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

Overview of TCAD modeling of components
Capabilities of ECORCE

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ECORCE?

Etude du COmportement sous Radiation des Composants Electroniques

Similar to SENTAURUS and ATLAS

Designed to **ease** TCAD implementation

Lacks

- Process modeling
- 3D

Special features

- Full graphical interface
- Control of model definition
- **Dynamic mesh**
- **Optimizer (equivalent to DOE)**
- **Radiation effect modeling**
  Single event, dose and dose rate effects
- Multiple trapping-detrapping model in insulator volume and at interfaces

→ suitable for **teaching** (11 years effects of radiation,13 years finite element method)

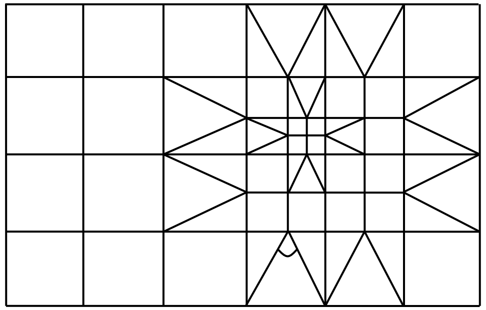
125000 lines of code, 34 years of development, university of Montpellier
Commercial distribution by the SAS Delphea

Mesh design

TCAD → Technological Computer Aided Design

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

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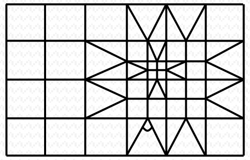
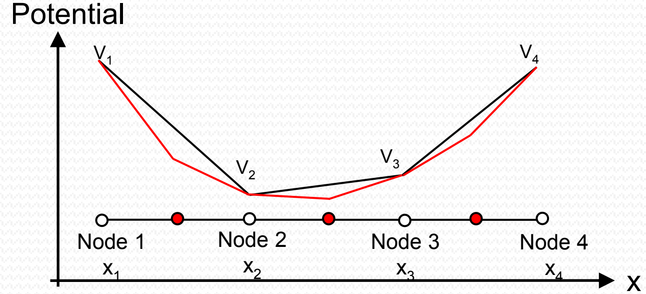
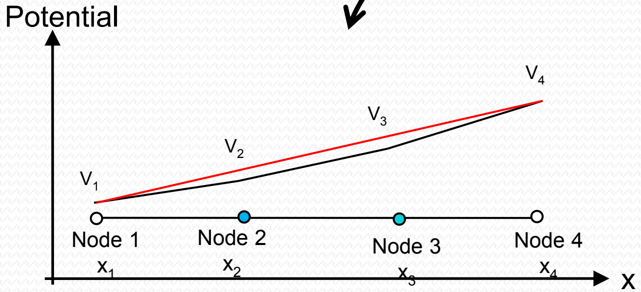
Mesh design





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

With ECORCE, no more convergence problem induced by the mesh

Is it really so important for results precision?

Mesh Design

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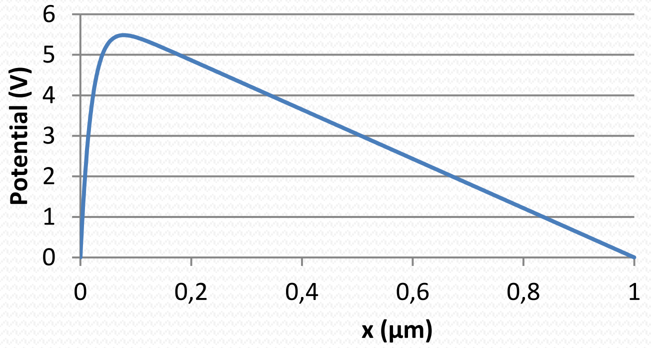
Q_{max} (cm^{-3})	σ (µm)	q (C)	(Rel.)	L (µm)
10^{18}	0.02	1.6×10^{-19}	11.9	1



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

Analytical solution:

Poisson :

Electric charge :

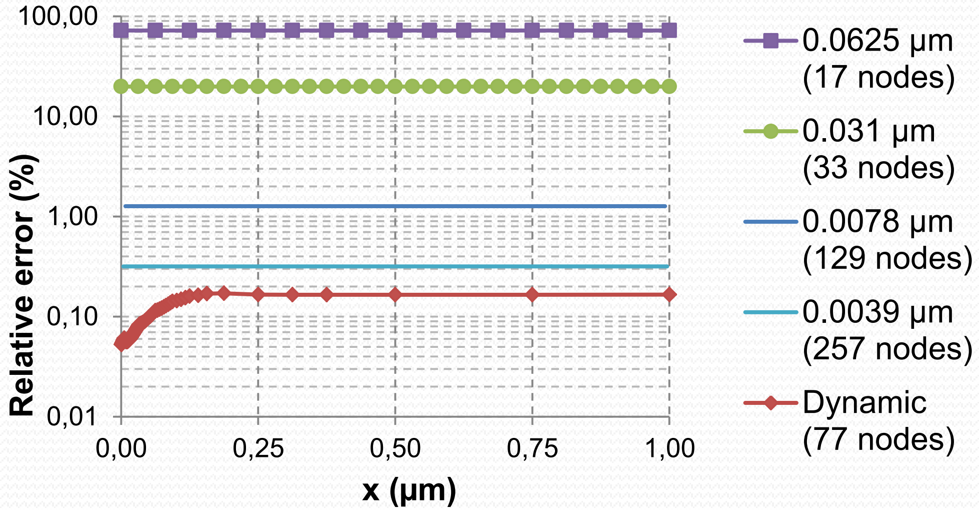
Error:

70% → 62.5 nm mesh size (17 nodes)

0.3% → 3.9 nm mesh size (257 nodes)

0.16% → variable mesh size (77 nodes)

Mesh quality is critical for results reliability.



