STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

VRIJE UNIVERSITEIT BRUSSEL • SCIENTIA VINCERE TENEBRAS •

Gamma Radiation Induced Effects in Si p-i-n Photo Diodes

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SCK•CEN
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Outline

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- **Problem statement**
  - **Objectives**
  - **Approach**
- **Progress**
  - **Physics**
  - **First calculations**
- **Summary and Perspectives**

Instrumentation Department: studies of opto-electronics for applications in different nuclear environments

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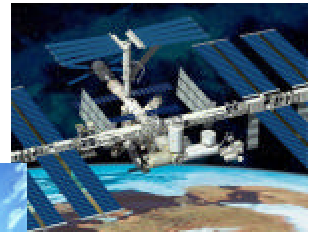
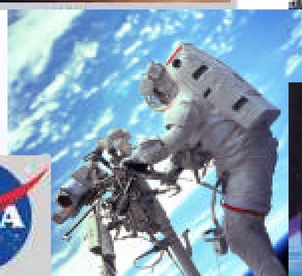
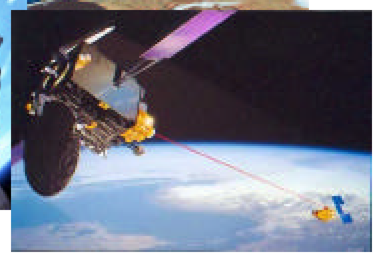
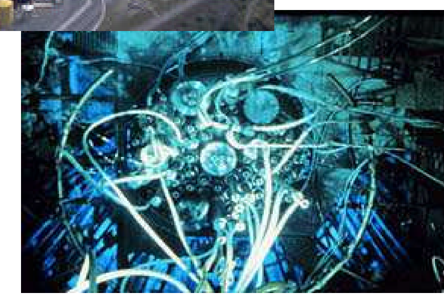
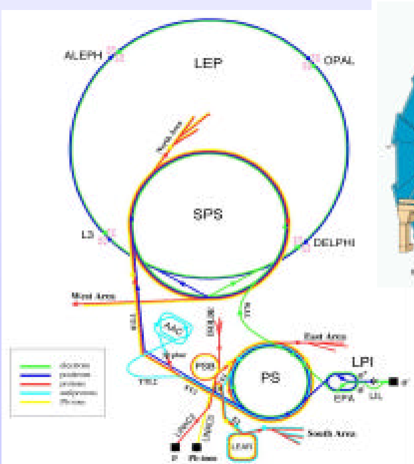
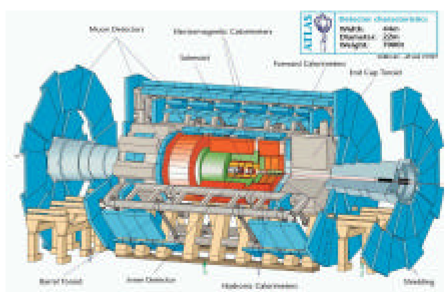


