SERESSA 2022

5th to 9th of December at CERN, Geneva

Fundamental Mechanisms of Non-Destructive SEEs in Devices and Circuits

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Outline

1. **Introduction to SEEs**
2. **Types of SEEs**
3. **Steps in SEE Formation**
   A. ***Charge Generation***
   B. ***Charge Collection and Recombination***
   C. ***Circuit Response***
4. **Summary**

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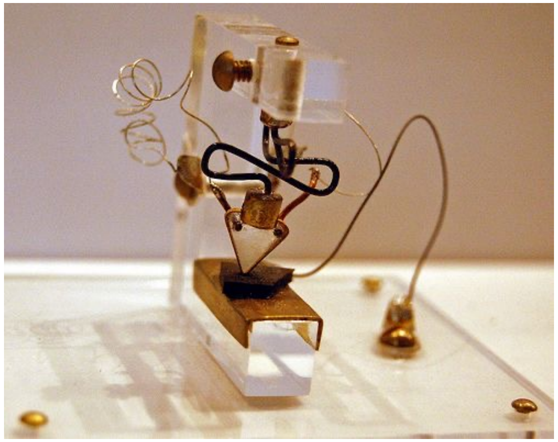
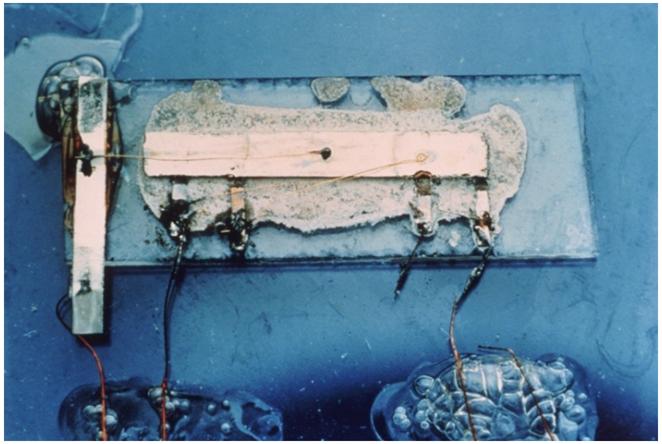
History Lesson

- Prior to 1947, switches in computers consisted of vacuum tubes that were not sensitive to single-event effects.
- The first solid state transistors were sufficiently large to be insensitive to SEEs
- Jack Kilby made the first integrated circuit in 1958. It functioned as an oscillator with a single transistor in a distributed feedback loop with capacitors and resistors on a piece of Ge. Miniaturization was born.



First transistor made at Bell Labs in 1947



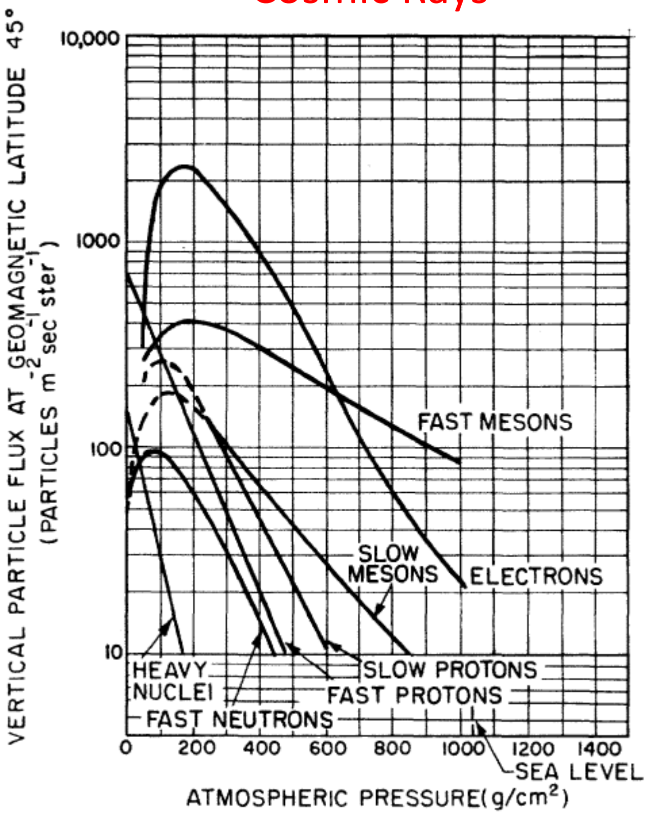
Single transistor and other components on Ge single crystal in 1958.

Minimum Transistor Size Prediction

- In 1962, Wallmark and Marcus predicted cosmic rays would cause SEUs in circuits that would limit non-redundant miniaturization of the circuits for use on Earth. They predicted a minimum feature size for a non-redundant circuit of 10 μm^3.

- However, redundancy techniques offer a way of partly circumventing the scaling limitations.

Cosmic Rays



J.T. Wallmark, et al, Proc. of the IRE, vol. 50, no. 3, pp. 286-298, March 1962

First Observations of SEUs.

- The first actual satellite anomalies were reported in 1975. SEUs in J-K flip-flops with emitter are of 10^{-6} cm^2

  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*

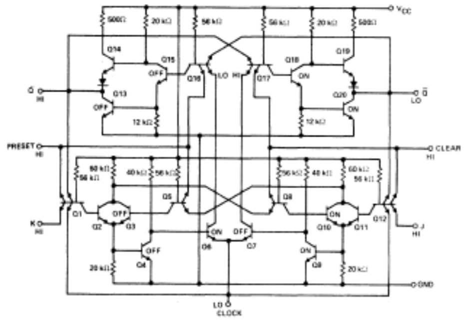
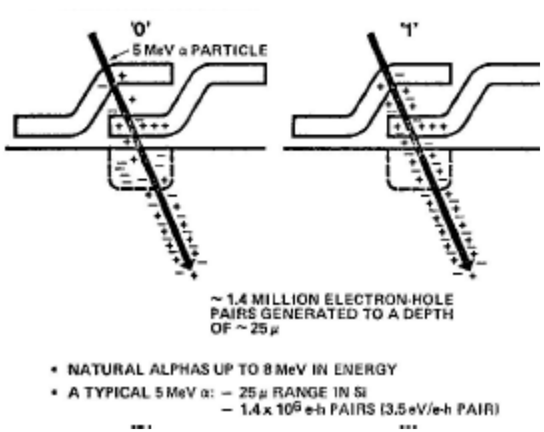


Figure 1. J-K Flip-Flop Circuit with Transistor States

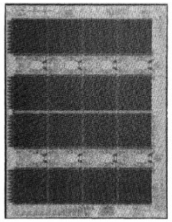
- First observation of SEUs on earth was in 1978. Observed in RAM caused by the alpha particles released by U and Th contaminants within the chip packaging material and solder. Vendors purified material to eliminate.

  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.*

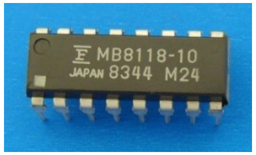


Continuing Observations of SEEs.

- First report of SEUs due to cosmic rays on earth in 1979. *J. F. Ziegler and W. A. Lanford, "Effect of Cosmic Rays on Computer Memories", Science, 206, 776 (1979)*
  - 64-kbit CCD memory array
  - 16-kbit DRAM, fabricated with a per-bit area of 170 um^2 and operating at 5 volts.

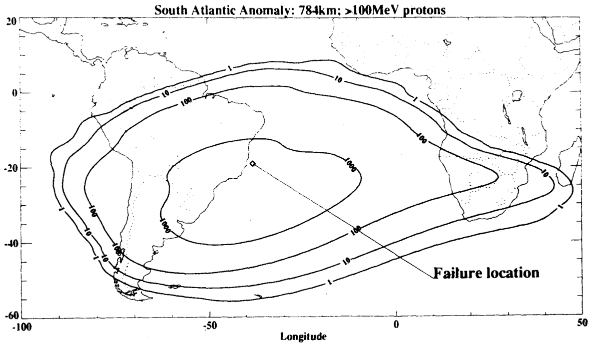


64 Kbit CCD

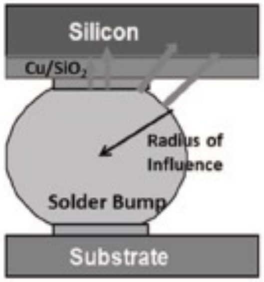


16 Kbit DRAM

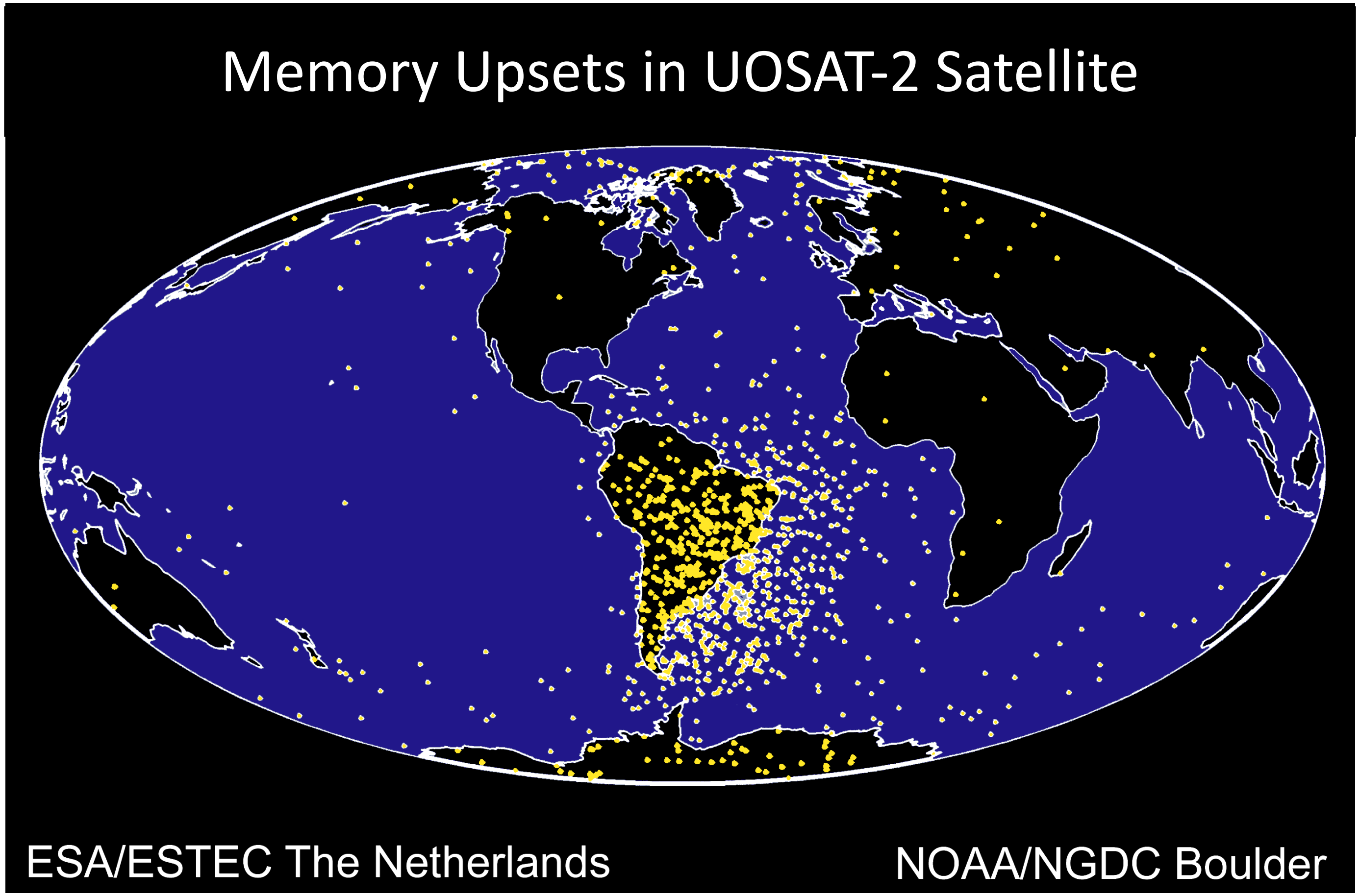
- First report of destructive SEE (proton induced latch-up) in a memory operating in space in 1992
  L. Adams et al. *"A Verified Proton Induced Latch-up in Space," IEEE TNS vol. 39, No. 6, pp. 1804 – 1808, Dec. 1992*
  - 64-kbit CMOS memory (NEC D4464G-15L) in a microwave instrument on board ERS-1 satellite passing through SAA.



- Increased α-particle induced SEU rate caused by Po diffusing to surface of solder bumps during high temp. operation reported in 2017. *B. Narasimham et al. "Influence of Polonium diffusion at Elevated Temperature on the Alpha Emission Rate and Memory SER Performance," 2017 IEEE International Reliability Physics Symposium (IRPS), Monterey, CA, 2-6 April, 2017.*



SEEs Occur Everywhere: Ground to Space



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Types of SEEs

Non-destructive	Destructive
Single-Event Transient (SET)	Single-Event Latchup (SEL)
Single-Event Upset (SEU)	Single-Event Burnout (SEB)
Multiple-Bit Upset (MBU/MCU)	Single-Event Gate Rupture (SEGR)
Single-Event Functional Interrupt (SEFI)	Single-Event Snapback (SESB)

This presentation will not consider:

- Destructive SEEs (SEL, SEB, SEGR, SESB)
- SEEs in linear circuits (op-amps, comparators, voltage references etc.)

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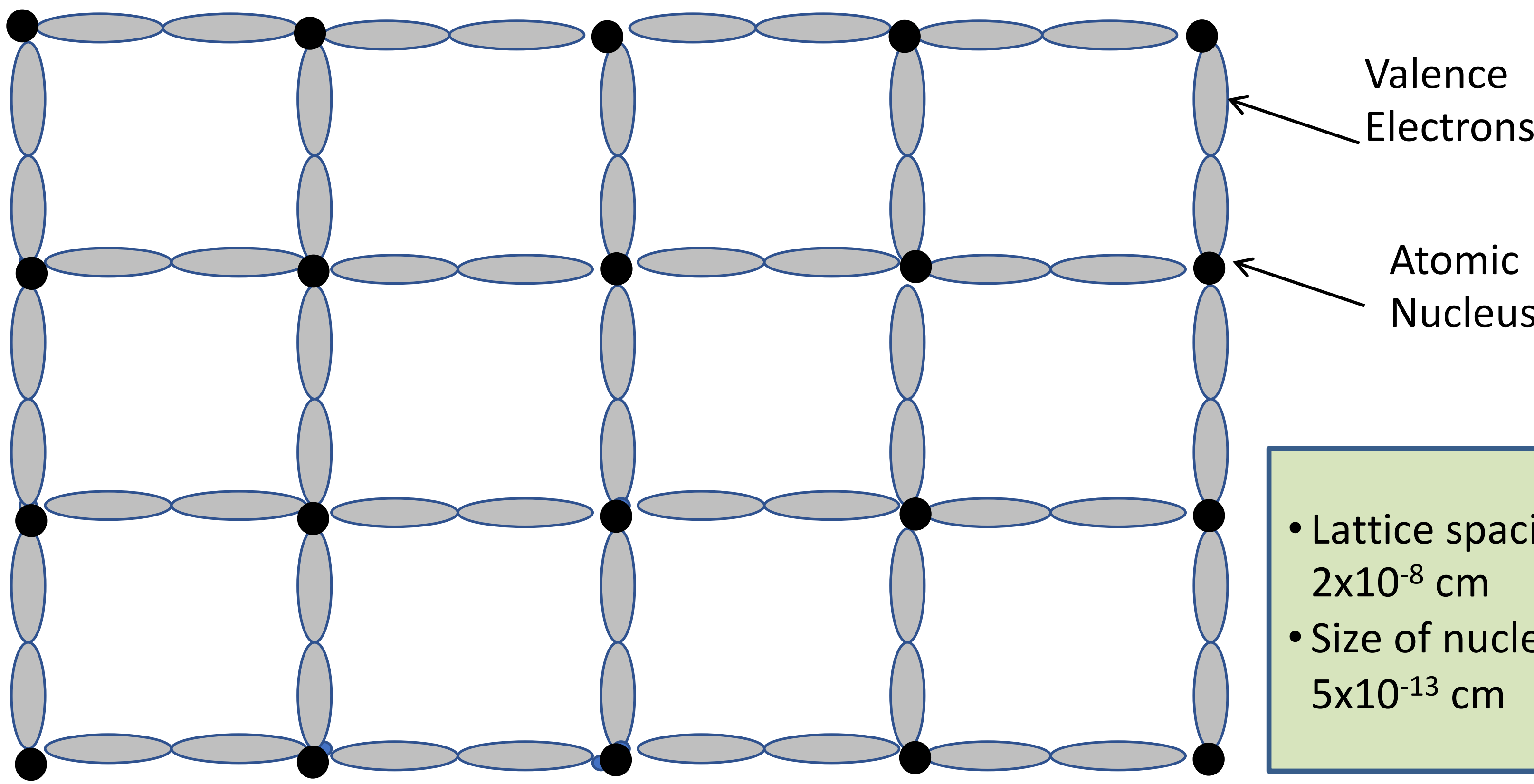
Charge Generation

- SEE produced by 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

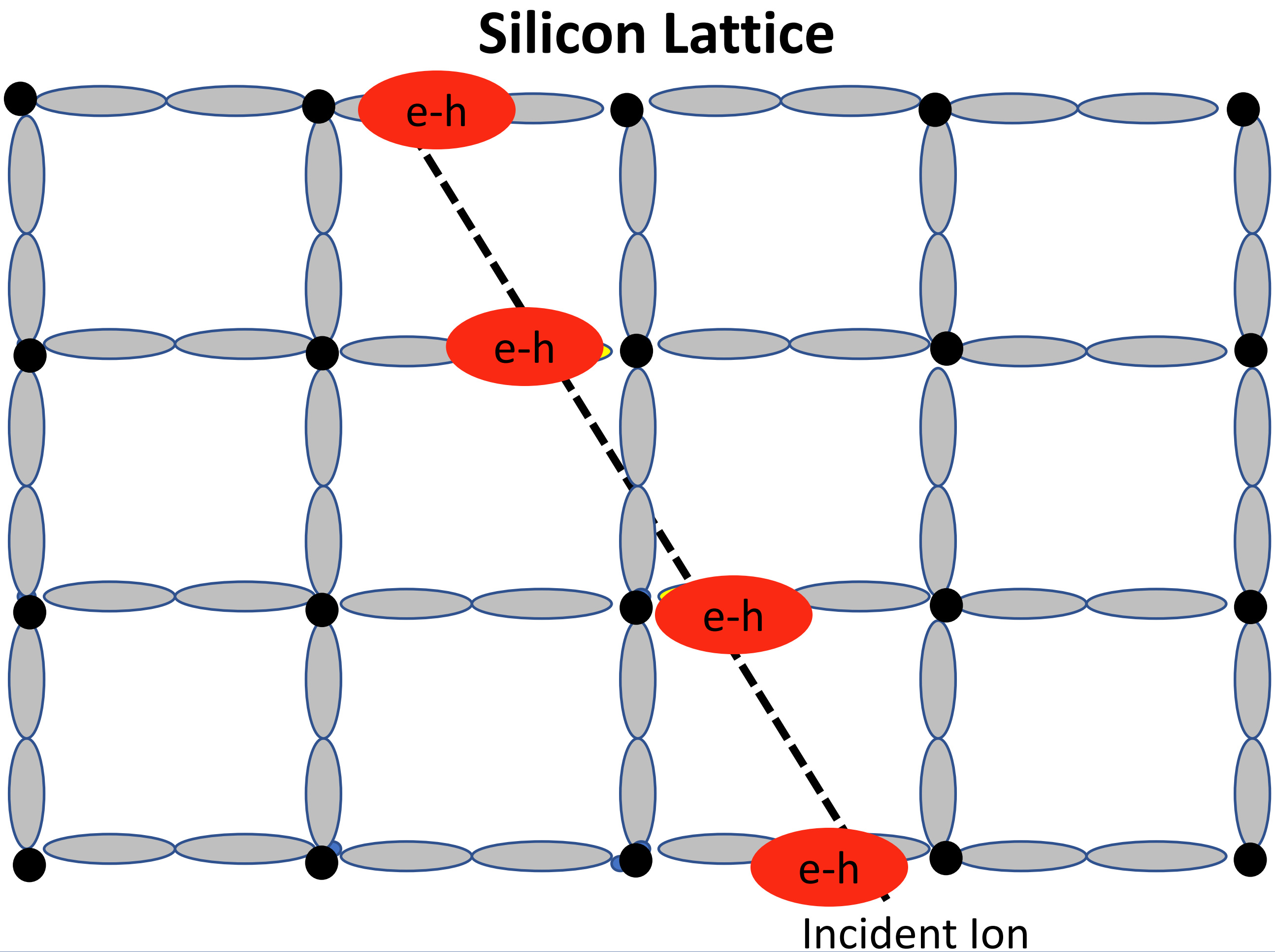
A. Elastic Scattering between Incident Ions and Bound Electrons

Silicon Lattice (not to scale)



- Lattice spacing: $2x10^{-8}$ cm
- Size of nucleus: $5x10^{-13}$ cm

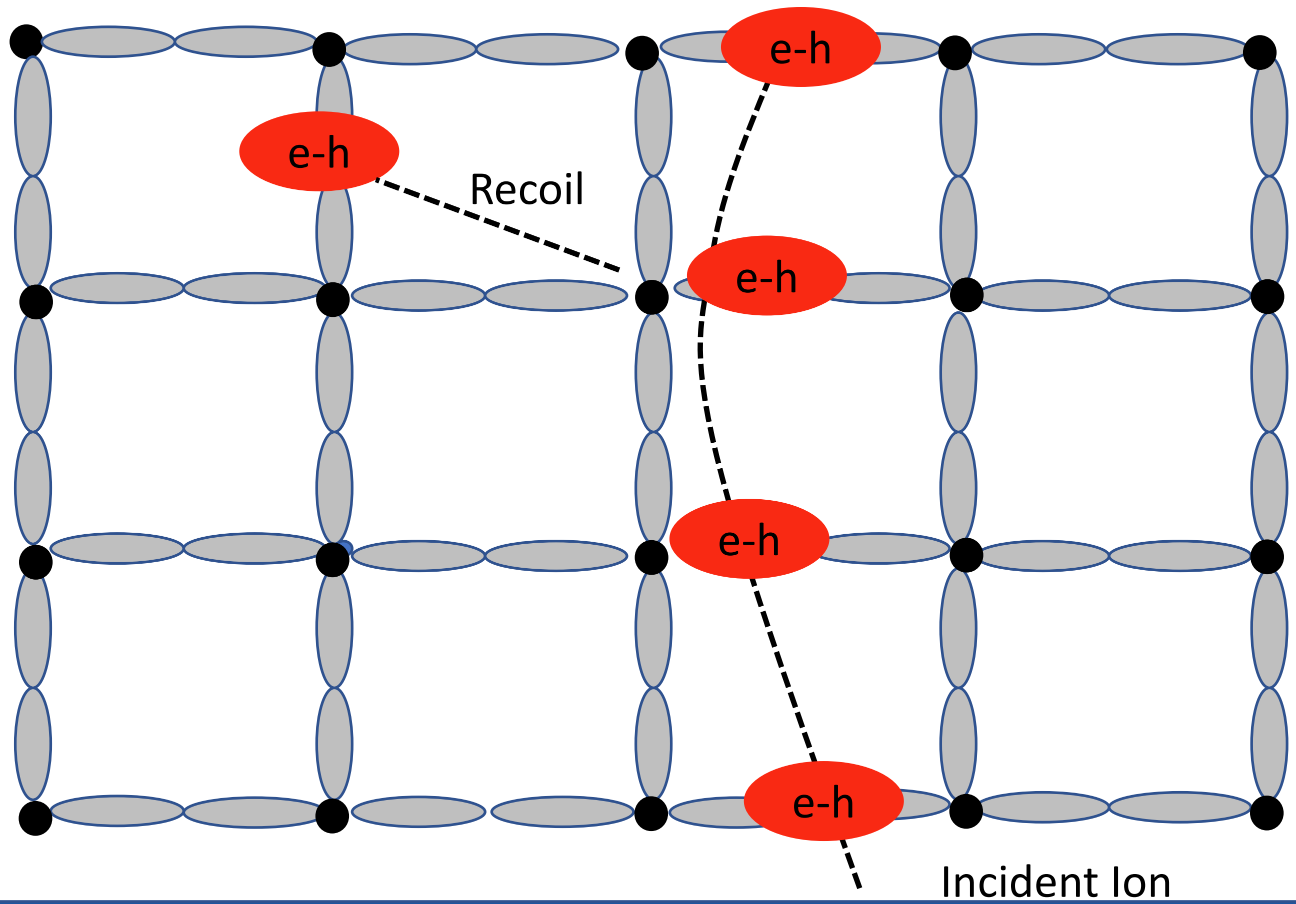
A. Elastic Scattering between Incident Ions and Bound Electrons



- Stochastic Process
- Energy loss depends on ion energy, charge, etc
- Less than 5% of energy loss is via displacement damage

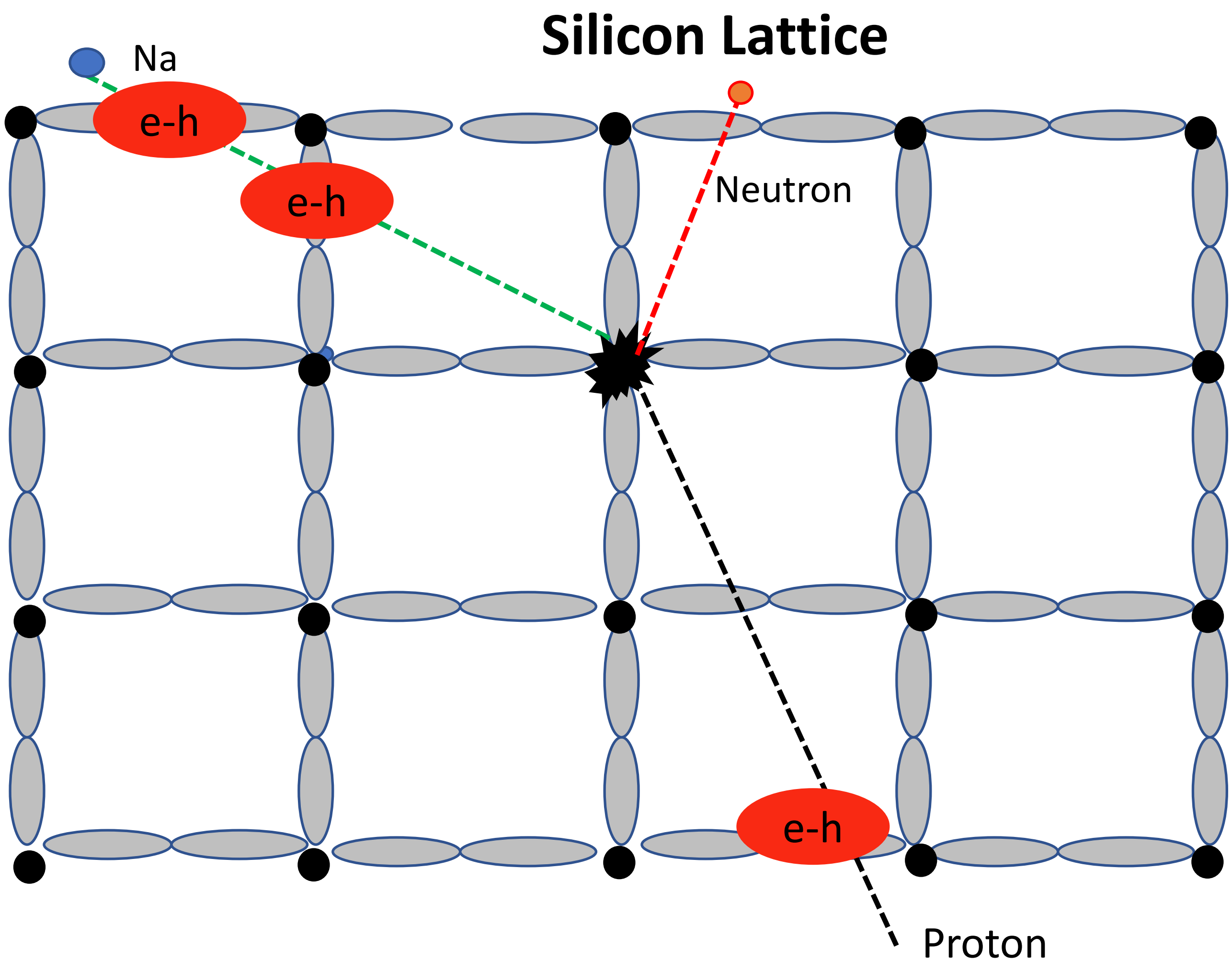
B. Elastic Scattering – Coulomb Scattering off Nucleus

Silicon Lattice



- Both incident ion and recoil silicon can produce e-h pairs
- Cross-section is much smaller than for direct ionization
- Largest LET for Si recoil is 15 $MeV.cm^2/mg$ with a short range

