Basic Mechanisms: Total Ionizing Dose

LANL Radiation Effects Summer School

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Radiation Effects & Reliability

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Overview

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- Annealing and Unbiased Irradiation
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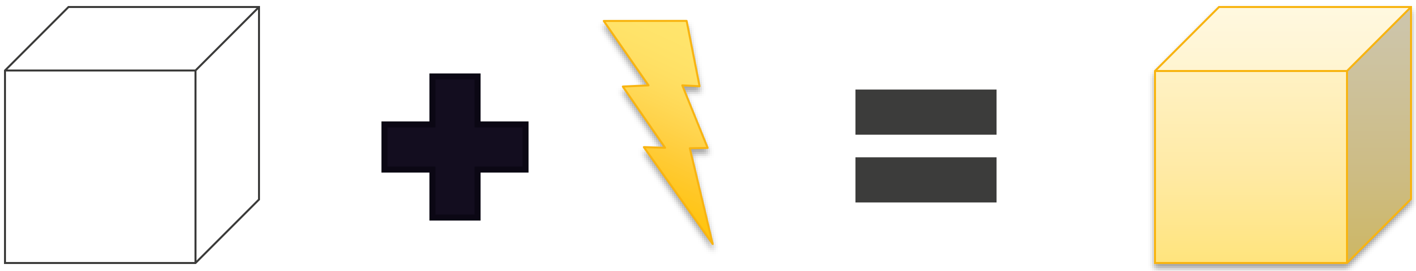
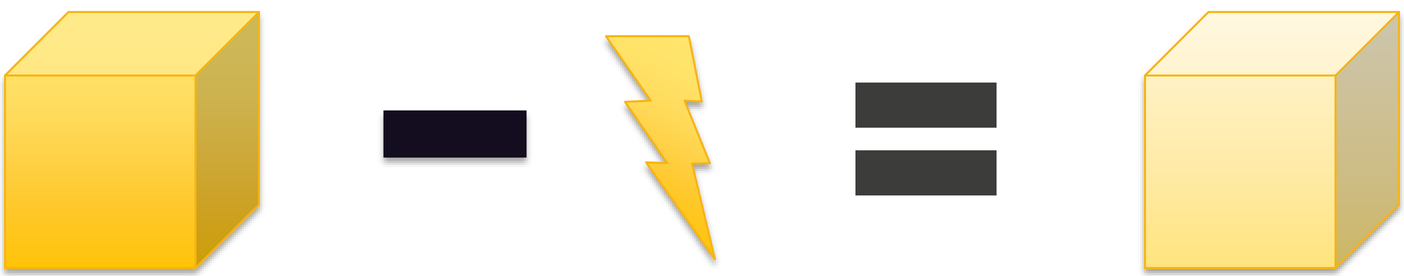
- Q&A (throughout discussion, don’t wait until the end)

Introduction:
Dose vs. Radioactivity

- What is absorbed dose?
  - It’s how we measure energy deposited in a unit mass



- What is radioactivity?
  - It’s how we measure energy released over a period of time



- What is the difference between dose and radioactivity?

Introduction:
Unit Considerations

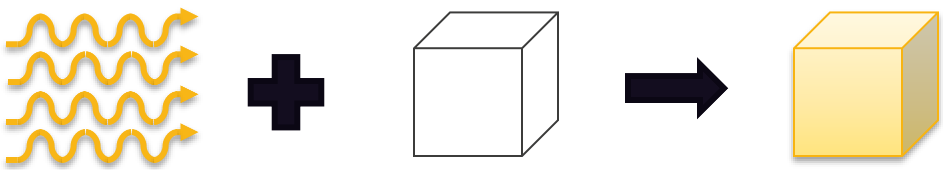
- Absorbed Dose (Ionization)
  - ergon (erg) = 10^{-7} joules/gram [J/g]
    - Greek for “work” or “task”
  - radiation absorbed dose (rad) = 100 ergs per gram [erg/g]
    - 1000 rad(Si) = 1 krad(Si)
    - 1000 rad(SiO_2) = 1 krad(SiO_2)
  - Gray (Gy) = joules per kilogram [J/kg] << SI unit

