Overview of Single Event Effects

Stephen Buchner and Dale McMorrow

Naval Research Laboratory

Washington, DC USA

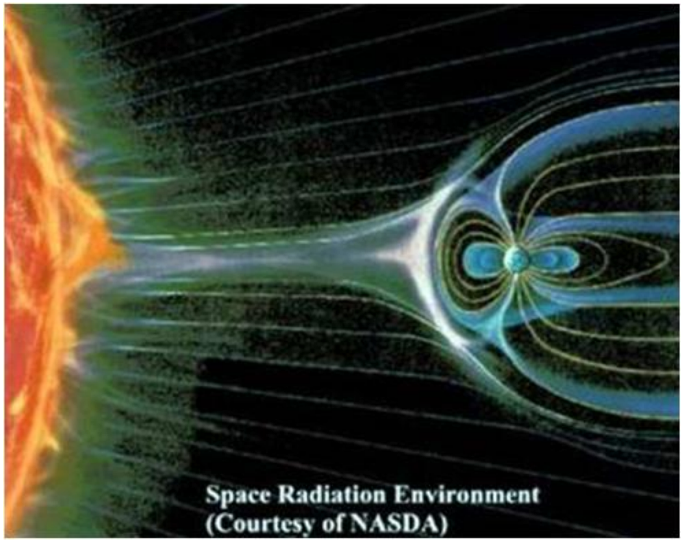
Presented at SERESSA 2015, Puebla, Mexico
by S. Buchner

Outline

1. Environments
2. Definition of SEE
3. History
4. Fundamental Mechanisms
5. Testing
6. Rate Prediction
7. Mitigation (Avoiding SEEs)
8. Current Issues

Environments

- Threat to Electronics in Space.
  - Highly energetic particles found in space that can penetrate the spacecraft and the IC packaging and cause **Single Event Effects**.
- Where do they come from?
  - Sun: solar wind and solar particle events
  - Galactic cosmic rays: very high energy
  - Radiation belts: planets with magnetic fields
- Types of Particles and Flux.
  - All atoms in the periodic table, protons, and bremsstrahlung
  - Flux depends on orbit and time.
- Terrestrial Threat
  - Neutrons produced by interaction of cosmic rays and nitrogen cause SEEs in avionics and in ground-based electronics.
  - Radioactive impurities



Space Radiation Environment
(Courtesy of NASDA)

Outline

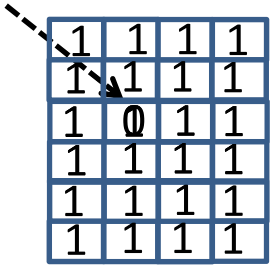
1. Environments
2. Definition of SEE
3. History
4. Fundamental Mechanisms
5. Testing
6. Rate Prediction
7. Mitigation (Avoiding SEEs)
8. Current Issues

Definition of Single Event Effect

- A single event effect is an electrical disturbance that disrupts the normal operation of a circuit. It is caused by the passage of a single ion through or near a sensitive node in a circuit.
- Single event effects can be either destructive or non-destructive.

Single Event Upsets

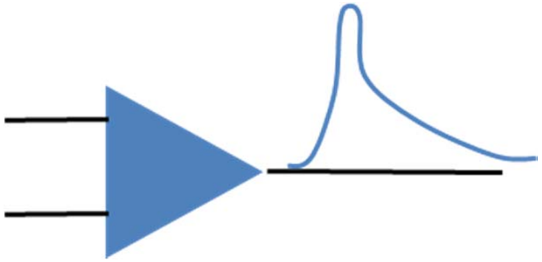
- Single Event Upsets (SEUs) occur in memories (SRAMS, SDRAMS) and sequential logic such as registers (Flip/flops).
  - The result of a SEU is that “1” goes to “0” or “0” goes to “1”.
  - There is no permanent damage
  - The error can be corrected by rewriting the original information
  - SEUs can result in serious system malfunction or no effect at all.



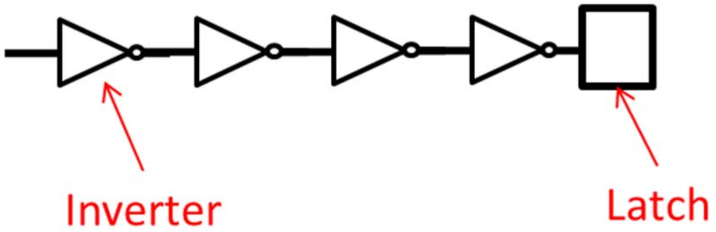
Single Event Transients

- Single Event Transients (SETs) are voltage glitches in circuits caused by single ions. They are fundamental to all types of SEEs (SEU, MBU, SEL, SEL.)
  - ASETs occur in analog devices (Operational amplifiers, Comparators, etc)
  - DSETs occur in digital devices (Combinational logic – AND and OR gates, memories, etc.)
  - SETs may or may not be a problem.
  - If SETs are converted into SEEs they can become a problem.

1. Comparator



2. Inverter String



Outline

1. Environments
2. Definition of SEE
3. **History**
4. Fundamental Mechanisms
5. Testing
6. Rate Prediction
7. Mitigation
8. Current Issues

History

- Single Event Upsets (SEUs) in electronics first proposed in 1962. (***J.T. Wallmark and S.M. Marcus***, *"Minimum size and maximum packaging density of non-redundant semiconductor devices," Proc. IRE, vol. 50, pp. 286-298, March 1962).*
- *Predicted cosmic rays would limit scaling of devices. Determined that the minimum device size was a cube* ***10 um*** *on a side. This was based on the amount of charge deposited by a cosmic ray that would disrupt the operation of a device.*
- *Particles interact with matter through:*
  - *Ionization – creation of charge track*
  - *Displacement damage – creation of traps*
  - *Nuclear events – creation of secondary particles*
- *Sources of particle radiation:*
  - *Galactic*
  - *Trapped*
  - *Solar*

History

- The first actual satellite anomalies were reported in 1975. SEUs in flip-flops on board a communications satellite. ***D. Binder***, *E.C. Smith, A.B. Holman, "Satellite anomalies from galactic cosmic rays," IEEE Trans. on Nuclear Science, vol. 22, no. 6, pp. 2675-2680, Dec. 1975*
- First observation of SEUs on earth was in 1978. Observed in RAM caused by the alpha particles released by U and Th contaminants within the chip packaging material and solder. Vendors took specific actions to reduce it. ***T. C. May and M. H. Woods***, *"A New Physical Mechanism for Soft Errors in Dynamic Memories", Proceedings 16 Int'l Reliability Physics Symposium, p. 33, April, 1978*
- First report of SEUs due to cosmic rays (95% neutrons) on earth in 1979. *J. F. Ziegler and W. A. Lanford, "Effect of Cosmic Rays on Computer Memories", Science, 206, 776 (1979)*
- First report of destructive SEE (proton-induced latch-up) was in a memory on Earth Resources Satellite – 1 (ERS-1) operating in space in 1992 **L. Adams** et al. *"A Verified Proton Induced Latch-up in Space," IEEE TNS vol. 39, No. 6, pp. 1804 – 1808, Dec. 1992*

Outline

1. Environments
2. Definition of SEEs
3. History
4. Fundamental Mechanisms
5. Testing
6. Rate Prediction
7. Mitigation
8. Current Issues

3. Fundamental Processes

A. Charge Generation

- Incident ion interacts with material to produce free charge carriers (electrons and holes)

B. Charge Recombination and Collection

- Electrons and holes move by diffusion and drift through the material (oxides and semiconductors) to a sensitive node while they also recombine

C. Circuit Response

- The additional charge on the node alters the voltage that ultimately leads to single event effects. Voltage glitches may propagate through a circuit

3A. Charge Generation

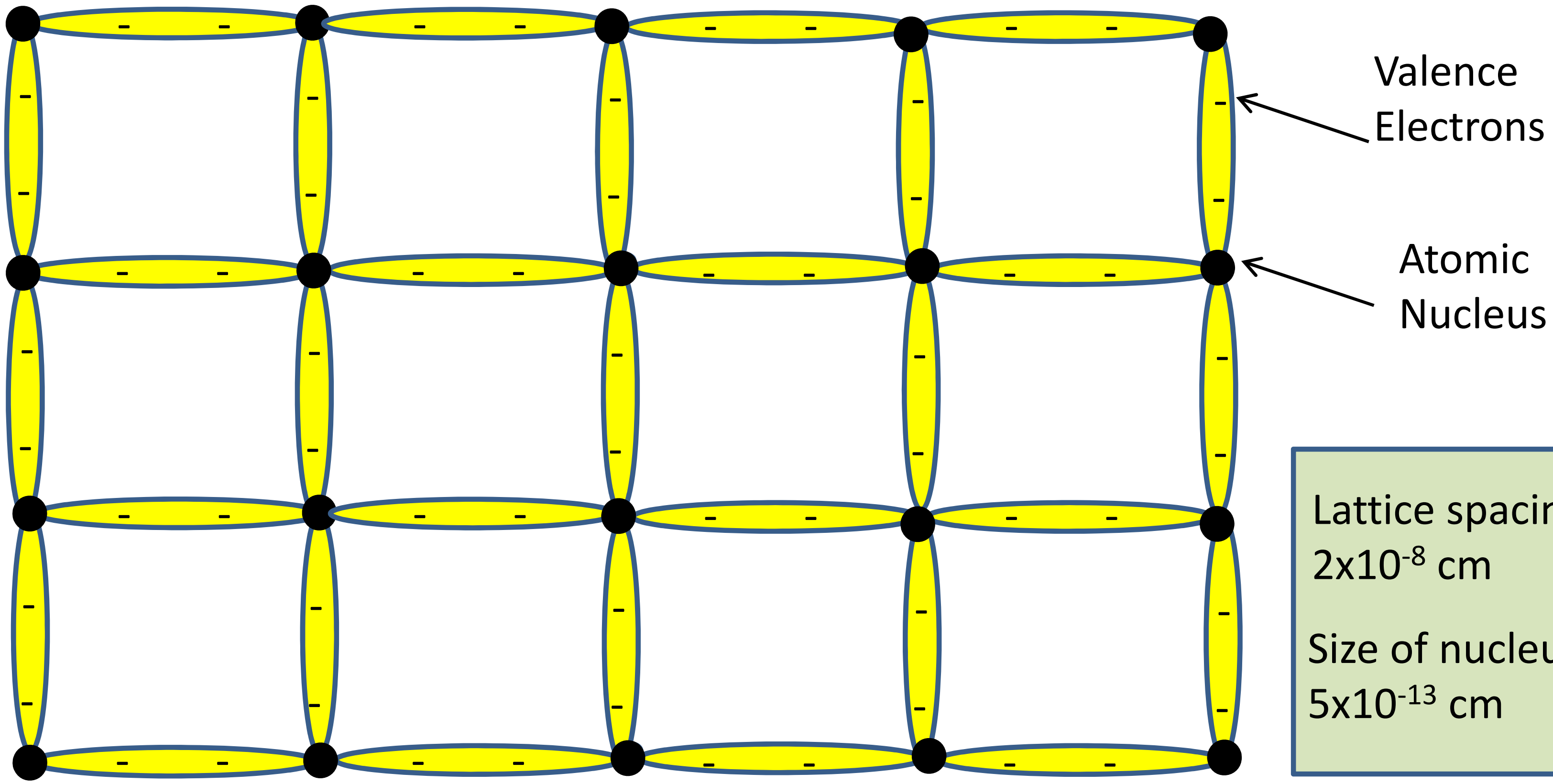
Presented at SERESSA 2015, Puebla, Mexico
by S. Buchner

Ion-Material Interaction

- Interaction of an incident ion with material.
  A. Elastic Coulomb Scattering between incident ion and bound electrons of target material
  B. Elastic Coulomb and Nuclear Scattering between incident ion and nucleus of target material
  C. Inelastic Scattering between incident ion and nucleus of target material - Spallation

