Effects of ionizing radiation in semiconductor devices: simulation with *Geant4*

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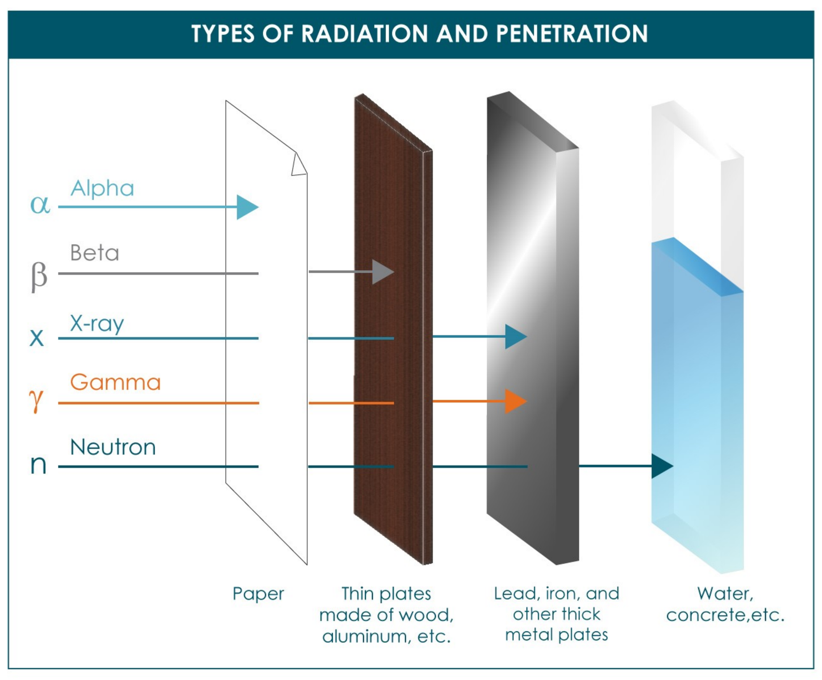
Goal of this work

to analyze and simulate the effects of ionizing radiation on silicon-based integrated circuits.



https://v2.mirion.com/introduction-to-radiation-safety/types-of-ionizing-radiation/

When ionizing radiations collide with a semiconductor, they create electron-hole pairs:

- α and β particles progressively lose their kinetic energy when crossing the material
- γ rays pass through or are absorbed (photoelectric, Compton effect or e+e- pair production) → secondary charged particles if absorbed
- neutron particles interact with nuclei either elastically or inelastically → Si atoms recoil or secondary particles

Depending on the nature and energy of the ionizing radiations, their stopping power in matter is different. From least to most penetrating: alpha, beta, gamma and neutron.

Simulations

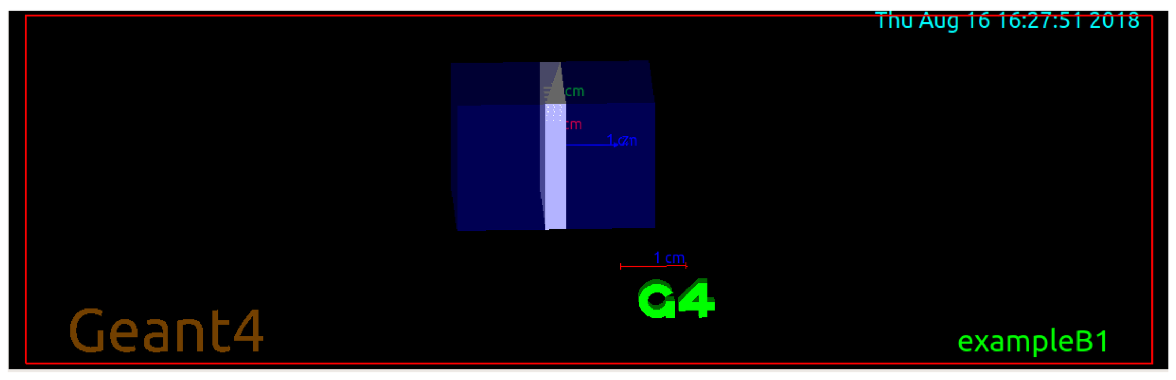
Aim: determination of the charge (number of deposited electron-hole pairs) in a block of silicon by ionizing radiations.

Tool: GEANT4 A SIMULATION TOOLKIT

- → software Geant4 (for Geometry and Tracking) developed by CERN
- → output = absorbed dose value & tracking visualization
- → platform for the simulation of the passage of radiations through matter, using Monte Carlo methods [1]

Our work: implementation of a block of silicon of variable width (2 x 2 x *z* cm³) inside an air envelope (2 x 2 x 3 cm³).

