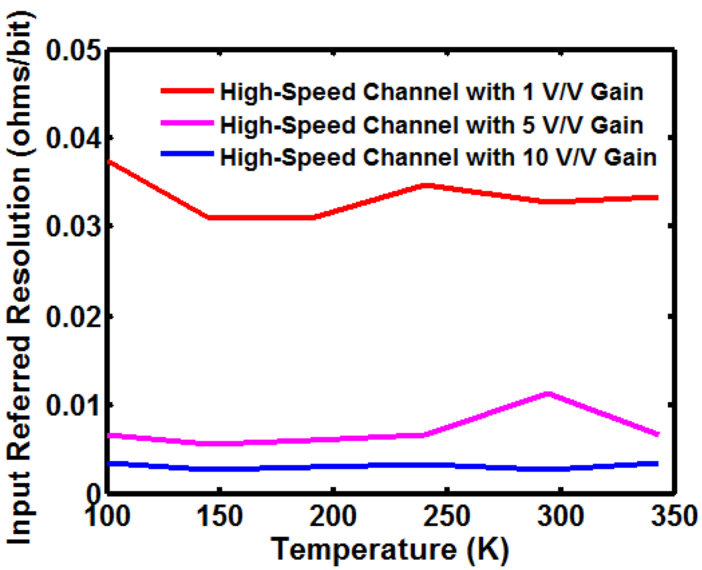
- Calculate RMS value of sampled sine and convert to peak-to-peak