A. Elastic Scattering between Incident Ions and Bound Electrons

Silicon Lattice

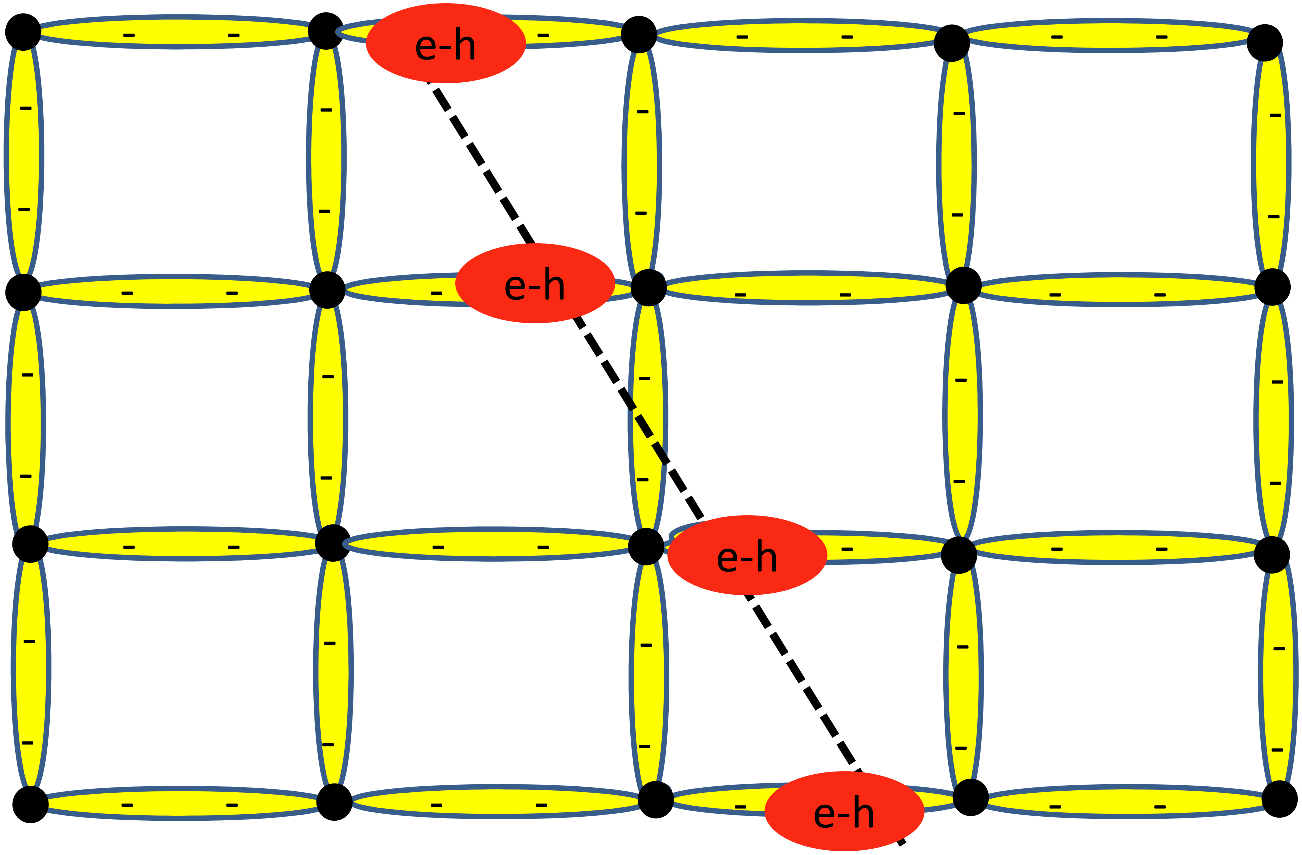


Lattice spacing:
2×10^{-8} cm

Size of nucleus:
5×10^{-13} cm

A. Elastic Scattering between Incident Ions and Bound Electrons

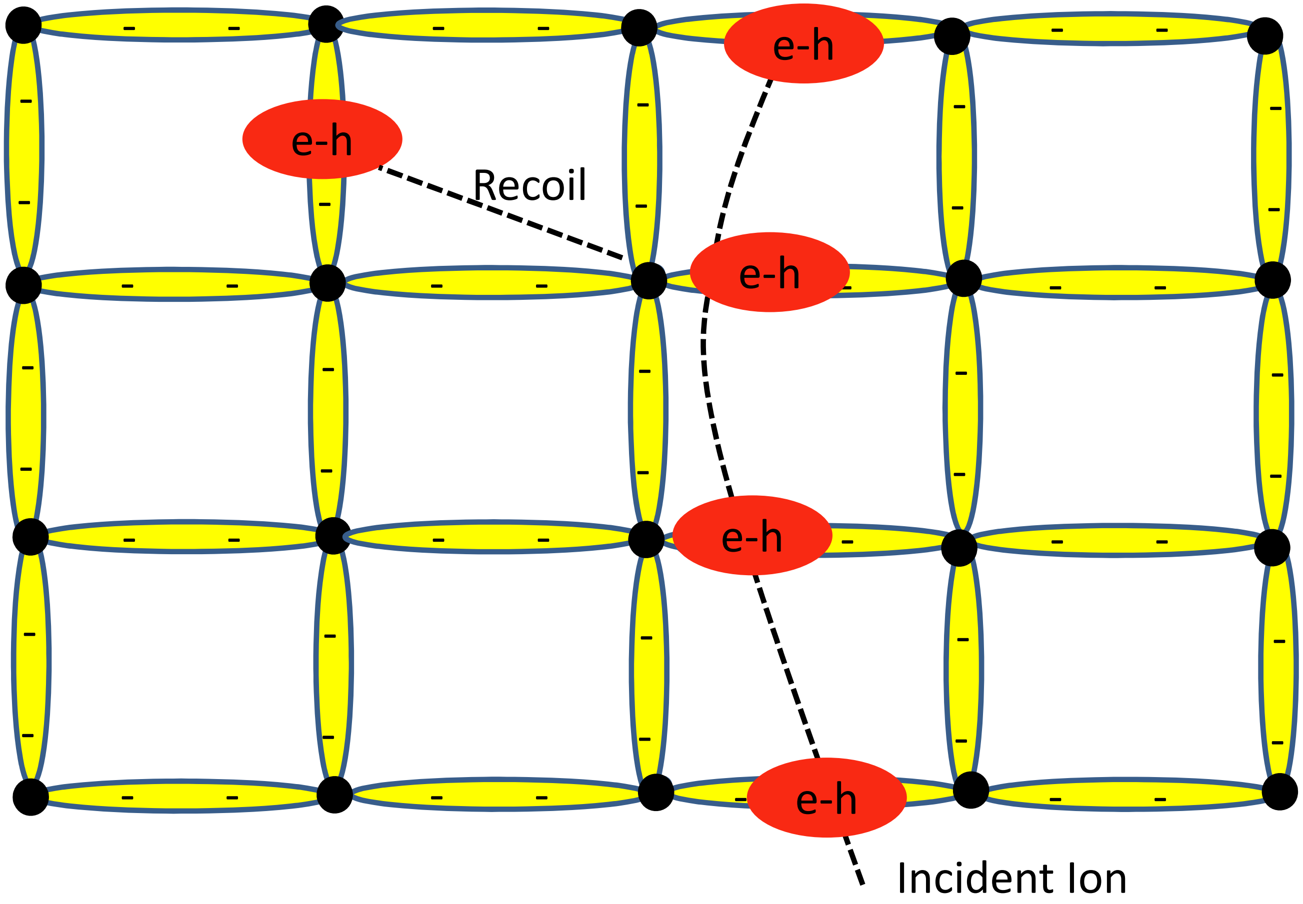
Silicon Lattice



- *Stochastic process i.e. probability of collisions.*

B. Elastic Scattering – Coulomb Scattering off Nucleus

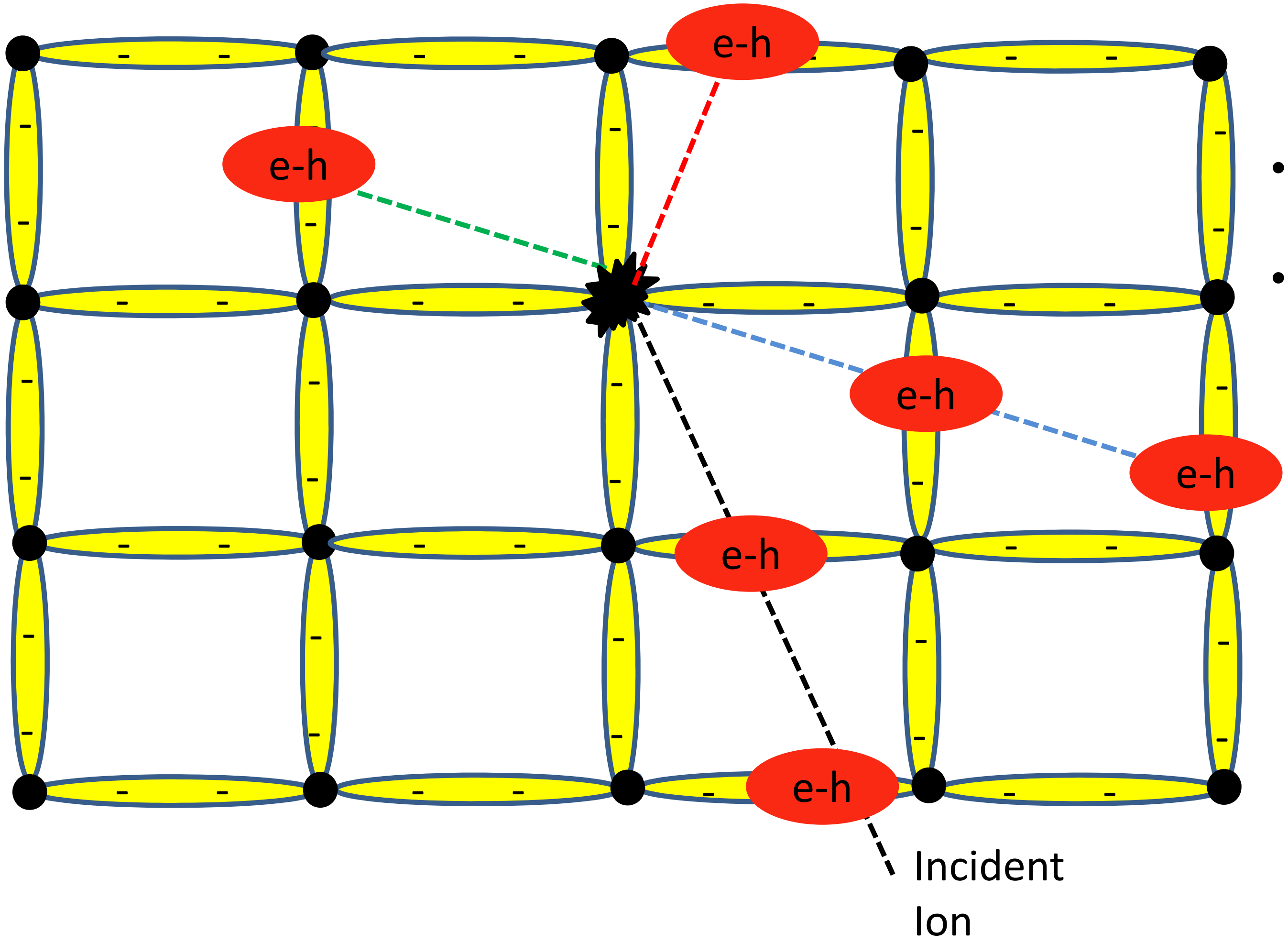
Silicon Lattice



- Incident and recoil particles can both produce e-h pairs
- Cross-section much smaller than for direct ionization

C. Inelastic Scattering - Spallation

Silicon Lattice



- Coulomb barrier for proton/Si is ~2 MeV
- Protons usually produce SEUs by nuclear interactions

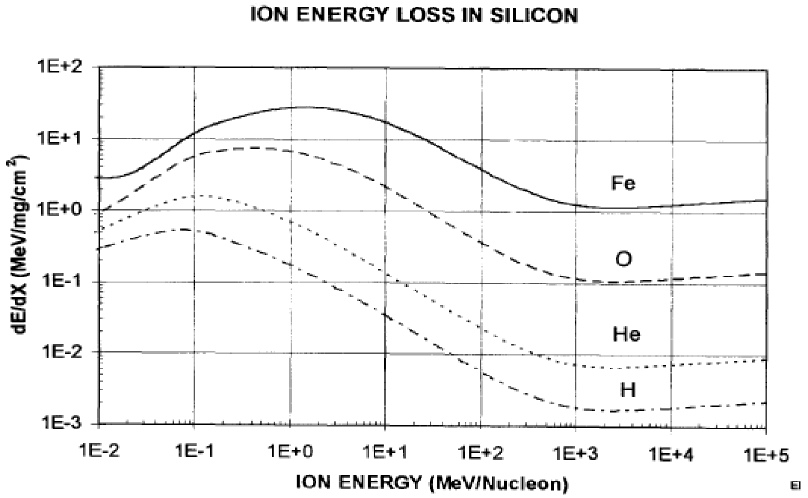
Ionization

- Incident ion energy loss dominated by Process A - direct ionization via Coulomb scattering (electron-hole generation) to produce delta rays.
- ***Convert stochastic process to continuous process***
- Bethe-Bloch Formula $\frac{dE}{dx} = -\frac{4\pi N z^2 e^4}{m_0 v^2} B \sim \frac{Z^2}{\text{K.E.}}$

z = atomic number of incident ion
K.E. = kinetic energy

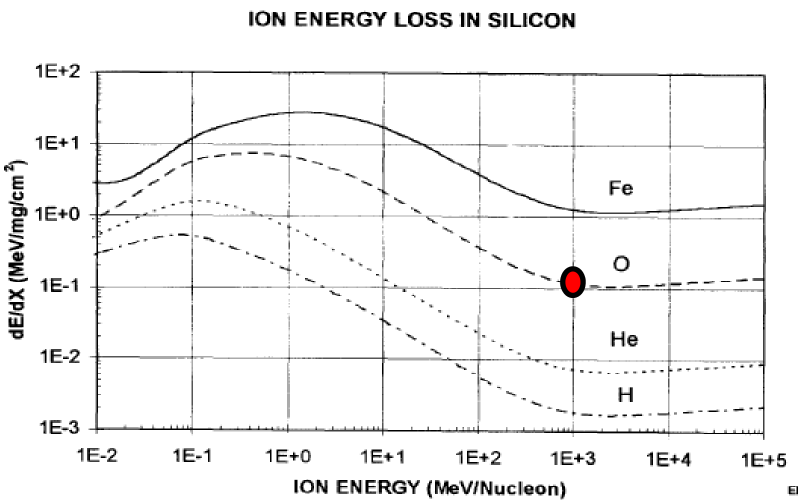
$$B = Z\left[ln\frac{2m_0 v^2}{I} - \ln\left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$$

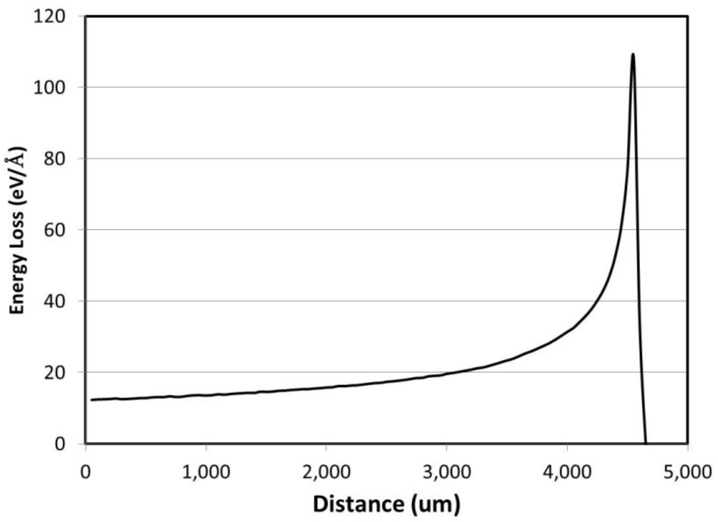
Z = atomic number of target



Ionization

Oxygen Ions (1000 MeV) into Silicon using SRIM

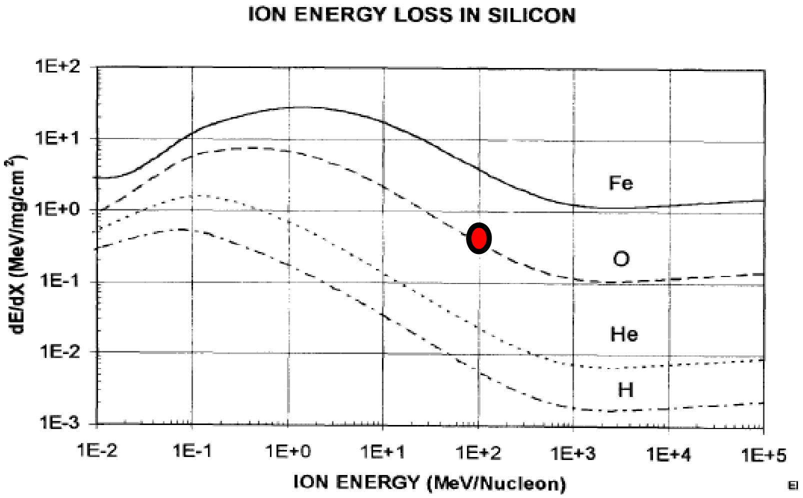


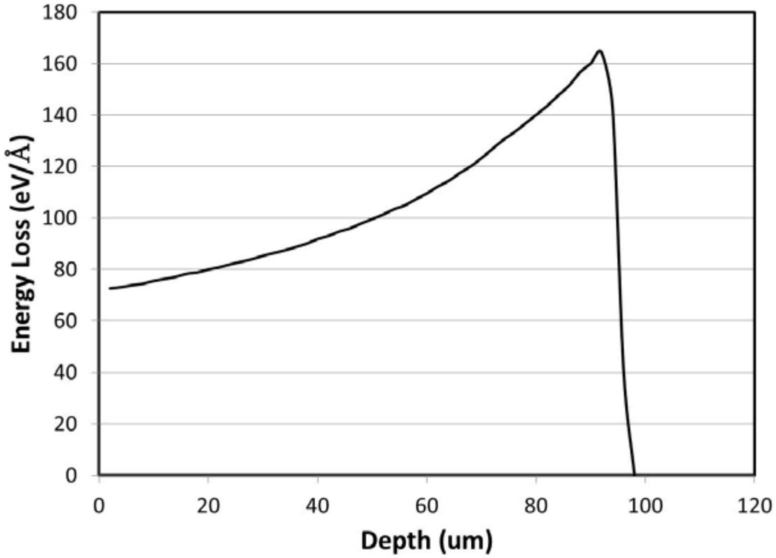


For an ion energy of 1000 MeV, ions penetrate to 4,800 um and maximum energy loss is 110 eV/Å

Ionization

Oxygen Ions (100 MeV) into Silicon using SRIM

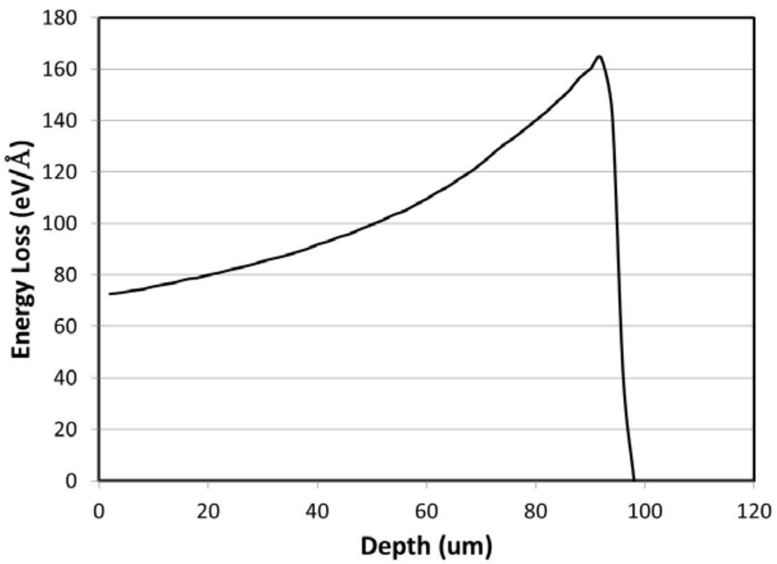


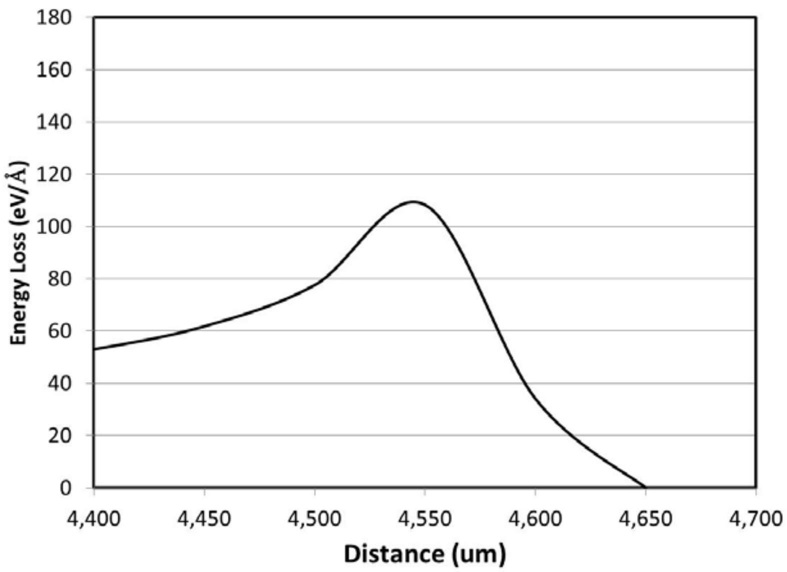


For an ion energy of 100 MeV, ions penetrate to 95 um and maximum energy loss is 165 eV/Å