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

Adding complex models useless if mesh badly designed

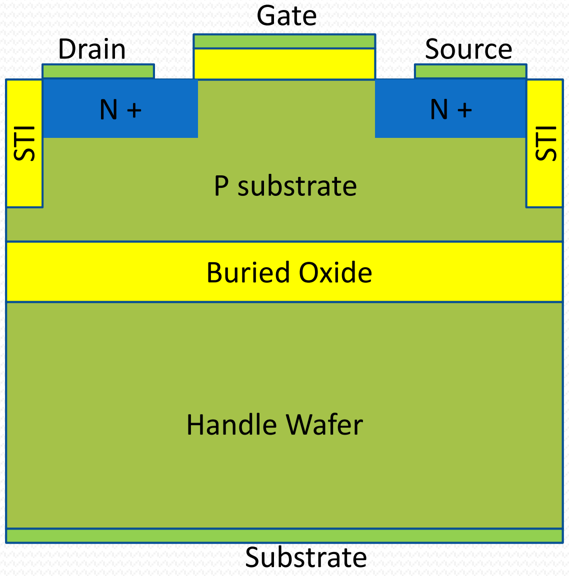
TID

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

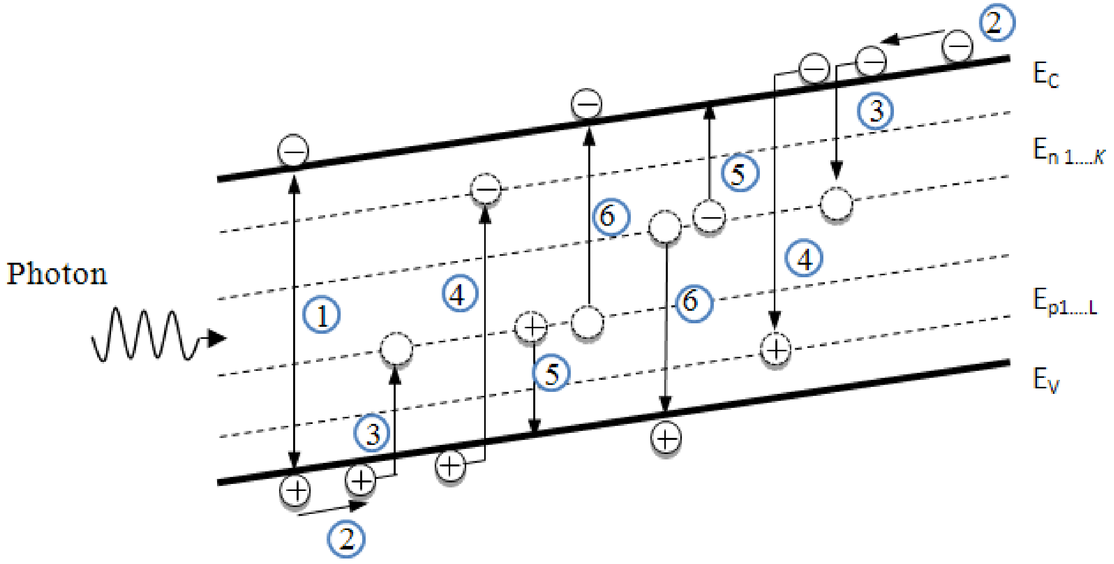
TID: Srour Model

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

Semiconductor → displacement damages
Oxide/semiconductor interface -> interface trap



Trapping-detrapping on defects inside the band gap during irradiation.

Phenomena taken into account

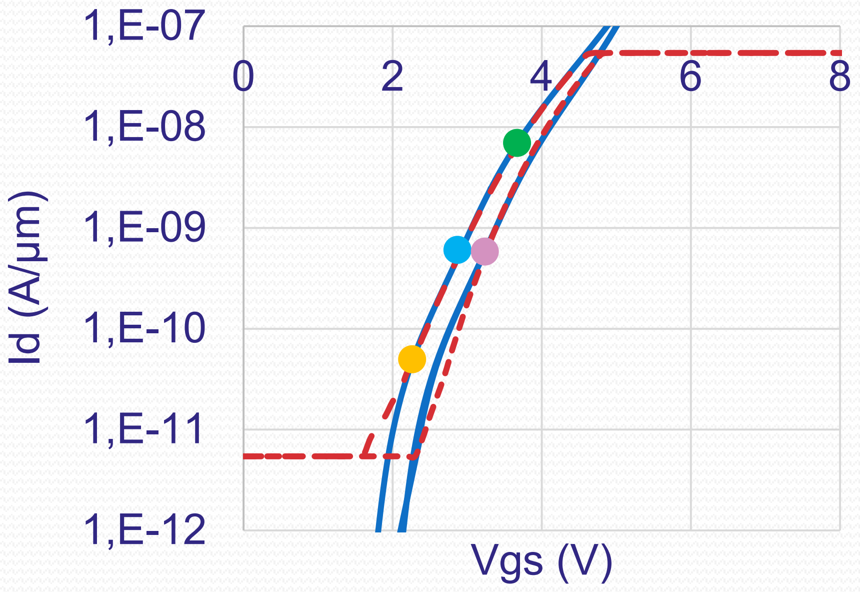
① electron-hole pairs generated by radiation
② drift-diffusion of carriers in their respective allowed band
③ trapping of free carriers
④ recombination of trapped carriers by free carriers of the opposite type
⑤ thermal reemission of trapped carriers to their respective allowed band
⑥ thermal reemission of a free electron or hole from an empty trap

Srour model → Traps are considered to be pre-existing in the oxide
ECORCE also provides an improved model (traps are created during irradiation)

Wide gap semiconductors

SiC power NMOSFET → interface states
Adjusting the experimental characteristic
4 seconds between Id=f(Vgs) measures

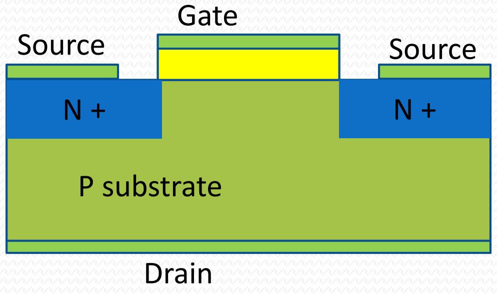
Id(Vgs) @ Vds=Vgs – logarithmic scale



	Activation Energy (eV)	Traps density (cm^{-2})	Capture cross section (cm^2)	Recombinaison cross section (cm^2)
Hole traps Level 0	2.77 Curve @ ●	4.39×10^{11}	1.5×10^{-13}	1.6×10^{-12}
Hole traps Level 1	2.88 Curve @ ●	6×10^{11}	1.5×10^{-13}	1.6×10^{-12}
Hole traps Level 2	2.94 Curve @ ●	3.49×10^{11}	1.5×10^{-13}	1.6×10^{-12}
Electron traps Level 0	1.2 High enough to remove thermal reemission	1.7×10^{11}	8×10^{-22} Shift ● → ●	4.8×10^{-12}

