The RadFxSat-2 Mission to Measure SEU Rates in FinFET Microelectronics

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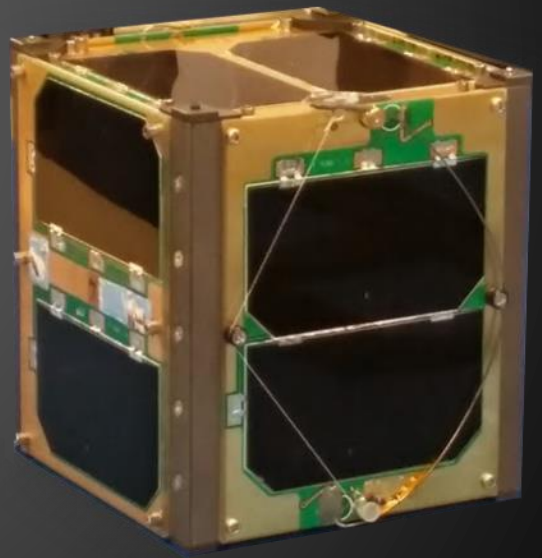
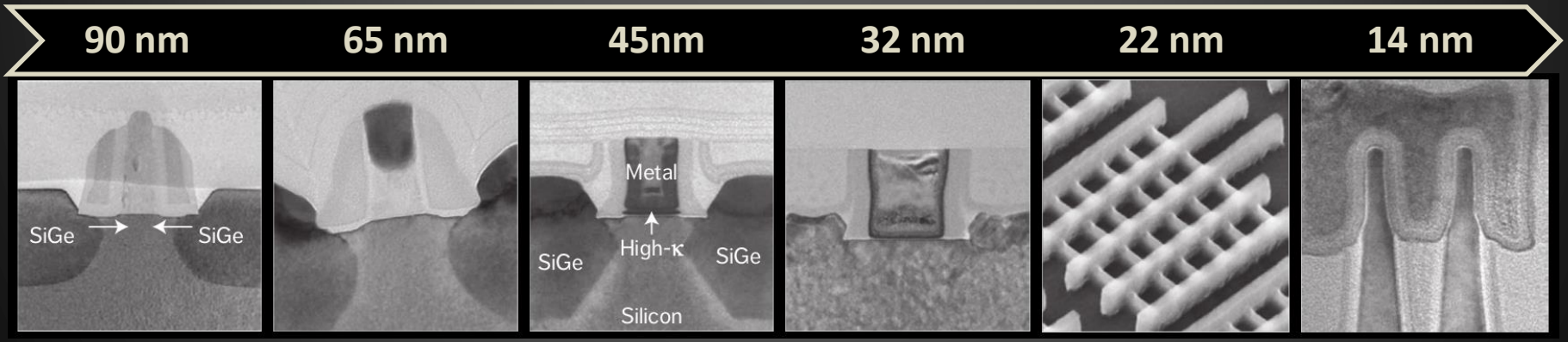
Introduction

- **The Institute for Space and Defense Electronics (ISDE) conducts basic and applied research on the effects of radiation on microelectronics**
  - Design, test, analysis, simulation
  - Specialization on novel technologies
- **The Radio Amateur Satellite Corporation (AMSAT) is a worldwide group of Hams designing, building, and communicating with satellites**
- **Joint missions conceived to generate on-orbit data for radiation effects modeling**
- ***RadFxSat-2 was dedicated to collecting data on a 16 nm FinFET process technology***



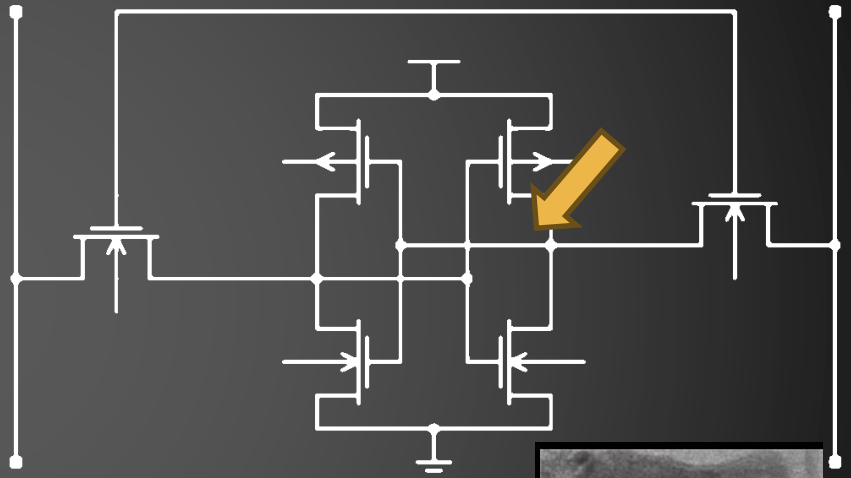
Microelectronic Process Technology Trend