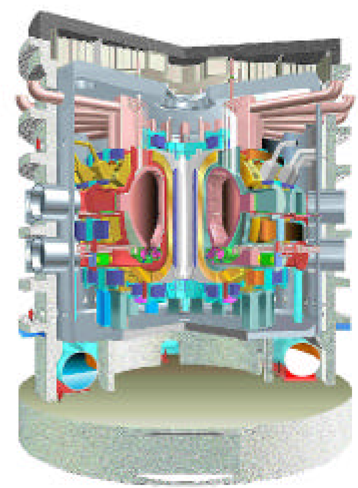


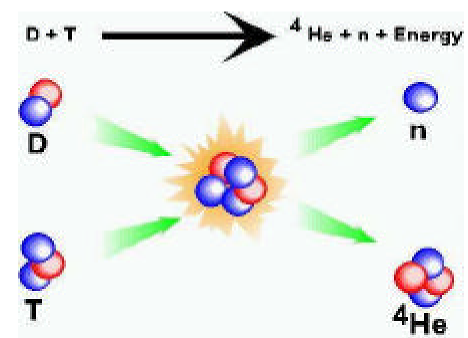






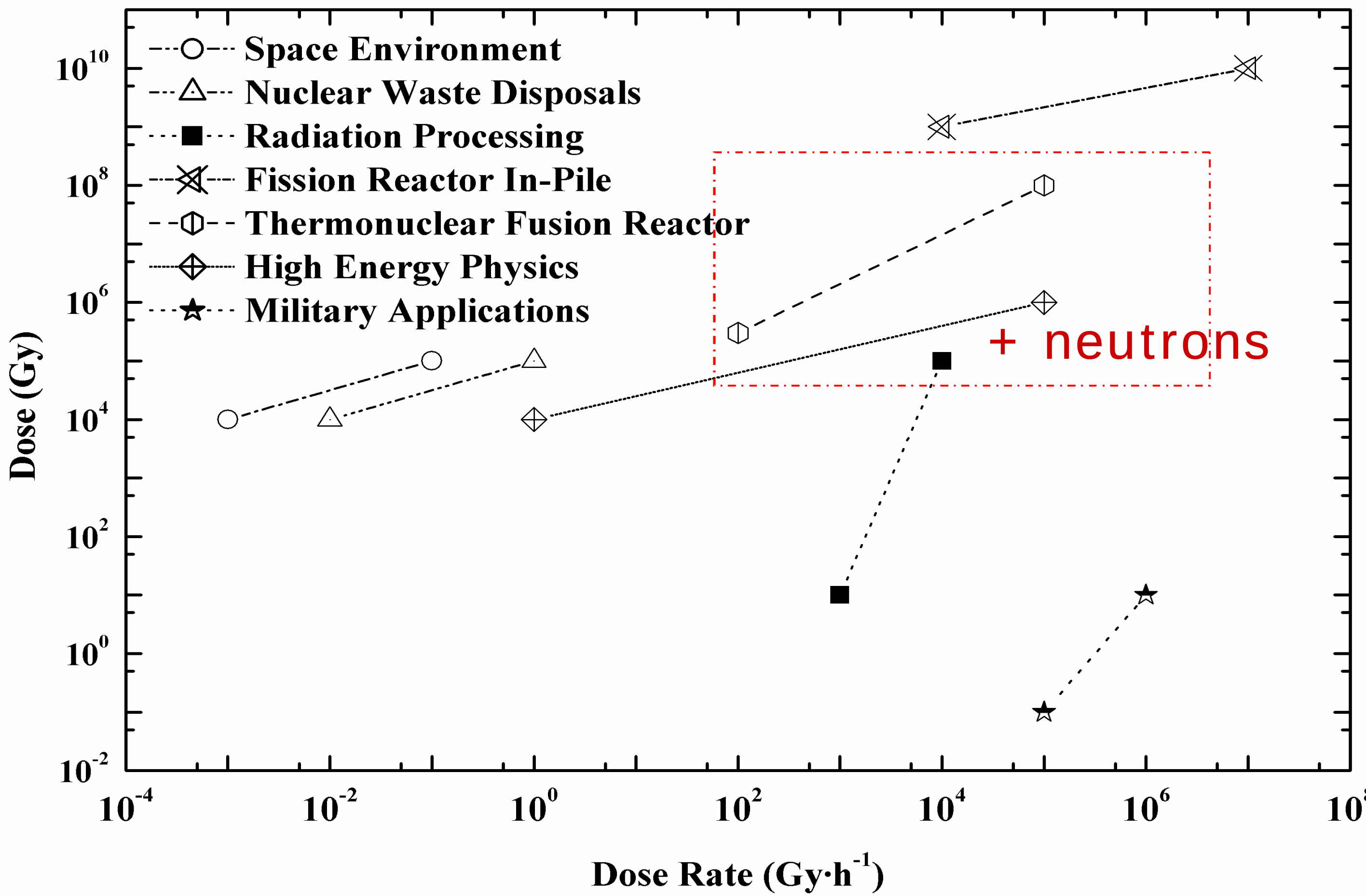






EUROPEAN FUSION DEVELOPMENT AGREEMENT

We mainly focus on high gamma doses



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Laser Diodes and Photo Diodes under radiation

- Mainly studied for space applications
  - particle irradiation (electrons, protons, ions)
  - kGy level gamma doses

- Observe the effects without in depth physical explanation
  - Damage correlation to the displacement (NIEL)
  - NIEL is a macro model for "bulk" structures

✓*Modern O/E devices have complicated layered structures.*
✓*We are interested in MGy level ionizing doses.*

