Campus di Arcavacata
UNIVERSITÀ DELLA CALABRIA

Evaluation on neutron SEB threshold of COTS power MOSFETs with TCAD simulations

Ing. Carlo Giordano, PhD

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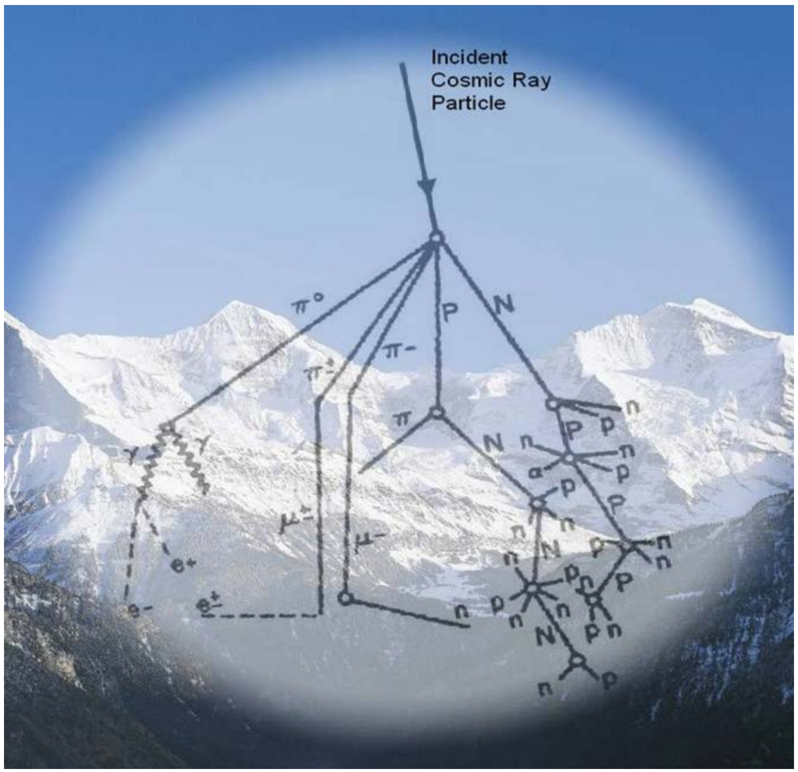
Contents

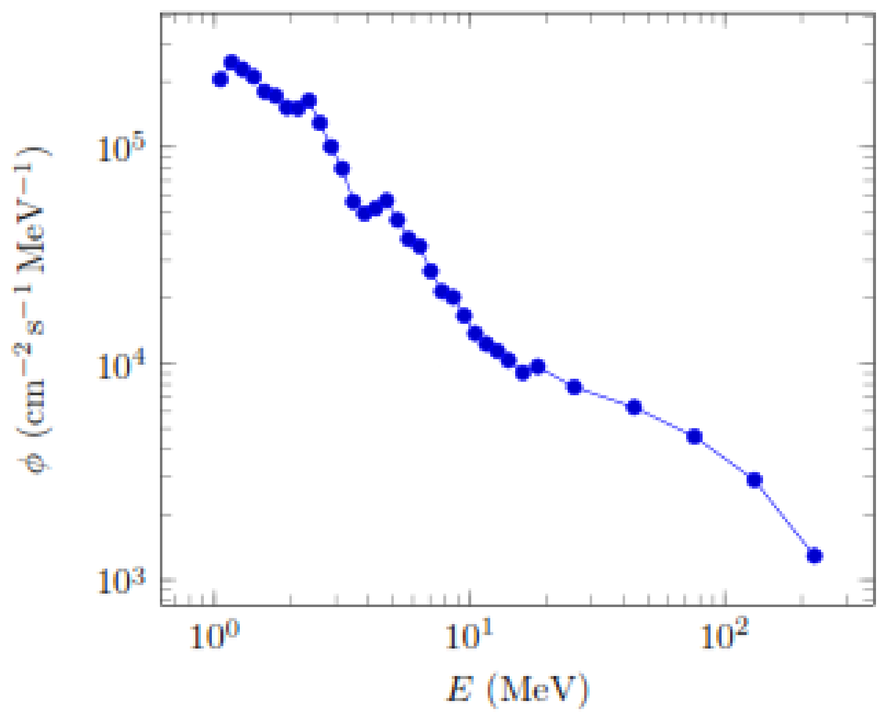
- **Introduction;**
- SEB experiments;
- TCAD simulations;
- conclusions.

What is a Single Event Burnout?

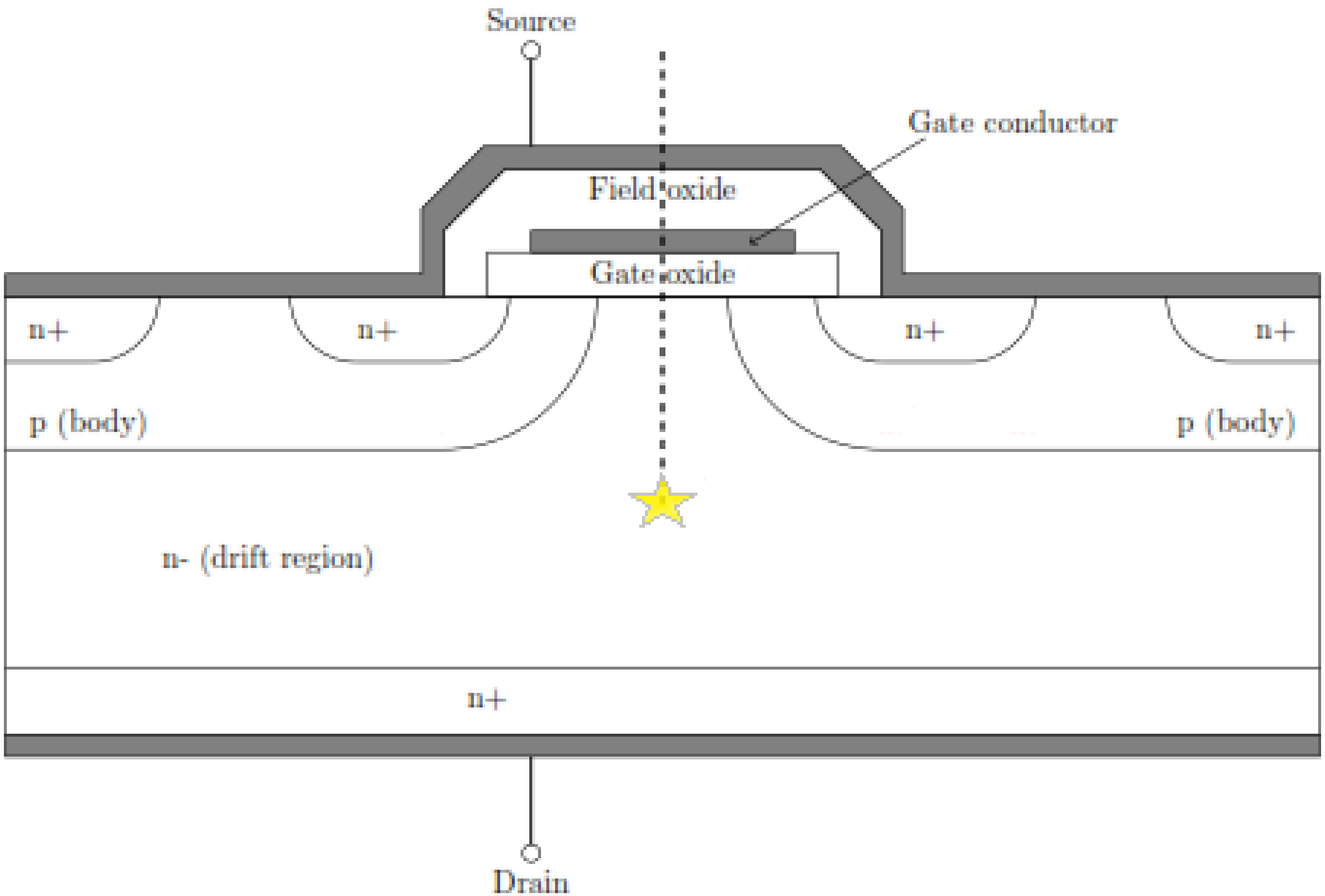
- Single Event Burnout (SEB) is a catastrophically failure mode for power transistors, triggered by a single energetic particle, when the device is biased in blocking mode (Vgs=0);
- the macroscopic effect of SEB is a localized short circuit between drain and source contacts;
- very popular topic inside the aerospace community since the early ‘90s