C. Inelastic Scattering



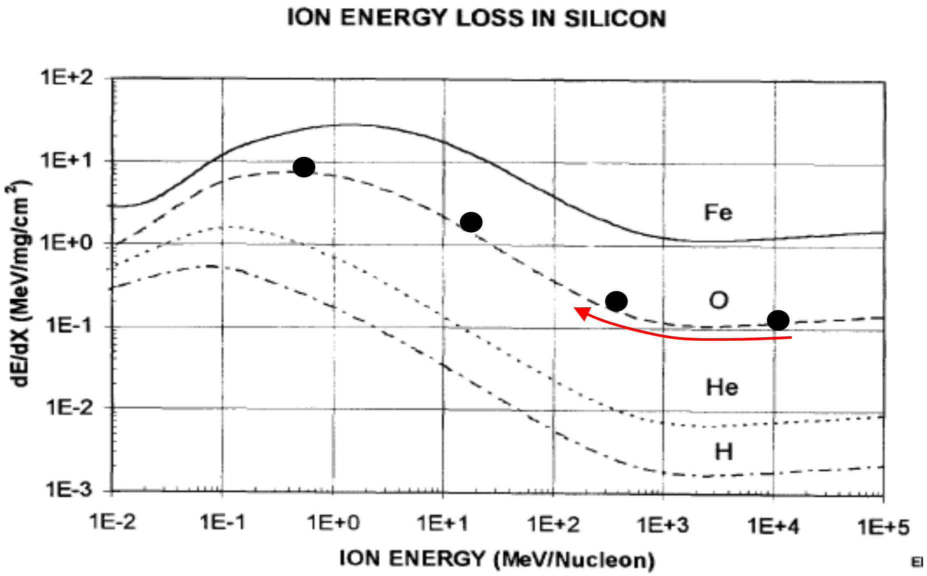
- Incident particle overcomes nuclear and Coulomb forces
- The nucleus breaks up and emits particles having masses smaller than Si. Probability depends on mass and energy of emitted particles

Direct Ionization

- Energy loss by incident ion dominated by Process A - Coulomb force between ion and valence electrons.
- Assuming a **continuous energy loss** leads to the Bethe-Bloch formula for stopping power dE/dx:

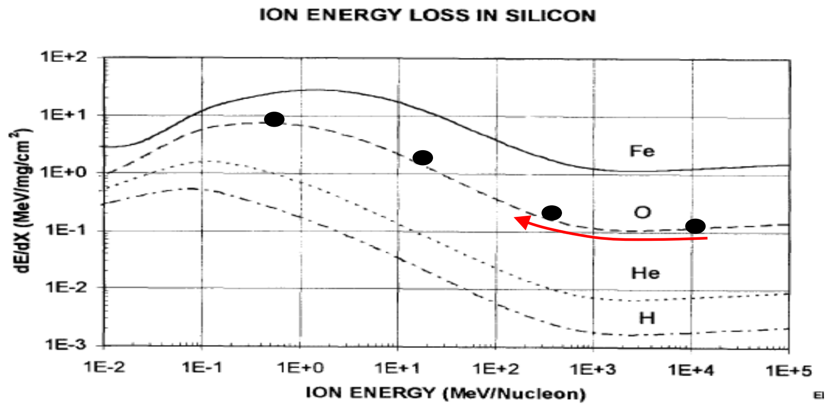
$$\frac{dE}{dx} = -\frac{4\pi N z^2 e^4}{m_0 v^2} B$$

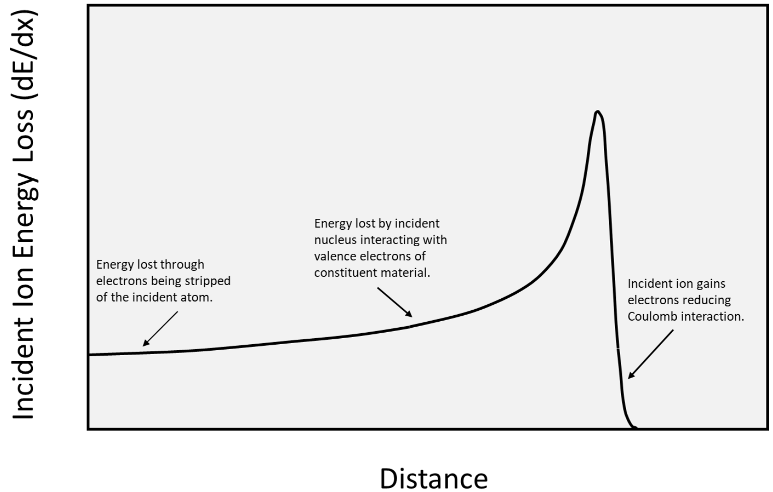
- z = charge on incident ion (At. No.)
- v^2 = kinetic energy
- *B* = relativistic correction for high energies



Direct Ionization – Bragg Peak

- Electrons stripped off ion as it enters material, so Coulomb interaction is a maximum.
- But energy loss is small because of short interaction time
- As it slows down, interaction increases until reach maximum of Bragg Peak
- At the peak it is slow enough that electrons can be captured by the ion, which reduces interaction
- LET drops rapidly with distance as more electrons are picked up by slowing ion
- Plot is an <u>average</u> over many particles

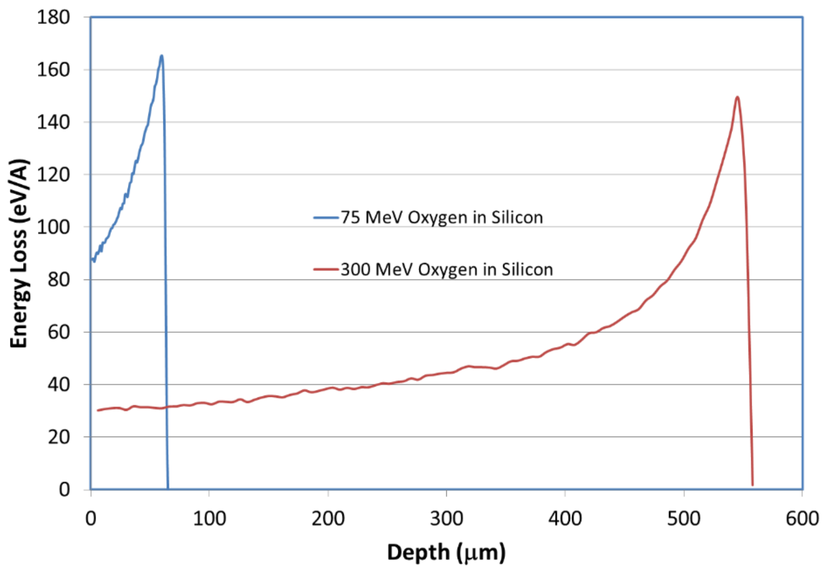




Bragg Peak Changes with Energy

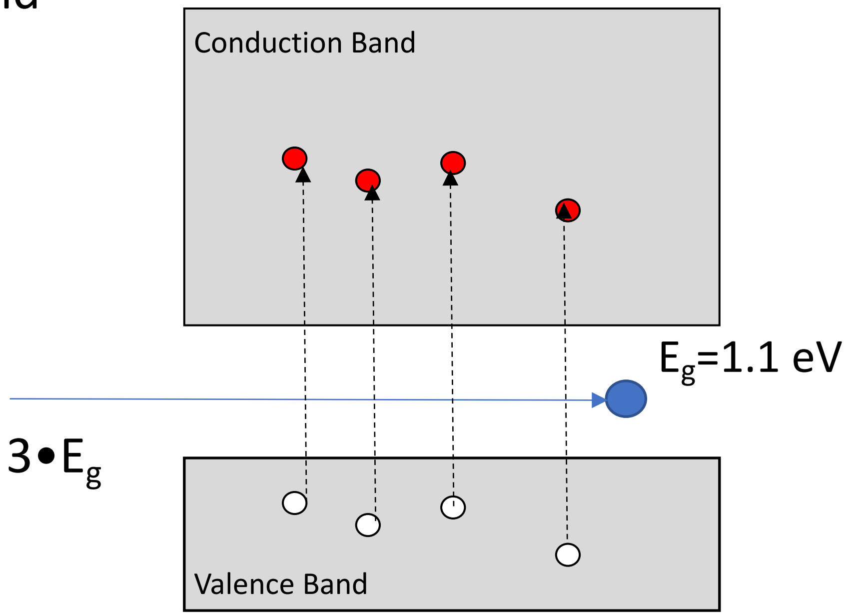
- With increase in particle energy, Bragg Peak:
  - ➢ Moves **deeper** into material
  - ➢ Spreads out due to **straggling**
  - ➢ Decreases in **size**

- Spread is worse for light particles that are more easily scattered



Direct Ionization

- Electrons are excited out of the valence band and well into the conduction band
- Mobile charge carriers (electrons and holes) are responsible for SEEs
- Random events in space and time so electron cloud is not uniform
- Average energy for e-h production $\varepsilon \approx 3 \bullet E_g$ (3.6 eV in Si and 17 eV in SiO_2)

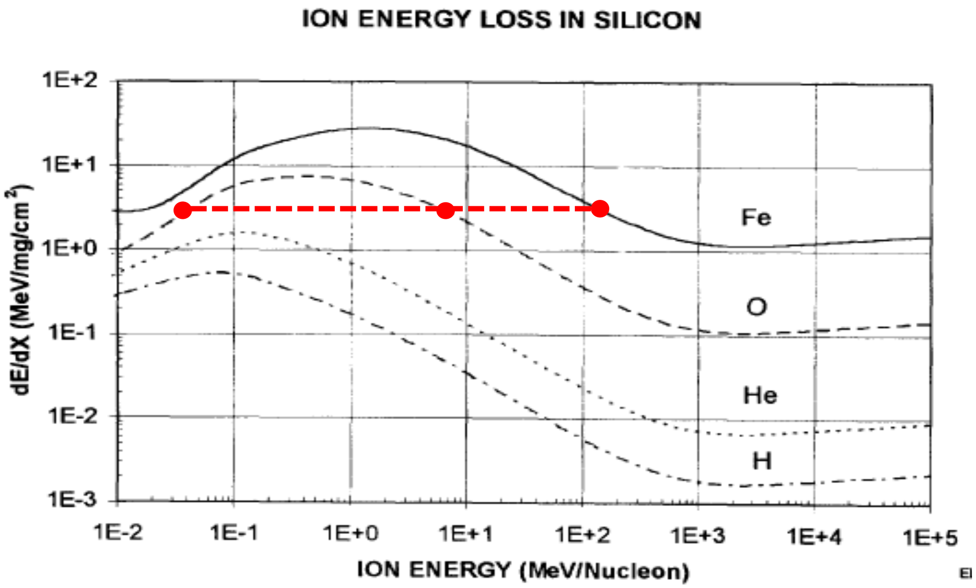


C. Klein, JAP, vol. 39, no. 4, pp. 2029-2038, March 1968.

Linear Energy Transfer (LET)

- Linear Energy Transfer (LET) is the energy received by the medium from the ion. It is the stopping power normalized by the medium's density.
- $LET = \frac{1}{\rho}\frac{dE}{dx} = \left(\frac{cm^3}{Mass}\right)\left(\frac{Energy}{cm}\right) = MeV \cdot cm^2/mg$ (ρ= material density).
- LET averages over the energy losses that are random in space and time.
- When the distance the ion travels through a sensitive volume is comparable to the distances between collisions, the concept is no longer valid.

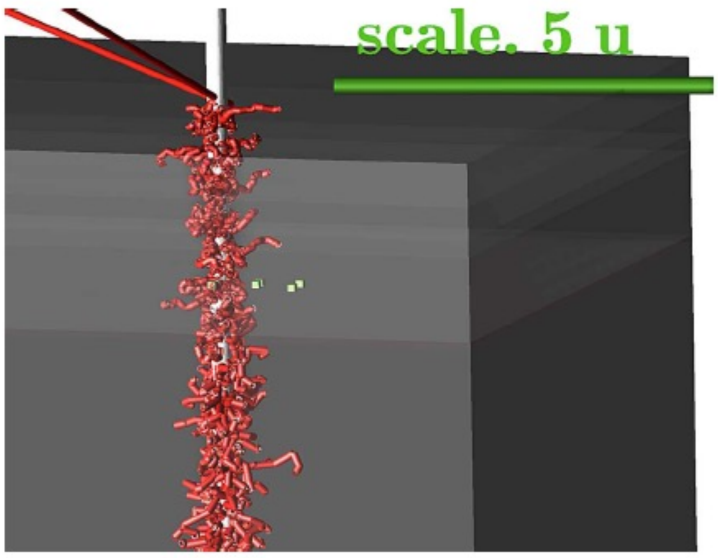
LET is not Single Valued Function



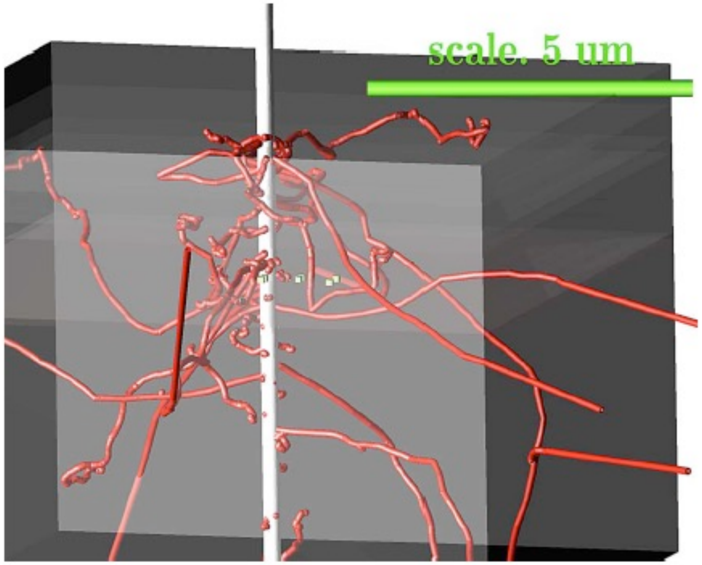
- Same ions with different energies can have the same LET
- Different ions with different energies can have same LET
- Although LET may be the same, the radii of the charge tracks are not

Charge Track Diameter

Energy Loss is stochastic (random collisions), i.e., not continuous



Low-energy track - 280 MeV Iron

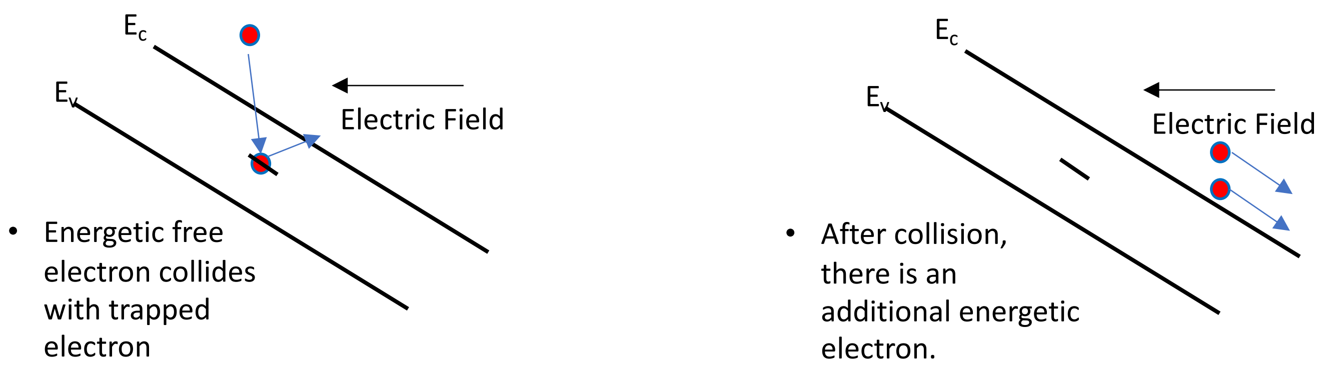


High-energy track - 28 GeV Iron

M. King et al. IEEE TNS vol. 57, no. 6, pp. 3169-3175, Dec. 2010

Additional Charge Generation via Impact Ionization

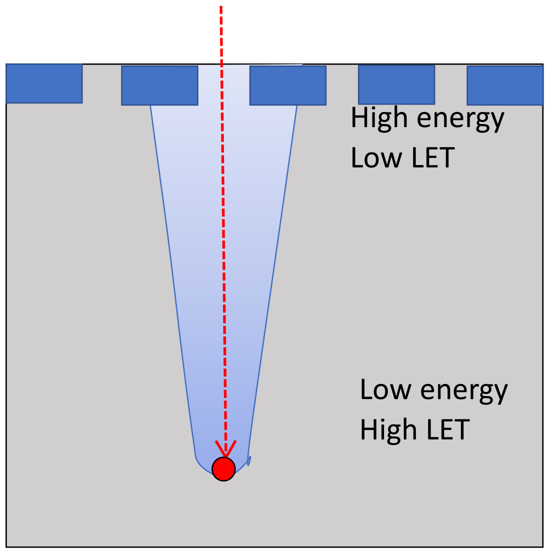
- Energetic delta rays collide with valence electrons, transferring some of their energy to excite valence electrons into conduction band. This is called **impact ionization**
- Some electrons liberated via impact ionization can, in turn, excite additional electrons, giving rise to a **multiplicative effect**.



