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Displacement Damage Effect assessment :

a discussion about the NIEL scaling approach

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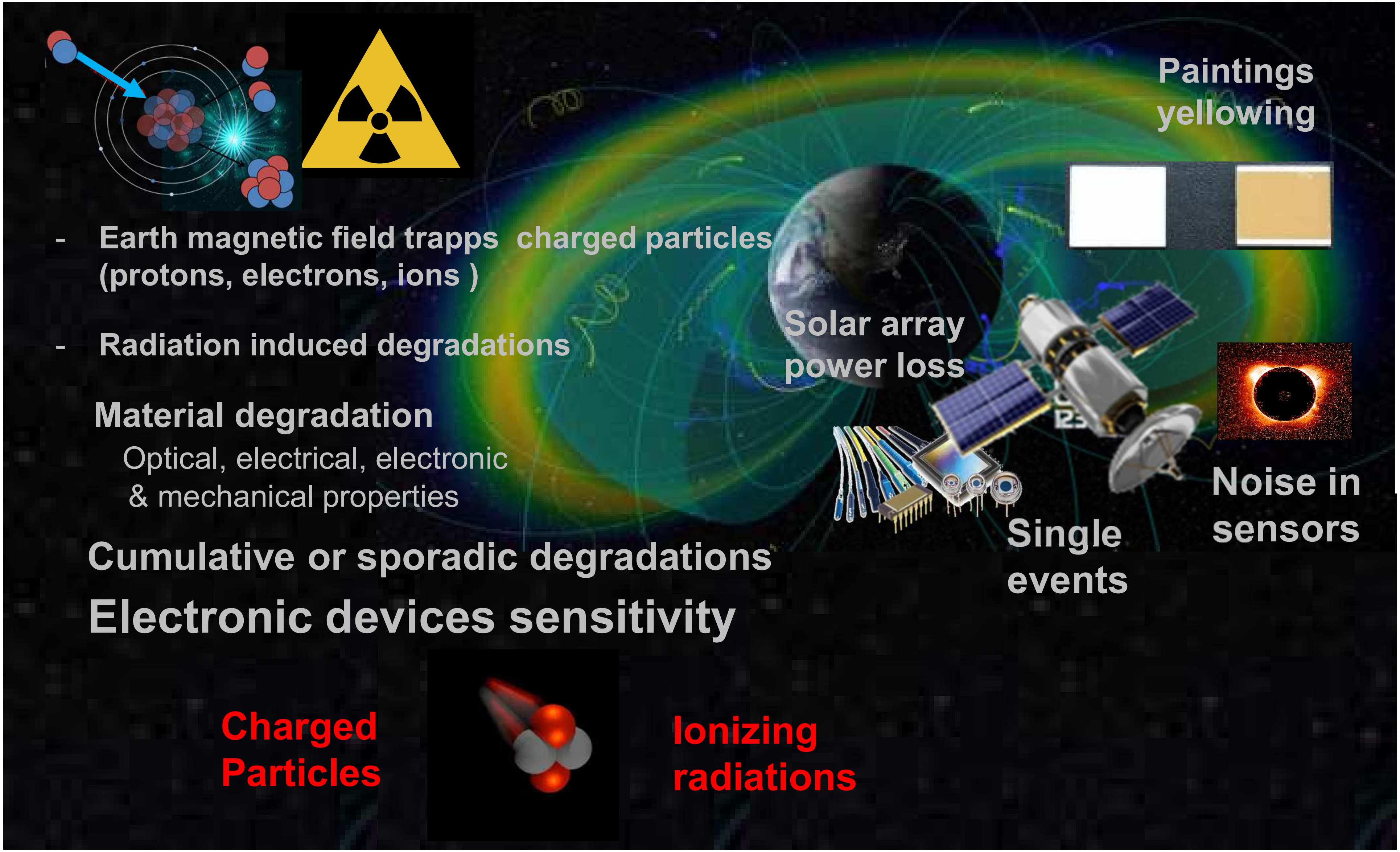
RADOPT
29-30 Nov 2023
ISAE - Toulouse

OUTLINE

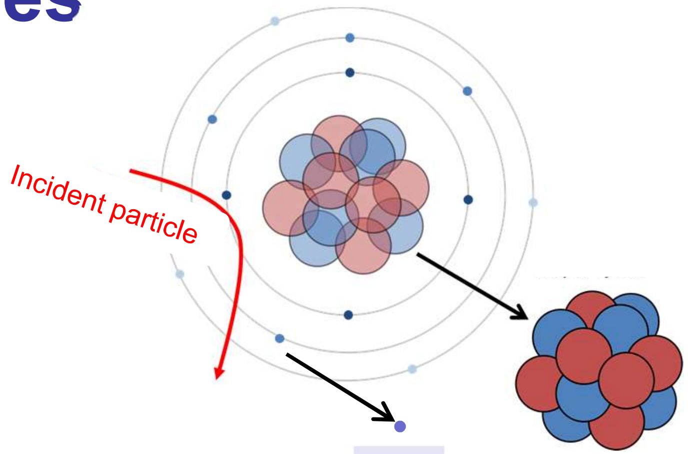
- Radiative space environment
- DOSE to quantify degradations
- Energy loss by unit path length : NIEL
- NIEL scaling approach
  - Relevance and observed deviations
- Conclusion & Perspectives

Natural and anthropic radiation environment

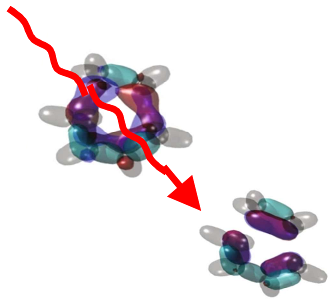


Slowing down of incident particles

Slowing down = interactions with
electrons & nuclei



Electrons and nuclei are put into motion



Broken atomic bounds

Degradation (proportional to the number of interactions)

Each interaction = ENERGY LOSS

DOSE

DOSE & Energy loss by unit of length

Dose = deposited energy by unit of mass of the medium

$$\phi$$

Number of incident particle

Deposited energy

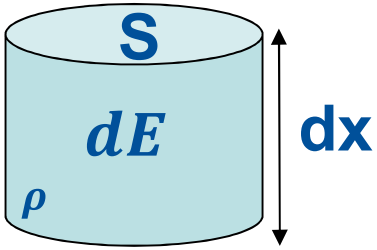
$$Dose = N\frac{dE}{(\rho S dx)}$$

Density of the irradiated volume

Irradiated volume

Mass of the irradiated volume

$$Dose = \phi \frac{1}{\rho}\frac{dE}{dx}$$

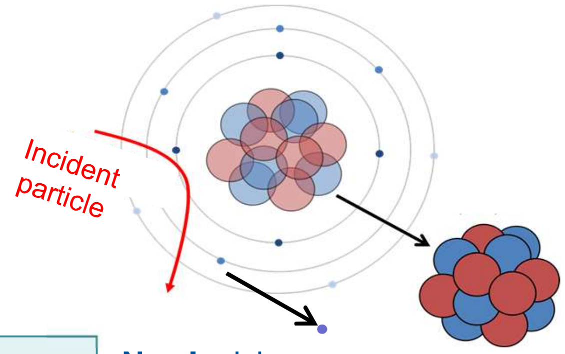


$$Degradation \propto Dose$$

$$\frac{Degradation}{\Phi} \propto \frac{dE}{dx}$$

Displacement damage a specific radiation induced damage of optoelectronic devices

$$\frac{dE}{dx}\Big)_{Total} = \frac{dE}{dx}\Big)_{Electronic} + \frac{dE}{dx}\Big)_{Nuclear}$$



TID
Ionizing Dose = ϕ x LET

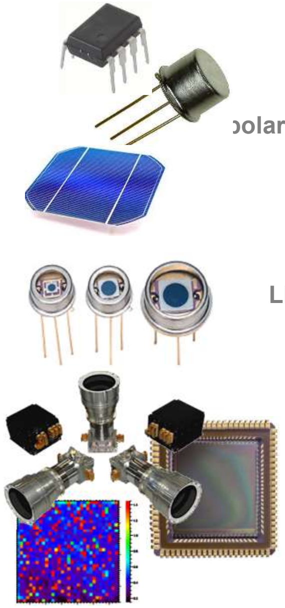
DDD
Displacement Damage Dose = ϕ x **NIEL**

Non **I**onizing **E**nergy **L**oss

NIEL scaling approach

Degradations relatated to atomic displacements by unit of fluence proportionnal to the NIEL

Displacement damage a specific radiation induced damage of optoelectronic devices



Optocoupler (charge transfer ratio (CTR) degradation)

Bipolar and III-V transistors (gain degradation & increased leakage currents)

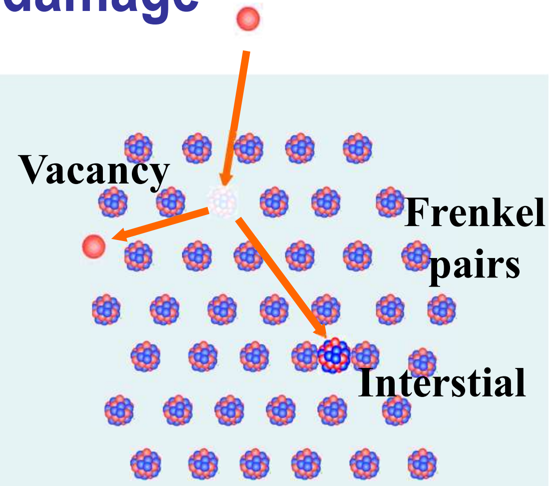
Solar array (power loss)

LED & Laser diodes (light output degradation)

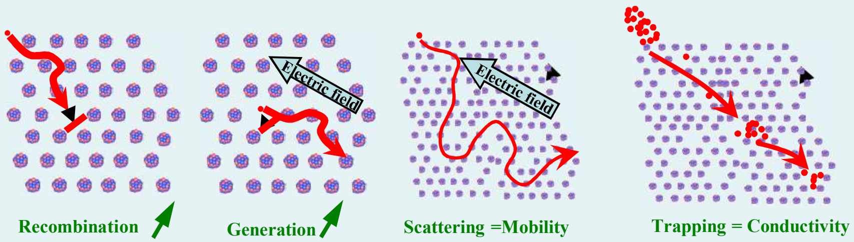
Photodiode (photocurrent loss & dark current increases)

Dark current non uniformity In image sensors

Electrical active defects that modify the Physical properties of semiconductors



Trapping → Conductivity reduction
Recombination → Mobility reduction
Carrier generation → Noise increase

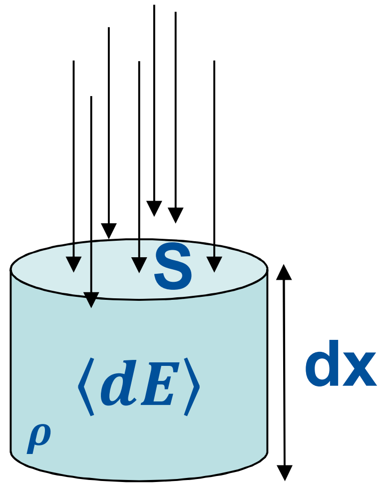


NIEL scaling approach

BUT the relevance of the degradation prediction lays on the accuracy NIEL

NIEL : an average parameter

$$DDD = N\frac{1}{\rho S}\frac{\langle dE\rangle}{dx}$$



Each incident particle deposit a different energy

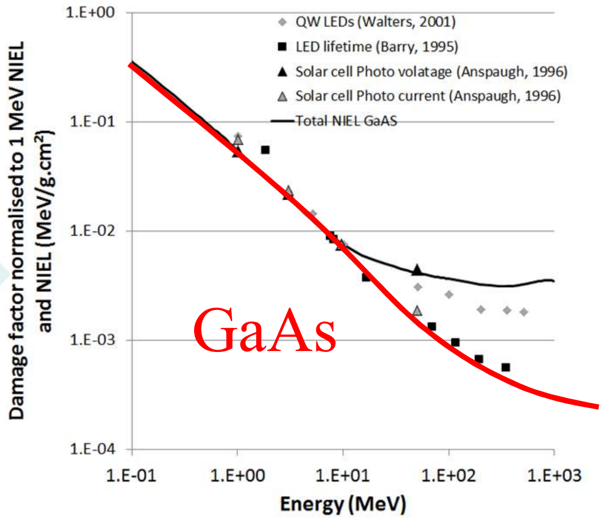
DDD and NIEL make sense only for a large number of interactions in a way that the DDD is proportional to the total deposited energy

Degradation vs. applied fluence

$\Phi = 10^{+09}$ protons/cm²
V = 100µmx100µmx10µm

	Number of interactions		
E	Coulombian	nuclear elastic	nuclear inelastic
MeV	mm	mm	mm
1	10000.0	2.2	
10	1100.0	0.4	0.6
60	190.0	1.0	0.3
100	115.0	0.9	0.3
200	57.5	0.5	0.2
300	42.5	0.5	0.2

Number of interaction ~<1



Damage factor
Coulombian dependence
For protons

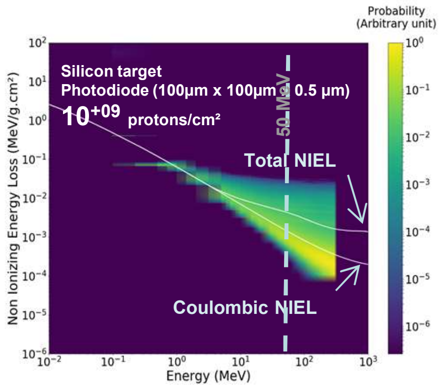
Si, GaAs, InGaAs

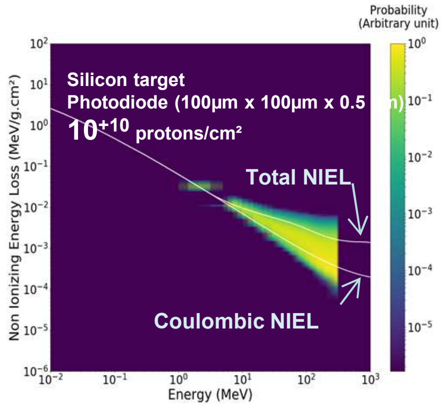
NIEL is an average parameter which makes sense only if sufficient fluence has been applied

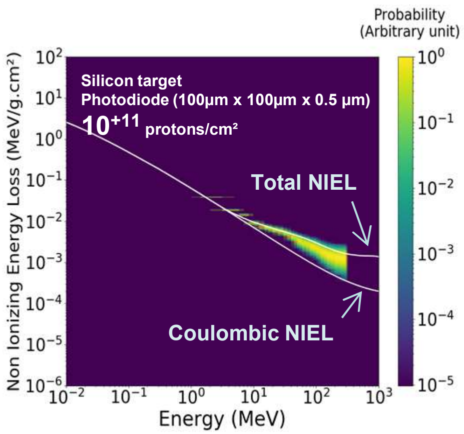
At low fluence level NIEL OVERESTIMATES the degradation

G. P. SummersIEEE Trans. Nucl. Sci., vol. 35, no. 6, pp. 1221-1226, Dec. 1988.
A. L. Barry, IEEE Trans. Nucl. Sci., vol. 42, no. 6, pp. 2104–2107, Dec. 1995.
B. E. Anspaugh., "GaAs Solar Cell Radiation Handbook", JPL Pub. 96-9, July, 1996
R. J. Walters, "IEEE Trans. Nucl. Sci., vol. 48, no. 6, pp. 1773–1777, Dec. 2001.

Degradation vs. applied fluence



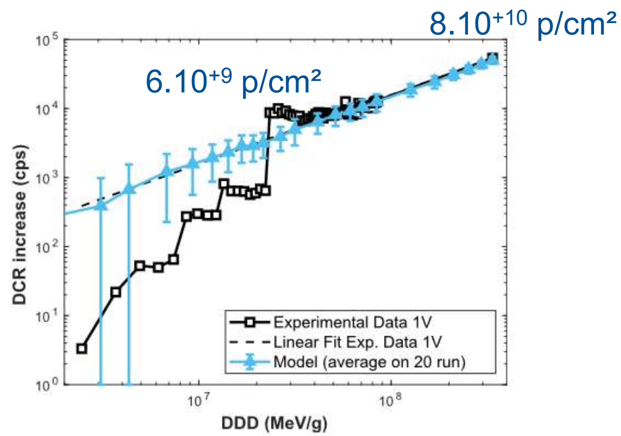




C. Inguimbert, et al. "Statistical spread on the displacement damage degradation of irradiated semiconductors," Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, vol. 490, pp. 7–17, Mar. 2021, doi: 10.1016/j.nimb.2021.01.002.

The most probable damage level of a device irradiated with a low fluence is lower than the NIEL explaining some deviations reported in the litterature

Experimental confirmation

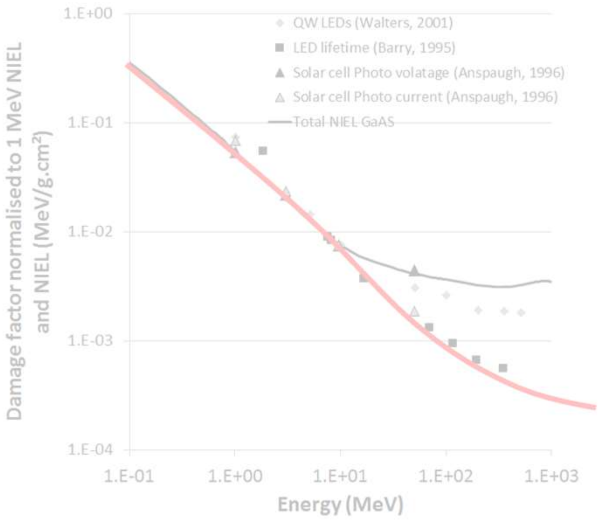


900 x 5µm x 5µm x ~1nm

Ali Jouni et al.
Proton-Induced Displacement Damages in 2-D and Stacked CMOS SPADs: Study of Dark Count Rate Degradation IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 70, NO. 4, APRIL 2023