- Radioactivity
  - Becquerel (Bq) = number of transformations per second << SI unit
  - Curie (Ci) = 3.7×10^{10} transformations per second
  - Rutherford (Rd) = 10^6 transformations per second

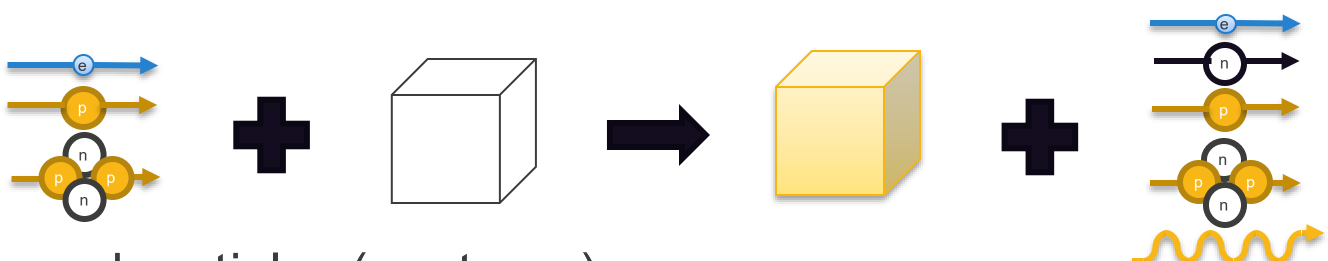
- Which to use? – well, it depends who you are talking to…
  - biology or medical professional? try Gray & Becquerel.
  - particle physics, aerospace, or electronics professional? try krad & Curie.

Ionization:
Gross Oversimplification

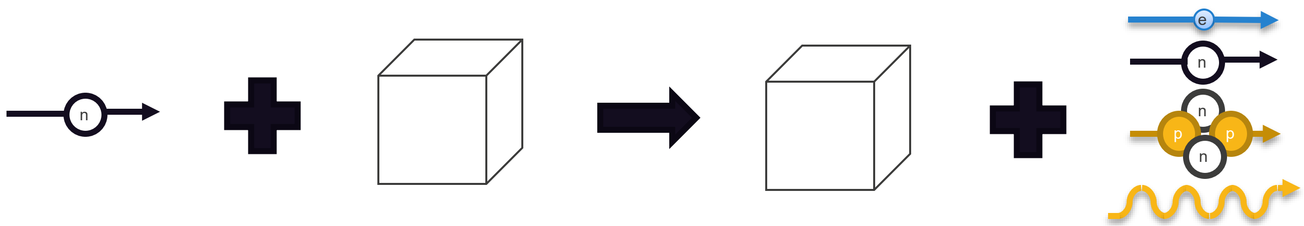
- Photons (X-rays and gamma rays)
  - **Direct ionization** occurs and negligible mass activation



