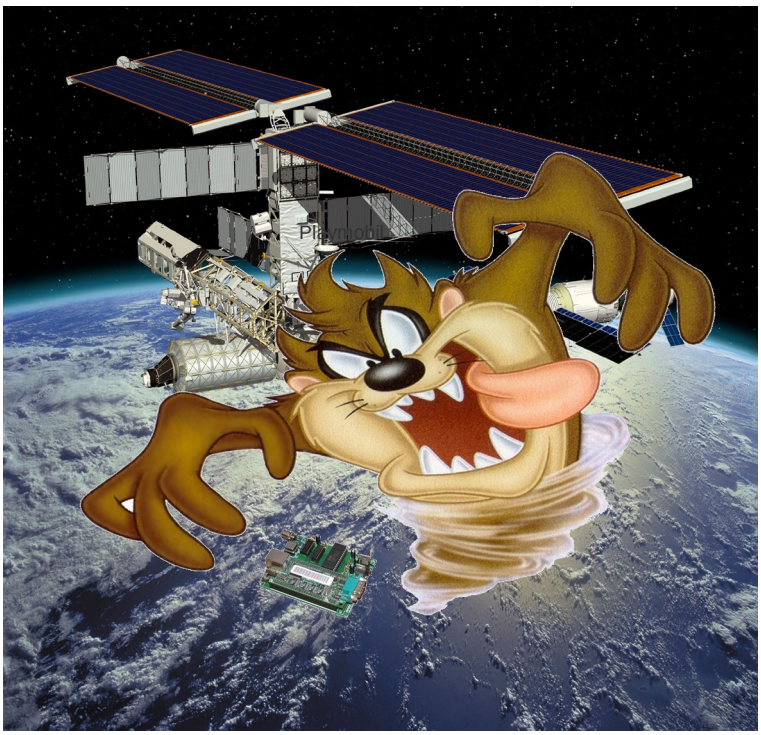
Last name

Group

First Name



Radiation effects modeling

SUMMARY

Year 24/25

Results calculated with ECORCE release 2.27/8808

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RECOMMENDATIONS

Objectives

This lecture addresses 3 topics:
- TCAD modeling
- Physics of electronic components
- Effect of radiation on electronic devices

Technological information

Technological information included in this document is copyright free. You will create academic devices but the same principles of fabrication and operation apply to real components.

Software

Modeling software using the finite element method uses many functions, sometimes complex. When creating models, each new function will be detailed. Take time to understand and ask questions if necessary. For the **following models**, commands **already seen** will **not be re-explained**.

Physics

Modeling software, in most cases, reach a result even if the input data are false. They do not return message to warn the operator when the model is physically absurd.
To use these tools you must understand the associated physics and control at each step the validity of your results.

Results

The answer to a question is given after the question in italics. So you will have very little to write during these sessions and you can concentrate on understanding the physics. But **before you read** this response, **play the game**, try to find it by yourself!

Exam

The exam will take place at the final session and will last 1.5 hours. You will be allowed to use the handout.

You will have to create a new model, execute modelings and explain the observed phenomena.

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.I Introduction

Electronic components used in space and nuclear areas are subjected to radiation that cause failures. These failures can lead to the destruction of the device. Depending on the device and the type of radiation, we observe:

Memory cells: SEU (Single Event Upset),
SHE (Single event Hard Errors)

MOS transistors: SEB (Single Event Burnout),
SEGR (Single Event Gate Rupture)
shift of the caracteristic $I_d=f(V_{gs})$

IGBT: SEGR (Single Event Gate Rupture)

Bipolar transistors: SET (Single Event Transient),
shift of the current/voltage caracteristics

These phenomena are mostly not well understood. Modeling allows a better understanding of radiation effects on the distribution of electrical charges in the device materials, and help to find rules for hardening and/or annealing.

There are several software to perform these modelings: Sentaurus from company SYNOPSIS, ATLAS from company SILVACO ...
Software from universities are also available: PREDICSEE, ECORCE ...

For this course, we will use ECORCE (Etude du Comportement des Composants Electroniques) (Study of electronic devices under radiation). This software models the effects of Total Ionizing Dose (TID) and high-energy particles on MOS and bipolar components. It is one of the few that can model the trapping-detrapping of electrical charges on insulators defects. You can download ECORCE at: https://www.delphea.eu/.

ECORCE is still experimental. It can sometimes crash, especially when defining the geometry. Save regularly ...

Furthermore, modeling sometimes gives inconsistent results when the model is inadequate or when some input values are incorrect (**50m long diode ...**). When considering the results you must keep a critical mind and verify that the modeling results are consistent with the experimental results.

And finally, some explanations proposed to understand the effects induced by irradiation are still being checked. Indeed, ECORCE uses models that are constantly evolving and it is likely that the explanations proposed today will be challenged in the coming months.

.II Bulk NMOS transistor, 100nm oxide thickness

.A Id=f(Vgs) characteristic

Consider this NMOS transistor:

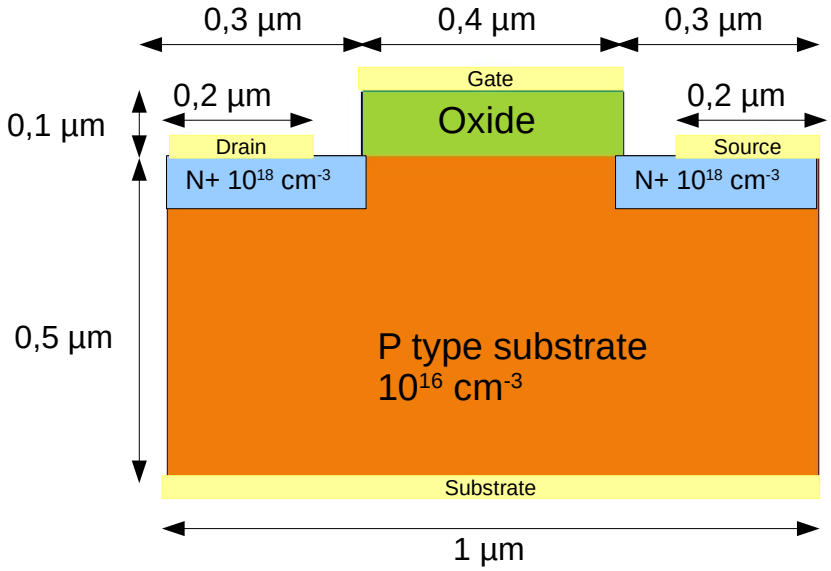


Illustration 1: Schematic view of the NMOS transistor

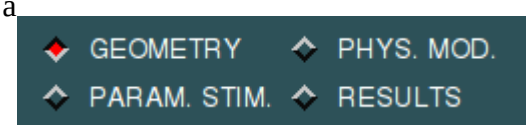
We will create a 2D model that represents this device.

Note: The following steps are very detailed to familiarize yourself with the operation of ECORCE. Take the time to understand and ask questions if necessary. For the following models, commands already seen will not be re-explained.

Under ECORCE, modeling is carried out in five steps :

- definition of the device geometry
- definition of the physical model (materials, equations, laws)
- definition of simulation parameters and stimuli (analysis mode, bias, radiation, ...)
- performing calculations
- visualization and analysis of resuls.

Within ECORCE commands must be scrolled from left to right and from top to bottom to go through all the steps necessary to create a component.



1) <u>Definition of the device geometry</u>

- Launch the software by clicking one time on the icon "ECORCE" on the desktop.
- Select default units: "Semiconductors->OK".
- Create a new device: "File->New simulation". Select "2D" and click "OK" to confirm.

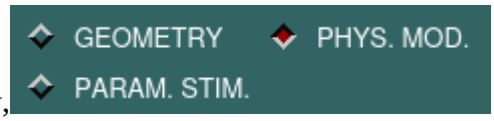
- Move the mouse in the drawing (central widget) over the grid points (white crosses) and look the changes in the mouse tracker to the right. The magnetization effect if activated (Stick to grid) so the coordinates are sticked on the grid points.

- Change the device size to the top/right: 1 µm for x and y axis.
- Clicking on the grid points, create the outline for the silicon, then add the outline for the oxide

- Select "Create contact" in the left window and create contacts for the Drain, Gate, Source and Substrate contact.

- Select "Create surface" in the left window and create materials by clicking inside the outlines.

2) Definition of the physical model



- Select the physical model definition, left window, "PHYS. MOD." button.

- Select Poisson, electron transport, hole transport equations : buttons « Psi », « n », « p »,

- Change contact names: « Contact->Name», according to the device schematic. Click on the drawing to select the contact to rename or use buttons:

- Define gate and substrate material: click on "Materials".
Observe the parameters values read from the library:

Illustration 2: Defaut parameters for Si and SiO_2

- Define doping: click on "Functions".
  "Acceptor" -> "New", "Value": 10^{16} /cm^3,
  "xmin": 0 µm, "xmax": 1 µm,
  "ymin": 0 µm, "ymax": 0.5 µm.
  To avoid overflows into the oxide,Sans_nom select the associated material: "Silicon".
Sans_nom
  "Donor" -> "New", "Value": 10^{18} /cm^3,
  "xmin": 0 µm, "xmax": 0.3 µm,
  "ymin": 0.4 µm, "ymax": 0.5 µm,
  "Sigma x": 0.05µm, "Sigma y": 0.05 µm

  "Donor" -> "New", "Value": 10^{18} /cm^3,
  "xmin": 0.7 µm, "xmax": 1 µm,
  "ymin": 0.4 µm, "ymax": 0.5 µm,
  "Sigma x": 0.05µm, "Sigma y": 0.05 µm

What is the purpose of the Sigma parameters?

3) Definition of stimuli

- Select the stimuli and parameters definition: left window, button "PARAM. STIM."
  (Automatically done after saving.)

- Define contact biases: "Stimuli->Bias->New"
  Drain: "Constant" 0.1V
  Gate: "Ramp" from 0V to 5V increment 0.1V
  Source: "Constant" "0 V"
  Substrate: "Constant" "0 V"

- Save your device: "File->Save".
  Create a new folder(Icon "New folder").
  Rename it: "Radiation_effects" (Right click, option "Rename").
  Go in this folder, enter the name of your device: "nmos_100nm"
  and the name of your simulation: Sans_nom"Id=f(Vgs)".
  Confirm by clicking "OK."

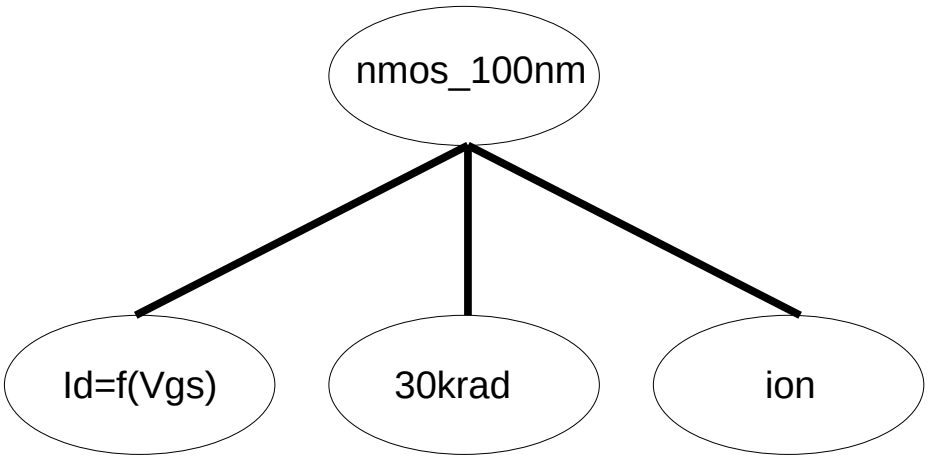
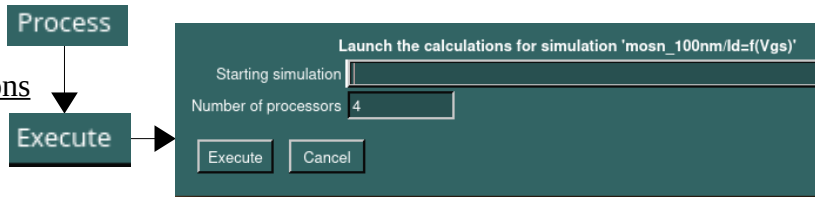


Illustration 3: Example of device with 3 associated stimuli

For one **device** (nmos_100nm) we can create several **stimuli** also called **simulations** (Id=f(Vgs), 30krad, ion, ...) by changing the biases and/or the radiation effect. Thus, when creating a new device, you must define two names: on for the device and another for the first stimuli.