Studied parameters
- block's thickness
- incident radiations' properties including:
  - type (alpha…),
  - number of particles, and
  - energy.

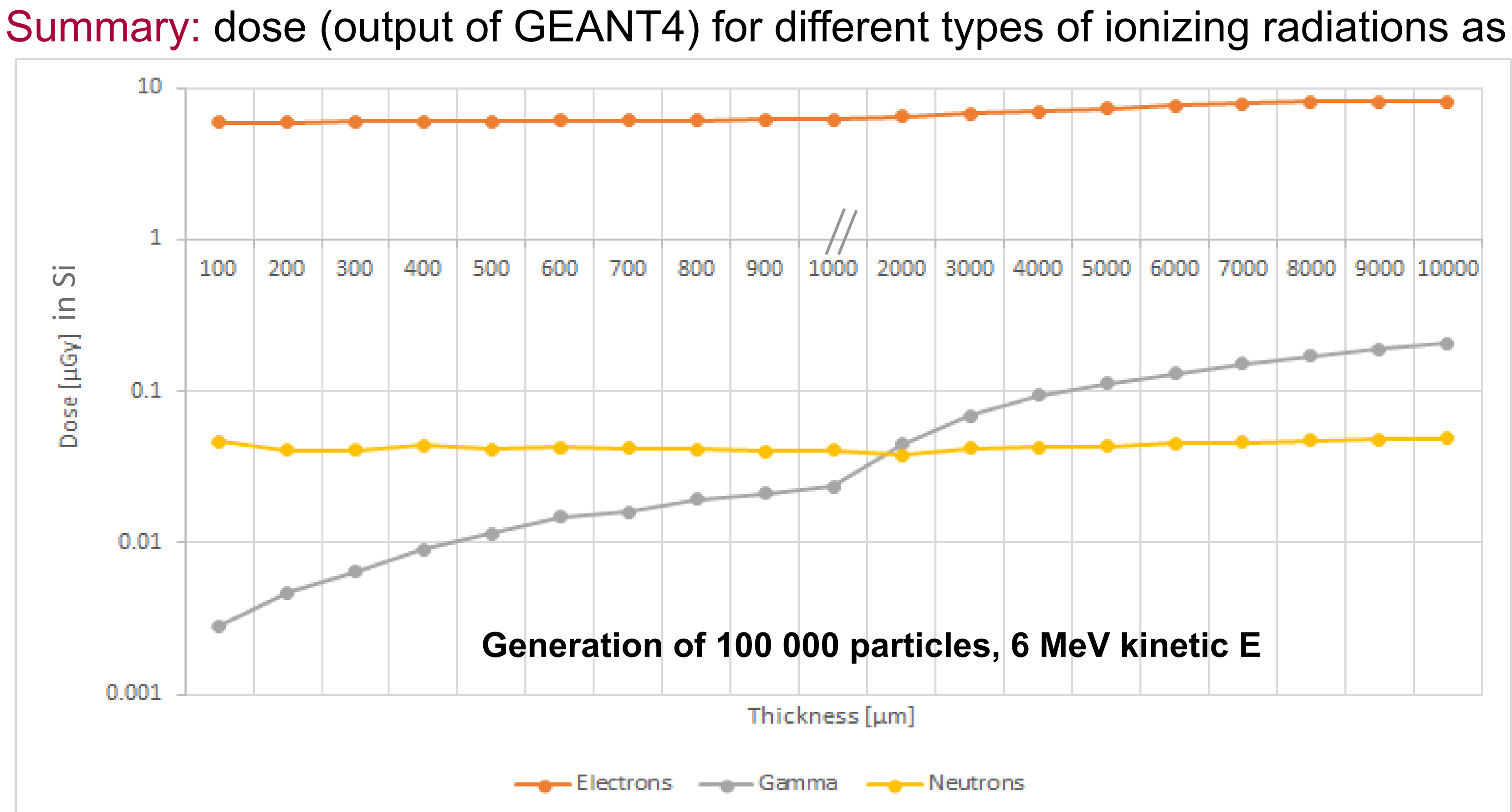


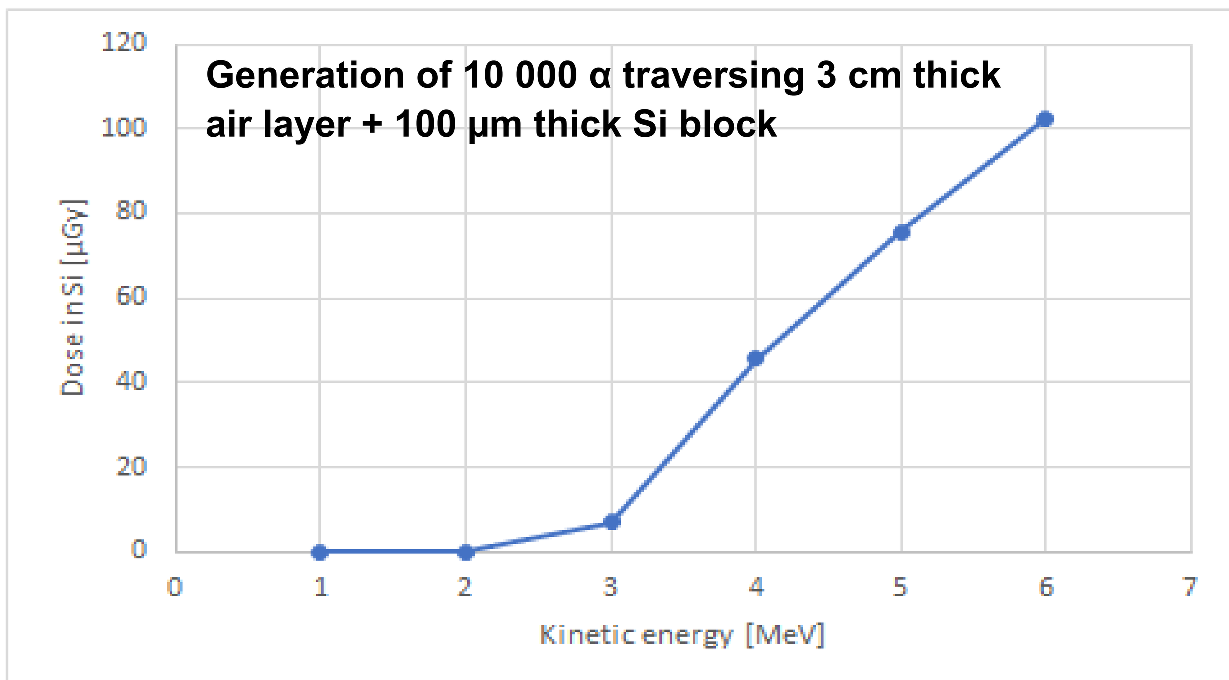
Visualisation of the silicon block on Geant4

For integrated circuits fabrication, the silicon is doped. Nevertheless, considering the low concentration of dopants (typically maximum 10^{18} atoms/cm³ of dopants for approximately 10^{22} atoms/cm³ in intrinsic crystalline silicon), simulating a block of pure silicon is a good approximation.

Results

Summary: dose (output of GEANT4) for different types of ionizing radiations as a function of silicon thickness or kinetic energy.





Comments:

- electrons lose their kinetic energy gradually with a longer range compared to α → the dose slowly increases with thickness
- fast MeV neutrons interact mainly by nuclear elastic scattering processes
  → ionizing energy deposition due to recoil Si atoms
  → few ionization events in Si layer
- γ flux decreases exponentially $N(x) = N_0 e^{-\mu x}$
  → the number of γ stopped in Si increases with thickness.
- α radiations interact strongly with matter → loss an important part of their energy in a 3 cm thick air layer before reaching the silicon block → fully stopped by 3 cm of air + 100 µm Si.

Validation: The dose values obtained as well as their variation vs Si thickness are consistent with the way that the ionizing radiations are expected to interact in a solid silicon layer.

6 MeV radiation → path in Silicon [2][3]
α range ≈ 30 µm, β range ≈ 1.5 cm, γ half-value-layer ≈ 15 cm

Conclusion and future work

- neutron radiations: further studies are needed in order to understand the importance of Non-Ionizing Energy Loss events → possible damages in the Si lattice.
- β radiations lead to the highest dose in Si. Computation of the deposited charge (number of e-h pairs) from the passage of 100 000 ionizing β radiations of 6 MeV in a 500 µm thick silicon block:

  D ≈ 8 µGy → ΔQ ≈ 0.6 nC
- Further simulation studies: passage of ionizing radiations in doped Si, pn junctions, circuits to evaluate the intensities of transient currents created by charge deposition.

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References

[1] https://geant4.web.cern.ch/
[2]https://www.nist.gov/pml/stopping-power-range-tables-electrons-protons-and-helium-ions
[3]https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients