

# *Proton Irradiation Effects in Semiconductor Devices –S1328*

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- Overview of radiation-induced effects – total ionizing dose and single-event effects
- *Proton Radiation Effects in Semiconductor Devices* – Tasks for 2011

# Galactic Cosmic Rays

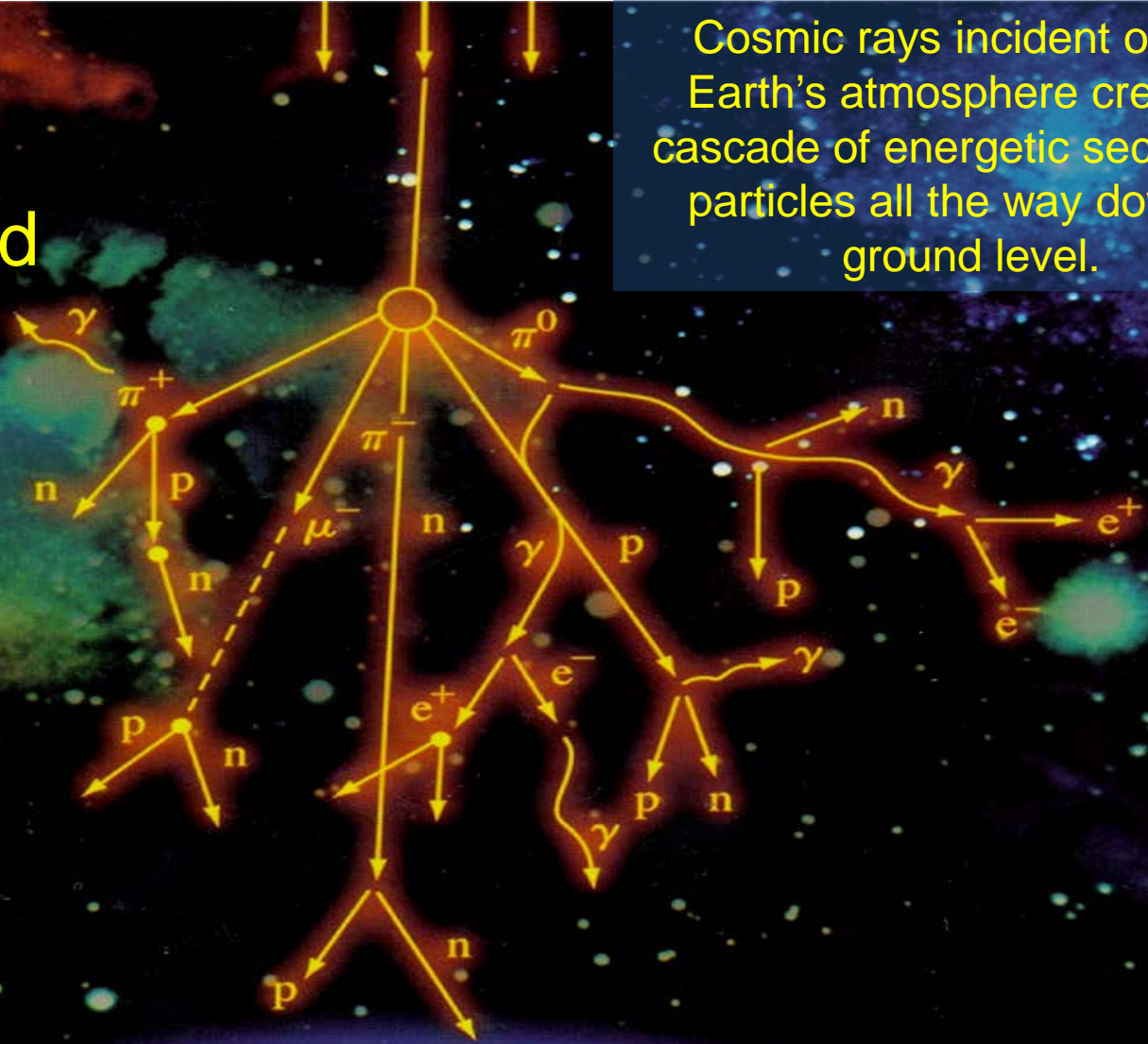
A diagram illustrating the interaction of cosmic rays with Earth's magnetic field. On the left, a bright orange and red sun emits a stream of particles. These particles, represented by blue and green lines, travel towards Earth. The Earth's magnetic field is shown as a complex structure of blue and yellow lines, with a central blue sphere representing Earth. A white arrow points to a region of trapped particles near the equator, and a yellow arrow points to a region of trapped particles near the poles. The background is a dark blue and black space with a grid of lines.