Vth value
Curvature
Vth shift
Useless

TID: Precursor Model



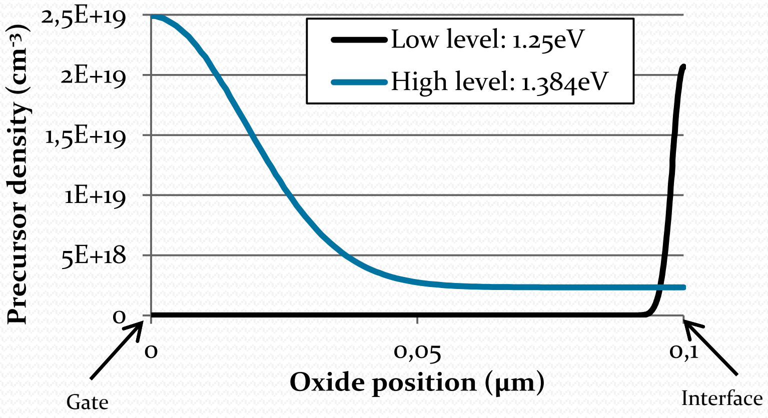
Experimental results

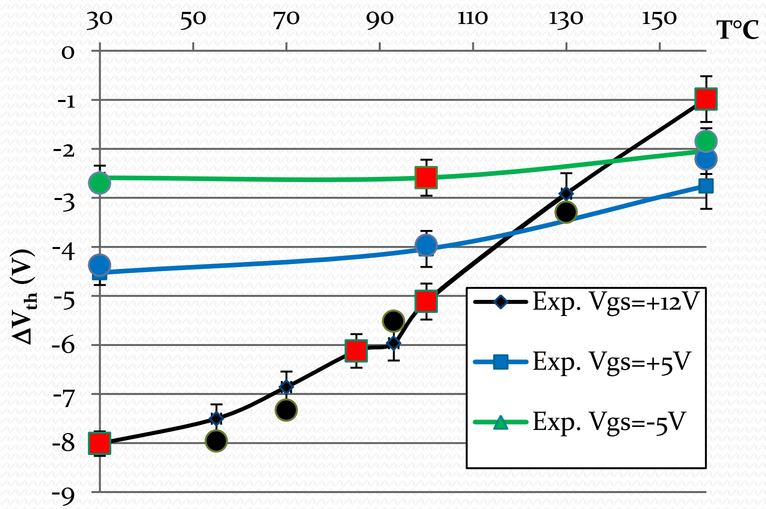
- N MOSFET, IRF130 batch, same datecode
- 70krad, 100rad/s, X-ray
- 3 biases Vgs : -5V, +5V et +12V
- 8 temperatures during irradiation:
  30°C, 55°C, 70°C, 85°C, 93°C, 100°C, 130°C and 160°C

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

Single Event Effects

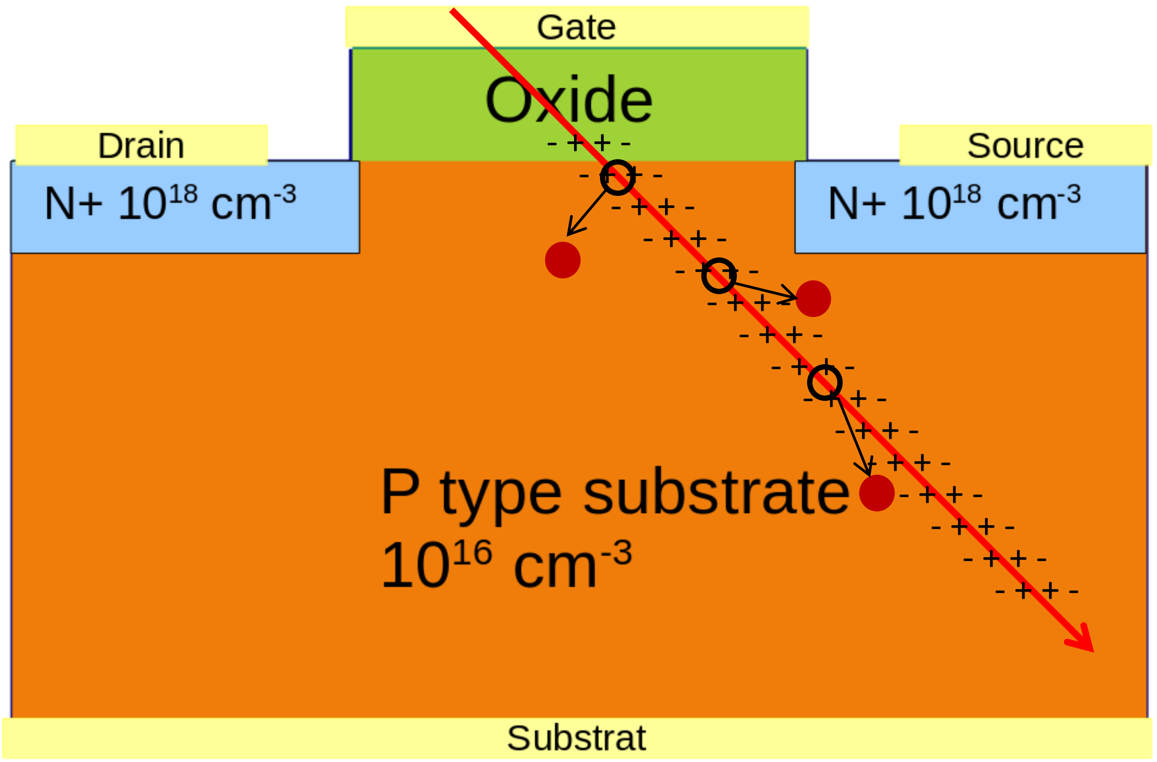
SEE: Effects induced by a single particle (ions, protons, neutrons, …)

→ Generation of electron hole pairs along the track

→ Creation of displacement damages along the track

○ : vacancies

● : interstitial atoms



Reported effects

Transient currents

Latchup of parasitic thyristor PNPN structure

Burnout of power devices

MOSFET gate rupture

Upset of one or multiple bits of memory

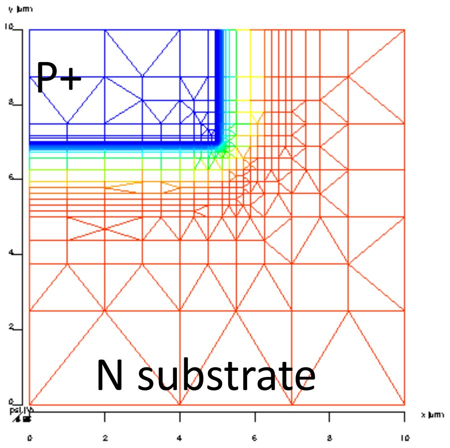
Stuck bit of memory

…

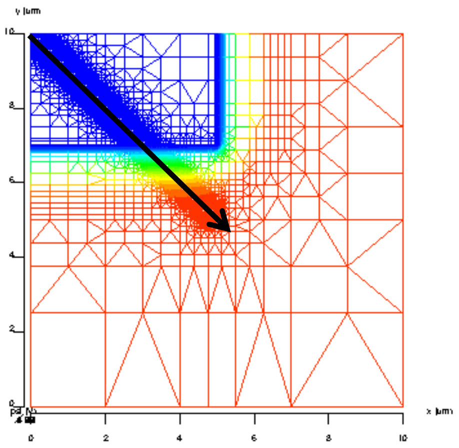
Mesh Design

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

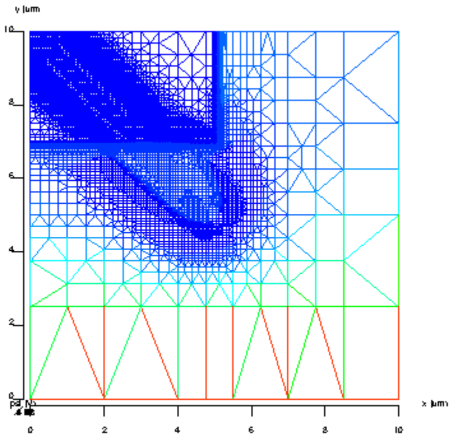
ECORCE → mesh corrected according to all variables, for all steps including transient modeling
→ Essential for Single Event Effect (Example: ion effect on a negatively biased PN junction)