Terrestrial neutrons

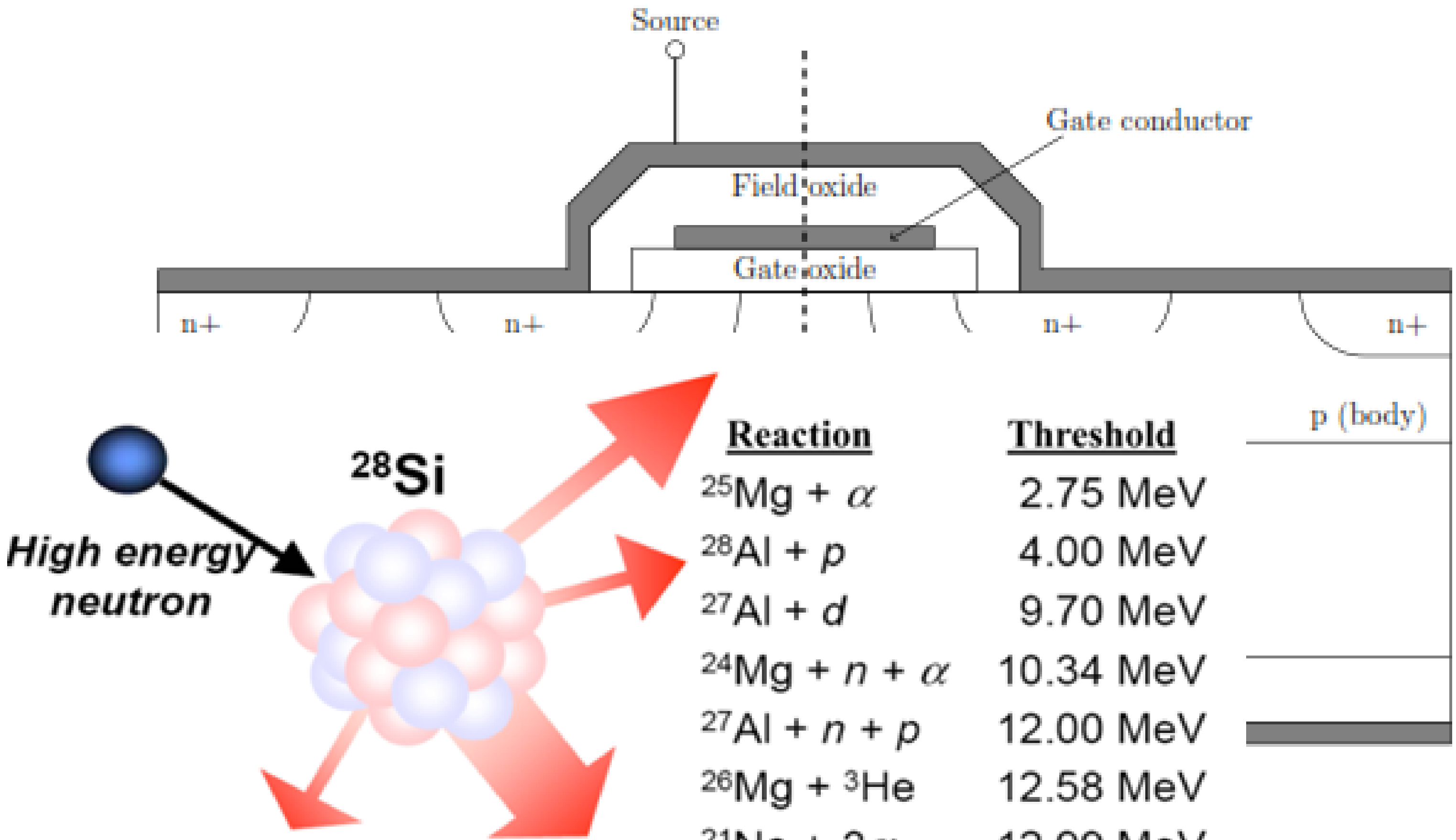




SEB dynamics

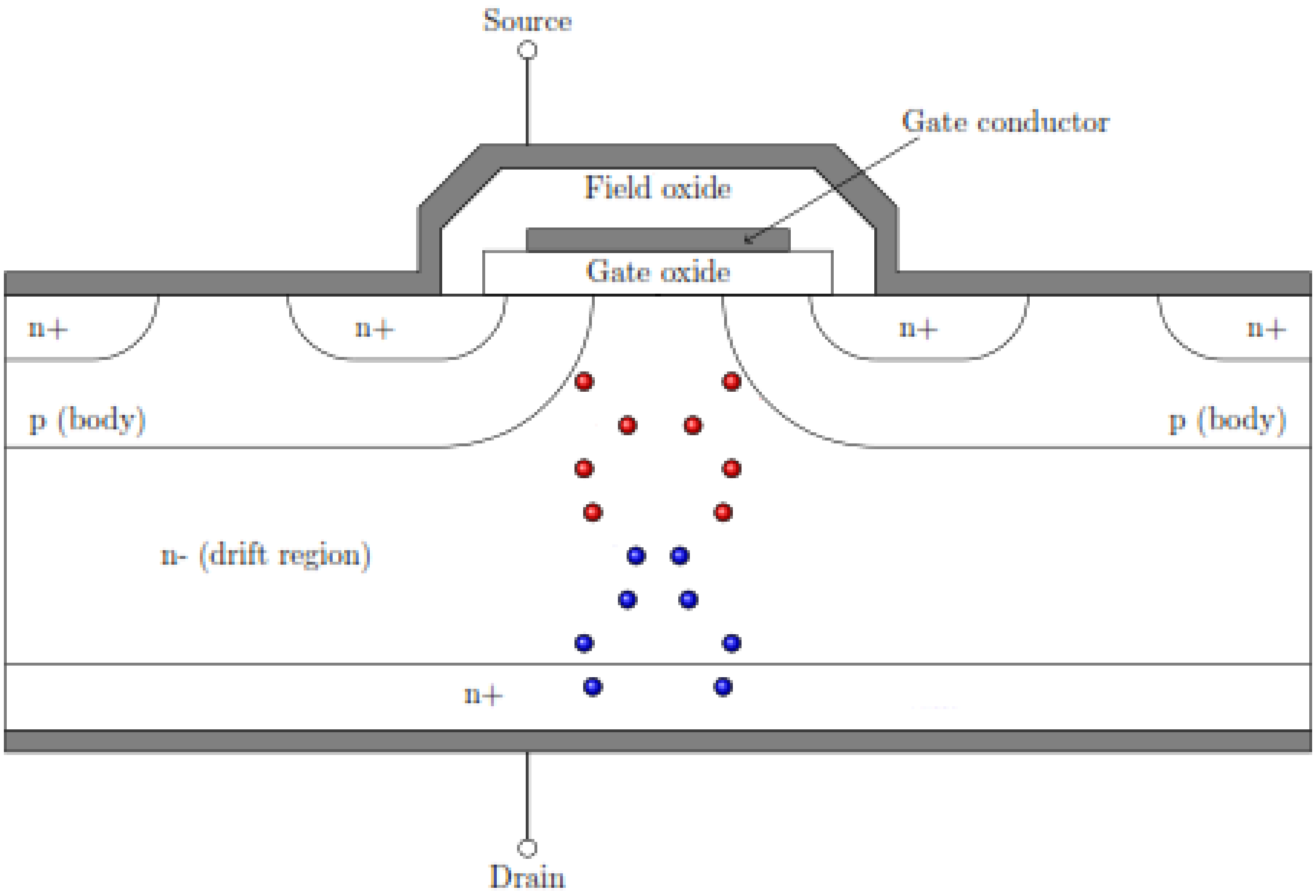


SEB dynamics

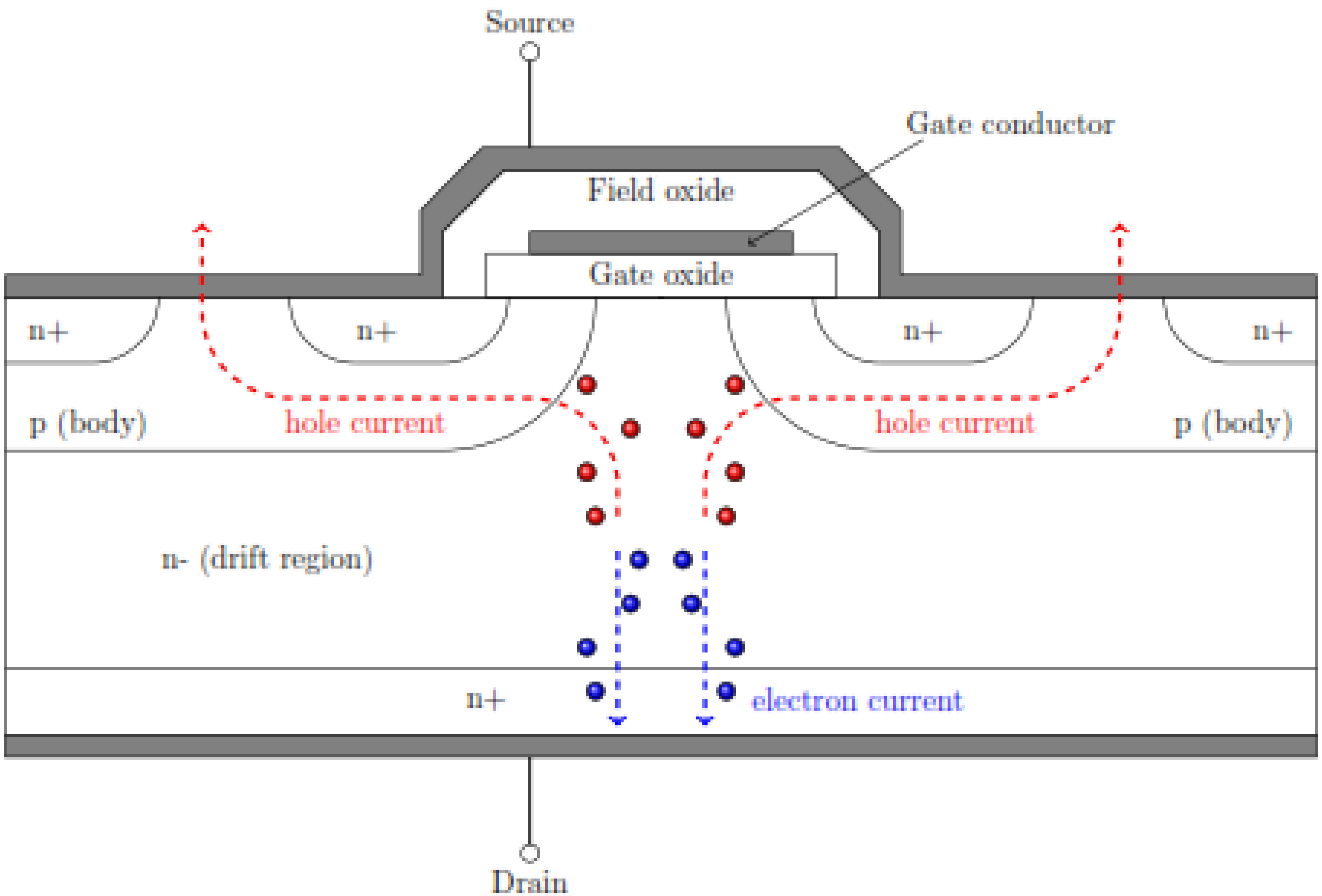


Reaction	Threshold
$^{25}Mg + \alpha$	2.75 MeV
$^{28}Al + p$	4.00 MeV
$^{27}Al + d$	9.70 MeV
$^{24}Mg + n + \alpha$	10.34 MeV
$^{27}Al + n + p$	12.00 MeV
$^{26}Mg + {}^{3}He$	12.58 MeV
$^{21}Ne + 2\alpha$	12.99 MeV