Solar Protons  
&  
Heavier Ions

Trapped Particles

# Terrestrial Cosmic Ray Neutrons and Muons

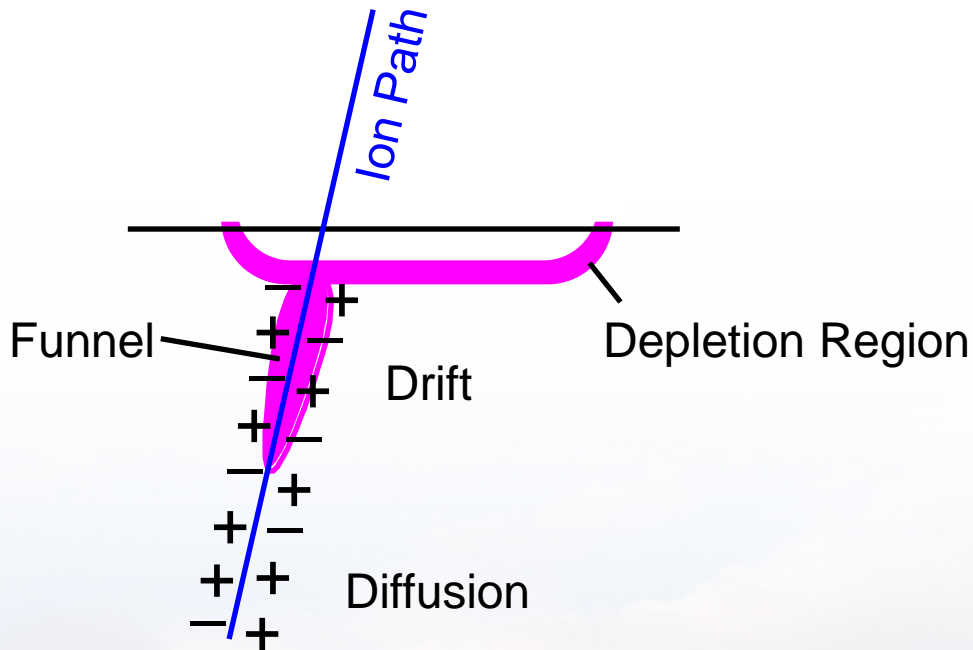
Cosmic rays incident on the Earth's atmosphere create a cascade of energetic secondary particles all the way down to ground level.



The increasing SEU sensitivity of advanced microelectronics technologies raises reliability concerns for terrestrial and high-altitude electronics.

After Ziegler, et al., IBM J. Res. Develop. 40, 1996.

# Single-event upsets are caused by charge collection following an energetic particle strike



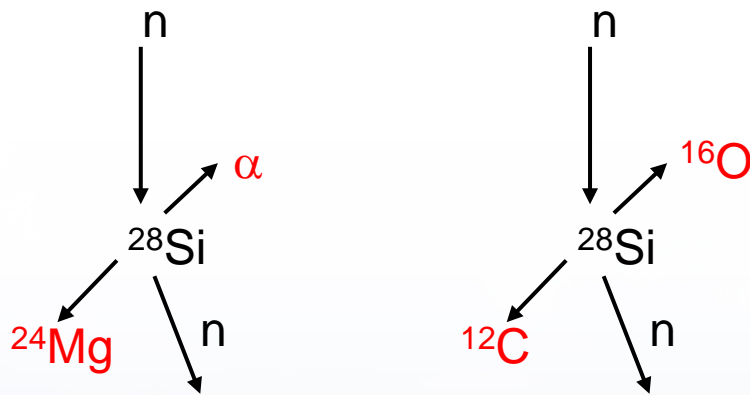
- Correctable by reprogramming the circuit into its correct logic state
- If error rate is too high, it can cause system degradation and potentially mission failure

Charge liberated by the particle strike is collected at reverse-biased junctions, and the resulting current transient upsets normal operation of the circuit.