TECHNICAL HIGHLIGHTS

Channel Resolution Results



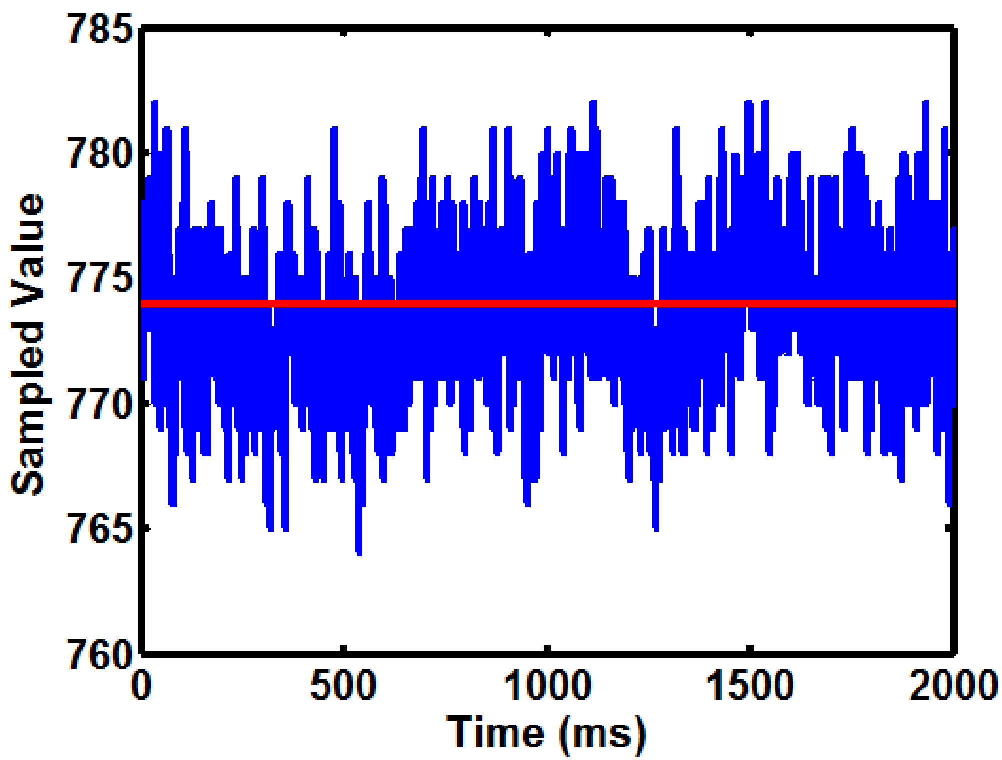




- Better than 60 mΩ or 0.6 pC /bit in lowest gains

TECHNICAL HIGHLIGHTS

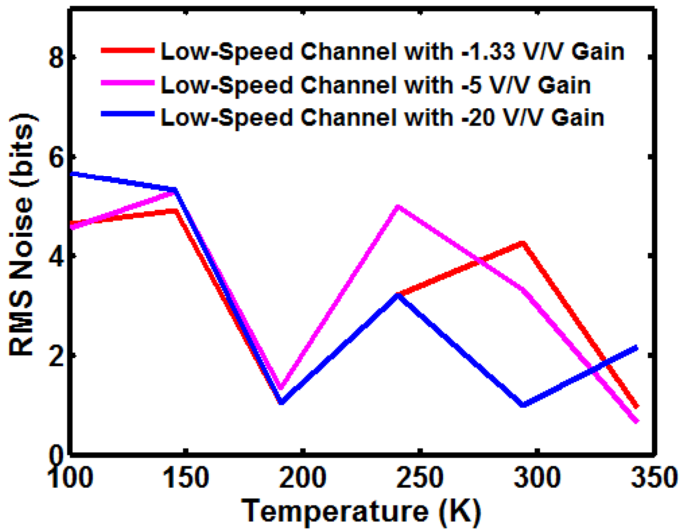
Noise Analysis Theory

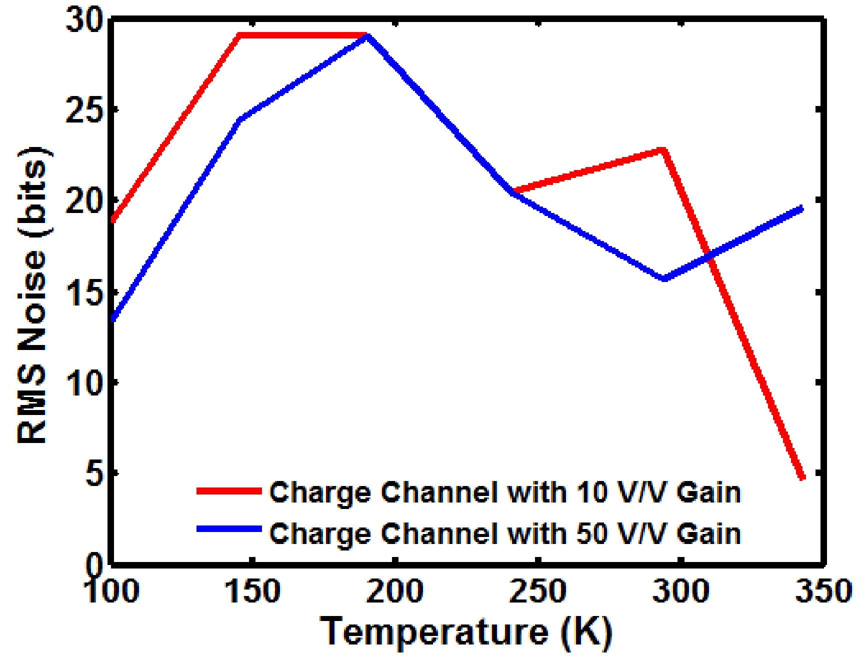