Ionization

Oxygen Ions (100 MeV vs 1000 MeV) into Silicon

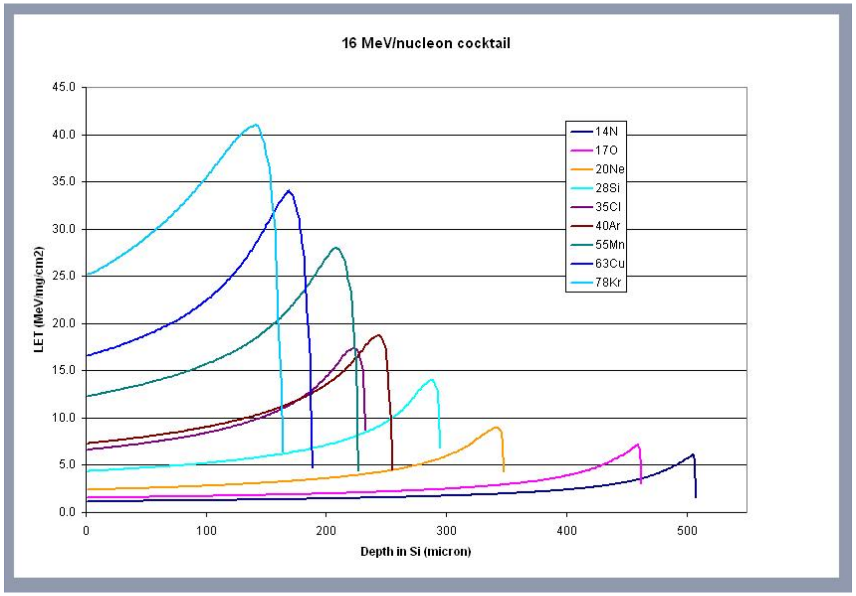




As energy increases, Bragg peak moves deeper into Si and broadens and decreases

Ionization

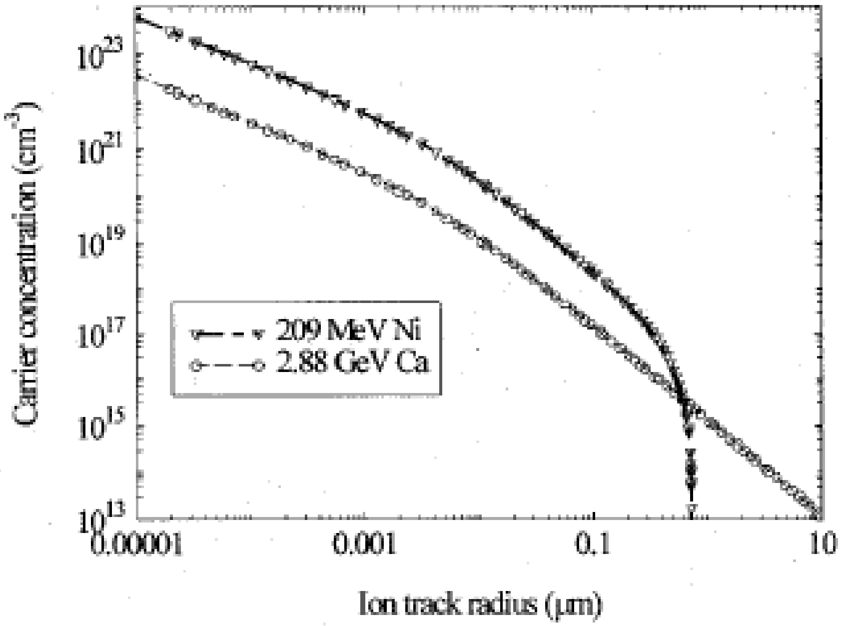
- Ion range is an important parameter. It should be longer than charge collection depth
  - Lower LET (higher energy or lower mass) has longer range
  - Sensitive volume of integrated circuit has depth ~ 1 micron in CMOS devices and up to 100 μm in linear bipolar devices.



$$\frac{dE}{dx} = \frac{Z^2}{K.E.}$$

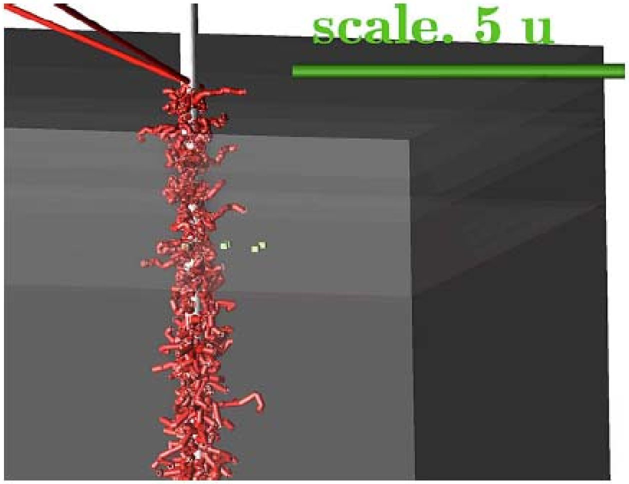
Charge Track Diameter

- High-energy ions produce more energetic delta rays that move further from track center, producing a track with a larger diameter
- Tracks with larger diameters produce:
  - More Multiple Bit Upsets
  - Less e-h recombination

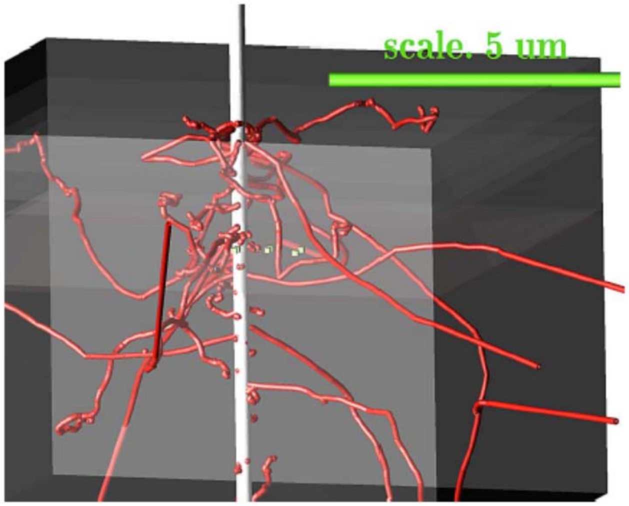


Ionization

- Delta rays (energetic electrons) lose energy via electron-hole generation
- Average energy for e-h production is 3.6 eV in Si and 17 eV in SiO_2
- Energy loss metric is Linear Energy Transfer (LET)
- $\text{LET} = \frac{1}{\rho}\frac{dE}{dx}$ $\text{MeV.cm}^2/\text{mg}$ (ρ= material density)



280 MeV Iron

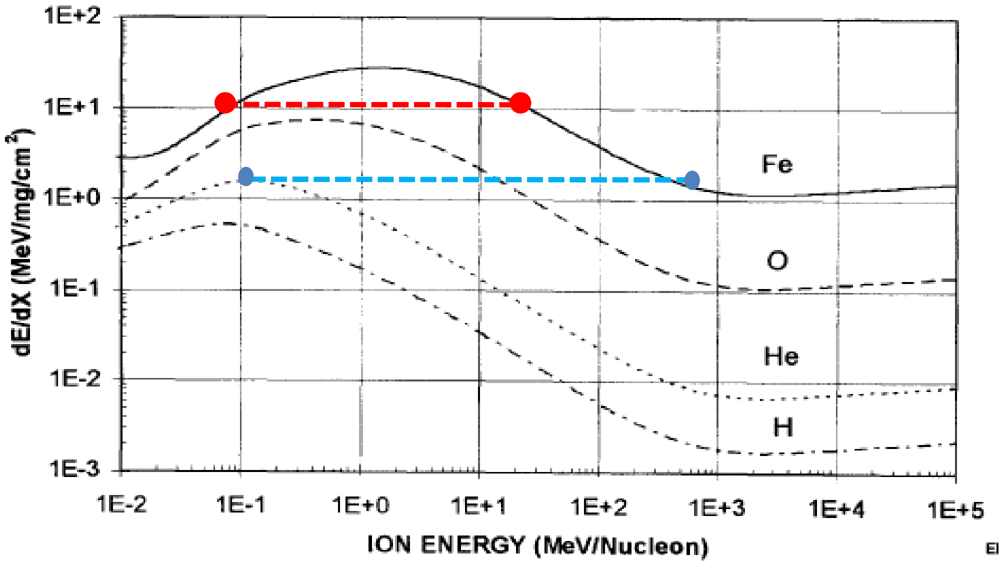


28 GeV Iron

M. King et al. IEEE TNS 2010

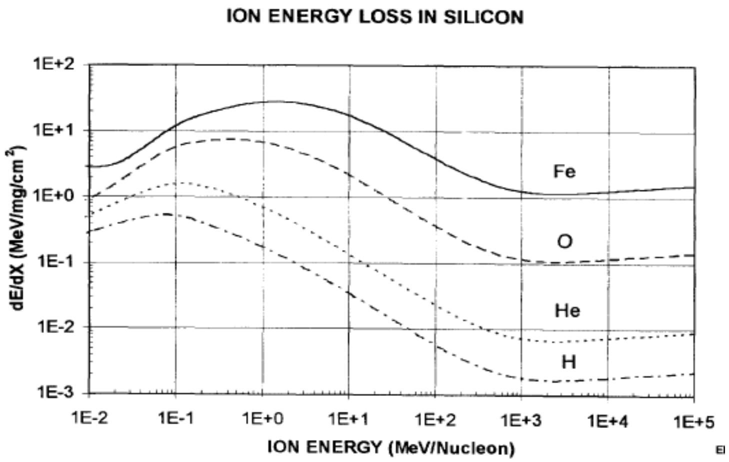
Ionization

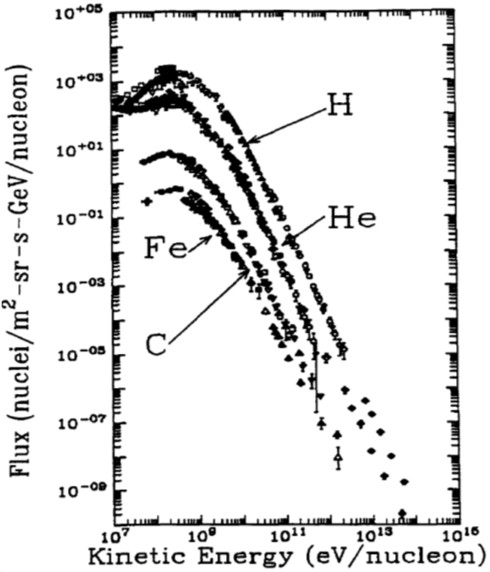
- Ions with different energies can have the same LETs
  - In space more particles with lower energy
  - Shielding will reduce energy of particles
- For same LET, high-energy ions produce charge tracks with bigger diameters than do low-energy ions
- Higher energy ions will produce less dense tracks. Recombination (Auger) reduced, and probability of MBU increased.



Proton-Nucleus Interactions

- Because of proton abundance in space, they pose a significant SEE threat.
- Since protons have a single charge, their interaction with the silicon electrons is weak, i.e., they have small LETs and generally do not contribute to SEEs by direct ionization.
- However, when high-energy protons interact with the silicon nuclei, either elastically or in-elastically, they produce secondary particles with larger masses, and larger LETs. Only 1 in 10^4 protons collide with a nucleus.
- The secondary particles can have LETs up to ~ 15 MeV.cm^2/mg **in silicon** which can cause SEUs.
- Circuits with dimensions of 90 nm and less have been shown experimentally to upset by direct ionization when irradiated with low-energy protons.

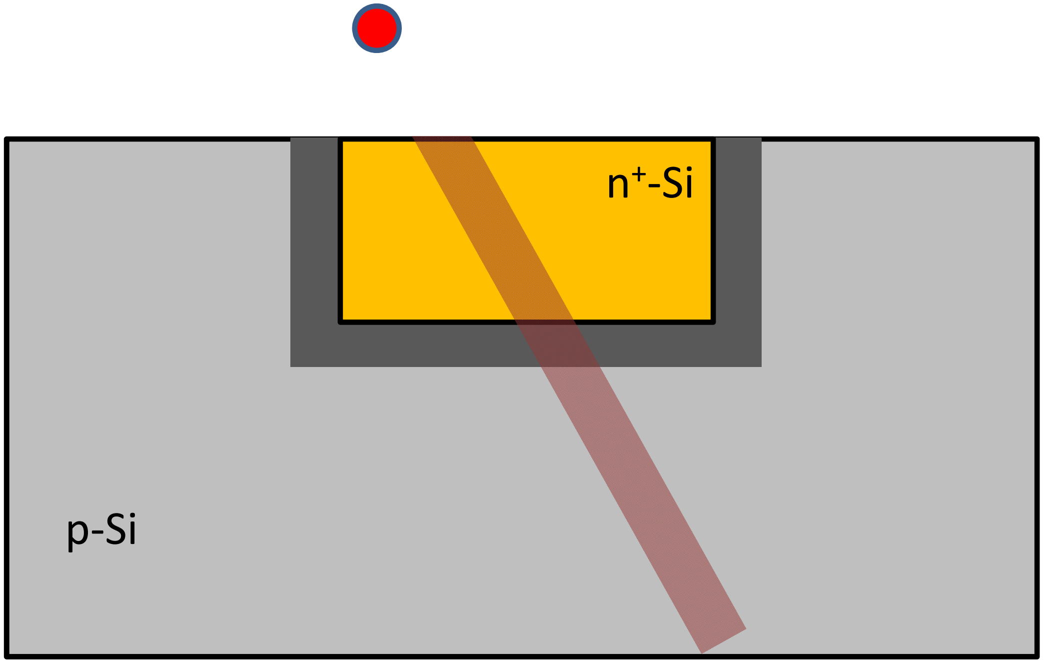




3B. Charge Collection and Recombination

Presented at SERESSA 2015, Puebla, Mexico
by S. Buchner

Charge Collection Mechanisms



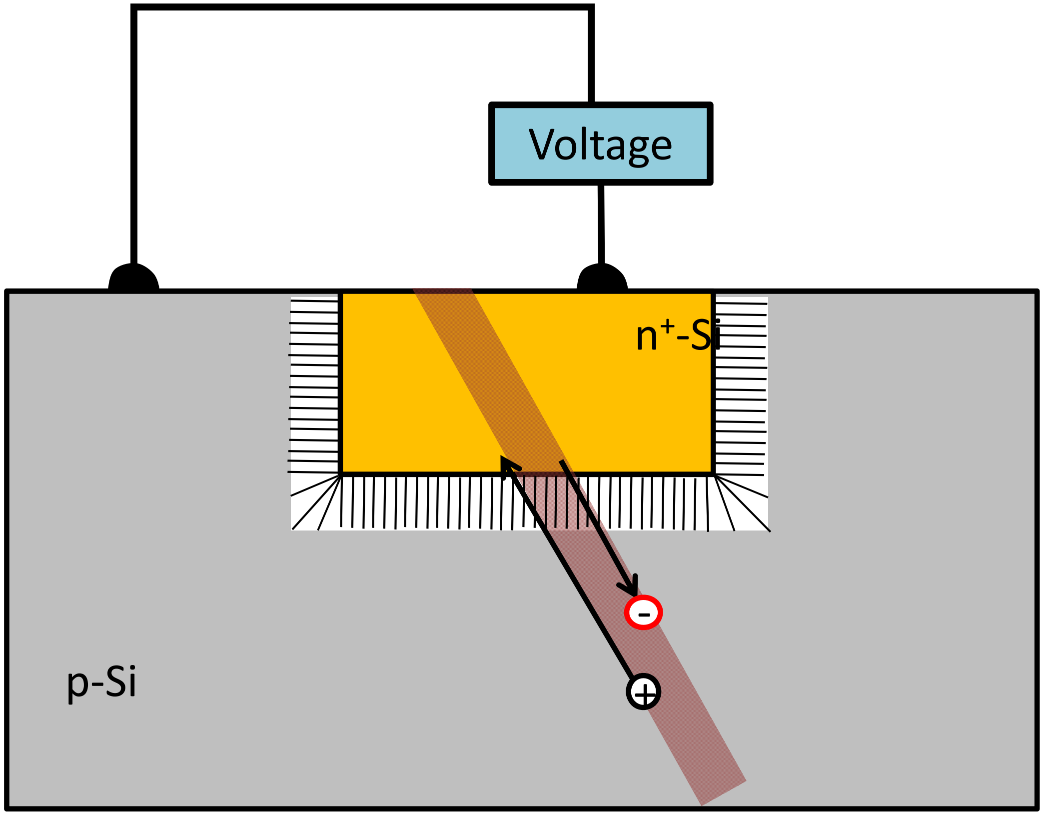
Charge Collection Mechanisms

- Charge movement driven by:
  - Drift current in an electric field

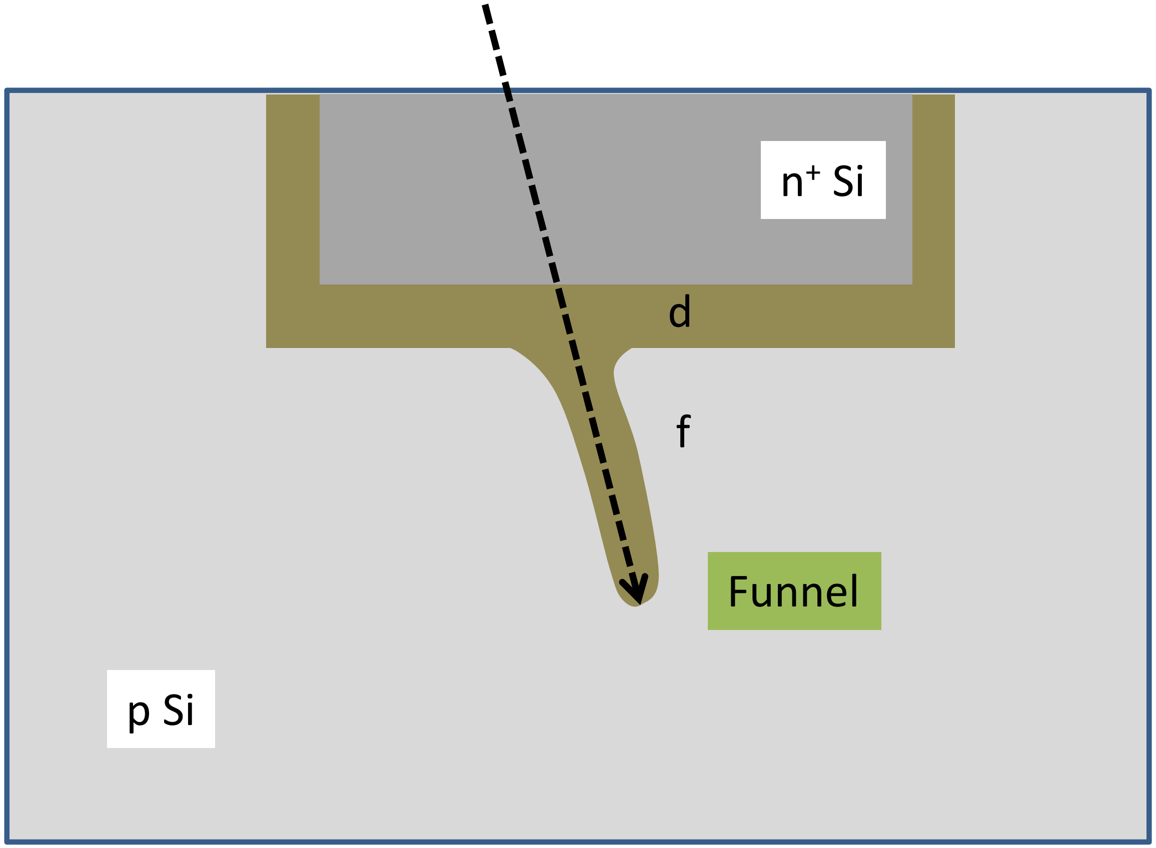
    $\mathbf{J} = qn\mu\mathbf{E}$
  - Diffusion current where no field is present