- **Scaling MOSFET transistors below 32nm required greater electrostatic control of the channel for performance and low-power**
  - Planar CMOS fabrication transitioned to 3D FinFET
  - Gate wraps around channel[1-2] reducing leakage and threshold voltage
- ***FinFET on-orbit radiation susceptibility not yet assessed***



Single Event Upsets

- **Ionizing radiation introduces transient current in semiconductors**
- **Reduced voltage margins and capacitance *increase susceptibility* to single event upsets in memory cells[4]**
  - Transient changes state ‘0’ or ‘1’
- **Error rates in Static Random Access Memories (SRAM) characteristic of technology**
  - Impact mitigation and reliability



SRAM cell hit by charged particle, represented by gold arrows, in sensitive regions

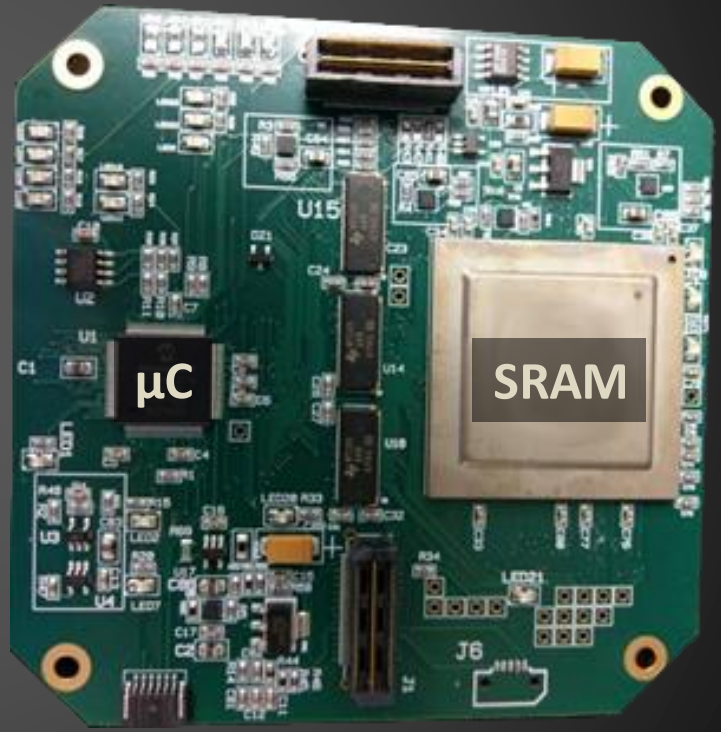
Mission Objective

- **Monitor the effects of radiation on the 16 nm FinFET technology node**
  - Determine on-orbit error rate of memory
  - Evaluate impact of low-power retention on error rate
  - Compare error rates to previous technology nodes
- **First recorded launch and operation of FinFET technology on-orbit**
  - Also onboard: experiments from previous RadFxSat flights using 65 nm (LEP) and 28 nm (REM) memory devices[4-6]

