[반도체 산·학·연 교류 Workshop]

Radiation Environment and Its Effects In ICs

2019. 10. 10

김진상 교수 (경희대학교)

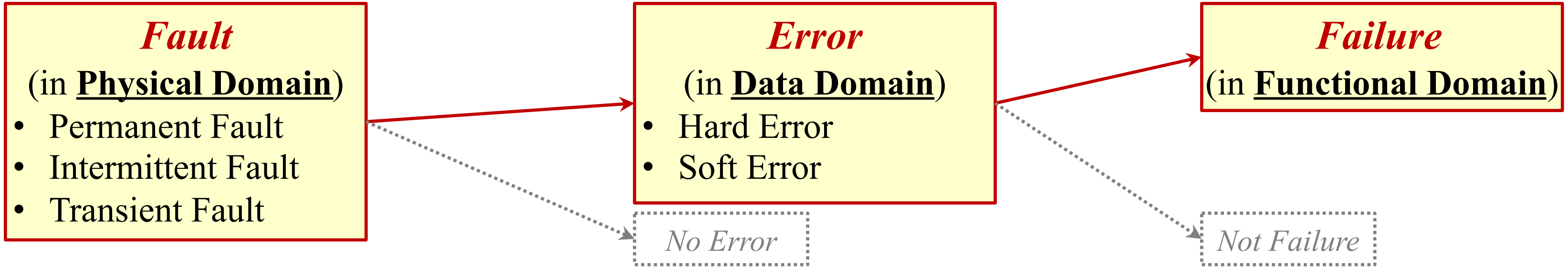
Reliability and Safety

- **Reliability and safety are universal expectations**
- **Reliable electronics will make possible many wondrous things**
  - Automotive: Driver-supporting technologies, autonomous driving
  - Cross-industries: all kinds of autonomous robots from delivery drones to agricultural machines
  - Medical: deeply embedded (implanted) life-monitoring and life-supporting technologies
  - Networking/IT: dependable networks and data centers
  - Computing: from mobile devices to high-impact decision-taker tools
- **Durability is a key issue for several application fields**
  - Automotive, aeronautic, medical, industry ...



Source: Raoul Velazco (TIMA), "Single Event Effects Basic," Automotive Semiconductor Safety Innovation Conference 2019. [QRT 제공]

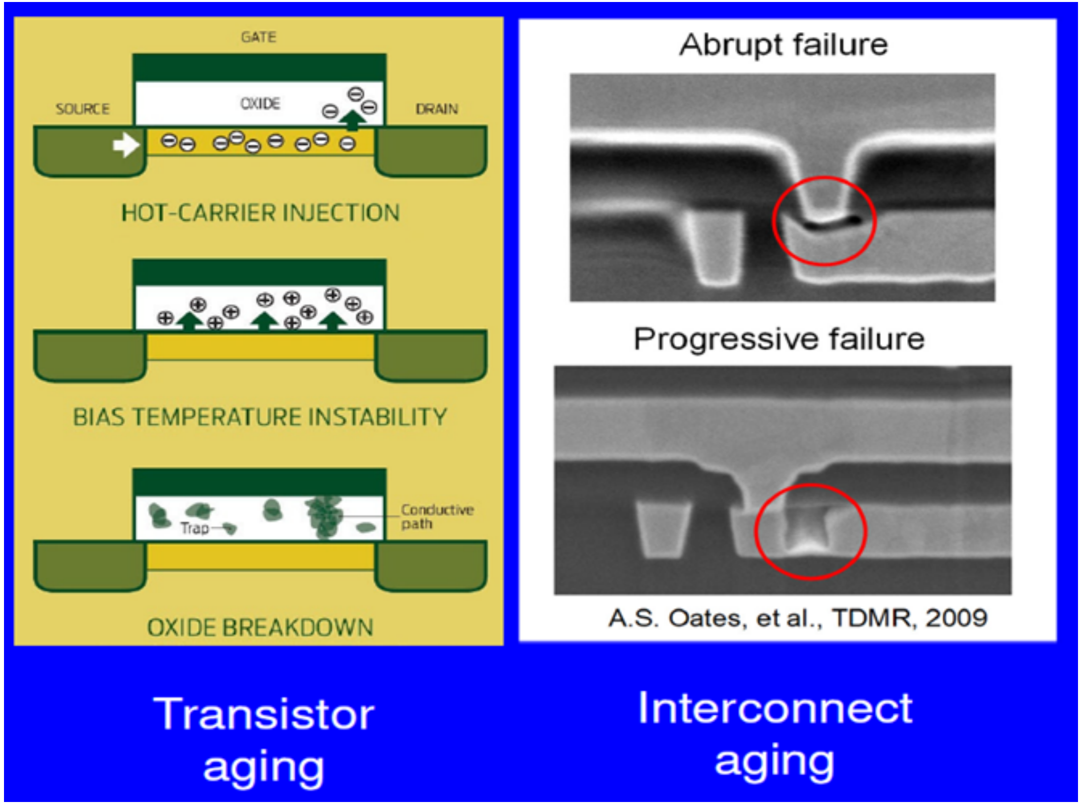
Fault, Error, and Failure in Semiconductor



✓ ***Faults** are reasons for errors and **errors** are reasons for **failures***: They can be cured/managed by Redundant Design (Redundancy: Hardware/Software, Time/Information).

- ***Fault***: a <u>physical</u> defect, imperfection, or flaw that occurs in some hardware or software component
  - *Permanent fault* (hard fault): *fault persists*, physical damage to processor
  - *Intermittent fault*: *fault occurs and recurs over time*, faulty connections can recur → *<u>conditional</u>*
  - *Transient fault* (soft fault): *fault occurs but may not recur*, cross talk/EMI/particle-induced SEU (Single Event Upset)
- ***Error***: a deviation from correctness or accuracy in <u>computation</u>
  - Hard Error: A *residual error* caused *by a physical defect in the system* (by Permanent Fault and Intermittent Fault)
  - Soft Error: A *temporal error*, which is *not due to any defect in the physical system* (by Transient Fault and Intermittent Fault)
- ***Failure***: a <u>non-performance</u> of some action which is due or expected

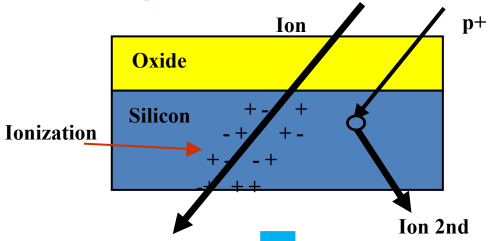
Semiconductor Fault/Error: Transistor/Interconnect Aging



Source: Professor Chris Hyung-il Kim, 세미나 자료 (2018. 7)

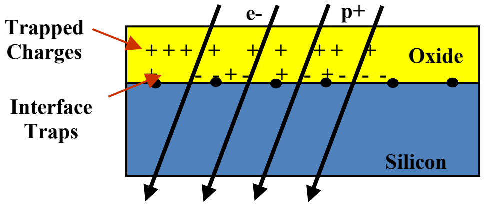
Semiconductor Fault/Error: Cosmic Ray Radiation Effects