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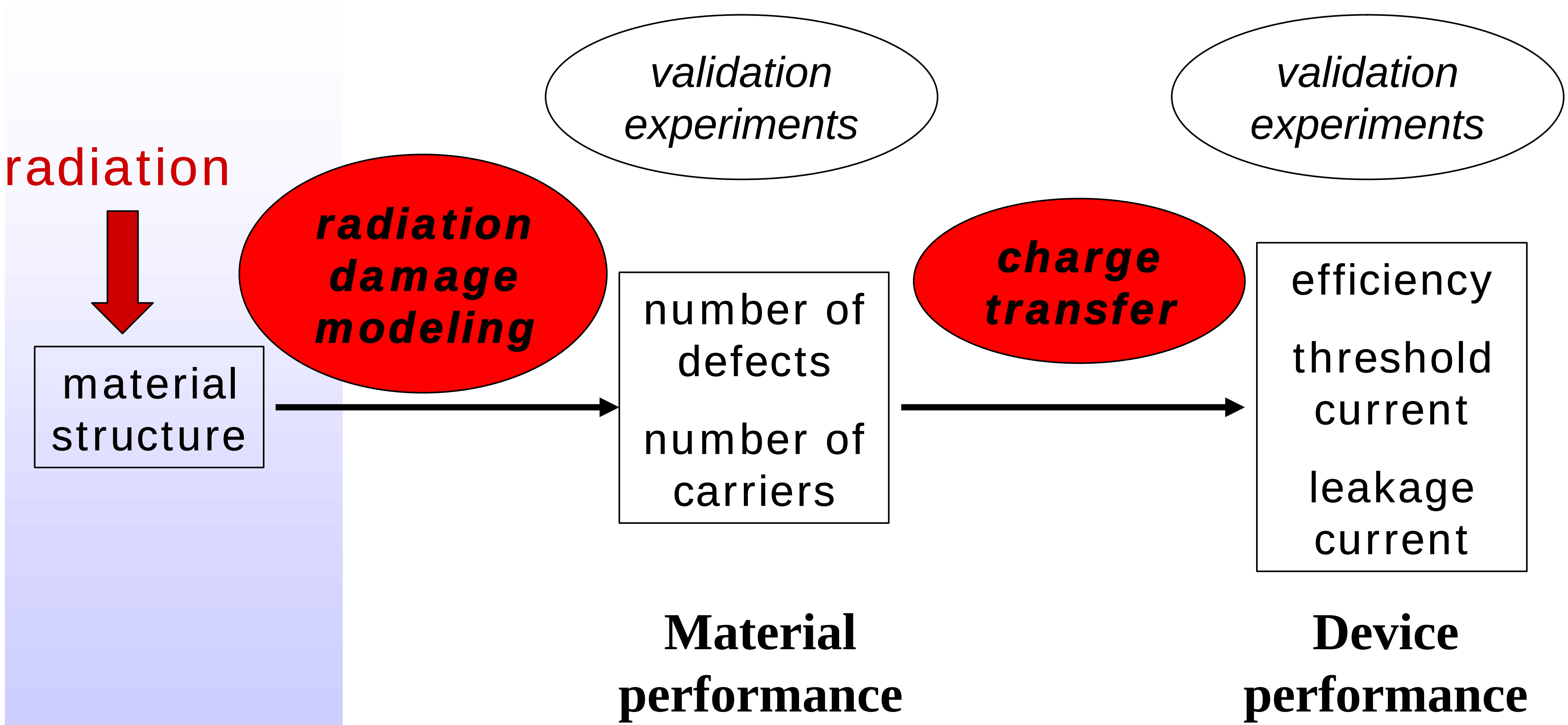
Our final objectives are to

1. define predictive radiation damage models for 2 case studies
   1. P-i-n photodiodes – *Si, InGaAs*...
   2. Vertical-cavity surface-emitting lasers (VCSELs) - *GaAs, AlGaAs*...

2. find parts of the answer to
   1. Is degradation of modern optoelectronic devices due to bulk or interface damage ?
   2. How does downscaling of modern optoelectronics affect their radiation response ?