LEPF Experiment Design

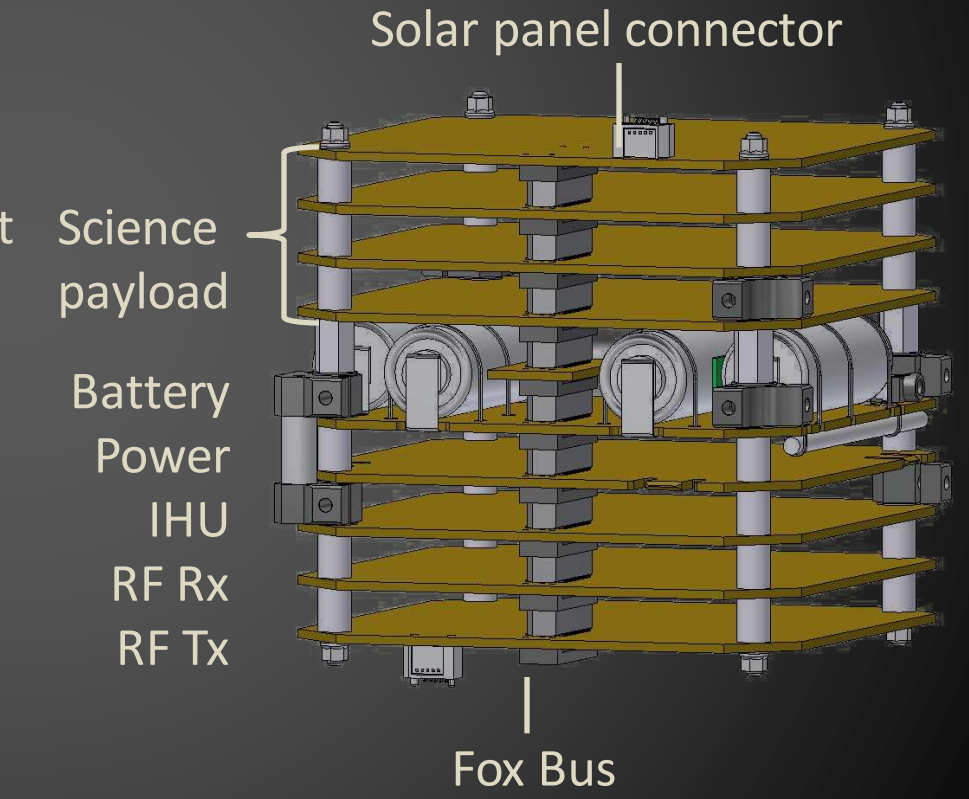
- **16-nm FinFET SRAM chip used as device under test (DUT)**
  - Nominal voltage mode (850 mV) and low-voltage mode (500 mV)
  - Memory initialized to known pattern, scanned for errors each 5 minutes
  - Total error count and livetime stored in non-volatile memory

- **Outside of DUT, peripherals tested for radiation susceptibility and designed to be radiation tolerant**



Satellite Specifications

- **AMSAT's Fox-1 CubeSat bus**
  - 12 space-rated UTJ solar cells
  - 4 Ni-Cd batteries
  - 2 m and 70 cm whip antennas
  - 250 mW payload power budget
- **Manifested on Virgin Orbit LauncherOne Launch Demo 2 through ELaNa 20**
- **Designated AO-109 upon commissioning**



Orbit

AO-85
Launch: 10/8/2015
518 km × 810 km
65° incl., 7.54 km/s
435.172 / 145.980 MHz

AO-95
Launch: 12/3/2018
568 km × 586 km
98° incl., 7.57 km/s
435.300 / 145.920 MHz

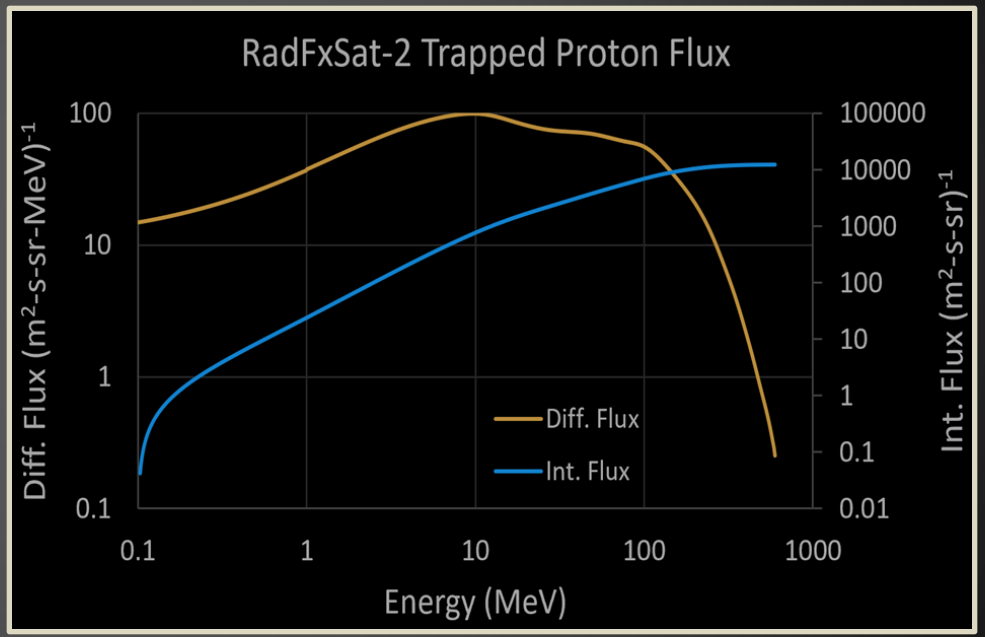
AO-91
Launch: 11/18/2017
456 km × 784 km
98° incl., 7.46 km/s
435.240 / 145.960 MHz