Single Event Effects

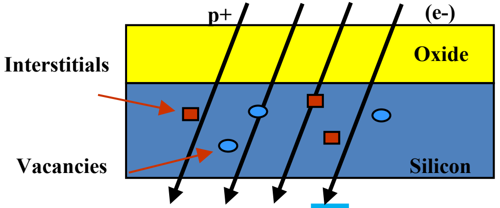


SET: transient
SEU: upset
SEL: latch-up
SEB: burn-out
SEGR: rupture

Ionising Dose



Atomic Displacement



Parametric Drift
Function Loss

Lifetime

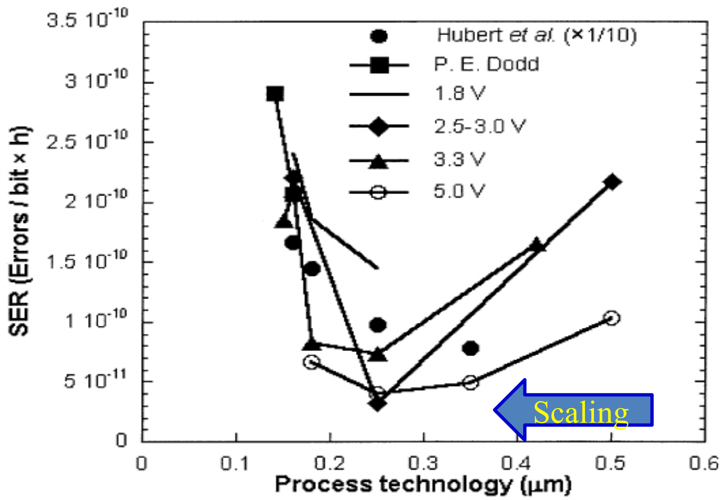
Operating Safety
Dependability
Performances

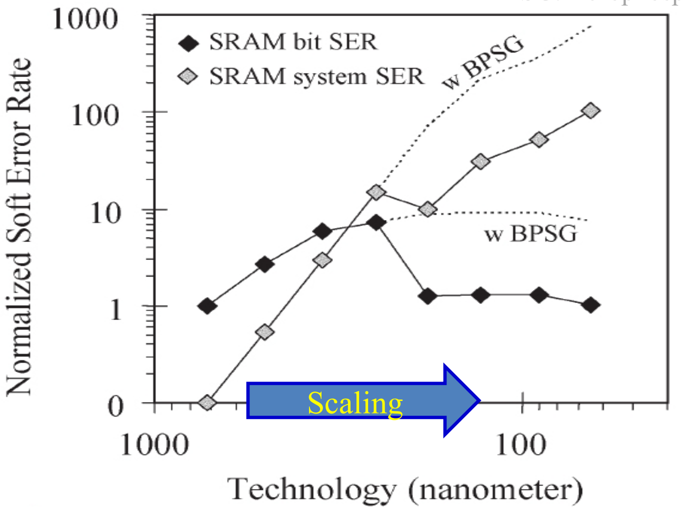
Hot Pixels
RTS
(Random Telegraph Signal)

Source: Robert Ecoffet (CNES), "Anomalies associated with radiation effects and the role of space agencies," CERN Seminar, June 10, 2014. [QRT 제공]

Semiconductor Fault/Error: Dependence on Process Technology

BPSG: Borophosphosilicate glass



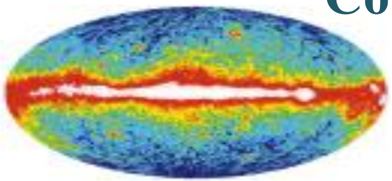


- The present trend is to minimise the typical layout length
- This has helped to decrease the sensitive volume but, also, the critical charge does
- ICs issued from advanced microelectronic technologies are sensitive to the natural radiation
- Their reliability and security are threatened
- Some techniques to deal with such a conjuncture exist but faults due to radiation remain a high concern

Source: Raoul Velazco (TIMA), "Single Event Effects Basic," Automotive Semiconductor Safety Innovation Conference 2019. [QRT 제공]

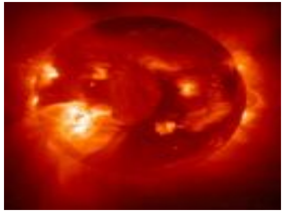
Cosmic Ray에 의한 Soft Error (SEU) 발생 과정

Galactic Cosmic Rays



Trapped Particle Ion Belt

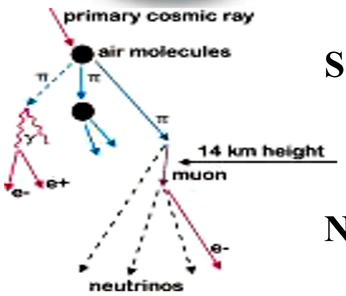
Sun Solar Particles



대기권으로 들어온 중성자의 차단은 불가능하다.

Atmospheric Interaction

Terrestrial Particles

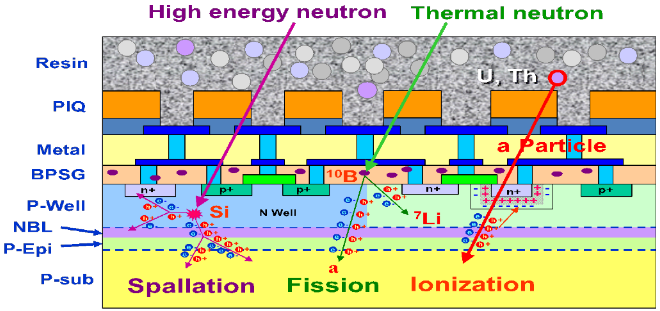


Secondary Showers:
Proton, Neutron, Muon, Pion, Electron

Neutron, Muon, Pion, Electron

반도체로 들어가는 중성자를 막을 수가 없다

Device

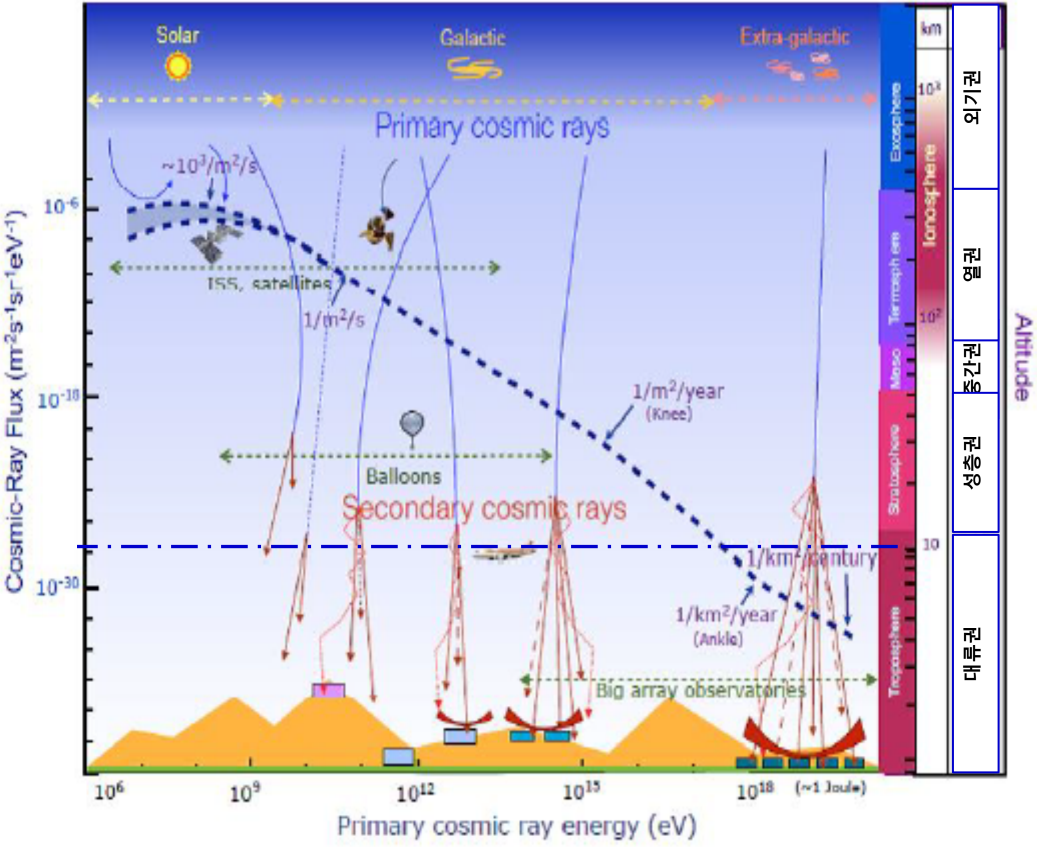


SEU happens when the total electric charges accumulated at the storage cell(s) are greater than the Critical Charges (Qcrit) to upset the logic