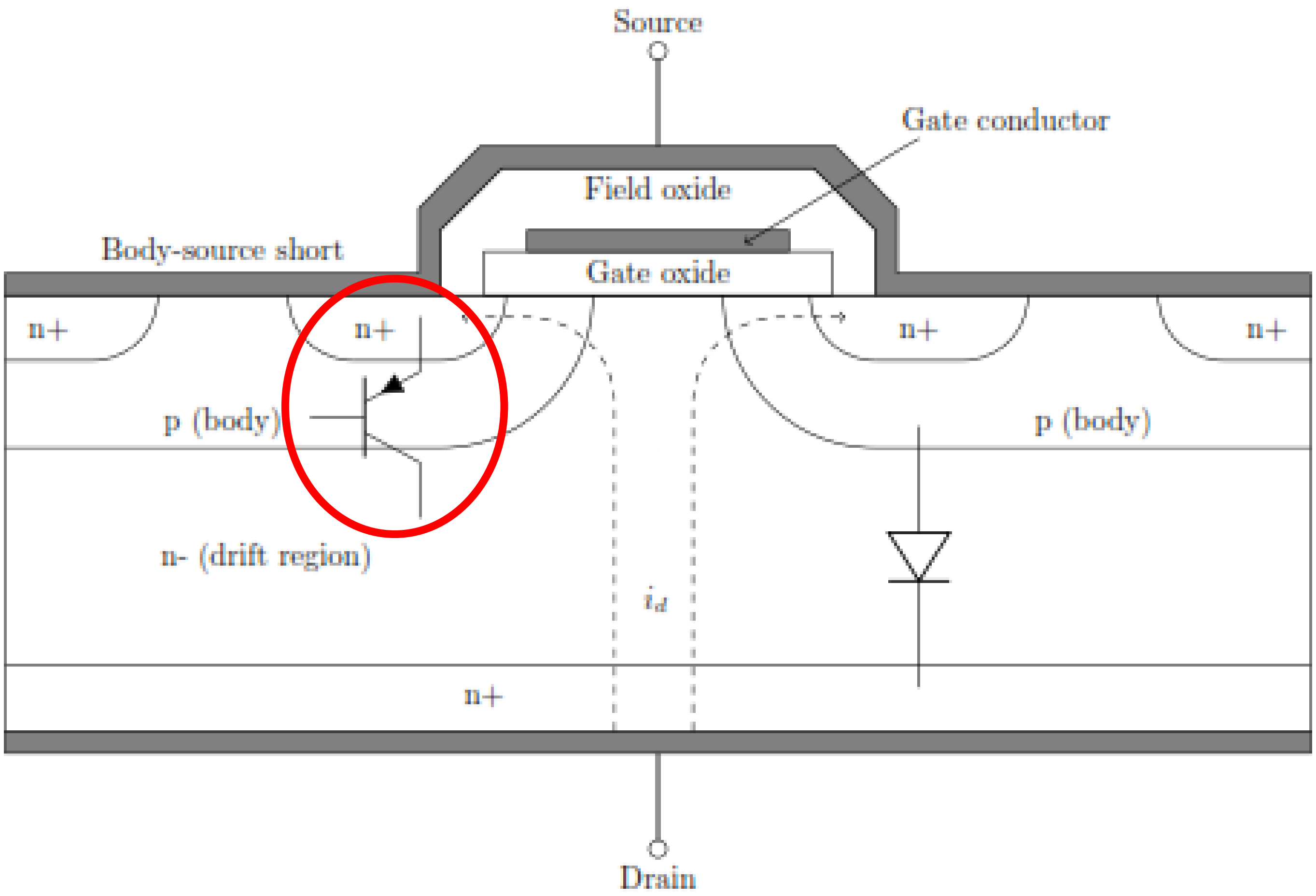
SEB dynamics



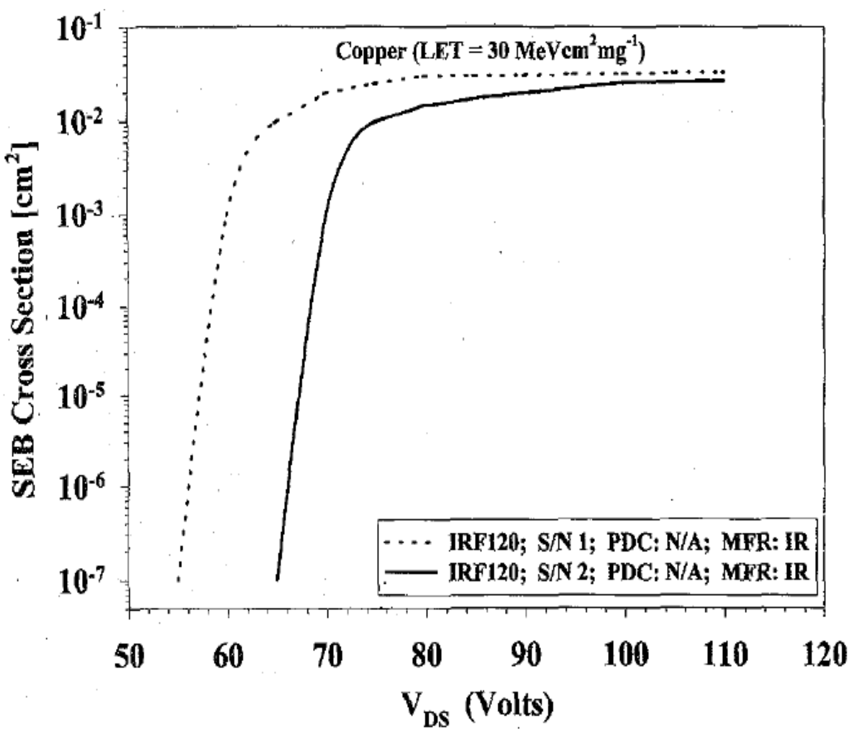
SEB dynamics



SEB dynamics



SEB threshold voltage



- SEB can be observed if the applied bias is greater of a threshold value;
- in order to decrease SEB occurrences, the maximum applicable voltage can be de-rated (performance penalty)

$$R_{DS(on)} \sim V_{BR(DSS)}^{\;2.4\,...\,2.6}$$

TCAD predictions

- SEB threshold voltages of COTS power transistors can be characterized:
  - experimentally;
  - TCAD simulations.
- In this work, we estimate the SEB threshold voltage of a commercially available power MOSFET by mean of TCAD simulations and we compare the simulation results with the experimental data obtained from irradiation tests