# Charge deposition can occur by indirect or direct ionization

Direct ionization by nuclear reaction products can deposit enough charge to cause SEE.

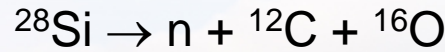
E. L. Petersen, IEEE TNS (1981)



a-particle Reaction

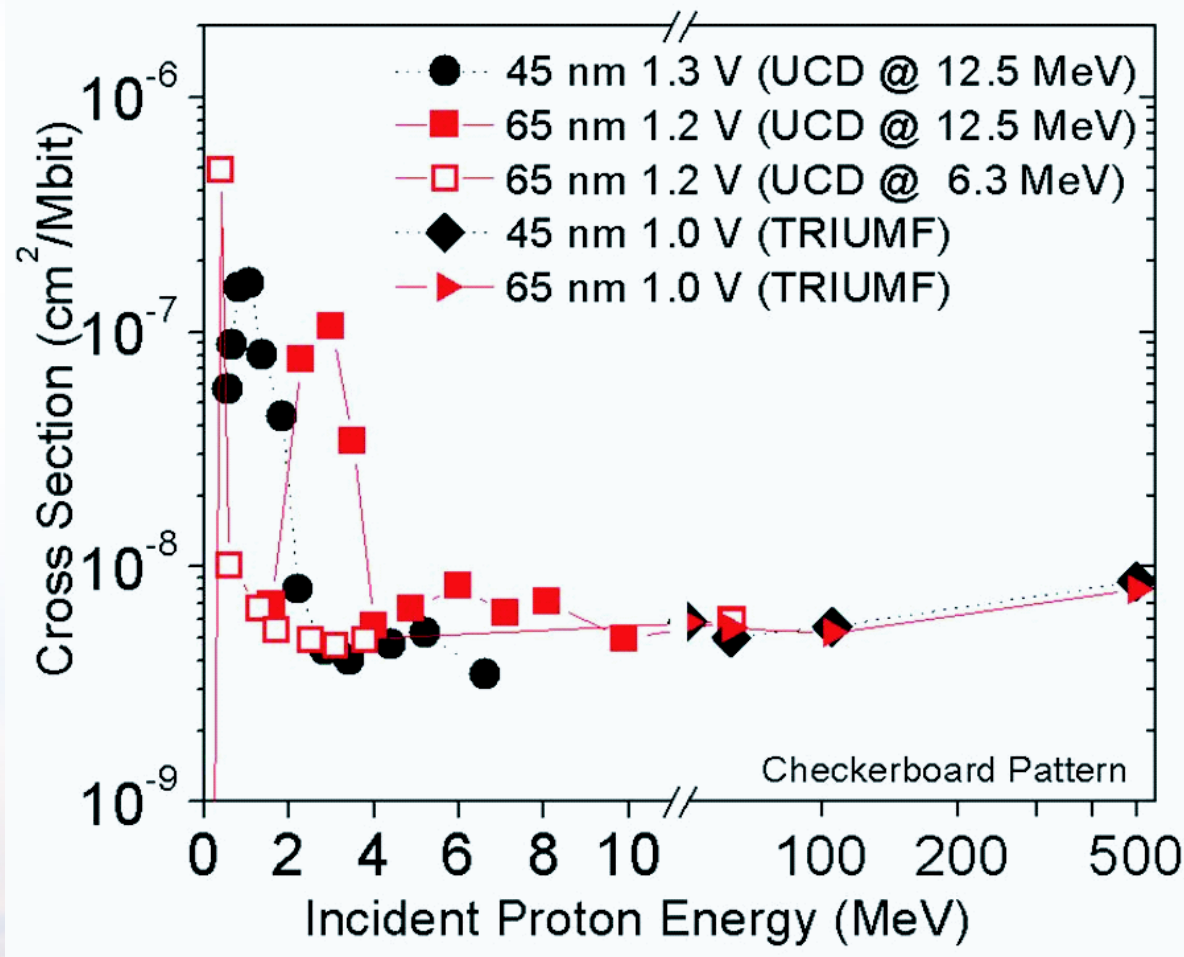


Spallation Reaction



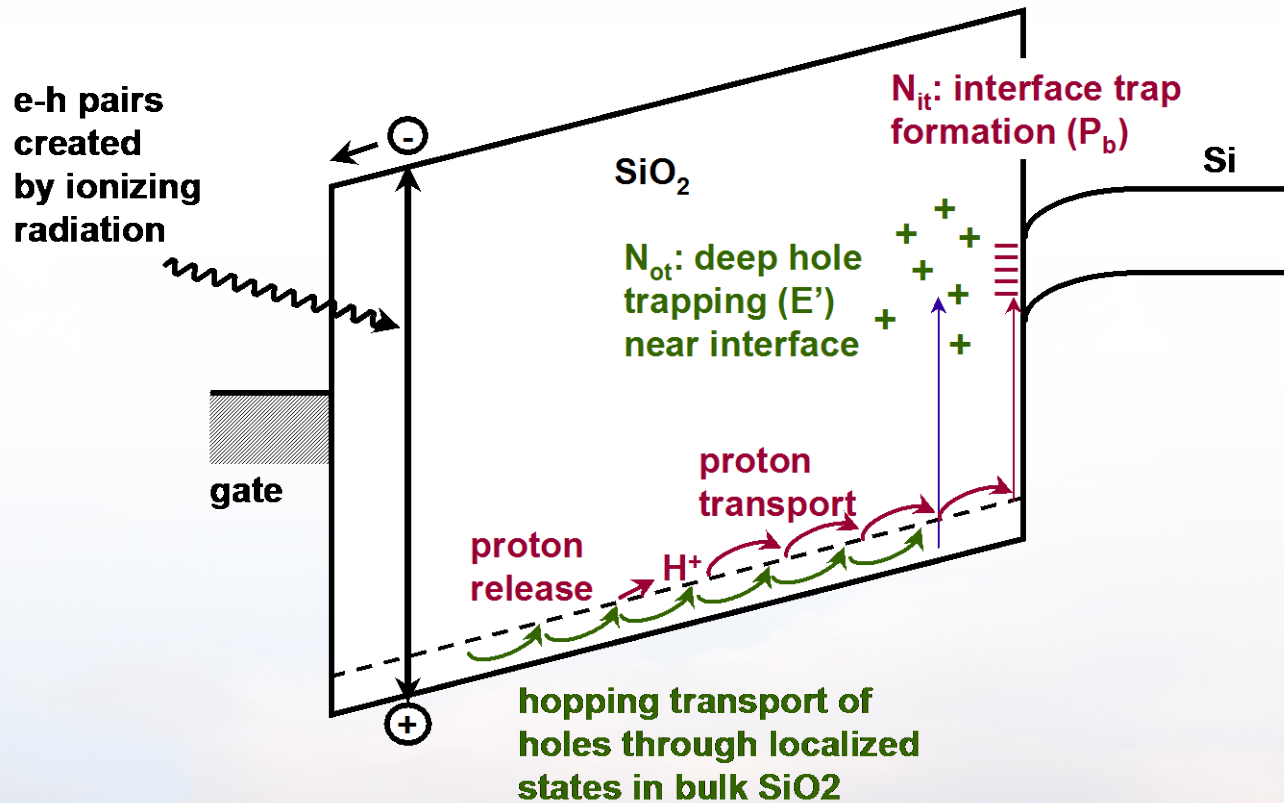
- Historically, indirect ionization has been the primary charge deposition mechanism for protons
- Recent works have shown that protons and muons can lead to upset by direct ionization
- Flux of protons (space) and muons (terrestrial) can be very high
- Cross section for electronic stopping (direct ionization) of protons and neutrons can be orders of magnitude higher than for indirect ionization