Single Event Upset (SEU)

Source: QRT

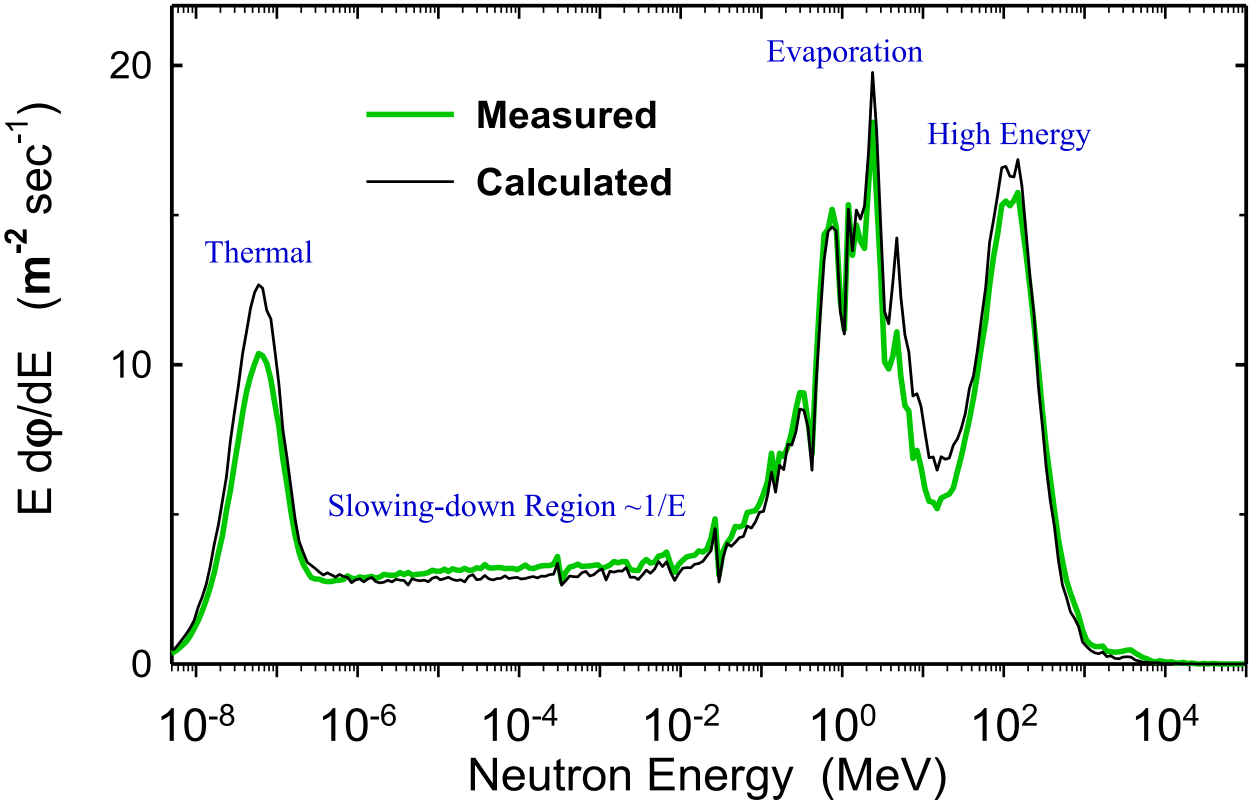
Sources of Cosmic Ray: Cosmic Ray Shower



- **Galactic Energetic Charged Particles (GCR)**: *mostly protons (~ 85 %)* and *helium ions* (~ 12 %)
  - Proton이 대기 중의 산소 (O_2)나 질소 (N_2) 분자와 Scattering을 일으켜서 Neutron 등을 생성
  - Charged Particle은 공기분자와 Coulomb Scattering에 의해 Energy가 소멸 됨
  - 생성된 중성자는 Scattering 확률이 매우 낮으므로 지표면까지 도달함
- **Solar Energetic Charged Particles**: Only a small fraction of the SPE (Solar Particle Event)s, on average one per year, causes an increased dose rate at aviation altitudes.

✓ __Alpha Particle__: Solder balls are usually made from Sn and Pb, which come from minerals where there may be uranium and thorium traces. Nevertheless, the designer forgets this detail and places the solder balls too close to critical nodes!

Cosmic Ray Neutron Spectrum on the Ground



Source: Paul Goldhagen, "Use of Cosmic-Ray Neutron Data in Nuclear Threat Detection and Other Applications," Neutron Monitor Community Workshop, 2015. [QRT 제공]

Radiation Sources

Characteristics	Ionization Radiation (E_K = 1 MeV)				
	Alpha (α) : fast-moving helium nucleus	**Proton (p)**	**Beta (β)** : high energy electron	**Photon (γ or X-ray)** : electromagnetic ray	**Neutron (n)** : free neutrons
Symbol	${}^{4}_{2}\alpha$ or He^{2+}	${}^{1}_{1}p$ or H^{1+}	${}^{0}_{-1}e$ or β	${}^{0}_{0}\gamma$	${}^{1}_{0}n$
Charge	+2	+1	-1	Neutral	Neutral
Ionization	Direct	Direct	Direct	Indirect	Indirect
Mass [amu]	4.001506	1.007276	0.00054858	-	1.008665
Velocity [cm/sec]	6.944×10^{8}	1.38×10^{9}	2.82×10^{10}	$c = 2.998\times10^{10}$	1.38×10^{9}
Speed of Light	2.3%	4.6%	94.1%	100%	4.6%
Range in Air	0.56cm	1.81cm	319cm	82,000cm*	39,250cm*

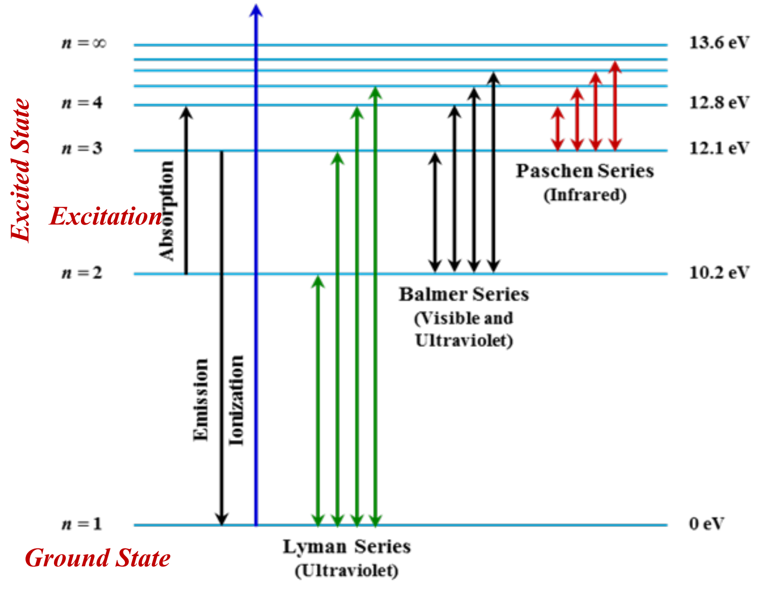
* Range based on a 99.9% reduction

- **Two Sources: *Galactic Cosmic Radiation* and the *Sun* (solar flares, coronal mass ejections).**
  - Cosmic Rays: Continuous flux of very energetic protons and heavy ions
  - Solar Particles: Energetic protons and heavy ions produced sporadically at high intensities
  - Atmospheric & spacecraft: secondary generated by nuclear reactions of the above
  - Radiation belt protons
  - Radioactivity in packaging