AO-109
Launch: 1/17/2021
449 km × 487 km
61° incl., 7.62 km/s
145.760 / 435.760 MHz

Champagne, Small Satellite Conference, 2023

Mission Environment

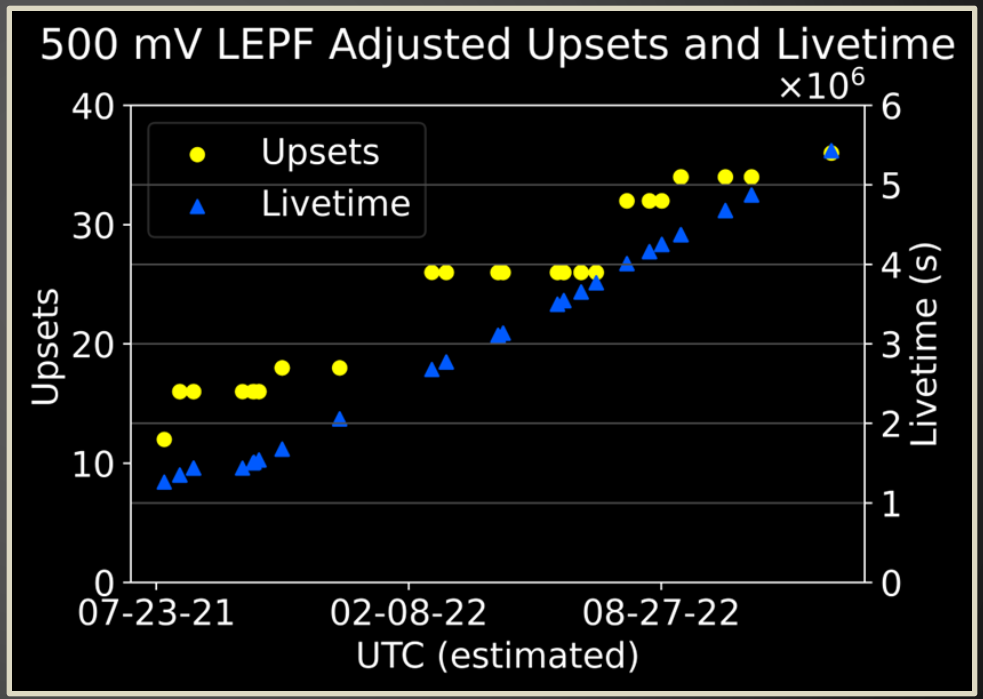
- **LEO environments dominated by proton flux**
- **Previous investigations showed *proton ionization capable of causing SEU* in ≤ 65 nm SRAM cells[7,8]**
  - SEU rate *models do not account for this* mechanism
  - On-orbit SEU data from a low-energy proton-rich environment (like LEO) desired to assess susceptibility



Trapped proton flux within RadFxSat-2's orbit, calculated with CREME96.