4) Perform the calculations



- Run calculations:
  "Process->Execute->Execute"

When ECORCE performs calculations, it creates a "log file" that details the followed steps This file contains:

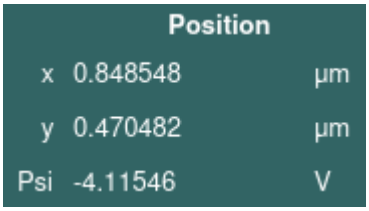
- The device description that you created: geometry and physical model.
- The description of the applied stimuli: contact bias, irradiations, ...
- The stages to create the initial mesh.
- For each calculation step:
  - The number and time of step.
  - The stimuli applied to the contacts: temperature, bias, …
  - The Newton-Raphson iterations used to solve the equations.
  - The total calculation time and the calculation time of the step.
  - The results to the contacts: electron current, hole current, ...

- Open the log file: "Log file" and take a look at the informations given.
  You can move in the text using the scrollbar to the left
  or with the commands available in the top banner: Device, Stimuli, Begin Exec, ... »

- Return to the display results commands: "Results->Display"

5) Visualization of results

- The potential distribution in the device is displayed by default: "Psi" button is checked in the left window. Move the mouse in the drawing and look at the changes in the mouse tracker in the right window.



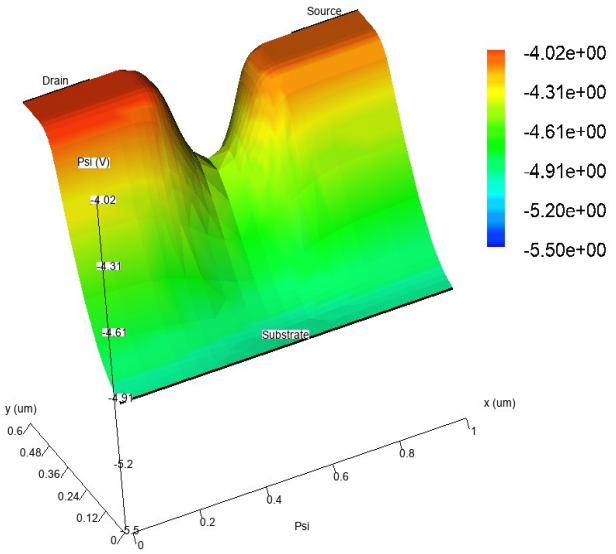


Illustration 4: Potential for VGate = 0 V

- You applied 0V bias on the Source, Substrate and Gate and 0.1V on the Drain. However, the displayed values are very different. Why?

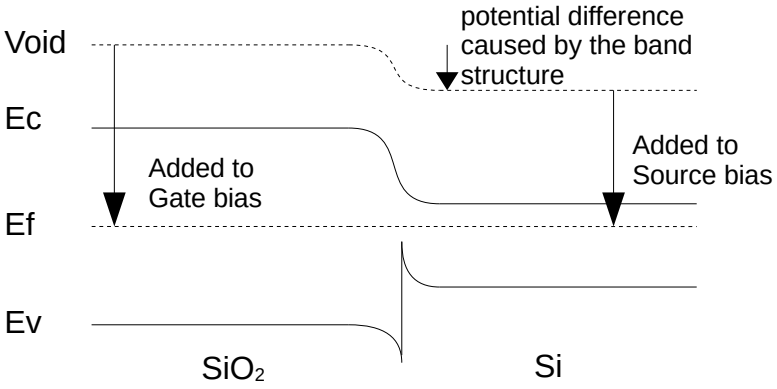


Illustration 5: Difference of potential induced by the energy difference between two materials (not biased).

Answer: when assembling two semiconductors, a potential difference appear because of the energy differences between the two material. To take into account this difference, ECORCE apply to the Gate the bias (ramp from 0V to 5V) + the potential of the fermi level in SiO_2 and to the Source the bias (0V) + the potential of the fermi level in the Si doped n.

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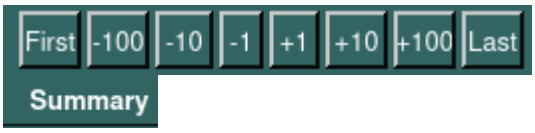
- Switch over steps with the buttons:



  Read the biases and currents for each step in:

- Go back to step 0
  Display the electron density by clicking on "n":

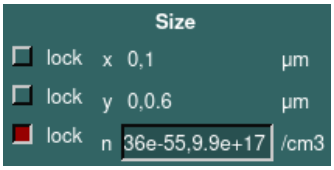
  Switch again over steps, explain what you observe. Displaying the electron density in log scale is useful :

Answer: For V_{Gate} = 0V there is no electron under the oxide because the substrate has a p type doping. Furthermore, the Drain N+ area is biased to +0.1V and the pn junction between this area and the p substrate is locked. Thus no current can go from the Drain N+area to the Source N+ area.

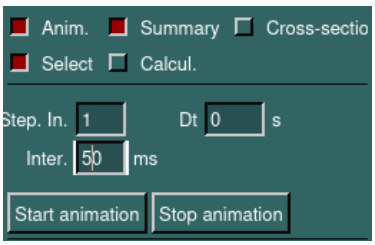
Increasing the bias on the Gate, electron accumulate under the oxide and a conductive channel is created between the N+ area of the Drain and the Source.

The Gate bias for which the conduction starts is called the threshold voltage.

- To see the creation of the channel, go back to step 0, and fix the n scale:



  Then start the animation with these values:



- **This NMOS transistor is normally OFF. It is an enhancement type transistor that needs a bias applied on the gate to be turned ON.**
  Normally ON transistors are depletion type transistors that needs a bias applied on the gate to be turned OFF.

- For now, you displayed values in the volume of the device. It is also interesting to see what occurs at the contact, for example Id=f(Vgs).

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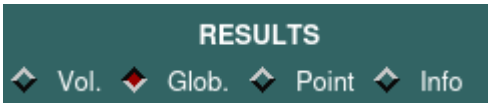
Select Global results display:



Choose Gate Potential (Pot) for X axis
and Drain total current (Itotc) for Y axis

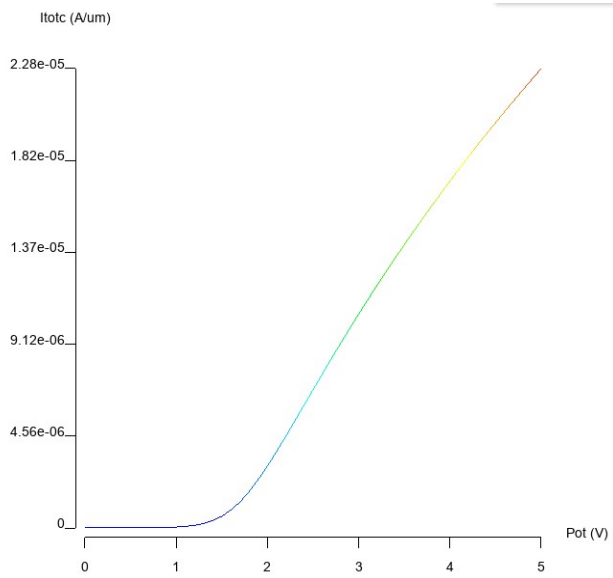
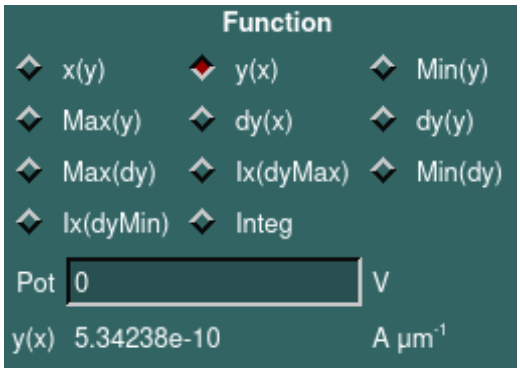
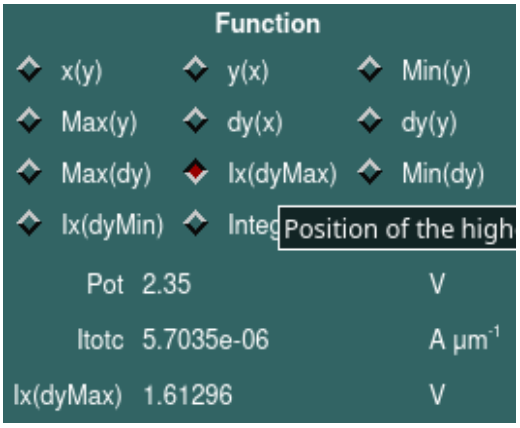


Illustration 6: Id=f(Vgs) for 100nm oxide NMOS

Measure the leakeage current at V_{gs}=0V and the threshold voltage with the functions:





Explain the calculation of the function: Ix(dyMax)

Answer: This function calculate the position of the highest derivative of the curve (in absolute value) and gives the intersection of the tangent at this point with the X axis. This gives a good approximation of the threshold voltage (V_{th}).

What is the maximum number of node?

Answer: 736 nodes

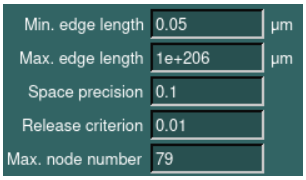
.B Id=f(Vgs) characteristic for different meshes

Mesh design significantly change the results of a modeling. To highlight this we will calculate the characteristic Id=f(Vgs) with 2 meshes: a coarse mesh and a highly refined mesh.

1) Id=f(Vgs) with a coarse mesh

Copy the stimuli "Id=f(Vgs)" of the device "nmos_100nm" and rename the copy "Id=f(Vgs)_coarse_mesh": File->Open
Right click on "Id=f(Vgs)", and Copy
Right click on "Id=f(Vgs)_copie", and Rename

Change the mesh definition according to these values:



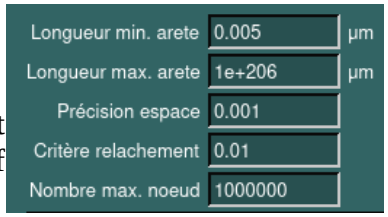
Execute the calculation and measure the leakage current at Vgs=0V, the threshold voltage and the maximum number of nodes. Compare with the previous Id=f(Vgs) characteristic.

Answer: $Id_{Vgs=0V}=3.92\ 10^{-12}$ A /µm, Vth=1.6175V, $Node_{max}=79$
The number of nodes is much lower and the calculation is faster, the threshold voltage is the same but the leakage current is 100 times lower compared to the previous modeling.

2) Id=f(Vgs) with a fine mesh

Duplicate the simulation "Id=f(Vgs)" and rename the copy "Id=f(Vgs)_fine_mesh".

Change the mesh definition according to these values:



Execute the calculation and measure the leakage current at Vgs=0V, the threshold voltage and the maximum number of nodes.

Answer: $Id_{Vgs=0V}=3.55\ 10^{-10}$ A /µm, Vth=1.6342V, $Node_{max}=5521$

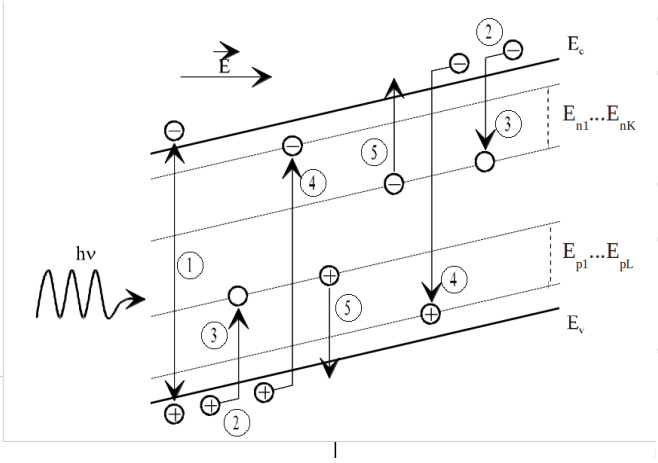
The number of node is much higher and the calculation is slower. The higher computational effort is not justified since the threshold voltage is the same and a change of 30% is observed on the leakage current compared to the previous modeling.

.C Model of trapping-detrapping used by ECORCE

In electronic components, ionizing radiations create high densities of electron-hole pairs. When these charges are deposited in conductive areas (Si, SiC, …) they are quickly recombined and/or collected at the contact and only generate a transient current. However, charges deposited in insulators (SiO_2, $Al2O_3$, ...) will be trapped on defect that are inside the gap of the insulator. Depending on the activation energy of the defects, charges can stay trapped for years in the material and long term effects appear. These charges can cause a malfunction of the whole electronic system or a destruction of the component itself.

Usually TCAD software apply fixed charges in the oxide to modelize Total Ionizing Dose. This is a rough method since the dynamics of trapping/detrapping of charges is not taken into account and that the density of fixed charges can only be calculated approximately.

To get a more precise solution, ECORCE uses the "Multiple Trapping-Detrapping" model (O. L. Curtis 1973). Considering the band diagram of an insulator, this model takes into account these phenomena:



① Pairs generated by radiation

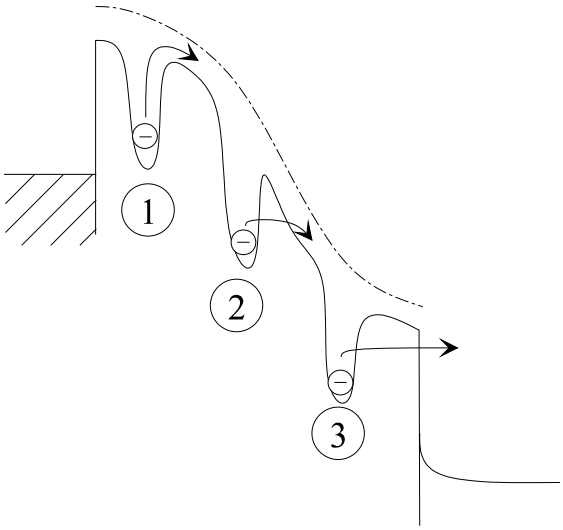
② Carriers drift-diffusion in their respective allowed band

③ Free carriers trapping

④ Recombination of trapped carriers by free carriers of opposite type

⑤ Thermal reemission of trapped carriers to their respective allowed band

This model assumes that in an insulator, a carrier moves through a series of trapping, detrapping and transport in the allowed band as shown in the following chart:



The direct transition of a carrier from a trap to another trap is not taken into account.

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For each electron trap level, ECORCE solves the equation:

$$q\frac{\partial n_t^{(i)}}{\partial t} = C_n^{(i)} - Rec_n^{(i)} - Ree_n^{(i)} \quad with$$

$$C_n^{(i)} = \sigma_{n_t}^{(i)}\left(N_n^{(i)} - n_t^{(i)}\right)\left|\vec{J}_n\right| \quad Rec_n^{(i)} = \sigma_{p_r}^{(i)} n_t^{(i)}\left|\vec{J}_p\right|$$

$$Ree_n^{(i)} = q R_n^{(i)} n_t^{(i)} \quad R_n^{(i)} = \sigma_{n_t}^{(i)} v_{th_n} N_c e^{-q(E_c - E_n^{(i)})/kt}$$

and for each hole trap level:

$$q\frac{\partial p_t^{(j)}}{\partial t} = C_p^{(j)} - Rec_p^{(j)} - Ree_p^{(j)} \quad with$$

$$C_p^{(j)} = \sigma_{p_t}^{(j)}\left(N_p^{(j)} - p_t^{(j)}\right)\left|\vec{J}_p\right| \quad Rec_p^{(j)} = \sigma_{n_r}^{(j)} p_t^{(j)}\left|\vec{J}_n\right|$$

$$Ree_p^{(j)} = q R_p^{(j)} p_t^{(j)} \quad R_p^{(j)} = \sigma_{p_t}^{(j)} v_{th_p} N_v e^{-q(E_v - E_p^{(j)})/kt}$$

where $n_t^{(i)}$, $\sigma_{n_t}^{(i)}$, $N_n^{(i)}$, $\sigma_{p_r}^{(i)}$ et $E_n^{(i)}$ (respectively $p_t^{(j)}$, $\sigma_{p_t}^{(j)}$, $N_p^{(j)}$, $\sigma_{n_r}^{(j)}$ et $E_p^{(j)}$) are the trapped carrier density, the capture cross section, the trap density, the cross section of recombination of a trapped carrier with a carrier of opposite type and the trap energy level, for electrons on level (i) (respectively for holes on level (j)),

v_{th_n}, N_c et E_c (respectively v_{th_p}, N_v et E_v) are the thermal velocity, the density of state in the allowed band and the energy level of the allowed band for electrons (respectively for holes).

.D TID 30 krad XRay on bulk NMOS, V_{gs}=0V

Copy the d evice "nmos_100nm" and rename the copy "nmos_100nm_TID".
Copy the stimuli "Id=f(Vgs)" of the device "nmos_100nm_TID" and rename the copy "30krad_Vgs_0V": File->open

Right click on "Id=f(Vgs)", and copy
Right click on "Id=f(Vgs)_copie", and rename

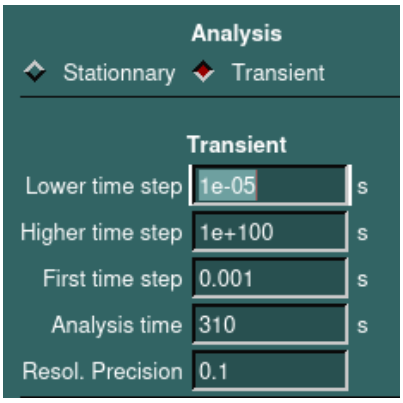
- Select electron trapping and hole trapping equations : buttons « n_t » and « p_t ».
- Change the activation energy of hole traps in the oxide: 1.3eV instead of 1.4eV:
  Phys. Mod.->Material->Oxide

- Define traps in the oxide: click on "Functions".

  "Trap n" -> "New", "Value": 10^{19} /cm^3,
  "xmin": 0.3 µm, "xmax": 0.7 µm,
  "ymin": 0.5 µm, "ymax": 0.6 µm.
  To avoid overflows into the silicon, select the associated material: "Oxide".

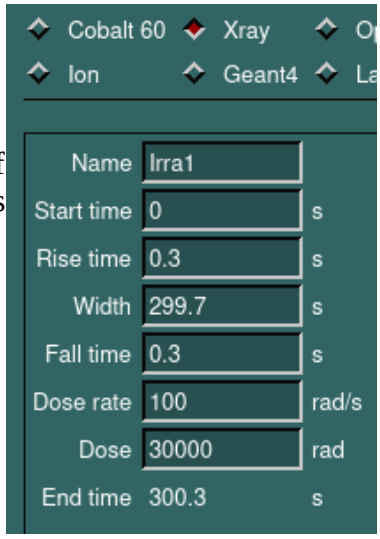
  "Trap p" -> "New", "Value": 10^{19} /cm^3,
  "xmin": 0.3 µm, "xmax": 0.7 µm,
  "ymin": 0.5 µm, "ymax": 0.6 µm.

- Select transient analysis and apply the following values:

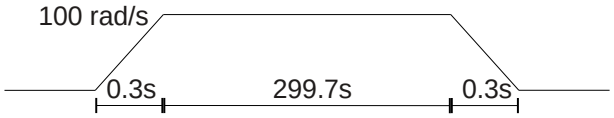


- Check the biases: Gate, Source and Substrate 0V and Drain 0.1V

- Create a dose rate and apply the following values (PARAM. STIM->Stimuli->Irradiation):



Draw by hand the corresponding dose rate as a function of time. Integrate this dose rate and check that the total dose is 30000 rad.



*Answer: TID = 299.7 s * 100 rad/s + 0.3s * 100 rad/s / 2 * 2 = 30 krad*

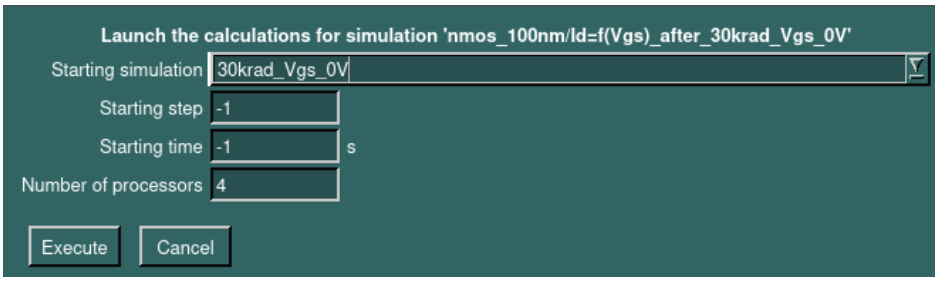
- Execute calculations
  Since the device model is changed ECORCE warns you because previous results will be removed (Id=f(Vgs)).

- This modeling is in transient mode, so the time changes at each step.
  Look at the evolution of the date when switching overs steps.

  Start an animation displaying the potential (Psi).
  The potential increases in the oxide and at the interface.
  Explain the reason of this change. To understand, you can display the electron and hole trapped densities in the oxide : ntot0 and ptot0 and check the activation energies of electron and hole traps in the gate oxide.

  Answer: When electron-hole pairs are generated in the oxide and are trapped in the 10^{19} traps /cm^3 we added in the model. As many electrons as holes are generated in the oxide. However the net charge in the oxide is positive (Displayed with Qtot). Reading the activation energies in the gate oxide (Phys. Mod.->Material) we get Ean = 0.8eV and Eap = 1.3eV. Then electrons are reemitted quickly and are collected at the interface or at the gate contact while holes stay much longer in the device. The positive net charge add a positive potential in the oxide.

- The positive charge will change the Id=f(Vgs) characteristic of the transistor.
  Duplicate the stimuli "Id=f(Vgs)" and rename the copy "Id=f(Vgs)_after_30krad_Vgs_0V"
  Execute the calculation, starting form the last step of the simulation "30krad_Vgs_0V":



  Since the simulation "Id=f(Vgs)_after_30krad_Vgs_0V" is in stationary mode the electron and hole trap densities will not be changed during the calculation. They will be considered as fixed charges and will be taken into account for the Id=f(Vgs) characteristic calculation.

- Check that the electron and hole trap densities are not changed over all steps.
  Display the Id=f(Vgs) characteristic and measure the leakage current for V_{gs}=0V, the threshold voltage, and calculate the threshold voltage shift induced by the TID applied.

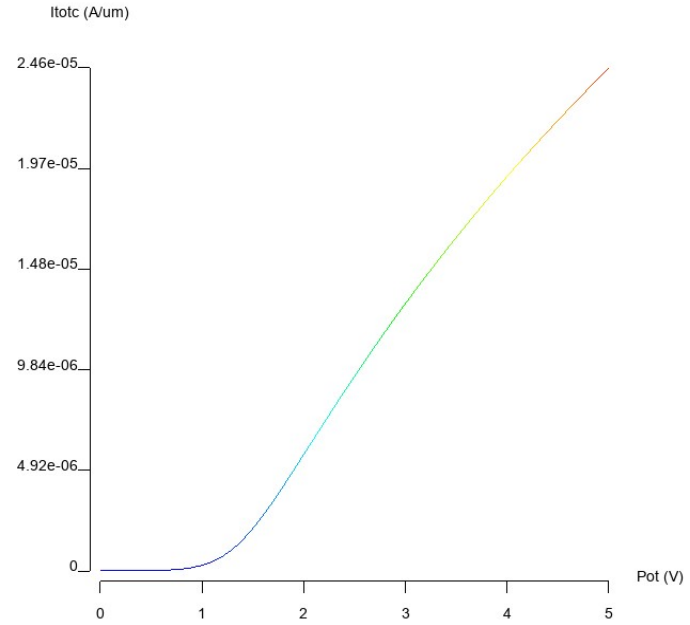


Illustration 7: Id=f(Vgs) characteristic of the NMOS transistor after 30krad with Vgs=0V

Answer: $Id_{Vgs=0V}$=1.81 10^{-9} A/µm, Vth=1.27V, ΔVth=0.34V. You can notice that the leakage current is 4 times higher than for the pristine device.

- To compare the pristine device characteristic and the one after 30krad, you can add both characteristic in an excel file.
  Display Id=f(Vgs) for the pristine device then export it to the file "Id=f(Vgs).xlsx" with the command File->Export
  Display Id=f(Vgs) for 30krad and export it in the same file. This will add this curve to the previous one.
  Open the file: Result file->.../Id=f(Vgs)->Open this file

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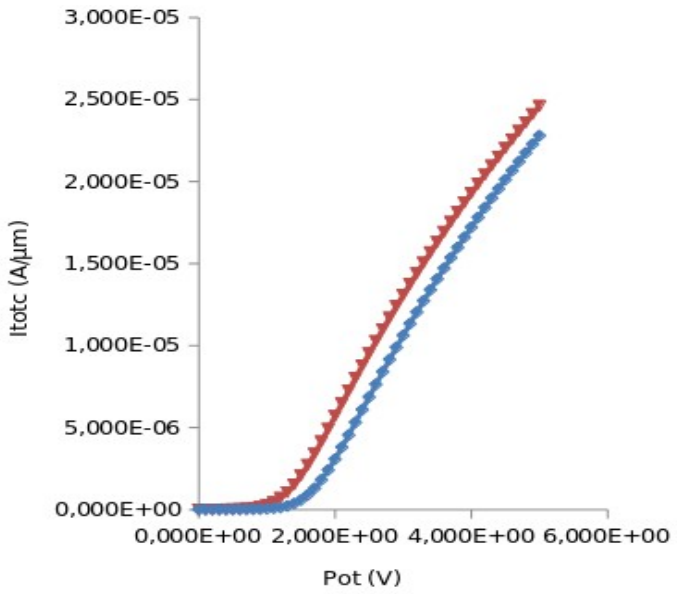

Illustration 8: Id=f(Vgs) characteristic of the NMOS transistor, pristine (blue curve) and after 30 krad (red curve)

- Change Y axis to logarithmic scale and compare the leakage currents below the threshold voltage.

.E Effect of the electric field, TID 30 krad XRay on bulk NMOS, V_{gs}=5V

- The electric field applied in the oxide plays a major role for component degradation under TID.
  To study the effect of the electric field, duplicate the simulation "30krad_Vgs_0V" and rename the copy "30krad_Vgs_5V".
  Change the bias applied to the gate : 5V and start calculations.

- Compare the electron and hole trapped densities to the one for V_{gs}=0V. The net positive charge in the oxide is higher for V_{gs}=5V. Calculate the simulation "Id=f(Vgs)_after_30krad_Vgs=5V".
  Measure the leakage current for V_{gs}=0V, the threshold voltage, and calculate the threshold voltage shift induced by the TID applied.

  Answer: $Id_{Vgs=0V}$=1.39 10^{-7} A/µm, Vth=0.4V, ΔVth=1.21V. You can notice that the leakage current is around 260 times higher than for the pristine device.

- Add the characteristic Id=f(Vgs) in the excel file "Id=f(Vgs).xlsx". You observe a high shift to the right of the characteristic. Go back to the simulation "Id=f(Vgs)_after_30krad_Vgs=5V" and explain the two main effects of the electric field in the oxide during the irradiation.

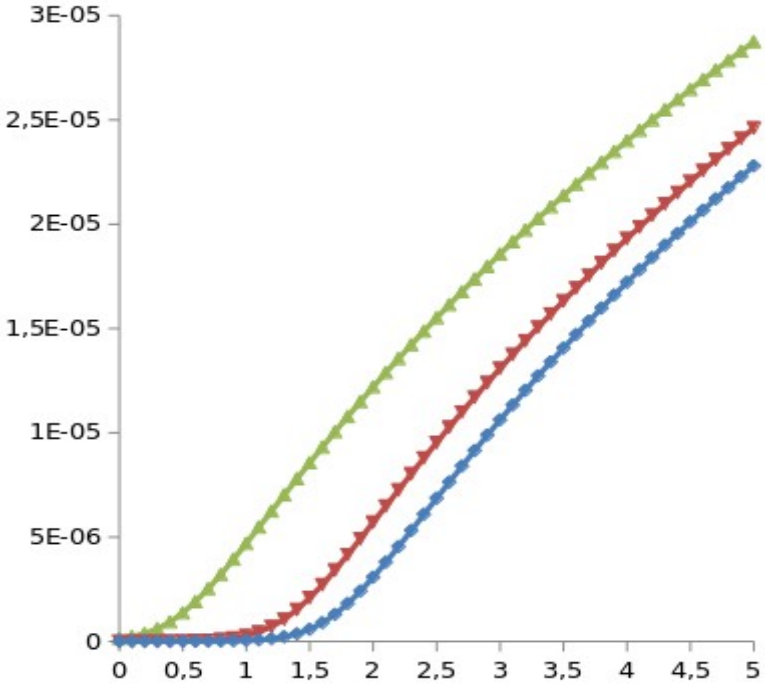

Illustration 9: Id=f(Vgs) characteristic of the NMOS transistor, pristine (blue curve), after 30 krad Vgs=0V (red curve) and after 30krad Vgs=5V (green curve)

Answer, first effect of electric field: When electron hole pairs are generated a fraction of these pairs is instantly recombined. The recombined fraction depend on the electric field. The yield function calculate the fraction of electron hole pairs that are not recombined. Its value lies between 0 and 1. It depends on the intensity of the electric field (unit MV/cm).

- In ECORCE, a tool displays laws that are used. Open Tools->Physical Models. Display the yield function for Xray as a function of the electric field.

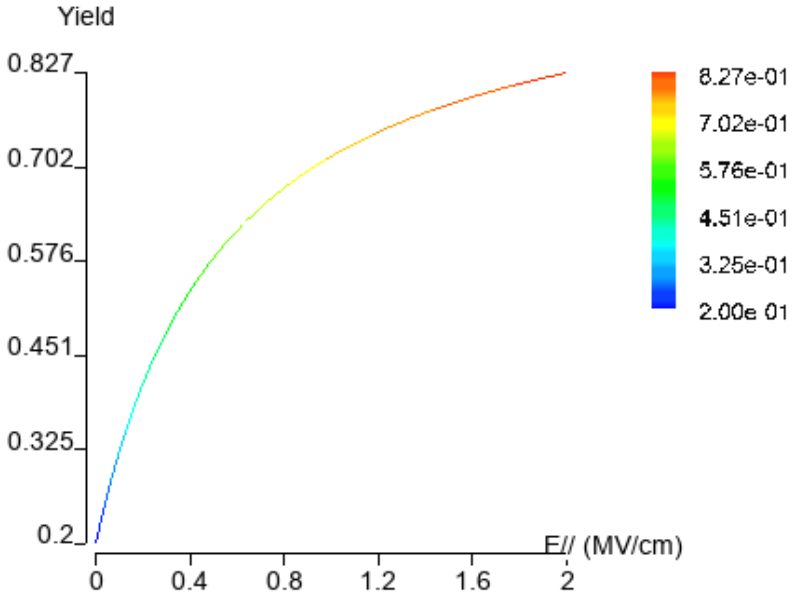

Illustration 10: Yield function as a function of the electric field for XRay.

Measure the electric field at step 0 of the simulations "30krad_Vgs_0V" and "30krad_Vgs_5V", at the point x=0.5µm and y=0.6µm. Using the physical model tool, calculate the fraction of electron-hole pair that are not recombined for both simulations.

Answer: $E_{Vgs=0V}$*=0.097 MV/cm and* $E_{Vgs=5V}$*=0.358 MV/cm*
$Y_{Vgs=0V}$*=0.32 and* $Y_{Vgs=5V}$*=0.515*
The charges generated for V_{gs}*=5V are nearly twice the one generated for* V_{gs}*=0V.*

- The second effect of the electric field is related to charges position in the oxide.
  Display a cross-section of the electrons and holes trapped in the device, along a vertical line for x=0.5µm for "30krad_Vgs_0V" and "30krad_Vgs_5V". Explain the position of these charges and the effect on the threshold voltage shift.

Answer, second effect of electric field: electrons have a negative charge and holes have a positive charge. Their direction of displacement depend on the direction of the electric field. Electron go to the positive bias while hole go to the negative bias.
For Vgs=0V electrons are pushed to the interface and holes are pushed to the Gate contact.
For Vgs=5V electrons are pushed to the Gate contact and holes are pushed to the interface.
The threshold voltage shift can be calculated by integrating the first moment of charges in the oxide: $\Delta V_t = \frac{-q}{\varepsilon_{SiO_2}} \int_0^{e_{ox}} xQ(x)\,dx$ (1)
With Q(x) the electric charge within the oxide and e_{ox} *the oxide thickness (the gate is located at x=0).*
Thus, the threshold voltage shift induced by a charge Q is proportional to $\boldsymbol{Q * d^2}$ *with d the distance between the Gate contact and the charge Q.*
Since trapped hole are close to the interface for Vgs=5V they induce a higher threshold voltage shift than for Vgs=0V.

.F TID modeling with fixed charges

As you can see, the mecanisms in irradiated insulators are complex. Is it possible to modelize TID applying fixed charges in the oxide?

Find within ECORCE the absorption coefficient of the oxide and calculate the density of electron hole pairs generated in the oxide for a 30krad dose. You must also take into account the value of the yield function previously calculated.

Answer: $g = 7.6\ 10^{12}\ rad^{-1}cm^{-3}$. $Qfix\_total = 7.6\ 10^{12} * 30000 = 2.28\ 10^{17}\ cm^{-3}$
For V_{gs}*=0V, Y=0.32,* $Qfix\_effective = 2.28\ 10^{17} * 0.32 = 7.29\ 10^{16}\ cm^{-3}$
For V_{gs}*=5V, Y=0.515,* $Qfix\_effective = 2.28\ 10^{17} * 0.515 = 1.17\ 10^{17}\ cm^{-3}$

Remark: For Vgs=5V we can consider that before irradiation, the electric field is constant inside the oxyde since it changes from 0.351 to 0.360 MV/cm depending on the position.
For Vgs=0V the electric field changes from 0.097 to 0.155 MV/cm, so we did a rought calculation for the fixed charge.

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Furthermore, at the end of irradiation the electric field is modified by the trapped charges.
For Vgs=0V it changes from 0.061 to 0.2 MV/cm depending on the position and for Vgs=5V it changes from 0.28 to 0.48 MV/cm.

For the calculation of the fixed charges, we considered that the electric field stayed constant during the irradiation. This is another rought approximation.

Duplicate the device "nmos_100nm" and rename the copy "nmos_100nm_fixed_charge_Vgs_0V".

Open the simulation "Id=f(Vgs)" and add in the oxide the fixed charge you calculated for Vgs=0V: Phys. Mod.->Functions->Fixed Q
Execute calculation and calculate the leakage current for V_{gs}=0V, the threshold voltage and the threshold voltage shift.

Duplicate the device "nmos_100nm_fixed_charge_Vgs_0V" and rename the copy "nmos_100nm_fixed_charge_Vgs_5V"
Execute calculation and calculate the leakage current for V_{gs}=0V, the threshold voltage and the threshold voltage shift.

Answer:
For fixed charges at V_{gs}=0V, $Id_{Vgs=0V}$=1.22 10^{-6} A /µm, Vth=-0.074V, Δvth=1.68V. You can notice that the leakage current is 2.2 10^{3} times higher than for the pristine device.

For fixed charges at V_{gs}=5V, $Id_{Vgs=5V}$=8.5 10^{-6} A /µm, Vth=-1.09V, Δvth=2.7V. You can notice that the leakage current is 1.5 10^{4} times higher than for the pristine device.

Remark: for fixed charges, the threshold voltage shift is so high that you must change the voltage ramp applied to the gate. Sweep from -2 to +5 V in steps of 0.1V

.G Effect of the temperature, TID 30 krad XRay on bulk NMOS, V_{gs}=5V

According to model defined in .C the re-emission rate Ree_n and Ree_p vary as an exponential of the activation energy and the temperature.
In the following, you will study the effect of high and low temperature on the "nmos_100nm_TID" device irradiated at 30krad with V_{gs}=5V.

Remark: check the temperature of the previous modeling. By default, the background temperature is 300K within ECORCE.

1) High temperature, 550K

Duplicate the simulation "30krad_Vgs_5V" and rename the copy "30krad_Vgs_5V_550K".

Change the background temperature to 550K: Param. Stim.->Stimuli->Back. temp.
Execute calculation.

Create a new simulation (which one ?) to calculate the leakage current for V_{gs}=0V, the threshold voltage and the threshold voltage shift. The calculation of Id=f(Vgs) must be done at 300K.

The change is much lower than for the modeling at 300K. By comparison of the trapped charges for 300K and 550K explain the differences of the Id=f(Vgs) characteristic changes:

- measure the maximum value of nt, pt at the end of irradiation (310s)
- measure the thermal reemission rate at t=100s.

➢ *Answer: $Id_{Vgs=0V}$=3.96 10^{-10} A /µm, Vth=1.618V, ΔVth=+0.008V (mesh effect).*

At the end of irradiation:

	n_t (cm^{-3}) (310s)	p_t (cm^{-3}) (310s)	Ree_n ($cm^{-3}s^{-1}$) (100s)	Ree_p ($cm^{-3}s^{-1}$) (100s)
300K	*1.38 10^{12}*	*8.66 10^{16}*	*3.04 10^{13}*	*2.28 10^{8}*
550K	*2.24 10^{-14}*	*1.83 10^{-34}*	*4.78 10^{14}*	*1.02 10^{17}*

The density of trapped hole is 0 at 550K. Because the thermal re-emission rate of hole is 10^9 times higher at 550K, the trapped holes are re-emitted during the irradiation and are collected at the interface. Thus, the positive charge in the oxide is 0 at the end of the irradiation and there is no change of the characteristic compared to the pristine device. The small difference is induced by the number of nodes (at the end of irradiation, 787 nodes at 300K and 806 at 550K).

2) Low temperature, 100K

Duplicate the simulation "30krad_Vgs_5V" and rename the copy "30krad_Vgs_5V_100K".

Change the background temperature to 100K: Param. Stim.->Stimuli->Back. temp.
Execute calculation.

Calculate the leakage current for V_{gs}=0V, the threshold voltage and the threshold voltage shift.

Explain the differences with irradiation at 300K.

➢ *Answer: $Id_{Vgs=0V}$=2.36 10^{-8} A/µm, Vth=0.729V, ΔVth=0.88V.*

At the end of irradiation:

	n_t (cm^{-3}) (310s)	p_t (cm^{-3}) (310s)	Ree_n ($cm^{-3}s^{-1}$) (100s)	Ree_p ($cm^{-3}s^{-1}$) (100s)
300K	*1.38 10^{12}*	*8.66 10^{16}*	*3.04 10^{13}*	*2.28 10^{8}*
100K	*4.25 10^{16}*	*9.45 10^{16}*	*1.8 10^{-13}*	*5.66 10^{-37}*

The density of trapped hole is very similar at 100K than at 300K. Because the thermal re-emission rate of electron is 10^{26} times lower at 100K, the trapped electrons are no more reemitted during the irradiation. Thus, the sum of trapped electron and trapped hole gives a lower positive charge in the oxide. The threshold voltage shift is lower at 100K than at 300K but a short duration annealing at 300K will be enough to get back to the shift obtained for an irradiation at 300K.

.H Annealing after irradiation

Increasing the temperature of an irradiated device will release the trapped charge in the oxides and can restore the functioning of the component. This regeneration method has been applied at regular intervals to maintain the proper functioning of the image sensor of the Hubble telescope.

1) Low electric field, V_{gs}=0V at 400K

You will apply a thermal annealing at 400K, with V_{gs}=0V during 24 hours.

Duplicate the simulation "30krad_Vgs_0V" and rename the copy "annealing_400K_Vgs_0V_after_30krad_Vgs_5V".

Remove the Xray TID.

Change the background temperature to 400K, change the analysis duration (lower and first time step = 1s) and check the bias applied to the gate.

Execute calculation starting from the end of simulation "30krad_Vgs_5V".

Calculate the leakage current for V_{gs}=0V, the threshold voltage and the threshold voltage shift at the end of this annealing.

Compare the electron and hole trap densities at the end of irradiation to the one at the end of annealing.

- *Answer: $Id_{Vgs=0V}=6.57\ 10^{-10}$ A/µm, Vth=1.489V, ΔVth=0.12V.*

At the end of irradiation and at the end of annealing:

	n_t (cm^{-3})	p_t (cm^{-3})
End of Irradiation 300K	$1.38\ 10^{12}$	$8.66\ 10^{16}$
End of annealing 400K	$8.24\ 10^{-32}$	$1.75\ 10^{16}$

The trapped hole density at the end of annealing has been divided by more than 2 compared to the trapped home density at the end of irradiation. This explains the reduction of Δvth after annealing.

2) High electric field, V_{gs}=5V at 400K

The electric field has also a significant effect on activation energies. Applying an electric field in the gate will change the re-emission rate of trapped carriers during annealing.

Duplicate the simulation "annealing_400K_Vgs_0V_after_30krad_Vgs_5V" and rename the copy "annealing_400K_Vgs_5V_after_30krad_Vgs_5V".

Change the gate bias: V_{gs}=5V.

Calculate the leakage current for V_{gs}=0V, the threshold voltage and the threshold voltage shift at the end of this annealing.

Compare the electron and hole trap densities at the end of annealing with the one for annealing with V_{gs}=0V.

➢ *Answer: $Id_{Vgs=0V}$=4.2 10^{-10} A/µm, Vth=1.615V, ΔVth=-0.003V.*

At the end of both annealing:

	n_t (cm^{-3})	p_t (cm^{-3})
End of annealing Vgs=0V	*8.24 10^{-32}*	*1.75 10^{16}*
End of annealing Vgs=5V	*7 10^{-32}*	*2.3110^{-35}*

The annealing with V_{gs}=5V is much more efficient than the one with Vgs=0V. **Explain**.

➢ *Answer: the activation energy is a function of the electric field following the formula:*

$$E_a = E_{a0} - \sqrt{\frac{qE}{4\pi\varepsilon_{ox}}}$$

with E: the electric field
E_{a0}: the activation energy for E = 0 MV/cm
ε_{ox}: the permittivity of the oxide.
E_a the activation energy depending on the electric field

This is known as the Poole-Frenkel effect.

At step 1 of both annealing:

	E (MV/cm)	*Ean (eV)*	*Eap (eV)*	*Ree_p ($cm^{-3}s^{-1}$)*
Annealing Vgs=0V	*0.21*	*0.79*	*1.29*	*5.41 10^{14}*
Annealing Vgs=5V	*0.48*	*0.7*	*1.2*	*8.65 10^{16}*

The activation energies for E=0 MV/cm are:
- *Ean=0.8 eV*
- *Eap=1.3 eV*

Applying an electric field slightly reduces these values but, since the re-emission rate varies as an exponential of the activation energy (see section .C) this small change increases the re-emission rate by a factor 5.

The next chart displays a graphical explanation of the activation energy reduction. It shows the activation energy of a trapped charge without electric field (left drawing) and the activation energy with electric field (right drawing).

It appears that curving the conduction and valence band with an electric field, induces a reduction of the energy needed by a trapped carrier to go back to its allowed band.

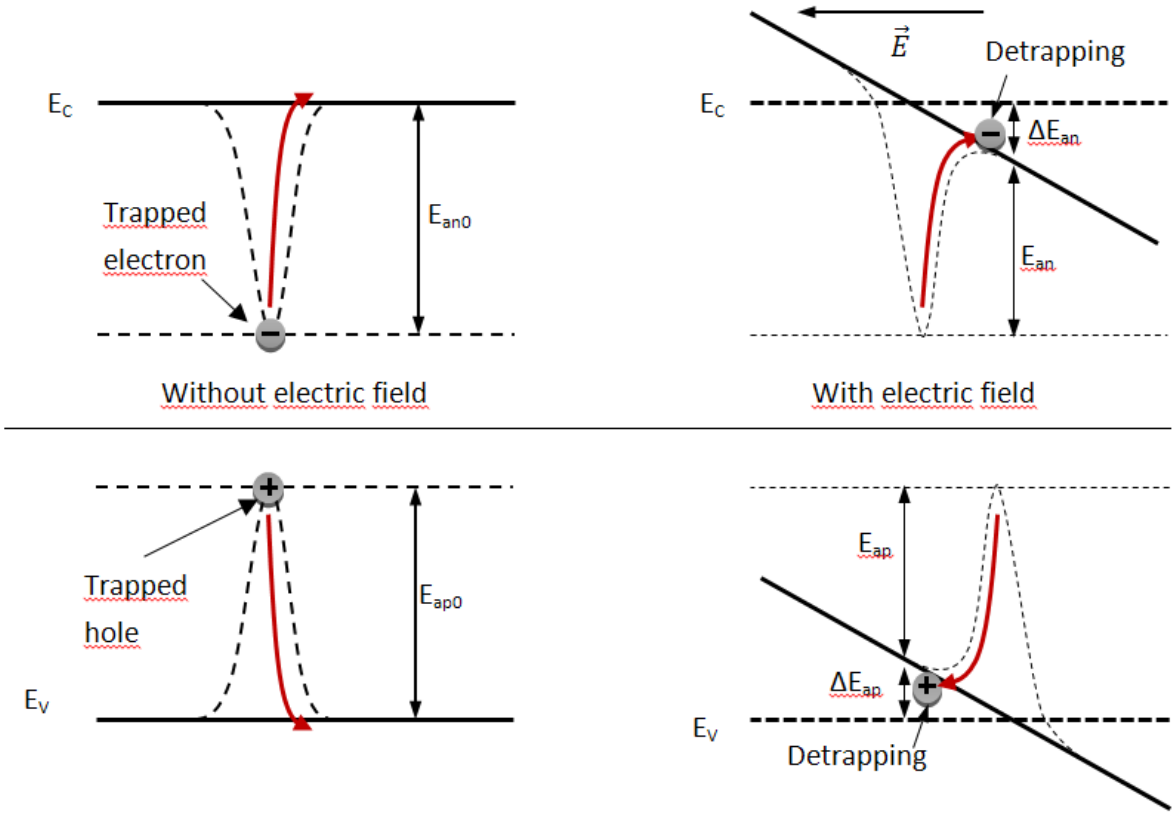


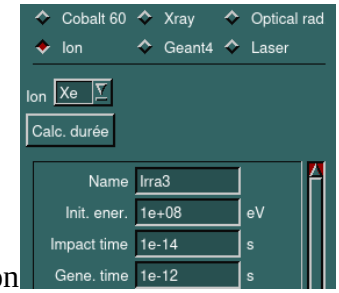
Illustration 11: Principle of the Poole-Frenkel effect: reduction of the activation energies

.I 100 MeV Xe ion on bulk NMOS, V_{gs}=0V

Single events effects (SEE) are induced by on ion that hits an electronic component. In the next steps you will apply an ion on the "nmos_100nm_TID" device and study its effects.

1) Xe 100 MeV for V_{gs}=0V

Duplicate the simulation "30krad_Vgs_0V" and rename the copy "Xe_100MeV_Vgs_0V". Replace the Xray TID by an ion with these parameters:



Define the impact point: x=0.5 µm, y=0.6 µm
and the angle: -90°

The impact point and direction of the ion is shown in next chart.

The Linear Energy Transfert (LET) is also displayed as a function of the ion range. Can you explain the step of the LET for the 0.1 µm range?

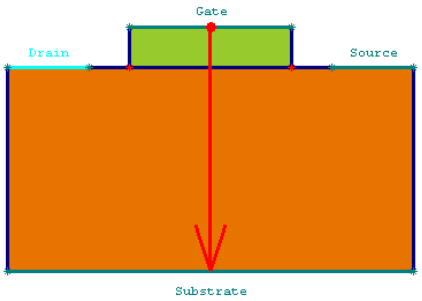


Illustration 12: Impact point and direction of the 100 MeV Xe ion in NMOS with gate oxide 100nm

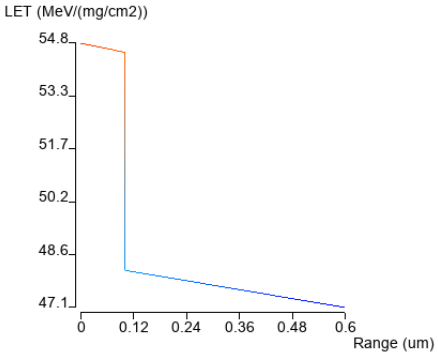
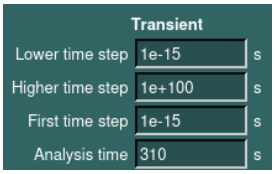


Illustration 13: LET of the 100 MeV Xe ion as a function of the range in NMOS with gate oxide 100nm

Answer: The energy transferred by the ion depends on the material. Considering the impact point and the direction of the ion, from range 0 to 0.1µm the ion crosses the oxyde and from range 0.1 to 0.6 µm it crosses the silicon. Thus, the LET of the 100 MeV ion is higher in the oxide than in the silicon.

This ion will cross the device in 1 ps.



Correct the time parameters:
The higher time step is very high and will have no effect on the modeling.

Execute calculation.

Analyze the results: display the evolution of electron and hole densities over time. What occurs in the oxide?

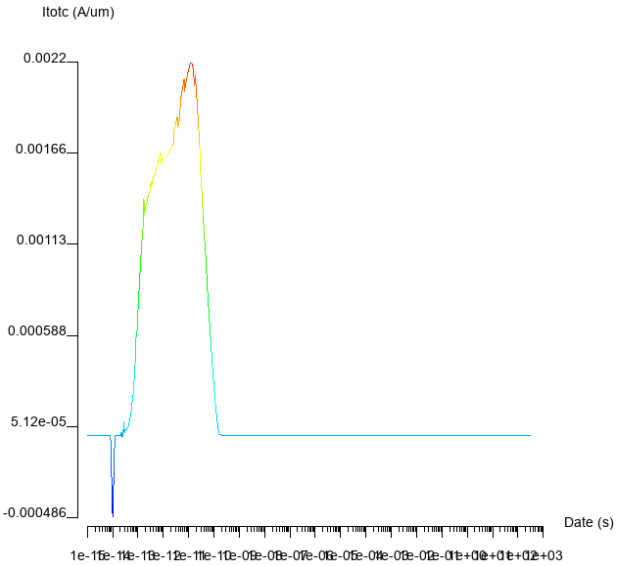


Illustration 14: Drain current as a function of Time, induced by a 100 MeV Xe ion.

Display the Drain current Itotc as a function of Date (logscale)
Peaks of current are observed at $t=10^{-14}$s and at others time.
These peaks are induced by the numerical methods used by ECORCE.
Do you have any idea where these peaks come from?

To understand, add on the same excel file the Drain current as a function of time and the number of nodes as a function of time. Use different Y scale for the two curves.

Answer:At each step of modeling ECORCE changes the mesh, adding or removing nodes.
In some cases, the change of the mesh induce a change of the global solution that results in peaks of current.

The Drain current Itotc is calculated by integrating the current density at the Drain contact. The Drain current Itotv is calculated by integrating the current density in the full volume of the device. The peaks of current are much lower when calculating the current with Itotv than with Itotc.

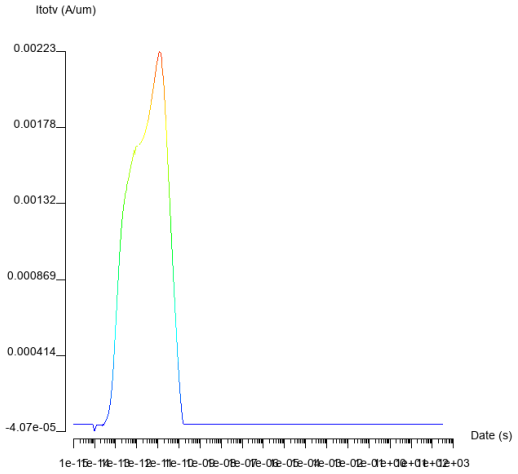


Illustration 15: Drain current as a function of time calculated by integration on the full volume of the device (Itotv).

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Display the Drain current (Itotv in logscale) as a function of time (logscale).

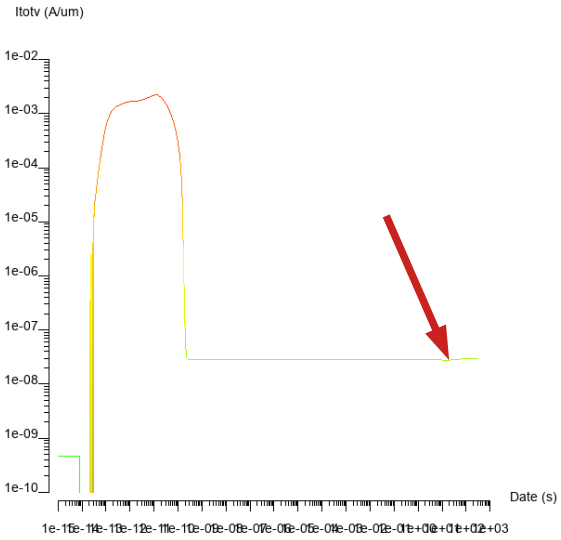


Illustration 16: Drain current (Itotv log scale) as a function of time (log scale)

Explain the small current increase that starts around t=1s.

Answer:the electron-hole pairs generated in the oxide are trapped on defects (see nt and pt). The transient current induced by the collection of charges at the Drain, Source and Substrate contacts last less than 1ns.
When applying a TID, the holes are trapped for a long time in the oxide because of the high activation energy of the hole traps.
The duration of the transient current if low (1ns) and electron are not detrapped on such a short time but starting at 1s the electron thermal detrapping becomes significant and the negative charge is removed from the oxide leaving only hole trapped in the oxide.
Thus the leakage current increases since a higher positive charge is in the oxide at t=1000s than at t=1s.

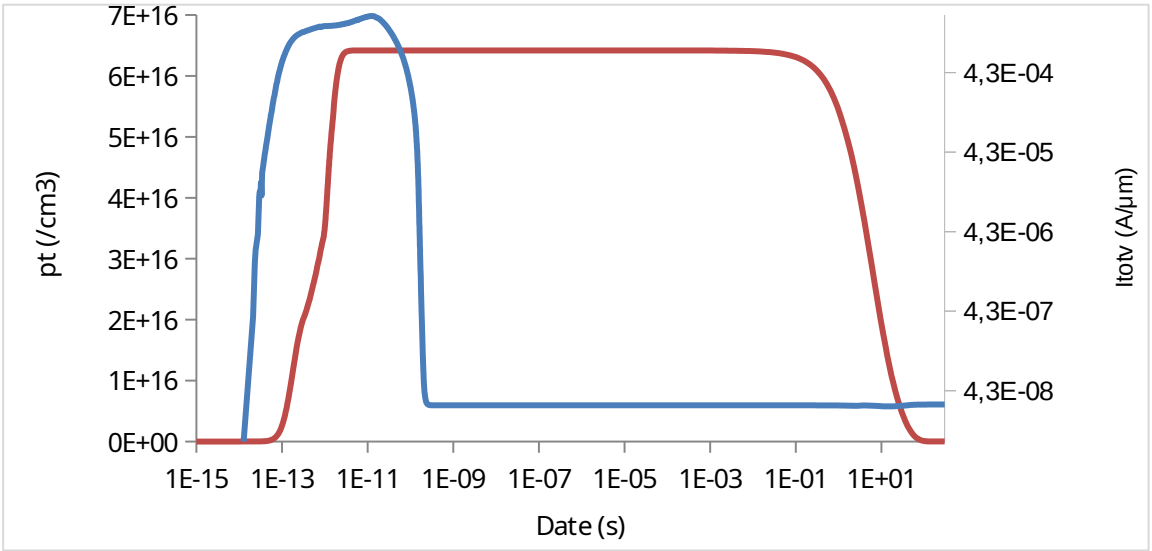


Illustration 17: Drain current (blue curve) and maximum trapped electron density (red curve) as a function of time

Create a new simulation to calculate the leakage current for V_{gs}=0V, the threshold voltage and the threshold voltage shift.

Compare the results with the simulation "30krad_Vgs_0V".

➢ *Answer: $Id_{Vgs=0V}$=2.33 10^{-8} A /µm, Vth=0.685V, ΔVth=0.93V*

At the end of irradiation:

	n_t (cm^{-3}) (310s)	*p_t (cm^{-3}) (310s)*
30krad Vgs=0V	*1.64 10^{15}*	*5.07 10^{16}*
100 MeV Xe ion Vgs=0V	*64.8*	*2.38 10^{17}*

The trapped hole density for the Xe ion is around 5 times higher than for the Xray 30krad.
This explains the higher threshold voltage shift induced by the ion (0.97V) than by the 30krad TID (0.38V)
Furthermore, the trapped electron density is lower for the Xe ion because electron have been generated in 1ps by the ion while they are generated during 300s for 30krad TID.
Thus trapped electron have more time to be reemitted when they are generated by the ion than when they are generated by the 30krad TID.
*Charge deposited in oxide by ions is called **microdose**. Depending on the kind and energy of the ion, the microdose deposited by one ion can be equivalent to tens of krad.*

2) Xe 100 MeV for V_{gs}=5V

Duplicate the simulation "Xe_100MeV_Vgs_0V" and rename the copy "Xe_100MeV_Vgs_5V".

