Single-Event Effects
Part 1 - General Principles

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**Special thanks to R. Davies and M. Casey*

Module 3: Objective and Outcomes

- This module will
  - Summarize the basic definitions related to Single-Event Effects
  - Overview the Interactions of the Ionizing Particles with Semiconductors
  - Introduce Energy Loss, Stopping Power, and Linear Energy Transfer
  - Detail SEE charge generation processes
  - Detail SEE charge collection processes

- Student Outcomes
  - 1. Students will demonstrate an understanding of the fundamental interactions of ionizing particles and semiconductor materials.
  - 2. Students will be able to describe the SEE charge generation and collection processes.

Outline

- Charge Generation due to Single-Events (Review of Module 2)
- Charge Collection
- Summary of SEE Charge Generation and Collection

Motivation

A Little Single-Event History

1962 Prediction of space-system upsets from ionizing particles
Wallmark and Marcus, RCA
1975 Cosmic-ray-induced upsets observed in spacecraft BJT flip-flop circuits
Binder and Smith, Hughes
1978 Upsets in 16k DRAMs observed and attributed to alpha particles from packaging contaminants
May and Woods, Intel
1978 Cosmic-ray-induced upsets observed in spacecraft RAM circuits
Pickel and Blandford, Rockwell
1979 Heavy-ion-induced latchup in SRAMs discovered
1983 Galileo refit

1989 Solar Flare Event:
INTELSAT 46 pitch glitches, potential orbit disruption
TDRS-A 53 hits in 3 days, near catastrophic loss of attitude control

Bottom Line

- Single event effects (SEEs) are taking a prominent position in the mainstream integrated circuit industry
- Many commercial manufacturers are coming to grips with the problem as a key reliability issue
- The problem is of growing importance as noise margins diminish with scaling
- GHz logic, terabyte RAM, low-power circuits are leading to new upset scenarios
- Clearly, there is a recognized need for SEE analysis integrated into accepted design flows

Definitions

Single Event (SE) or Single Event Phenomena (SEP) -
interaction of a single ionizing particle with a semiconductor device - localized interaction - event occurrence does not depend on flux or total exposure - event is spatially and temporally random - event seems (though not scientifically verified) to perfectly implement Murphy's Law

Single Event Effect (SEE) -
a circuit or system response to a SE

Single Event Upset (SEU) -
a bit flip or other *corruption* of stored information due to an SEE (usually applied to memory circuits)

Single Event Error or Soft Error-
the observable, measurable *manifestation* of an SEE as a incorrect circuit operation (usually a system response)

Definitions (cont)

Single Event Transient (SET)
- a signal glitch caused by an SE
  - ASET - analog single event transient
  - DSET - digital single event transient

Single Event Error Rate or Soft Error Rate (SER) -
the frequency of errors in a particular environment (e.g. an orbit, mission trajectory, etc) -- can be related to FITs

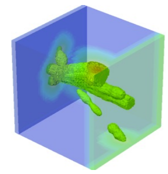
01

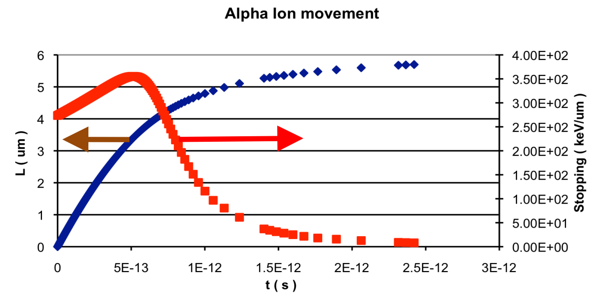
CHARGE GENERATION DUE TO SINGLE EVENTS

Interactions of the Particles with Semiconductors

Energy Loss or Stopping Power

- **Charged particle passes through a material**
- **Loses energy by Rutherford scattering with the lattice nuclei**
- **Energy transferred to bound electrons -- ionized into the conduction band**
- **Imparts a dense track of electron hole pairs (EHPs)**





Interactions of the Particles with Semiconductors

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Incremental rate of energy loss along the ion's path
= stopping power (dE/dx)
units of energy per unit length (typical: MeV/cm)

Interactions of the Particles with Semiconductors

LET and the Amount of Charge Liberated

Stopping power: **Depends on mass, energy of particle and density of material**

Linear energy transfer (LET) normalizes out the density of the target material (units = MeV/mg/cm^2)

LET (MeV/mg/cm^2) * Target Density (mg/cm^3) = Energy deposition (MeV/cm)

Charge creation: **3.6 eV needed to create one EHP in silicon**

Amount of charge liberated (pC/μm) = LET (MeV/mg/cm^2) * 0.01035
(approximately 100 to 1 conversion factor)
(e.g. Particle of LET=100 MeV/mg/cm^2 --> 1 pC/μm)

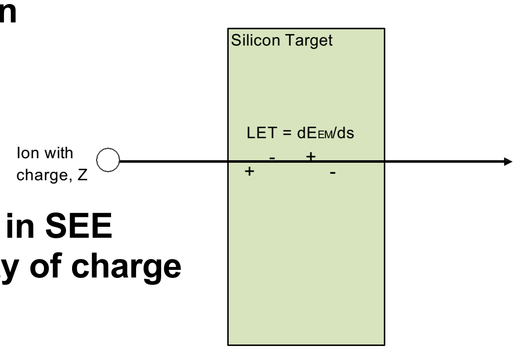
Stopping powers and LETs for various ions, energies, and target material are tabulated, or can be calculated using SRIM code (www.srim.org)