# Direct ionization of protons can greatly increase SEU cross section of highly-scaled ICs at low proton energies



D. F. Heidel, IEEE Trans. Nucl. Sci. 2009

# Hole transport and trapping leads to the generation of oxide- and interface-trap charge



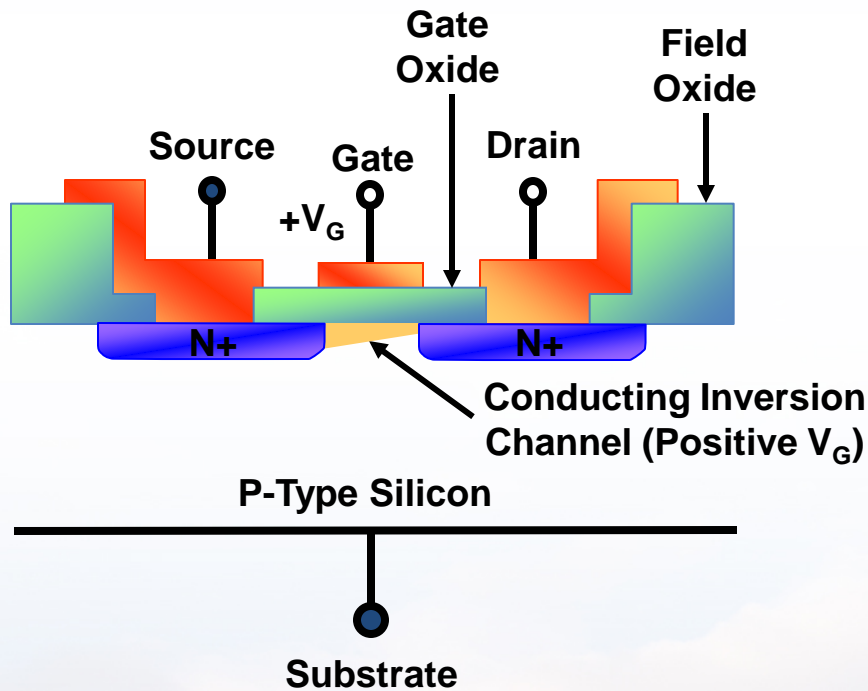
To determine the effects of irradiation need to know the charge yield for holes

$$\Delta V_{th} = \Delta V_{ot} + \Delta V_{it}$$

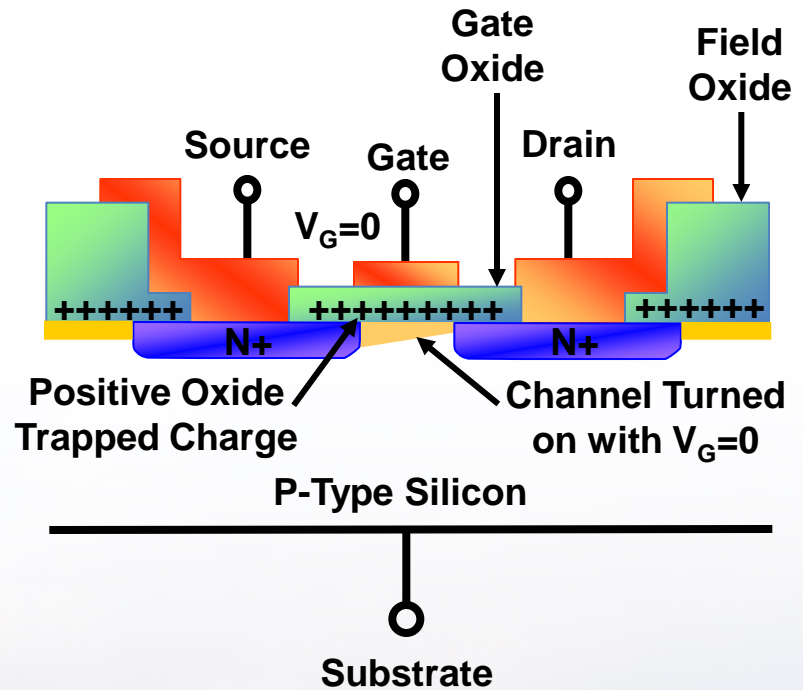
$\Delta V_{ot}$  = voltage shift due to oxide trap charge ( $N_{ot}$ )