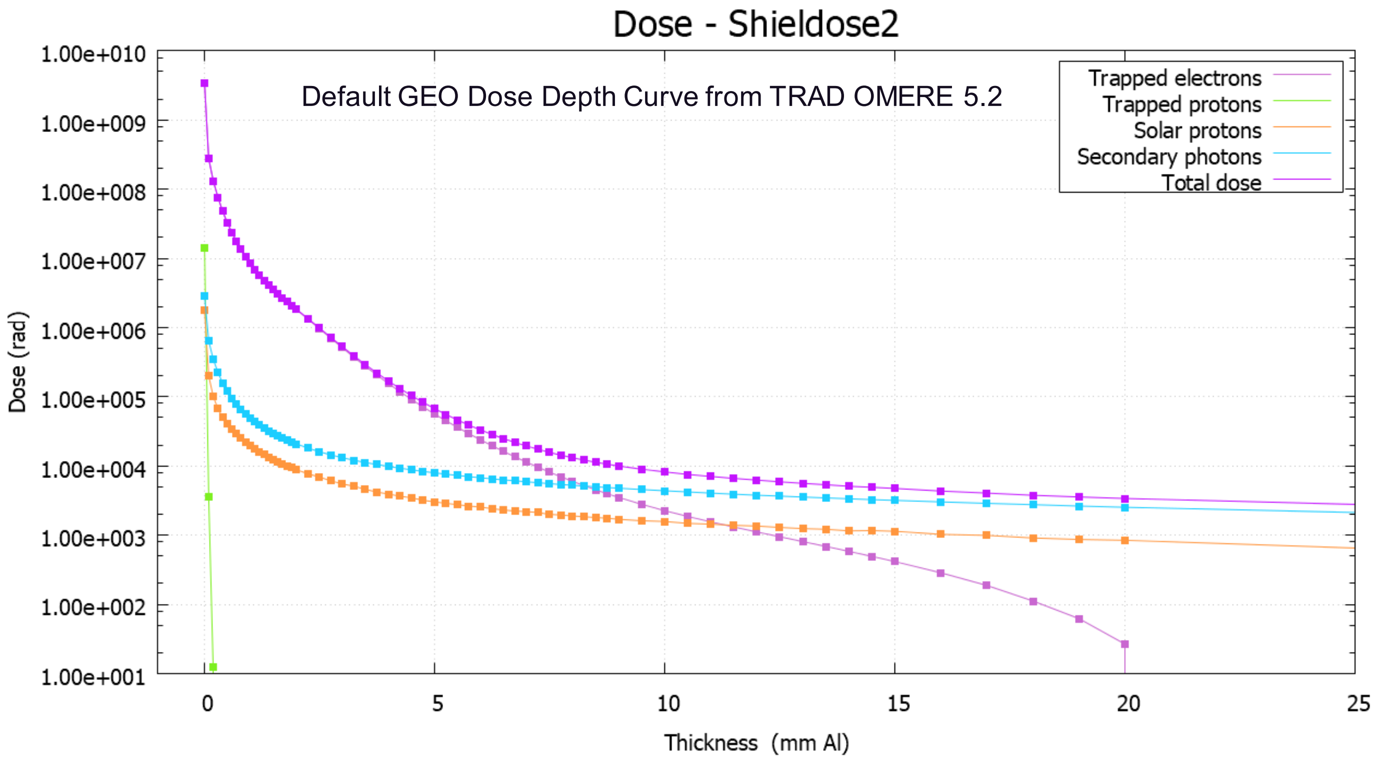
- Charged particles (electrons, protons, and heavy ions)
  - **Direct ionization** occurs, indirect ionization negligible, and mass **activated**



- Uncharged particles (neutrons)
  - Indirect ionization negligible and mass **activated**



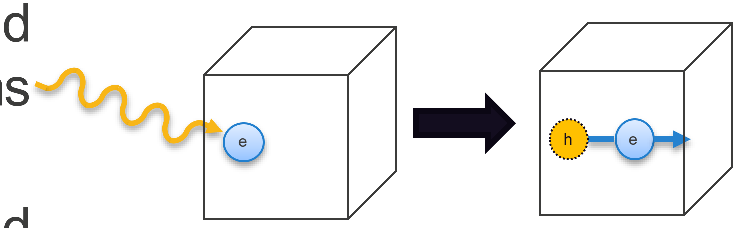
Ionization:
Total Ionizing Dose (TID)

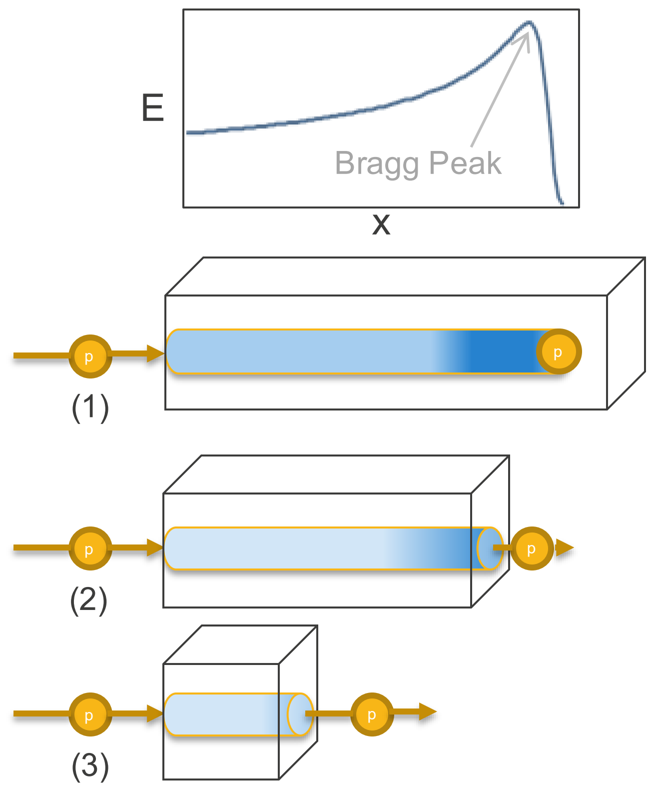


- Total Ionizing Dose (TID) is the summation of the overall accumulated dose from various sources (electrons, protons, heavy ions, x-rays, gamma rays, etc.)
- Sensitivity to TID can affect reliability and functionality of microelectronics

Ionization:
Direct Ionization

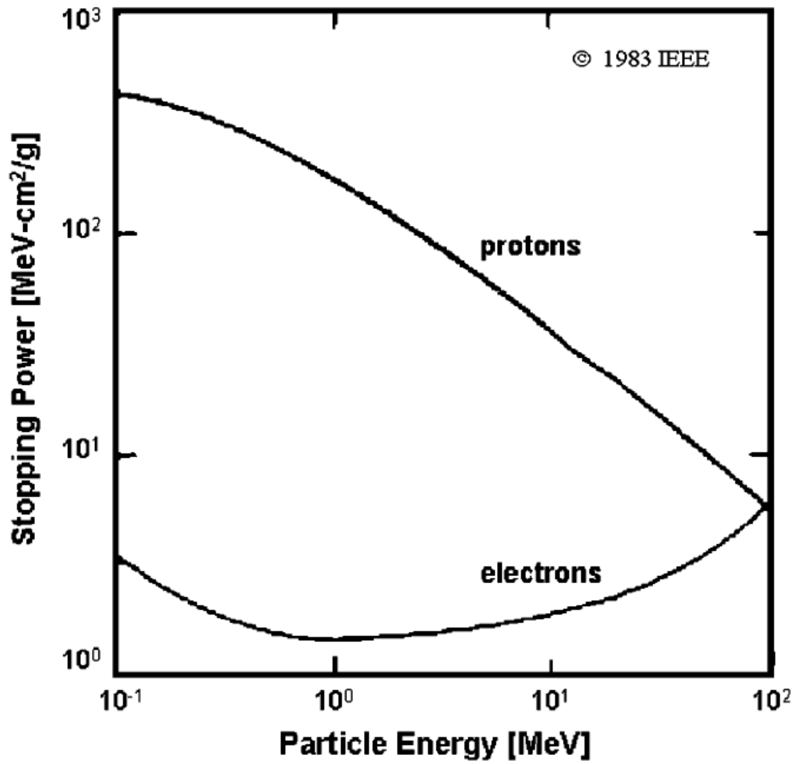
- Ionization of a target material is caused by the interaction of high-energy photons or charged particles
- Photon and charged-particle induced ionization are the result of electron-hole-pair (ehp) generation along a track of secondary electrons emitted via material interactions
- Stopping power or Linear Energy Transfer (LET) expresses the energy loss per unit length (dE/dx)
  - LET, in preferred units of MeV-cm^2/mg, is a function of particle mass and energy as well as the target material's density