- Recombination of electrons and holes occur via **geminate and columnar** recombination – reduced by large electric fields in depletion layer.

Direct Ionization – Charge Track Diameter

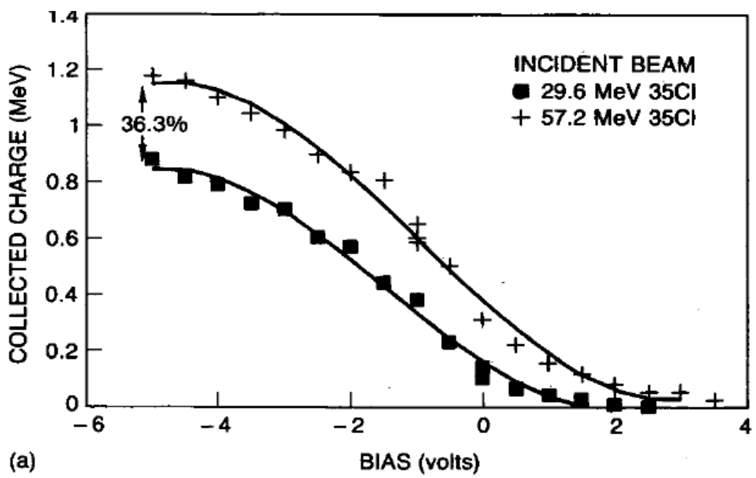
- Charge track diameter depends on ion energy through energy lost to delta rays (electrons).
- High-energy ions produce more energetic delta rays that move further from track center, producing a track with a larger diameter.
- Tracks with larger diameters produce:
  - More Multiple Bit Upsets
  - Less e-h recombination.
- As ion moves loses energy, the liberated charge density increases and the radial extent decreases



Direct Ionization – Track Structure

- For same LET, high-energy ions produce charge tracks with larger diameters that will be less dense. The amount of deposited energy is the same for the two ion energies, so the deposited charge densities are not the same.
- High-energy ions – lower density electron cloud – less recombination – more charge collected.
- Probability of MBU/MCU increases as track diameter increases.
- High electric field means less recombination and more collected charge.

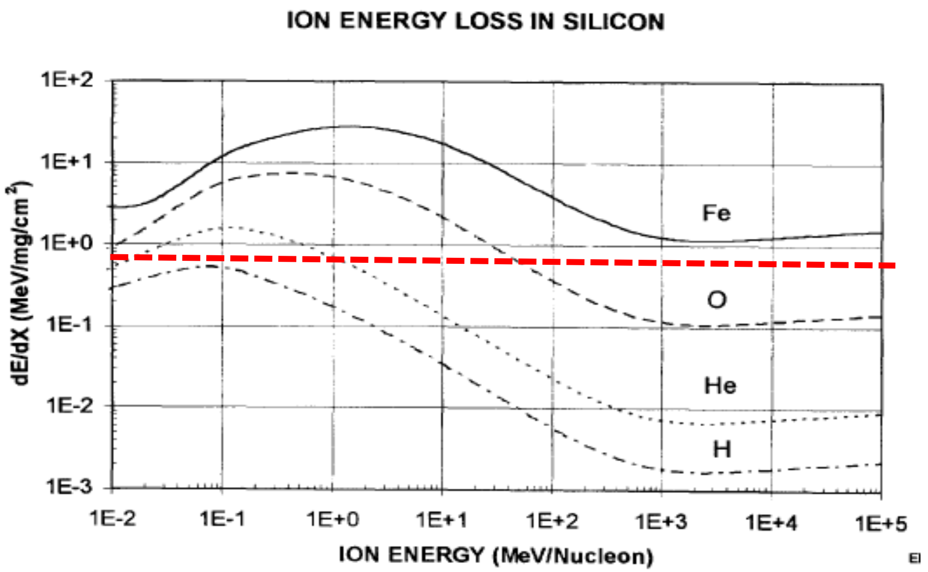
LET(Si)=18.1 MeV.cm^2/mg



CMOS/SOS Transistor tested

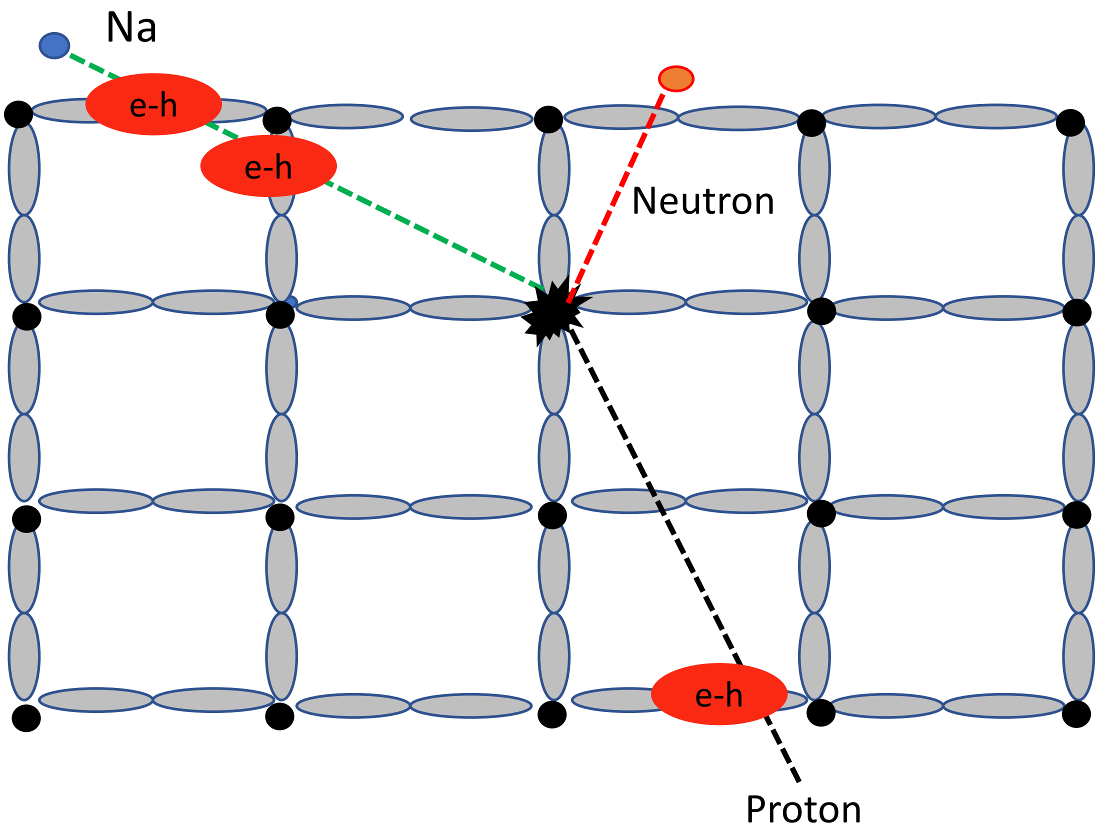
Proton-Nuclear Interactions

- Protons have a single charge (Z=1), so LET is small, i.e., < 0.5 MeV·cm^2/mg
- Protons ***do not contribute*** to SEEs by direct ionization in older technologies > 90 nm because LET is not sufficient.



Dashed red line is the minimum amount of energy needed to produce an SEU in Si devices with minimum dimensions > 90 nm.

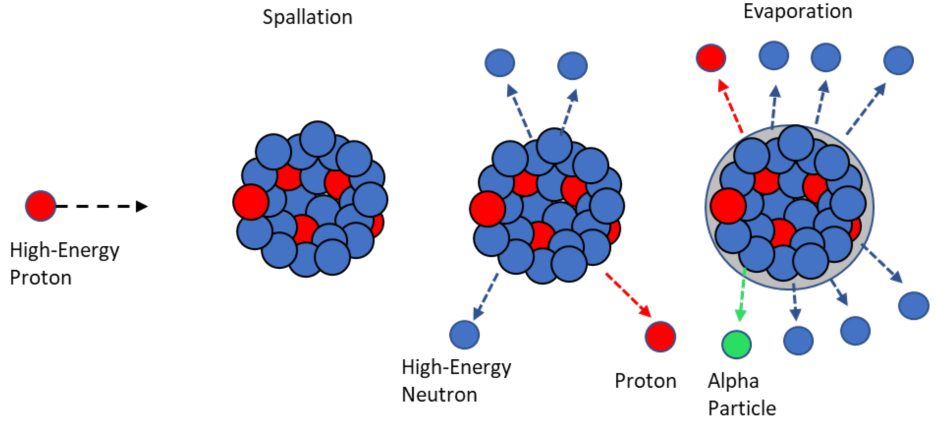
Proton-Nuclear Interactions



- Track of charge created by protons not sufficient to create SEE
- After collision with Si nucleus, particles having masses smaller than Si are emitted
- Those particles have higher LETs than protons so they liberate more EHPs that can cause SEEs

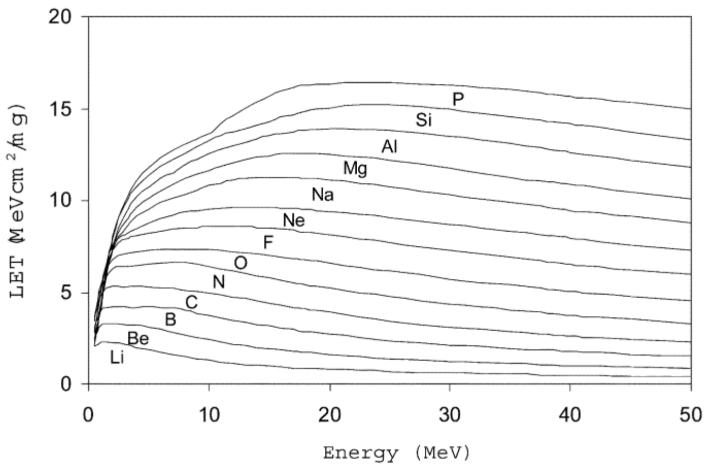
Indirect Ionization – Protons

- Protons cause SEEs via nuclear interactions
- Protons interact both **elastically and in-elastically** with the silicon nucleus.
- In the case of inelastic scattering, the **silicon nucleus emits particles** with masses greater than that of the proton, therefore with higher LETs.
- Although the probability of a collision is down by 10^4 for inelastic scattering, GCRs are more than 83% of the environment so they can make significant contributions to the SEE rate.

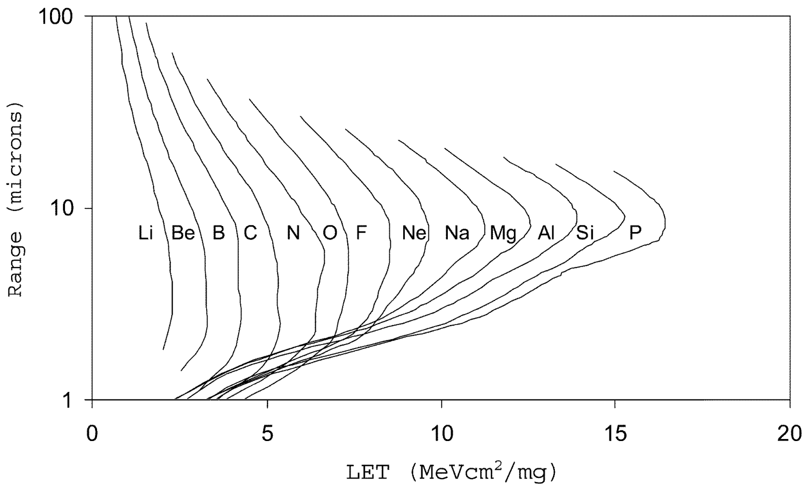


Indirect Ionization – Protons

- The secondary particles can have **LETs up to ~ 15 MeV.cm²/mg** which can cause SEEs in sensitive devices.