    $\mathbf{J} = -qD\,(\mathbf{dn/dx})$ i.e. proportional to concentration gradient

    $D = kT\mu$
- Recombination of electrons and holes occurs at the same time via:
  - Shockley Reed Recombination
  - Auger Recombination (for high e-h density at center of track)



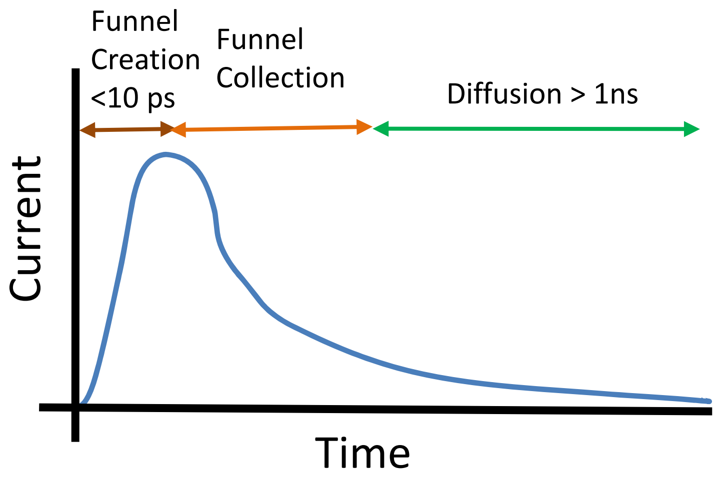
Enhanced Charge Collection - Funnel



C . M . HSIEH, Electron Device Letters, EDL-2, no 4, April, 1981

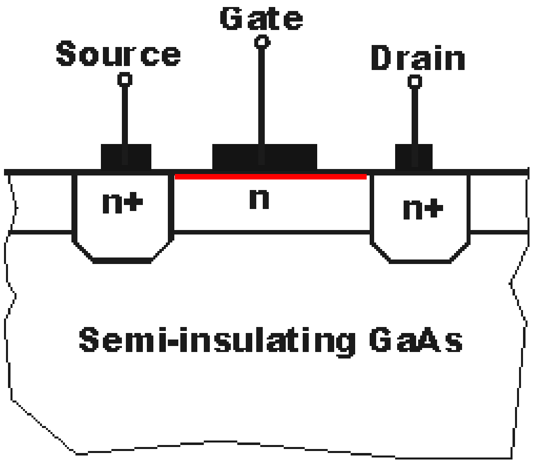
Time Evolution

- Charge moving to a sensitive node (drain of a MOS transistor) is equivalent to current flow to that node.
- Current transient has fast (drift in depletion layer and funnel) and slow (diffusion) components – faster than circuit response to cause SEE.
- Total collected charge, Q_{coll} is integral over time of current
- The charge modifies the voltage at the node
- SEE occurs if Q_{coll} = LET •(d + f) > Q_{crit} in a time shorter than the response time of the circuit
- Flow of charge to node depends on factors such as mobility of holes, charge trapping, doping levels, contacts to remove charge

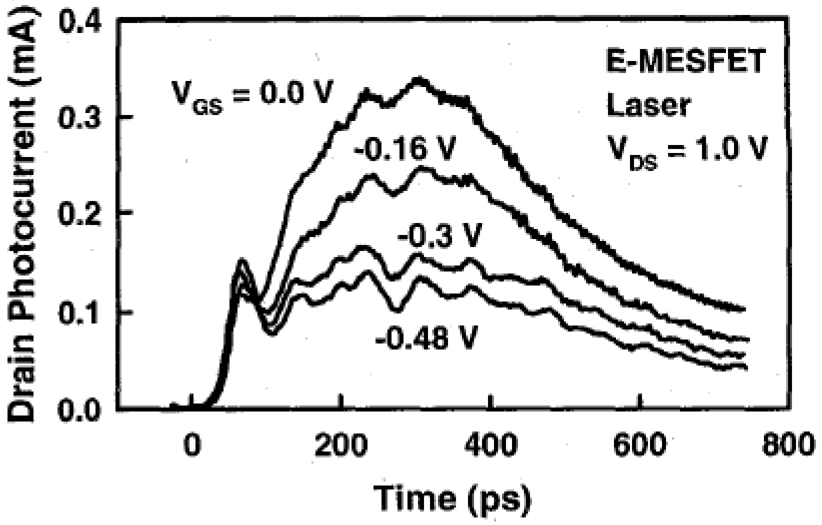


Integral under curve equals total collected charge

Enhanced Charge Collection



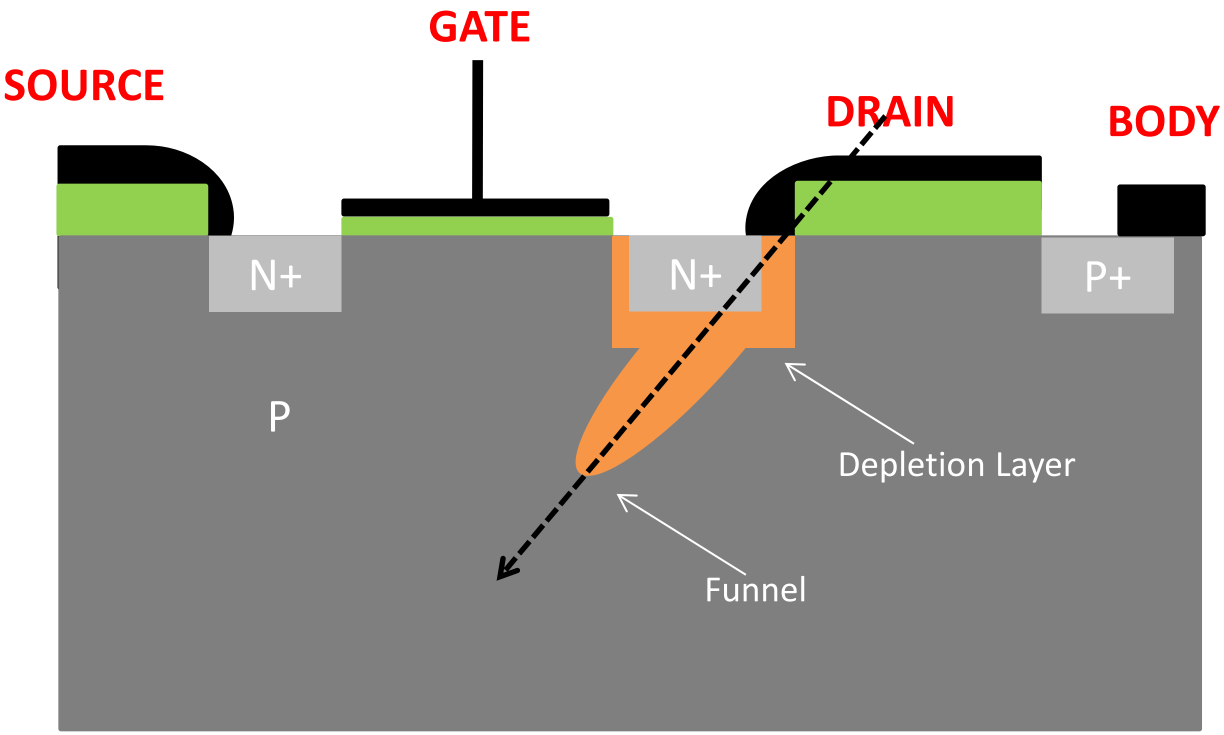
Normally off if V_{sg} = 0 V



- At V_{GS} = 0 V, transistor biased near pinchoff.
- Expect only sharp peak in SET
- Broad peak means **more charge collected than deposited** **= more sensitive to SEEs**
- Caused by:
  - Carrier-induced channel modulation due to excess holes in low-field region
  - Forward biasing source-substrate junction

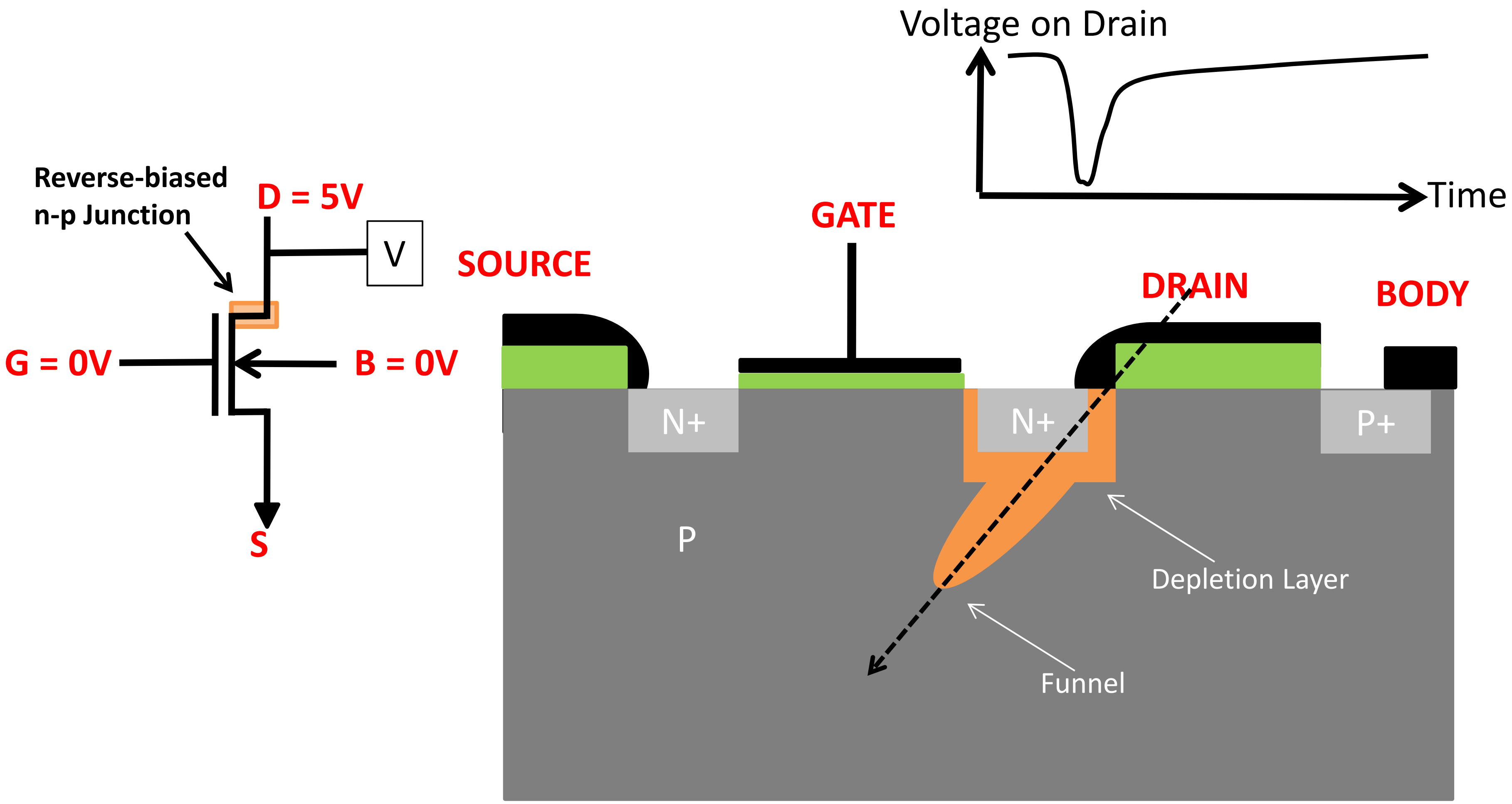
3C. Circuit Response

N-Channel Si MOS Transistor



Presented at SERESSA 2015, Puebla, Mexico
by S. Buchner

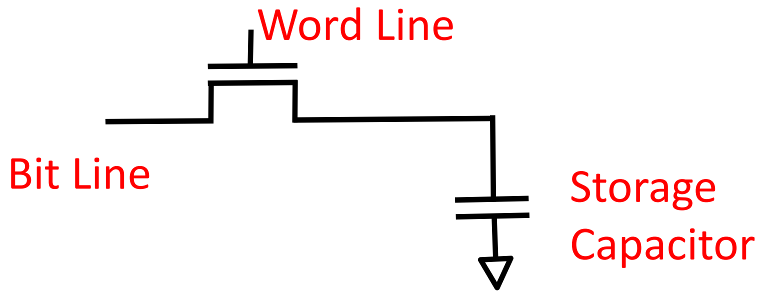
N-Channel Si MOS Transistor



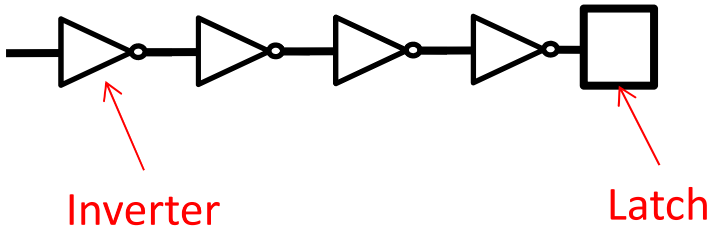
Presented at SERESSA 2015, Puebla, Mexico
by S. Buchner