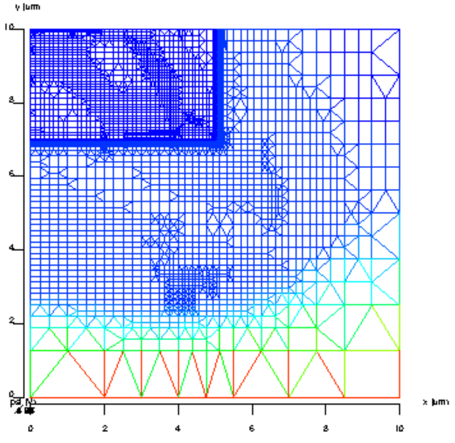
Before Ion, 678 nodes



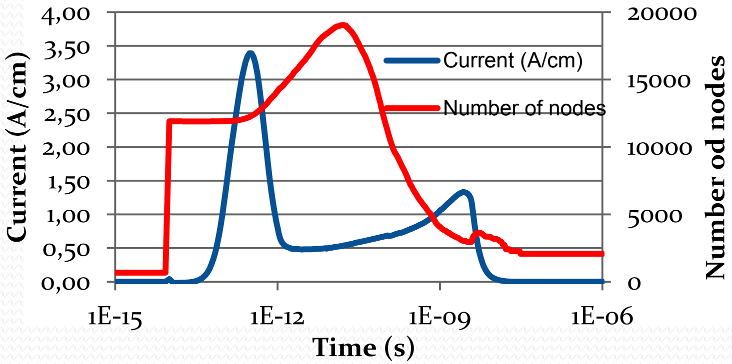
Ion impact, 11904 nodes



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)

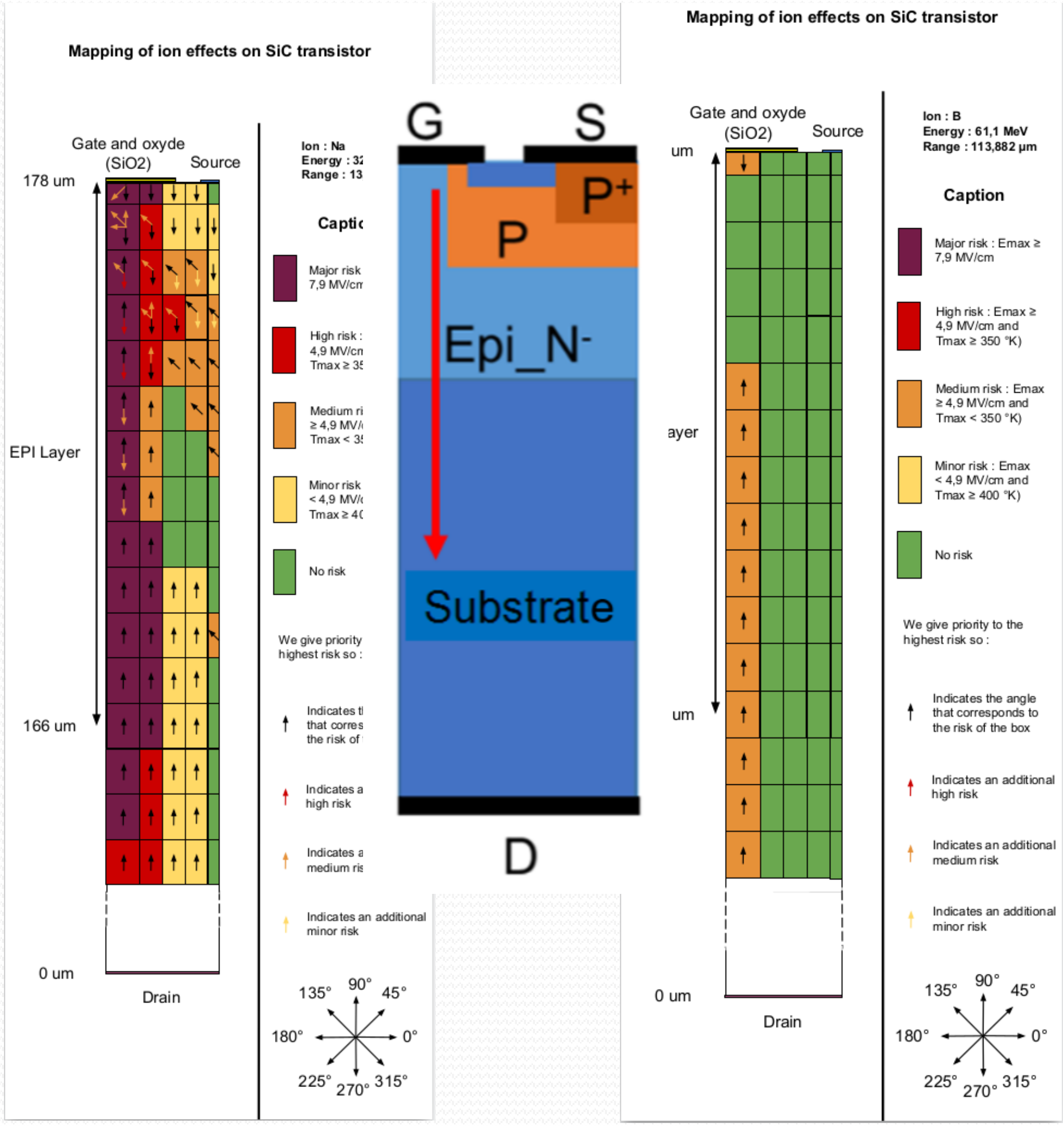
SEE: Neutron effect on SiC power MOSFET

6 secondary ions tested:
→ Si 26 and 100 MeV
→ Al 27.6 MeV
→ Mg 30.7 MeV
→ Na 32 MeV
→ B 61.1 MeV

For each ion:
→ 80 positions
→ 8 directions

All calculations:
→ 3600 simulations
→ 12000 calculation hours on one processor
→ 7 days with 72 processors

Burnout strongly rely on initial LET
No burnout for low Z ions



Flux of particles

Effects induced by a flux of particles (ions, protons, …)

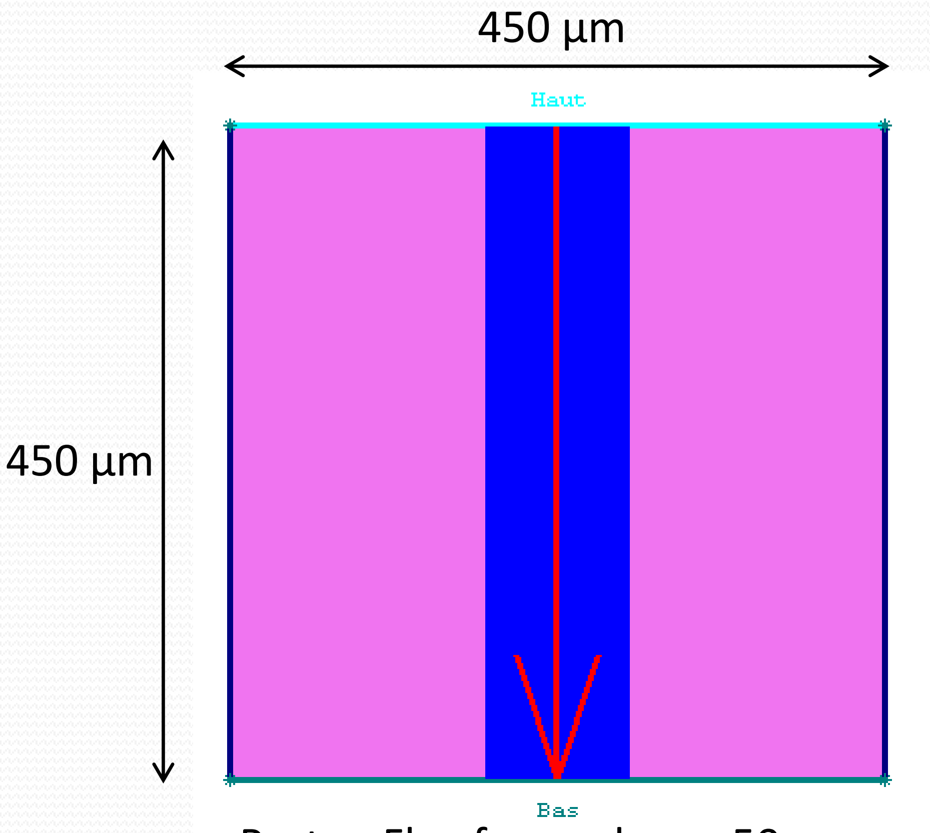
→ Generation of electron hole pairs along the track

→ Creation of displacement damages along the track

IN2P3 Grenoble

Robin Molle, Marie Laure Gallin Martel

Effect of proton flux on Diamond detectors



Proton Flux focused on a 50 µm radius area (blue rectangle)

Wide gap semiconductors

Silicon carbide (SiC): at the state of art (developed in collaboration with JAXA)
- Specific heat and thermal conductivity function of temperature
- Gap reduction function of doping and temperature
- Band to band tunneling function of electric field and gap
- Impact ionization function of temperature
- Mobility function of doping, temperature, carrier-carrier scattering, parallel and perpendicular electric field
- Recombination SRH and Auger

Gallium nitride (GaN): ready to use, improvement on the way (collaboration with LETI)
- Specific heat and thermal conductivity function of temperature
- Gap reduction function of doping and temperature
- Impact ionization (not function of temperature)
- Recombination SRH *(Auger not yet available)*
- *Band to band tunneling and mobility not yet available*

Diamond (C): all known laws implemented
- Incomplete doping ionization
- Impact ionization function of temperature
- Mobility function of temperature and P doping only
- Recombination SRH *(Auger not yet available)*
- *Specific heat, thermal conductivity, gap reduction and band to band tunneling not yet available*

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Add n
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- Sp
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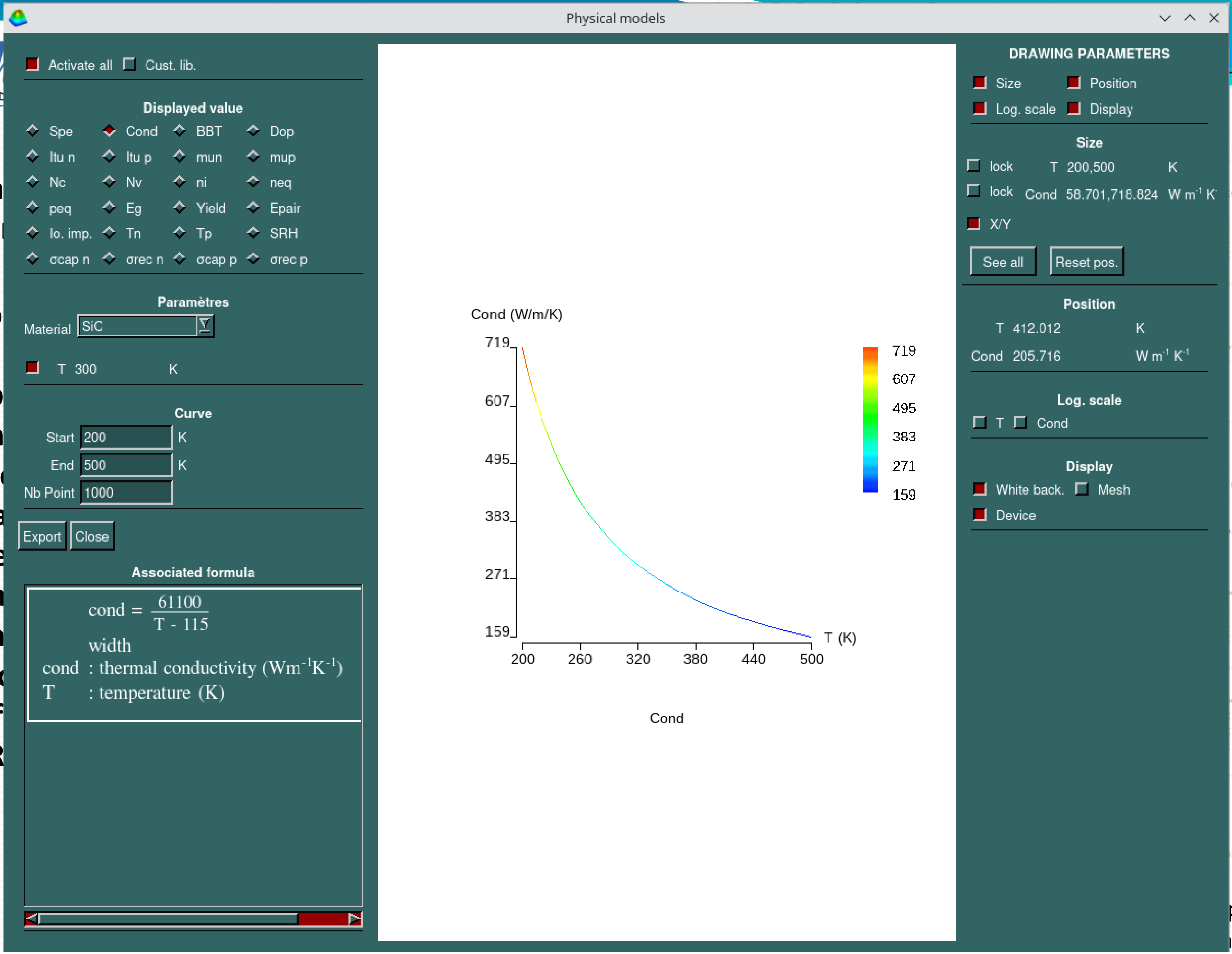


```
****************/
num Nitride ??? */
****************/
erial_name == "AlN" )

 Flottant T300 = 300; // en K
 Flottant K300 = 350; // en W/m.K
 Flottant alpha = -1.7;

n K300 * pow(temperature / T300,alpha);

*******/
n ??? */
*******/

( material_name == "C" )

n intrinsic_conductivity;

***************/
um nitride ??? */
***************/

s://www.iue.tuwien.ac.at/phd/vitanov/node55.html */
( material_name == "GaN" )

del 1
 Flottant T300 = 300;  // en K
 Flottant K300 = 130;  // en W/m.K
 Flottant alpha = -0.43;

n K300 * pow(temperature / T300,alpha);

del 2
 Flottant T300 = 220;  // en K
 Flottant K300 = 130;  // en W/m.K
 Flottant alpha = -1.2;

n K300 * pow(temperature / T300,alpha);

**********/
nium ??? */
**********/
```

ple of customizable source code:
l conductivity of several materials

Conclusion

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

Wide bandgap materials available

Customizable source code: mobility, impact ionization, … (C++ programming)

Radiation effects

→ Total Ionizing Dose: space, medical and power plant applications

→ Single Event Effect: occurs everywhere (neutron at ground level)

Live demonstration at coffee break/lunch

Thank you for your attention.

