ECORCE
A TCAD tool for SEE prediction

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Summary

I- ECORCE: a TCAD tool for prediction

Etude du COmportement sous Radiation des Composants Electroniques

Similar to SENTAURUS and ATLAS

Designed to **ease** TCAD implementation

Special features

- Full graphical interface
- Control of model definition
- **Dynamic mesh (correct mesh at each step)**
- **Optimizer (equivalent to DOE)**

- **Single Event: real profile of ion**
- **Dose and dose rate effect:**
  Multiple trapping-detrapping model in insulator volume and at interfaces.
  Low and high temperature
- **Displacement damages creation (experimental)**

→ suitable for **teaching** (7 years effects of radiation,10 years finite element method)

115000 lines of code, 30 years of development, university of Montpellier
Commercial distribution by the SAS Delphea
ITAR free

II- Failure induced by 200 MeV Neutron in SiC power MOSFET

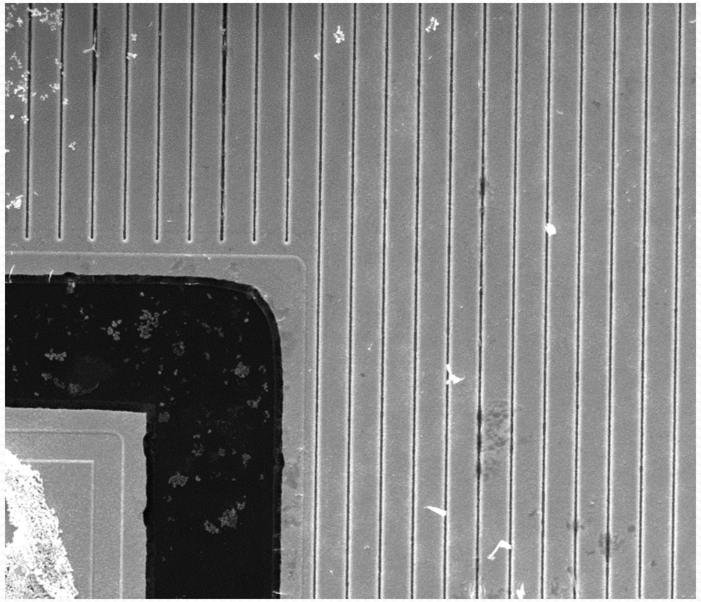
Objective

Calculate sensitivity of SiC VDMOS power MOSFET to ground level neutron

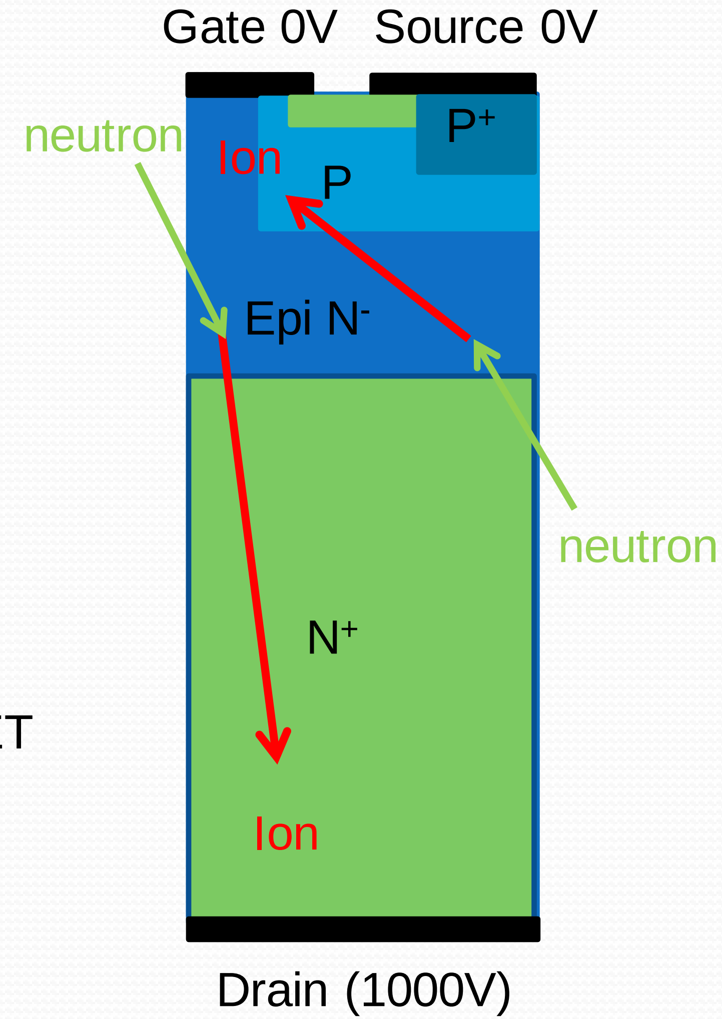
Multiple finger structure

High drain bias (1000V)

Worst case study: 200 MeV neutron



Exemple of multiple finger MOSFET



Half cell view

Neutron → no direct effect
→ **generation of a secondary ion can trigger a failure**

II- Failure induced by Neutron in SiC power MOSFET

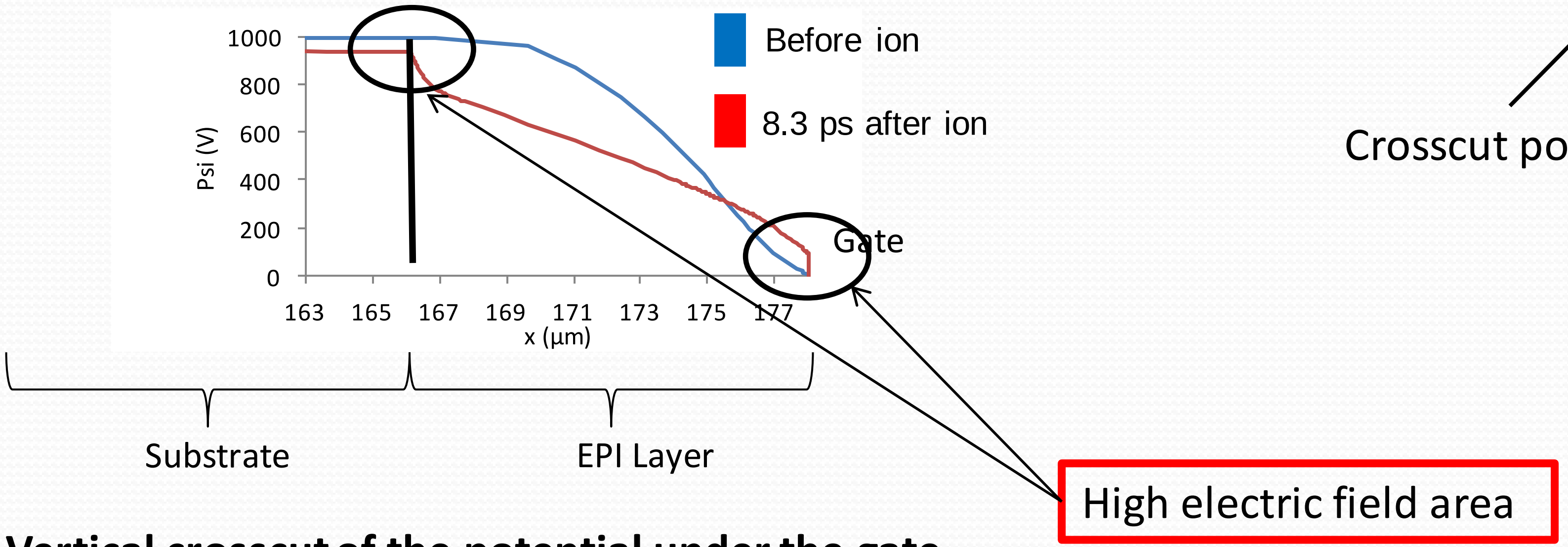
TCAD tool: Mechanism at play

→ Ion creates a conductive path in the EPI layer below the gate oxide

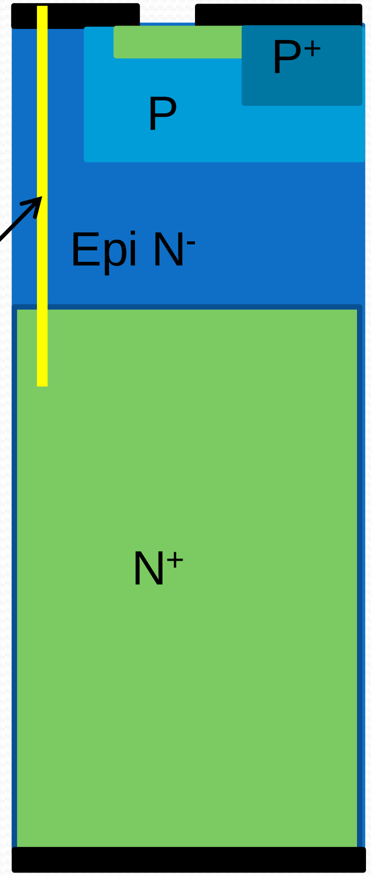
→ The difference of potential in the EPI layer is reduced.

→ A high electric field appears in the gate oxide

→ An increase of temperature appears because of joule effect



Vertical crosscut of the potential under the gate



II- Failure induced by Neutron in SiC power MOSFET

<u>6 secondary ions tested</u>

→ Si 26 and 100 MeV

→ Al 27.6 MeV → Mg 30.7 MeV

→ Na 32 MeV → B 61.1 MeV

(Al, Mg, Na and B generated by nuclear reaction)

<u>For each type of ion (Si, Al, Mg,…)</u>

→ 80 impact points by ion, in the EPI layer

→ 8 ion directions by position

→ 640 simulations by ion

3840 simulations for all ions

<u>Calculation time with one processor</u>

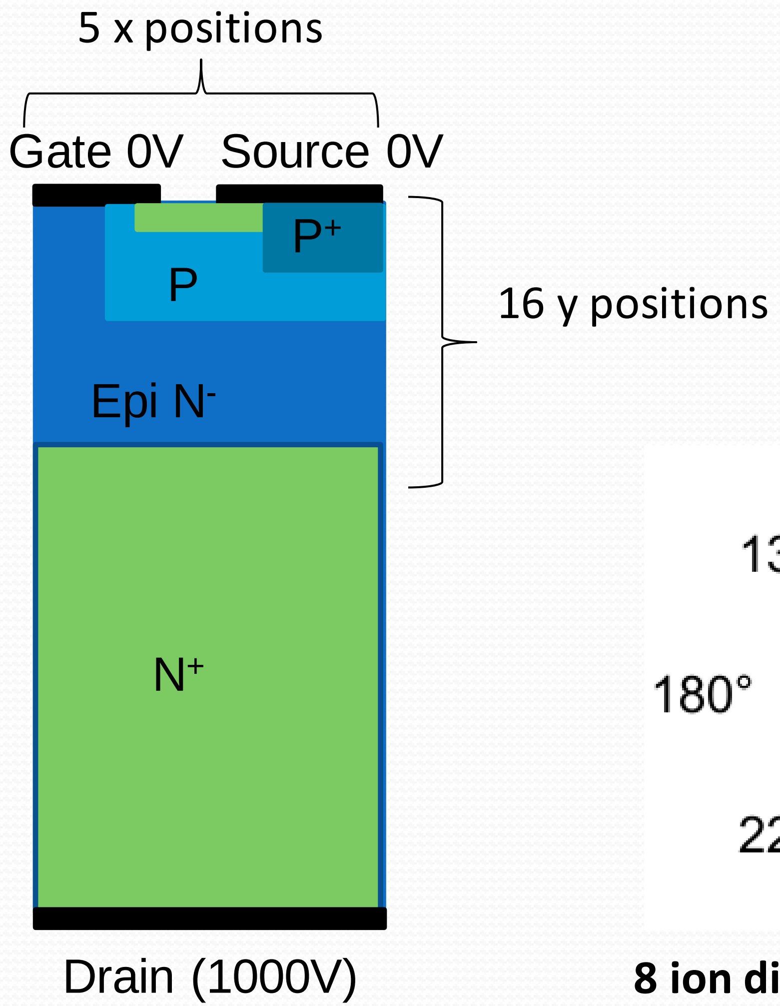
→ Most simulations: 1 hour

→ 1 simulation over 10: 24 hours

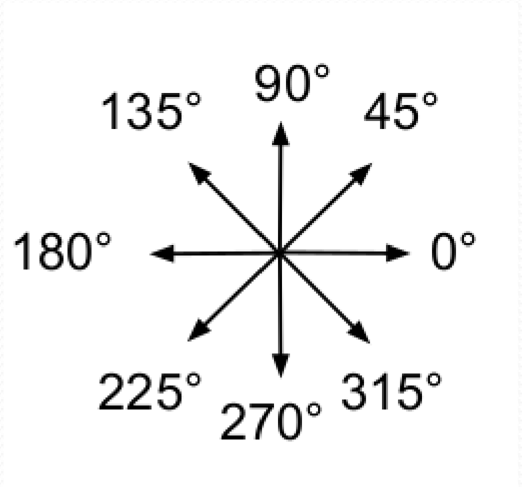
→ **Total 12000 hours with one processor**

With a 72 processors computer:

→ **7 days of calculation**



80 impact points by ion
In the EPI layer



8 ion directions by position

II- Failure induced by Neutron in SiC power MOSFET

Failure criteria based on

→ Maximum electric field in the gate oxide

(can induce a gate rupture)

→ Maximum temperature during ion crossing

(can trigger a burnout ,

image of the duration of the ion effect)

(dark purple)	Major risk : Emax ≥7.9 MV/cm
(red)	High risk : Emax ≥4.9 MV/cm and Tmax ≥ 350 K
(orange)	Medium risk : Emax ≥4.9 MV/cm and Tmax < 350 K
(yellow)	Minor risk: Emax < 4.9 MV/cm and Tmax ≥ 400 K
(green)	No risk

II- Failure induced by Neutron in SiC power MOSFET

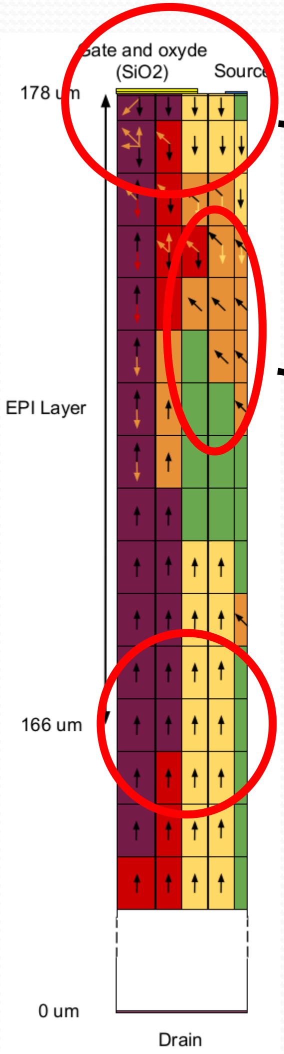
ECORCE
Finite volume software
http://www.ecorce.eu

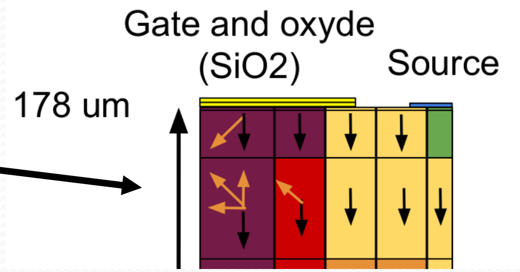
Ion: Na (Z=11)
Energy: 32 MeV
Range: 9.93 μm

Black arrow:
ion direction for the main risk

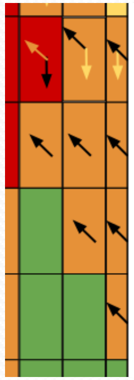
Colored arrow:
ion direction for a secondary risk

Arrow color indicates the risk level

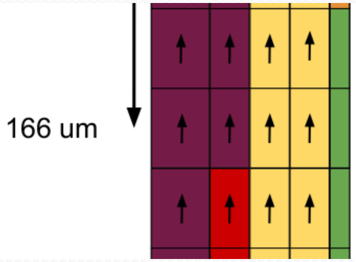




Impact point below gate, close to the gate
→ Major and high risk, direction ↓



Impact point below source, Middle of EPI layer
→ Medium risk, direction ↖



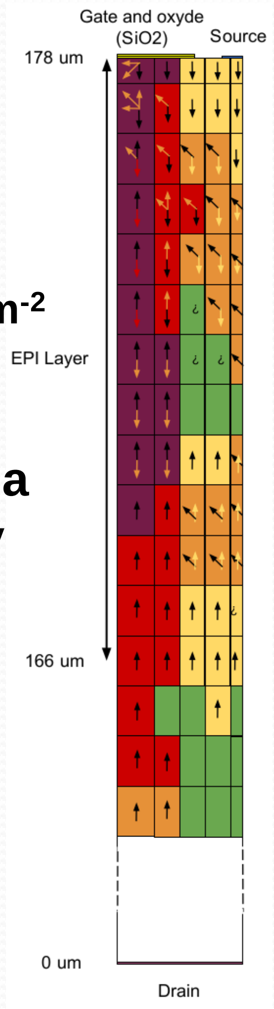
Impact point below gate, close to the substrate
→ Major and high risk, direction ↑

Failure mainly triggered for charges deposited all along the EPI layer

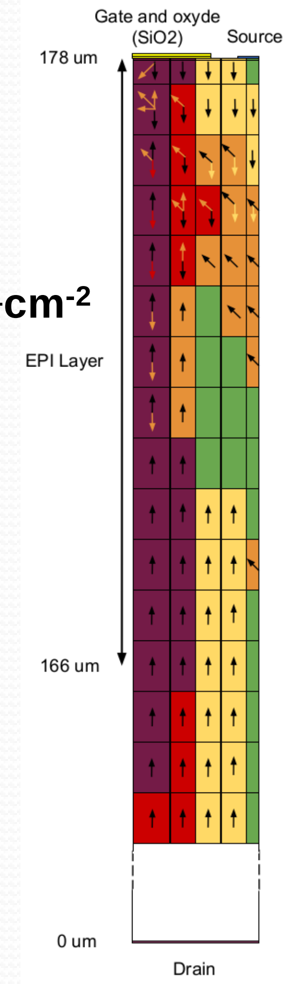
II- Failure induced by Neutron in SiC power MOSFET

Ion: Mg (Z=12)
Energy: 30.7 MeV
Range: 8.73 µm
LET: 12.2 MeV mg^{-1}cm^{-2}

Higher LET but lower range than Na → lower sensitivity

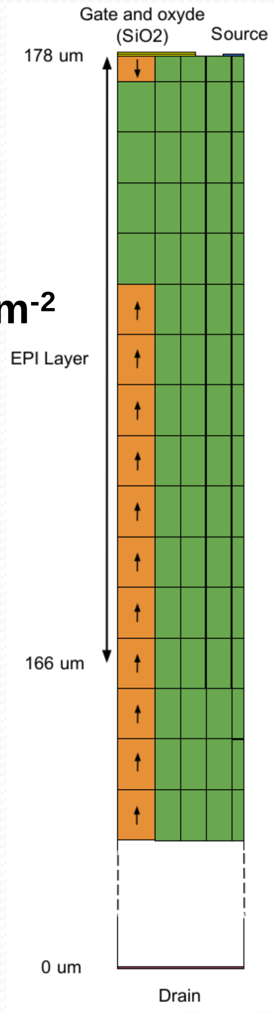


Ion: Na (Z=11)
Energy: 32 MeV
Range: 9.93 µm
LET: 10.6 MeV mg^{-1}cm^{-2}



Ion: B (Z=5)
Energy: 61.1 MeV
Range: 81.1 µm
LET: 1.47 MeV mg^{-1}cm^{-2}

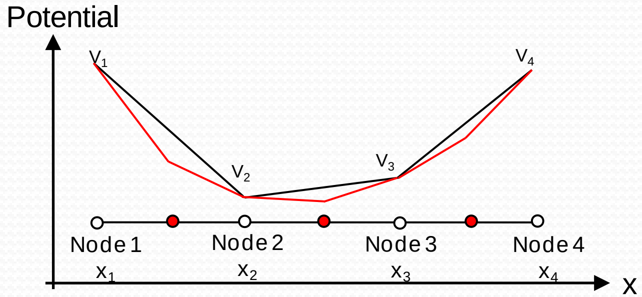
Higher range but lower LET than Na → No sensitivity



Burnout strongly rely on ion range and initial LET
No failure for low Z ions

III- Dynamic mesh, why?

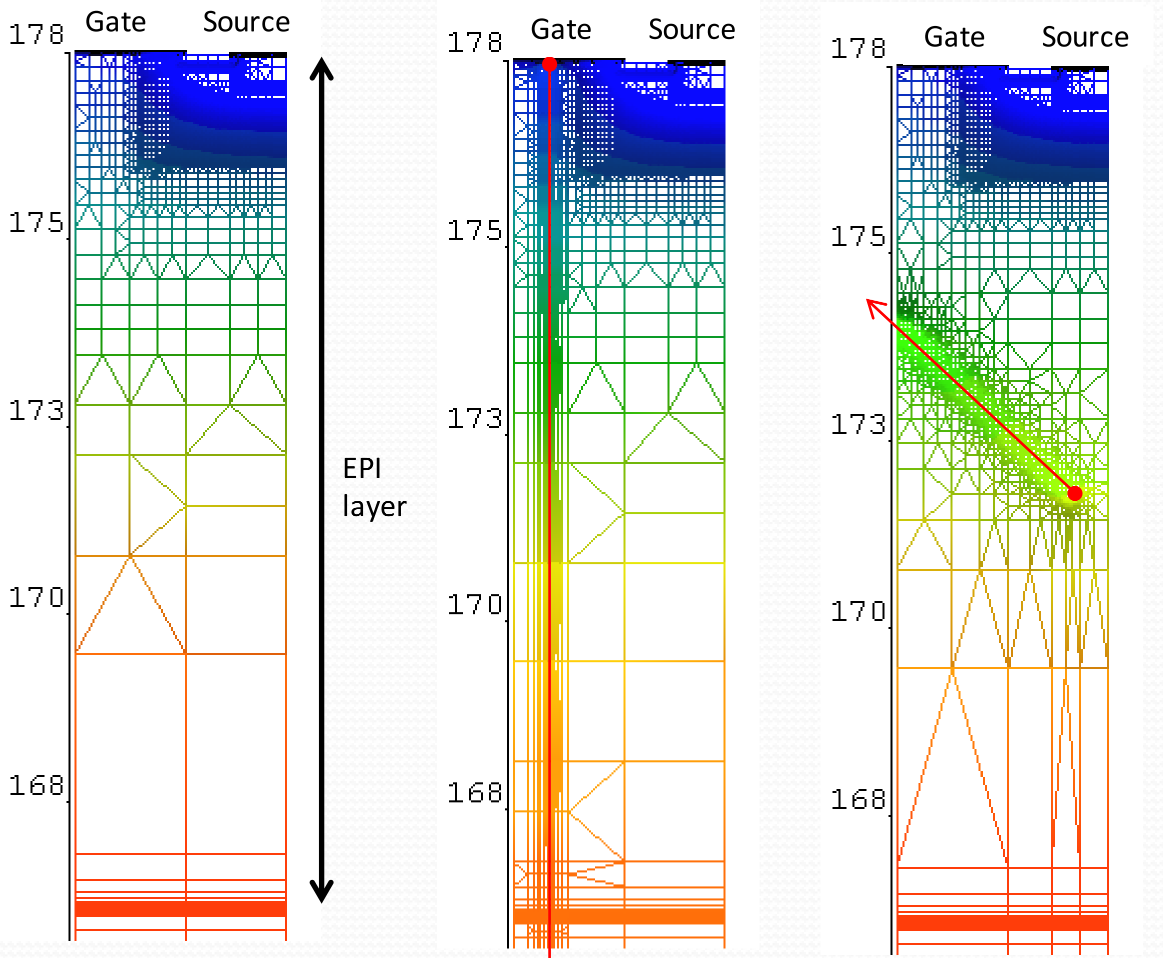
Mesh design
→ Small change of gradients between 2 elements
→ Difficult to handle by hand
→ Gradients change at each step, need to refine



High gradient area, need to add nodes

Badly designed mesh
→ Unprecise result (error > factor 2)
→ Convergence problem

<u>Mesh changed for each simulation</u>
→ With ECORCE, mesh created automatically
→ Work made by hand with all other TCAD tools

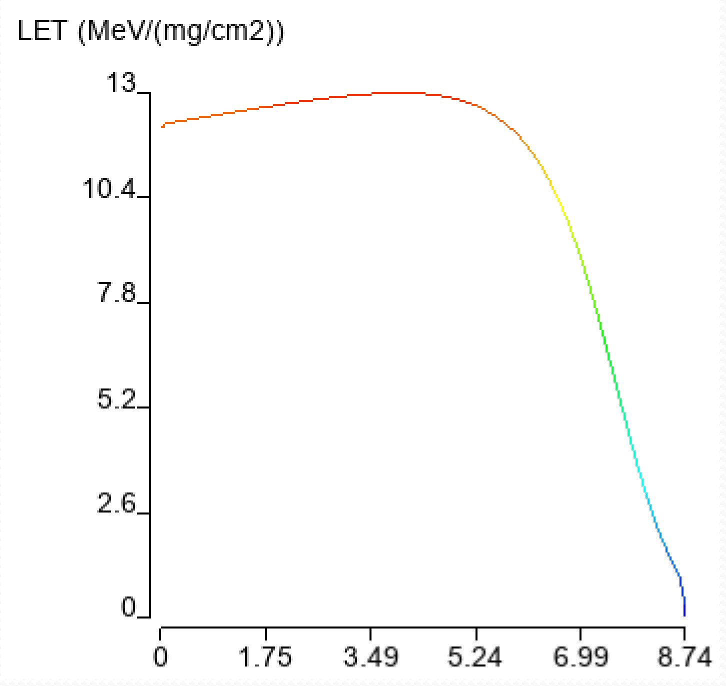


Mesh before ion

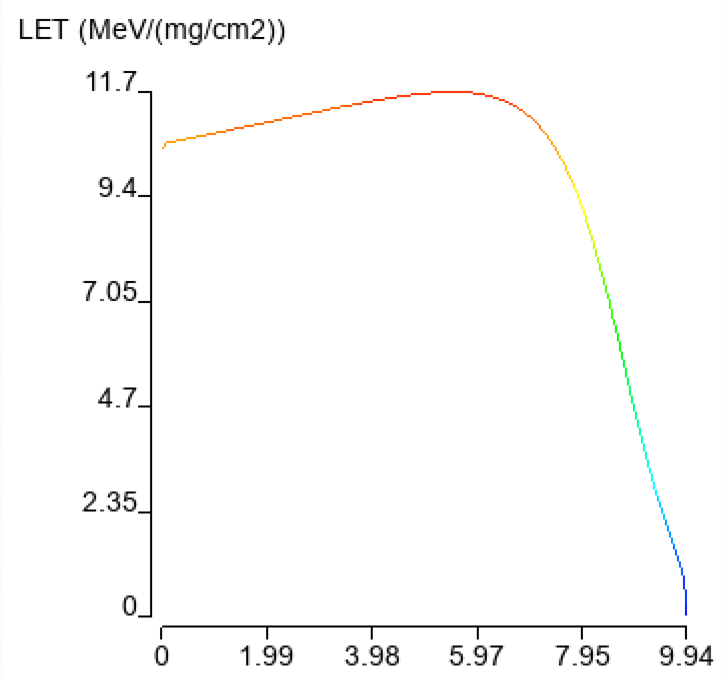
Mesh impact x= 0.5, y=178.022, angle 270°

Mesh impact x= 2.5, y=172, angle 135°

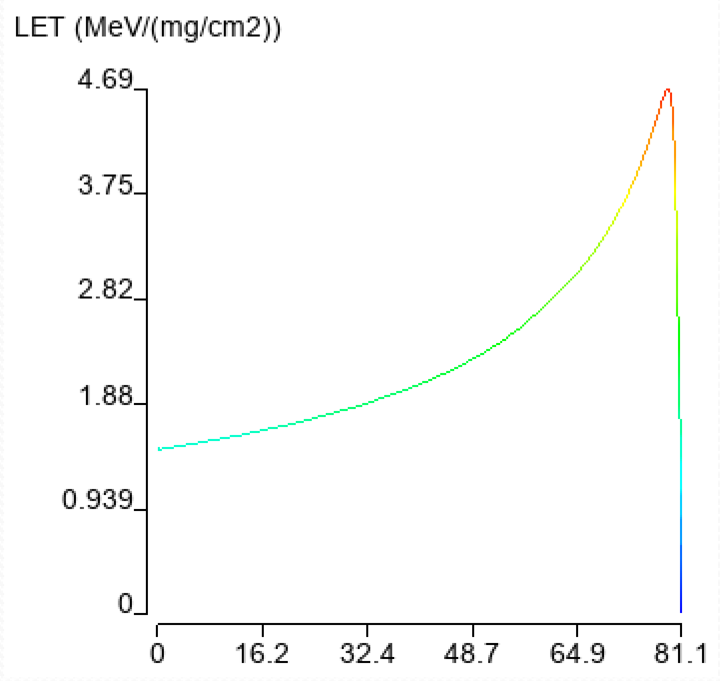
IV- Ion profile definition



LET profile ion Mg 30.7 MeV



LET profile ion Na 32 MeV



LET profile ion B 61.1 MeV

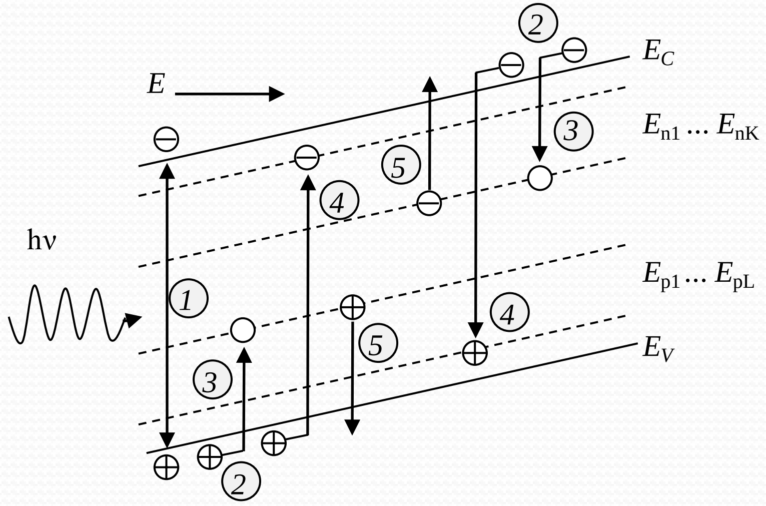
Ion profile most often constant in TCAD tool
→ With ECORCE, full profile taken into account
→ All ions available for all materials

V- Trapping-detrapping model for microdose

O. L. Curtis Jr and J. R. Srour, “The multiple-trapping model and hole transport in SiO2”, *J. Appl. Phys.*, vol. 48, no. 9, pp. 3819–3828, 1977

Oxide → wide band gap semiconductor
→ defects inside the gap, trap charges

Traps defined by → activation energy
→ density



Band diagram in insulators

Phenomena taken into account

① electron-hole pairs generated by radiation
② drift-diffusion of carriers in their respective allowed band
③ trapping of free carriers
④ recombination of trapped carriers by free carriers of the opposite type
⑤ thermal reemission of trapped carriers to their respective allowed band

Used to modelize Total Ionizing Dose (more precise than fixed charges)
For low (≥ 100K) and high temperature
Mandatory to simulate microdose deposited by ion in insulators.
Microdose can induce long term effects in devices

VI- Conclusion

Compared to prediction tools:

→ **No calculation of cross-section**

→ **Longer calculation time than simplified tools that do not take into account all the physical mechanisms**

→ **More precise results**

→ **Analysis of failure mechanisms**

Thank to the dynamic mesh and the graphical interface
→ **quick implementation and solving faster than any other TCAD tool**

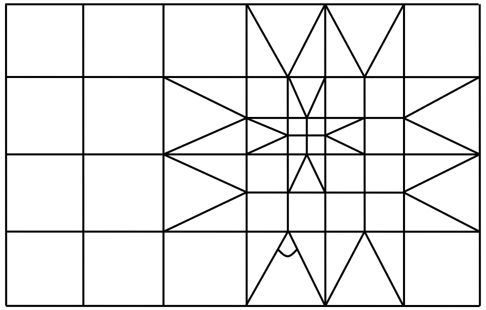
Many materials including : Si, SiC, GaN, Diamond

Demonstration at coffee break?

Mesh design

TCAD → modeling of component based on semiconductors and insulators,

by solving differential equations: Poisson, Transport, Heat, Trapping, …

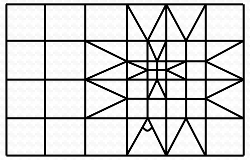


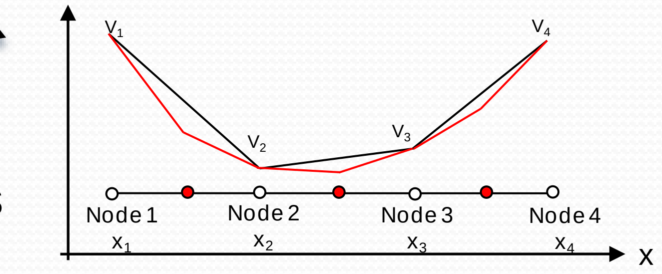
No analytical solution, solving method:

→ **Discretisation** of differential equations: **Variation of DF linear** in each element

→ Approximate solution: mesh adjusted to control the error

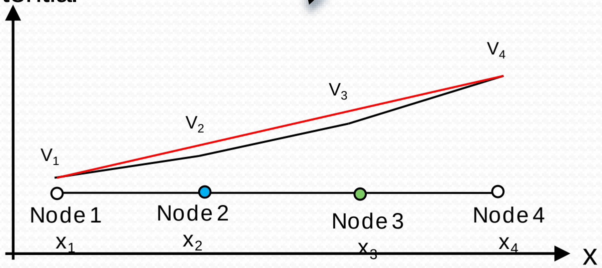
Mesh design





High gradient area, need to add nodes

Finer mesh on high gradient area
→ improves precision of results



Low gradient area, need to remove node

Coarse mesh on low gradient area
→ reduces computation time

“Dynamic mesh for TCAD modeling with ECORCE”, A Michez et al 2016 J. Phys.: Conf. Ser. 738 012128

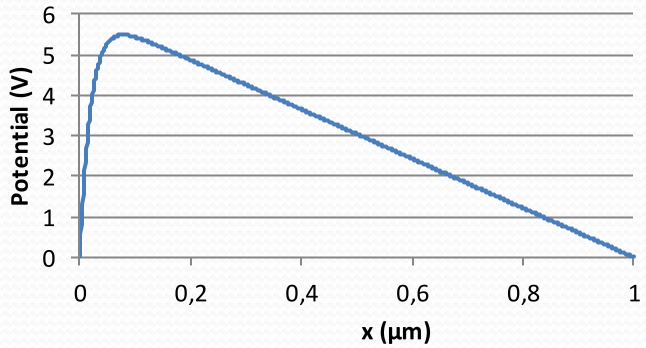
Complicated task → difficult to design an optimized mesh by hand

Should be automatically handled by the TCAD tool.
ECORCE provides a dynamic mesh generator that add and remove nodes at each step of the modeling

Is it really so important for results precision?

Mesh Design

Q_{max} (cm^{-3})	σ (μm)	q (C)	(Rel.)
10^{18}	0.02	1.6×10^{-19}	11.9



Potential induced by Q(x) for a 1um wide device (Analytical solution)

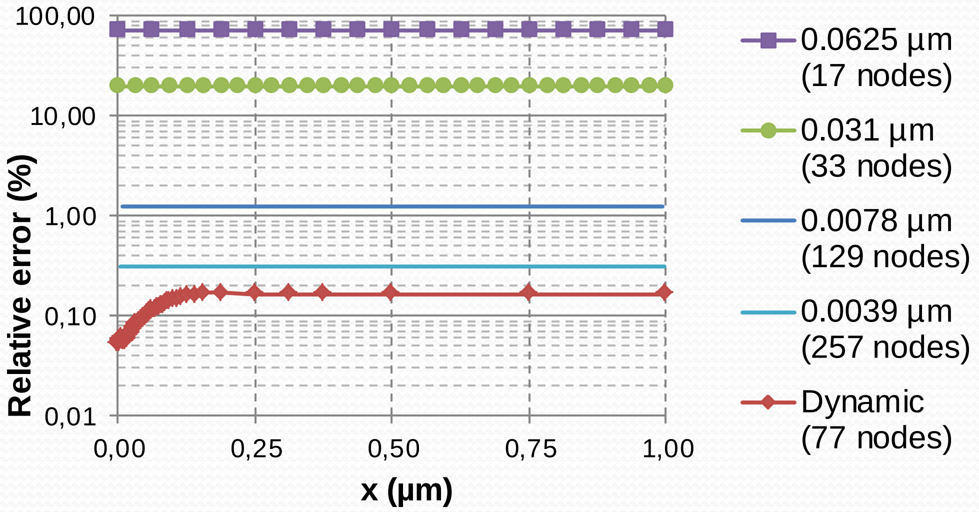
Analytical solution:

Poisson :

Electric charge :

Error:

100% → 62.5 nm mesh size (17 nodes)
0.3% → 3.9 nm mesh size (257 nodes)
0.16% → variable mesh size (77 nodes)



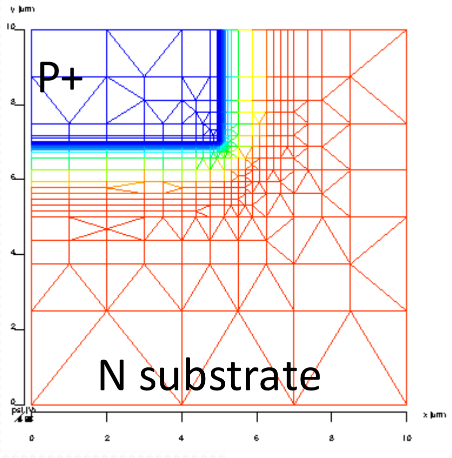
Relative error compared to the analytical solution as a function of the mesh size (markers: nodes of the mesh)

Mesh quality is critical for results reliability.
Adding complex models useless if mesh badly designed

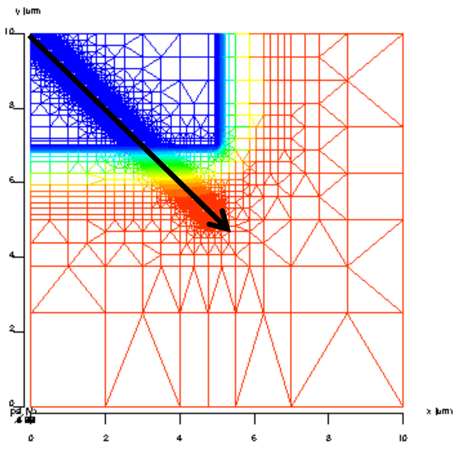
Mesh Design

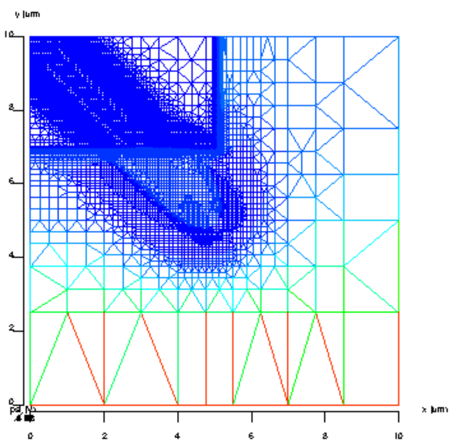
Usually mesh adapted only on doping profile → high changes of potential and carriers distribution not taken into account.

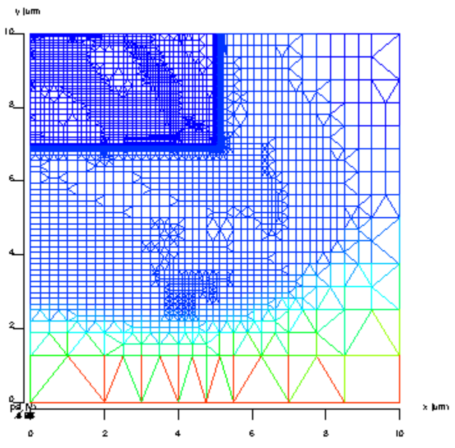
ECORCE → mesh corrected according to all variables, for all steps including transient modeling
→ Essential for Single Event Effect (Example: ion effect on a negatively biased PN junction)

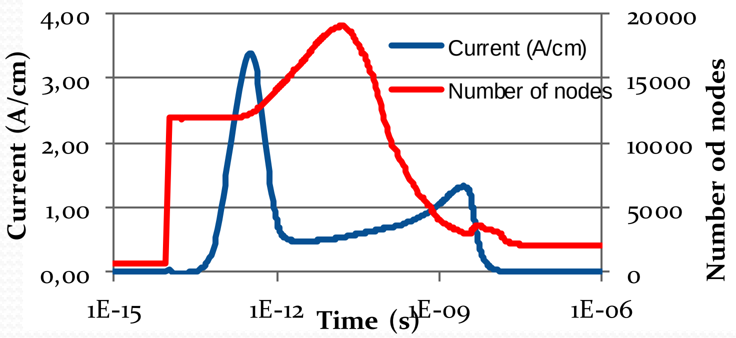


Before Ion, 678 nodes


Ion impact, 11904 nodes


10^{-10} s after impact, 11253 nodes


10^{-9} s after impact, 4009 nodes



As expected: 2 peaks of current (blue curve)

Number of nodes ranging from 678 to 19549 (red curve)

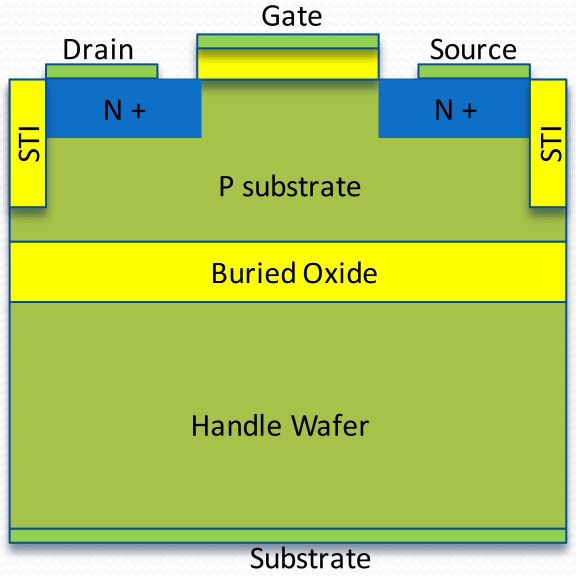
TID

Total Ionizing dose -> electron/hole pairs generated
in the whole structure

Silicon → charges quickly recombined/collected at the contact
Oxide → positive charge trapped on defects.

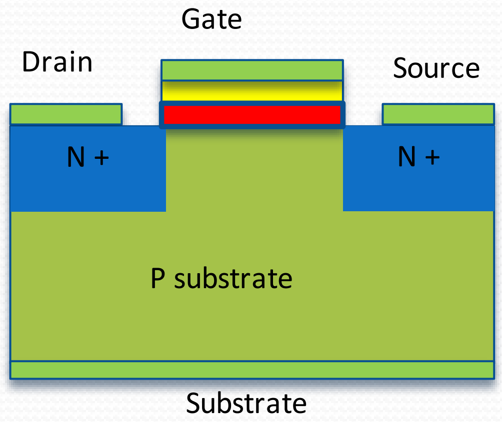
Many oxides used in all components: MOSFET, Bipolar, ...

3 models available: → Fixed charge (available with all TCAD tools)
→ Srour model (available with ECORCE and ???)
→ Precursor model (available only with ECORCE))



Oxides in a PDSOI structure

TID: Fixed Charge



Example: 10 krad Co60, Vgs = 12 V

Density generated in the gate oxide: $7.6\ 10^{16}\ cm^{-3}$

Electric field: 1.2 MV/cm

Initial separation of generated pairs: 0.92

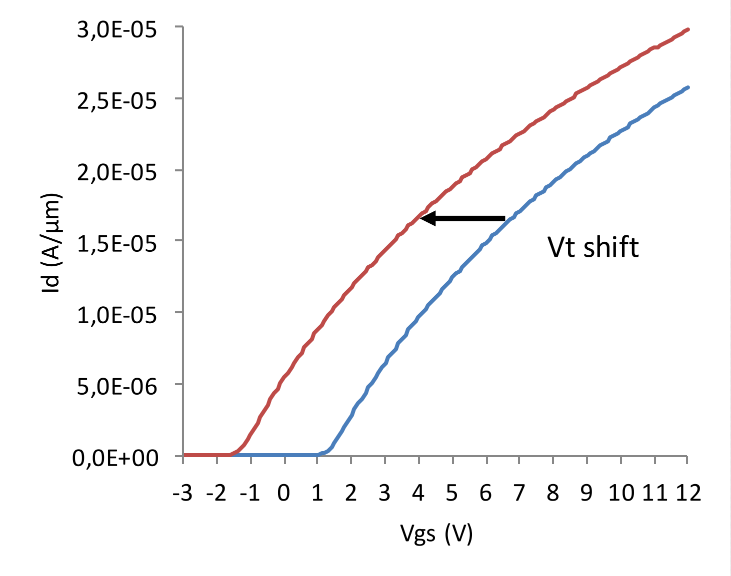
→ Fixed charge density applied: $7\ 10^{16}\ cm^{-3}$, full oxide volume

→ Or $1.4\ 10^{17}\ cm^{-3}$ half oxide volume, close to the gate

→ Threshold Voltage Shift: -2.65 V

Thick oxide: 100nm

Similar to power MOSFETS



Easy to implement

Low calculation time

Does not take into account

→ change of the electric field during irradiation

→ Real displacement of charges in the oxide

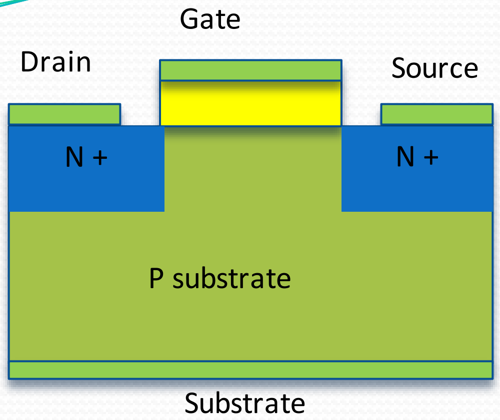
→ Temperature

→ Recombination of trapped holes with electrons

→ Thermal reemission of trapped hole

Fast but weak method.
Many phenomena are not taken into account

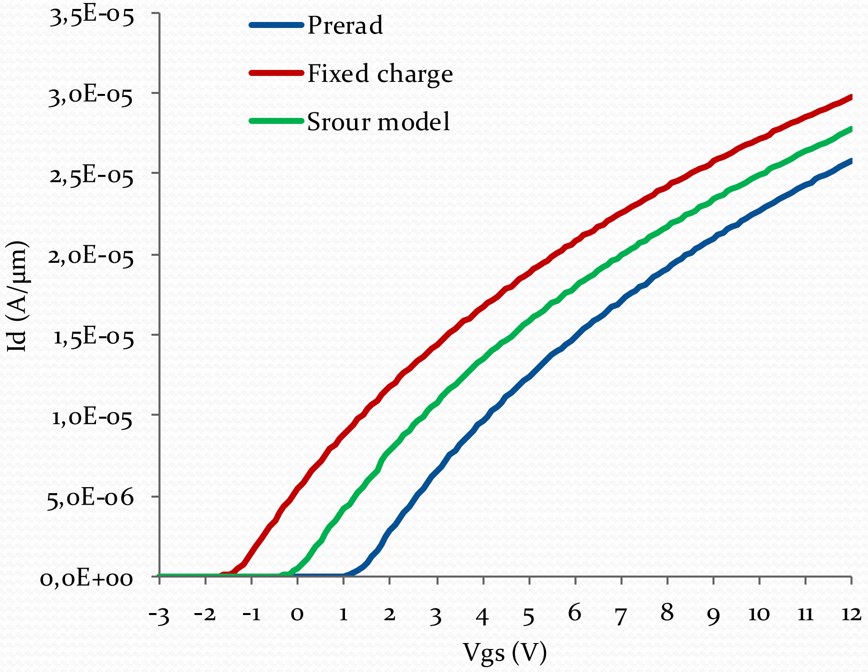
TID: Srour model



Example: 10 krad Co60, Vgs = 12 V

→ Density of n and p traps : 10^{19} cm-3, full oxide volume
→ Activation energy n: 0.8 eV, p: 1.4 eV

→ Threshold Voltage Shift: -1.37 V

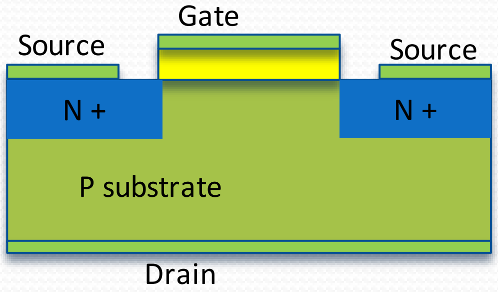


Take into account

→ change of the electric field during irradiation
→ Real displacement of charges in the oxide
→ Temperature
→ Recombination of trapped holes with electrons
→ Thermal reemission of trapped hole

Allow to quantitatively fit most of experimental results.
Many phenomena are taken into account

TID: Precursor Model



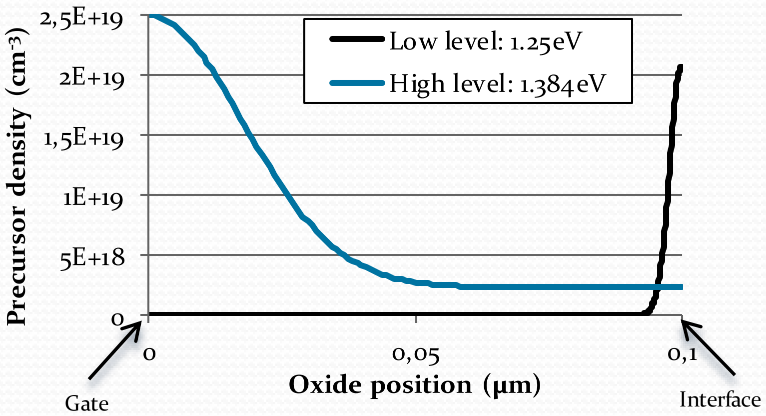
Experimental results

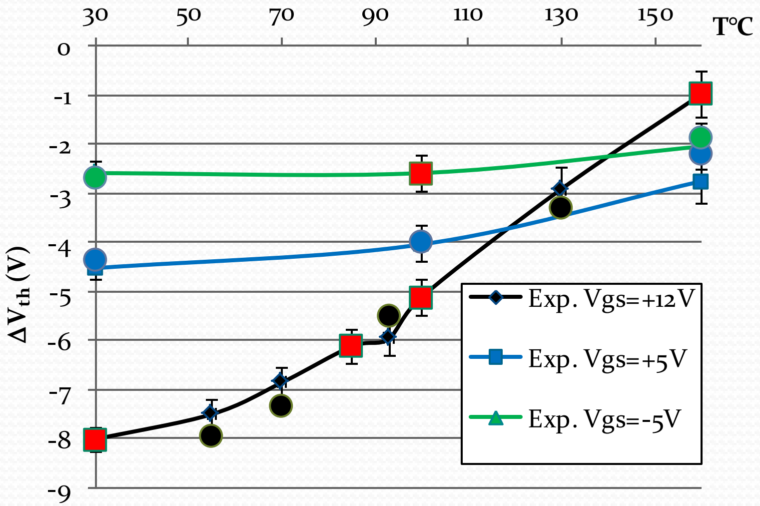
- N MOSFET, IRF130 batch, same datecode
- 70krad, 100rad/s, X-ray
- 3 biases Vgs : -5V, +5V et +12V
- 8 temperatures during irradiation:
  30°C, 55°C, 70°C, 85°C, 93°C, 100°C, 130°C and 160°C

Only 2 precursors energy levels

→ 5 parameters fitted using 5 experimental results

(2 energy levels and 3 spatial distribution parameters)





Threshold voltage shifts for positive and negative biases consistent with experiments

No fitting with Srour model

5. Summary

Mesh design

→ essential for results precision and realistic modeling
→ dynamic mesh reduces TCAD implementation time

TID

→ 3 models available
→ choice based on the results relevance needed and computation effort accepted
→ fit quantitatively experimental results
→ Model of interface state creation available (experimental)

SEE

→ Take into account the LET distribution along the ion track
→ All ion energies and type available for all materials

Thank you for your attention.

Questions ?

Outline

1. **Goal of TCAD for component under radiation**
2. **Importance of the mesh quality**
3. **Single Event Effects modeling**
4. **Total Ionizing Dose modeling**
5. **Conclusion**

1. TCAD goal

Goal: understand phenomena induced by radiation on components

- Single Event Effects (**SEE**)
- Total Ionizing and Non Ionizing Dose (**TID**) (**TNID**)
- ElectroStatic Discharge (ESD)
- Combined effects:TID, TNID, SEE, ESD

Advantages over experiments:

→ **model in a reduce time long duration phenomena.**

→ fast and easy(?) results

→ insight of the mechanisms at play

Drawbacks:

→ not a qualification tool

→ reduce set of components

→ results reliability?

→ keep in mind: « Garbage In, Garbage Out » (GIGO)

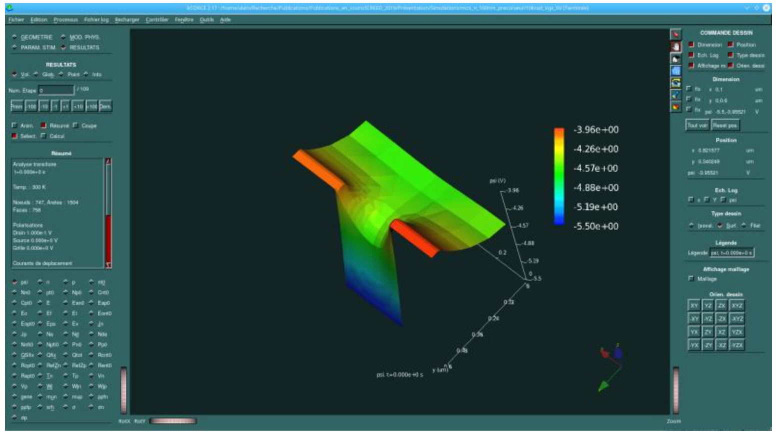
It is essential to carefully check inputs and correlate modeling with experiments

1. TCAD tools

Many TCAD software are available

PISCES, Fielday, Sentaurus, Atlas, Genius, NanoTCAD, Lumerical, FLOODS, …
(see www.tcad.com for a more exhaustive list)

Commercial or Open Source, general or dedicated to a specific domain
- → Dimensions: 1D, 2D, Axisymmetric, 3D
- → Materials: Si/SiO2, SiC, GaN, Graphene, …
- → Applications: Radiation effects, Solar cells, nano devices, optoelectronic, …

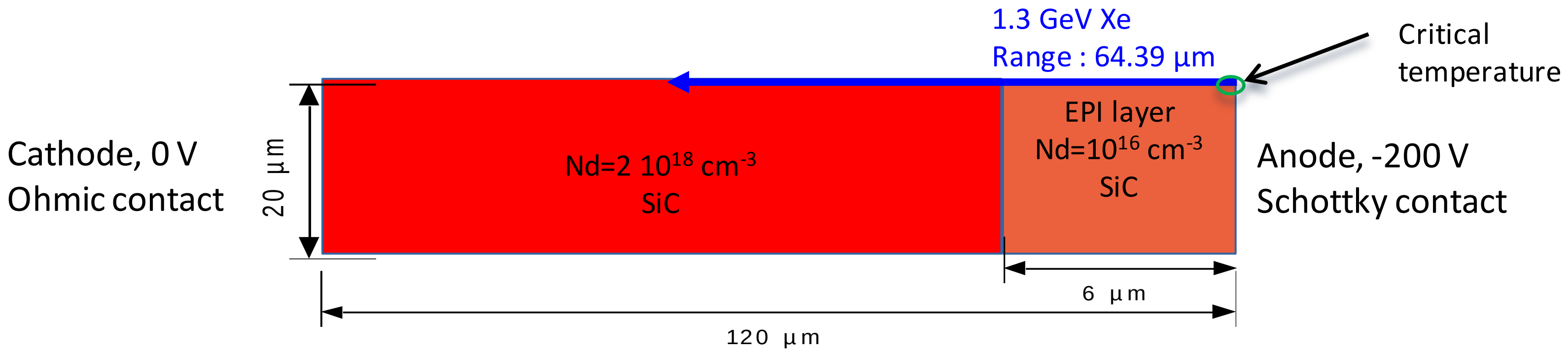


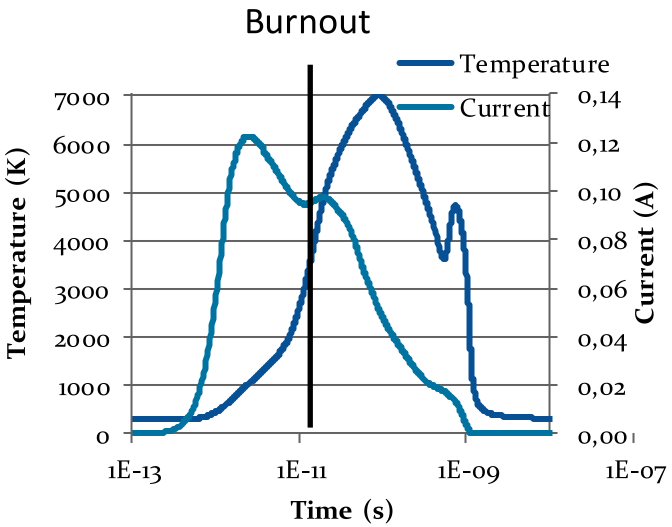
This presentation
- → Examples of the influence of mesh design and model choice for SEE and TID modeling
- → Highlight the advantages of the dynamic mesh of ECORCE

“ECORCE: A TCAD Tool for Total Ionizing Dose and Single Event Effect Modeling”. IEEE Transactions on Nuclear Science, 2015, 62 (4), pp.1516 - 1527.

3. SEE case study

Case Study: SiC Schottky diode used in satellite power supply





Ion experiments (2006)

→ Unexpected failure for low reverse bias.

→ **No sensitivity for Si Schottky diode. Why?**

3 TCAD model, same results:
A. Javanainen (2017),
A. F. Witulski (2018),
S. Kuboyama (2019)

TCAD model including heat equation and Impact Ionization (all models proposed)

Axisymmetric modeling→ same results as 3D.

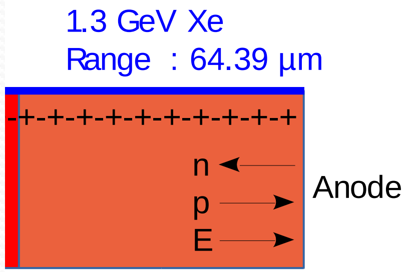
Dynamic mesh, lowest edge size: 0.02 µm

Critical temperature (reached very close to Schottky contact) exceeds SiC melting point (3100K)

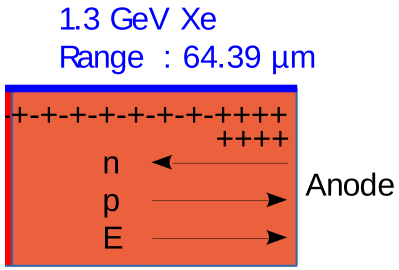
What are the mechanisms at play?

3. SEE case study

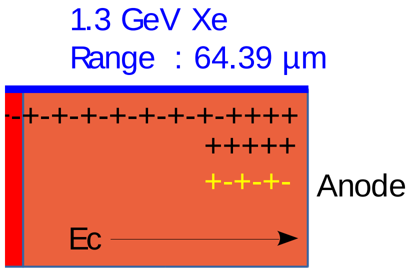
Mechanism located in the low conductivity area, between 110 and 120 µm (EPI layer)
Electric field: 0.2 MV/cm because of -200V applied on Anode



Generation and separation of charges



High positive charge appears at the contact
→ increase the electric field
→ speed up the pairs separation.



Impact Ionisation triggered
→ Additionnal pairs generation (yellow)
→ ceiling of the electric field when the generation rate is high enough.

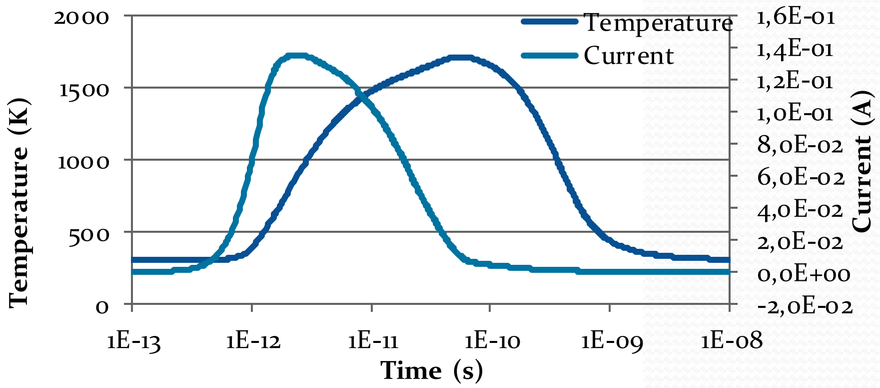
Critical electric field, Si : 0.3 MV/cm, SiC : 3 MV/cm
→ Power heat density (W/µm^3) ≈ E^2, x 100 in SiC than in Si

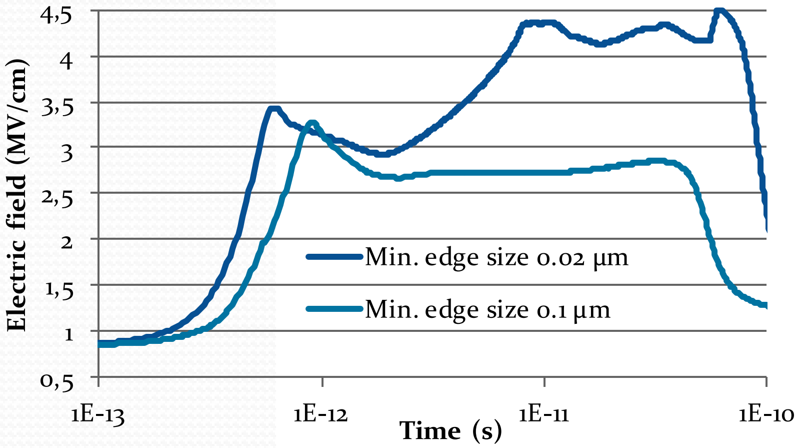
3. SEE Issue on mesh design

Thermal runaway mechanism, very sensitive to parameters variation. (mobility laws, Impact ionization, …)

What about mesh sensitivity?

New modeling, dynamic mesh → lowest edge size from 0.02 to 0.1 µm





Highest temperature: 1700 K

Thermal runaway disappears → unrealistic modeling, badly designed mesh

Electric field for finest mesh is high (blue curve) → Impact Ionization triggered

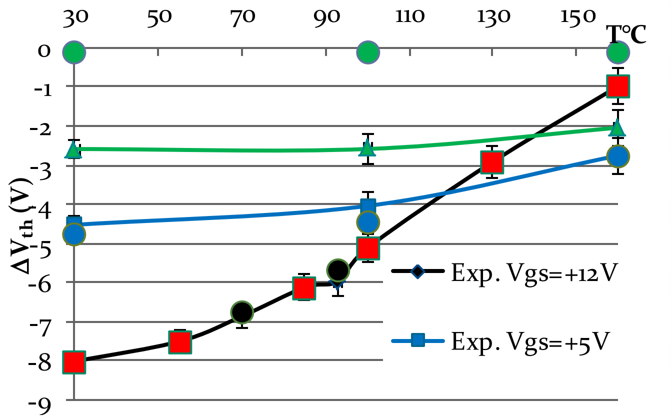
Electric field for large mesh is low (red curve) → Impact Ionization not triggered

Two large edges at the anode do not take into account this localized effect
According to user parameters, the dynamic mesh automatically compute the right solution

4. TID: Srour model

Experimental results

- N MOSFET, IRF130 batch, same datecode
- 70krad, 100rad/s, X-ray
- 3 biases Vgs : -5V, +5V et +12V
- 8 temperatures during irradiation:
  30°C, 55°C, 70°C, 85°C, 93°C, 100°C, 130°C and 160°C



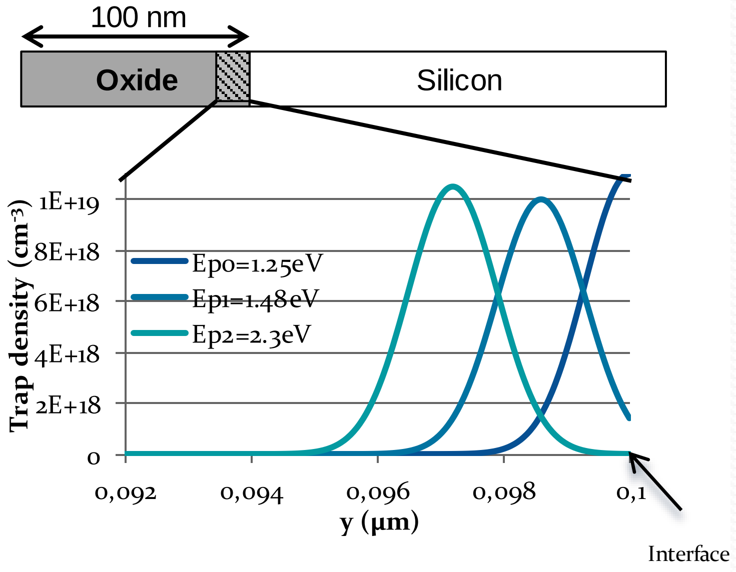
Best model

3 traps levels: density and activation energy fitted

→ 6 parameters fitted using 6 experimental results.

Traps are close to the interface

Threshold voltage shifts for others experimental points?



Srour model

→ Impossible to fit positive and negative biases with the same trap distribution

→ Positive biases: traps close to the interface

→ Negative biases: traps close to the gate