$\Delta V_{it}$  = voltage shift due to interface trap charge ( $N_{it}$ )

# Total-dose effects on transistor operation



Normal operation



Post-irradiation



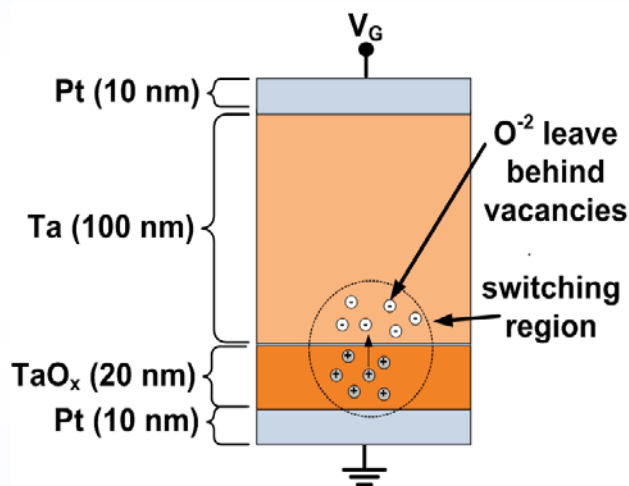
# Protons can also cause displacement damage

- Protons can knock atoms free from their lattice sites producing interstitial atoms and vacancies
- Creates deep and shallow level traps
- Shallow traps
  - Compensate majority carriers
  - Carrier removal
- Deep level traps
  - Generation, recombination, or trapping centers
  - Decrease minority carrier lifetime
  - Increase thermal generation rate
  - Reduce carrier mobility
- Important for minority carrier (e.g. bipolar) and optoelectronic devices

# Task 1: Proton-induced degradation of state-of-the-art optical fibers

- Optical fibers have numerous advantages for communication systems in high radiation environments – space, high-energy particle accelerators
- The use and hardening of optical fibers in these radiation environments requires detailed understanding of the effects of radiation
- Protons generate point defects that increase light absorption
- Past work at TRIUMF has enabled us to develop hardened Cerium co-doped Ytterbium/Erbium doped fibers
- In this task, we will investigate the effects induced by protons in these Cerium co-doped Ytterbium/Erbium doped fibers
- Degradation in optical fiber waveguides will be characterized by measuring the radiation-induced optical losses at different wavelengths
- The attenuation spectrum can reveal the defect types and density induced by proton irradiation

# Task 2: Tantalum oxide memristors



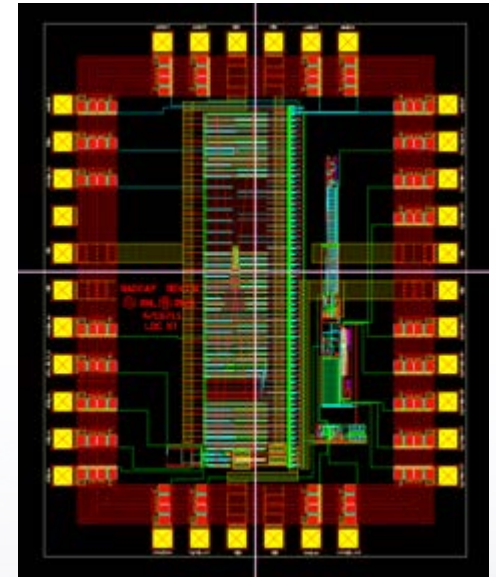
- DRAMs, SRAMs, and flash memories are nearing physical scaling limits
  - International Technology Roadmap for Semiconductors has identified memristors as a top candidate for replacing them
  - Switching mechanism in TaO<sub>2</sub> believed to be due to O<sup>-2</sup> anions dissociating from the TaO<sub>x</sub> when subject to a positive bias leaving behind positively charged vacancies
- 
- Memristors may be especially vulnerable to proton-induced displacement damage effects and also to total ionizing dose effects
  - In this task, we will investigate the mechanisms for proton-induced degradation in memristors
  - Proton results will be compared to gamma radiation results to distinguish between total ionizing dose and displacement damage effects