Ionization:
Direct Ionization

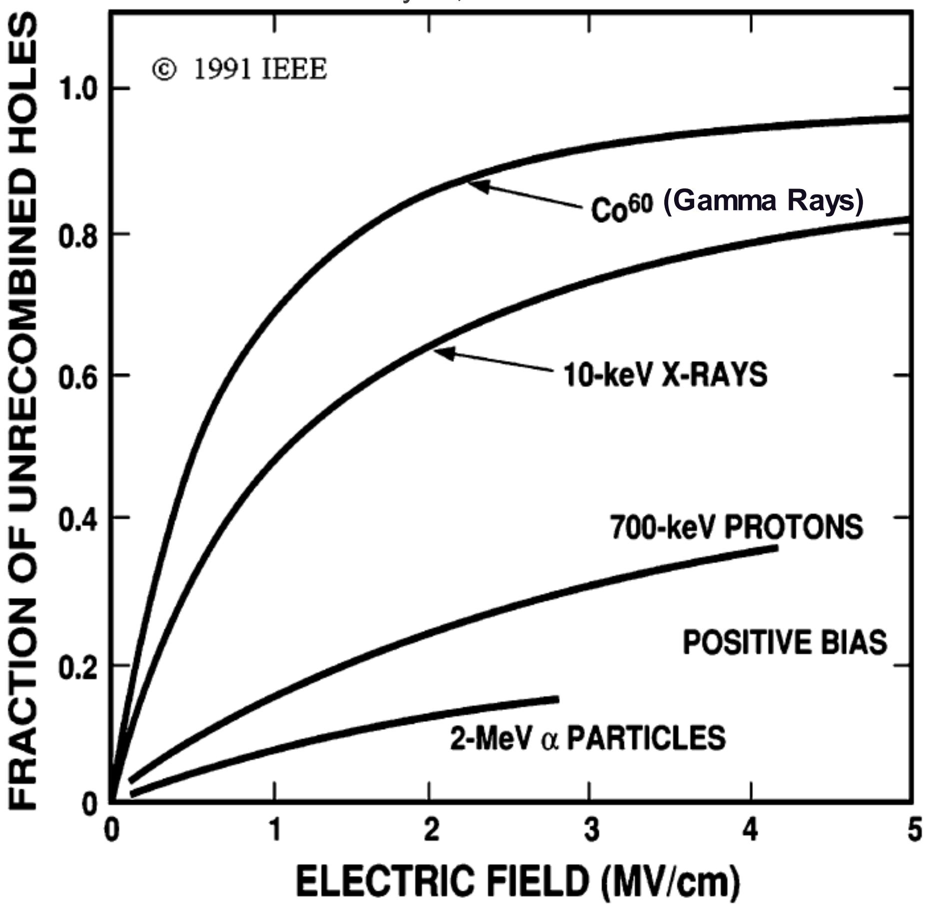
Srour, IEEE NSREC Short Course 1983



- At a given energy, LET for protons is greater than electrons due to more mass
- Also, for higher energy charged particles, energy deposited in a material is lower
  - Think about kinetic energy, $E_k = \frac{1}{2}mv^2$ (higher energy = higher velocity)
  - At higher velocities, a charged particle spends less time within a material