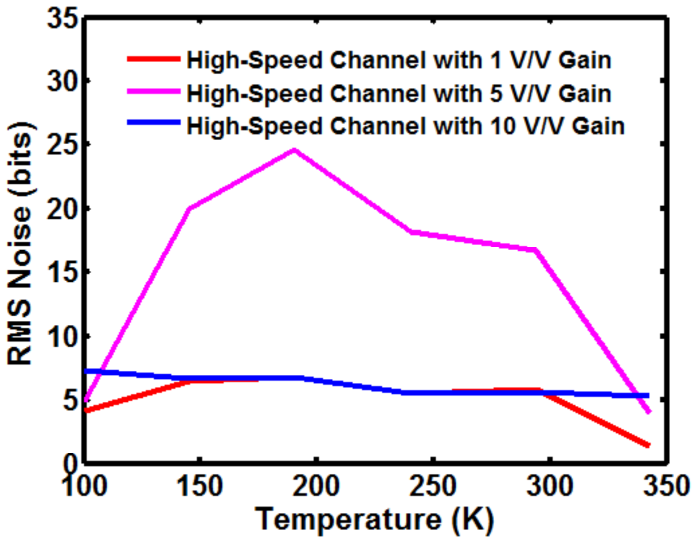
- Setup DC output
  - Balanced Wheatstone bridge on LSC and HSC
  - Use V Zero Bar on CHC
  - Sample output
  - Find mean (red) and subtract it out
  - Calculate rms value of AC coupled result
  - Result is rms noise in units of bits