LET versus energy of nuclei produced by protons in silicon

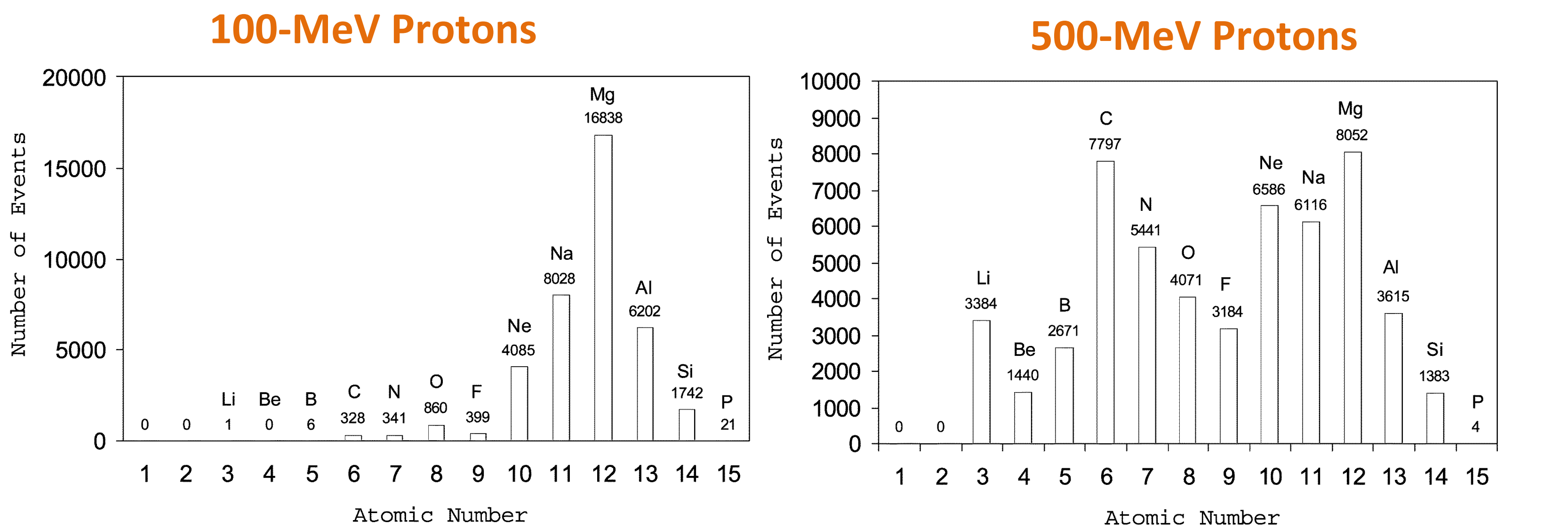


Range versus LET of nuclei produced by protons in silicon

D. M. Hiemstra, IEEE Trans. Nucl. Sci. Vol. 50, No. 6, December 2004

Indirect Ionization – Protons

- The secondary particle spectrum depends on the incident particle energy

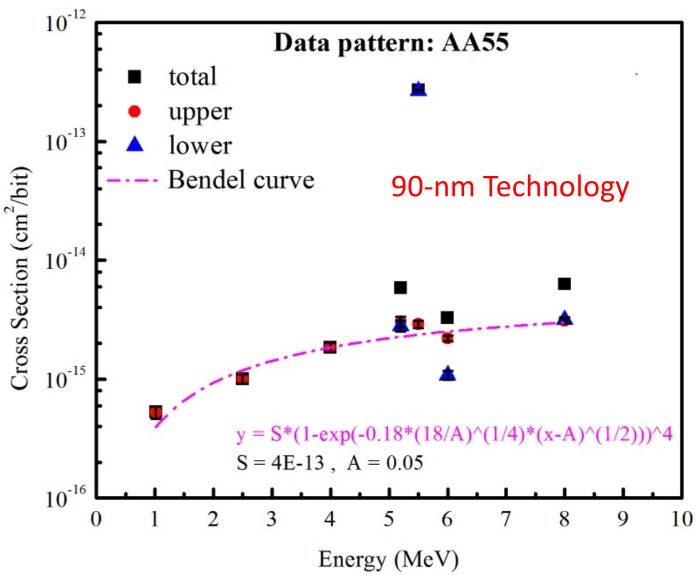


D. M. Hiemstra, IEEE Trans. Nucl. Sci. Vol. 50, No. 6, December 2004

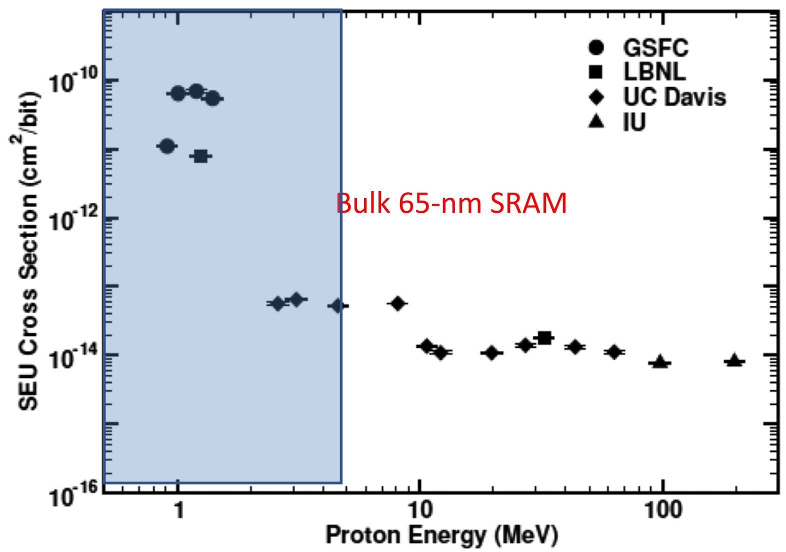
- The protons can also interact with heavy metals, like Au and Ti, used in the manufacture of modern ICs, to produce particles with masses greater than silicon and **LETs > 15 MeV·cm²/mg**. New standard is 37 MeV·cm²/mg

SEUs Induced by Low-Energy Protons

- For devices with minimum dimensions ≥ 90 nm, protons produce SEUs via indirect ionization.
- For devices with minimum dimensions < 90 nm, protons produce SEUs via direct ionization at low energies
- That means that the error rate is increased proportional to the number of low-energy protons.



Z. He, Microelectronics Reliability, 2020



N. Dodds, IEEE Trans. Nucl. Sci. 2014

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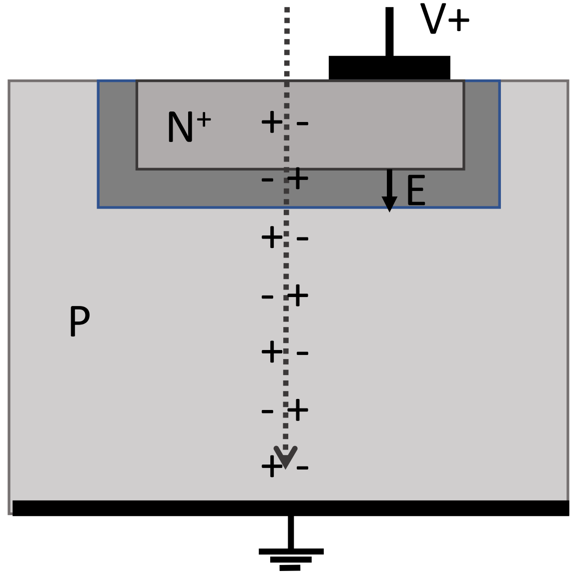
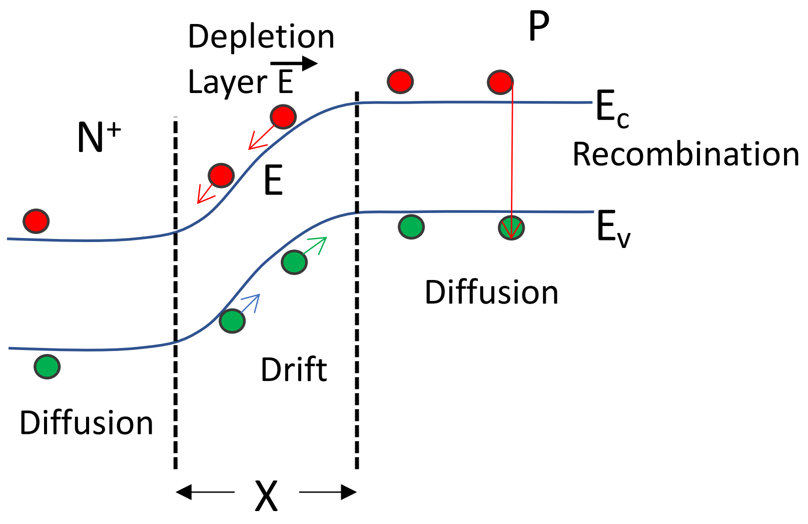
Charge Collection Mechanisms

- Charge collection occurs wherever there is an electric field (p/n junction), especially in reverse-biased junctions
- Charge collection occurs via:
  - Drift occurs where there is an electric field to separate electrons and holes
    - **V** = q**E**τ/m – the larger the field the more charge is collected
  - Diffusion is driven by concentration gradients where no fields are present
    - **J**=-D (**dC/dx**)
      - D = kTμ is the diffusion constant
      - dC/dx is the charge concentration gradient

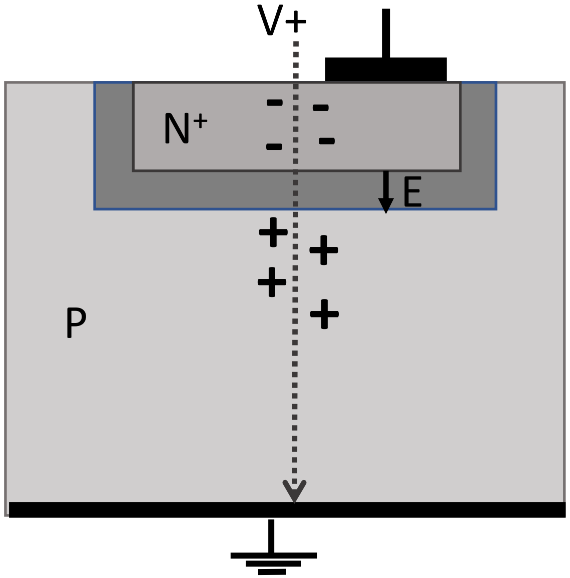
Charge Collection from Depletion Layer

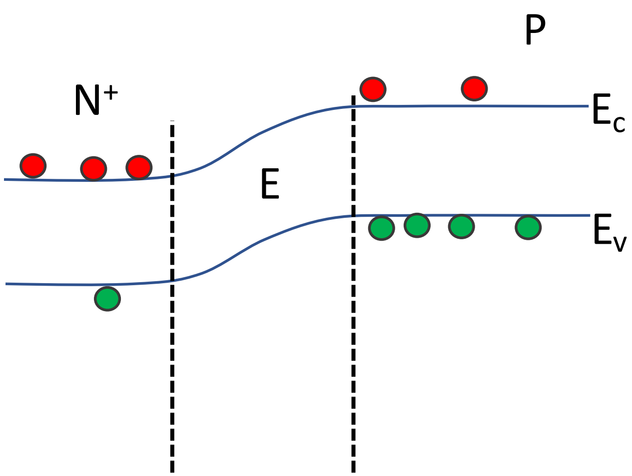




- **Electrons drift** to N^+ region rapidly in depletion layer electric field.
- **Holes drift** to P region rapidly in depletion layer electric field.
- **Q_{col} = LET•X** (X=depletion width) is a first approximation assuming 100% charge collection efficiency, normal incidence, and no diffusion.

Charge Collection from Depletion Layer

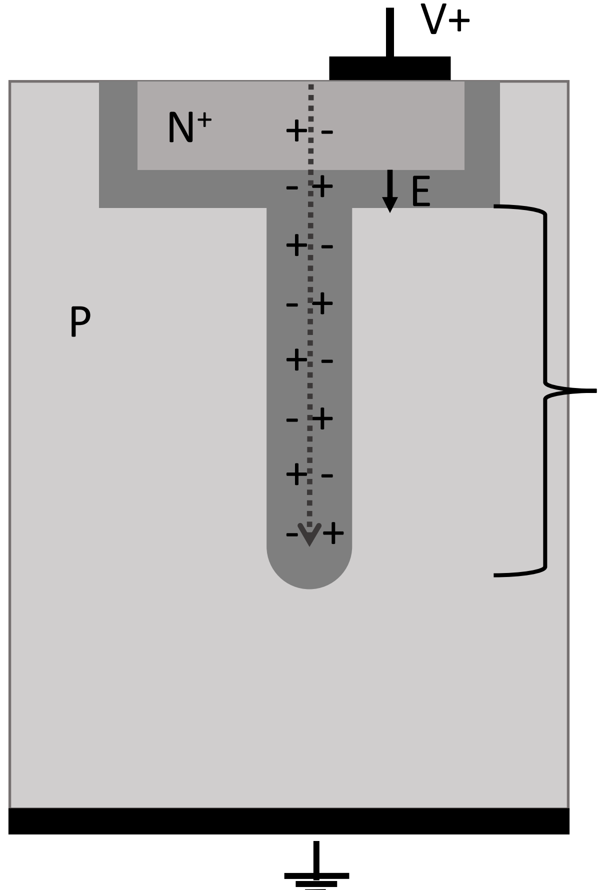




- Separation of electrons and holes sets up a counter field that reduces the overall field and the potential barrier.
- The result is a voltage glitch

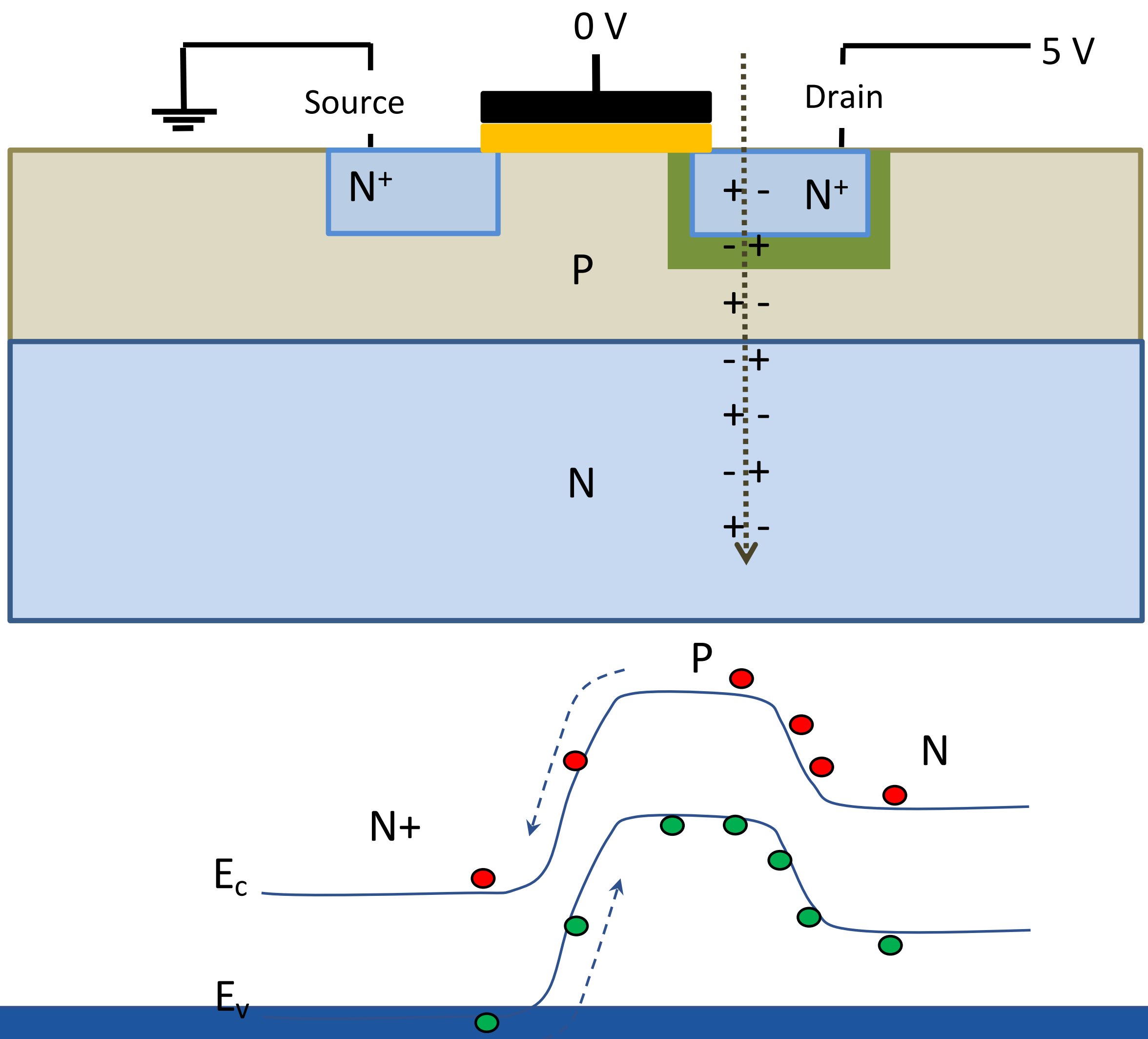
Extra Charge Collected via Funnel Effect

- Funnel is the distortion of the depletion layer by the high density of charge that cancels the depletion layer field.
- Its length can be several times the width of the depletion layer.