Transient Propagation

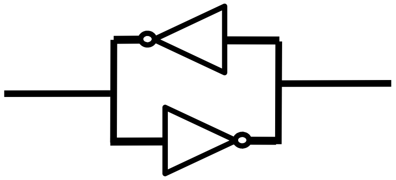
1. DRAM



2. Inverter String

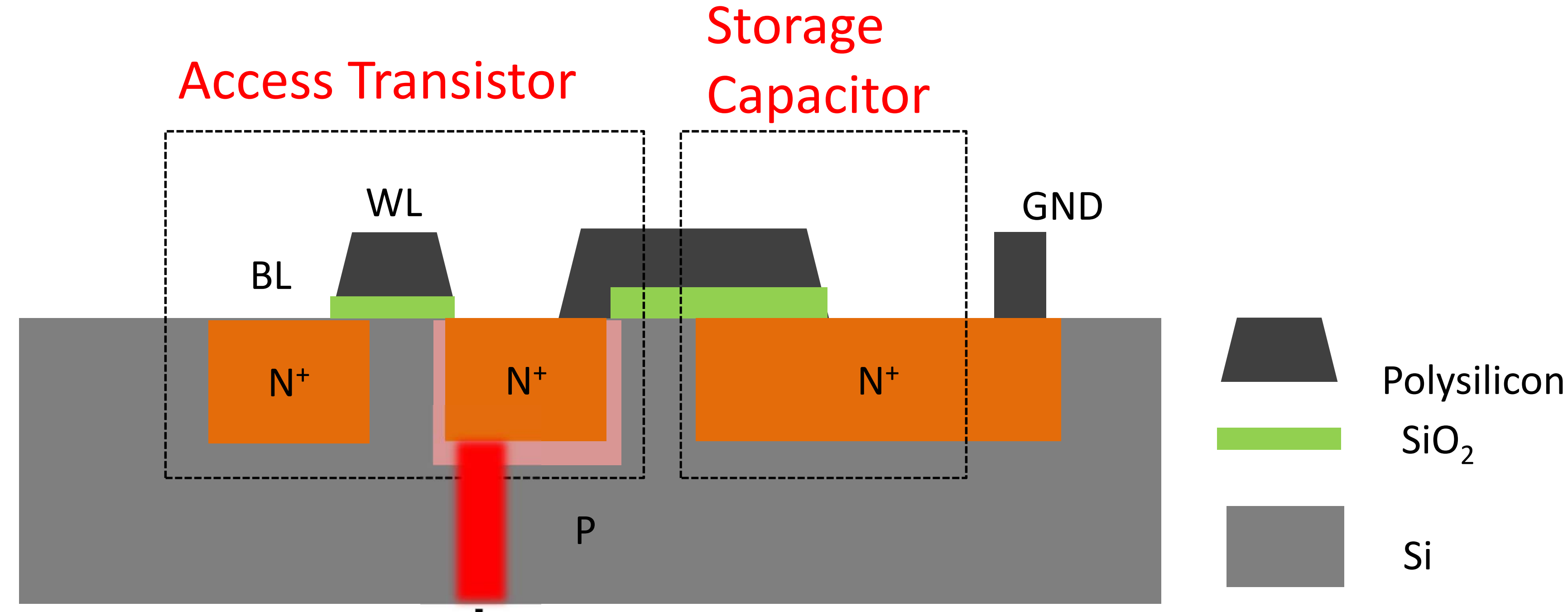


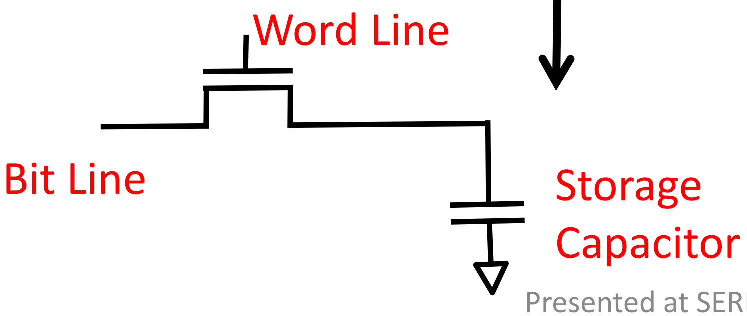
3. SRAM

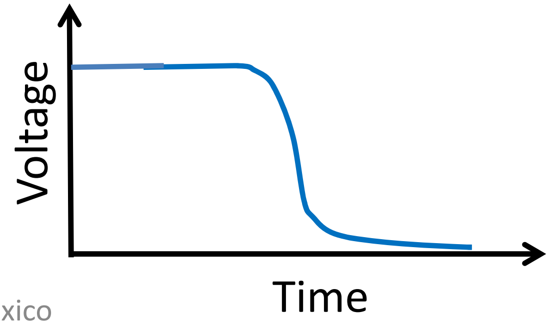


Two Cross-Coupled Inverters

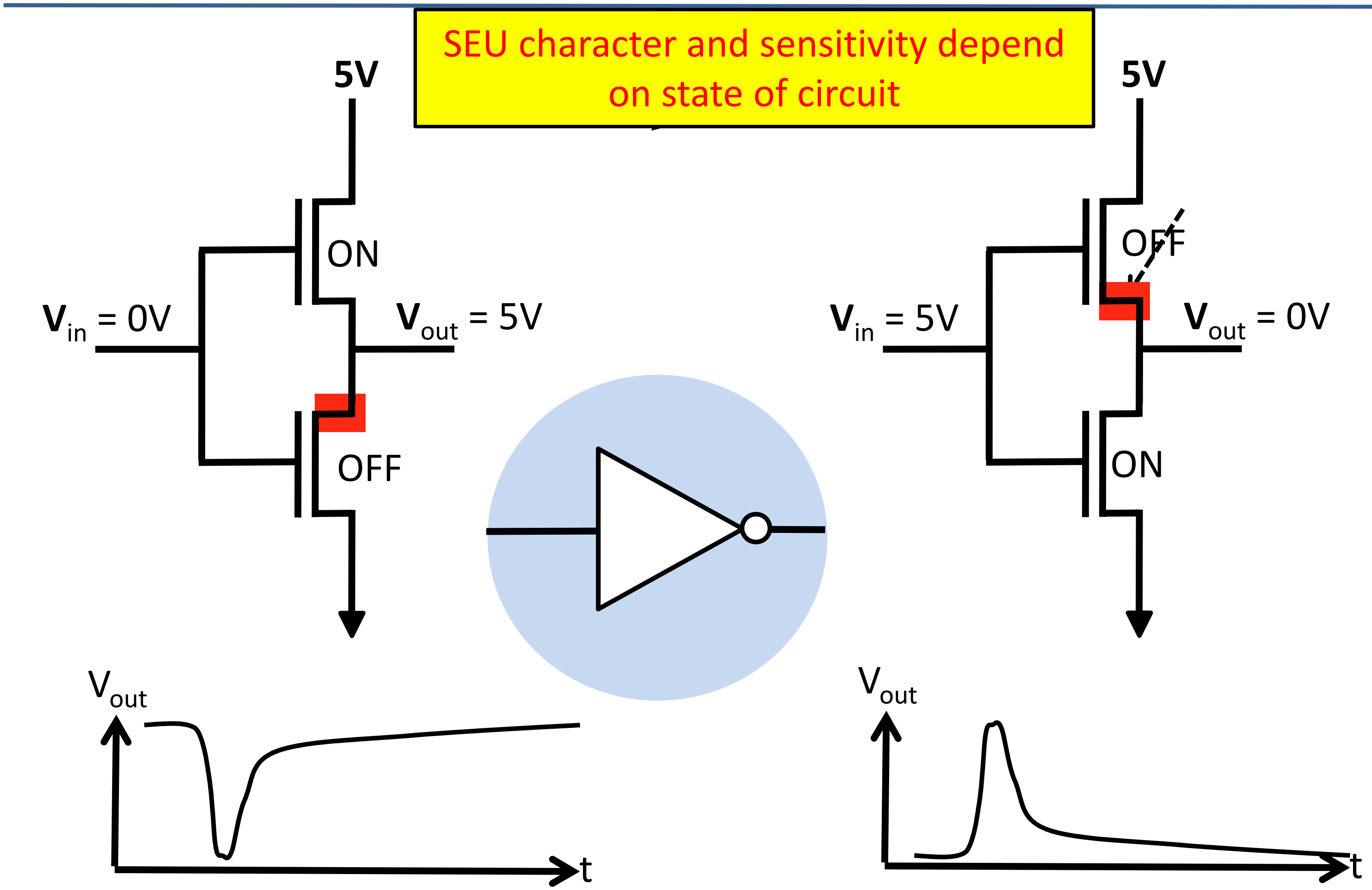
SEU in DRAM – No Propagation





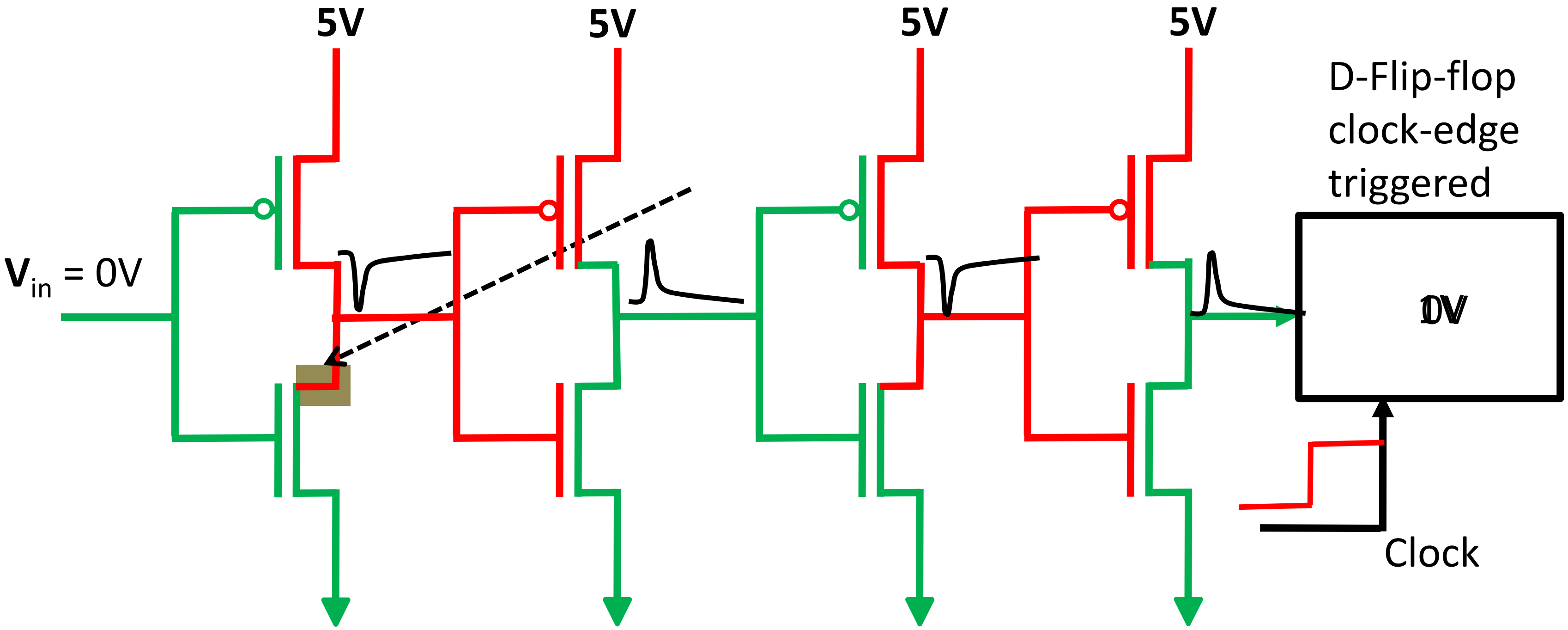


Transient in CMOS Inverter



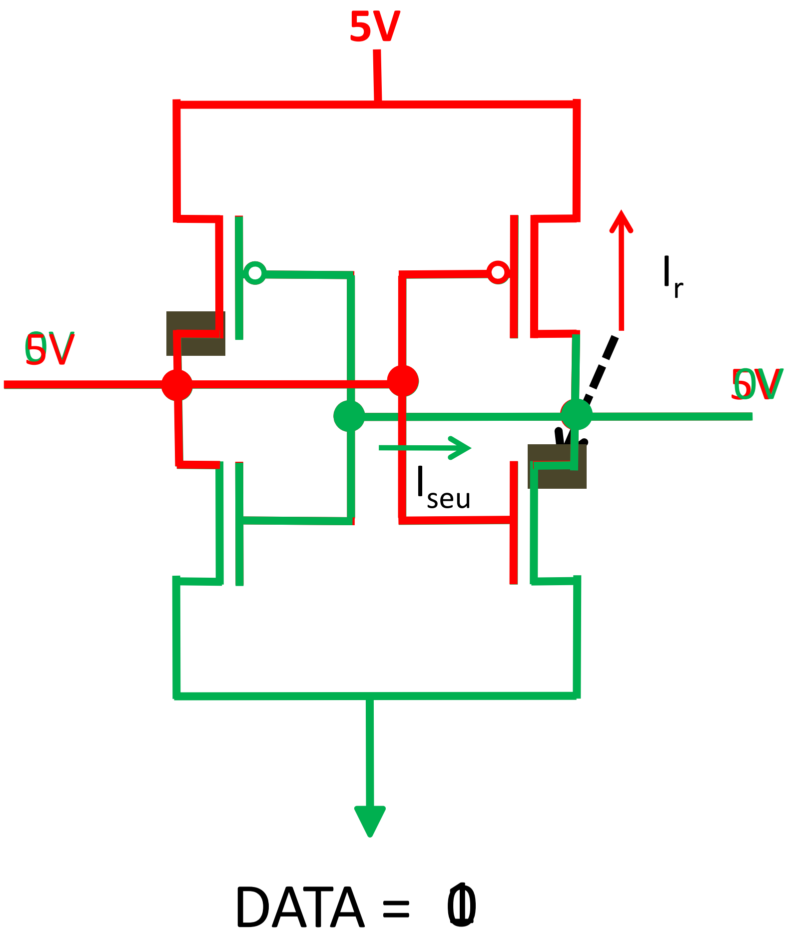
SEU character and sensitivity depend on state of circuit

Transient in CMOS Inverter String



Upset in CMOS SRAM

- Competition between upset (I_{seu}) and restoring (I_r) currents
- If charge deposited by ion over a time period comparable to the response time of the circuit exceeds Q_{crit} an SEU will occur
- There are two sensitive nodes for this SRAM cell – OFF n-channel and OFF p-channel transistors.
- If this occurs in a memory cell, it is called a single event upset (SEU) and if it occurs in a register of a processor, it can result in a single event functional interrupt (SEFI).



SEFIs and MBUs

- Single Event Functional Interrupts (SEFIs) is a SEU that causes circuit to stop operating. SEFIs occur in a register that controls configuration in, for example, processors, reconfigurable FPGAs or SDRAMs
  - The stored bit upsets, i.e., “1” goes to “0” or “0” goes to “1”.
  - There is no permanent damage to the device.
  - The error can be corrected by rewriting the original information which might involve hard reboot (power cycle) or soft reboot (software restart)
  - SEFIs (functional interrupt) are more serious than SEUs (e.g. data upset)

- Multiple Bit Upsets (MBUs) consists of multiple SEUs caused by a single ion
  - MBUs occur through charge spreading (diffusion) or through track intersection with more than one storage element.
  - On a 16 Mbit DRAM a single ion produced more than 50 SEUs
  - MBUs are harder to mitigate using error detection and correction
  - To avoid MBUs in memories physically separate bits in same word

Outline

1. Environments
2. Definition of SEEs
3. History
4. Fundamental Mechanisms
5. Testing
6. Rate Prediction
7. Mitigation
8. Current Issues

SEE Testing

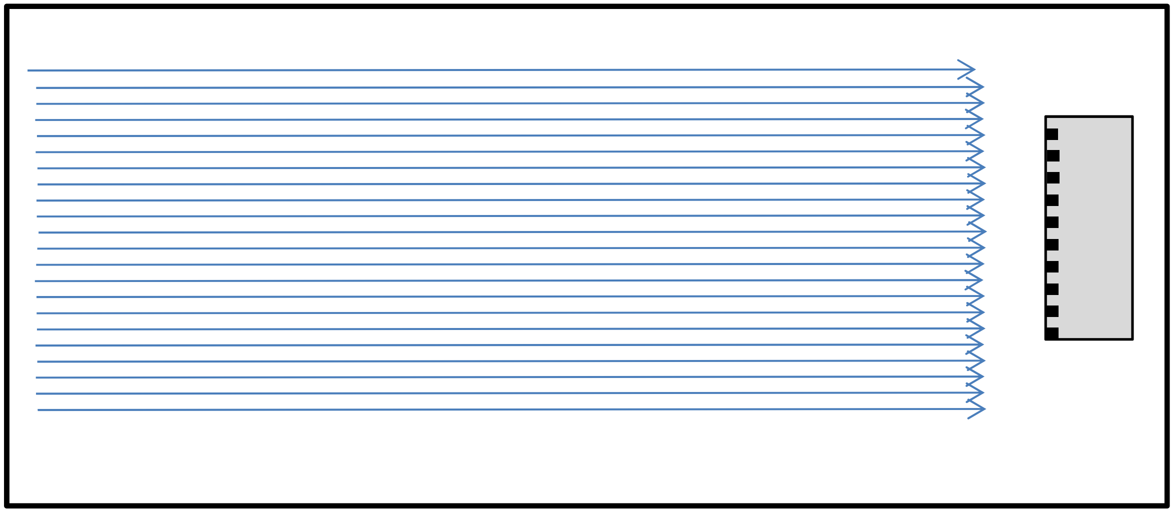
- Why do testing?
  1. To determine the presence and characteristics of single events
     - Destructive or non-destructive
     - SEU or MBU
     - Voltage and temperature dependence
     - Amplitude and width of SET
  2. To calculate the SEE rate for a radiation environment
- What guides the test?
  1. Function
  2. Application

SEE Testing

- SEE testing is usually done at accelerators, (cyclotrons or tandem Van der Graaff machines) that irradiate the whole device with ions. Some in air and some in vacuum.
- Package must be opened for low-energy ions
- Flip-chip mounted devices present a problem – back side irradiation
- Other testing methods that provide spatial and temporal information include:
  - Focused Ion Beam
  - Focused, Pulsed Laser Beam

SEE Testing

- SEE Test Setup to Measure Cross-Section (SEE-sensitive area of chip).
  - Beam must be larger than target area
  - Beam **flux** = N/cm^2/t based on exposure time and "pileup" of events – much higher than in space
  - Beam **fluence** is time integral of flux. Depends on required statistics, i.e., 400 events for a 1σ of 5%. As high as 10^7 particles/cm^2 to ensure no destructive SEE. For protons up to 10^{12} particles/cm^2

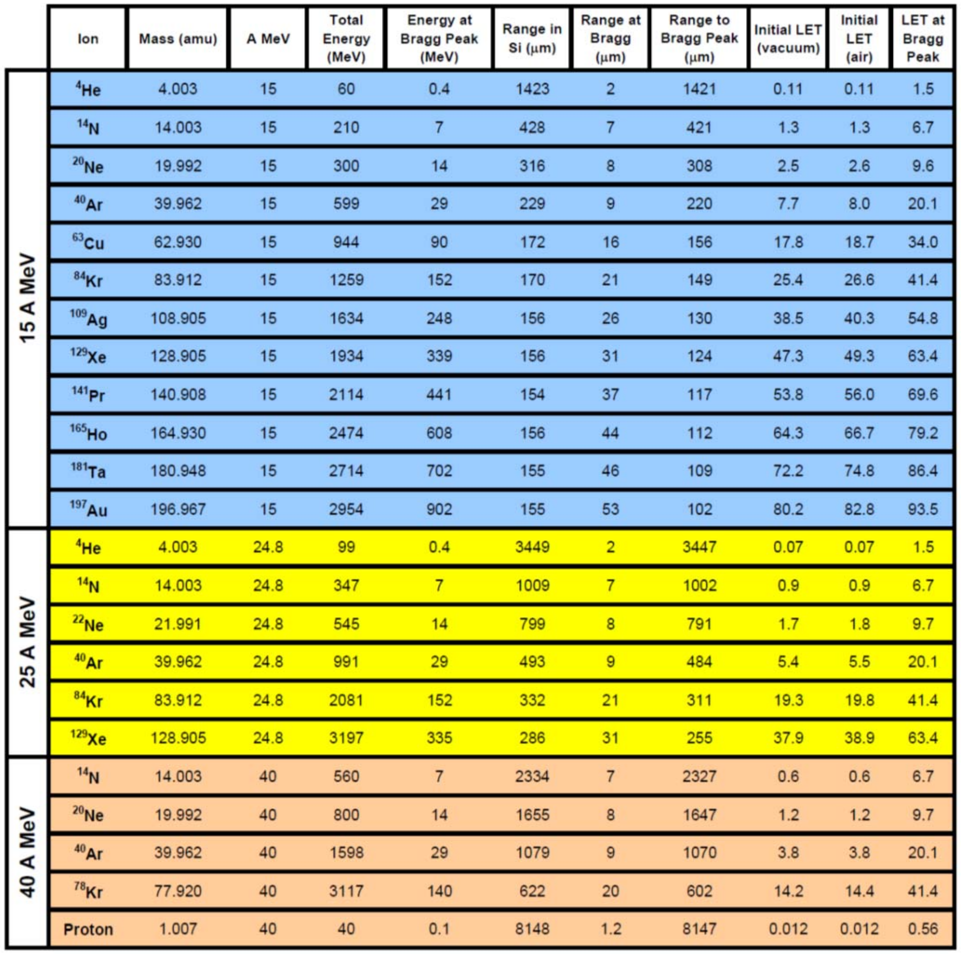


$$\sigma\ (\mathrm{cm}^2) = \frac{N(\text{events})}{N(\text{fluence})}$$

SEE Testing

- Selection of ions and their energies based on required LET and range:
  - 1 < LET < 100 MeV.cm^2/mg
  - Range > 50 μm (SEL vs SEU)
- Testing in air vs vacuum
- Time required for beam change
- Remote testing (cabling)
- Flux, fluence, data storage, temperature, angle, bias during testing, activation, number of samples.