# Task 3: Aluminum nitride microresonators

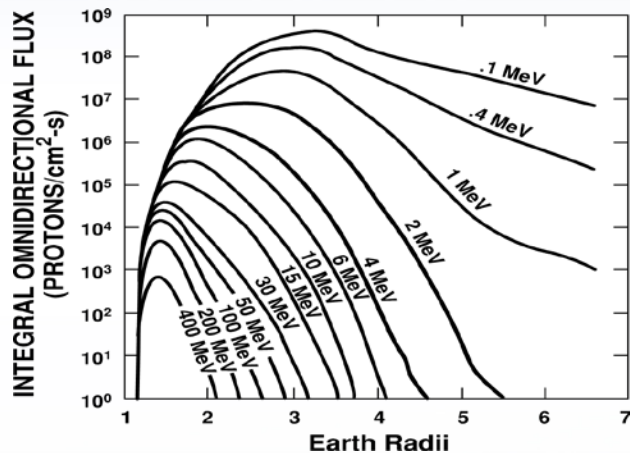
- Aluminum nitride (AlN) microresonators have numerous advantages including small size and the potential for monolithic integration
- Monolithic integration of microresonators with electronics is vital for miniaturization of communication systems
- Resonator consists of a piezoelectric AlN layer sandwiched between two electrodes
- An applied electric signal transduces via the piezoelectric material an acoustic wave
- Effects of proton irradiation on AlN piezoelectric materials is unknown – they may be especially sensitive to proton-induced displacement damage
- In this task, we will investigate the physical mechanisms for proton radiation-induced effects in AlN microresonators
- Proton results will be compared to gamma radiation results to distinguish between total ionizing dose and displacement damage effects

# Task 4: Proton radiation effects in active pixel sensors

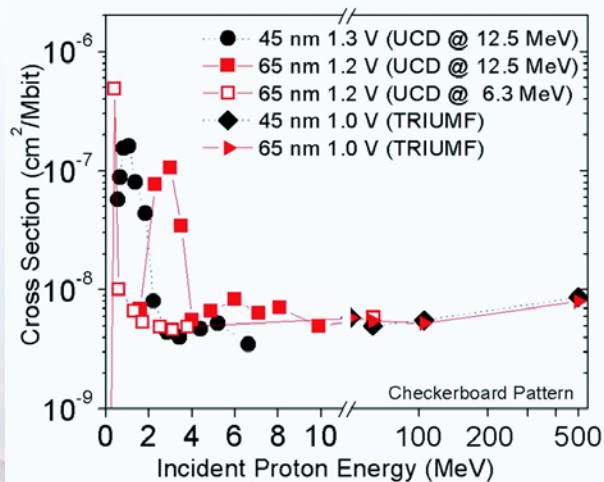
- Active pixel sensors are an image sensor consisting of an integrated circuit containing an array of pixel sensors
- Alternative to CCD imagers for radiation-hardened applications
- Being investigated for applications at NIF (U.S) and ITER (France) and numerous space systems
- In this task, we will investigate the mechanisms for proton-induced degradation, e.g., noise signal and dark current
- Proton results will be compared to neutron, heavy-ion, gamma, and x-ray radiation results