TECHNICAL HIGHLIGHTS

Noise Results



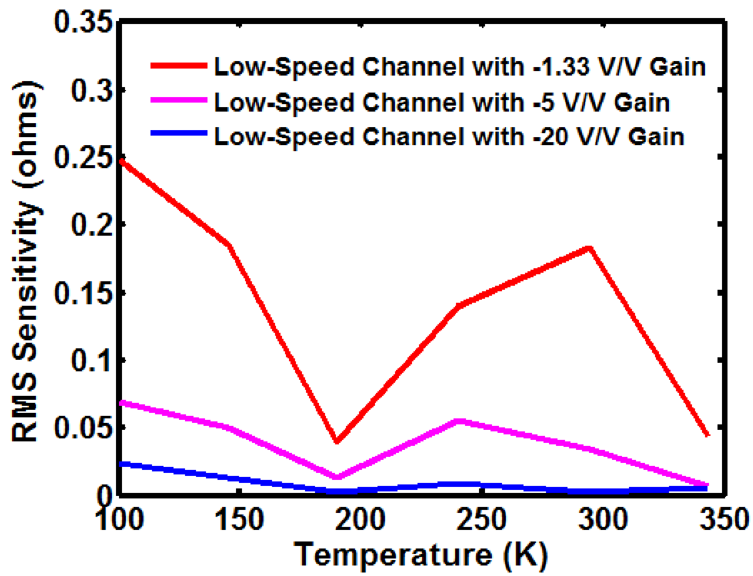


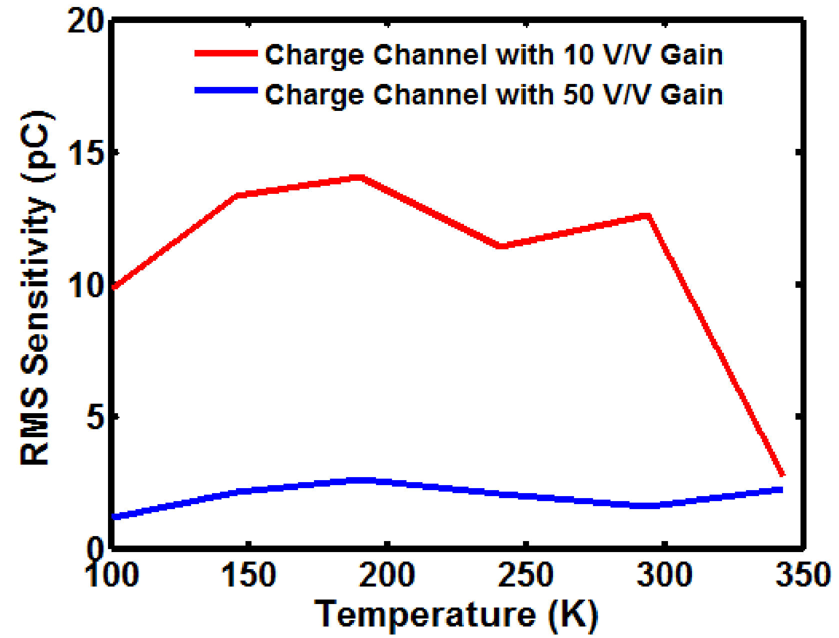


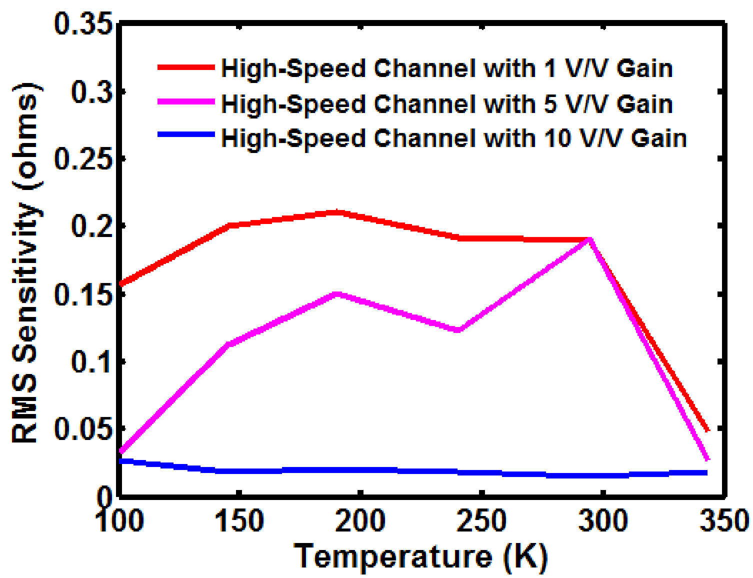
- LSC has lowest noise < .2%
- HSC and CHC < .8%