On-Orbit Error Counts

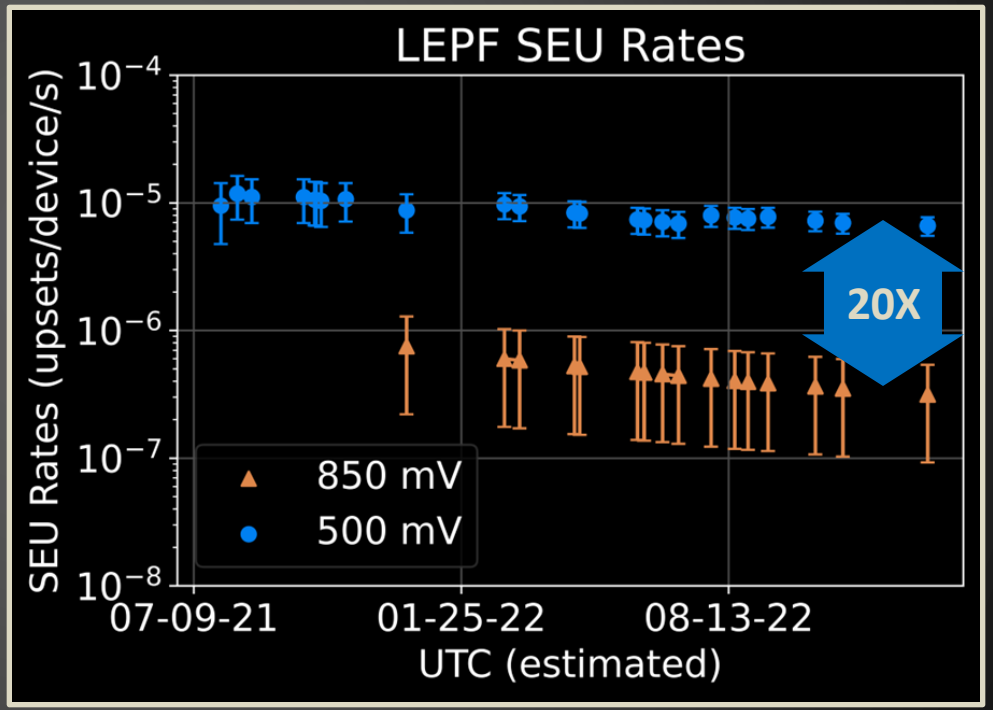
- **Over roughly 1.5 years, the 500 mV mode encountered 70 errors and the 850 mV mode encountered 2 errors**
  - Reduced voltage mode expected to encounter more errors
- **500 mV mode experienced a large jump in errors, likely due to effects beyond SRAM SEUs**
  - ex. Corruption of total error count, SEFI in memory, control error



On-Orbit Error Rates

- Per-device error rates computed from upsets and livetime
- Low power (500 mV) mode experienced ~20X increase in error rate

Experiment	Error rate (upsets/device/s)
LEPF (500 mV)	8.4×10^{-6}
LEPF (850 mV)	4.4×10^{-7}
LEP*	8.7×10^{-6}
REM	DOA



*Rate not directly comparable. Experiments contain different number of undisclosed bits.

Challenges

- **6-month delay from the RadFxSat-2's launch and reception of telemetry**
  - Signals were transmitting, but very weak – most stations could not detect
  - Hypothesized that a dual power amplifier chip onboard shorted which, coupled with an antenna that did not fully deploy, resulted in weak signal[9]
  - See *The AMSAT Journal*, pg. 9, Aug. 2021.

- **Dwingeloo 25m radio telescope, owned by ASTRON, picked up telemetry frames, allowing for communication debugging**

The Dwingeloo radio telescope in Netherlands capture ~90% of data. (courtesy of CRAF)[10]

Lessons Learned

- **RadFxSat-2 used whole orbit data (WOD) transmission**
  - Satellite telemetry and experiment data stored together in a ring buffer
  - Buffer continuously downlinked along satellite's orbit
  - In non-WOD transmission, downlink only within specific transmission footprints along orbit

- **Method of data transmission helped tremendously in recovering RadFxSat-2**
  - Very few ground stations are capable of receiving the weak signal
  - Can recruit any ground station along satellite's path to attempt to establish contact

Summary

- **The RadFxSat-2 satellite has successfully completed its mission, providing the first on-orbit SEU data for a FinFET-based SRAM**
- **The detected SEU rates leave the authors optimistic for FinFETs in LEO**
  - SEU rates for sub-65 nm technology within a proton-rich environment may still be within acceptable limits for many missions
  - Use of error correction and nominal bias further improves outlook
- **Usage of WOD-type transmission in CubeSats allows for flexibility in data retrieval should problems arise with comms**
  - Allowed RadFxSat-2 to overcome *multiple* failures and complete mission

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