# Task 5: Proton and muon radiation effects in advanced, highly-scaled ICs



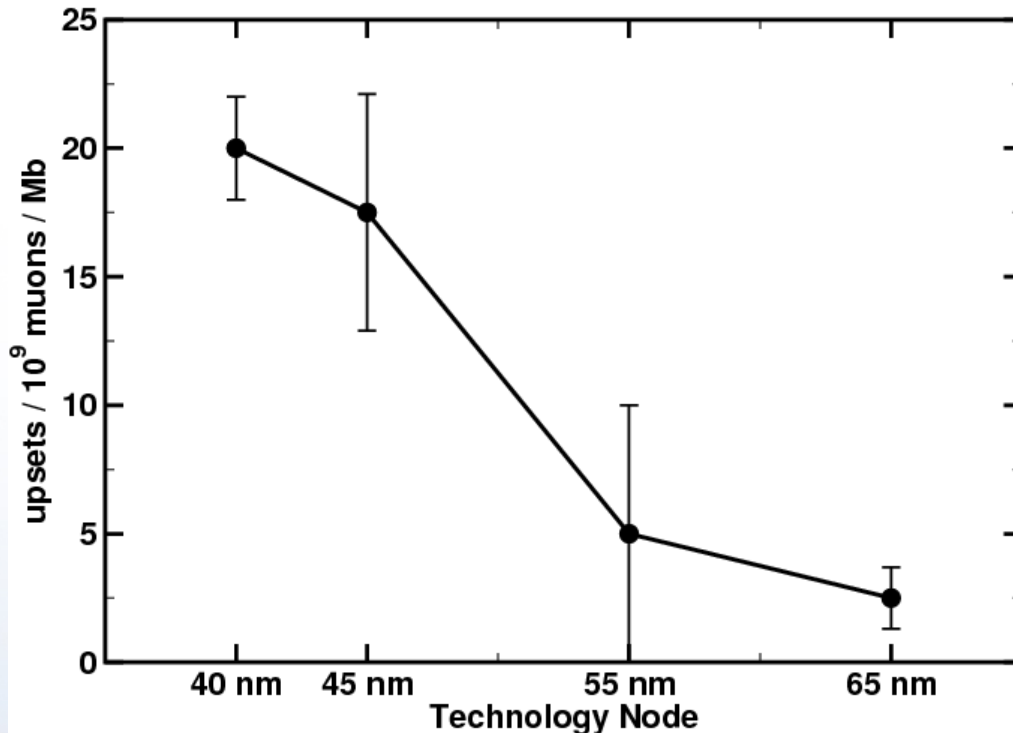
E. G. Stassinopoulos and J. P. Raymond, Proc. of the IEEE, 1988



D. F. Heidel, IEEE Trans. Nucl. Sci. 2009

- Recent work we performed at TRIUMF and elsewhere has shown large increases in single-event upset cross section at low proton energies in highly-scaled ICs due to the direct ionization of protons
- Increase in cross section can impact soft error rate in space systems
- Direct ionization effects expected to get worse as technologies scale to smaller dimensions
- Hardness assurance test methods for proton direct ionization effects not available

# Task 5 (continued)



Sierawski, et al., Proc. of the Int. Rel. Physics Symp, May 2011.

- Muons, like low-energy protons, can induce upsets in semiconductor devices
  - Data collected in Apr. 2010 at TRIUMF established the effect
- The probability of muon effects are increasing for smaller devices
- The implications of these effects must be further investigated to determine the extent to which the reliability of terrestrial devices will be impacted
- The mechanisms for upset must be fully understood and reliable hardness assurance test methods must be defined to ensure the reliability of earth-based systems incorporating advanced ICs

# Task 5 (Continued)

Partner	Part
Cisco Systems	SEU test chip in 28-nm process
Texas Instruments	SRAMs in 40-nm and 28-nm processes
Broadcom	Dual and triple-well SRAMs in 40-nm and 28-nm processes
Marvell Semiconductor	SRAM in 28-nm processes
IBM	Flip-Flop chain in 32-nm process

- In this task, we will investigate the charge collection mechanisms in highly-scaled devices to understand direct ionization effects due to protons and muons and to develop reliable hardness assurance test methods
- Devices from multiple manufacturers will be used to investigate different technology features, e.g., feature size, bulk versus silicon-on-insulator, dual-well and triple-well technologies
- GEANT4 radiation transport simulations will be used in combination with the experimental results to fully understand the charge collection mechanisms