Working on the developing of a European standard for DD testing

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retour sur innovation

Context 1/3

- Some guidelines already exist
  - Total dose (ESCC 22900, MIL-STD-883G, method 1019.9)
  - Single events (ESCC 25100)
  - Some documents exist for displacement damage
    - Proton testing in general (“Proton Test Guideline – lessons learned” NASA NEPP document),
    - Displacement damage for imaging devices (“Displacement Damage Guideline,” ESA document 0195162),
    - But no equivalence to other test activities

⇒ Need of displacement damage guidelines

Context 2/3

- Why is there a lack of standardisation for displacement damages?
  - Do not concern all the device types
    - Mainly devices that interact or emit optical radiation (photonic or optoelectronic devices)
    - but also some other device types (bipolar transistors)

    ⇒ limited list of device types

  - Wide range of materials (Silicon, GaAs, InGaAs, HgCdTe, InSb (Infrared detectors)
    - Wider domain of study

    ⇒ More complex to interpret the result

  - Available literature not as large as for TID and SEE
    - Lesser technological interest
    - Difficulties in device testing (dedicated optical equipments, time consuming measurements)
    - High cost of devices

Context 3/3

- Goal of the study
  - Propose a DD test standard
  - Should be available by the end of the year after ESA and Components Technology Board (*CTB*)/Radiation Working group (*RWG*) comments

- Goal of this presentation

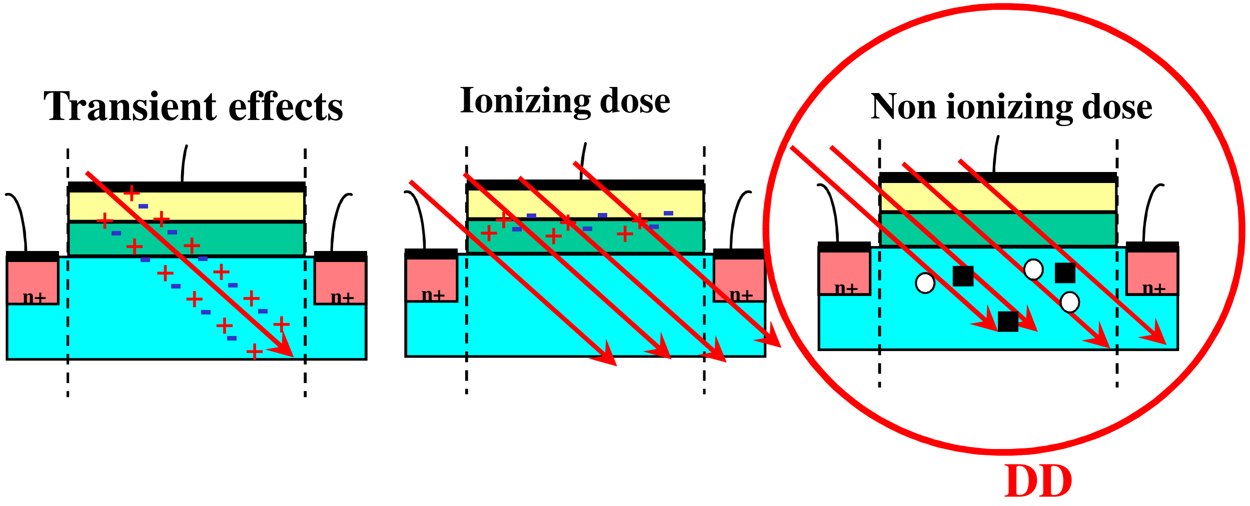
  ⇒ Not a draft of the future guidelines, but:
  - Remind the physical processes responsible of the displacement damages
  - Remind the electrical effects
  - List the main parameters that should be taken into account

Outline

- Displacement damage (DD) causes and effects
  - Particle-matter interaction
  - Displacement damage main effects
  - Introduction to NIEL parameter

- Key parameters for a displacement damage guideline from pre- to post-irradiation
  - Measured parameters,
  - Irradiation and dosimetry
  - Bias and annealing
  - …