LET – Linear Energy Transfer

- **The rate of ionization energy deposition per unit of path length**

  $$LET = dE_{EM}/ds$$

- **s is along the path of the particle**
- **LET is a critical metric for beams used in SEE testing because it quantifies the density of charge generated inside the target material**
- **LET depends on**
  - Charge of ion, Z
  - Target Material
  - Energy of ion
    - Initial ➔ “Surface LET”
    - At each location along the ion’s path ➔ Instantaneous LET



Linear Energy Transfer (LET) is a fundamental quantity necessary in radiation effects modeling. LET is an approximation for the amount of energy a particle looses as it travels through a material. This energy transfer (deposition) is what leads to charge generation, and ultimately, to SEE and TID. LET is defined as the energy loss over the path length, *s*, traveled through the material.

LET depends on the energy and charge (atomic mass) of the ion, but also the density of the target material.

LET – Units

- **The rate of ionization energy deposition per unit of path length**

  $$LET = dE_{EM}/ds$$

- **s is along the path of the particle**
- **LET is a critical metric for beams used in SEE testing because it quantifies the density of charge generated inside the target material**
- **LET is dependent on the target material!!**

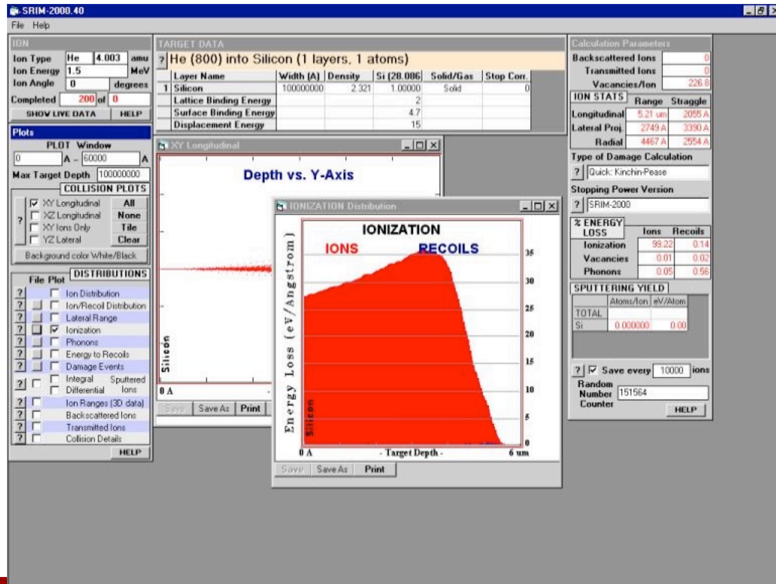
- **LET units**
  - MeV·cm²/mg
  - Think of it as:
    - MeV/(mg/cm²)
    - MeV/(cm · mg/cm³) ➔ dE/(ds*δ)
    - Energy deposited per unit of length normalized by density of the target material

Caution: "What is the LET of the beam?"
… in silicon(?)

Thus, LET is energy deposited per unit of length normalized by density of the target material. Note that LET is not a quality of the radiation, but a result of the interaction of the radiation with the material.

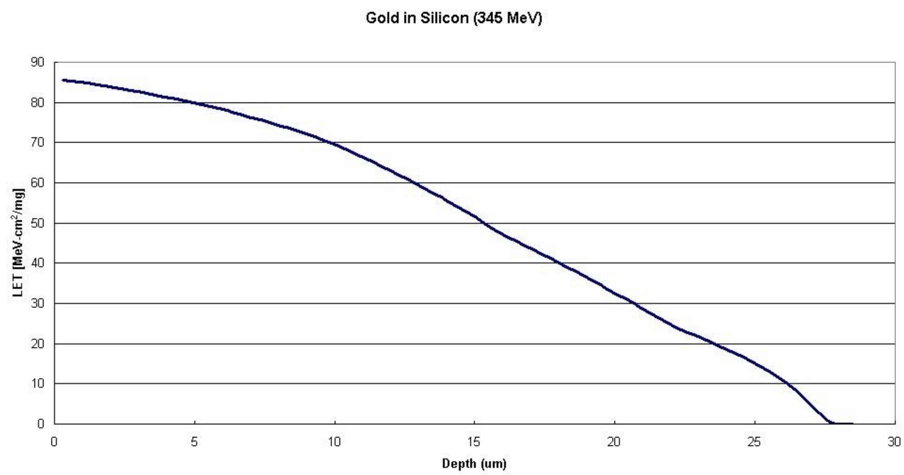
Interactions of the Particles with Semiconductors

SRIM Calculations



LET Curves for Typical Ions

Heavy-Ion Beam Examples (Brookhaven)