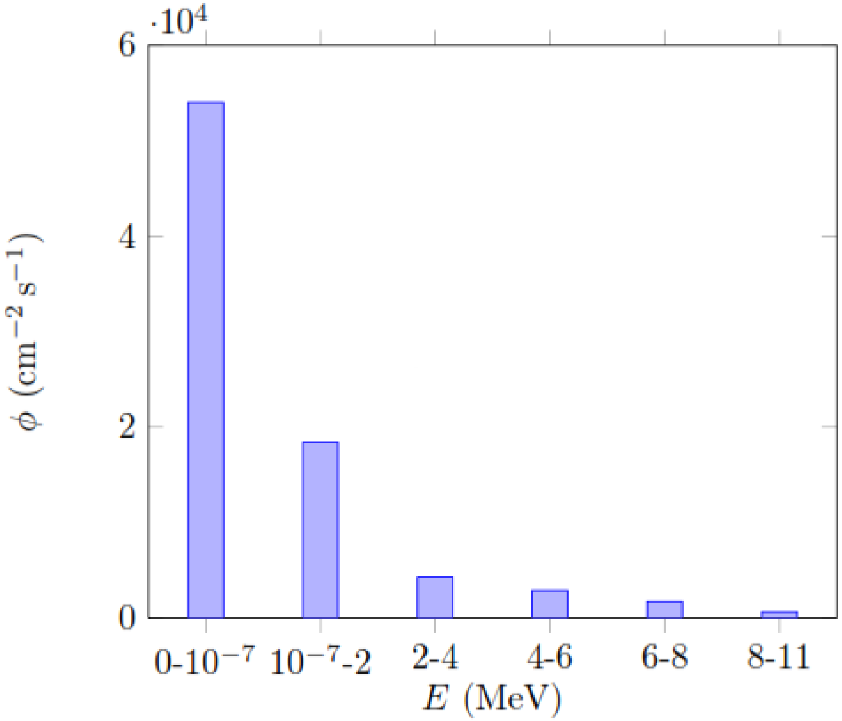
Contents

UniPA neutron facility

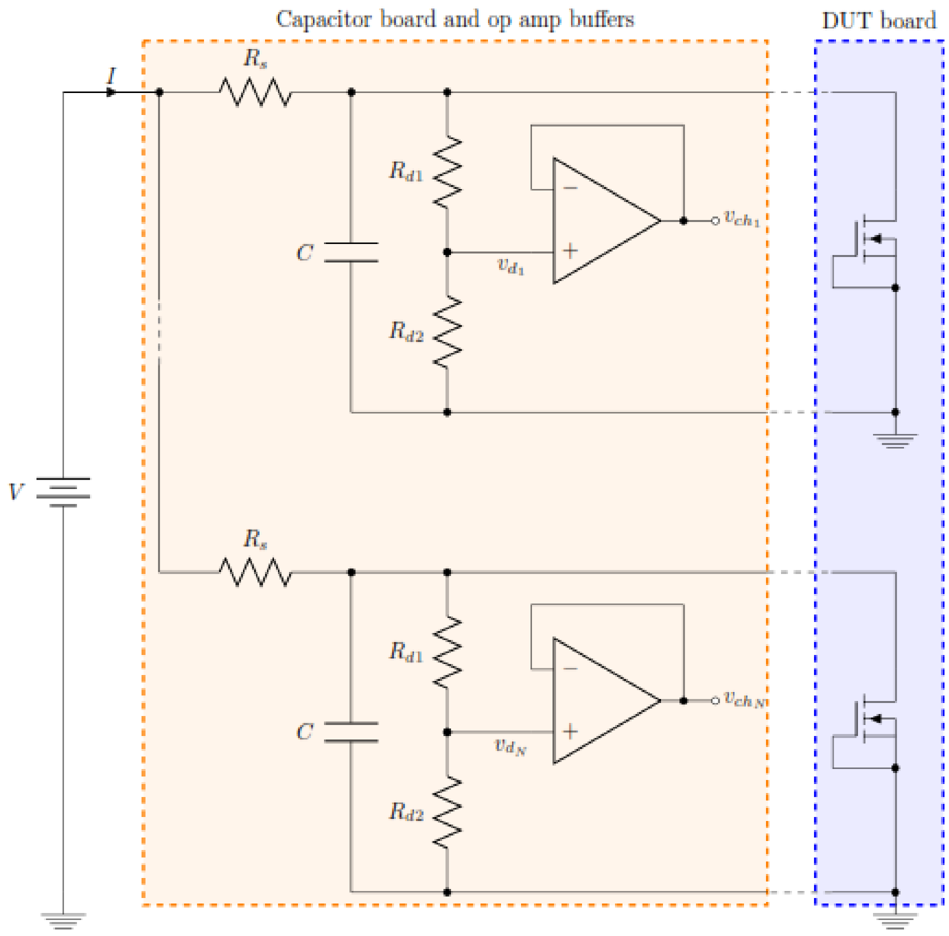
- Neutrons generated by 4 Am-Be sources, placed at the bottom of a water tank, with the following reaction:

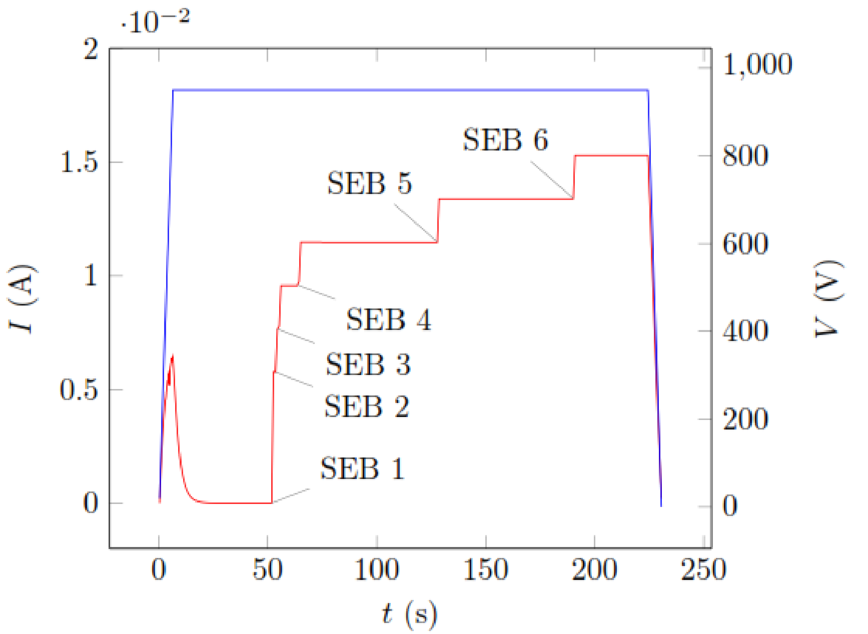
$$\alpha + {}^{9}_{4}\mathrm{Be} \longrightarrow \mathrm{n} + {}^{12}_{6}\mathrm{C}$$

- where alphas come from the natural decay of Am;
- continuous source.

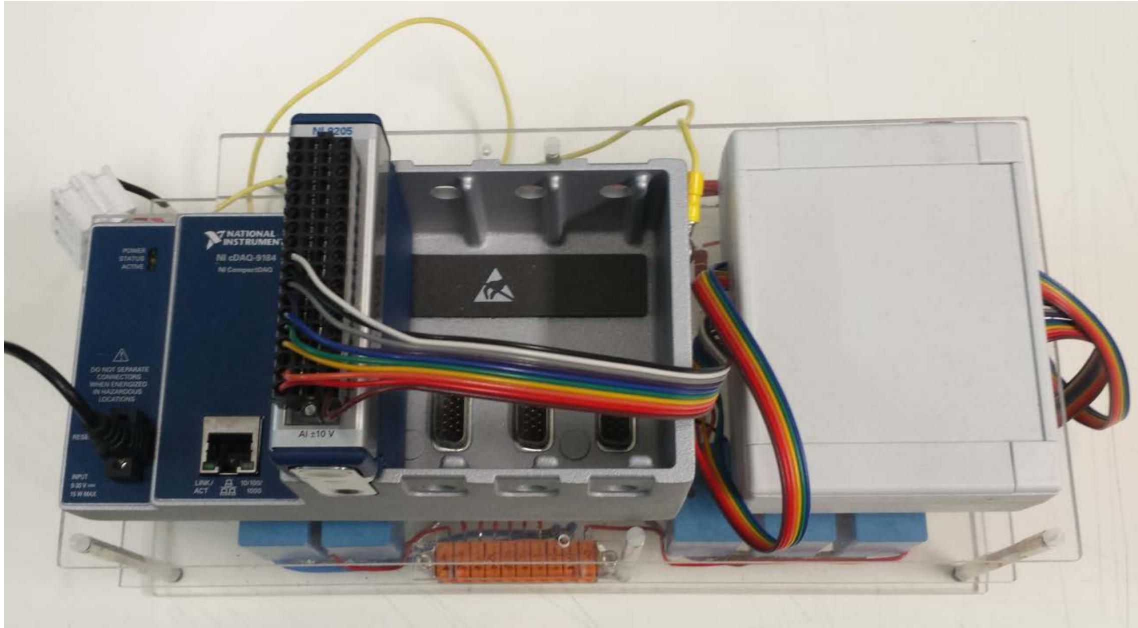


Test circuit

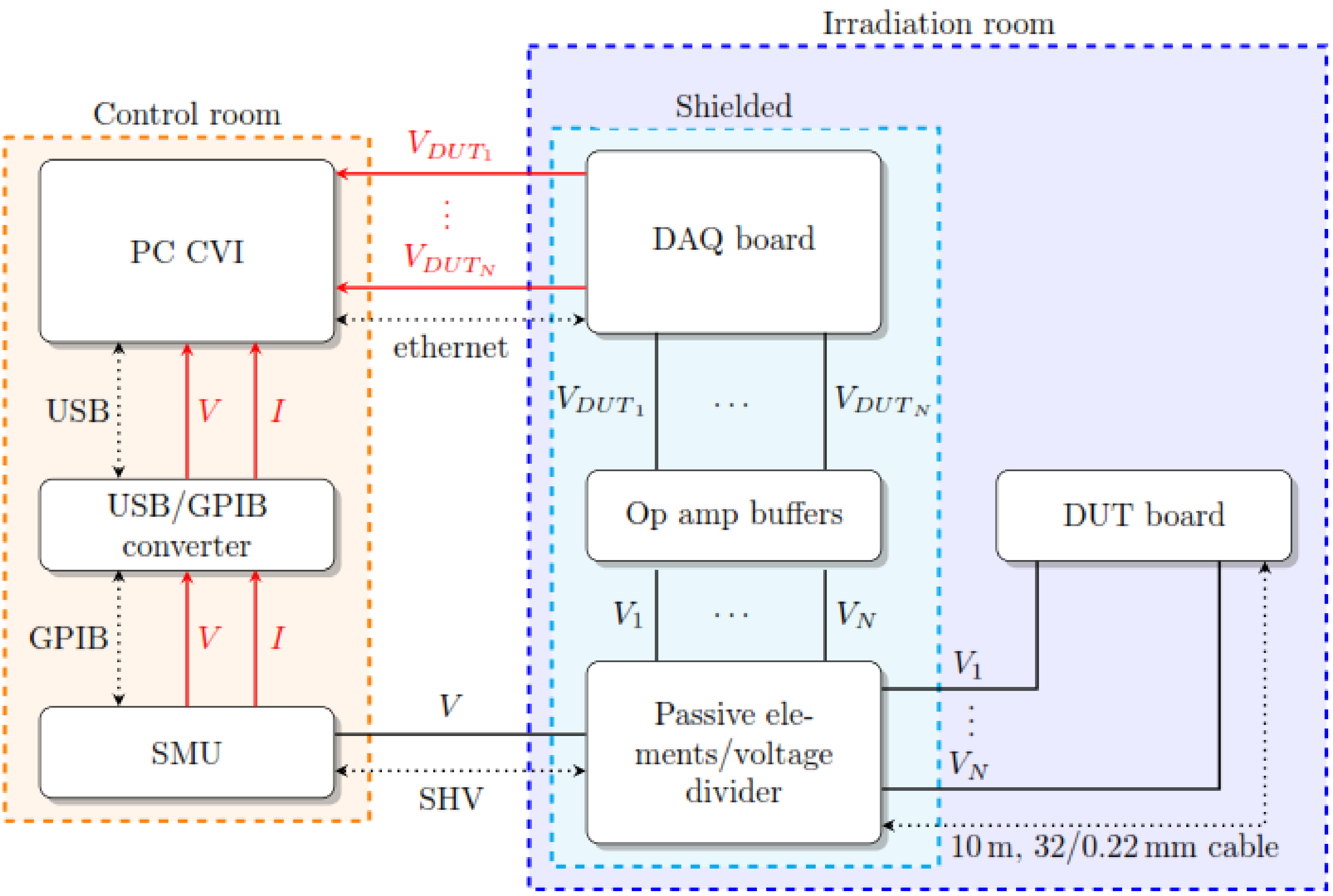




Capacitor and DUT boards



Test equipment block scheme



Weibull statistical analysis

- Failure times were recorded in order to calculate the empirical fraction yield that was compared with the cumulative pdf of the Weibull model:

t	$\hat{F}(t)$
t_1	$1/N$
t_2	$2/N$
$\vdots$	$\vdots$
t_N	1

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\tau}\right)^{\beta}\right]$$

- β and τ are respectively the shape and the scale parameters.