Ionization:
Direct Ionization

Shaneyfelt, IEEE TNS 1991

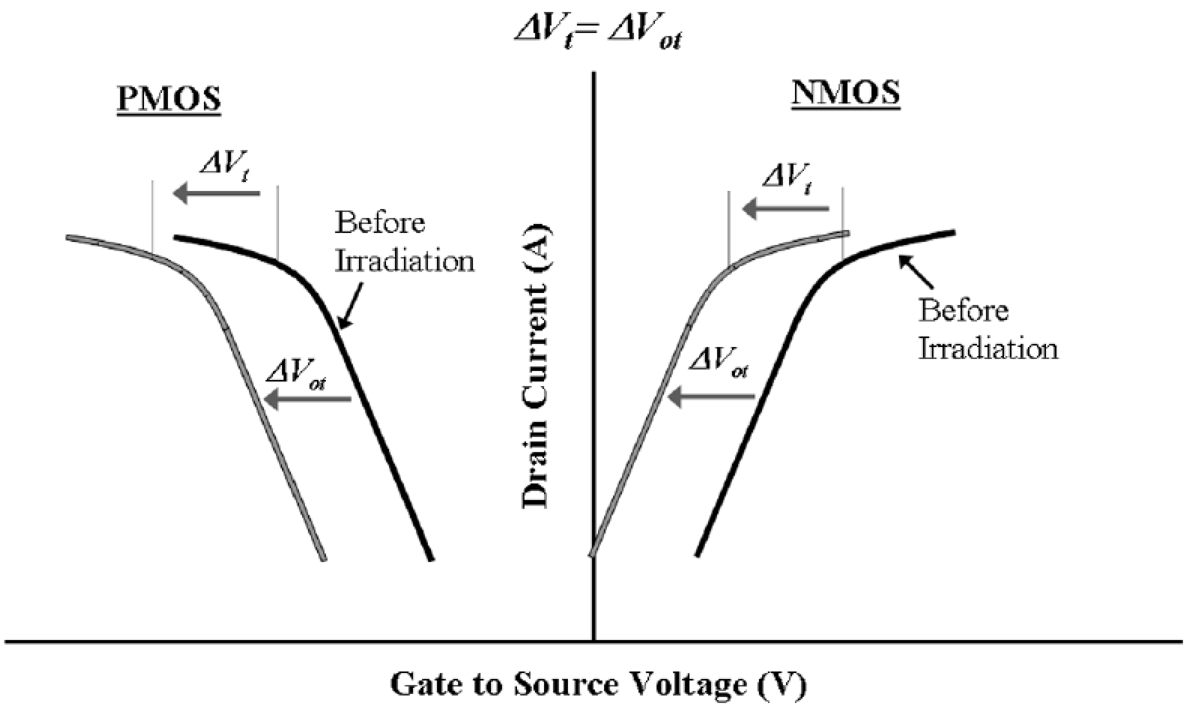


- The fraction of unrecombined holes in silicon varies with the energy of the photon or particle and the electric field generated by excess charge

Ionization:
Indirect Ionization

- We were just talking about direct ionization
- What is indirect ionization?
- Why is indirect ionization negligible for this discussion regarding Total Ionizing Dose (TID)?
- Any guesses at the ratio between direct and indirect ionization?
  - Protons
  - Neutrons
  - Heavy Ions
  - Can indirect ionization even happen with photons?

Materials and Devices:
Parametric Shifts in CMOS and Bipolar Devices



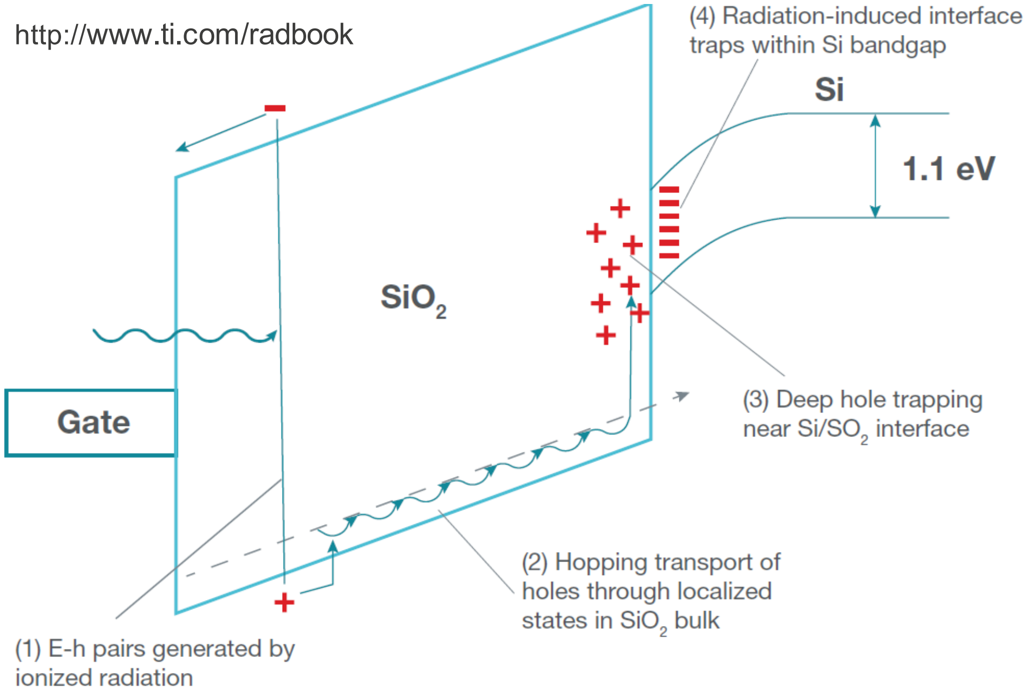
H. J. Barnaby, *IEEE TNS 2006*

- Accumulated dose effects are characterized by **lasting parametric shifts**, which eventually cause semiconductor devices to drift out of tolerance and ultimately fail
- In metal-oxide semiconductor field-effect transistors (MOSFETs) and bipolar junction transistors (BJTs), radiation exposure generates excess charge