Questions ?

5. Conclusion

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

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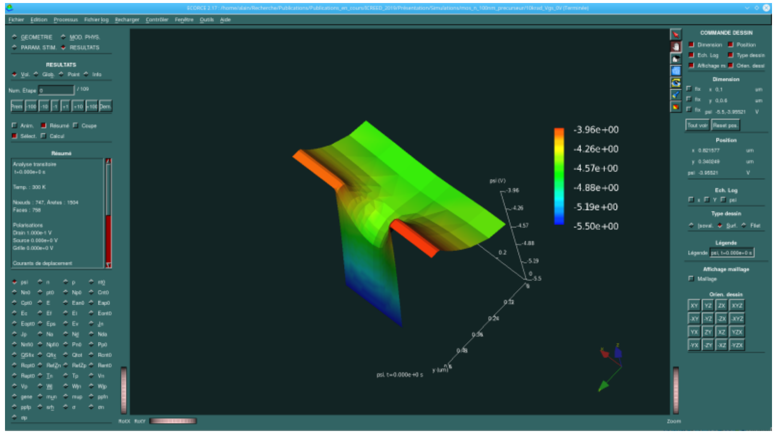
Finite volume software
http://www.ecorce.eu

Many TCAD software are available

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

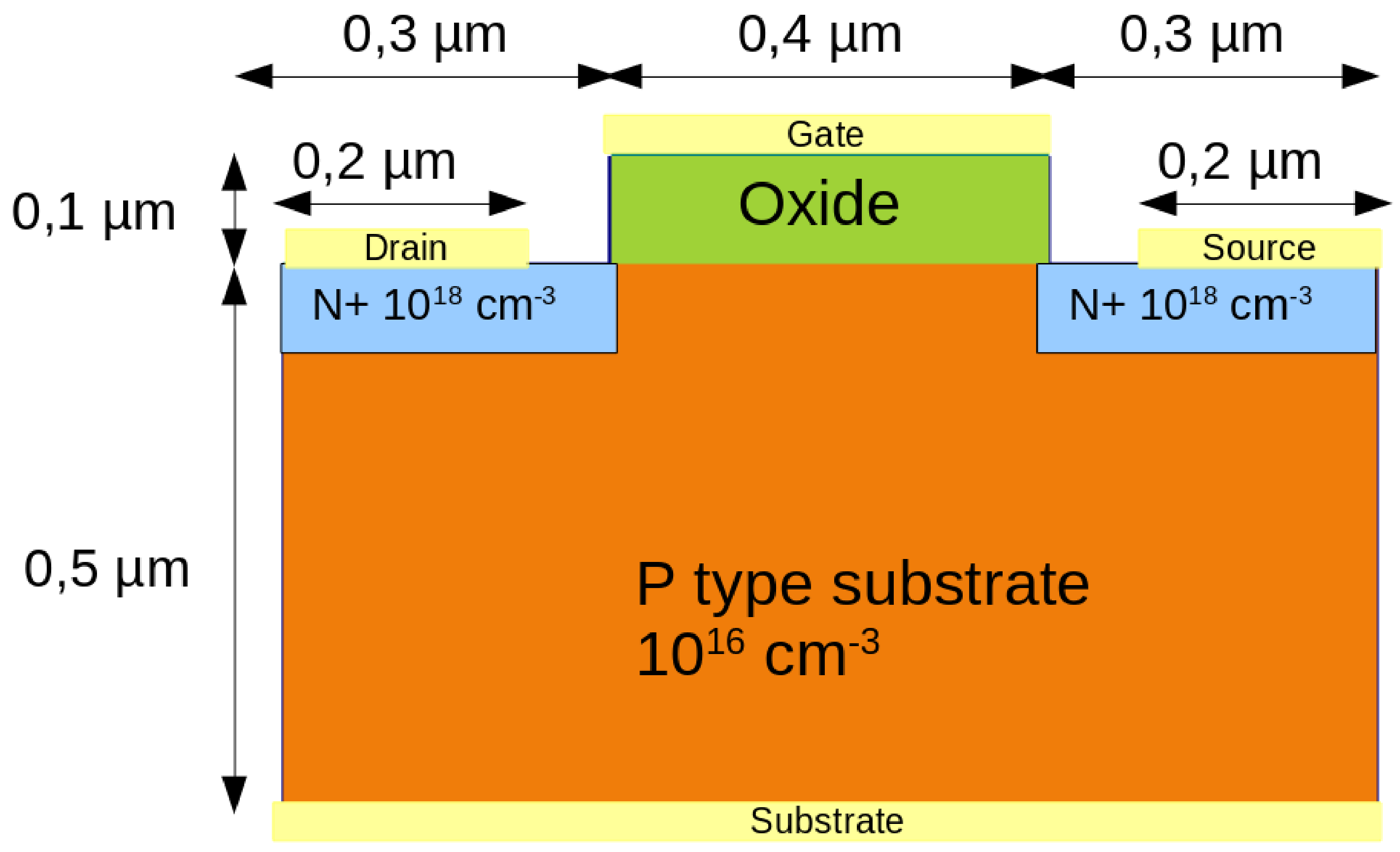
Commercial or Open Source, general or dedicated to a specific domain
- → Dimensions: 1D, 2D, Axisymmetric, 3D
- → Materials: Si/SiO2, SiC, GaN, Graphene, …
- → Applications: Radiation effects, Solar cells, nano devices, optoelectronic, …

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.

Example: academic MOSFET design



Within ECORCE modeling executed in 5 steps:

1) Geometry design
2) Definition of physical model equations, doping, …
3) Definition of stimuli bias, temperature, irradiation, …
4) Calculation of solution
5) Analysis of results

Live demonstration at the break

Adjusting the device parameters

TCAD model must be adjusted to fit experimental results.