Ionization Energy & Energy Band of Solid

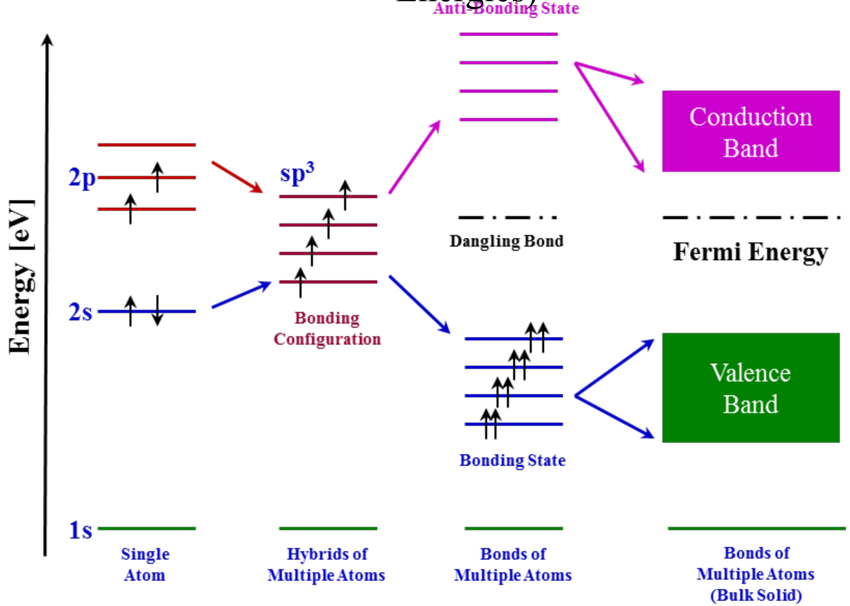
- Transition electron between different levels with frequency f: $\Delta E = hf$
  → Energy (Light) emit/absorb equal to difference between energy levels

Hydrogen Atom

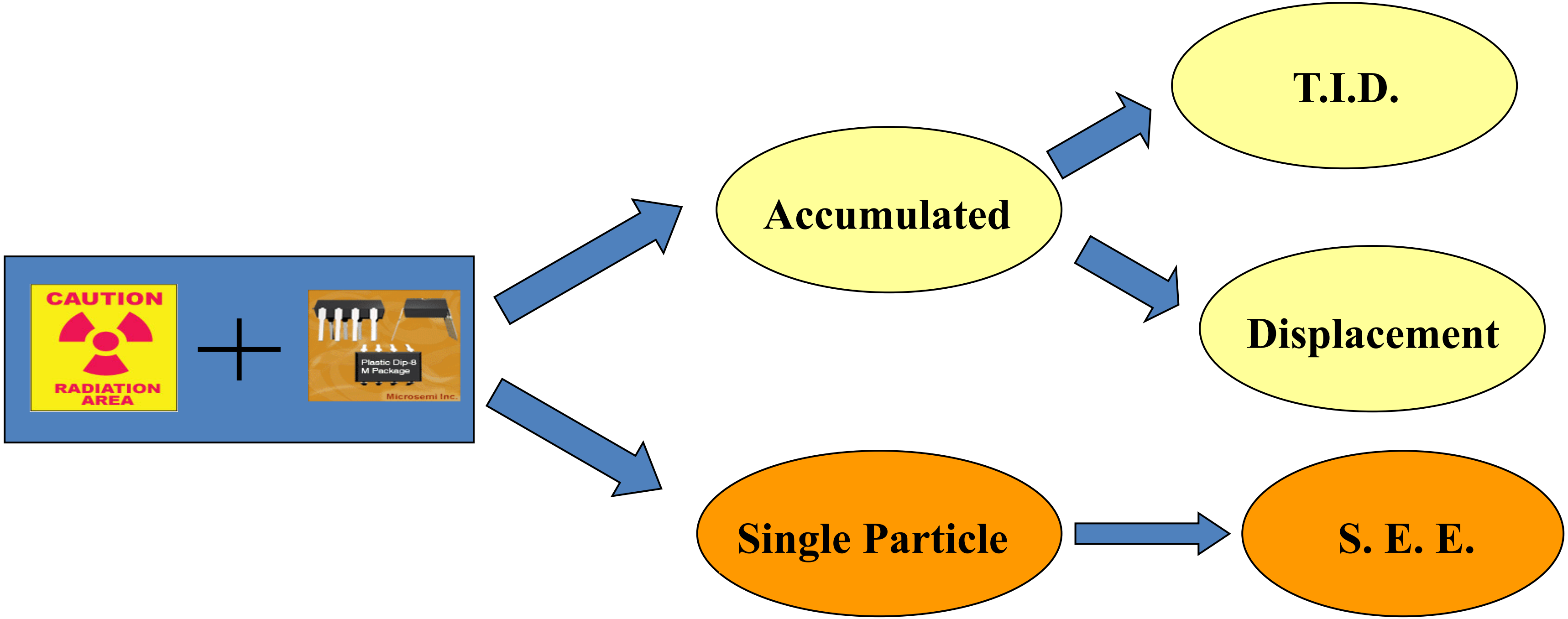


The electron volt (eV) is a unit of energy, 1 eV = 1.602×10^{-19} J

Energy Band of Solid (Orbital Energies)



Cosmic Ray Radiation and Electronic Devices



Source: Raoul Velazco (TIMA), “Single Event Effects Basic,” Automotive Semiconductor Safety Innovation Conference 2019. [QRT 제공]

Particle Interactions with Matter

- Energetic charged particle interactions with target materials: three basic processes
  1. **Energy loss** (dE/dx) by direct **ionization/excitation** of material along the particle track
     - Direct ionization effects – linear energy transfer (LET) – "slowing down"
       - Primary cause of single event effects (SEE) in susceptible electronic devices
       - Primary cause of total ionizing dose (TID) effects in susceptible electronic devices
  2. **High energy collisions** (inelastic/hadronic) triggering **nuclear reactions**
     - Nuclear hadronic reactions initiate *secondary particle showers* in the target mass
     - Further collisions of secondary particles with target nuclei lead to expansion and propagation of the secondary particle shower
     - *Secondary particles can produce direct ionization and more nuclear reactions*
  3. **Collisions with material nuclei** that produce **displacement damage (DD)**
     - Displacement of target atoms so as to disrupt crystal structure (**solids only**)

Nuclear Reaction: Fission, Fusion

→ Energy Loss (Direct Ionization, Excitation): IEL

→ Collision (Fission → Indirect Ionization by Recoil, Displacement): NIEL

IEL: Ionizing Energy Loss
NIEL: Non Ionizing Energy Loss

- **Conservation of Energy**: **Kinetic Energy + Potential Energy = Energy (E)**

Radiation Types

Radiation
- Particle Radiation
- Electromagnetic Radiation

Radiation

- ***Non-ionizing (Excitation)***
- ***Ionizing***
  - **Direct Ionizing**
    Charged particles: e^-, e^+, p^+, α, ions, etc.
  - **Indirect Ionizing**
    Neutral Particle (n^0), Photons (γ, X)

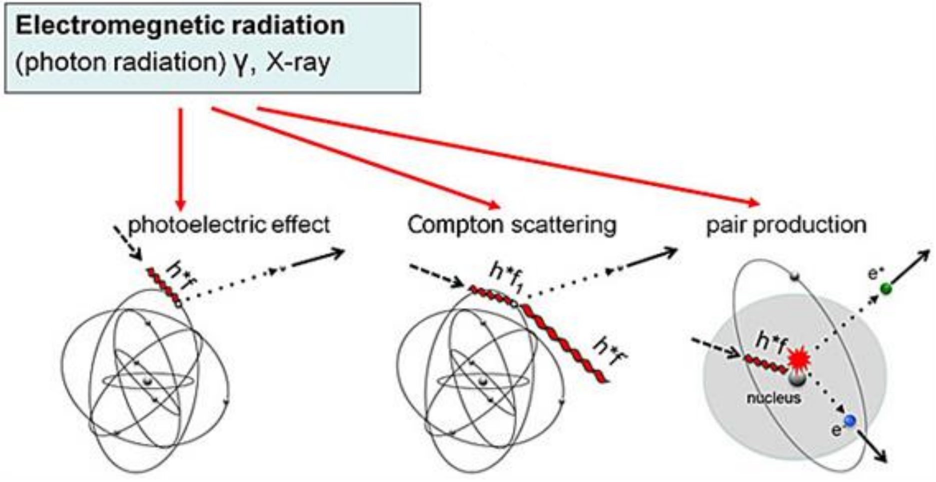
■ **Non-ionizing Radiation (excitation)**: any type of *electromagnetic (EM) radiation* that *does not carry enough energy per quantum (photon energy) to ionize atoms or molecules* - that is, to completely remove an electron from an atom or molecule.

