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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\times10^{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-cm²/mg, is a function of particle mass and energy as well as the target material’s density.
Ionization: Direct Ionization

- 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

- 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?
• 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
• 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 (SiO₂)
  – 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 SiO₂ 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!