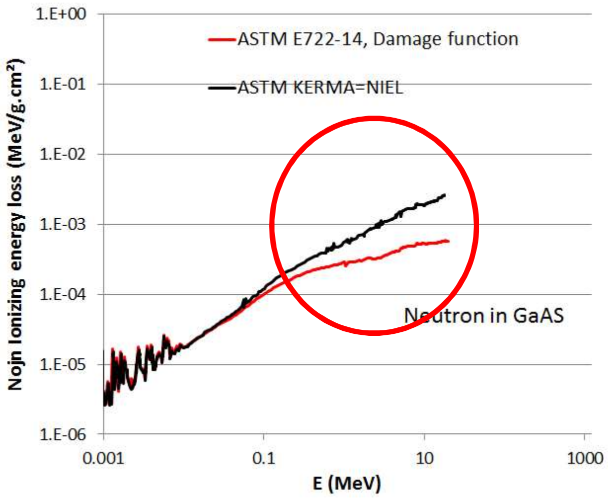
NIEL scaling law : observed deviations

Damage factor
Coulombian dependence
For protons



Si, GaAs, InGaAs

NIEL neutron overestimation



GaAs

NIEL Dependence to the Threshold Damage energy Ed

$$\left.\frac{dE}{dx}\right)_{Total} = \left.\frac{dE}{dx}\right)_{Electronic} + \boxed{\left.\frac{dE}{dx}\right)_{Nuclear} \equiv NIEL}$$

E_d: limit under which an atom cannot be displaced

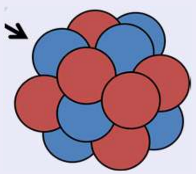
E_d is poorly known in most of cases

!!! NIEL of ELECTRONS Strongly depends on E_d

Reliability of ELECTRONS NIEL

500 keV

e-



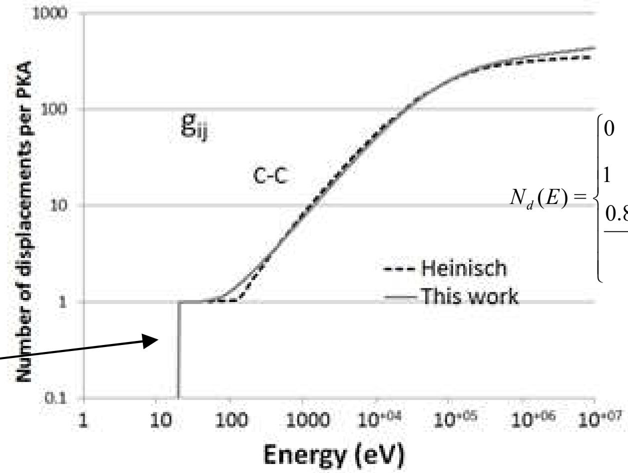
~ 50 eV

Maximum energy transfer

Lindhard partition function

$$NIEL(E) \propto \int_{E_d} \frac{d\sigma}{dE} \cdot n_d(E) \cdot dE$$

E_d

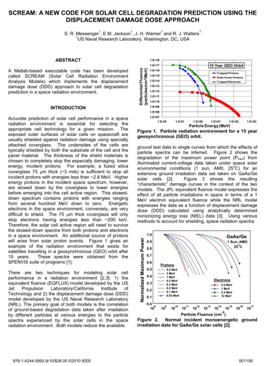


$$N_d(E) = \begin{cases} 0 & \text{if } E_{Damage} < E^d \\ 1 & \text{if } E^d \leq E_{Damage} < \frac{2 \cdot E^d}{0.8} \\ \frac{0.8 \cdot E_{Damage}}{2 \cdot E^d} & \text{if } \frac{2 \cdot E^d}{0.8} \leq E_{Damage} \end{cases}$$

A change in E_d strongly affects the NIEL of electrons

Observed NIEL deviation for electrons

NIEL scaling approach deviations observed in Si, InGaAs, GaAs…



SCREAM: A NEW CODE FOR SOLAR CELL DEGRADATION PREDICTION USING THE DISPLACEMENT DAMAGE DOSE APPROACH

S. R. Messenger[1], E.M. Jackson[1], J. H. Warner[1] and R. J. Walters[1]
[1]US Naval Research Laboratory, Washington, DC, USA

ABSTRACT

A Matlab-based executable code has been developed called SCREAM (Solar Cell Radiation Environment Analysis Models) which implements the displacement damage dose (DDD) approach to solar cell degradation prediction in a space radiation environment.

INTRODUCTION

Accurate prediction of solar cell performance in a space radiation environment is essential for selecting the appropriate cell technology for a given mission. The exposed outer surfaces of solar cells on spacecraft are usually shielded against radiation damage using specially attached coverglass. The undersides of the cells are typically shielded by both the substrate of the cell and the panel material. The thickness of the shield materials is chosen to completely stop the especially damaging, lower energy, incident protons. For example, a fused silica coverglass 75 μm thick (~3 mils) is sufficient to stop all incident protons with energies less than ~2.8 MeV. Higher energy protons in the incident space spectrum, however, are slowed down by the coverglass to lower energies before emerging into the cell active region. This slowed-down spectrum contains protons with energies ranging from several hundred MeV down to zero. Energetic electrons in the space environment, conversely, are very difficult to shield. The 75 μm thick coverglass will only stop electrons having energies less than ~200 keV. Therefore, the solar cell active region will need to survive the slowed-down spectra from both protons and electrons in a space environment. An additional source of protons will arise from solar proton events. Figure 1 gives an example of the radiation environment that exists for satellites travelling in a geosynchronous (GEO) orbit after 15 years. These spectra were obtained from the SPENVIS suite of programs [1].

There are two techniques for modeling solar cell performance in a radiation environment [2,3]: 1) the equivalent fluence (EQFLUX) model developed by the US Jet Propulsion Laboratory/California Institute of Technology and 2) the displacement damage dose (DDD) model developed by the US Naval Research Laboratory (NRL). The primary goal of both models is the correlation of ground-based degradation data taken after irradiation by different particles at various energies to the particle spectra experienced by the solar cells in the space radiation environment. Both models reduce the available

15 Year GEO Orbit
Trapped Protons
Solar Event Protons
Trapped Electrons
Differential Fluence (particles/cm²/MeV)
Particle Energy (MeV)

Figure 1. Particle radiation environment for a 15 year geosynchronous (GEO) orbit.

ground test data to single curves from which the effects of particle spectra can be inferred. Figure 2 shows the degradation of the maximum power point (P_{max}) from illuminated current-voltage data taken under space solar environmental conditions (1 sun, AM0, 25°C) for an extensive ground irradiation data set taken on GaAs/Ge solar cells [2]. Figure 3 shows the resulting "characteristic" damage curves in the context of the two models. The JPL equivalent fluence model expresses the effect of all particle irradiations in space in terms of a 1 MeV electron equivalent fluence while the NRL model expresses the data as a function of displacement damage dose (DDD) calculated using analytically determined nonionizing energy loss (NIEL) data [3]. Using various methods to account for shielding, space radiation spectra

GaAs/Ge
1 Sun, AMO
25°C
Protons
9.5 MeV
3 MeV
1 MeV
0.5 MeV
0.3 MeV
0.2 MeV
0.1 MeV
0.05 MeV
Electrons
0.6 MeV
1 MeV
2.4 MeV
12 MeV
Normalized Maximum Power
Particle Fluence (cm⁻²)

Figure 2. Normal incident monoenergetic ground irradiation data for GaAs/Ge solar cells [2].

978-1-4244-5892-9/10/$26.00 ©2010 IEEE

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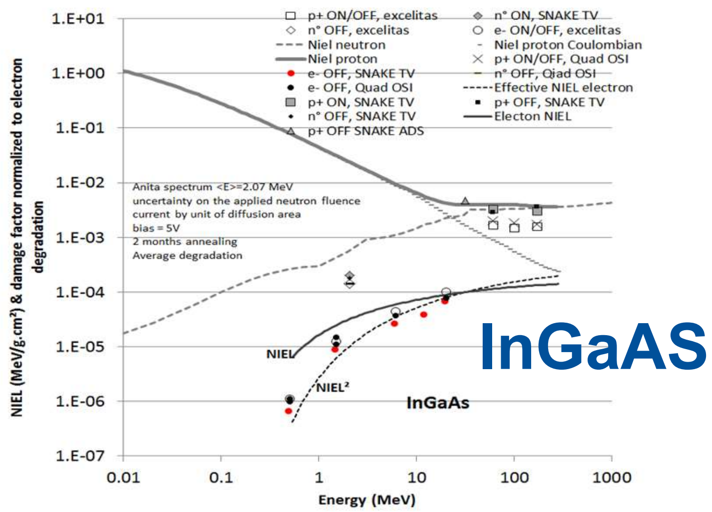
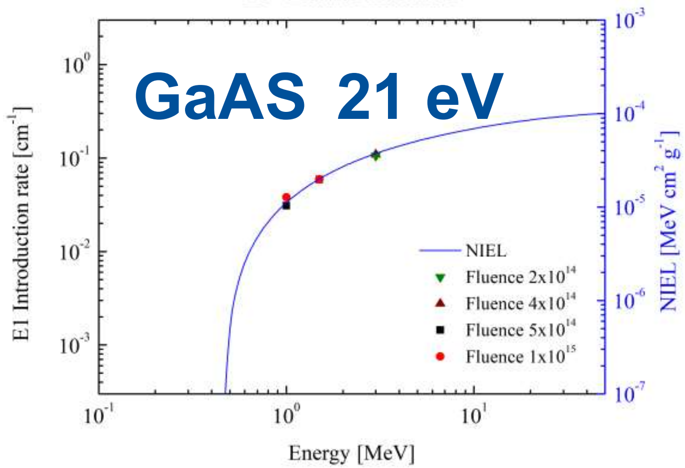




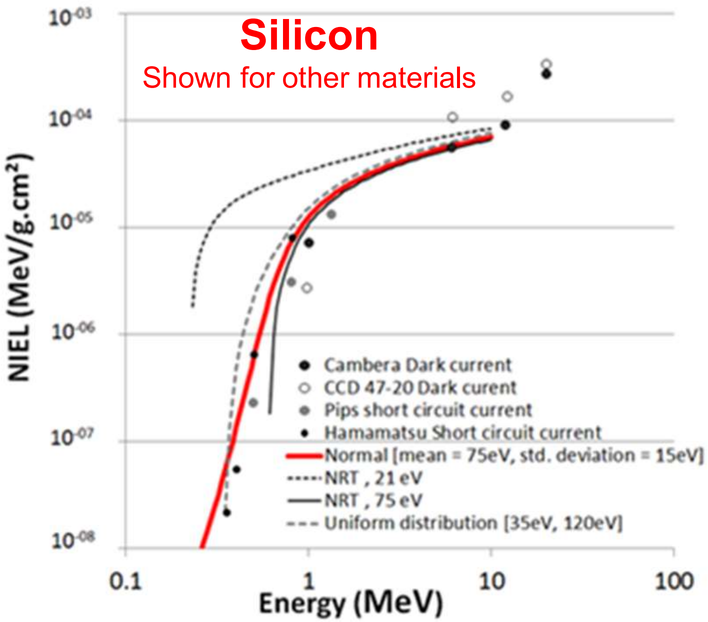
R. Campesato, C. Baur, M. Casale, M. Gervasi, E. Gombia, E. Greco, A. Kingma, P.G. Rancoita, D. Rozza, M. Tacconi (2018), Effects of irradiation on Triple and Single Junction InGaP/GaAs/Ge solar cells, Proceedings of the 35th European PV Solar Energy Conference, Brussels, 24-28 September 2018,

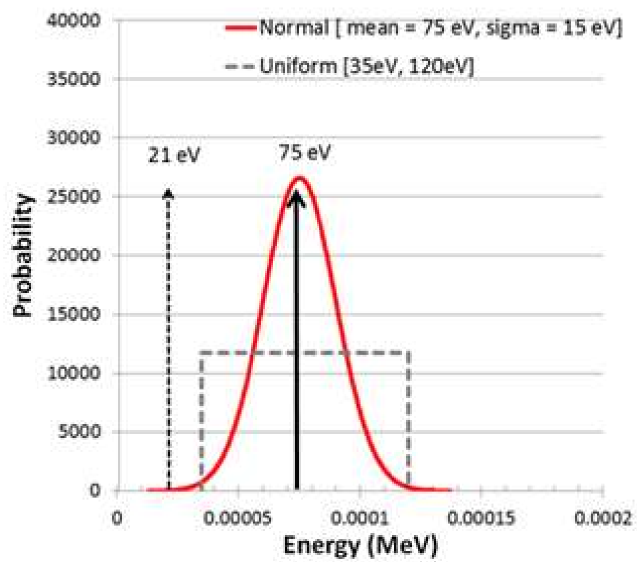
Applying an empirical power factor for NRL solar cell degradation prediction method

$NIEL^{\alpha}$ avec $\alpha \in [1, 2{,}5]$

Reliability of ELECTRONS NIEL

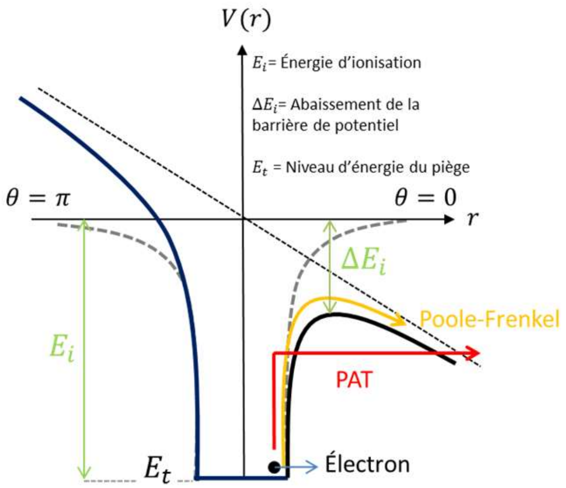
Including a distribution of threshold displacement damage energy provides NIEL in better agreement with experimental damage factors





C. Inguimbert, “Including a distribution of threshold displacement damage energy on the calculation of the damage function and electron’s Non Ionizing energy Loss,” Journal of Nuclear Materials, vol. 559, p. 153398, Feb. 2022, doi: 10.1016/j.jnucmat.2021.153398.

Damage factors depends on the electric field



Enhanced generation rate due to electric field

- Poole Frenkel (lowered potential barrier)
- Phonon Assisted Tunneling

Importance of electric field

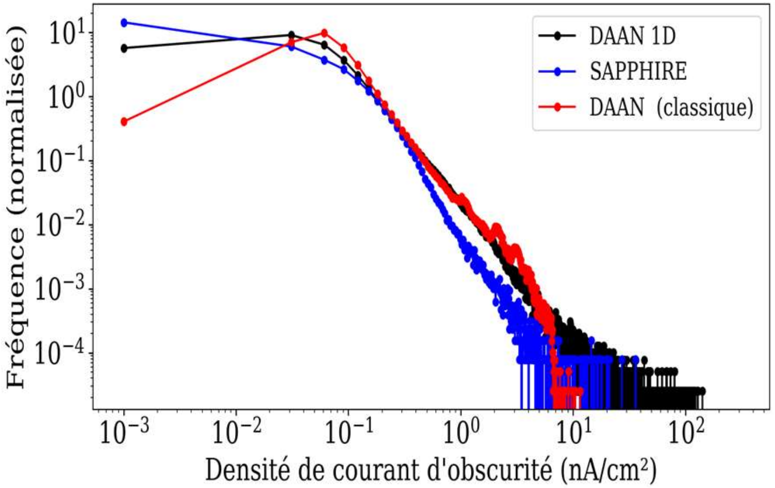
Better prediction of the tail of the Dark Current Non Uniformity

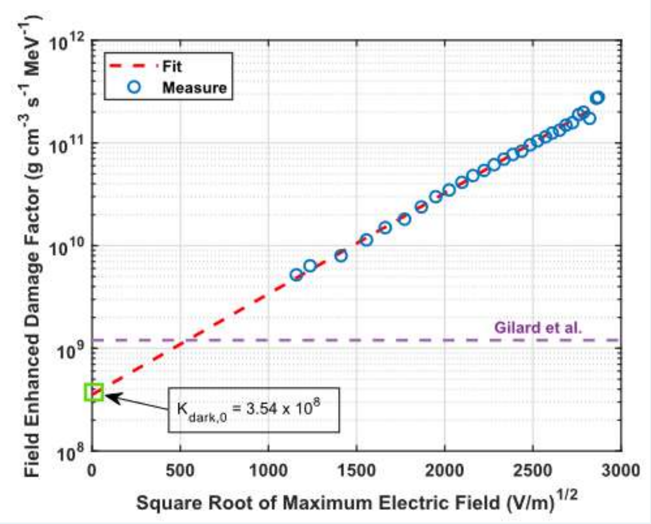
K. Lemière et al.
Influence of a 3D electric field enhancement model on the Monte Carlo calculation of the dark current in pixel arrays J. Appl. Phys. 128, 164502 (2020);

K Lemière PHD 2020

Mean enhancement factor **x2**

Silicon





Shown experimentaly for InGaAs devices
Stronger magnitude than for Si devices

InGaAs

Mean enhancement factor **x5**

Marco Benfante & al.
Electric Field-Enhanced Generation Current in Proton Irradiated InGaAs Photodiodes
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 70, NO. 4, APRIL 2023

Reliability of the NIEL scaling approach ?

NIEL SCALING WORKS QUITE WELL

Applied fluence

Threshold displacement damage energy(electrons)

Electric field

…

Degradation assumed proportional to the number of displacements ?

- Neglecting annealing effects,
- Neglecting nature of the defects,
- Neglecting electrical behaviours of the defects.

NIEL scaling puts aside the detailed functioning parameters of the devices

- Complexity of the devices functioning mode

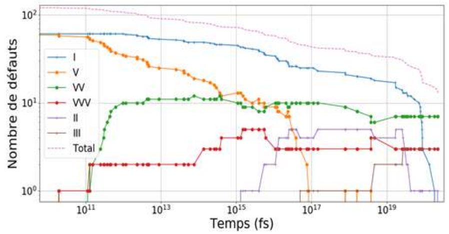
  Different trapps at different locations,
  Real carriers path through the device,
  All electrical parameters do not show a linear response with NIEL

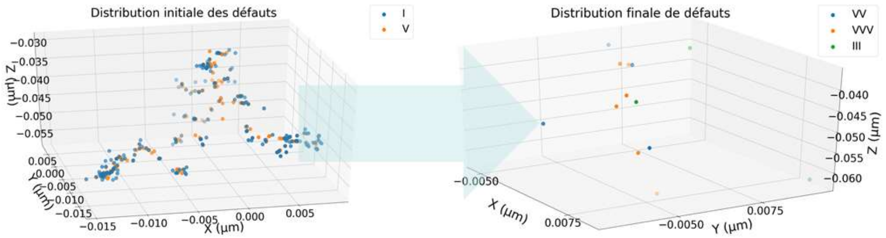
…

Conclusion & Perspectives

Need better knowledge of nature of defects with their physical characteristics

Atomic scale modeling (Ab initio, Molecular dynamic, Kinetic Monte Carlo)





T. Jarrin et al.
Simulation of Single Particle Displacement Damage in Si1−xGex Alloys—Interaction of Primary Particles With the Material and Generation of the Damage Structure
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 67, NO. 7, JULY 2020