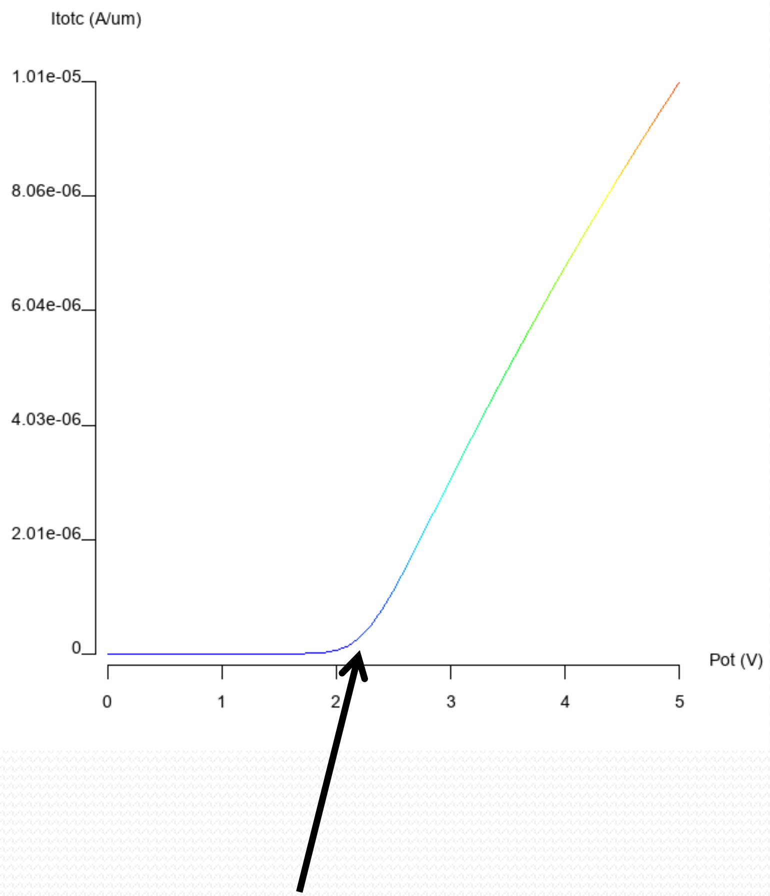
Considering the Id=f(Vgs) characteristic.

What is the effect of the P substrate density on the threshold voltage?

The optimizer automatically calculates Vth for several dopings

Live demonstration

	Substrate doping (/cm3)	Result 1 (V)
0	1e+15	1.14336
1	3e+15	1.40574
2	5e+15	1.61448
3	7e+15	1.81018
4	9e+15	1.97848
5	1.1e+16	2.13791
6	1.3e+16	2.29038
7	1.5e+16	2.42391
8	1.7e+16	2.55183
9	1.9e+16	2.67798



V_{th} = 2.23 V for Na = 10^{16} cm^{-3}

TID: Fixed Charge

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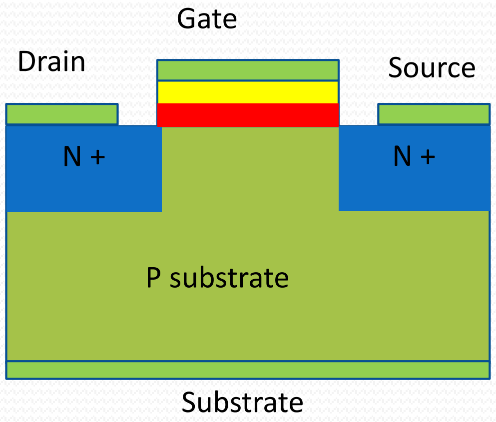
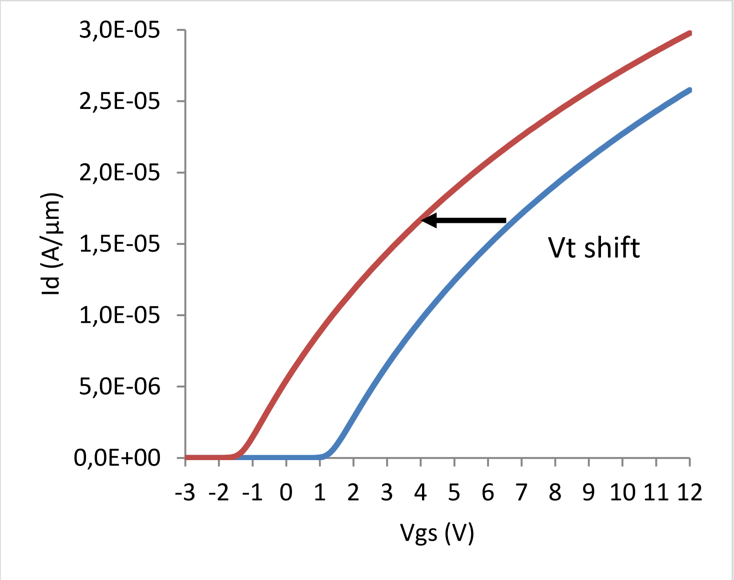


Thick oxide: 100nm

Similar to power MOSFETS



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

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

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?

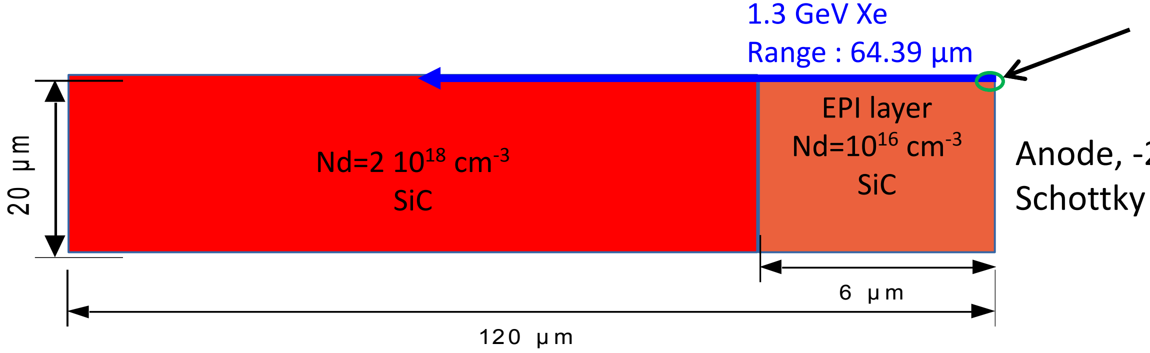
→ keep in mind: « Garbage In, Garbage Out » (GIGO)

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

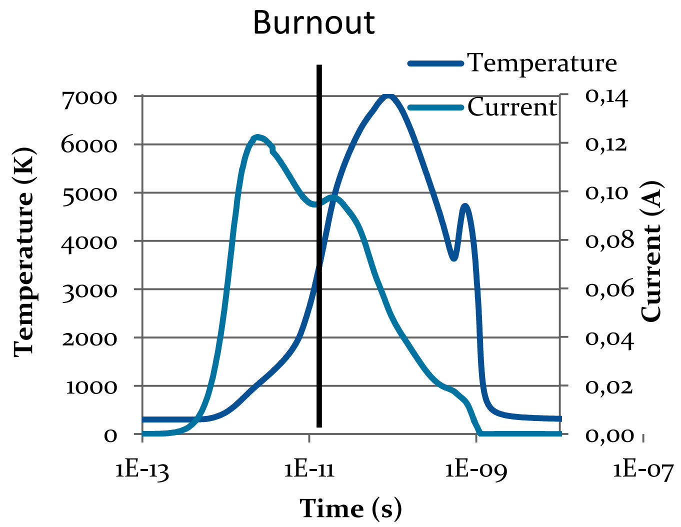
3. SEE case study

Case Study: SiC Schottky diode used in satellite power supply

Cathode, 0 V
Ohmic contact



Anode, -200 V
Schottky contact



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.