Materials and Devices: Parametric Shifts in CMOS and Bipolar Devices

- The holes generated by radiation exposure are relatively immobile in comparison to electrons
- The basic mechanism is hole generation and transport in silicon, then holes being trapped in doped silicon and insulation material (SiO_2)
  - gate and isolation oxides in metal-oxide semiconductor (MOS)
  - at or near silicon-oxide interfaces in bipolar
- In complementary MOS (CMOS), absorbed dose results in leakage currents in isolation layers that lead to functional failures
- In bipolar transistors, oxide charge and interface states in the isolation will increase e-h pair recombination rate, which causes increased base and collector currents that lead to reduced gain

Materials and Devices: Bandgap Diagram of MOS Stack



- The previous bandgap diagram illustrates excess charge generation by exposure to radiation, and the subsequent transport and trapping of that excess charge at or near the interface of SiO_2 and silicon
- The diagram represents distance (or depth) on the horizontal axis and electron energy on the vertical axis
- More energetic electrons appear higher on the diagram, and a positive voltage pulls the energy bands down

Materials and Devices: Bandgap Diagram of MOS Stack

- The positively biased polysilicon (or metal) gate electrode is to the left with an insulator layer in the middle
- The insulator energy bands are slanted electric field from the gate and silicon electrodes
- Energy from incident radiation is absorbed in the insulator by the formation of electron-hole (e-h) pairs
- Approximately 17 eV of energy is required for the production of each single e-h pair in silicon oxide
- The creation of excess charge occurs on the femtosecond timescale

Total Ionizing Dose (TID) Effects

- Oxide Trapped Charge
  - Typically net positive charge due to hole capture by oxygen atoms
  - Fixed oxide trapped charge can result in DC parameter shifts in CMOS device and integrated circuits (ICs)
- Interface Traps
  - Charge exchange with adjacent Si layers that drastically effect carrier mobility and ehps recombination rates
- 1/f noise in MOS Devices
  - Switching charge exchanges at oxide interfaces that cause noise

Enhanced Low Dose Rate Sensitivity (ELDRS)

- Some devices (mostly bipolar) are affected by receiving ionizing dose at very low rates
  - During accelerated terrestrial testing, a High Dose Rate (HDR) of >50 rad(Si)/s is the accepted worst-case scenario by convention
  - In space, a Low Dose Rate (LDR) of ~0.01 rad(Si)/s is more typical
  - During non-accelerated terrestrial testing, ELDRS has been observed in devices containing bipolar elements
  - As result, HDR and LDR testing may be necessary for these devices
- Need a weak electric field and an oxide with a “large density of defects”
- This is an area of active research – no one is quite certain what causes this sensitivity in some devices
- CMOS products can withstand a much higher TID at low dose rates than at high dose rates due to self-annealing effects

Annealing and Unbiased Irradiation

- Annealing is the process of e-h pair recombination
  - Often occurs at room temperature and can be accelerated via heating
  - When a CMOS device is irradiated at an HDR and is then biased after the radiation source is removed, the device may begin to functionally recover
- Unbiased irradiation of devices yields lower rates of long lasting e-h pair generation
  - Unbiased = not powered
  - A lack of an electric field (think back to the bandgap diagram) makes electrons less mobile and therefore increases e-h pair recombination

Occurrence

- TID effects are a common problem in space
  - Some parts can withstand 1 Mrad(Si) of dose
  - Other parts can only withstand 5 krad(Si) of dose
- Mission duration and location, and shielding are used to determine the amount of dose your system will get
- Some missions require at least a minimum of 25 krad(Si) of dose, but 100 krad(Si) is often the ‘magic number’ for multi-year missions
  - Rad-hard parts are typically qualified to 100 krad(Si) of dose

Q&A

- Questions, comments, and concerns?
- Thank you!