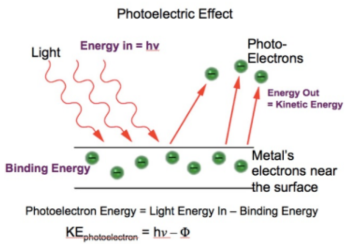
- Instead of producing charged ions when passing through matter, non-ionizing electromagnetic radiation has sufficient energy only for *excitation*, the movement of an electron to a higher energy state.

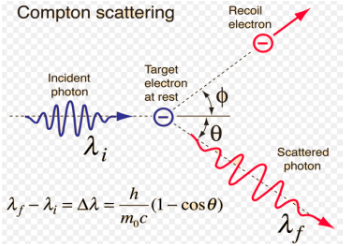
■ Types of Ionizing Radiation

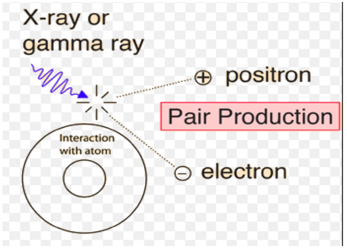
- Directly Ionizing Radiation
  - Fast Charged Particles
  - Deliver energy to matter directly
  - Coulomb interactions
- Indirectly Ionizing Radiation
  - Neutral Particle (Neutrons)
  - High energy Photons (X-rays, γ-rays): EM Radiation
  - Transfer energy to charged particles
  - Secondary charged particles deliver energy to matter

Ionizing Radiation: Electromagnetic Radiation - Photon (γ or X-ray)









Photoelectric Effect

- *The emission of electrons or other free carriers* when light falls on a material.

Compton Scattering

- *The scattering of a photon by a charged particle*, usually an *electron*: It results in a decrease in energy of the photon. Part of the energy of the photon is transferred to the recoiling electron.

Pair Production

- *The creation of a subatomic particle and its antiparticle from a neutral <u>boson</u>*.

Particle Interaction: Proton Induced Spallation Reactions in Silicon

energy level of incident particles causes the nucleus to eject
mber and its atomic number.

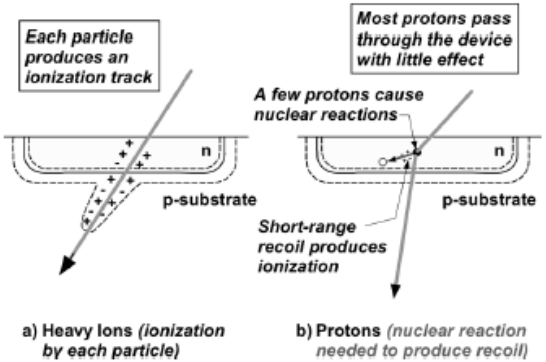


Figure 2.18: **Illustrations showing the Difference between Direct Ionisation and Spallation Reactions [Johnston and Guertin, 2000]**

Source: Sammy Kayali, Allan Johnson, et al, "Space Radiation Effects on Microelectronics," JPL, California Institute of Tech., July 2001.

	Reaction	L_{max}		L_{max}		L_{max}
(1)	$^{28}_{14}Si + ^{1}_{1}P = ^{1}_{1}P$	0.5	$+\ ^{4}_{2}\alpha$	1.5	$+\ ^{24}_{12}Na$	11
(2)	$^{28}_{14}Si + ^{1}_{1}P = ^{1}_{1}P$	0.5	$+\ ^{12}_{6}C$	6	$+\ ^{16}_{8}O$	7.5
(3)	$^{28}_{14}Si + ^{1}_{1}P = ^{1}_{1}P$	0.5	$+\ 2(^{14}_{7}N)$	6.5		
*(4)	$^{28}_{14}Si + ^{1}_{1}P = ^{1}_{1}P$	0.5	$+\ ^{4}_{2}\alpha$	1.5	$+\ ^{24}_{12}Mg$	12
(5)	$^{28}_{14}Si + ^{1}_{1}P =$ —	—	$+\ ^{4}_{2}\alpha$	1.5	$+\ ^{25}_{13}Al$	12
(6)	$^{28}_{14}Si + ^{1}_{1}P = ^{1}_{1}P$	0.5	$+\ ^{28}_{14}Si$	14		

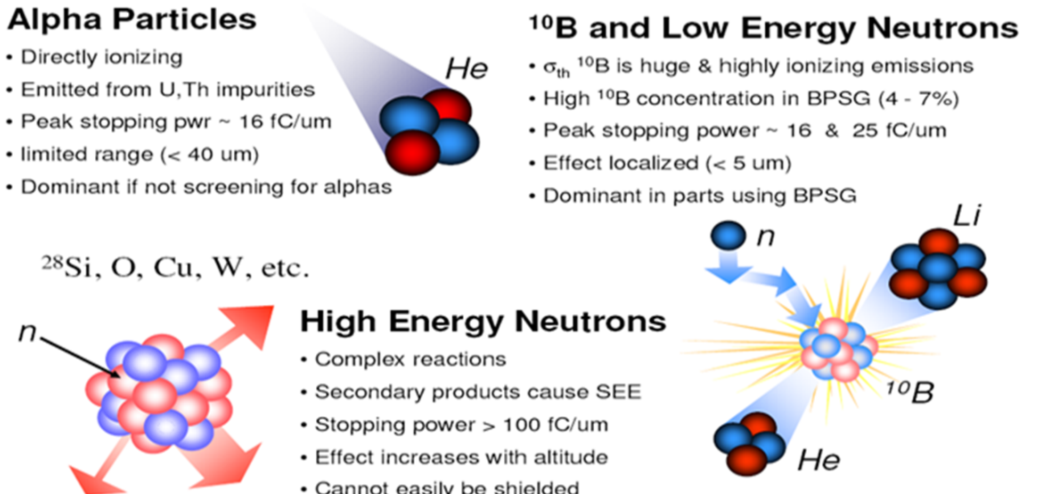
* Ex (4): $^{28}_{14}Si + ^{1}_{1}P = ^{1}_{1}P + ^{4}_{2}\alpha + ^{24}_{12}Mg$

Note: L_{max} measured in MeV cm^2/mg

Figure 2.19: Proton Induced Spallation Reactions in Silicon [Messenger and Ash, 1997]

Ionizing Radiation: Particle Radiations

- **Charged Particles (α, β)**: interact strongly and ionize directly → **Direct Ionizing Radiation**
- **Neutral Particle (Neutron): Indirect Ionizing Radiation**
  - A neutron collides with a proton of the target material, and then becomes a fast recoil proton that ionizes in turn. At the end of its path, the neutron is captured by a nucleus in an (n, γ)-reaction that leads to the emission of a neutron capture photon. *Such photons always have enough energy to qualify as ionizing radiation*.
  - High energy neutrons (cosmic ray byproducts, E > 1 – 10 [MeV])
  - Low energy neutrons (thermal): Indirect interaction via the ${}^{10}_{5}B(n,\alpha){}^{7}_{3}Li$ nuclear reaction



Source: QRT

Common Neutron Capture Reaction

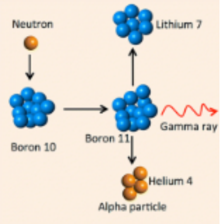
Reaction	Neutron Energy
(n, γ)	0 – 500 [keV]
(n, p) (n, α)	0.5 – 50 [MeV] 0.5 – 50 [MeV]
(n, $2n$) (n, np) (n, $2p$)	1 – 50 [MeV] 1 – 50 [MeV] 1 – 50 [MeV]
Fission	Thermal to Fast