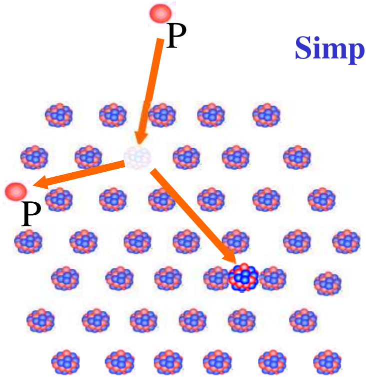
Energy transfer from particle to matter



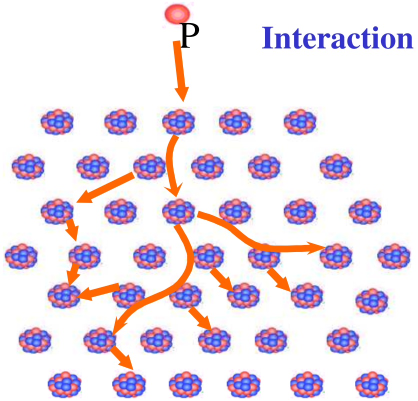
- Particle slowed down by transfering energy to the matter
- Main part of the deposited energy is ionisation (interaction with the electrons), the rest is atomic displacements (interaction with the nuclei)
  - Fraction depends on particle type and energy, target material
  - Fraction decreases when the energy increases
- Displacement damage: degradation in the bulk of the device

Particle matter interaction for DD

Atomic Displacements: example of proton irradiation

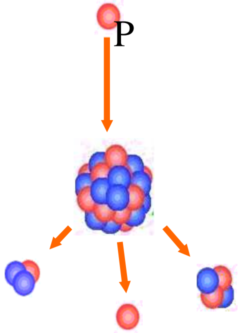


Simple Frenkel pair



Interaction cascade

Spallation



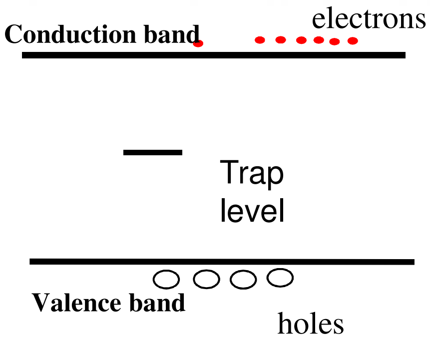
- 3 main interaction types, different energy transfers
  - Coulombian
  - Nuclear elastic
  - Nuclear inelastic

↓ Increasing transfered energy to the Primary Knock-on Atom and cascade size

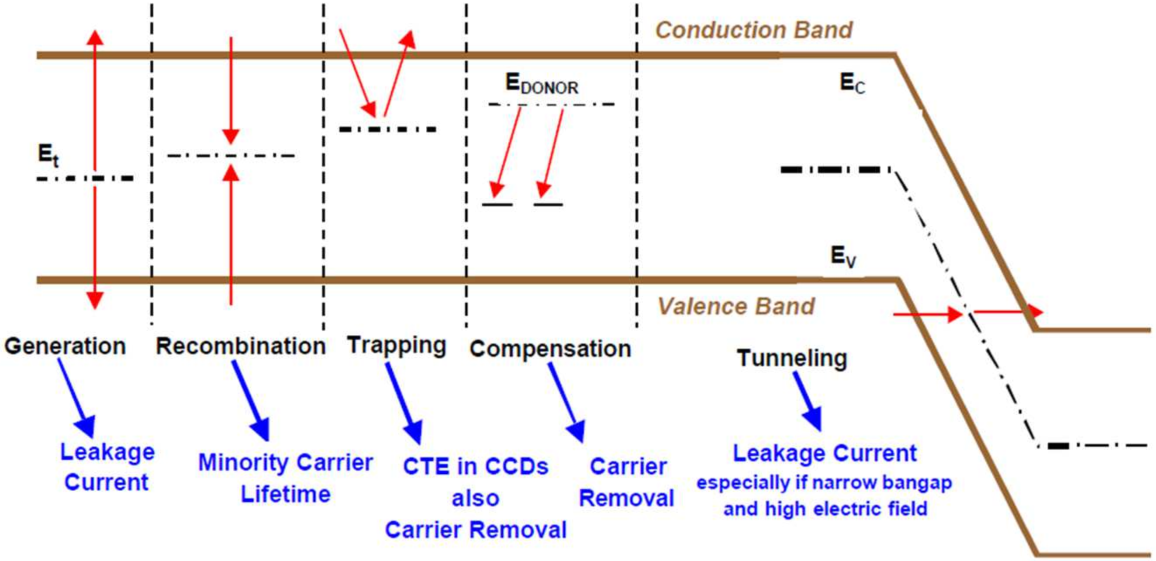
- Consequence
  - Single displaced atom or interaction cascade
  - Creation of Frenkel pairs (vacancy-interstitial pairs) or more complex lattice defects (high concentration of deposited energy)
  - Reorganisation of these pairs into stable defects. Phase of "annealing"
  - Introduction of levels in the gap that modify the electrical properties of semiconductors