Change the bias of the Gate: 5V
Execute calculation

Display Itotv as a function of time, maximum electron and hole densities in the oxide as a function of time.
You can also display the total charge in the oxide at position x=0.5µm, y=0.55µm.

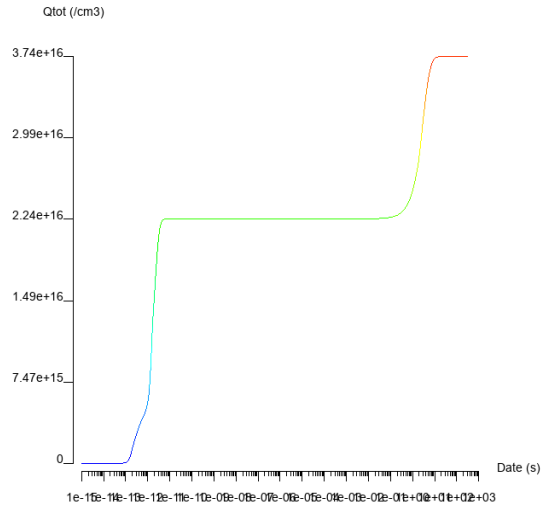


Illustration 18: Total charge (Qtot) as a function of time at point x=0.5µm, y=0.55µm

Create a new simulation to calculate the leakage current for V_{gs}=0V, the threshold voltage and the threshold voltage shift.

Compare the results with the simulation "30krad_Vgs_5V".

- *Answer: $Id_{Vgs=0V}$=2.04 10^{-5} A /µm, Vth=-4.06V, ΔVth=5.67V*

At the end of irradiation:

	n_t (cm^{-3}) (310s)	*p_t (cm^{-3}) (310s)*
30krad Vgs=5V	*1.38 10^{12}*	*8.65 10^{16}*
100 MeV Xe ion Vgs=5V	*6.22 10^{-12}*	*8.07 10^{17}*

When crossing devices, ions will generate a transient current that can trigger SEU and other transient effects, but if it crosses an oxide, it will also deposit a ionizing dose that is equivalent to several tens of krad.

.J Real TID 30 krad XRay on bulk NMOS, V_{gs}=5V

To accelerate test on ground, facilities provide much higher dose rate than dose rate in space environnement.

To understand the effect of small dose rate, you will apply 30krad with XRay source during 15 years. Consider that 15 years = 15 * 365 * 24 hours.

What dose rate will you use? *Answer: 30000rad/131400h = 0.23 rad/h*

Duplicate the simulation "30krad_Vgs_5V" and rename the copy "30krad_Vgs_5V_15_years".

Change the irradiation parameters according to your calculations.

Remember to correct the analysis parameters.

Execute calculation.

- Measure the leakage current for V_{gs}=0V, the threshold voltage, and calculate the threshold voltage shift induced by the TID applied.
  Compare results to 30krad XRay, Vgs=5V. Explain the reason why the shift is lower for real TID?

Answer: $Id_{Vgs=0V}$=3.75 10^{-8} A /µm, Vth=0.59V, ΔVth=0.98V.

At the end of irradiation:

	n_t (cm^{-3}) (310s)	*p_t (cm^{-3}) (4.71 10^8s)*
30krad Vgs=5V 310 s	*1.38 10^{12}*	*8.65 10^{16}*
30krad Vgs=5V 15 years	*4.66 10^{-9}*	*3.06 10^{13}*

The threshold voltage shift is lower for the real TID because the trapped hole density have more time to be reemitted. Thus at the end of the irradiation, the trapped hole density is lower for the real TID than for the short duration one. High dose rate tests lead to a significant over-estimation of the TID effect in space. With the choosen parameters (activation energy, ...) the threshold voltage shift is 30% higher with test at ground level compared to real TID.

.III Bulk NMOS transistor, 20nm oxide thickness

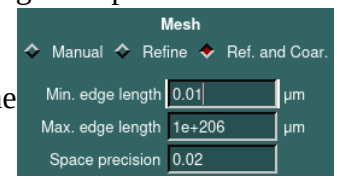
.A Id=f(Vgs) characteristic

Integrated devices can use gate oxides as thin as 2nm. To understand the importance of the gate oxide thickness you will reduce the thickness of your device and apply a TID.

Duplicate the device "nmos_100nm_TID" and rename the copy "nmos_20nm_TID".
Open the simulation "Id=f(Vgs)".

How do you proceed to change the thickness of the oxide to 20 nm?

Look at the mesh parameters. The minimum length of edges is high compared to the oxide thickness: 0.01 µm



For a good definition of the mesh in the oxide change the minimum edge length: 0.002 µm

Execute calculation and measure the leakage current for V_{gs}=0V and the threshold voltage.
Take a look at the electric field in the oxide for Vgs=5V and compare to the value for the 100nm oxide.

Answer: $Id_{Vgs=0V}=6.69\ 10^{-13}$ A /µm, Vth=1.394V
Reducing the oxide thickness lower the threshold voltage but increases the electric field in the oxide: for 20 nm oxide, $E_{Vgs=5V}=1.78$MV/cm for 100nm oxide, $E_{Vgs=5V}=0.36$MV/cm

.B TID 30 krad Xray, V_{gs}=5V

Execute calculation for 30krad_Vgs_5V (don't forget to change the minimum size of length).
Measure the leakage current for V_{gs}=0V, the threshold voltage, and calculate the threshold voltage shift induced by the TID applied.
Compare the trapped hole density at the end of irradiation for the 2 oxide thickness. Explain the higher density in the 20nm oxide and the difference of threshold voltage shift.

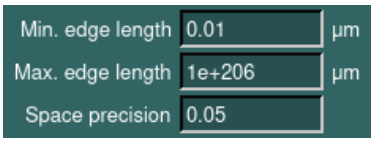
Answer: $Id_{Vgs=0V}=1.32\ 10^{-12}$ A /µm, Vth=1.24V, ΔVth=0.15V
For 20nm oxide, $pt=1.9\ 10^{17}$ cm^{-3} for 100nm oxide, $pt=8.66\ 10^{16}$ cm^{-3}

The trapped hole density is higher in the 20nm oxide because of the higher electric field that leads to a higher yield function: $Y_{20nm}=0.81$ and $Y_{100nm}=0.52$
Because of the thin oxide thickness, the distance between the electric charge deposited by the irradiation in the oxide and the gate contact is low. Then the threshold voltage shift is much lower for the 20nm oxide than for the 100nm oxide even if the trapped charge is higher in the 20nm oxide.
This is the reason why it is admitted that with low gate oxide thickness, the threshold voltage shift induced by TID on MOS transistors can be neglected.

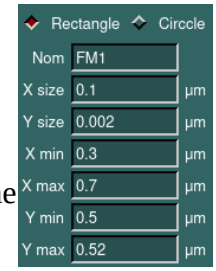
.C Xe 100 MeV for V_{gs}=5V

Execute the simulation "Xe_100MeV_Vgs_5V"
To reduce calculation time:

- correct the mesh parameters according to:



- and add a mesh function correction:



With these parameters, the results will be less precise but you the calculation will last only a few minutes.

Measure the leakage current for V_{gs}=0V, the threshold voltage, and calculate the threshold voltage shift induced by the TID applied.
Compare the trapped hole density at the end of irradiation to the one for 30krad, Vgs=5V.

Answer: $Id_{Vgs=0V}=2.88\ 10^{-6}$ A /µm, Vth=-0.12V, ΔVth=1.49V
For 100MeV Xe ion Vgs=5V, pt=3.19 10^{18} cm^{-3} for 30krad Vgs=5V, pt=1.85 10^{17} cm^{-3}

Modeling says that even for a thin oxide the threshold voltage shift induced by a 100MeV ion is significant. For our modeling, the transistor is on for Vgs=0V. Thus, the system that include this device will no longer work.

As shown in the following results, the effect of microdose for 100MeV Xe ion can be neglected for oxide thickness lower than 10 nm.

Results for à 10nm oxide are:
$Id_{Vgs=0V}=1.7\ 10^{-12}$ A /µm, Vth=0.9V, ΔVth=0.45V

Results for à 5nm oxide are:
$Id_{Vgs=0V}=1.5\ 10^{-13}$ A /µm, Vth=1.27V, ΔVth=0.08V

.D Interface states

Interface states are defaults at the interface between the semiconductor and the insulator. They are defined by their activation energy (relative to the valence and conductor band in the semiconductor) and their surface density.

Since these traps are also in the semiconductor, they are filled and emptied according to the density of carriers at the interface.

Depending on the process and the semiconductor (Si, SiC, GaN, ...) and the insulator (SiO_2, Al_2O_3, ...) used, pristine device can have interface states.

Interface states can also be created during an irradiation.

Since protons are used at some stages of process, part of these protons are trapped on defaults in insulators of the device. During the irradiation, these protons are released and, depending on the bias sign, move to the interface. When they reach the interface, they break bonds, creating new interface states.

It is also admitted that holes generated by irradiation in the insulator can create these defaults when they cross the interface (see Oldham for a full explanation of the model).

The full model of "proton release->proton transport->interface state creation" is already implemented within ECORCE but is not fully debugged.

In this section you will only study the effect of interface state on the characteristic Id=f(Vgs).

Duplicate the device "nmos_20nm" and rename the copy "nmos_20nm_interface_state".

Open the simulation "Id=f(Vgs)". Add equations "itn" and "itp".

Go to "PHYS. MOD.->Interfaces and change the interface state densities of electron and holes:

What are the activation energies of electron and hole interface traps?

Execute calculation. Display the evolution of electron and hole trapped at the interface during the calculation of the Id=f(Vgs) characteristic.

Add on the excel file "Id=f(Vgs)_interface_state" the characteristic with interface states and the one without interface states.

Explain.

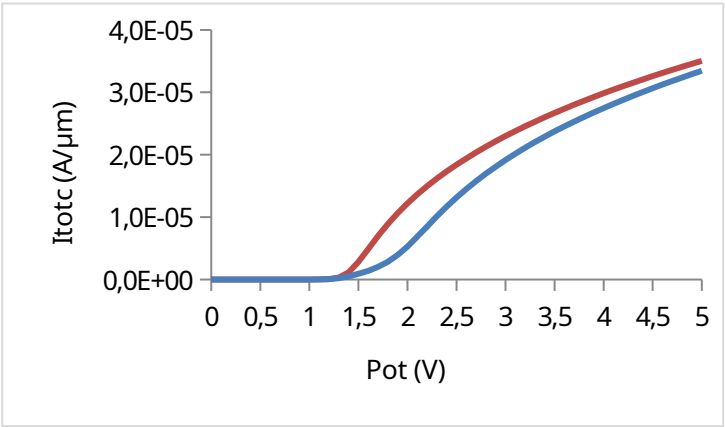


Illustration 19: Drain current as a function of Gate bias with 5 10^{11} cm^{-2} interface state (blue curve) without interface state (red curve).

Answer: Ea_{itn}= 0.2eV, Ea_{itp}=0.2eV. These values are low. Thus trapped electron and hole can be easily reemitted at room temperature. $Id_{Vgs=0V}$=1.05 10^{-12} A /µm, Vth=1.69V

For low Vgs, free holes are attracted to the interface. The hole interface traps are filed. The highest surface density is in the middle of the interface because this is the position where the density of free hole is the highest.

For Vgs > 1V, the holes are pushed away from the interface and the electron are attracted to the interface. Thus hole interface traps are empty and electron interface traps start to be filed.

With interface traps, the electrons move by jump from one trap to the other. Thus their apparent mobility is reduced. This change the shape of the characteristic. When the electron traps are completely filed (around Vgs=3.1V) the characteristic Id=f(Vgs) tends to return to the one without interface state. From this Vgs value, an increase of the bias attracts additional free electrons at the interface that are not captured by traps because they are filed.