Neutron Energy vs. Reaction: In B and Si

Fission by Thermal Neutron

$$ {}^{10}_{5}B + n \rightarrow {}^{7}_{3}Li + \alpha \quad (Qvalue = 2.792MeV, ground\ state) $$

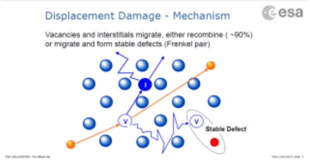
$$ {}^{10}_{5}B + n \rightarrow {}^{7}_{3}Li^{*}\,(0.84MeV) + \alpha(1.47MeV) + \gamma\,(0.478MeV) \quad (Qvalue = 2.310MeV, excited\ state) $$



Displacement Damage by High Energy Neutron

$E_{DT,n,Si}$ = Si의 Displacement Threshold Energy @ Neutron = 25eV

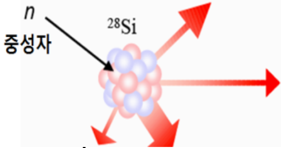
→ Total NIEL Dose = $\int_{E_{DT,N,Si}}^{E_{max}}$ NIEL(E) × Spectral Fluence(E) dE



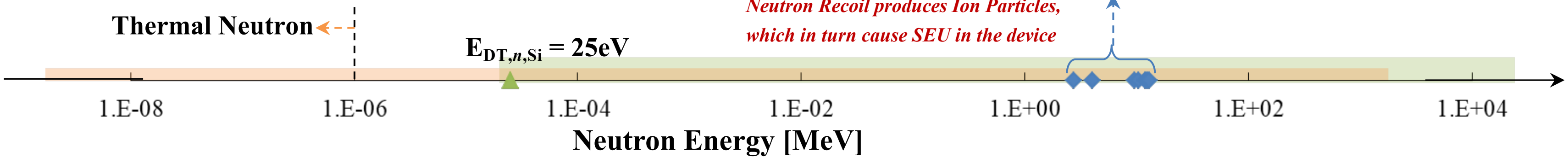
Fission by High Energy Neutron

Reaction Products and Threshold Energy For Neutron Reactions in Silicon

Reactions	Threshold Energy (MeV)
$n + {}^{28}_{14}Si \rightarrow \alpha + {}^{25}_{12}Mg$	2.75
$n + {}^{28}_{14}Si \rightarrow p + {}^{28}_{13}Al$	4.00
$n + {}^{28}_{14}Si \rightarrow d + {}^{27}_{13}Al$	9.70
$n + {}^{28}_{14}Si \rightarrow n + \alpha + {}^{24}_{12}Mg$	10.34
$n + {}^{28}_{14}Si \rightarrow n + p + {}^{27}_{13}Al$	12.00
$n + {}^{28}_{14}Si \rightarrow {}^{26}_{12}Mg + {}^{3}_{2}He$	12.58
$n + {}^{28}_{14}Si \rightarrow 2\alpha + {}^{21}_{10}Ne$	12.99



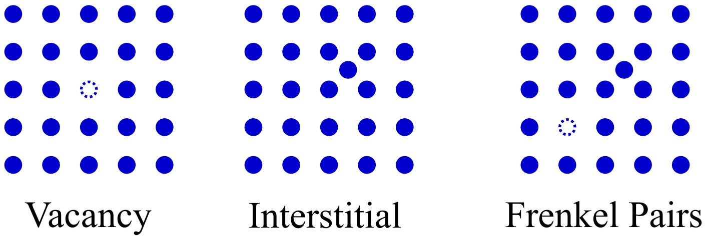
Neutron Recoil produces Ion Particles, which in turn cause SEU in the device

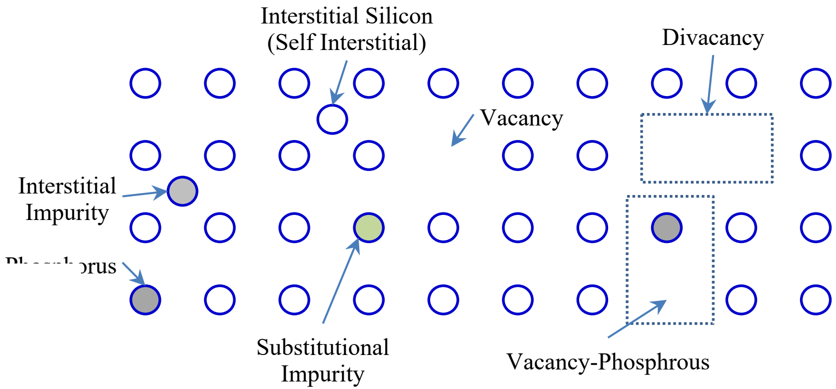


✓ **Effects depend on neutron energy distribution**

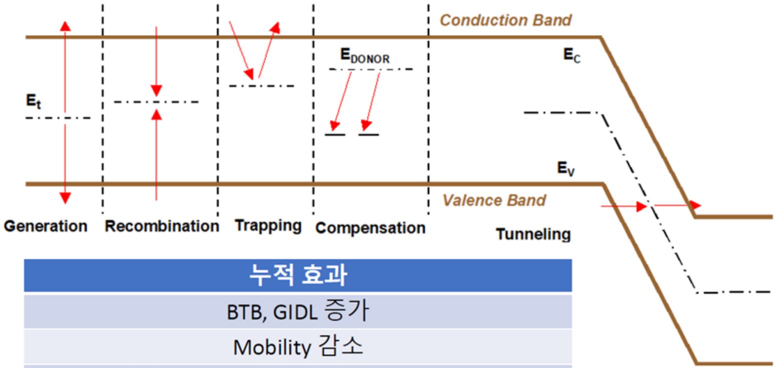
Particle Interaction: Displacement Damage

■ **Defects Structures**: Frenkel Pairs, Complex Defects





트랜지스터에서 실리콘 변위 효과



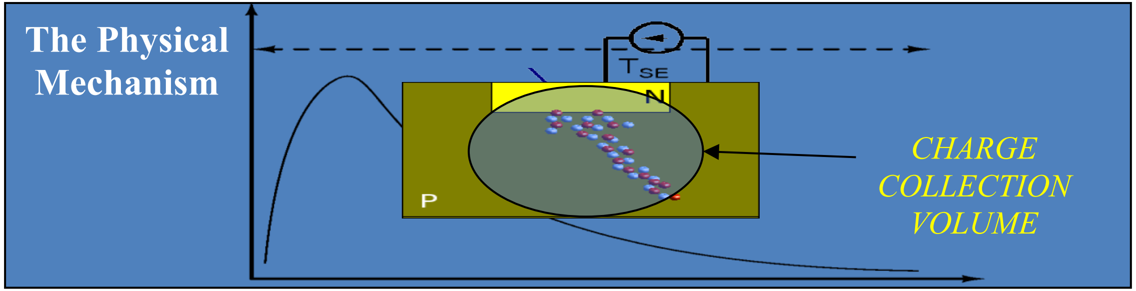
누적 효과
BTB, GIDL 증가
Mobility 감소
마이크로 스위치 (팝콘/blinking/VRT)
Stuck bit

Source: 세미나 자료 (J.W. Han, 2019.09.10)

SEE (Single Event Effects): A Description

What you always wanted to know about Single Event Effects (SEE's)

- *What are they?:*
  One of the result of the interaction between the radiation and the electronic devices
- *How do they act?:*
  Creating free charge in the silicon bulk that, in practical, behaves as a short-life but intense current pulse
- *Which are the ultimate consequences?*
  From simple bit-flips or noise-like signals until the physical destruction of the device



– The incident particle generates a dense track of electron hole pairs and this ionization cause a transient current pulse if the strike occurs near a sensitive volume.