Degradation mechanisms

- Some parameters define the defect
  - The position in the gap (energy level)
  - The capture cross sections
  - The emission rates



- The electrical effect depends on
  - The defect density (degradation) and their parameters
  - The carriers' concentration (state of the device)



G. Hopkinson, RADECS short course, 2003

Exemples of sensitive devices

- Solar cells
  - Output power
  - Short circuit current
  - Open circuit voltage

- Photodetectors
  - Leakage current (dark current),
  - Dark current non uniformity (DCNU) for arrays
  - Charge Transfer Efficiency (CTE) (CCDs)
  - Random Telegraph Signal (RTS)

- Bipolar transistors
  - Base current increase
  - Gain decrease

- Optocouplers
  - Ratio between input and output current (CTR) due to transistor and LED degradation

- LED
  - Light output decrease

- Laser Diodes
  - Thershold current increase

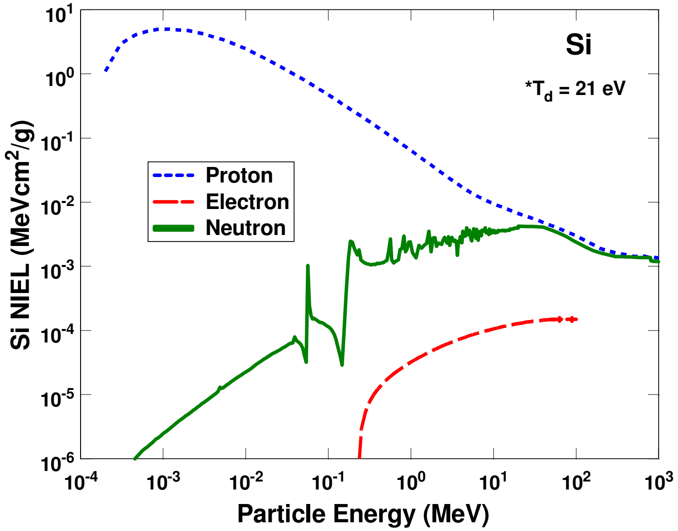
Non Ionizing Energy Loss (NIEL)

- NIEL
  - Rate at which energy is lost to displacement
  - Analogous to LET or stopping power for ionizing irradiation
  - Unit MeV.cm²/g
  - Depends on the target material, the particle type and energy
  - **NIEL is a mean parameter**

$$\mathrm{NIEL(E)} = \frac{\eta}{\rho} \int_{T_d}^{T_{\max}} \left(\frac{\partial \sigma}{\partial T}\right) \mathrm{T.L(T)}\, dT$$