TECHNICAL HIGHLIGHTS

Sensitivity Results







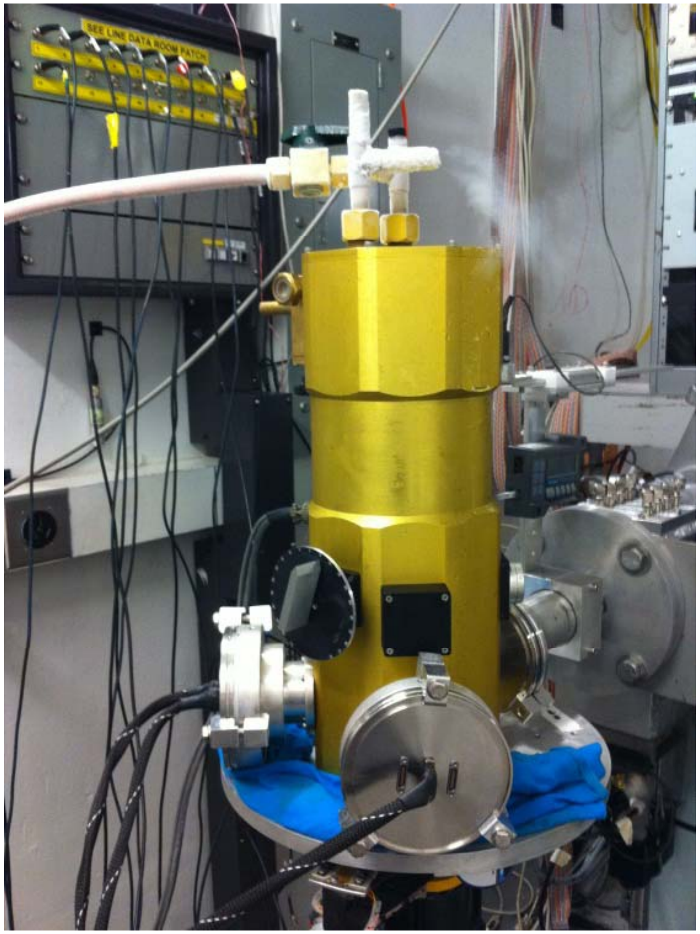
Noise level multiplied by Resolution

Input referred noise

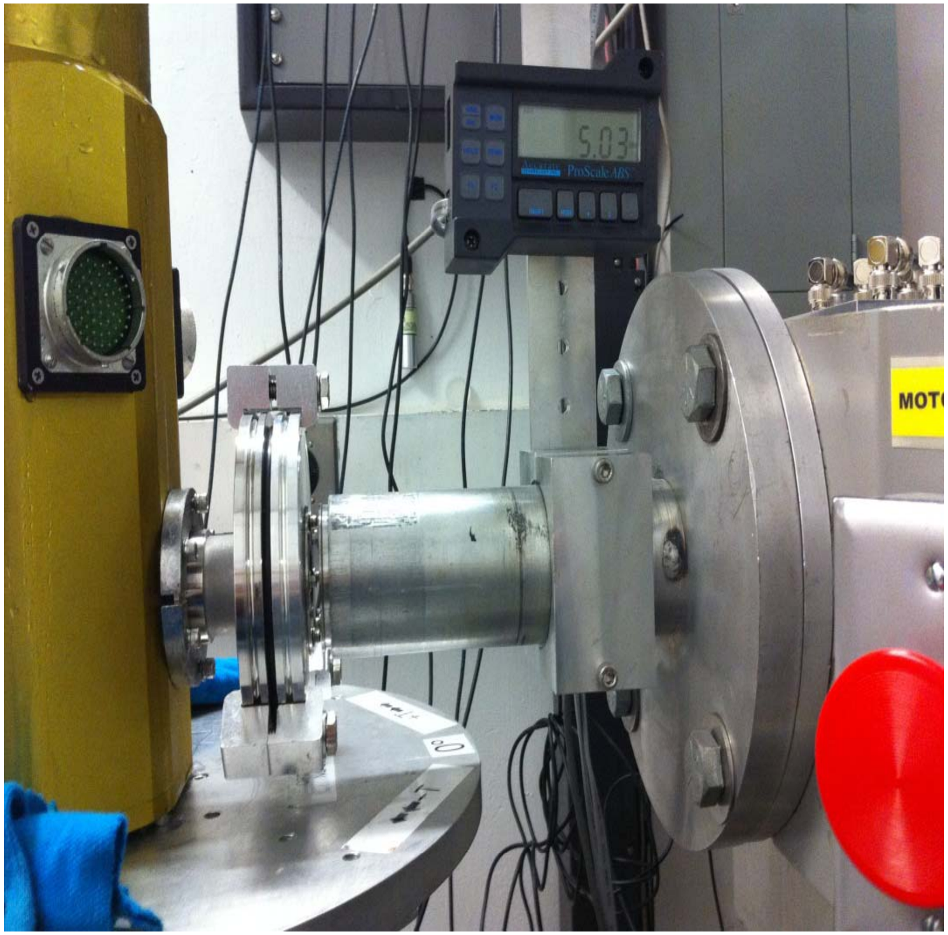
TECHNICAL HIGHLIGHTS

Over Temperature Radiation Testing

Dewar on the Radiation Stage



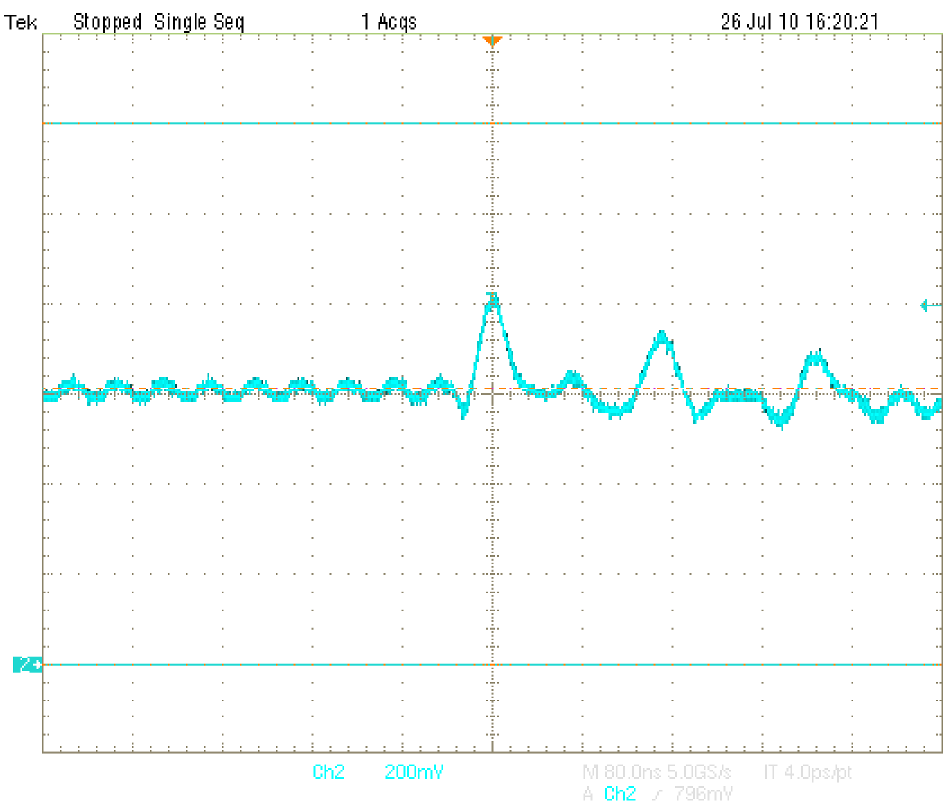
Up-close of Dewar Near Beam



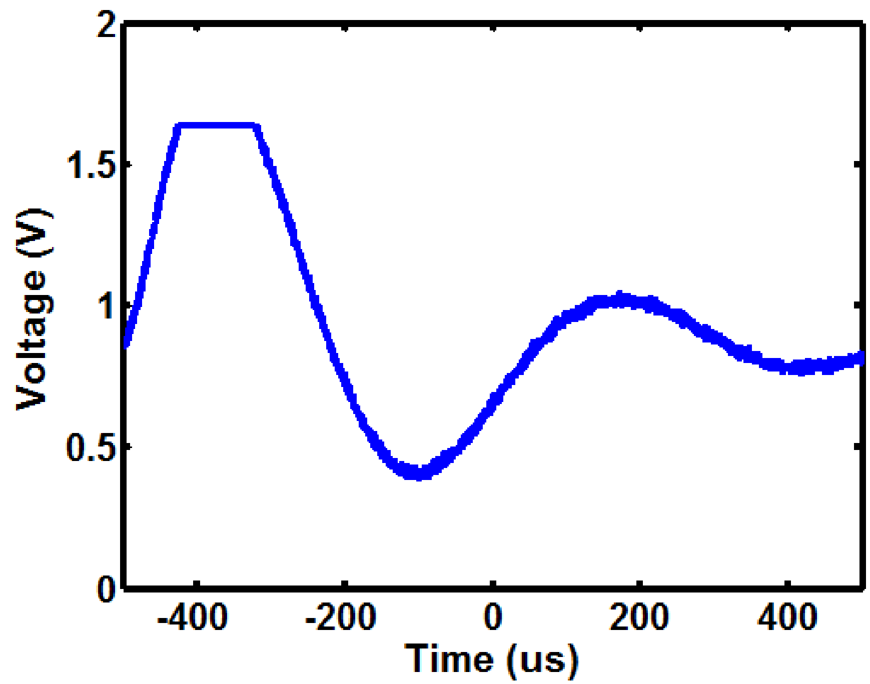
TECHNICAL HIGHLIGHTS