Source: Raoul Velazco (TIMA), "Single Event Effects Basic," Automotive Semiconductor Safety Innovation Conference 2019. [QRT 제공]

SEE (Single Event Effects): Classification

SEE's

SEE: Disturbance of an active electronic device caused *by a single energetic particle*

Trigger of Destructive Mechanisms

Trigger of Non Destructive Effects

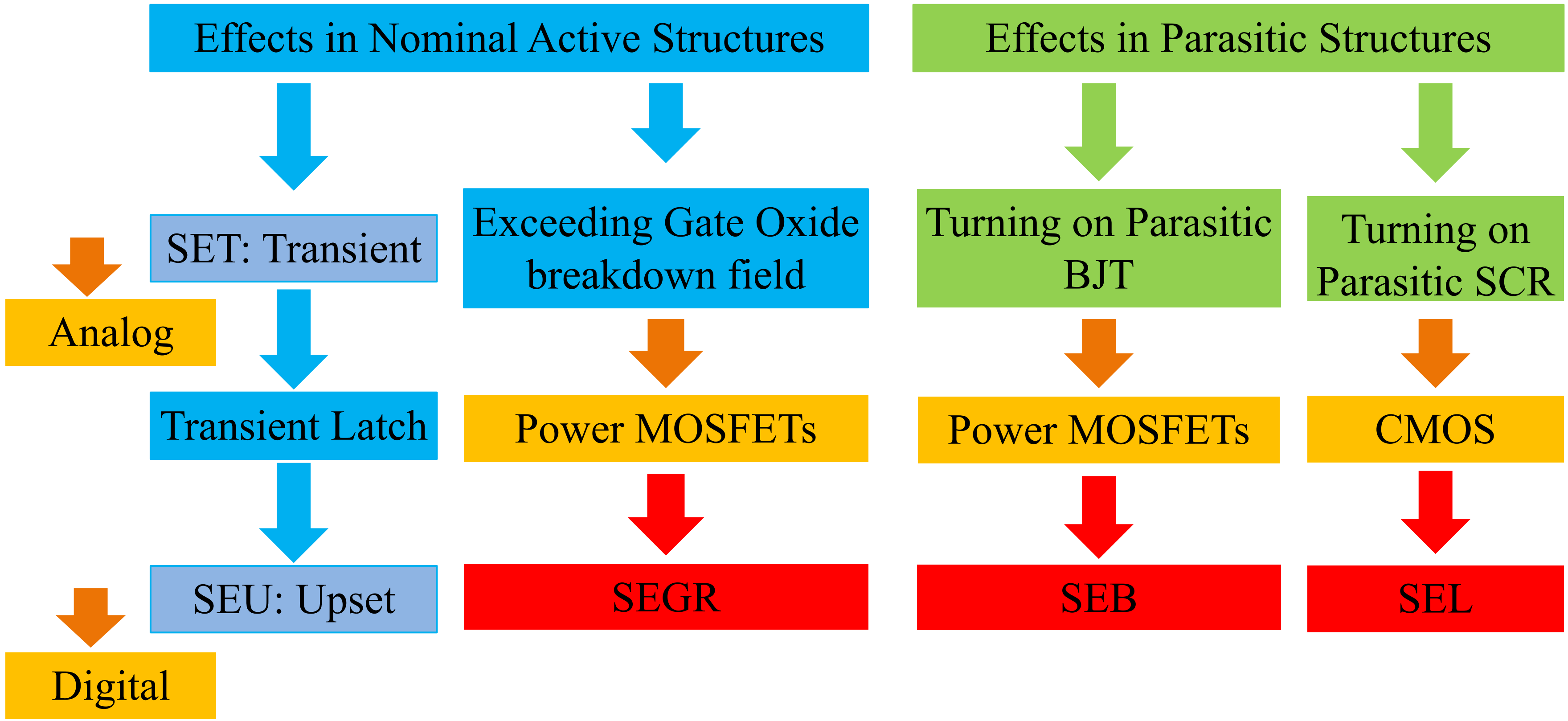
- Trigger of Destructive Mechanisms (Hard Errors)
  - SEL (Single Event Latchup): an event where the device has an abnormal conduction path established by ionizing radiation leading to an input current change (sharp increase in current). PNPN Structure in CMOS Bulk
  - SEB (Single Event Burnout): Damage or burnout of power transistor or other high voltage device
  - SEGR (Single Event Gate Rupture): Power MOST, IGBT

- Trigger of Non Destructive Effects (Soft Errors)
  - SET (Single Event Transient)
  - SEU (Single Event Upset): change in logic state, simplest example is a memory cell in RAM
  - SBU (Single Bit Upset), MBU (Multiple Bit Upset)
  - SEFI (Single Event Functional Interruption): malfunctions in more complex parts sometimes as lockup, hard error, *etc*.

❖ Many of CND (Can Not Duplicate) and NTF (No Trouble Found) from customer returns (RMA) for service are due to various soft errors

- <ins>Power devices</ins> do not follow down-scaling dimensions and voltages: they exhibit larger sensitivity to neutron-induced effects, even at sea level.

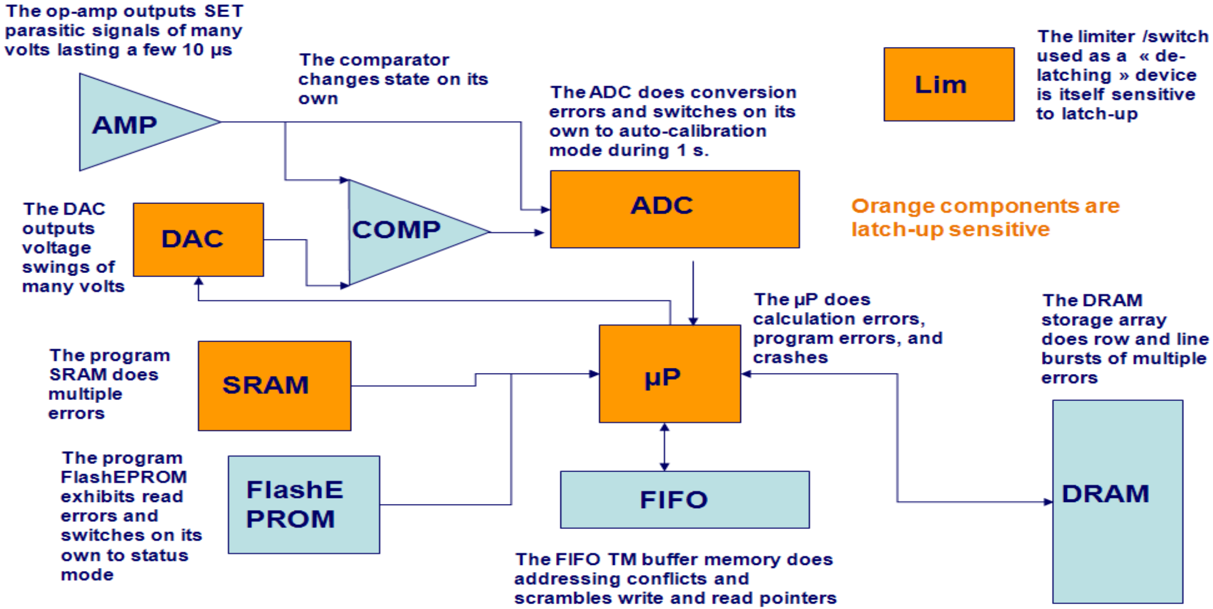
Single Event Effects in Semiconductor



Source: Robert Ecoffet (CNES), “Anomalies associated with radiation effects and the role of space agencies,” CERN Seminar, June 10, 2014. [QRT 제공]