3. possibly optimize optoelectronic devices for use in nuclear environments

Our approach: from materials to devices



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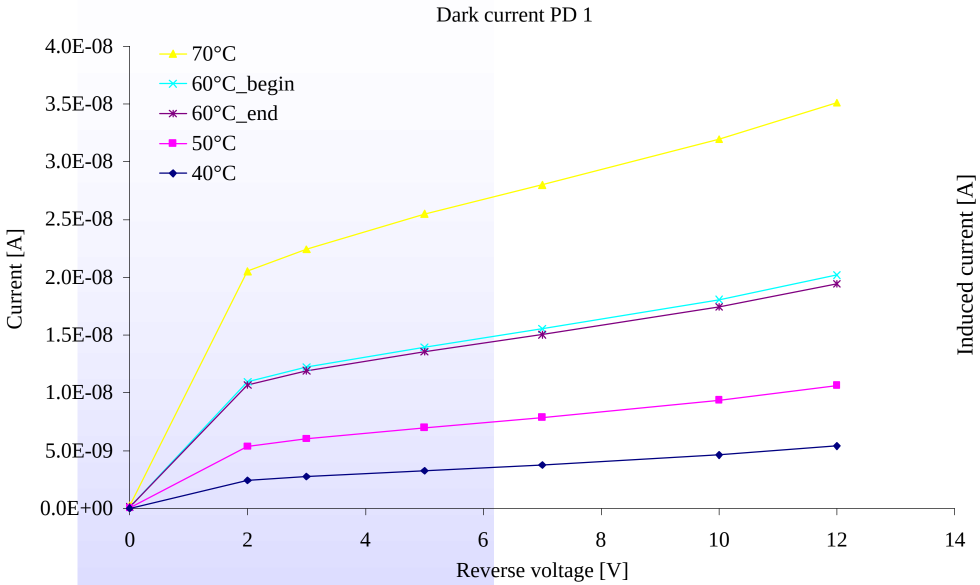
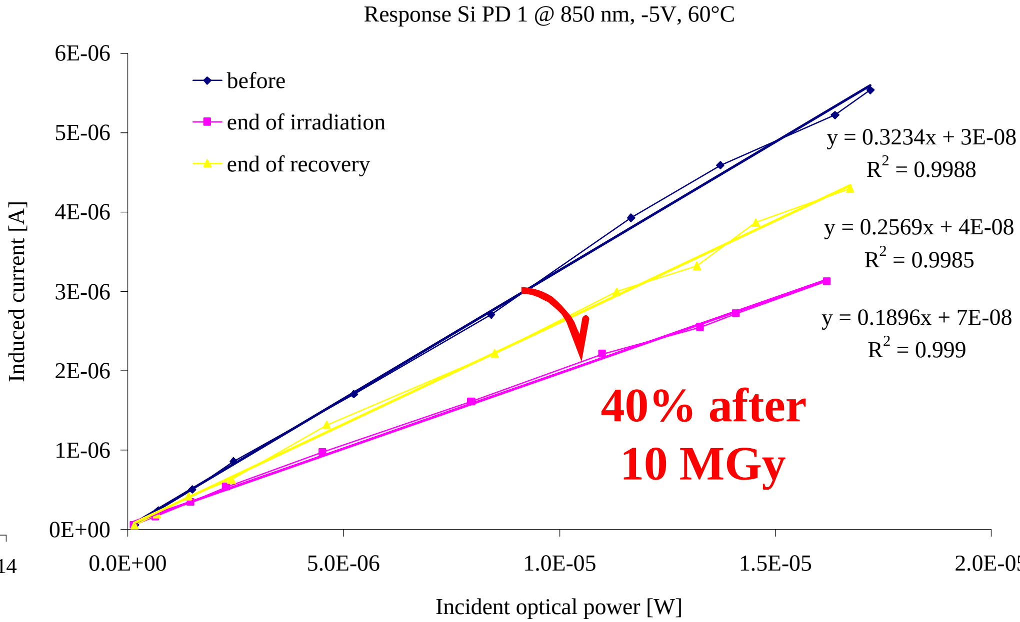
Si PD can withstand MGy dose levels, but...