Differential cross section

Lindhardt fraction



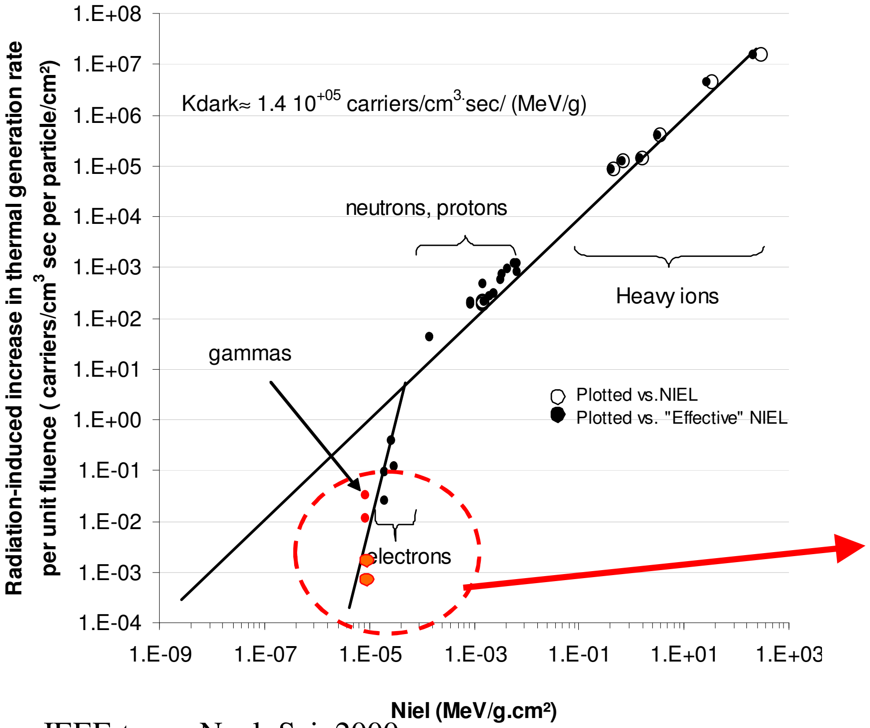
- The displacement damage dose (DDD)
  - For a monoenergetic irradiation: the product of the NIEL and the fluence
  - For a spectrum of energy

$$\mathrm{DDD} = \int_{E_{\min}}^{E_{\max}} \left(\frac{\partial \Phi}{\partial E}\right) \mathrm{NIEL(E)}\, dE$$

- The NIEL and the DDD are used for correlating the displacement damages
  - Various degradation models of electrical parameters with the DDD (linear, log…)
  - Evaluate the degradation for a mission (spectrum) supposes
    - An equivalence of the degradation from energy to energy using a damage factor
    - Correlation between the damage factor and the NIEL

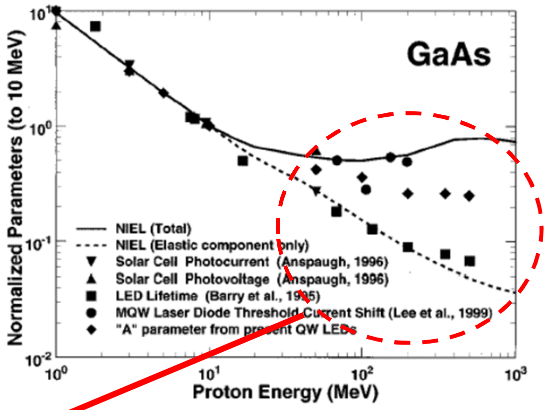
  ⇒ A good knowledge of the NIEL

NIEL scaling law observed deviations



Srour IEEE trans. Nucl. Sci. 2000

Walters et al. IEEE Trans. Nucl. Sci., vol. 48, pp. 1773-1777, 2001



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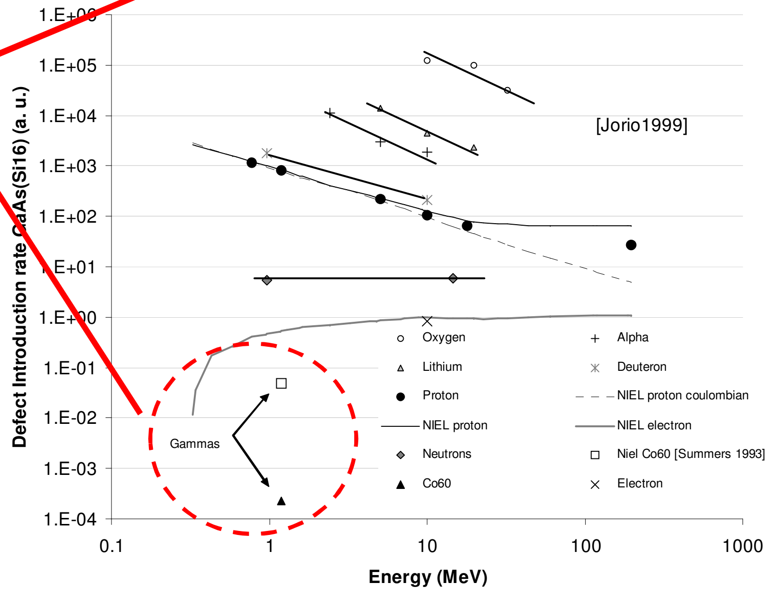
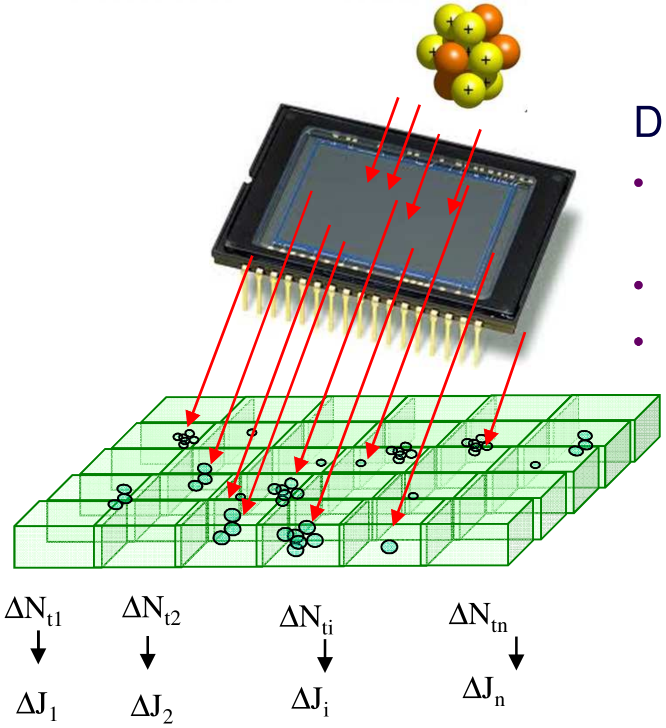


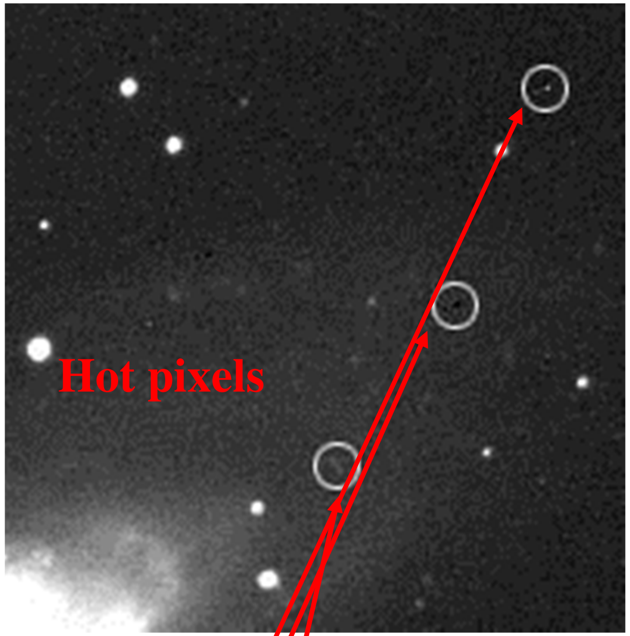
NIEL for electrons ?
NIEL for gammas ?
Protons > 50 MeV in GaAs ?
Other materials (AlGaAS, InP, GaInP) ?
Different electrical parameters ?