Classical SEE Effects

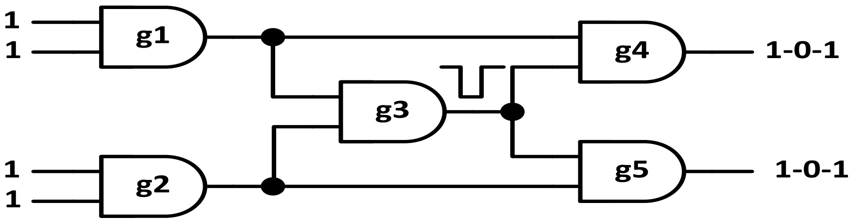
- Memory corruption: single errors to error bursts
- Processor crash
- Mode swapping
- Reset
- Switch-off
- ADC conversion errors
- ADC swapping to autocal. mode
- Gain change
- Reference voltage change
- VCO output frequency change
- Transient PLL lock loss
- False signals
- Star pattern loss
- Image corruption
- ....
- Equipment loss

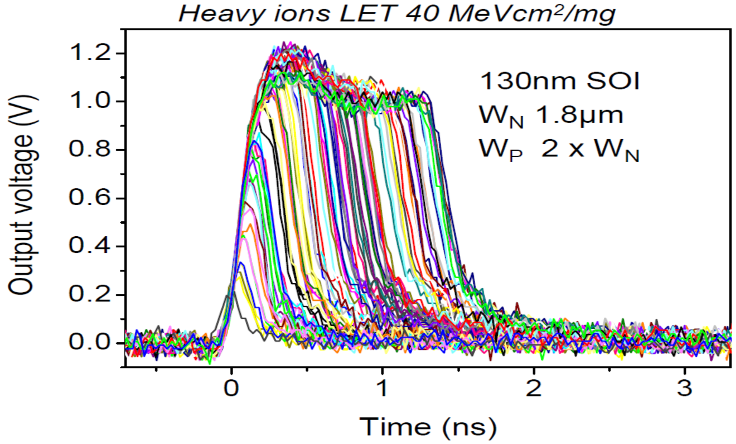


Source: Robert Ecoffet (CNES), “Anomalies associated with radiation effects and the role of space agencies,” CERN Seminar, June 10, 2014. [QRT 제공]

Single Event Transient (SET) in Logic Circuits

- **Logic circuits are shrinking physical size, reducing supply voltage and running higher operating frequency**
  - Extremely narrow noise margin makes single event transient start to impact logic circuit and circuit line
- **SET: radiation particle deposit current in a combinational circuit node**
  - Can be modeled at gate level as erroneous transition on the gate output





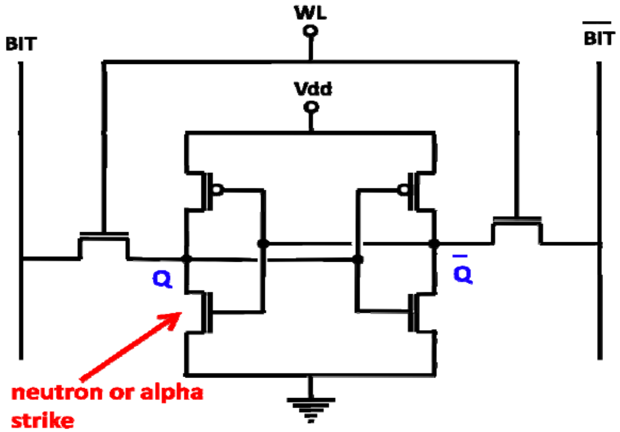
O. Goloubeva, M. Rebaudengo, M. Sonza Reorda, and M. Violante, “Software-Implemented Hardware Fault Tolerance,” 1st ed. Springer, 2010. [QRT 제공]
Véronique Ferlet-Cavrois, "Single Event Transients in Digital Circuits", 3rd RADECS Thematic Workshop on “Single Event Transient”, Jan. 29, 2009.

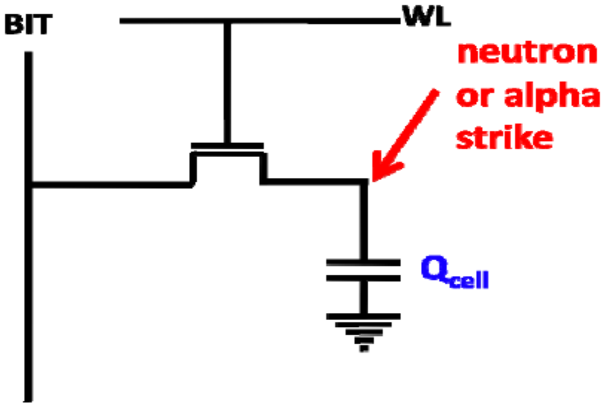
Single Event Upset (SEU) in a Memory

- **SRAM: If charge generated by alpha particle or neutron is large enough (Q_{crit}), cell is flipped**

  → ***bit-flip error !***

- **DRAM: Excess charge generated by alpha particle or neutron can**
  - discharge cell capacitor
  - upset sense amp during read/write operation
  - upset various logic/control circuits





Source: Charles Slayman, "Soft Error Trends and Mitigation Techniques in Memory Devices", 2011

Mitigation of SEE's

- **First Option: Removal of widely-used BPSG layer**
  - Used for planarization between metallic layers
  - If removed, the chance of SEUs is 8 - 10 times lower
  - The use of PSG process is recommended
    - If this removal is not possible, the SEU occurrence can be reduced by means of:
      - Boron purification: Only 20% of natural boron is ^{10}B, the rest being ^{11}B, insensitive to neutrons
      - Cover the IC with a 3-mm B_4Si_3 layer, which absorbs most neutrons and emits alpha particles far from the critical nodes
- **Second Option: Redesign the IC in SOI technology**
  - SOI technology has a tolerance of the order of five times higher than that of same typical length bulk technology
- **Third Option: Managing the doping profile. If SOI technologies are not available**
  - The doping profile can be modified to create wells
    - Thus, the charge collection area shrinks
    - The drawback is that there must be an additional layer as well as an extra thermal cycle… to reduce the sensitivity only to 25 - 50 [%]
- **Fourth Option: Hardening by Design Strategies (w/ Redundancy)**

Source: Raoul Velazco (TIMA), "Single Event Effects Basic," Automotive Semiconductor Safety Innovation Conference 2019. [QRT 제공]

The End

Radiation Related Quantities

Activity (A)

- the activity per quantity of a radionuclide and a physical property of that radionuclide
- **Becquerel (Bq)**: the activity of a quantity of radioactive material in which one nucleus decays per second.

Radiation Exposure (X)

- a measure of the ionization of air due to ionizing radiation from photons; that is, gamma rays and X-rays
- the electric charge freed by such radiation in a specified volume of air divided by the mass of that air
- As a measure of radiation damage exposure has been superseded by the concept of absorbed dose.

Absorbed Dose (D)

- a dose quantity which is the measure of the energy deposited in matter by ionizing radiation per unit mass
- **Gray (Gy)**: one Joule of energy absorbed per Kg of matter

Equivalent Dose (H)

- a physical quantity absorbed dose, but takes into account the biological effectiveness of the radiation
- $H_T = \sum_R W_R D_{T,R}$
  - H_T is the equivalent dose in sieverts (Sv) absorbed by tissue T
  - $D_{T,R}$ is the absorbed dose in grays (Gy) in tissue T by radiation type R
  - W_R is the radiation weighting factor defined by regulation
- **Sievert (Sv)**: a measure of the health effect of low levels of ionizing radiation on the human body

Quantity	Unit	Derivation
Activity (*A*)	becquerel	s^{-1}
	curie	$3.7 \times 10^{10}\ s^{-1}$
	rutherford	$10^6\ s^{-1}$
Exposure (*X*)	coulomb per kilogram	$C{\cdot}kg^{-1}$ of air
	röntgen	esu / 0.001293 g of air
Absorbed dose (*D*)	**gray**	$J{\cdot}kg^{-1}$
	erg per gram	$erg{\cdot}g^{-1}$
	rad	$100\ erg{\cdot}g^{-1}$
Dose equivalent (*H*)	sievert	$J{\cdot}kg^{-1} \times W_R$
	röntgen equivalent man	$100\ erg{\cdot}g^{-1}$