- dark current increase
- responsivity decrease



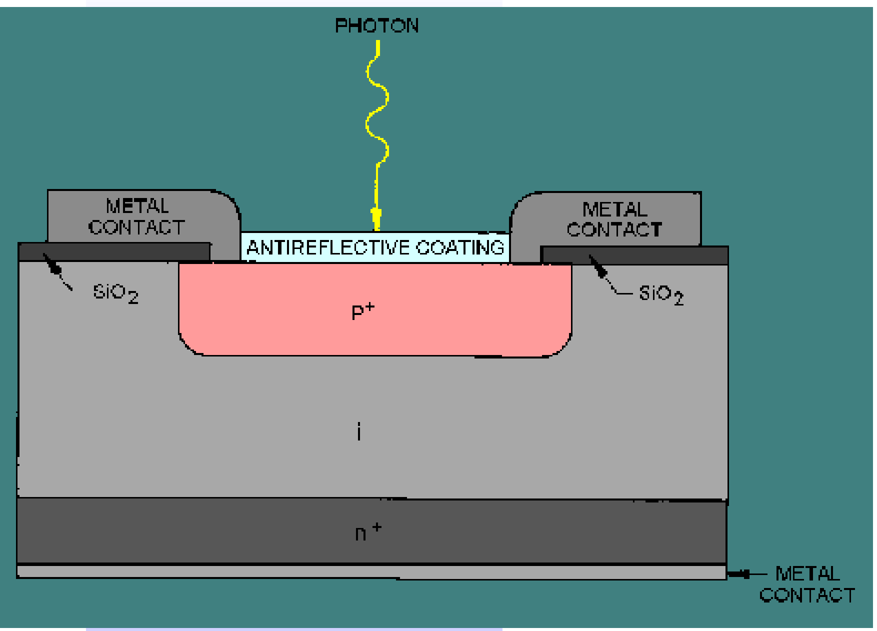


M. Van Uffelen et al., 2004, **SPIE Proceedings, vol. 5465**

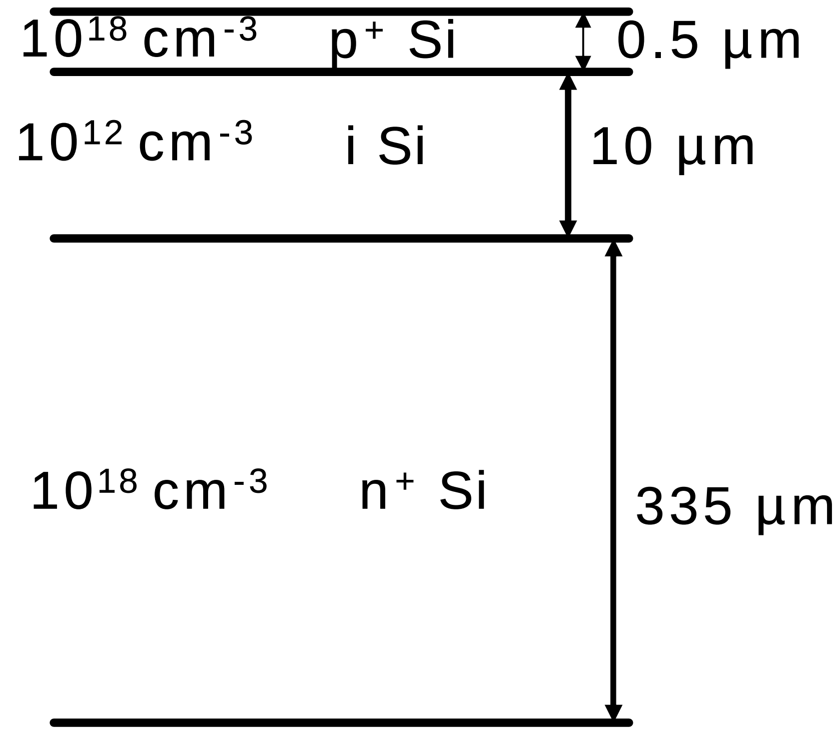
...this behavior is not yet well explained.

Test structures of a Si p-i-n photo diode

Device structure



Modeling structure



Onoda et al., NIM B 206 (2003) 444–447

Modeling tools for gamma radiation

Penelope

- Electron-photon transport
- 100 eV – 1 GeV

✓Depth-distribution of deposited charge.

✓Distribution of energy deposited into the target.

GEANT4

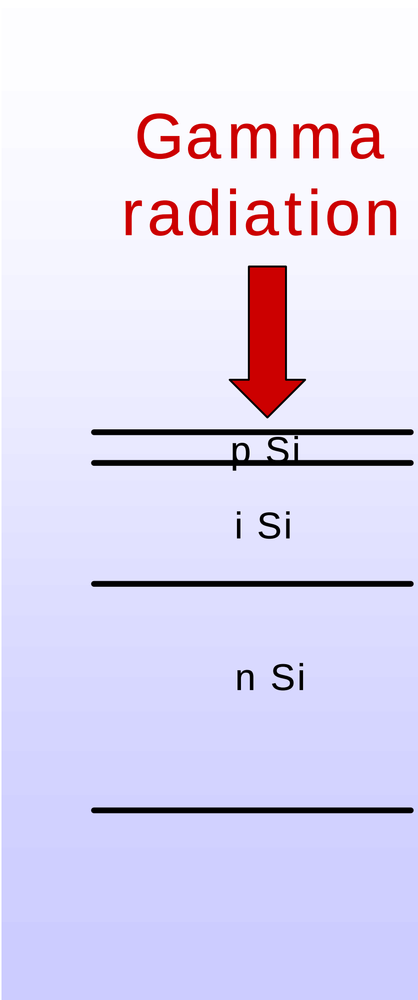
- CERN, Object-Oriented framework
- Electron, photon and particle transport
- Implemented the Penelope low energy physics

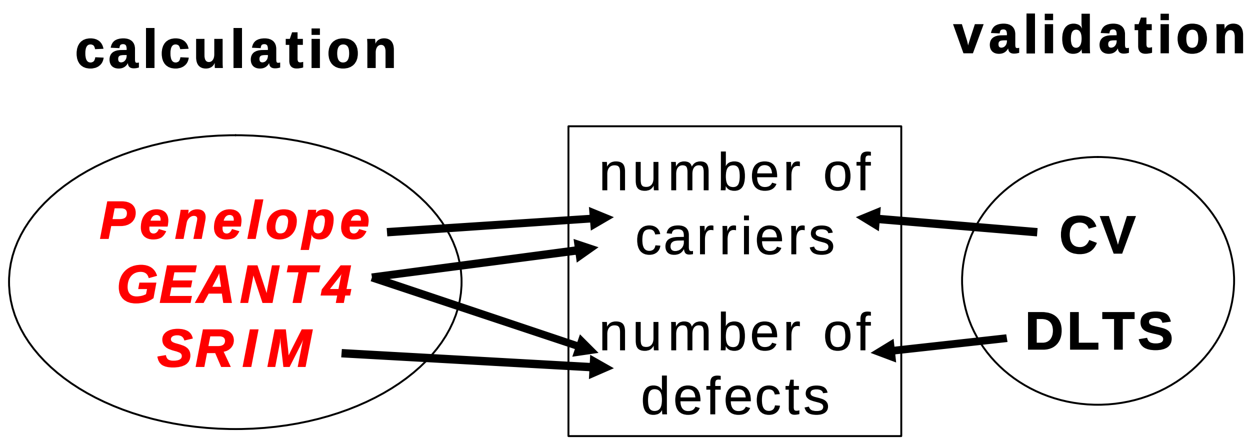
✓Depth-distribution of deposited charge.

✓Distribution of energy deposited into the target.

✓Displacement profile

Detailed approach for material performance modeling





Material performance

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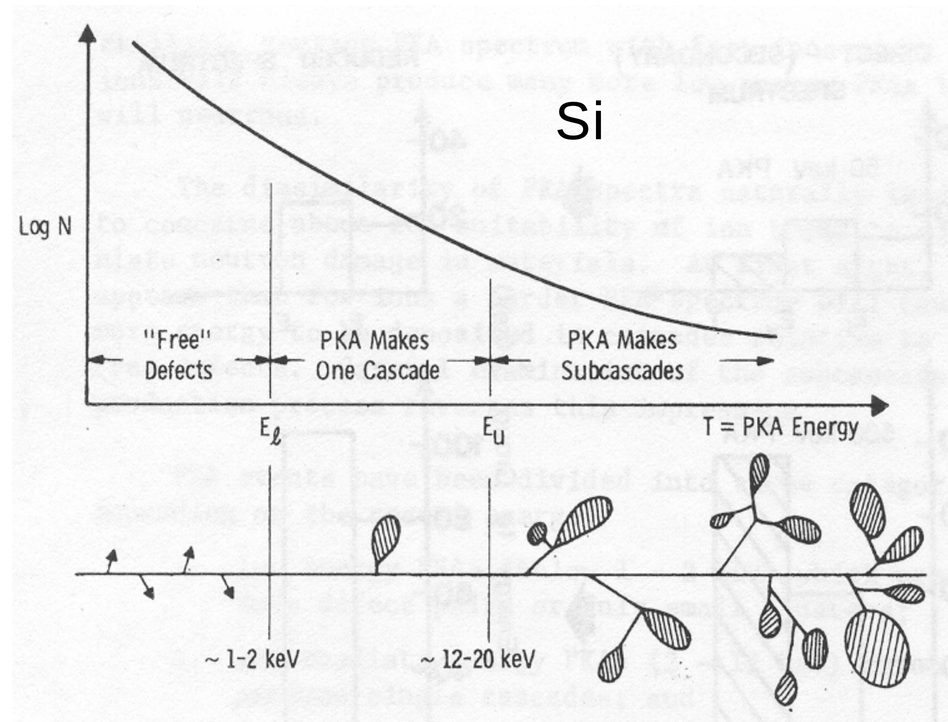
  - **Physics of the processes**
  - **First calculations**
  - **CV measurements**
- **Summary and Perspectives**

Total ionization dose effects are playing significant role in case of Gamma radiation

- Displacement
  - Through Compton electrons
  - Primary Knock-on Atoms with energy lower than 1 keV
  - Only individual defects



S.Wood at al, *IEEE Trans. Nucl. Sci.*, 1981.

Displacement of target atoms in Si upon electron and gamma irradiation

K. Gill et al., *NIM A,* 1996

- vacancy introduction rate- $10^{-3}cm^{-1}$
- divacancy introduction rate- $10^{-5}cm^{-1}$
- type inversion after 110Mrad

L. Fedina et al., *Phys.stat.sol.(a),* 1999.

- clusters of vacancies in Si formed after MeV electron irradiation
- depends on:
  - point defects
  - thickness of the sample
  - surface type
- clusters in Si are more stable compared to GaAs

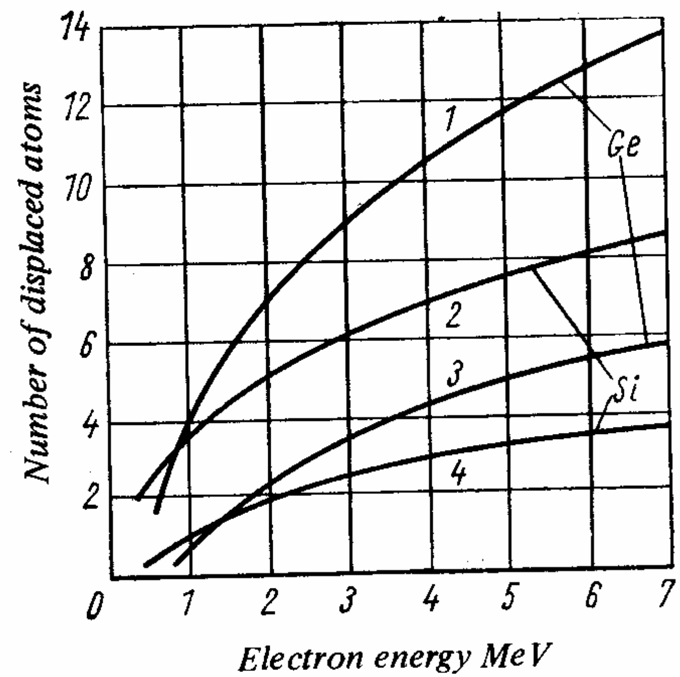
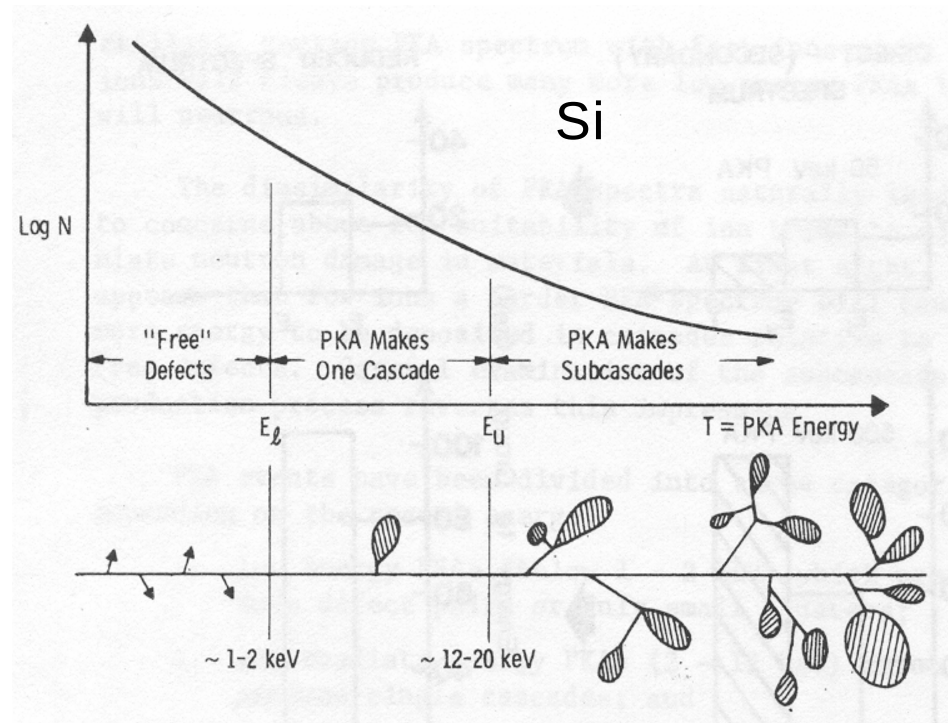


Figure 3. Number of displaced atoms of germanium and silicon per single incident fast electron [E_d15 /1,2/ and 30/3,4/ eV]

J. Kahn, *J.Appl.Phys.*, 1959.

Total ionization dose effects are playing significant role in case of Gamma radiation

- Displacement
  - Through Compton electrons
  - Primary Knock-on Atoms with energy lower than 1 keV
  - Only individual defects
- Heat
  - Annealing
- Ionization
  - Through Compton scattering and photo-electric effect



S.Wood at al, *IEEE Trans. Nucl. Sci.*, 1981.