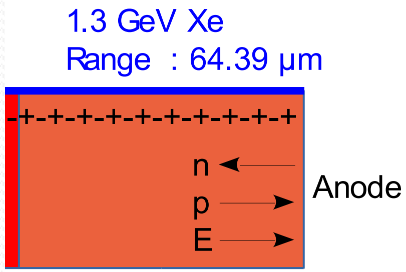
Dynamic mesh, lowest edge size: 0.02 µm

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

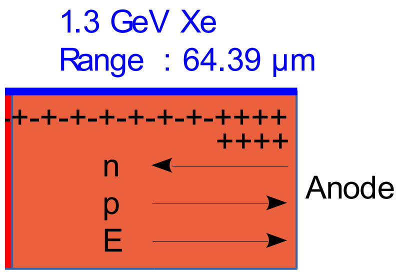
What are the mechanisms at play?

3. SEE case study

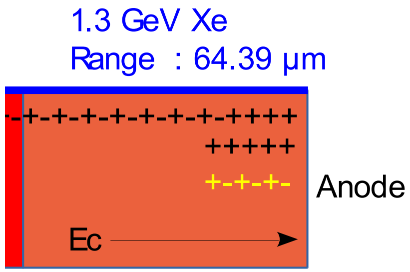
Mechanism located in the low conductivity area, between 110 and 120 µm (EPI layer)
Electric field: 0.2 MV/cm because of -200V applied on Anode



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.

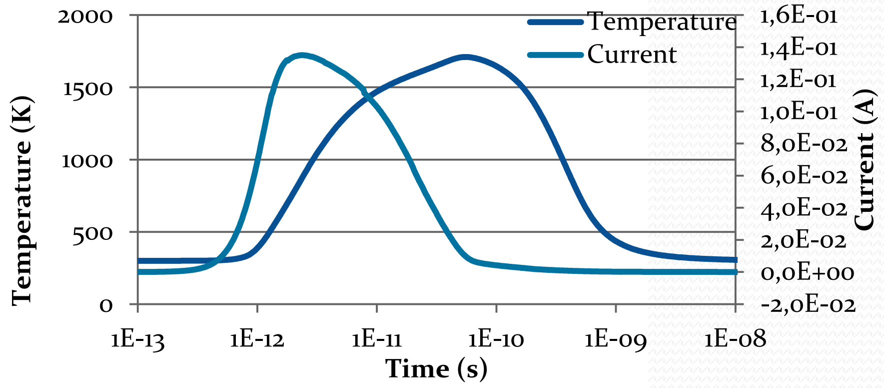
Critical electric field, Si : 0.3 MV/cm, SiC : 3 MV/cm
→ Power heat density ($W/\mu m^3$) ≈ E^2, x 100 in SiC than in Si

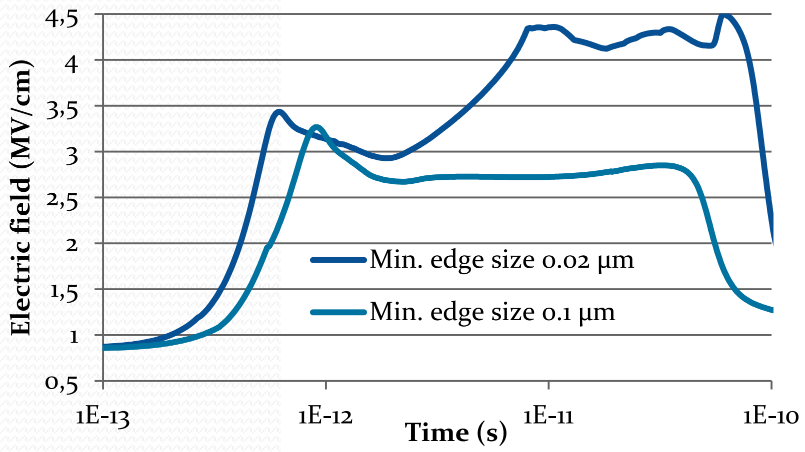
3. SEE Issue on mesh design

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

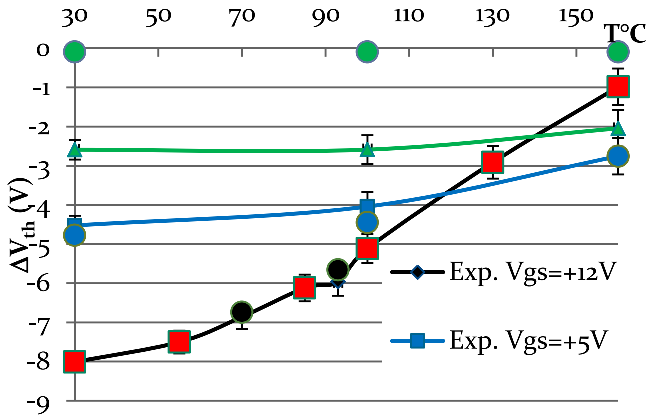
Electric field for large mesh is low (red curve) → Impact Ionization not triggered

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



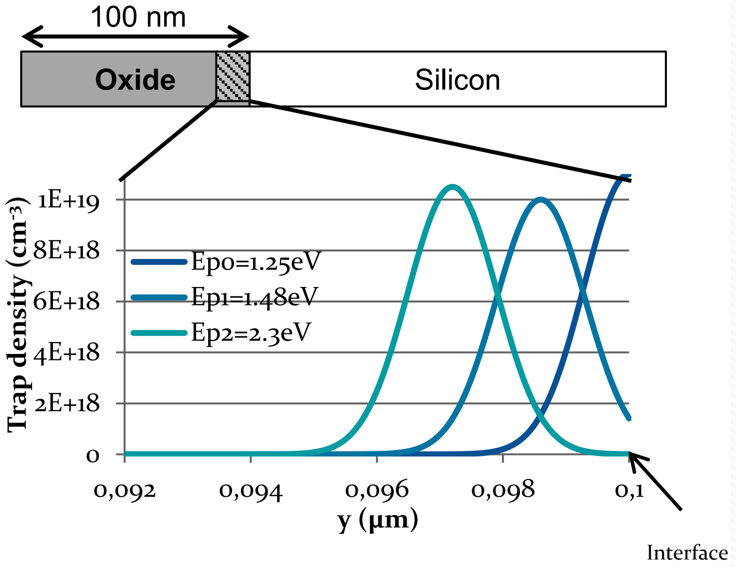
Best model

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