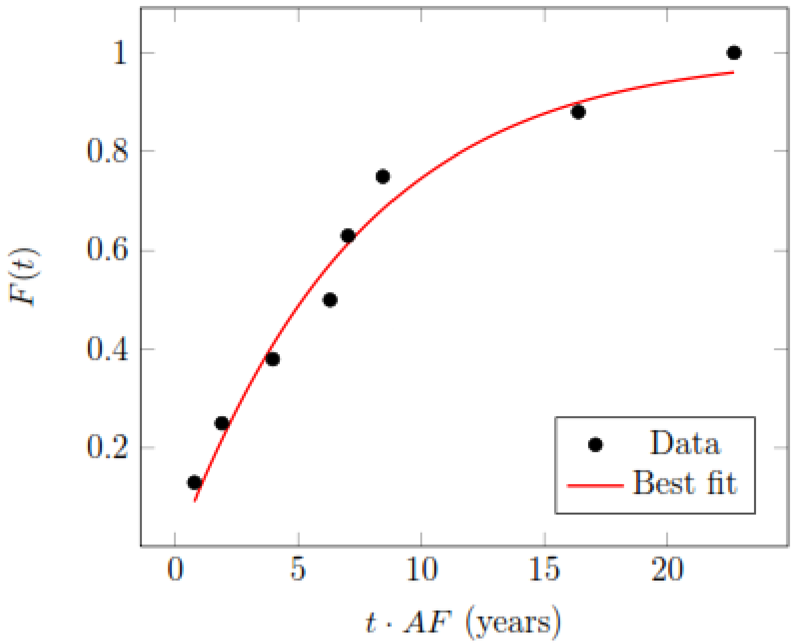
Failure rate and MTTF estimations

- Weibull fit of the empirical fraction yield allows the determination of β and τ;
- Failure rate and MTTF calculated as:

$$\lambda(t) = \frac{\beta}{\tau}\left(\frac{t}{\tau}\right)^{\beta-1}$$

$$MTTF = \tau\Gamma\left(1+\frac{1}{\beta}\right)$$

- In many experiments, β is close to 1



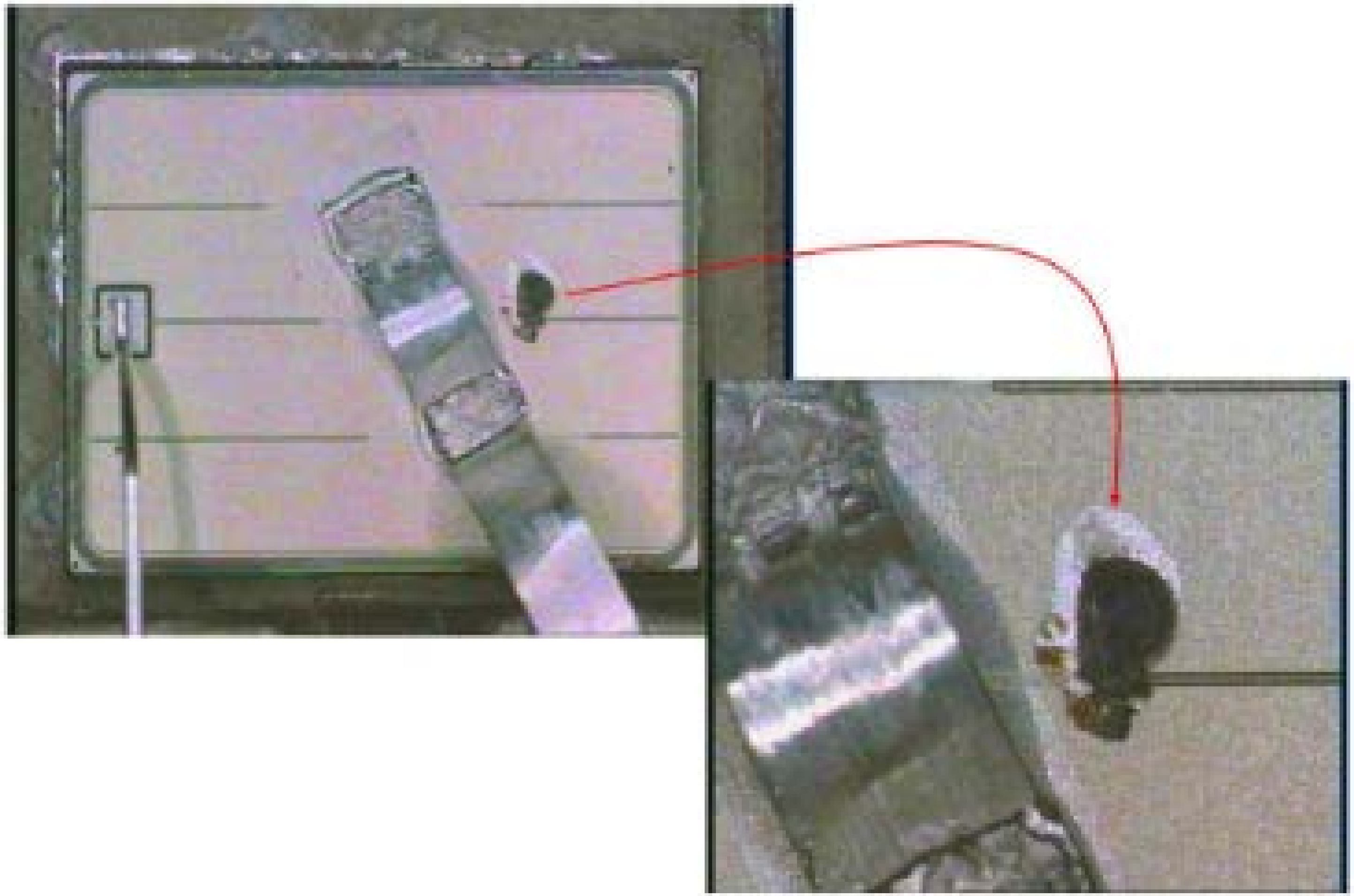
UniPA experiment results

- Tests performed on a commercial 950V power MOSFET;
- SEB threshold voltage roughly estimated as the average between the “last” safe and the “first” not safe test voltages;

#	V_t ($\%BV_{dss}$)	N_{failed}	β	MTTF (y)	λ (FIT)
1	80	0	n/d	n/d	n/d
2	85	0	n/d	n/d	n/d
3	95	7	1.4	14.6	7.8×10^3
4	100	16	0.9	3.8	3.0×10^4

- SEB not induced by radioactive decays.

Burnout traces



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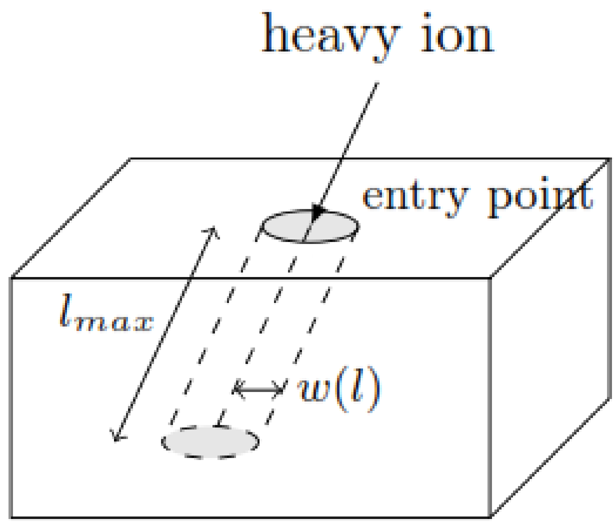
“Heavy ion” model



$$G_{ion}(l,w,t) = G_{LET}(l) \cdot R(l,w) \cdot T(t)$$

$$R(w,l) = \exp\left[-\left(\frac{w}{w_t(l)}\right)^2\right]$$

$$T(t) = \frac{1}{\sqrt{2\pi}t_c}\exp\left[-\frac{(t-t_0)^2}{2{t_c}^2}\right]$$

4 parameters are need to completely define a ionizing track:

- entry point and direction;
- LET or LCD;
- projected range.