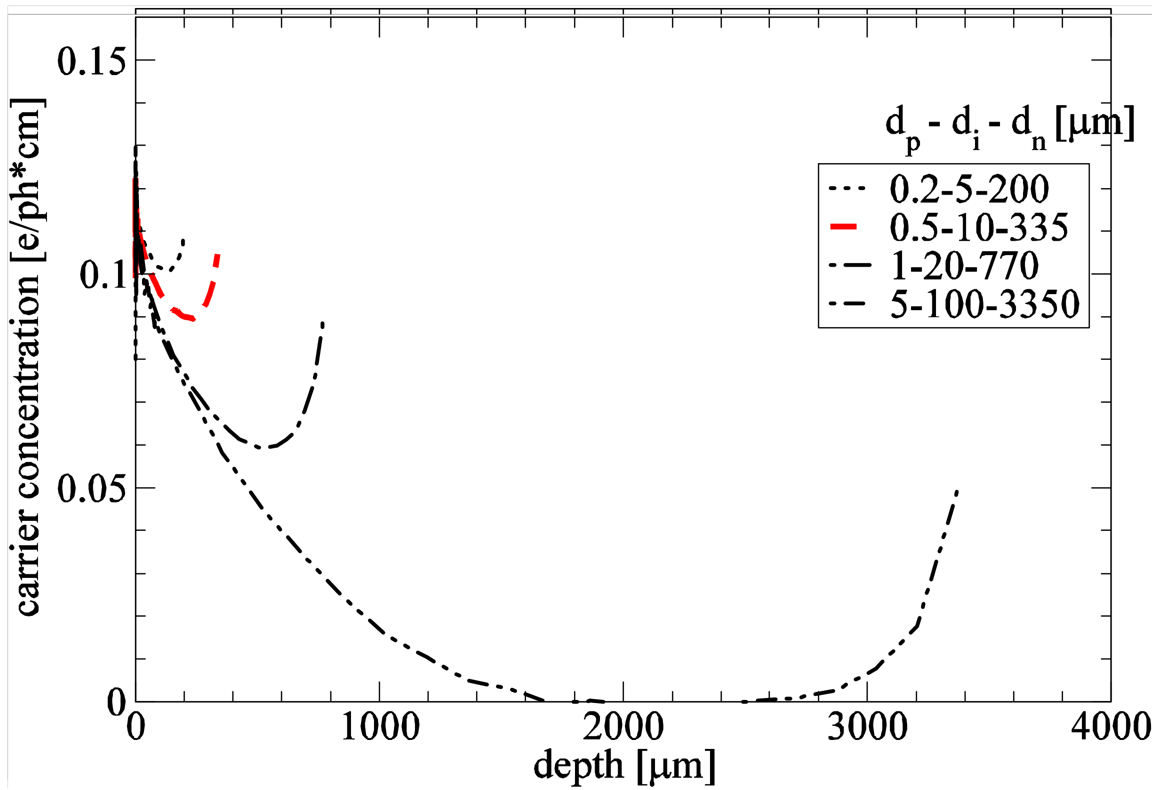
Outcome from Penelope and its limitations

- Charge depth profiling- consider only electron-photon transport
  - ➢thickness dependence
  - ➢material dependence

- Limitations
  - ➢does not take into account interface imperfections, bulk defects and impurities
  - ➢does not include annealing
  - ➢does not take dynamics into account (dose rate)
  - ➢does not cover displacement
  - ➢does not include electric field

Penelope calculations on Si p-i-n structures

- Two peaks structure
- There is not interface influence in the distribution
- The intensity of back peak decreases
- The code is not suitable for nm structures



Discussion

- insensitive to the doping levels
- missing any interface effects- the mean free path of the electrons is larger than the thickness of the device
- radiation induced carriers will affect lightly doped regions and those closer to the surface

Limits of the calculations

- temperature effects
- impurities and contaminations
- interface stresses
- dose rate effects and accumulation

  phenomenology, MD ….

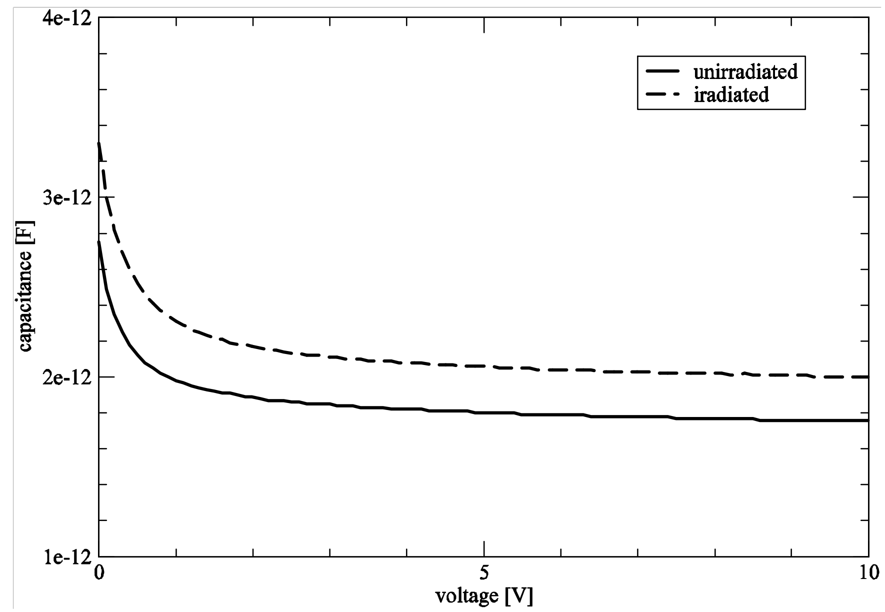
- electron particle transport
- electric field effects

  GEANT4

First CV trials of Si p-i-n PD

- change in the material properties

- accumulation of charge in the oxide layer?
- intrinsic layer?
- package effects?



Summary

- Penelope calculates almost homogeneous distribution up to 500µm thickness of the structure
  - “bulk” effects are dominant

- the thinner the device the smaller the amount of radiation induced charges and the smaller the amount of displaced atoms

- lightly doped regions are more affected

Future work

- investigate electric field effects and displacement with Geant4
- additional CV measurements and interpretation
- looking for other suitable techniques to characterize devices