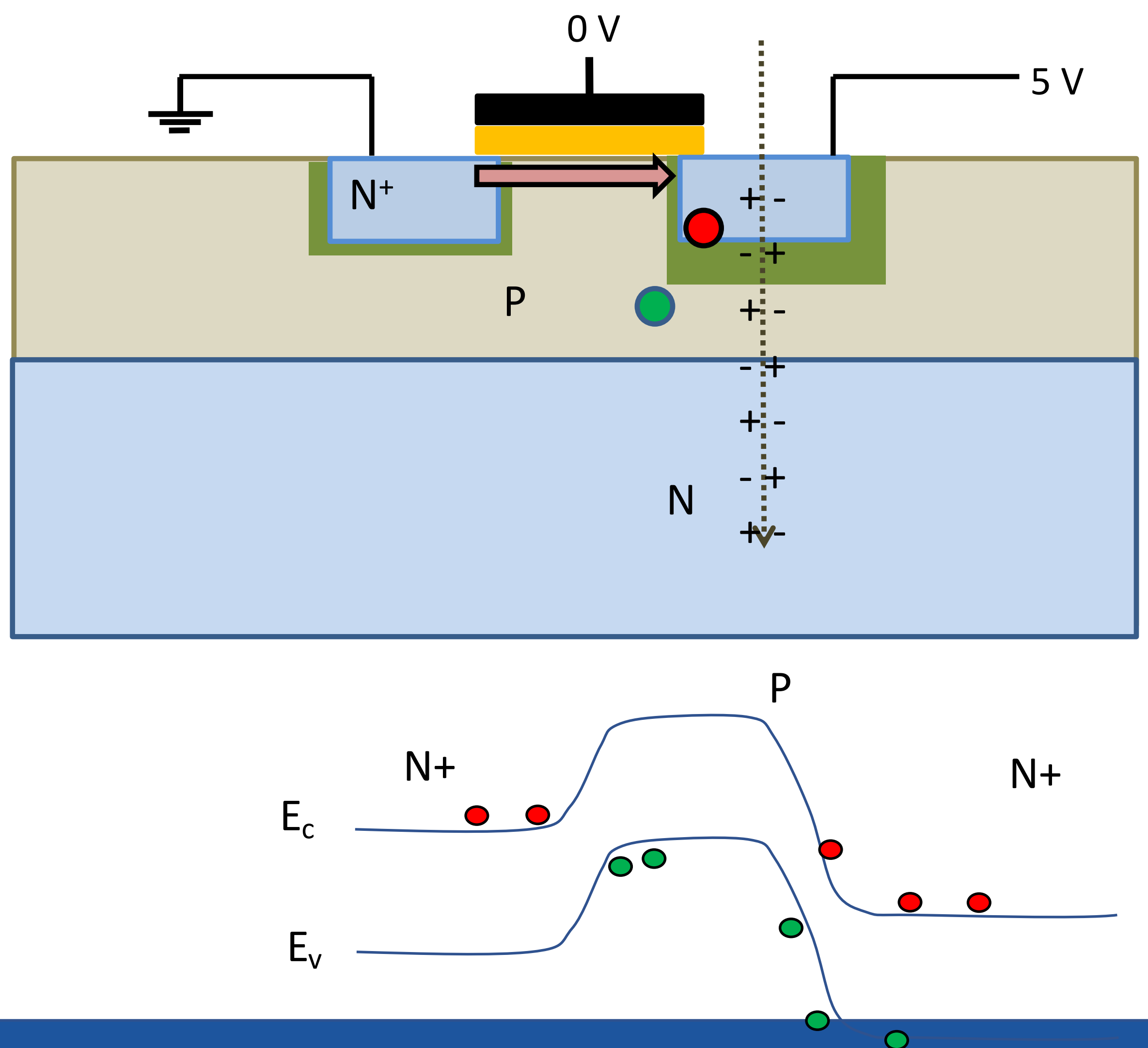
Funnel gives rise to extra charge collection via drift before it eventually collapses.

Extra Charge Collected via Bipolar Effect



- Charge collection is first from depletion layer and funnel of reverse-biased drain of n-channel transistor

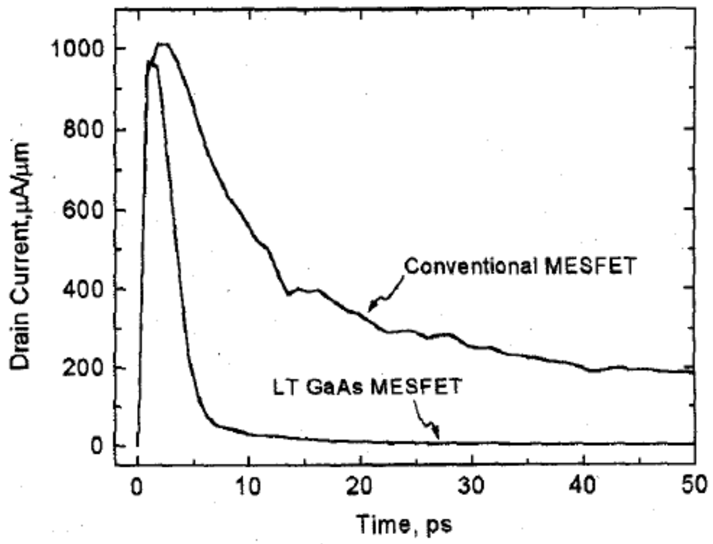
Extra Charge Collected via Bipolar Effect

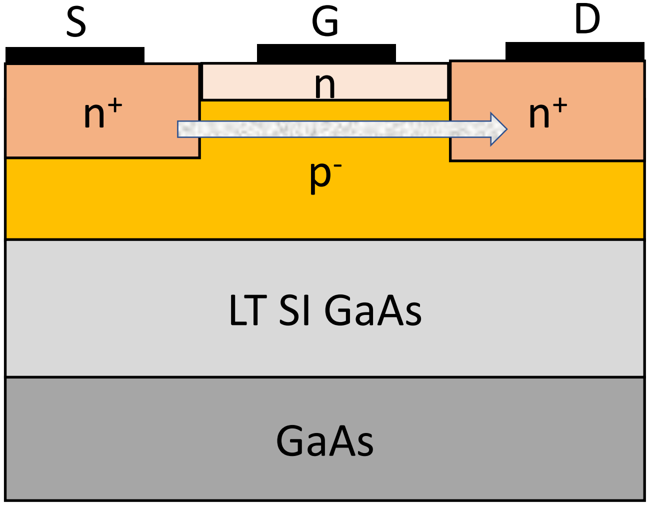


- Electrons are collected more quickly than holes due to higher mobility
- Remaining holes in P-region lower the potential barrier between source and body
- Extra charge injected into body and collected at drain
- Termed "**bipolar action**".
- Results in **enhanced charge collection.**

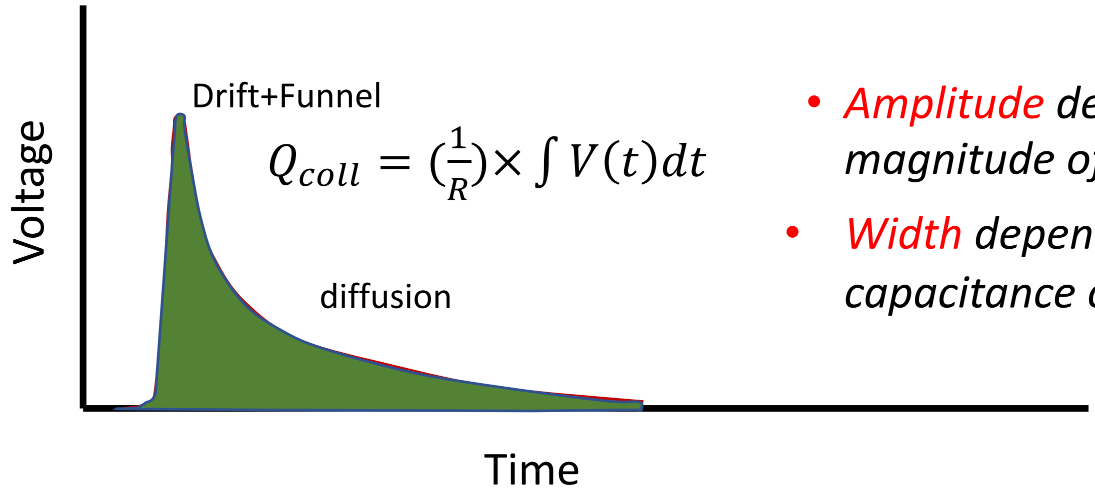
Extra Charge Collected in GaAs MESFET

- Long transients caused by bipolar effect result in enhanced charge collection
- Add a layer of low-temperature (LT) grown GaAs that has increased carrier recombination to remove excess holes and stop bipolar effect.





Time Evolution of SET

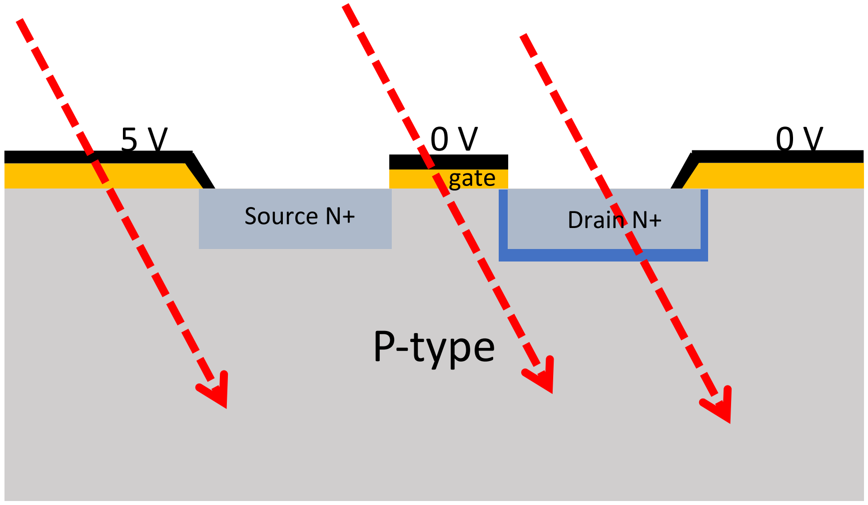


- *Amplitude depends on LET of ion, magnitude of E, capacitance of node, etc.*
- *Width depends on diffusion component, capacitance of node, charge trapping.*

- Charge moving to a sensitive node alters the voltage on that node.
- Transient has fast (drift in depletion layer and funnel) and slow (diffusion, bipolar effect, trapping) components – faster than circuit response.
- Total collected charge is integral over time of current flow onto node.
- **Q_{coll} can be greater or less than Q_{dep}**
- **Q_{crit}** is a circuit parameter that depends on capacitance, voltage etc.
- If **Q_{coll} > Q_{crit}** an SEU will occur

Summary

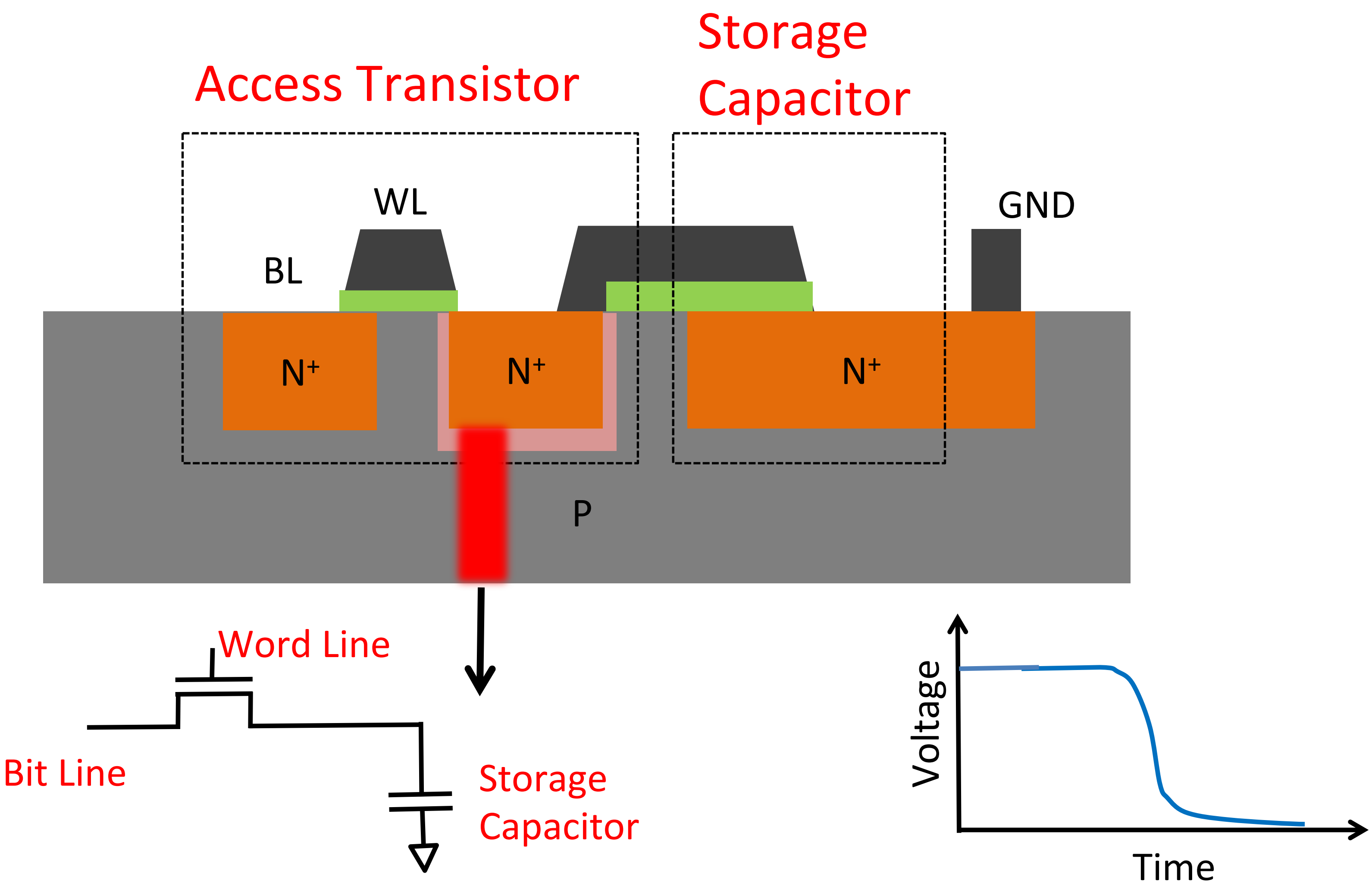
- <u>Single Event Effects depend on:</u>
  - *Particle species (protons, neutrons, heavy ions), energy and flux*
  - *Strike location and angle determine*
  - *Material (Si, GaAs, GaN…)*
  - *Transistor Structure (size, doping, SOI, wells, contacts)*
  - *Bias*
  - *Temperature*
  - *Total Ionizing Dose and Displacement Damage Dose*
  - *Follow-on circuit components – circuit response*
  - *Operating speed*