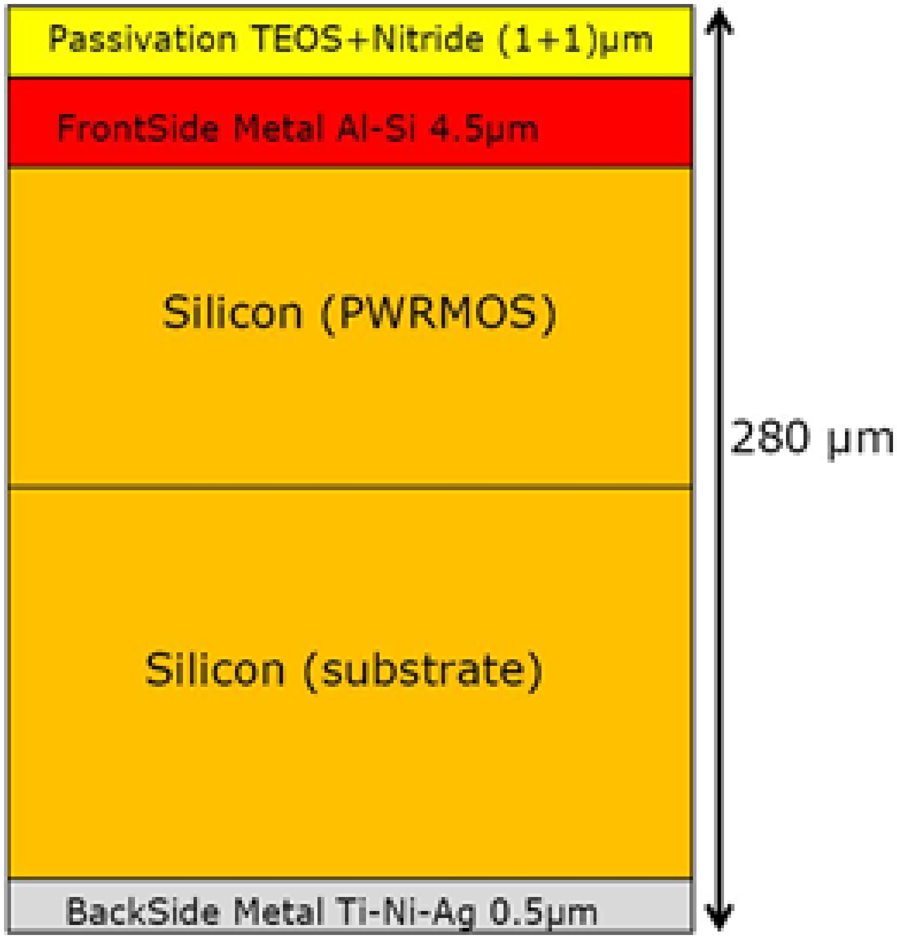
Problems arising with neutrons

- Neutrons ionize indirectly, inducing the emission of secondary charged particles, with a given probability;
- 2 or more charged recoils, multiple ionizing tracks:
  - for each track, LET and range are to be known;
  - neutron energy distribution among several products (recoil kinematics);
- the interaction point can be not only in the silicon area, but also in the other layers

Nuclear analysis

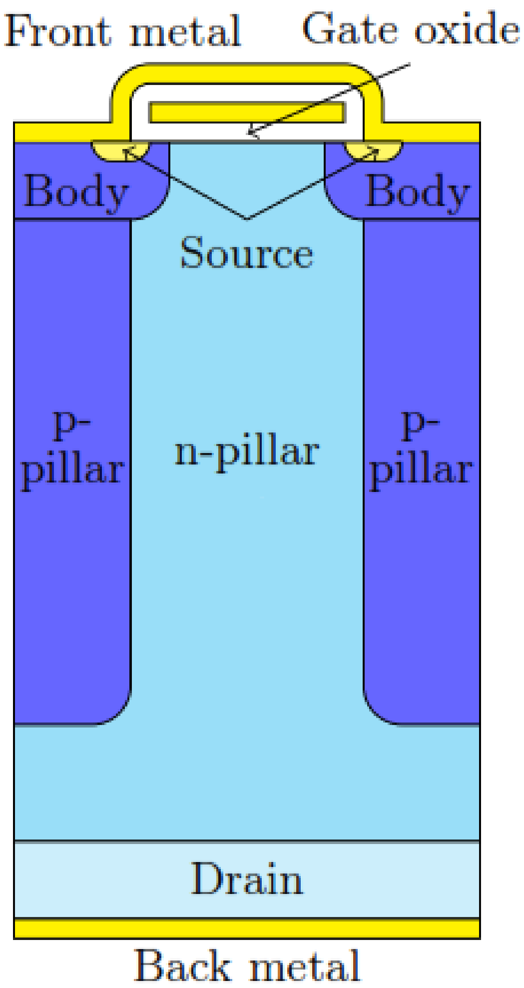
1. DUT material analysis
2. Most abuntant isotope identification for each material
3. 2 product nuclear reaction cross section from ENDF database
4. Reaction rates calculation
5. Most likely nuclear reactions identification, w.r.t. neutron energies
6. Nuclear products energy computation
7. SRIM/TRIM LET and projected range calculations
8. Heavy ion model for each product, multiple tracks
9. Charge density distribution

DUT materials analysis



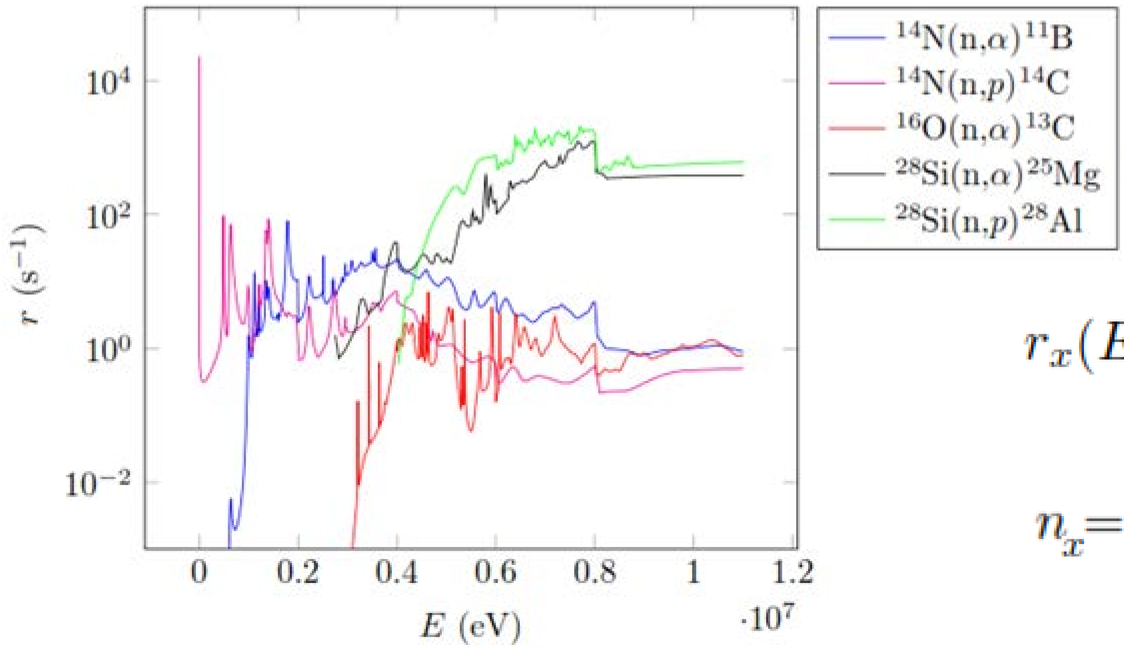
Region	Chemical elements
Active+Substrate	Si, B (body and p-pillar dopant), P (source and n-pillar dopant), As (drain dopant), O (SiO_2 oxide)
Passivation	TEOS ($Si(OC_2H_4)_4$) and Si_3N_4
Front metal	Al, Si
Back metal	Ag, Ni, Ti

Active area



Region	Doping	Concentration [cm^{-3}]
Source	$n+$	1×10^{20}
Body	$p+$	1×10^{19}
Drain	$n+$	1×10^{19}
N-pillar	n	1×10^{15}
P-pillar	p	3×10^{15}

Reaction rates

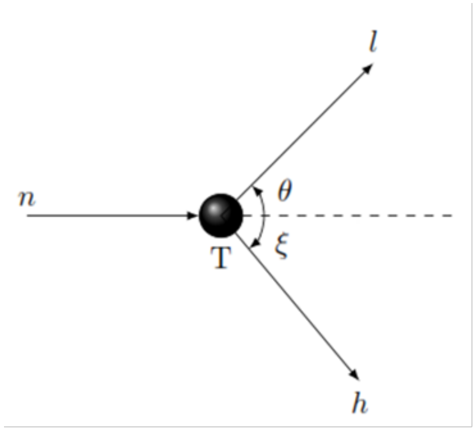


$$r_x(E) = \phi(E) \cdot \sigma_x(E) \cdot n_x \cdot V_x$$

$$n_x = \frac{\rho_x \cdot N_{av}}{M_x}$$

Reaction	Layer	E [eV]	r [s^{-1}]	Q-value [eV]	Decay	Half life	Decay product
^{14}N(n, α)^{11}B	Passivation	1.8×10^6	72	-1.6×10^5	-	Stable	-
^{14}N(n, p)^{14}C	Passivation	1.0×10^{-5}	23 008	6.3×10^5	β^-	5.7×10^5 years	^{14}N (stable)
^{14}N(n, p)^{14}C	Passivation	4.9×10^5	95	6.3×10^5	β^-	5.7×10^5 years	^{14}N (stable)
^{14}N(n, p)^{14}C	Passivation	1.3×10^6	58	6.3×10^5	β^-	5.7×10^5 years	^{14}N (stable)
^{28}Si(n, α)^{25}Mg	Active area	7.9×10^6	1176	-2.6×10^6	-	Stable	-
^{28}Si(n, p)^{28}Al	Active area	7.7×10^6	2063	-3.9×10^6	β^-	2.2 minutes	^{28}N (stable)