LET Curves for Typical Ions

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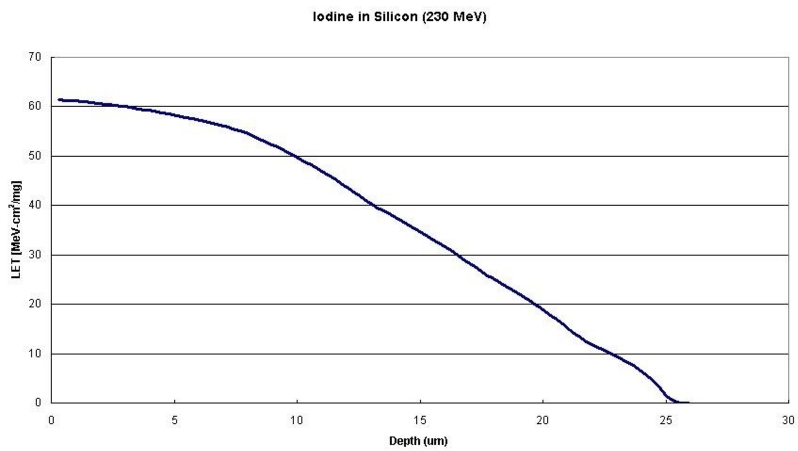

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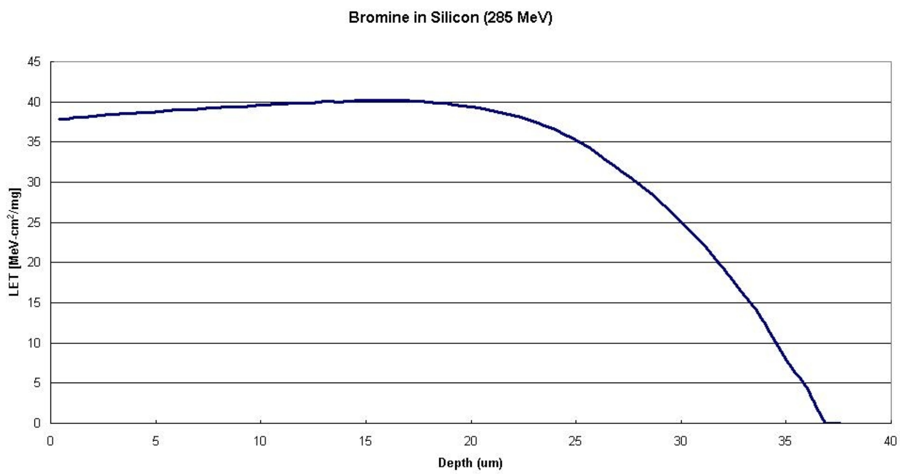

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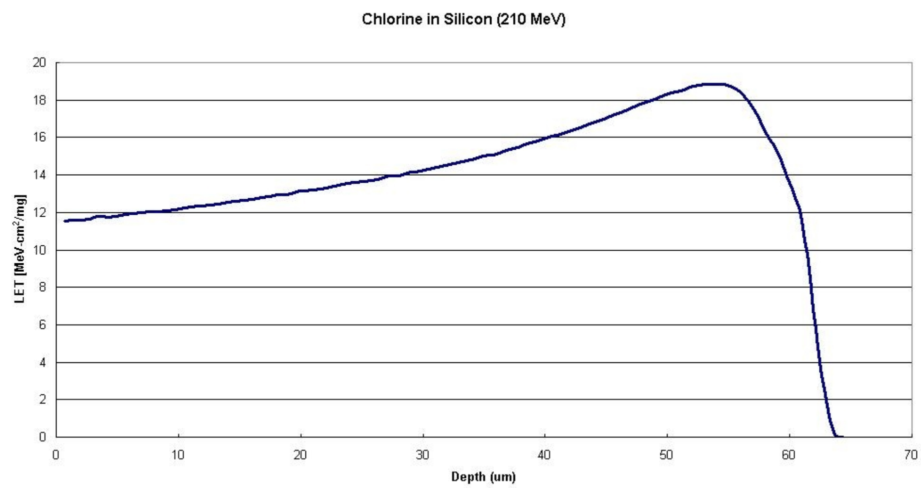

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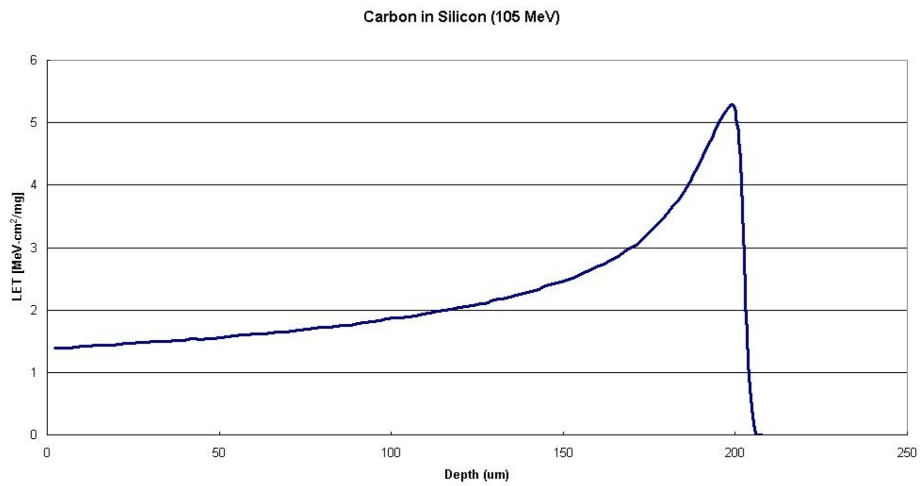
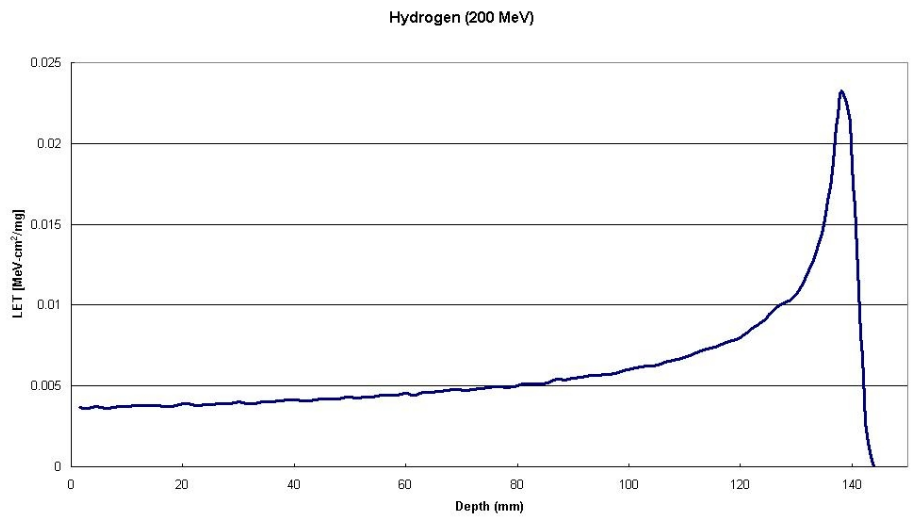


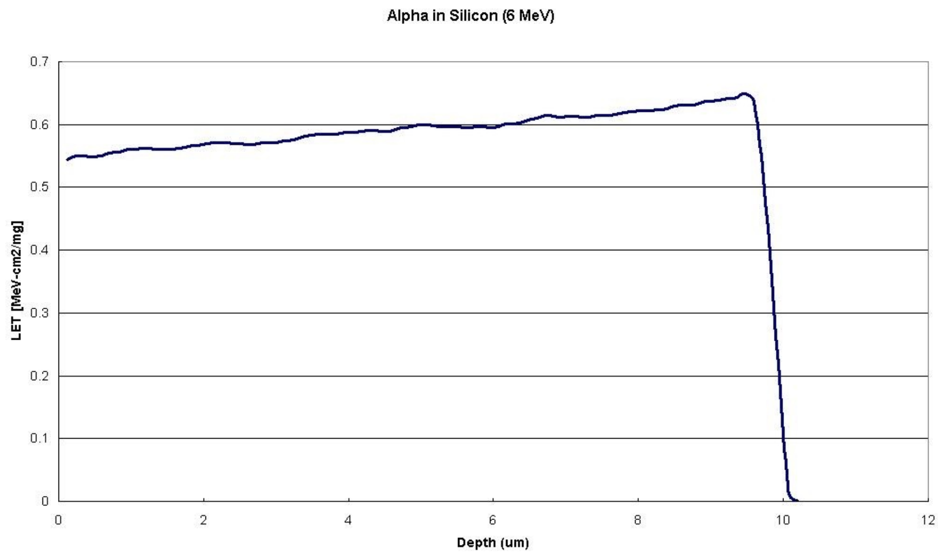
LET Curves for Typical Ions

Proton Beam Examples (Indiana University)



LET Curves for Typical Ions

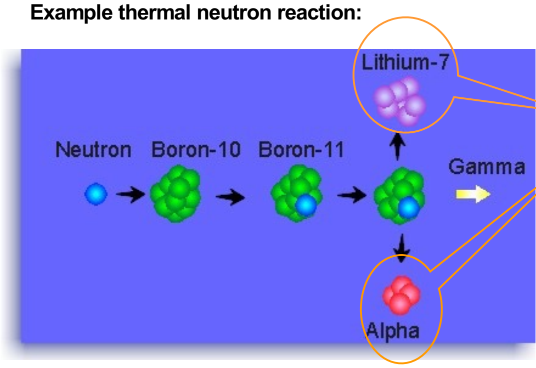
Packaging/Impurity Alpha Example



Terrestrial Neutrons

Created by cosmic ion interactions with oxygen and nitrogen in the upper atmosphere

Example thermal neutron reaction:

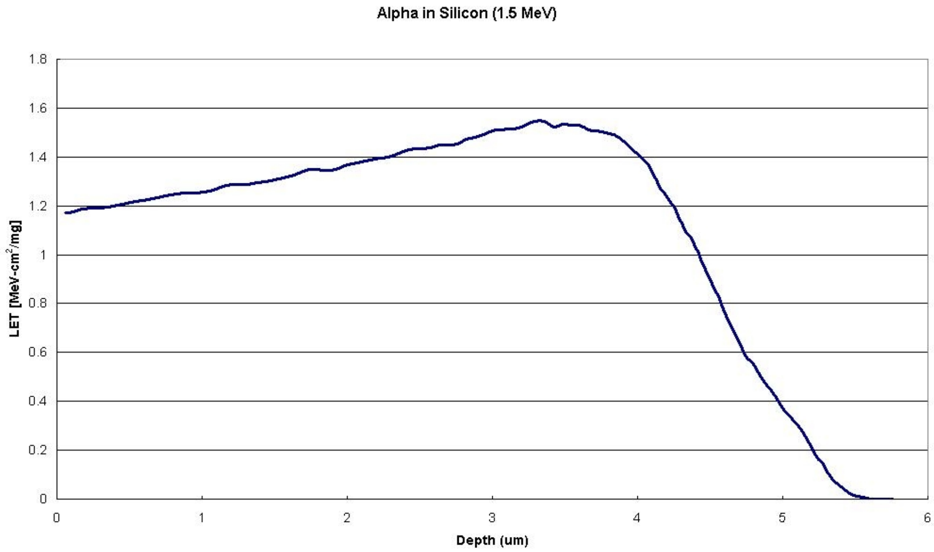


Energy; Range;
Time of Flight; Total Charge
0.8 MeV; 2.4µm; 1.5ps;
36fC

1.5 MeV; 5.2µm; 2.4ps;
67fC

LET Curves for Typical Ions

Terrestrial Neutron Product Examples



LET Curves for Typical Ions

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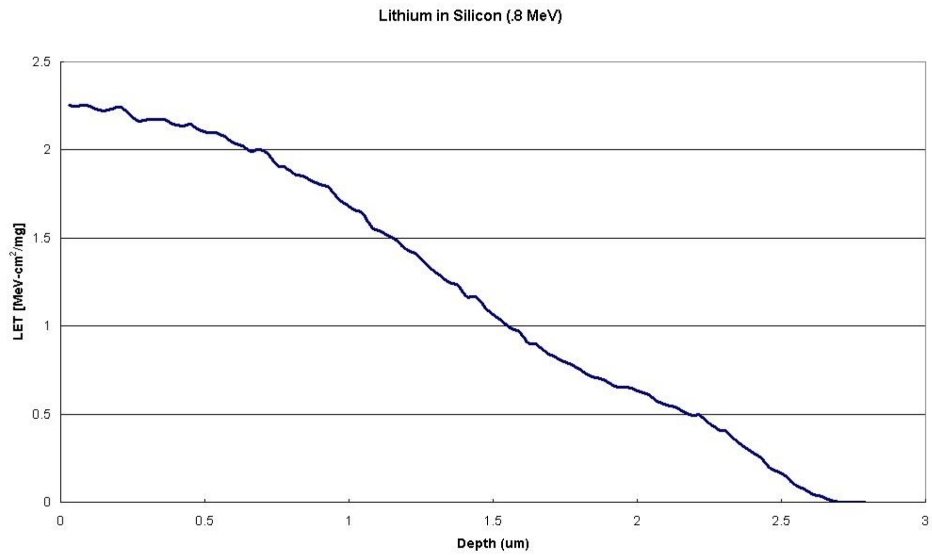
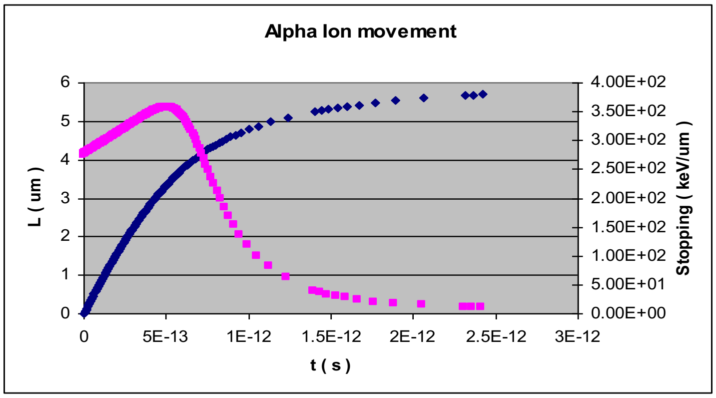


Further Information from Stopping Power Data

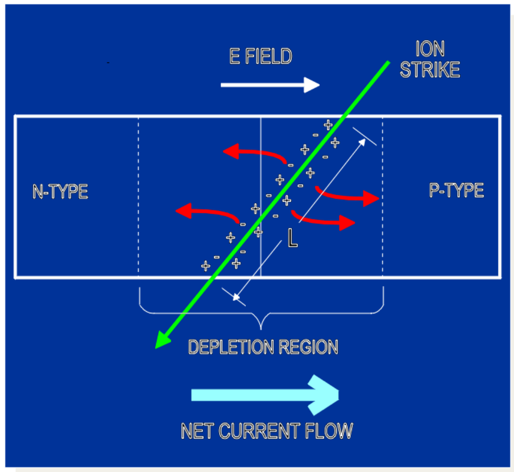


02

CHARGE COLLECTION

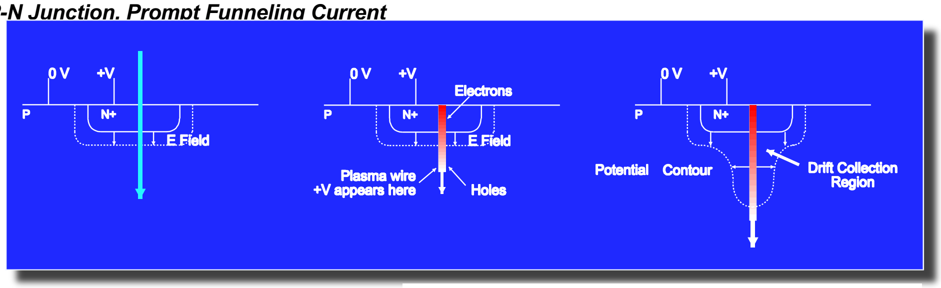
Depletion Region (Drift) Charge Collection

Simple P-N Junction, Prompt Current

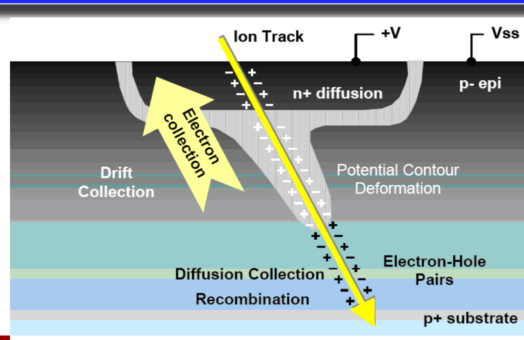


Enhanced Drift Charge Collection (Field Funneling)

Simple P-N Junction. Prompt Funneling Current



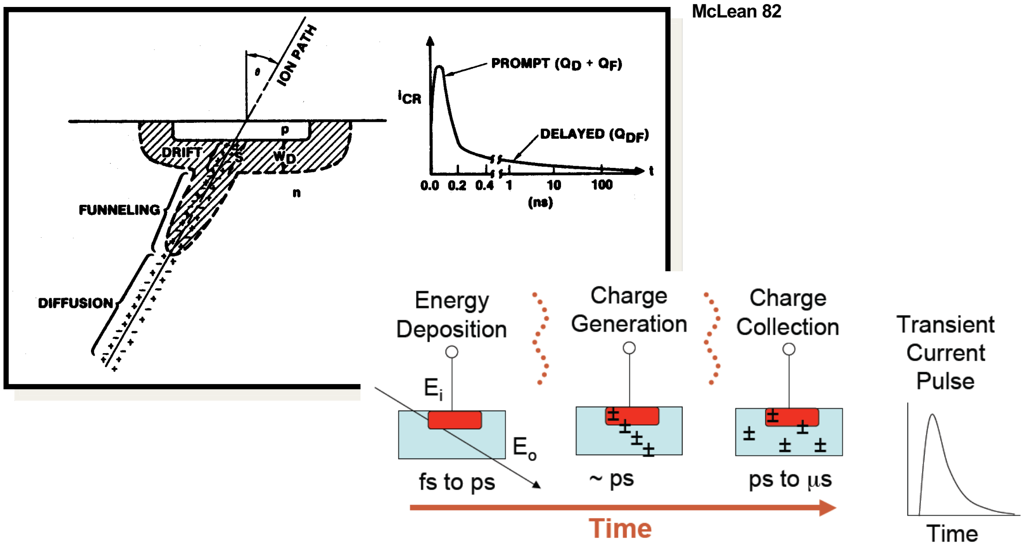
The track of ionized carriers can perturb the depletion region traversed by the path, leading to enhanced collection via drift processes



Diffusion Collection

Simple P-N Junction, Delayed Current

McLean 82



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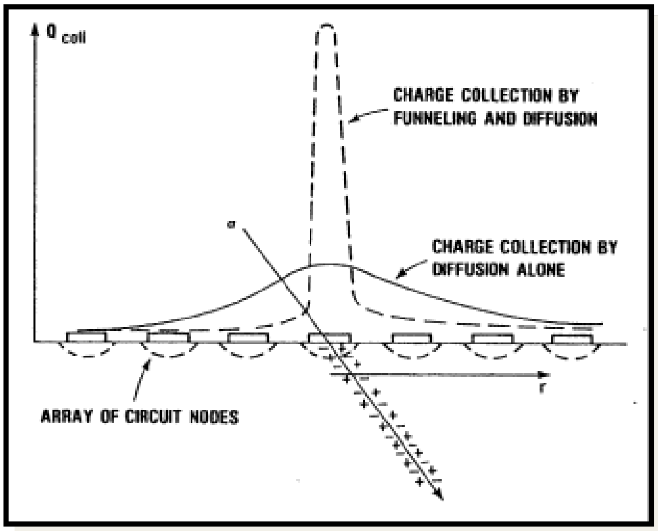
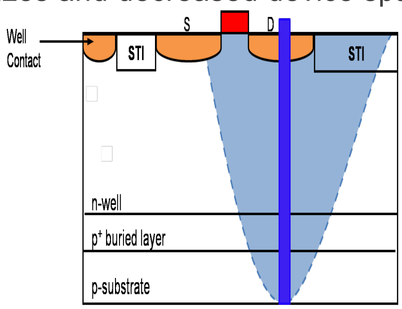


Pickel 83

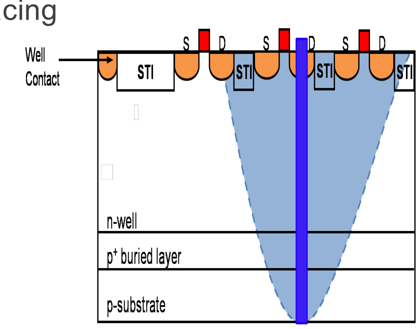
Charge Sharing

- Single-event (SE) generated charge may be "shared" between the device directly penetrated by the ionizing particle (hit device) and proximal devices

- Scaling technology increases the probability of charge sharing due to decreased device sizes and decreased device spacing