Outline

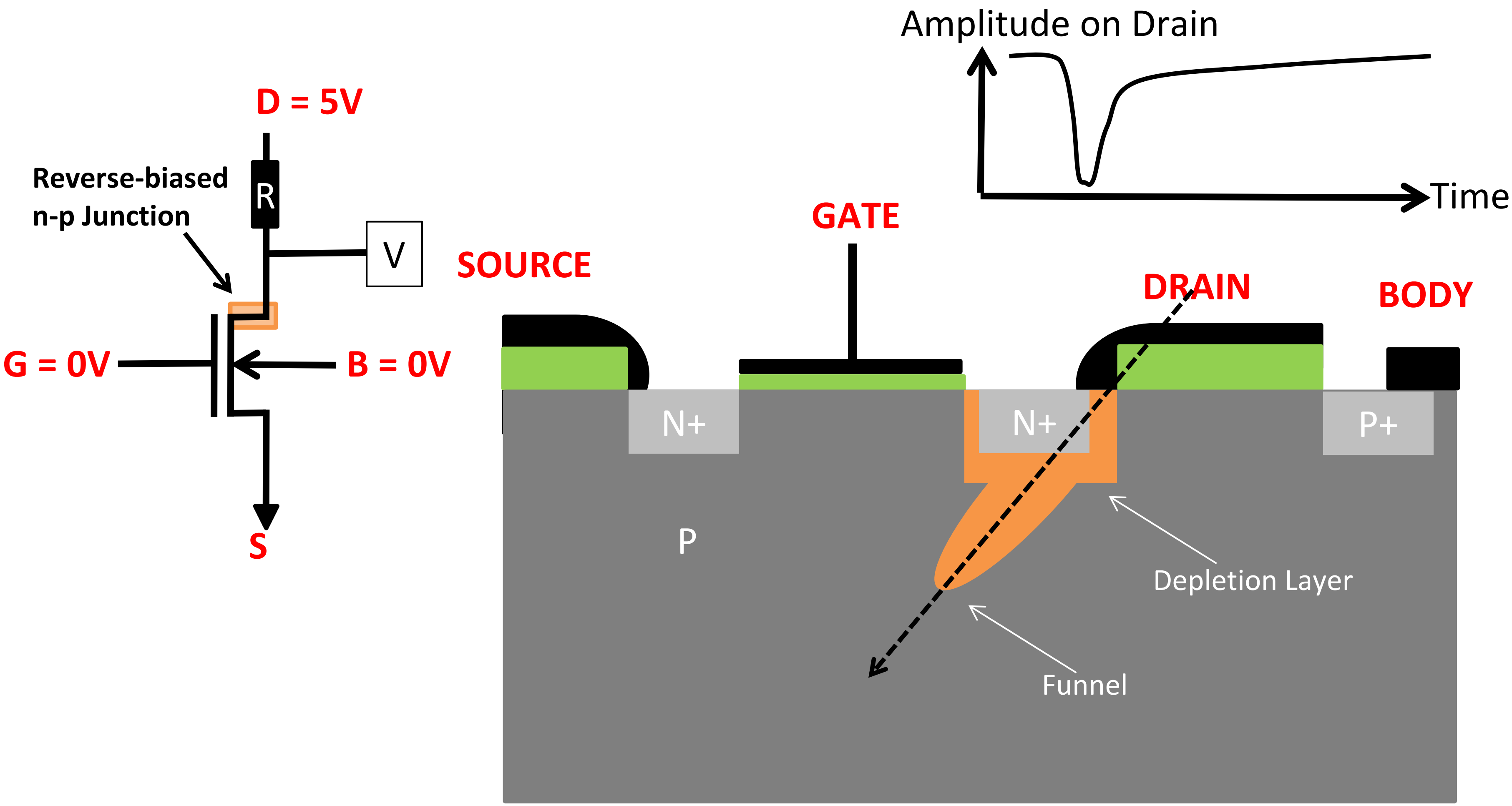
1. Introduction to SEEs
2. Types of SEEs
3. **Steps in SEE Formation**
    A. *Charge Generation*
    B. *Charge Collection and Recombination*
    C. ***Circuit Response***
4. Summary

SEU in DRAM



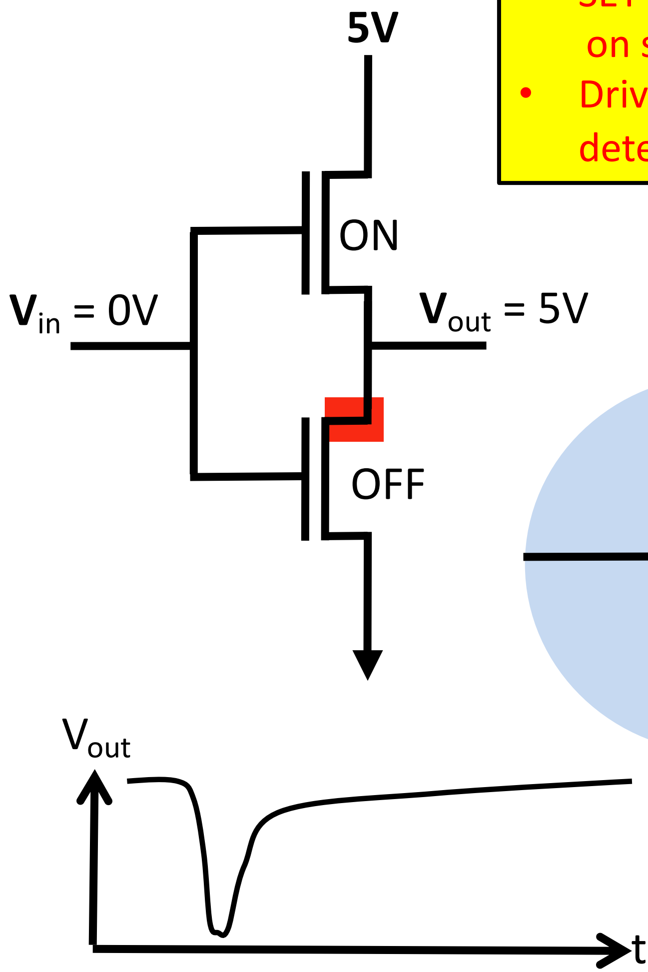
Access Transistor
Storage
Capacitor
WL
BL
GND
N+
N+
N+
P
Word Line
Bit Line
Storage
Capacitor
Voltage
Time

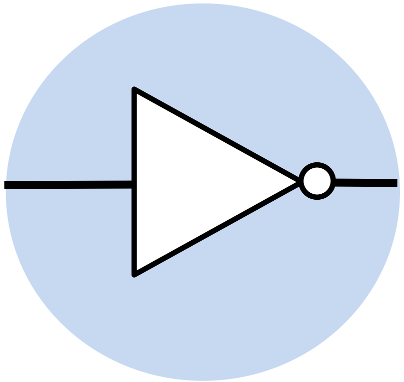
"Off" N-Channel MOS Transistor

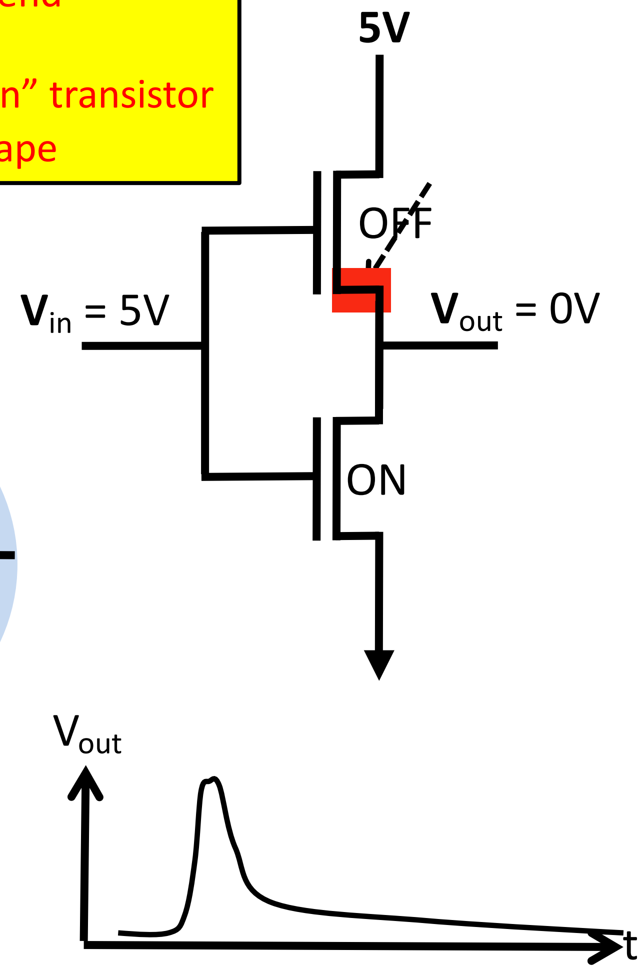


Transient in CMOS Inverter

- SET sensitivity depend on state of circuit
- Drive current of “on” transistor determines SET shape

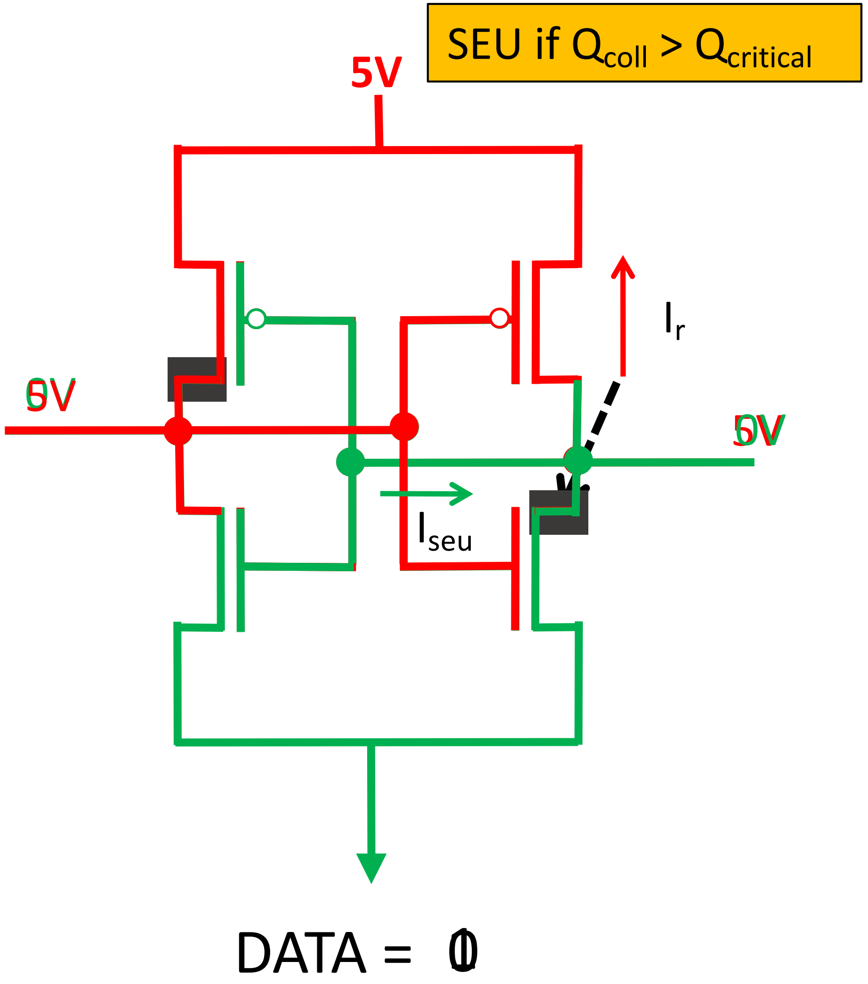




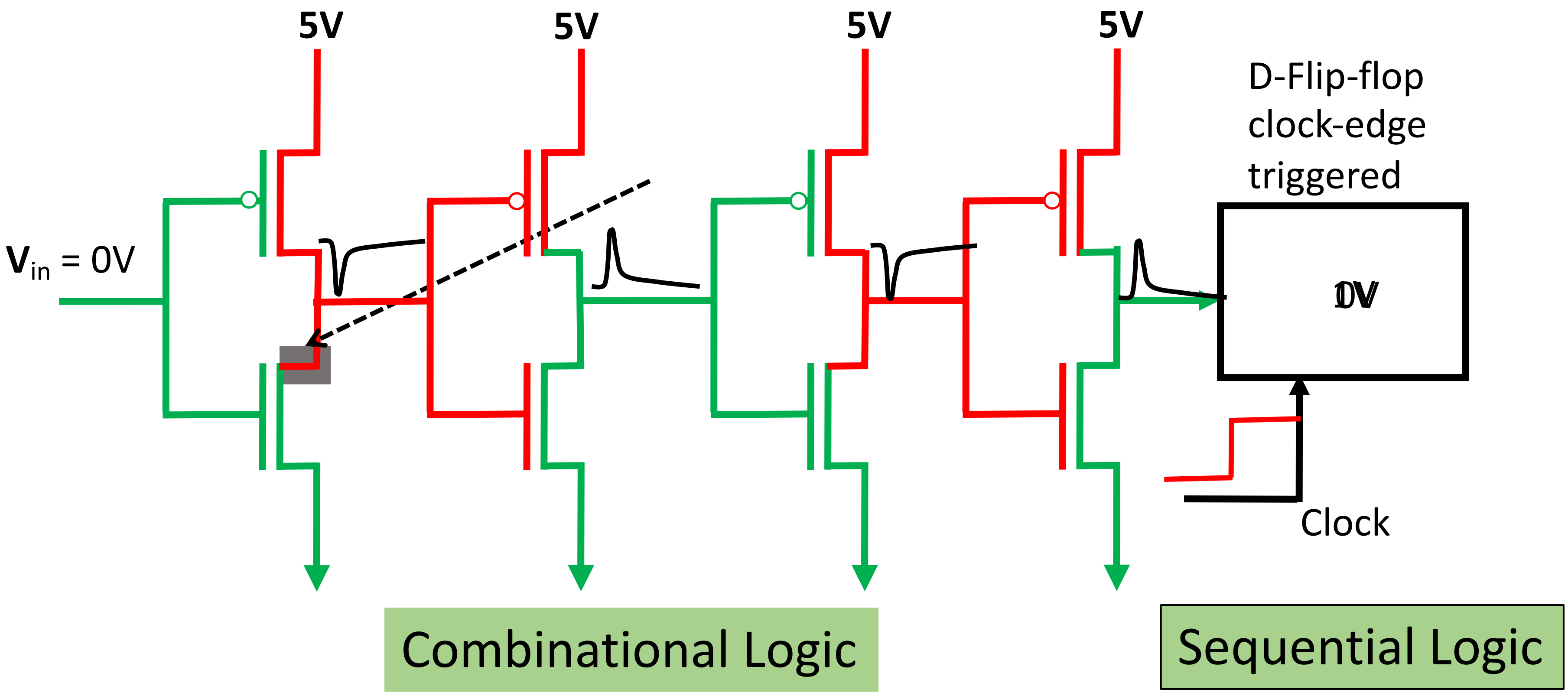


Upset in CMOS SRAM

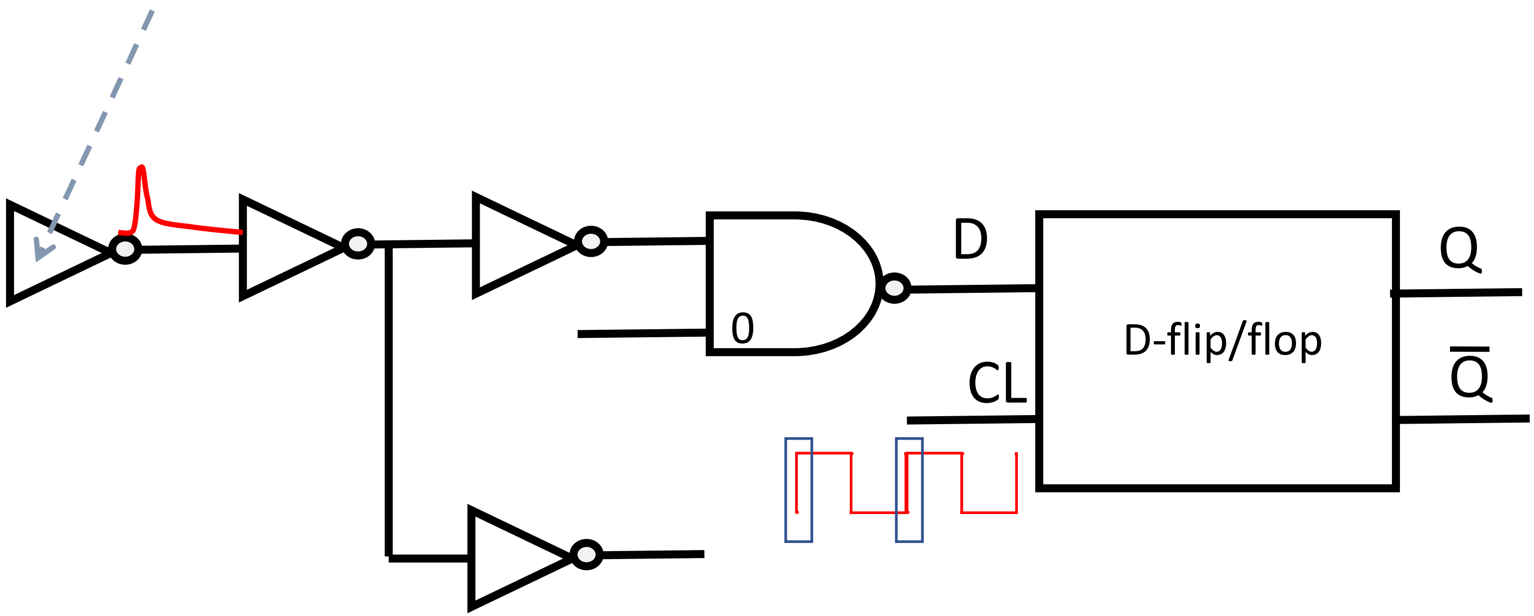
- Two sensitive nodes for this SRAM cell – OFF n-channel and OFF p-channel transistors.
- Competition between upset (I_{seu}) and restoring (I_r) currents
- If charge deposited by ion over a time period comparable to the response time of the circuit exceeds Q_{crit} an SEU will occur
- $Q_{critical}$ depends on circuit parameters - parasitic resistance and capacitance
- Q_{coll} depends on amount of deposited charge and on device structure



Transient Propagation in Logic Circuits



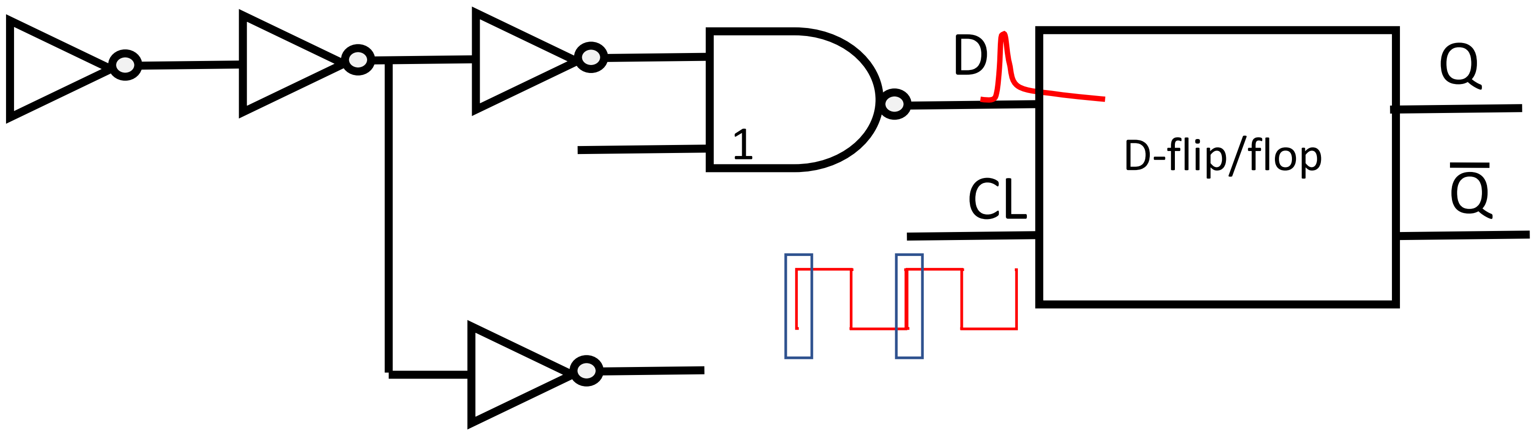
Transient Propagation in Logic Circuits

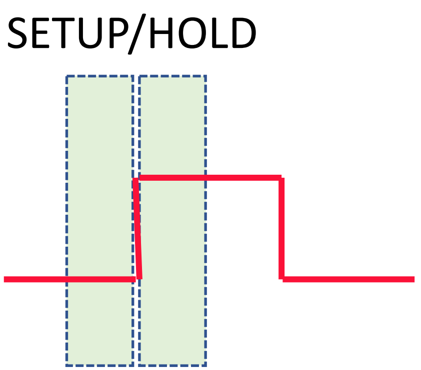


<u>SET Propagation Limited by Masking:</u>

- Electrical (node capacitance, branching……
- Logical (blocking such as 0 on NAND gate)
- Timing – Window of Vulnerability

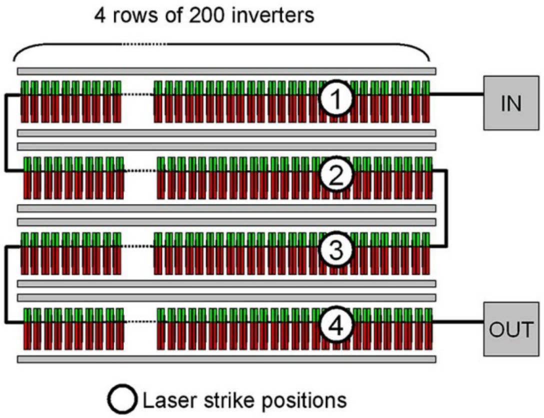
Transient Capture in Sequential Logic

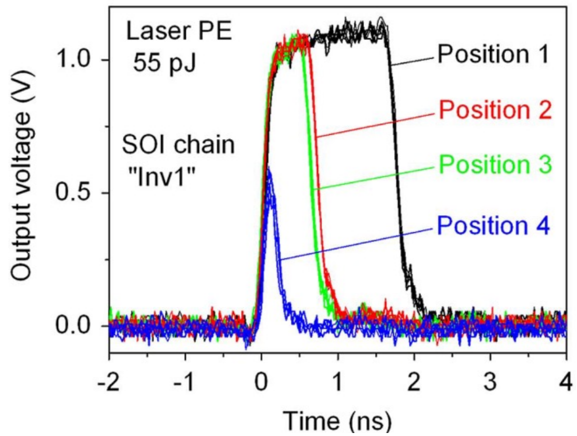


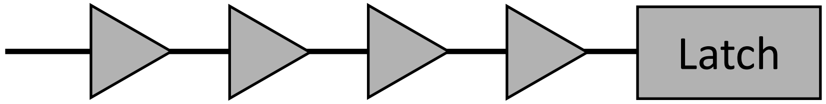


- SET must be above threshold during SETUP/HOLD TIMES.
- A Shorter SET will not latch.
- As clock speeds up, SETUP/HOLD time approaches clock period

SET Broadening

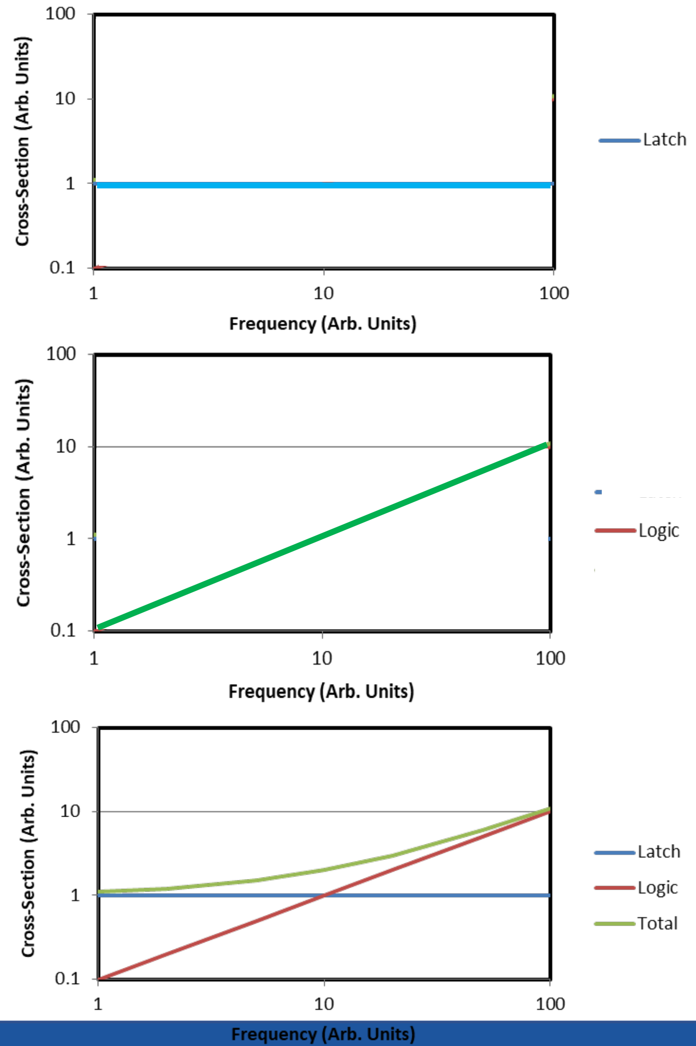


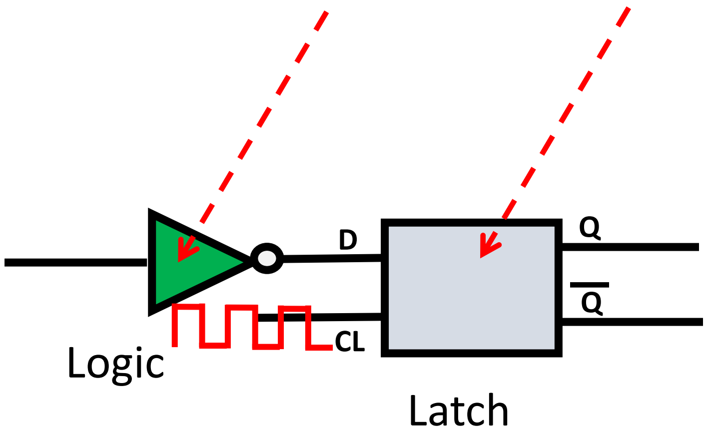




Ferlet-Cavrois, IEEE TNS vol. 54, no. 6, pp. 2338-2346, Dec. 2007

Effects of Clock Frequency on SETs





- Curves move with technology and design changes
- As circuits become faster, SETs will dominate SEUs

Outline

1. Introduction to SEEs
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   A. *Charge Generation*
   B. *Charge Collection and Recombination*
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4. **Summary**

Summary

1. Single-Event Effects may be both destructive and non-destructive
2. SEEs occur in most active devices – from diodes to logic and linear circuits
3. SEEs occur everywhere, in space and on earth, and rates are increasing
4. The three steps to formation of single event effects are:
    a. Charge deposition
    b. Charge collection
    c. Circuit response
5. Two important topics not discussed are:
    a. SEE Testing
    b. SEE Mitigation