Ionizing tracks, energy computation



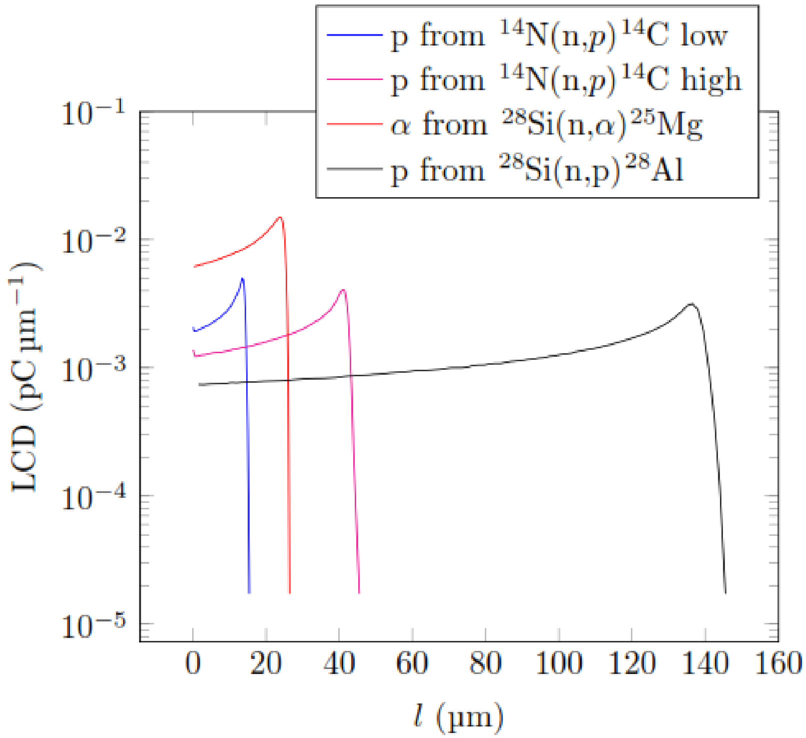
$$T_l^{1/2} = \frac{(m_n m_l T_n)^{1/2}\cos\theta}{m_h + m_l} \pm \frac{\{m_n m_l T_n \cos^2\theta + (m_h + m_l)\left[m_h Q + (m_h - m_n) T_n\right]\}}{m_h + m_l}$$

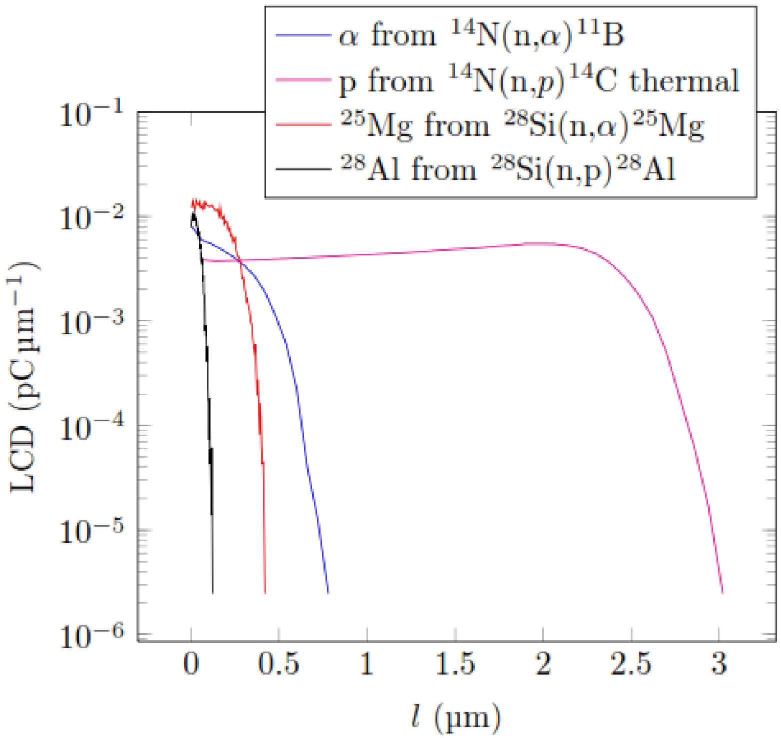
$$T_h = Q - T_l + T_n$$

$$\sin\xi = \left(\frac{p_l}{p_h}\right)\sin\theta$$

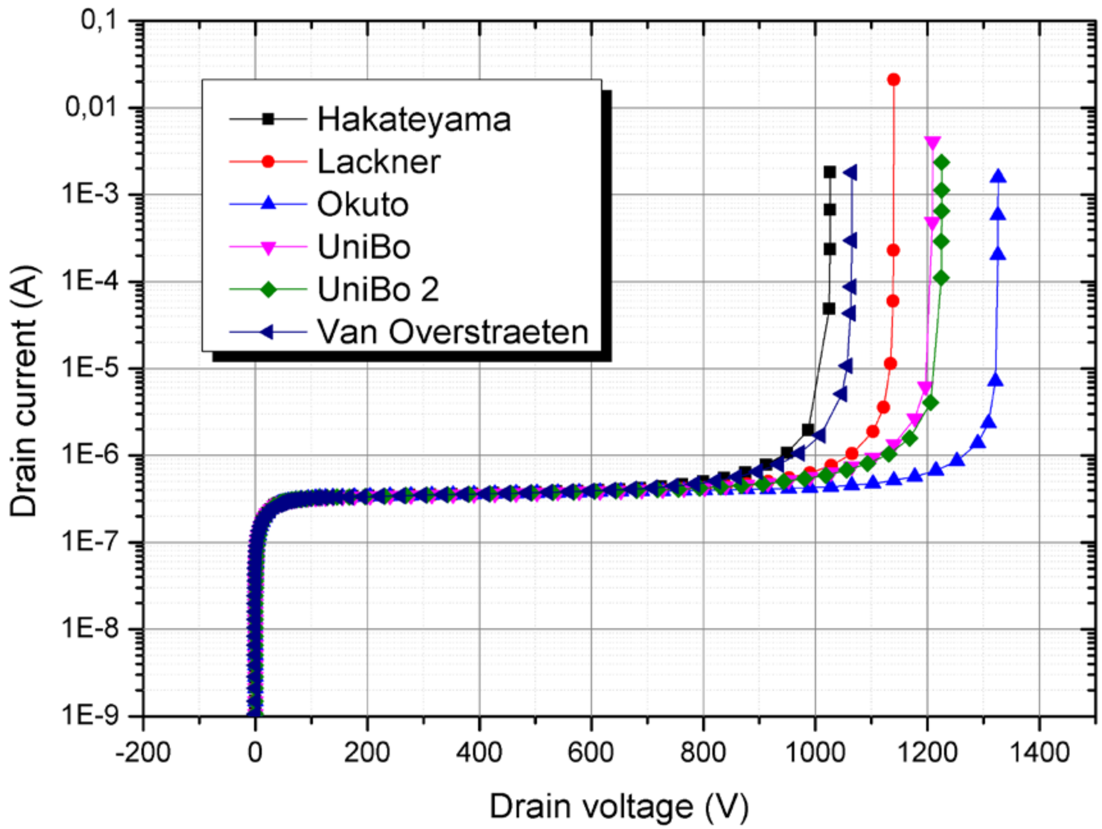
Reaction	T_n [MeV]	T_l [MeV]	T_h [MeV]	θ [°]	ξ [°]
$^{14}\mathrm{N}(\mathrm{n},\alpha)^{11}\mathrm{B}$	1.8	1.5	1.2×10^{-1}	5	11
$^{14}\mathrm{N}(\mathrm{n},\mathrm{p})^{14}\mathrm{C}$	1.0×10^{-11}	6.0×10^{-1}	4.2×10^{-2}	5	5
$^{14}\mathrm{N}(\mathrm{n},\mathrm{p})^{14}\mathrm{C}$	5.0×10^{-1}	1.1	9.3×10^{-3}	5	15
$^{14}\mathrm{N}(\mathrm{n},\mathrm{p})^{14}\mathrm{C}$	1.3	2.0	5.1×10^{-3}	5	27
$^{28}\mathrm{Si}(\mathrm{n},\alpha)^{25}\mathrm{Mg}$	7.9	5.2	1.2×10^{-1}	5	13
$^{28}\mathrm{Si}(\mathrm{n},\mathrm{p})^{28}\mathrm{Al}$	7.7	3.8	2.6×10^{-2}	5	12

Ionizing tracks, LCD and range (in Si)



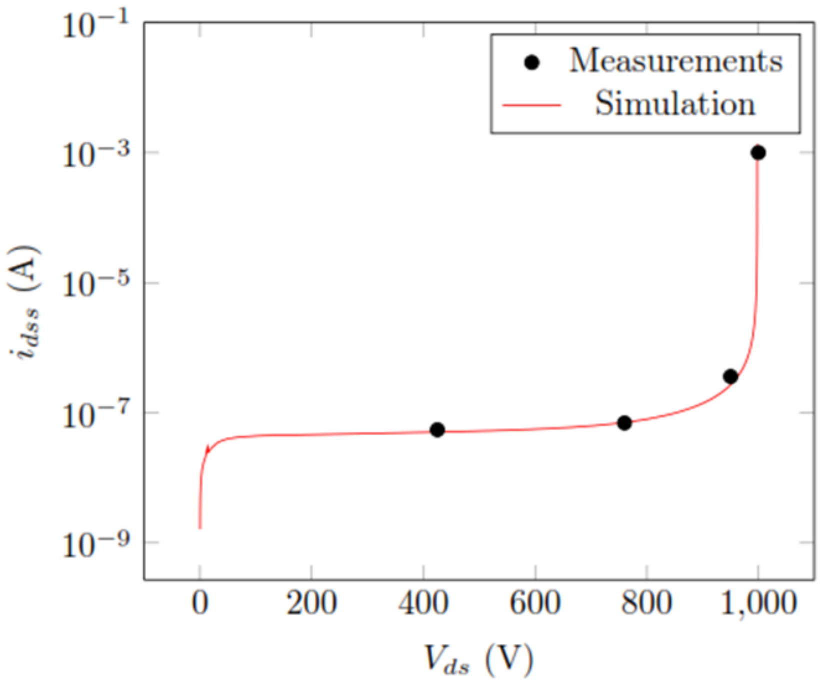


Calibration



In order to perform predictive SEB simulations, it is necessary to select an adequate impact ionization model and to proper calibrate the reverse static I/V curve.