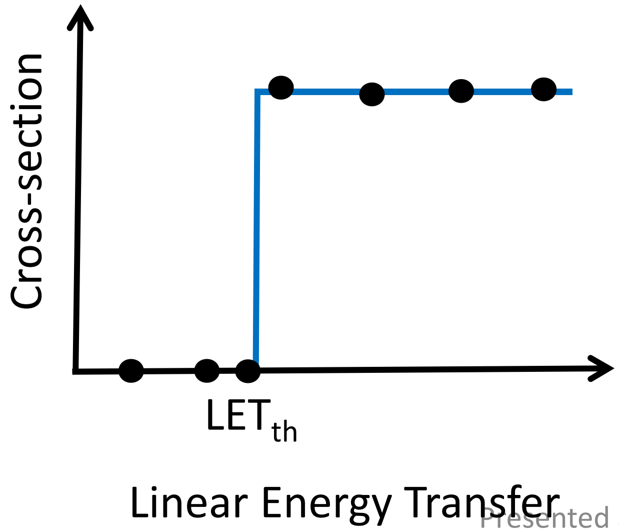
Available Beams at Texas A&M

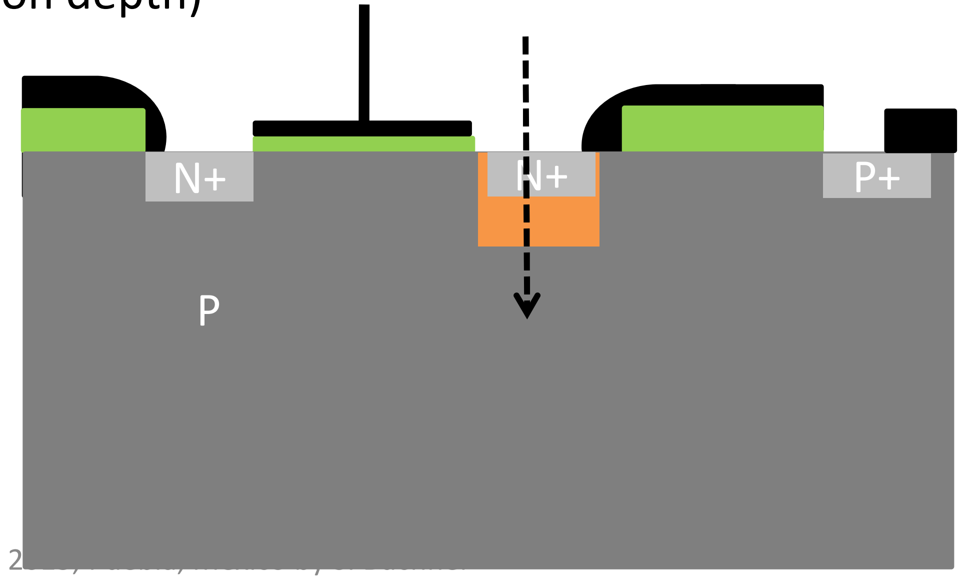


	Ion	Mass (amu)	A MeV	Total Energy (MeV)	Energy at Bragg Peak (MeV)	Range in Si (μm)	Range at Bragg (μm)	Range to Bragg Peak (μm)	Initial LET (vacuum)	Initial LET (air)	LET at Bragg Peak
15 A MeV	^{4}He	4.003	15	60	0.4	1423	2	1421	0.11	0.11	1.5
	^{14}N	14.003	15	210	7	428	7	421	1.3	1.3	6.7
	^{20}Ne	19.992	15	300	14	316	8	308	2.5	2.6	9.6
	^{40}Ar	39.962	15	599	29	229	9	220	7.7	8.0	20.1
	^{63}Cu	62.930	15	944	90	172	16	156	17.8	18.7	34.0
	^{84}Kr	83.912	15	1259	152	170	21	149	25.4	26.6	41.4
	^{109}Ag	108.905	15	1634	248	156	26	130	38.5	40.3	54.8
	^{129}Xe	128.905	15	1934	339	156	31	124	47.3	49.3	63.4
	^{141}Pr	140.908	15	2114	441	154	37	117	53.8	56.0	69.6
	^{165}Ho	164.930	15	2474	608	156	44	112	64.3	66.7	79.2
	^{181}Ta	180.948	15	2714	702	155	46	109	72.2	74.8	86.4
	^{197}Au	196.967	15	2954	902	155	53	102	80.2	82.8	93.5
25 A MeV	^{4}He	4.003	24.8	99	0.4	3449	2	3447	0.07	0.07	1.5
	^{14}N	14.003	24.8	347	7	1009	7	1002	0.9	0.9	6.7
	^{22}Ne	21.991	24.8	545	14	799	8	791	1.7	1.8	9.7
	^{40}Ar	39.962	24.8	991	29	493	9	484	5.4	5.5	20.1
	^{84}Kr	83.912	24.8	2081	152	332	21	311	19.3	19.8	41.4
	^{129}Xe	128.905	24.8	3197	335	286	31	255	37.9	38.9	63.4
40 A MeV	^{14}N	14.003	40	560	7	2334	7	2327	0.6	0.6	6.7
	^{20}Ne	19.992	40	800	14	1655	8	1647	1.2	1.2	9.7
	^{40}Ar	39.962	40	1598	29	1079	9	1070	3.8	3.8	20.1
	^{78}Kr	77.920	40	3117	140	622	20	602	14.2	14.4	41.4
	Proton	1.007	40	40	0.1	8148	1.2	8147	0.012	0.012	0.56

SEE Testing (Ideal Curve)

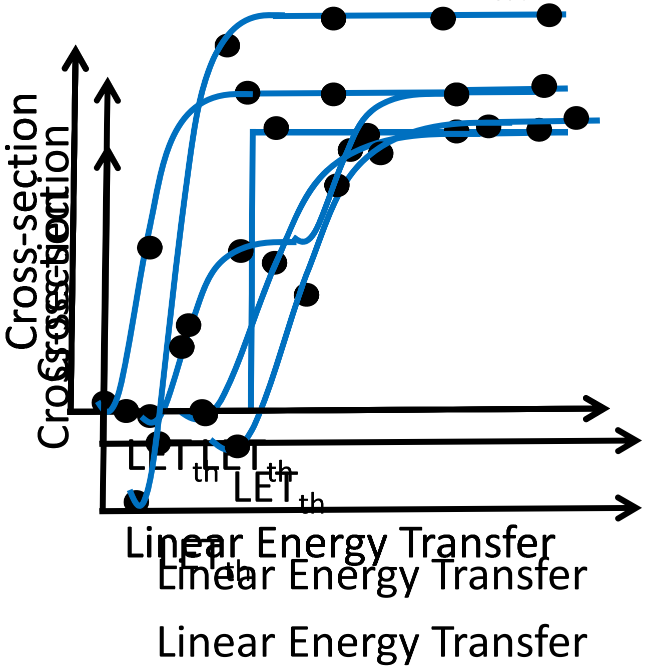
- Testing involves measuring **σ(LET)**, i.e., cross-section as a function of LET
- Cross-section = $\frac{N_e(\text{events})}{N_f(\text{Fluence})}$
- If the beam has a flux of N_f, and the device has SEE sensitive nodes that together add up to half the surface area, the measured cross-section will be $N_f/2$
- If collected charge > **critical charge**, an SEE occurs
- $LET_{th} = Q_{crit}/d$ (d=charge collection depth)

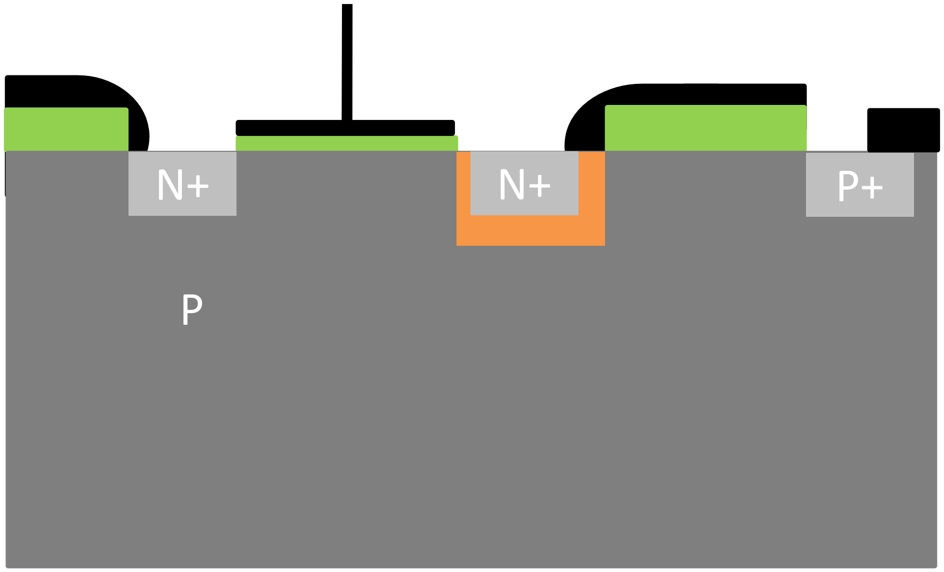




SEE Testing

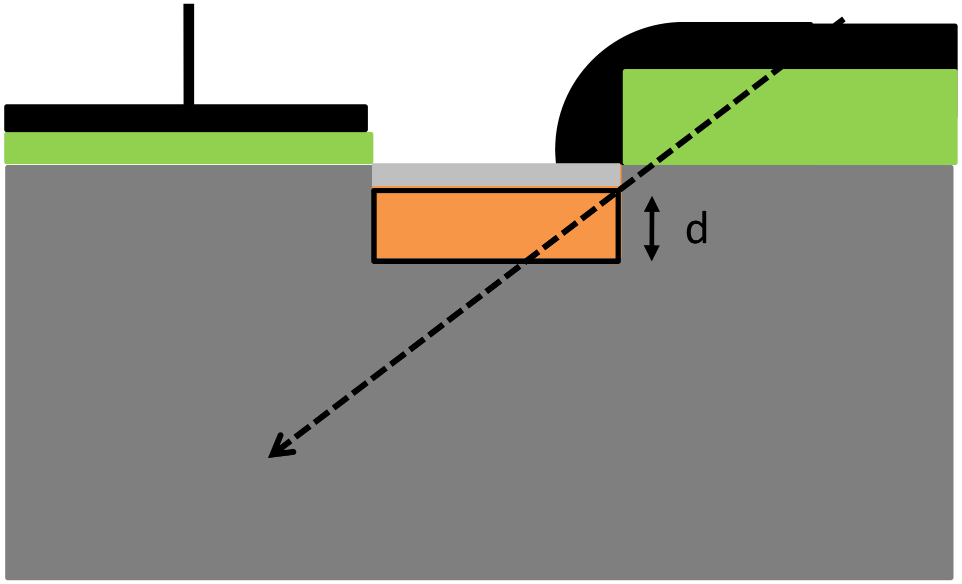
- σ(LET) deviates from ideal curve because:
  - Charge collection efficiency varies across sensitive area – broadens curve
  - Diffusion of charge from ion strikes near sensitive volume – increases σ_{sat}
  - Multiple junctions with different sensitivities and areas – change LET_{th} and σ
  - Funnel – lowers LET_{th}
  - MBU – increase σ_{sat}





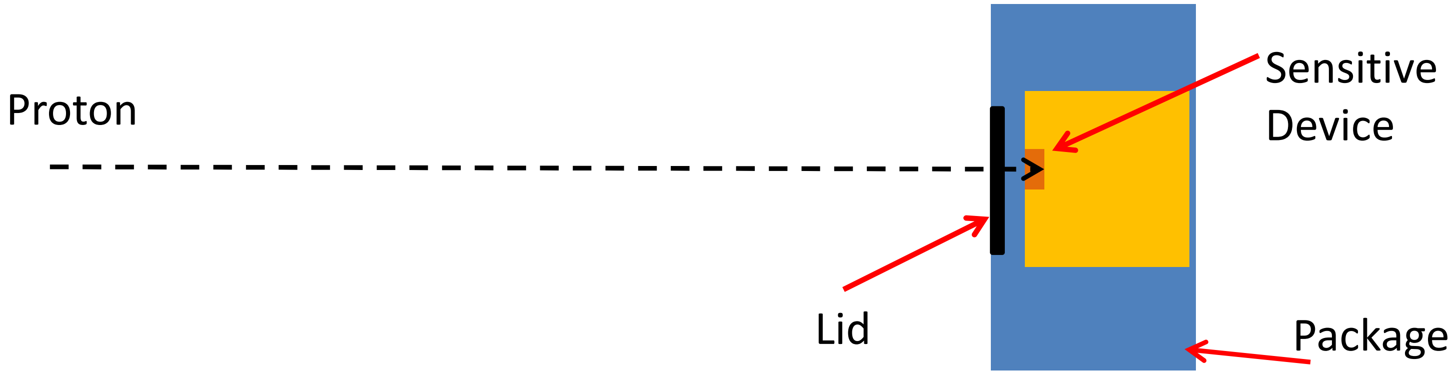
Testing at Non-Normal Incidence

- Testing is done at non-normal incidence to:
  - Increase LET – “effective LET” – without changing beam species
  - Determine sensitive volume depth (d)
  - Look for multiple bit upsets (MBUs)
  - Check SEU hardening that requires multiple nodes to upset for the cell to upset
- Total deposited charge given by product of LET and path length
  - $Q=LET.d.\cos(\theta)$
- Cross-section modified –
  - $\sigma = \sigma/\cos(\theta)$
- Adequate range is vital
- Shadowing by package limits angle of incidence



Proton Testing

- Devices sensitive should be tested for proton SEE sensitivity especially for devices with LET$_{th}$ < 15 MeV.cm^2/mg because space dominated by protons
- Since LET is not a well-defined number for the group of secondary particles emitted by the silicon nucleus, a better metric is proton energy
- Cross-section is calculated in the same way as for heavy ions
- SEUs are measured as a function of **proton energy**
- Since protons have long ranges in silicon, i.e., 60 MeV protons have a range of ~2 cm ,devices do not have to be de-lidded

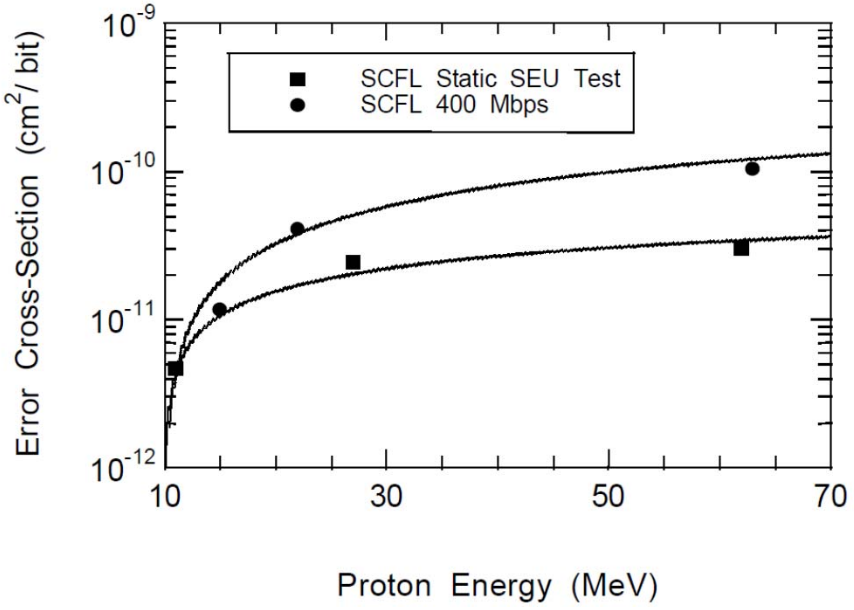


Proton Testing

- Measure number of SEEs normalized to the proton fluence

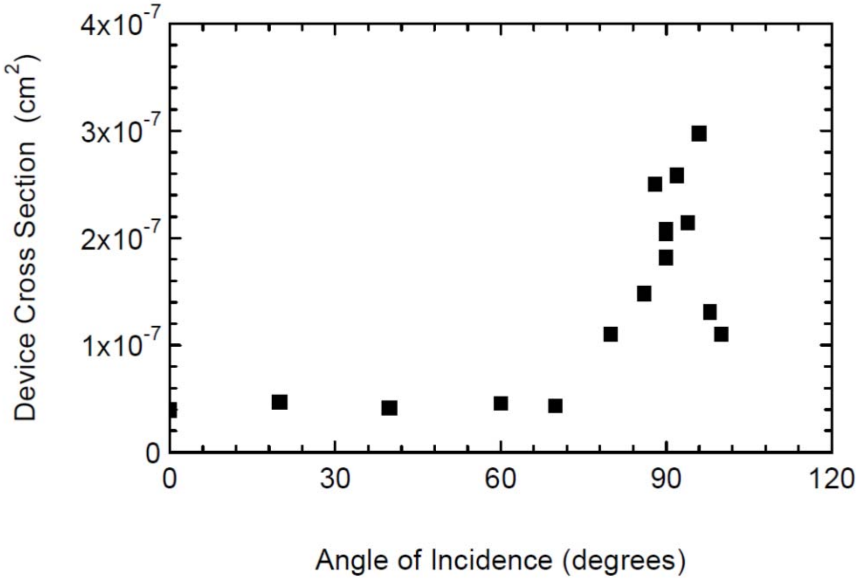
$$\sigma(E) = N_{SEE}/\text{Fluence}$$

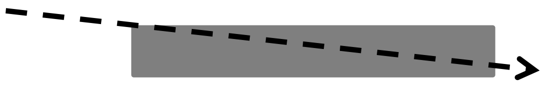
- Plot the data as a function of proton energy – $\sigma(E)$



Proton Testing

- Devices that have a small depth (Z-direction) and a large area (XY directions) can have a much higher cross-section at large angles.
- Although the proton LET is small, the long distance by which the LET is multiplied leads to a large Q_{coll}





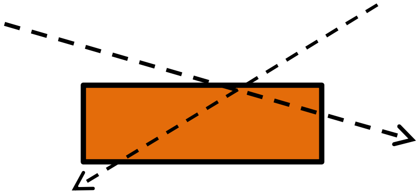
Outline

1. Environments
2. Definition of SEEs
3. History
4. Fundamental Mechanisms
5. Testing
6. **Rate Prediction**
7. Mitigation
8. Current Issues

Rate Prediction

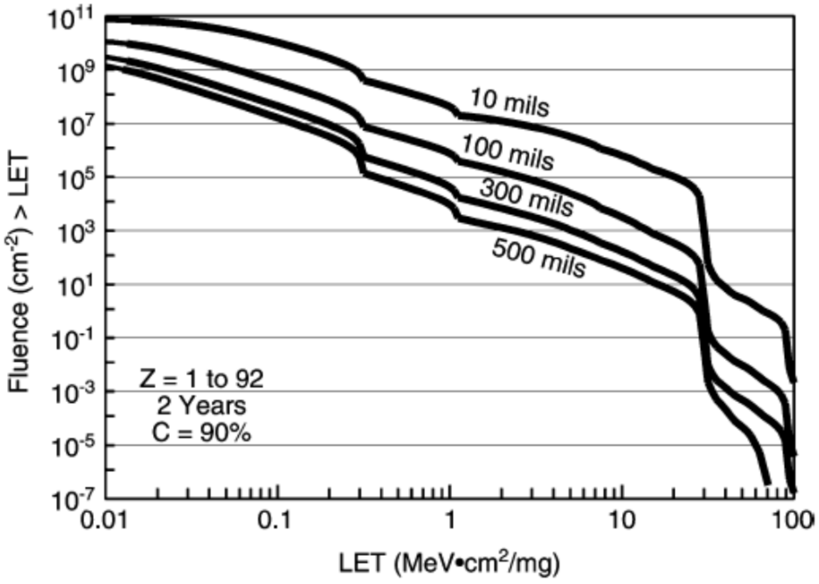
$$R = \iiint S(L, \varphi, \cos(\theta) f(L, \varphi, \cos(\theta))\cos(\theta) d(\cos(\theta)) d\varphi dL$$

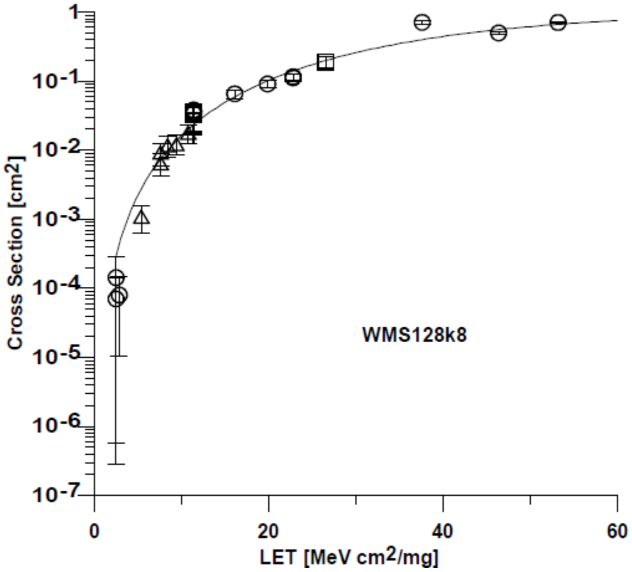
- Need to know:
  - Cross section $S(L,\phi,cos(\theta))$
  - Fluence $f(L,\phi,cos(\theta))$
  - Sensitive Volume Dimensions



Rate Prediction

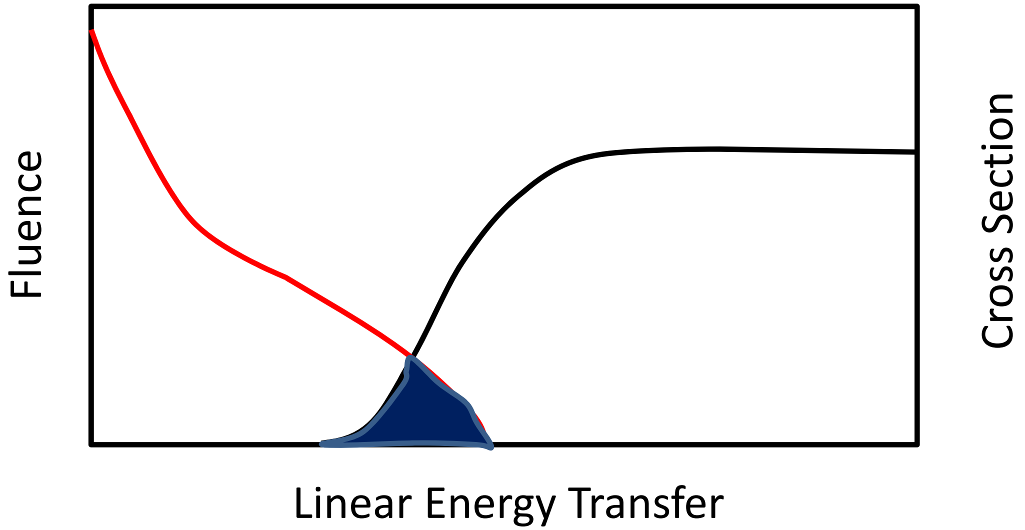
- Need to know:
  - Cross Section $S(L,\phi,\cos(\theta))$ Fit data with Weibull curve or Error Function
  - Fluence $f(L,\phi,\cos(\theta))$





Rate Prediction

- Need to know:
  - Cross Section *$S(L,\phi,\cos(\theta))$* Fit data with Weibull curve or Error Function
  - Fluence *$f(L,\phi,\cos(\theta))$*



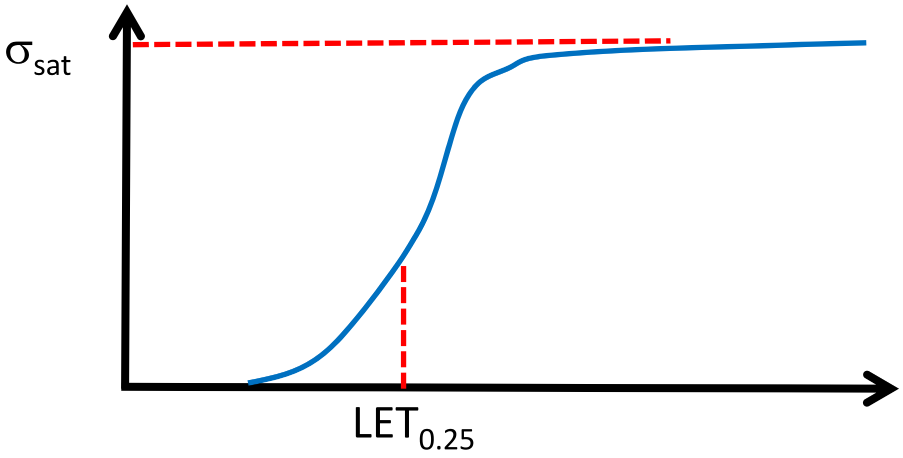
Rate Prediction

- The following programs may be used to calculate the error rates:
  - CRÈME-MC
  - SPENVIS
  - SPACERAD
  - OMERA

Rate Prediction

- Petersen Figure of Merit:
  - FOM depends on orbit (FOM=200 for Geosynchronous Orbit)

$$R = FOM\frac{\sigma_{sat}}{LET_{0.25}^{2}}$$

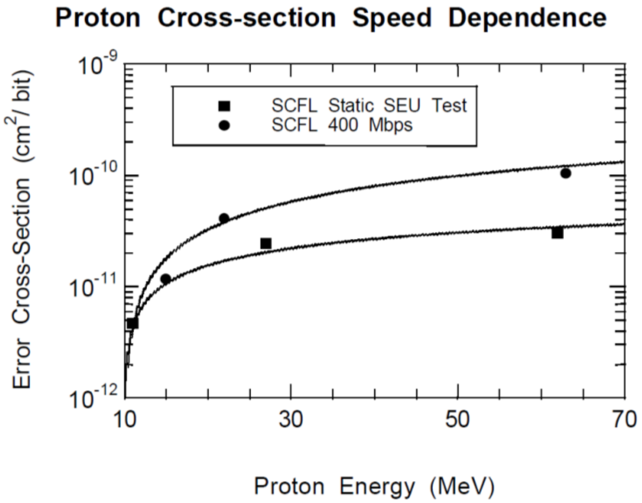


To harden a device to SEE:

- Increase LET_{th}
- Reduced σ_{sat}

Rate Prediction

- Proton-induced Upsets



gure 11a. Bit error rate testing of GaAs HIGFET shift registers showed that static upset easurements would underpredict the upset rates by large factors if the intended application involves st clock speeds [Mars-95]. These factors increase as the data rates increase and can approach 100.

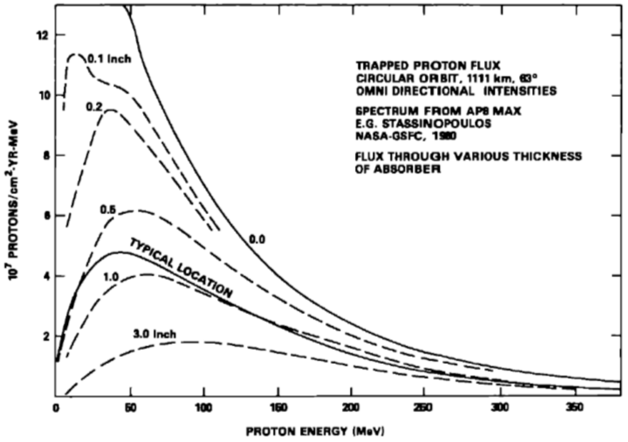
$$X = \left[\frac{B}{A}\right]^{14} \left\{1\text{-exp}(-0.18Y^{1/2})\right\}^4$$

where X is in units of 10^{-12} upsets per proton/cm^2 per bit and

$$Y = \left(\frac{18}{A}\right)^{1/2} (E - A)$$

E is the incident proton energy. E, A, and B are in units of MeV. T

with the apparent upset threshold, while the ratio $(B/A)^{14}$ is associa



Outline

1. Environments
2. Definition of SEEs
3. History
4. Fundamental Mechanisms
5. Testing
6. Rate Prediction
7. Mitigation
8. Current Issues

Approaches to Mitigation

Mitigation is not always needed.

- Temperature measurement monitored from ground – intervention only after persistent change.
- Scientific data (photograph of the sun) can stand to have a few bits of corrupted data.

Approaches to Mitigation

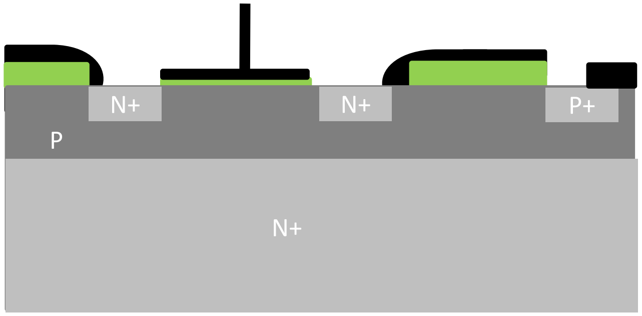
1. Reduce Charge Generation
   - Change to wide bandgap material, e.g. GaAs (e.g.=2 eV)
2. Reduce Charge Collection
   - Silicon-on-insulator
   - Highly doped substrate
   - Add resistor or capacitor
   - Cancellation
3. Modify Circuit Response
   - Add elements to slow circuit response (RC low-pass filters)
4. Modify System/Subsystem
   - Spatial and temporal redundancy with voting
   - EDAC (Hamming Code, Reed-Solomon, Parity bits, Checksums, etc)

Mitigation – Charge Generation

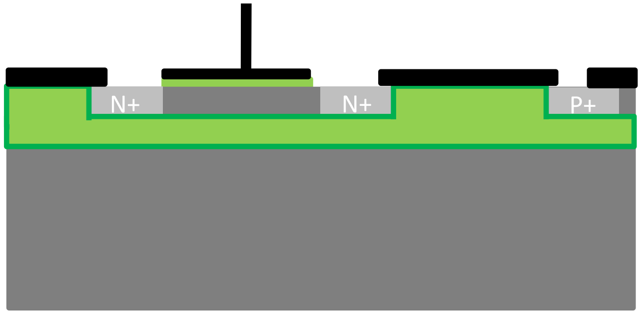
- Select material with bandgap larger than Si to reduce the initial electron-hole density
  - Si (3.6 eV)
  - GaAs (4.8 eV)
  - $Al_{0.7}Ga_{0.3}As$ (6.52 eV)
- Select materials that don't store charge (Still use silicon circuitry for control)
  - Magnetic Memories
  - Resistive Memories

Mitigation – Charge Collection

- Use highly-doped substrate

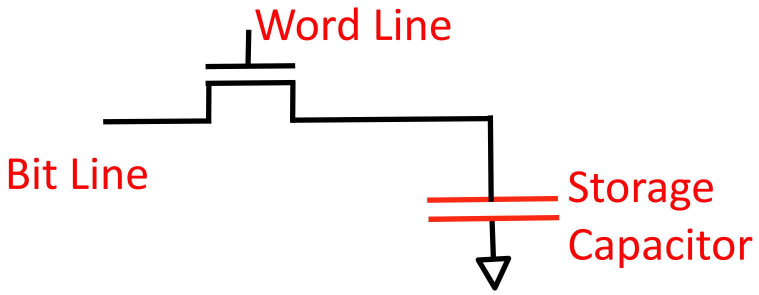


- Use silicon-on-Insulator

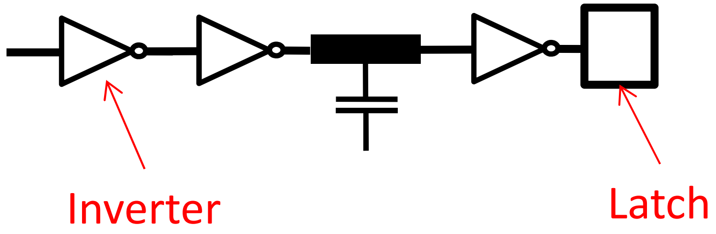


Mitigation – Circuit Response

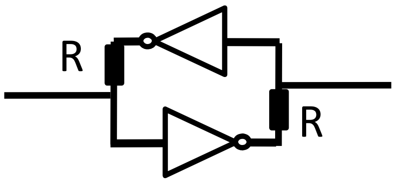
1. DRAM – Increase Capacitor Size



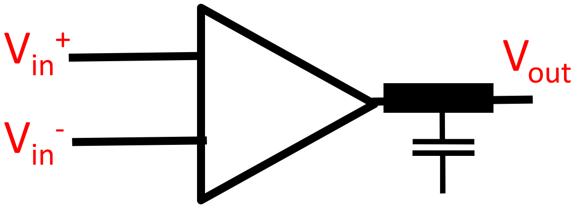
2. Inverter String – Add Low-Pass Filter
  - Increase Transistor Drive



3. SRAM – Add Decoupling Resistors
  - Insert Additional Transistors

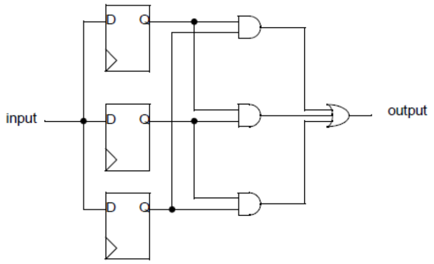


4. Comparator – Add Filter to Output

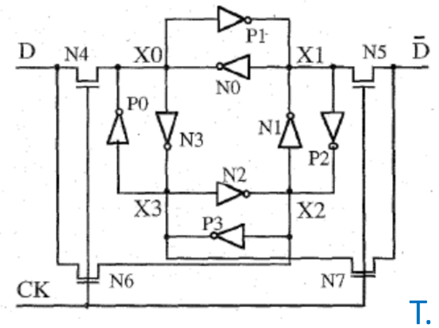


Mitigation – Redundancy

- Triple Modular Redundancy (TMR) – Majority Voting



- Spatial Redundancy – DICE Latch



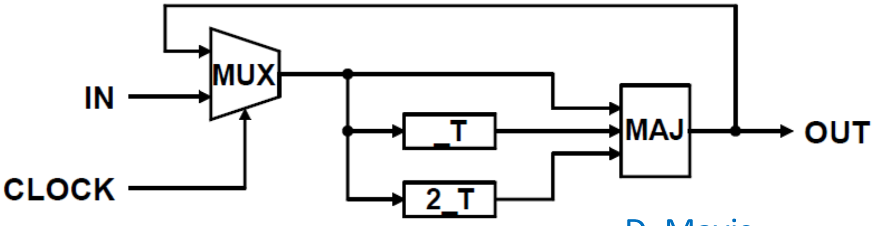
T. Calin

- Error Detection and Correction (EDAC) - Parity

010011001

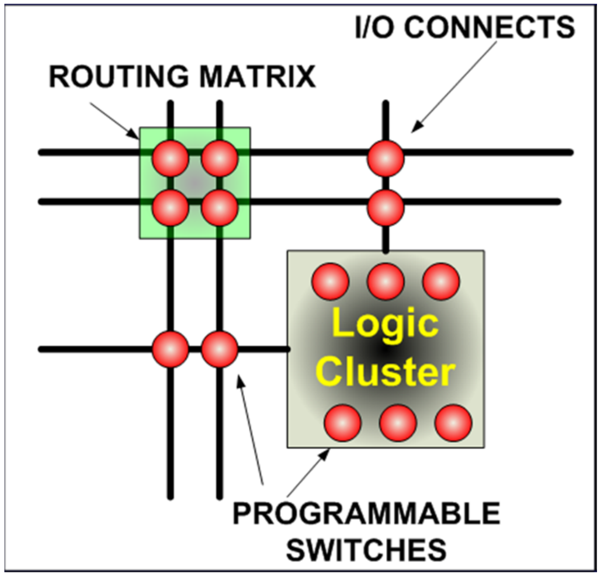
Mitigation – Redundancy

- Temporal Redundancy



D. Mavis

- Scrubbing - configuration memory in an FPGA
  - Internal vs External
  - Scrubbing Rate



M. Berg

Mitigation – Penalties

- All Mitigation Approaches have **penalties** in the form of:
  - Increased Area
  - Reduced Speed
  - Increased Power
  - Expensive Process Modifications
  - Immature Technology

Outline

1. Environments
2. Definition of SEEs
3. History
4. Fundamental Mechanisms
5. Testing
6. Rate Prediction
7. Mitigation
8. Current Issues

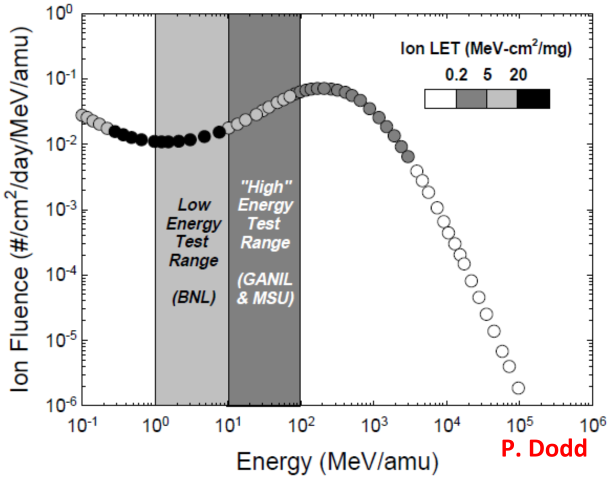
Current Issues

1. Fidelity of ground testing
2. Rate prediction
3. Proton LET/Energy sensitivity
4. Nuclear interactions
5. Angle sensitivity for DICE cells and others
6. Testing
7. Synergistic effects such as TID on SEE rate

1. Fidelity of Ground Testing

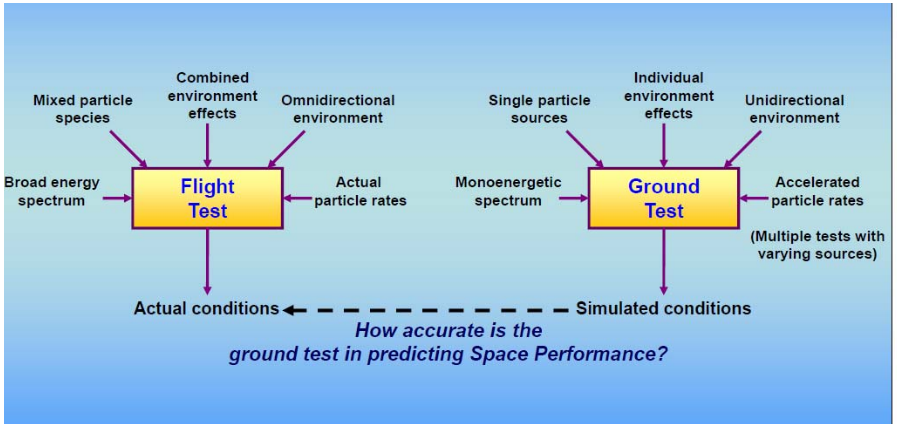
- Cosmic ray energies much greater than ion energies used at accelerators and can lead to nuclear interactions
- Importance of space test beds like MPTB to investigate validity of terrestrial test facilities

- Wide variety of ion species arrive from different directions having different energies during entire mission.
- Must consider TID and DD effects



P. Dodd

.15. Galactic cosmic ray iron spectrum *vs.* energy with LET denoted by symbol shading [118]. Ion energies available at typical accelerator facilities range from approximately 1-100 MeV/amu.



How accurate is the ground test in predicting Space Performance?

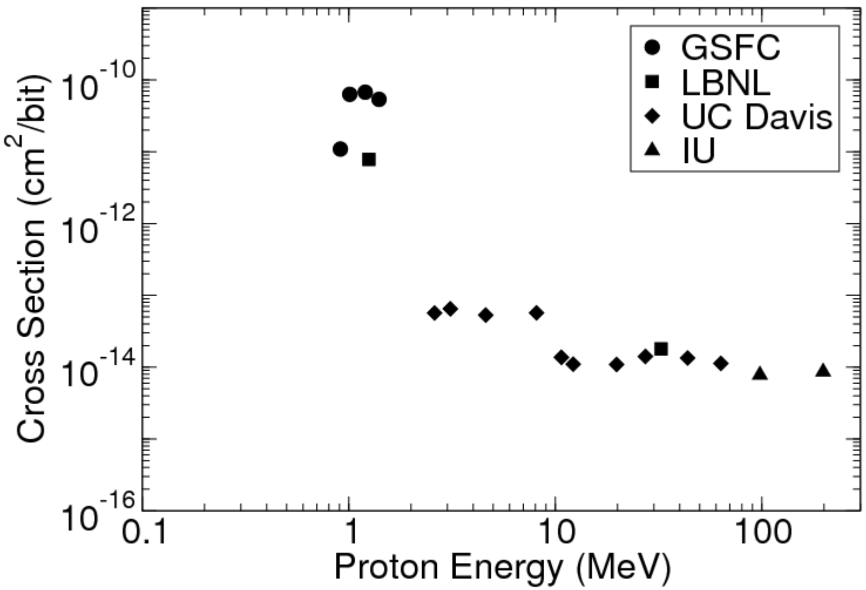
K. LaBel

2. Rate Prediction

- Codes based on RPP method are not sufficiently accurate because:
  - They ignore charge diffusion
  - They don’t consider short-term fluctuations in the environment
  - Don’t include nuclear interactions with heavy nuclei such as Tungsten
  - Ignore structural effects and assume a single charge collection efficiency
- Monte Carlo-based codes, do take these effects into consideration.
- CREME96 being replaced by CREME-MC
- Models for the environment such as AP8 and AE8 and the solar proton model of JPL have been updated and included

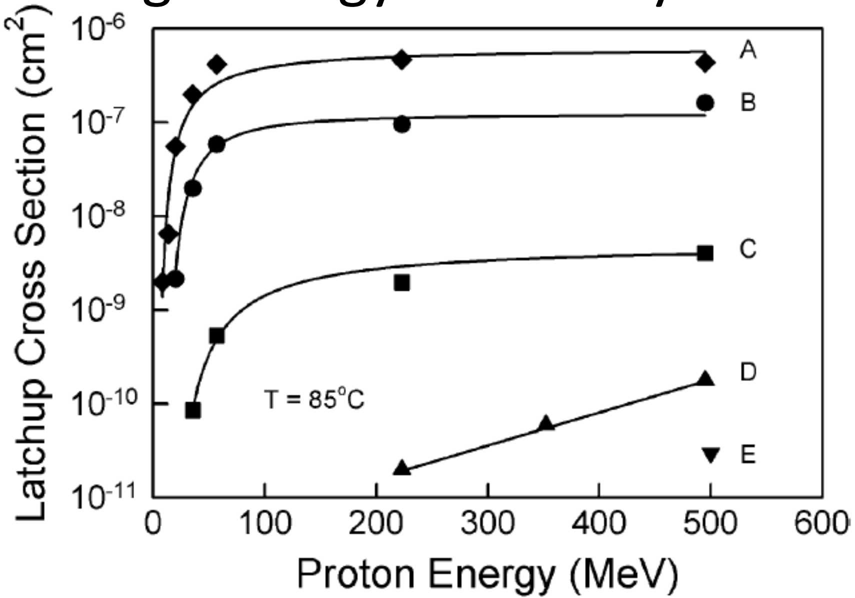
3. High and Low Energy Sensitivity

Low LET Sensitivity



J. Heidel

High Energy Sensitivity



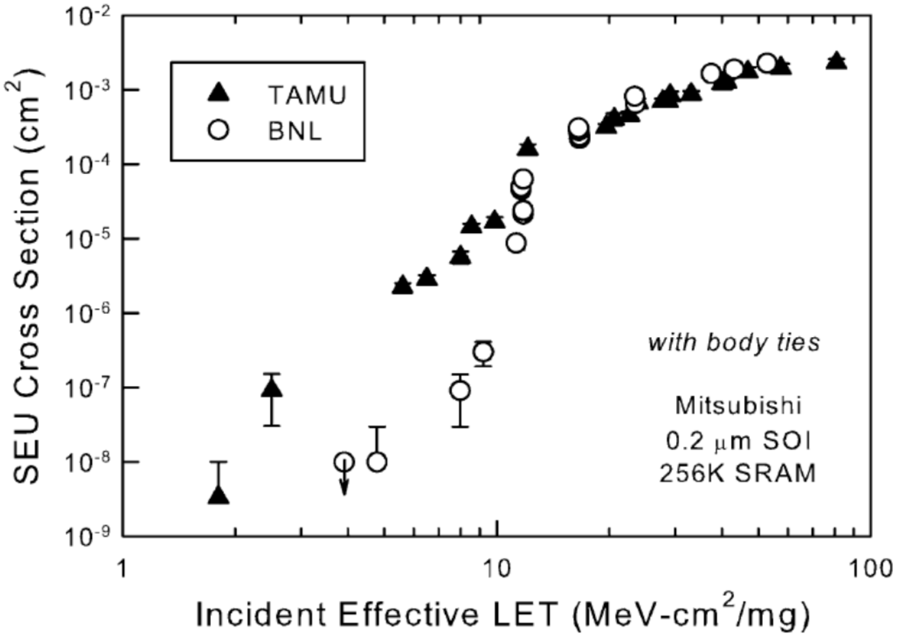
J. Schwank

For sensitive devices with low LET thresholds the cross-section for protons increases at lower proton energies due to direct ionization

Need to go to very high energies for proton exposures in order to observe saturation and actual onset (Device D)

4. Nuclear Interactions

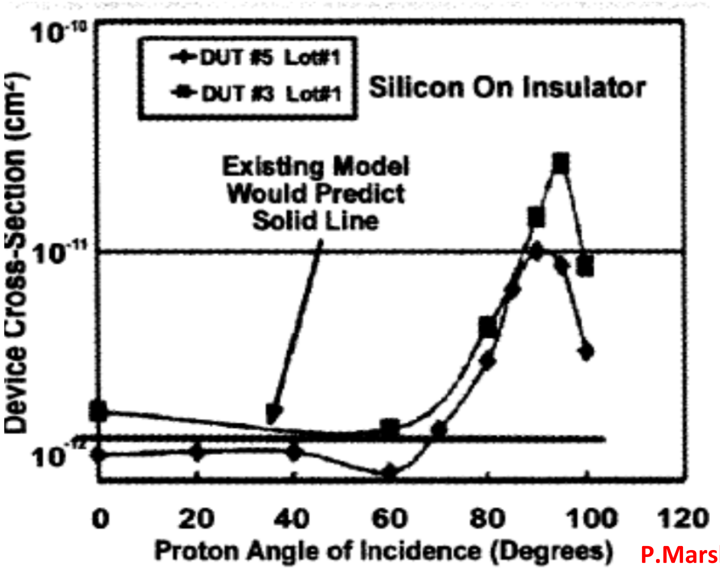
- LET is not a valid metric for devices containing heavy metals such as tungsten (W) because of nuclear interactions with higher energy ions



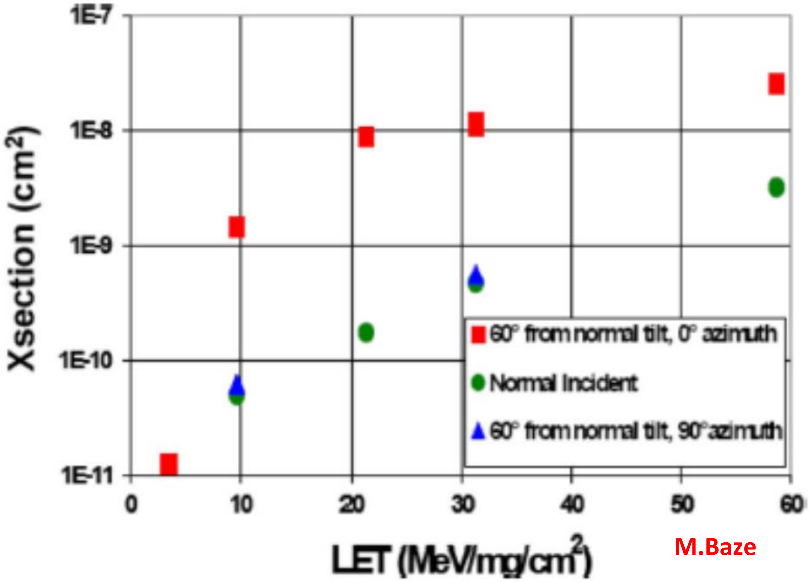
5. Angular Measurements

Silicon-on-insulator

DICE Cell



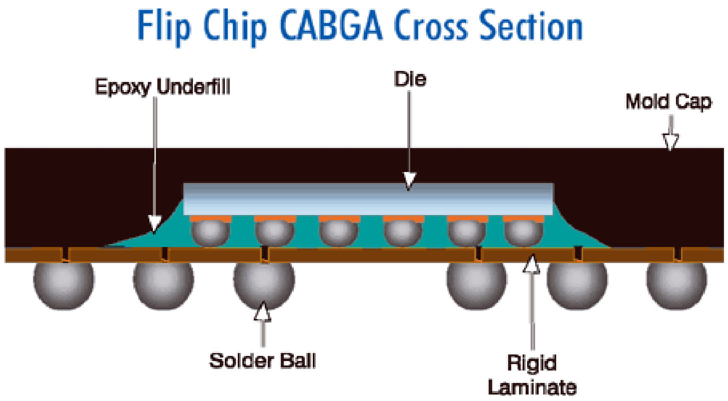
P.Marshall



M.Baze

8. Testing

Packaging



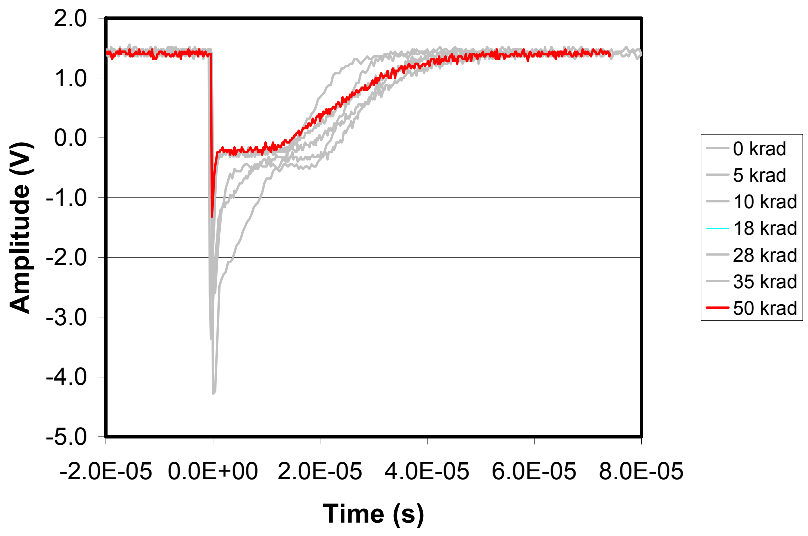
Difficult to open up a device that is flip-chip bonded in a ball grid array package

Test Equipment

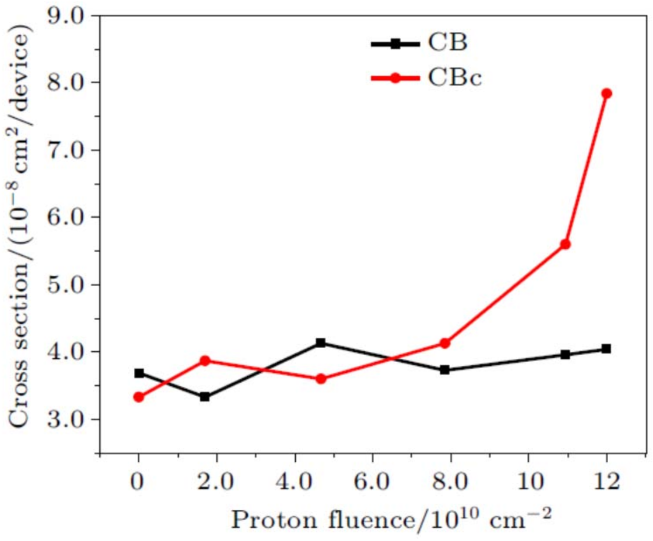
Risky to ship expensive, bulky and fragile test-equipment to test facility

7. Synergistic Effects

Effect of Total Ionizing Dose on SEE for linear bipolar circuit – change in SET shape



Effect of Total Ionizing Dose on SEUs for 0.25 μm SRAM - change in SEU cross-section



Summary

This very rapid overview has explained that:

- SEEs are caused by heavy ions and protons in space
- SEEs can be destructive or non-destructive
- There are three steps in the formation of an SEE:
  - Charge deposition
  - Charge collection
  - Circuit response
- Accelerator testing is done to characterize SEEs and to measure cross-section vs LET
- Convolute cross-section with environment to get SEE rate
- There are ways to minimize the effects of SEE, but there are always penalties associated with them.
- SEEs are not going away.