Older CMOS technology

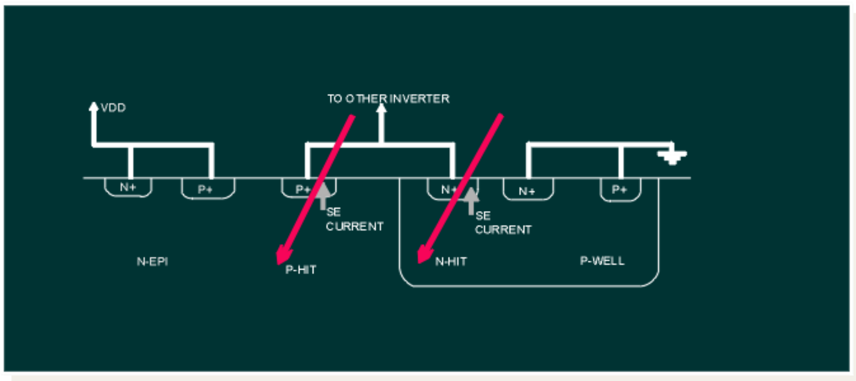


Sub-100 nm CMOS Technology

Complex Geometries

CMOS Structure

Charge collection influenced by neighboring junctions or boundary conditions

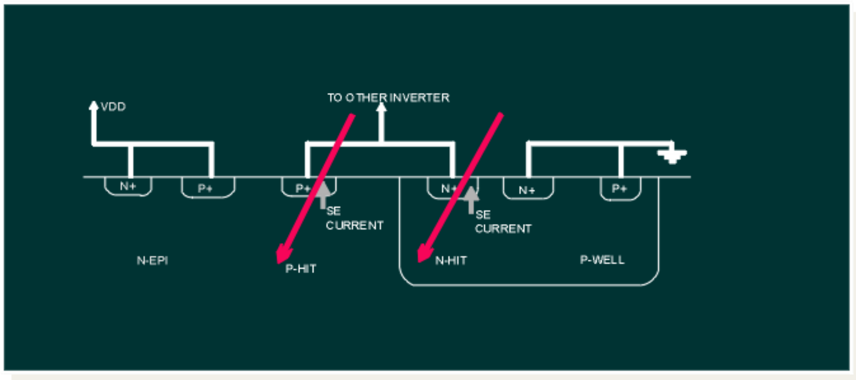


Complex Geometries

CMOS Structure

Charge collection influenced by neighboring junctions or boundary conditions

Junctions are vulnerable when reversed biased



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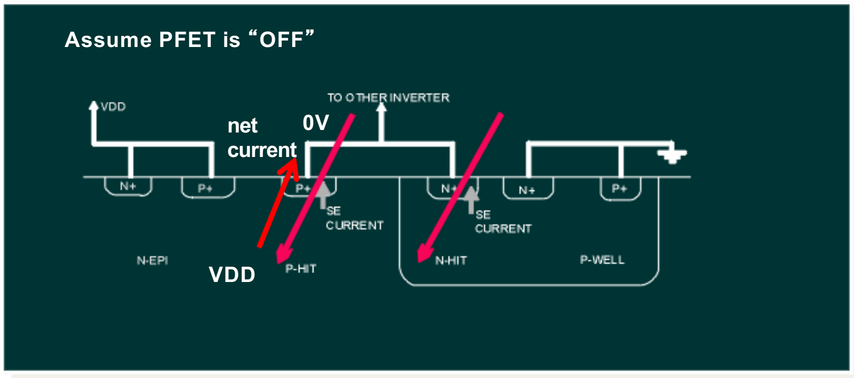

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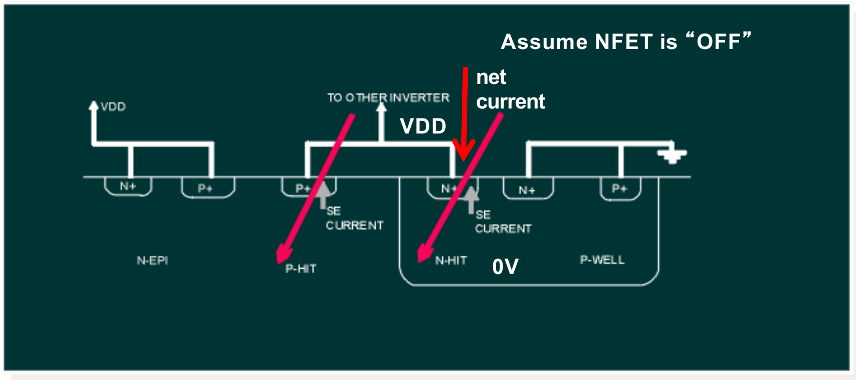

Complex Geometries

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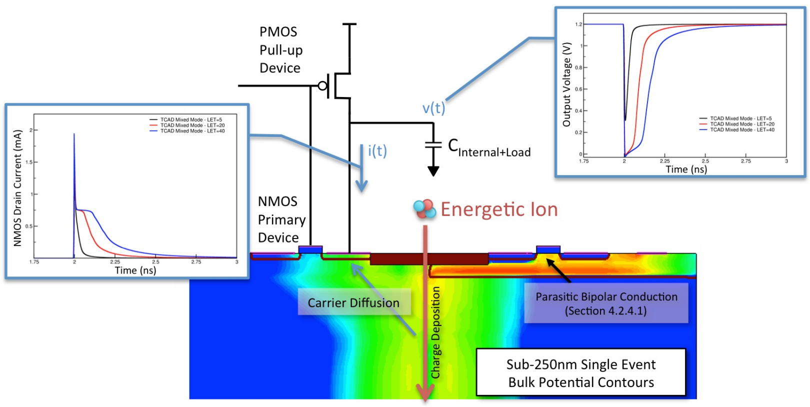

Massengill 2012

Complex Geometries

CMOS Structure

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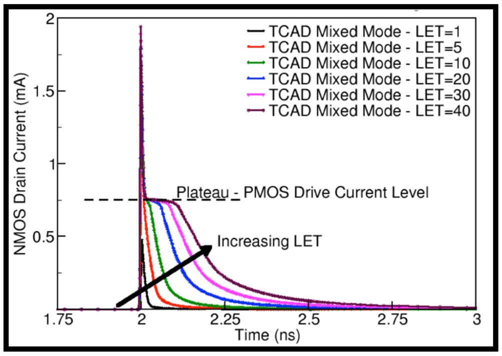
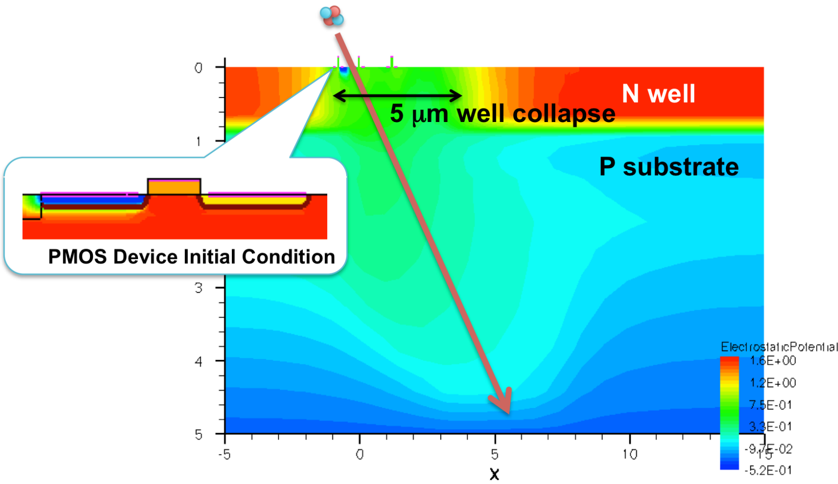


Kauppila 2009

The plateau region, caused by the collapse of the device depletion region, is the induced balance of charge collection current and resupply current)

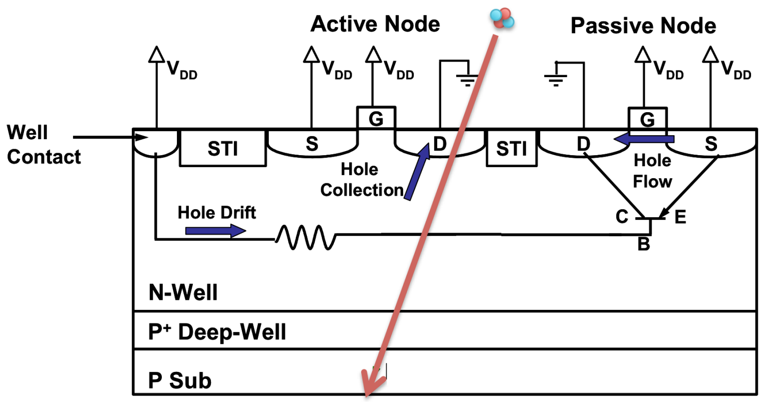
Complex Geometries

Well Potential Collapse



Olson 2007

Parasitic Bipolar Action Due to Well Potential Collapse

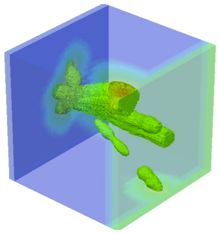


Olson 2005

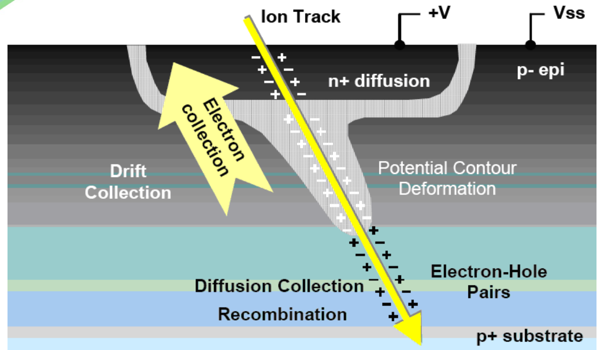
03

Summary of SEE Charge Generation and Collection

REMINDER: Single-Event Effects In Microelectronics



- Single-Event Effects (SEE):
  - Caused by the interaction of a single energetic particle



Example of Ion Penetrating Reverse-Biased p-n Junction

Ionizing Particles:

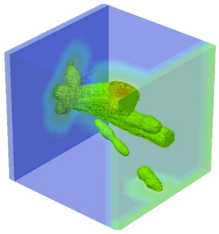
Heavy ions from deep space (galactic cosmic rays)

Energetic protons (trapped in the Van Allen belts)

Neutron products (terrestrial)

Alpha particles (from contaminants)

REMINDER: Single-Event Effects In Microelectronics



- Single-Event Effects (SEE):
  - Caused by the interaction of a single energetic particle
  - SEE are determined by:
    - Charge generation
    - Charge collection
    - Circuit response