Calibration (cont.)



$$\alpha(F_{ava}) = \gamma a \exp\left(-\frac{b}{F_{ava}}\right)$$

$$\tau_{dop}(N_i) = \tau_{min} + \frac{\tau_{max} - \tau_{min}}{1 + \left(\frac{N_i}{N_{ref}}\right)^{\gamma}}$$

Parameter	Default value	Tuned value
τ_{max} (electron)	$1.00 \times 10^{-5}\,\mathrm{s}$	$8.50 \times 10^{-5}\,\mathrm{s}$
τ_{max} (hole)	$3.00 \times 10^{-6}\,\mathrm{s}$	$2.55 \times 10^{-5}\,\mathrm{s}$
b (electron)	$1.23 \times 10^{6}\,\mathrm{V\,cm^{-1}}$	$1.17 \times 10^{6}\,\mathrm{V\,cm^{-1}}$
b (hole)	$2.04 \times 10^{6}\,\mathrm{V\,cm^{-1}}$	$1.93 \times 10^{6}\,\mathrm{V\,cm^{-1}}$

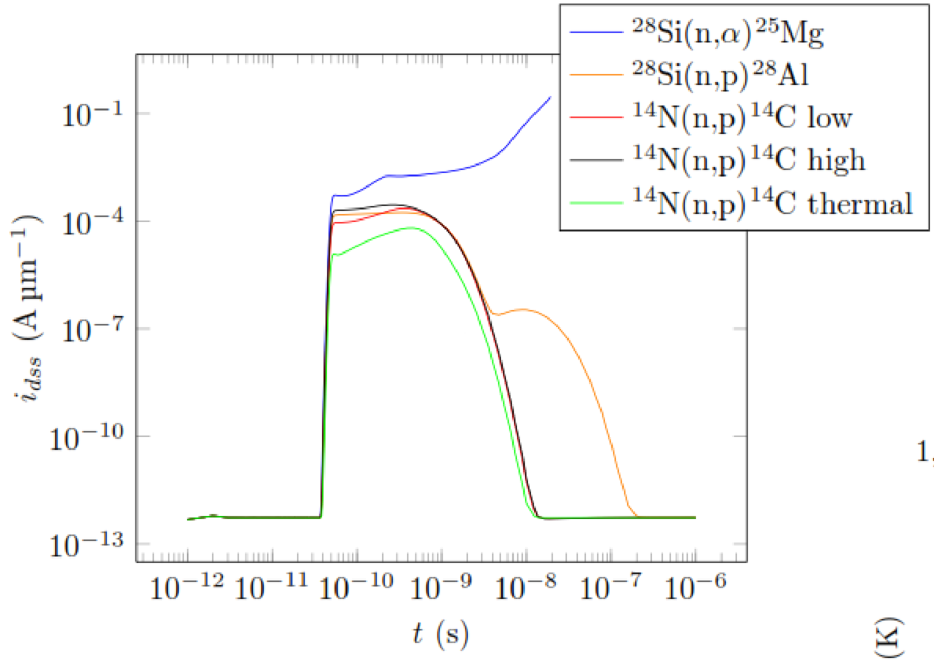
Design Of Experiments

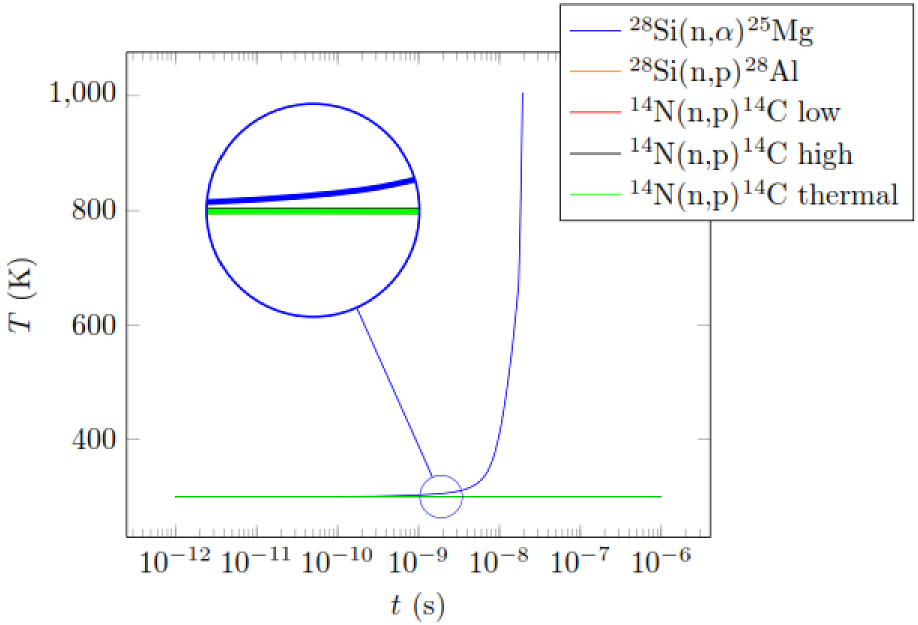
- The simulation parameters are:
  - test voltage (85%, 95% and 100% of BVdss);
  - several nuclear reactions;
  - interaction point in the active area: neck region, channel and body at 3 different depths

Results

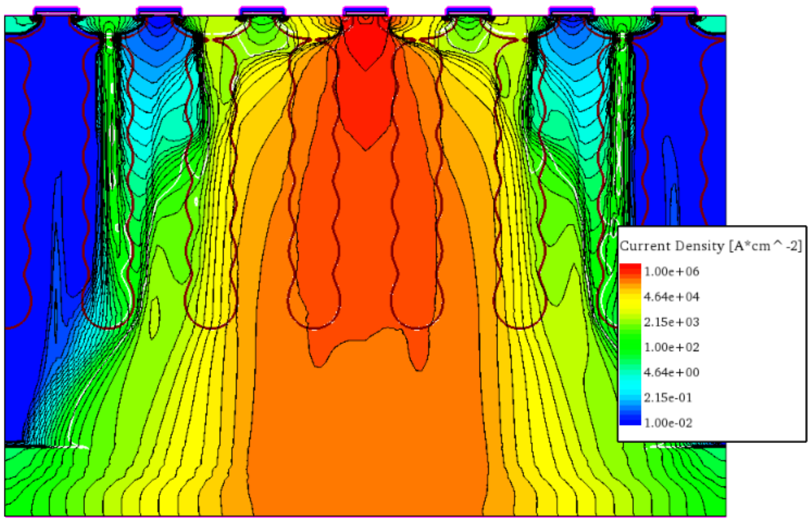
- As in the UniPA experiment, we detected SEB at the 95% of BVdss.
- In addition, the simulation gives us further details:
  - SEB are caused only by the nuclear reaction with alpha particle emission;
  - only few interaction point are really effective, even for drain voltages higher than the SEB threshold;
  - the most sensitive regions are the neck and the channel in the first 30 μm from the silicon/metal boundary.

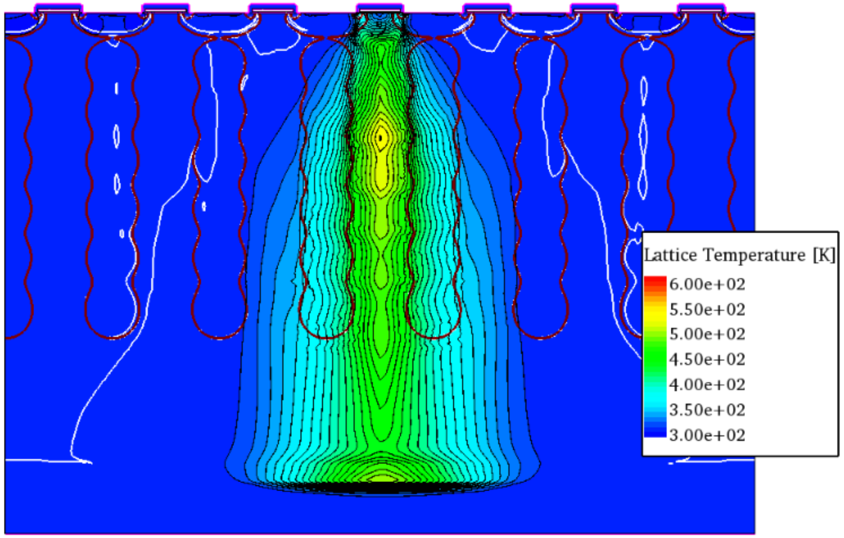
Drain current and lattice temperature

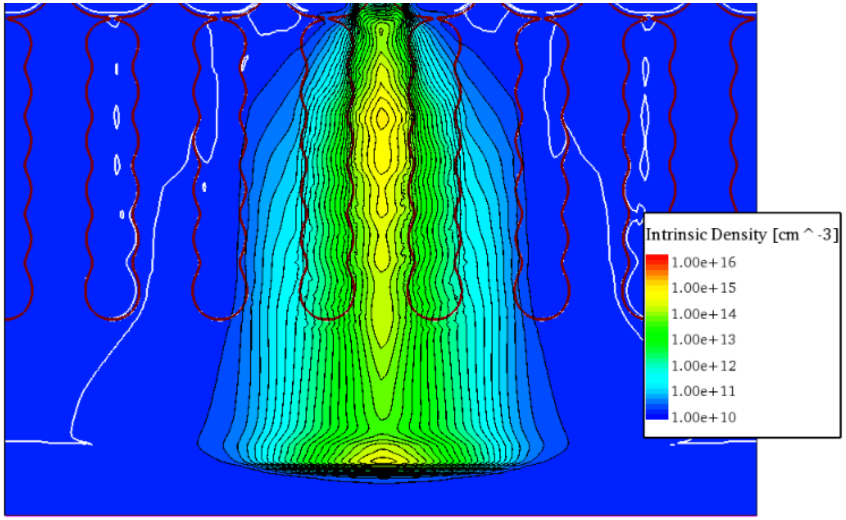




Field quantities







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Final remarks

- Simulation results are in agreement with the experimental data;
- TCAD simulations allow us to assess which nuclear interaction induces SEB and where!
- For more energetic neutrons (spallation phenomena), Montecarlo tools are needed.

Thanks for the attention!