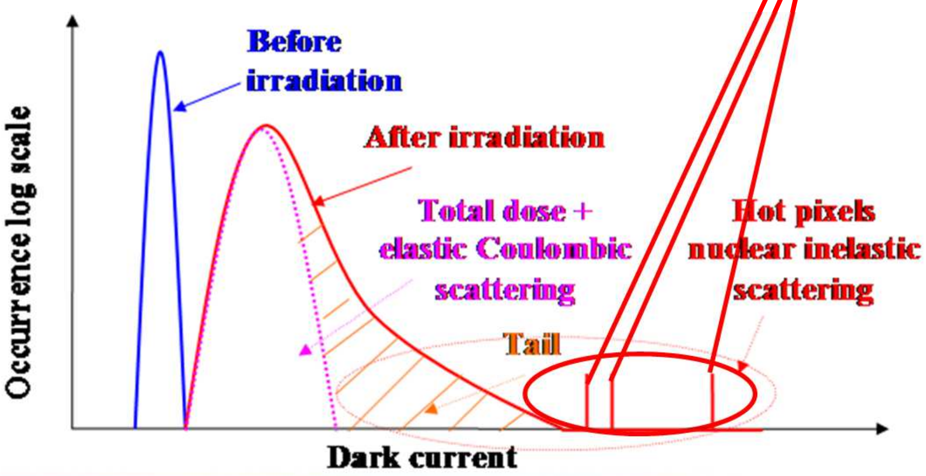
Limit of the NIEL: DCNU (Dark Current Non Uniformity) in Image sensors

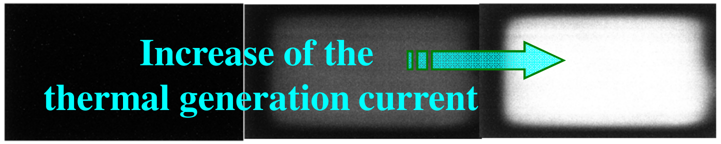


Distribution of deposited energy

- Increase of the mean dark current
- Increase of DSNU
- Introduction of spikes (hot pixels)







Points to clarify in order to perform a test 1/3

- Before irradiation
  - Particle type and energy
    - Protons versus neutrons, electrons
    - Relevance / equivalence for the mission
    - Range issues
    - One energy (which one), several energies, spectrum

  - Fluence
    - Have relevant NIEL data for an equivalent DDD
    - margins

  - Parameters to measure
    - Sensitivity to displacement damages
    - Depends on the component type (e.g. imagers, optocouplers, LED, laser, photodiode…)
    - Conditions of measurement (temperature, levels…). Care should be taken when conditions change

  - Number of samples
    - Part-to-part and Lot-to-lot variations
    - Samples preparation

Points to clarify in order to perform a test 2/3

- During irradiation
  - Bias conditions
    - Impact of bias on the degradation

  - Dosimetry requirements in term of accuracy
    - Energy (ex. straggling for degraded beams)
    - Flux and fluence
    - Beam uniformity

  - Irradiation temperature
    - Accuracy
    - Relevance of room temperature for low temperature application

  - Need of intermediate measurements?
    - Evaluate the response with the fluence and/or the DDD: concept of damage factor
    - Caution: damage factor could depend on measurement conditions and time after irradiation

  - Flux effect?

Points to clarify in order to perform a test 3/3

- After irradiation
  - Delay between irradiation and measurement
    - Annealing considerations
    - Activation of the devices
    - Availability of the test equipment on the irradiation site
  - Storage conditions between irradiation and measurement
    - Prevent unexpected annealing effects
    - Bias conditions
    - Temperature

Conclusion

- Interests of DD guidelines
  - Help the people in charge of test
    - Definition
    - Conduction
    - Interpretation
    - Comparison
  - Hardness assurance tool
    - Should ensure a worst case of degradation
  - Trade-off between knowledges and technical constrains