Single Event Transients

HSC Kr Strike at 145 K



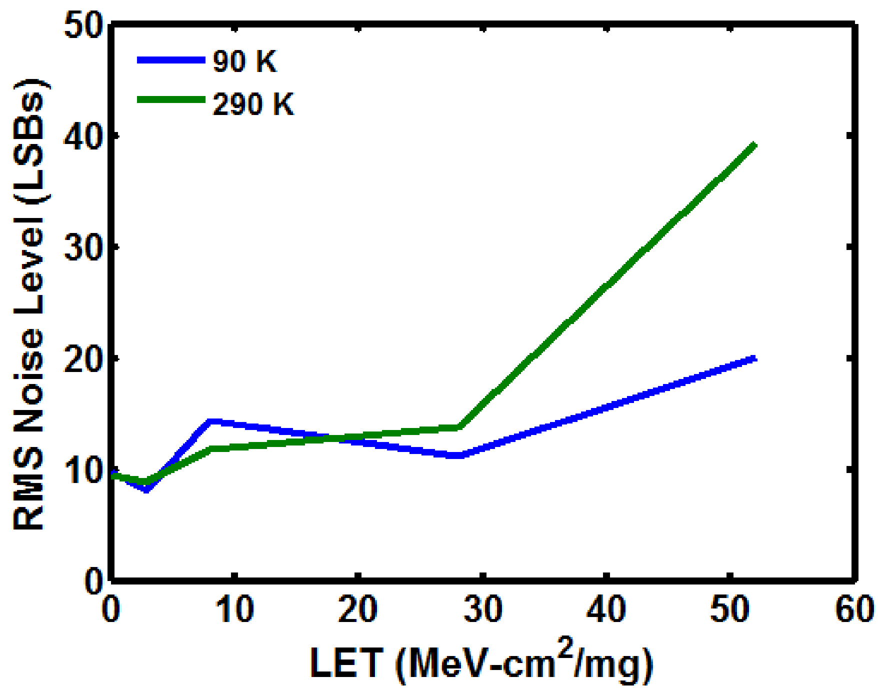
HSC Ar Strike at 191 K



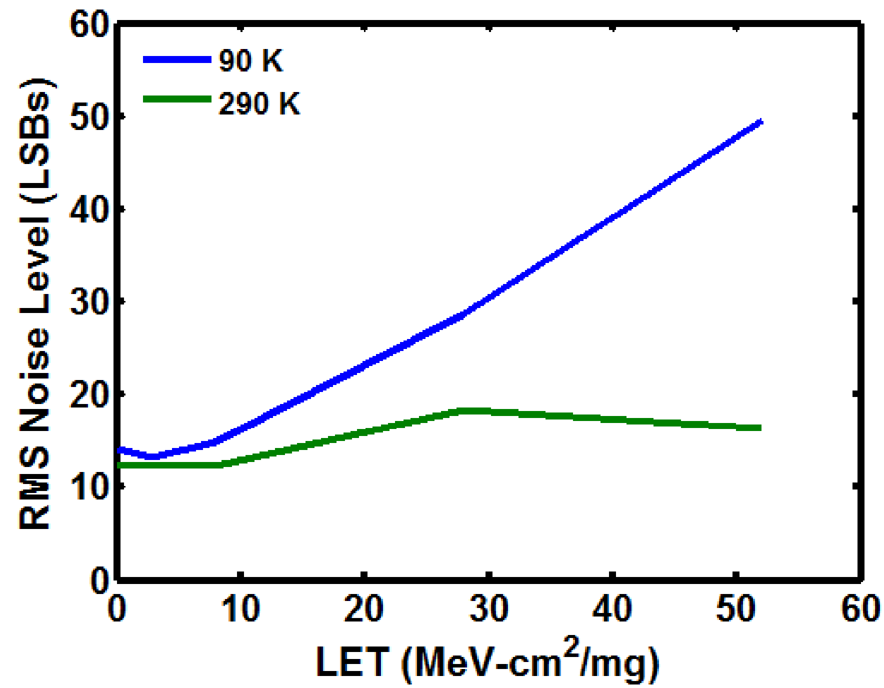
TECHNICAL HIGHLIGHTS

Single Event Effects as Noise

HSC in Low Gain State



CHC in High Gain State



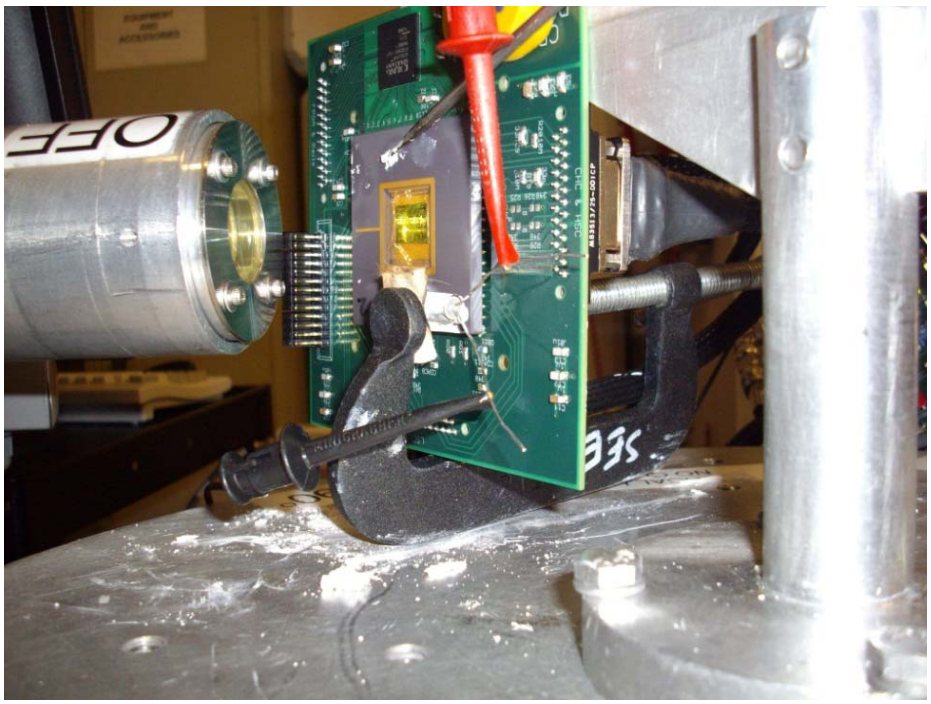
Overall, the trend is increased noise at higher LETs

But no degradation until LETs of 20

TECHNICAL HIGHLIGHTS

Single Event Latchup Testing

High-T Setup



- Represents the worst case
- DUT at 125° C
- Xe (LET of 52)
- 3 angles of incidence
  - 0°, 30°, and 45°
- No noticeable increase in current

TECHNICAL HIGHLIGHTS

REU Testing Conclusions and Accomplishments

- **Completed Resolution, Noise and Sensitivity Analysis from 100 to 343 K**
- **Completed Radiation Over-T from 85 to 293 K**
- **Completed Single Event Latchup Worst-Case Testing**
- **Completed Total Dose Testing to 100 krad, no degradation observed**

PLANS FOR NEXT QUARTER

Upcoming Radiation Experiments

Texas A&M – TBD

- **Inverse Mode Cascode Shift Registers on Jazz 120 Bulk SiGe**
- **SOI Shift Register implemented with Inverse-mode devices**
- **SOI Shift Register implemented with GFC latch architecture**

PROBLEMS AND CONCERNS

- **None**