.E ECORCE Optimizer (usually called Display Of Experiment)

TCAD software also provide tools to sweep over parameters of a model: doping, geometry, material parameters, …

These tools are usually called DOE (Display Of Experiment). In ECORCE, this tool is called "Optimizer" because it has additional features that we will see later.

1) Parameters sweep

You will apply the optimizer of ECORCE to the study of interface state effects.

Duplicate the simulation "Id=f(Vgs)" of the device "nmos_20nm_interface_state" and rename the copy "Id=f(Vgs)_min_edge_0.01µm".

Open the simulation "Id=f(Vgs)_min_edge_0.01µm" and correct the minimum edge length: 0.01µm. ECORCE will execute automatically several modeling and this lower precision mesh will reduce the calculation time.

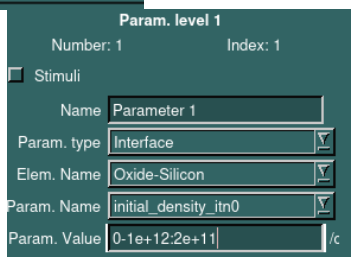
Save the simulation.

Change the skill level of the user, from beginner  to advanced 

Create a new optimization: "File->New optimization"

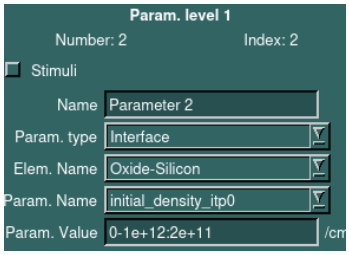
Create a new "Calculated results" 

Create the parameter for the electron interface trap density:

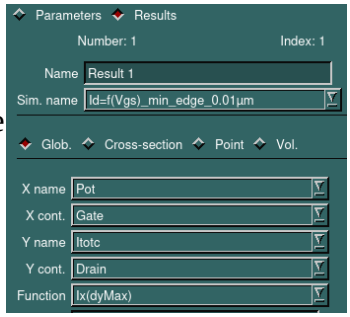


The "Param. Value" field defines the list of values:
0, 2 10^{11}, 4 10^{11}, 6 10^{11}, 8 10^{11}, 10^{12} cm^{-2}. Explain the syntax.

Create the parameter for the hole interface trap density:
(use Level 1 parameter)

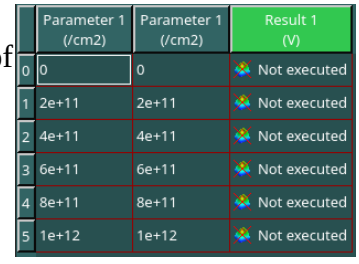


Create the result you want to calculate:



For each value of the parameters, the optimizer will calculate the characteristics Id=f(Vgs) and extract the threshold voltage.

You should obtain this display that resumes the combination of parameters and the results that will be calculated.



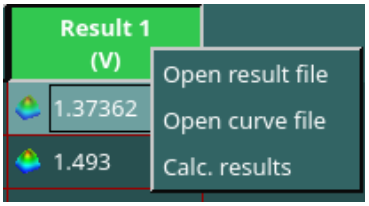
Execute calculation (save the optimization: "Id=f(Vgs)_function_interface state").

When calculation is finished you get the threshold voltage values:

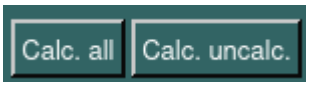
	Parameter 1 (/cm2)	Parameter 2 (/cm2)	Result 1 (V)
0	0	0	1.37362
1	2e+11	2e+11	1.493
2	4e+11	4e+11	1.6252
3	6e+11	6e+11	1.76524
4	8e+11	8e+11	1.90986
5	1e+12	1e+12	2.05932

Right click on one result and open the associated simulation. Check that the displayed Vth is correct for at least 2 results.

Export the results as a function of the first parameter values: Right click on "Result 1->Open result file".



You can also export in one shot all the Id=f(Vgs) curves in an excel file:
Right click on "Result 1->Open curve file".
If ECORCE claims that the file does not exists, recalculate results clicking on "Calc. all". This problem needs to be solved ...



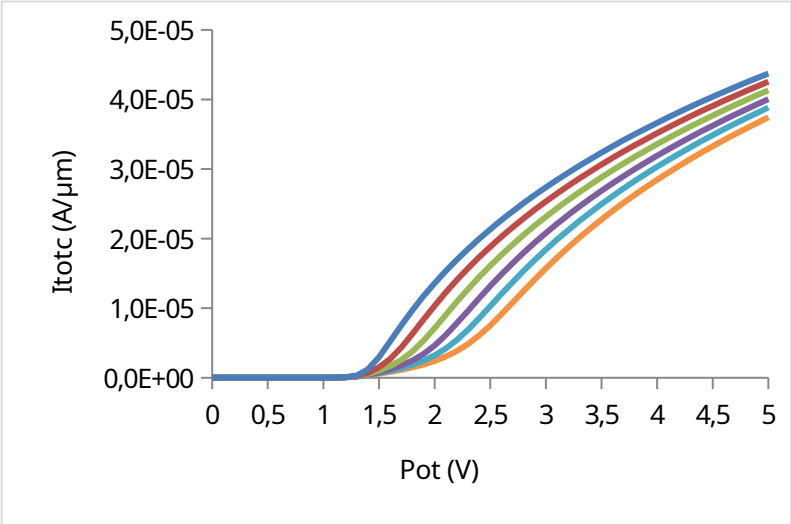


Illustration 20: Id=f(Vgs) characteristic for several interface state densities.

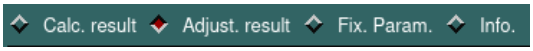
2) Adjusting result

The optimizer of ECORCE can also adjust parameters to get back a result value.

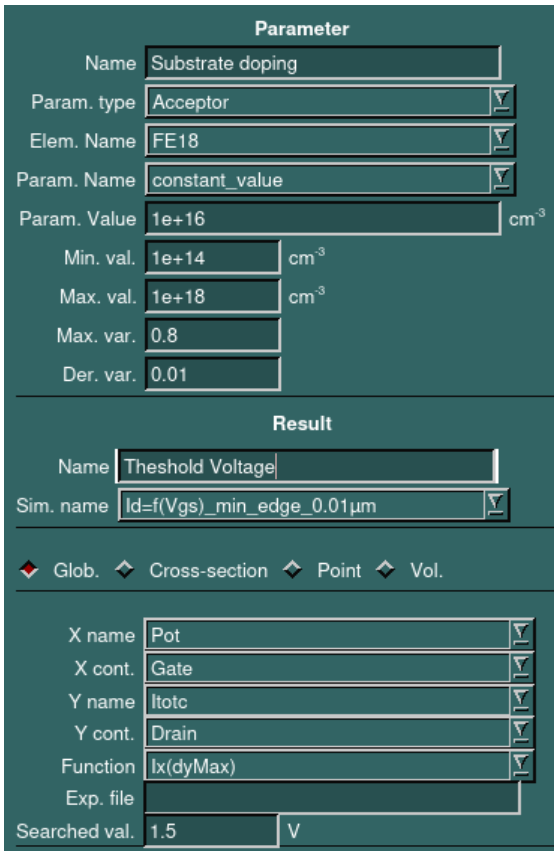
As an example, you will program the optimizer to get a 1.5V threshold value of the Id=f(Vgs) characteristic by changing the substrate acceptor doping value.

Display the simulation "Id=f(Vgs)_min_edge_0.01µm" of the device "nmos_20nm_interface_state".

Create a new optimization.
To have access to this function of the optimizer, you must change the skill level of the user to Expert 

The field "Adjust. result" appears, select it: 

Create a new adjusted result.
You must define the parameter to correct and the result that will be adjusted as following:



Execute calculation (save the optimization: "Vt_adjust_by acceptor").

The graphical display of results is not yet available.

Display the log file and follow evolution of result by clicking on "End Exec".

The next picture shows the iterations done to reach the good value for Vth. Three iterations are needed for a relative precision of 7 10^{-4}

Changed parameter

	N°	Type	Element	Name	Initial value	lowest value	highest value	Unit
1	0	Acceptor	FE18	constant_value	1e+16	1e+14	1e+18	/cm3

Adjusted result

	N°	Simulation	Result name	Expected value	Unit
1	0	Id=f(Vgs)_min_edge_0.01µm	Id=f(Vgs)_min_edge_0.01µm@@Pot@Gate@Itotc@Drain@0A/µm	1.5	V

Iteration0

	N°	Parameter	Value	Result	Result value	Expected value	Precision
1	0	Substrate doping	1e+16	Theshold Voltage	1.69426	1.5	0.121631

Iteration1

	N°	Parameter	Value	Result	Result value	Expected value	Precision
1	0	Substrate doping	2e+15	Theshold Voltage	1.45908	1.5	0.0276567

Iteration2

	N°	Parameter	Value	Result	Result value	Expected value	Precision
1	0	Substrate doping	2.96137e+15	Theshold Voltage	1.49895	1.5	0.000699538

Illustration 21: Iterations to adjust Vth by changing the substrate acceptor density.

.IV Bulk PMOS transistor, 20nm oxide thickness

PMOS transitors have a different behavior when submitted to TID than NMOS transistors.

Duplicate the device "nmos_20nm" and rename the copy "pmos_20nm".
Open the simulation "Id=f(Vgs)"

Change the doping:
- P+ Drain 10^{18} cm^{-3}
- P+ Source 10^{18} cm^{-3}
- N substrate 2 10^{17} cm^{-3}

Change the Gate bias: from 0 to -5V by step -0.1V

Execute calculation. Display the Id=f(Vgs) characteristic.
Measure the leakage current for V_{gs}=0V, the threshold voltage, and calculate the threshold voltage shift induced by the TID applied.

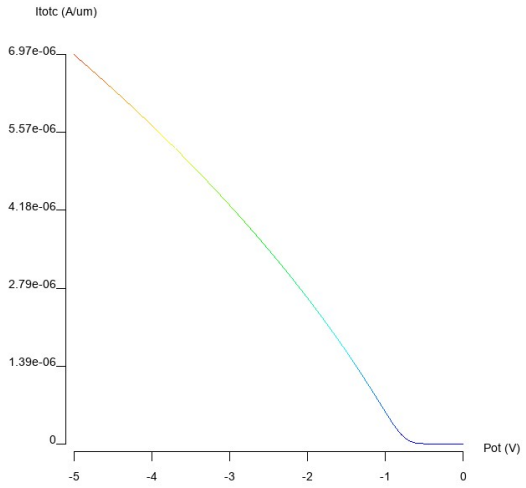


Illustration 22: Id=f(Vgs) characteristic of a 20nm oxide thickness PMOS transistor.

Answer: $Id_{Vgs=0V}$=1.9 10^{-13} A /µm, Vth=-0.74V

Open the simulation "30krad_Vgs_5V" and execute calculation.

Measure the leakage current for V_{gs}=0V, the threshold voltage, and calculate the threshold voltage shift induced by the TID applied.
Add the Id=f(Vgs) characteristic for the pristine device and for the 30krad dose to the same excel file. Observe the curves with linear and logarithmic scale on Y axis.

Answer: $Id_{Vgs=0V}$=1.21 10^{-14} A /µm, Vth=-0.89V, ΔVth=0.15V
For PMOS transistors, TID decreases the leakage current and increases the threshold value. The transistor can never be locked in ON state. For this reason industrials consider that PMOS transitors can not induce failure in a circuit because of TID.

.V Leakage between transistors

Integrated circuits have millions of transistors. To avoid leakage between the transistors, they are separated by insulators. To study the effect of radiation on these insulators, we will consider two NMOS transistors simulated in the same device, separated by an insulating oxide called Shallow Trench Insulator (STI).

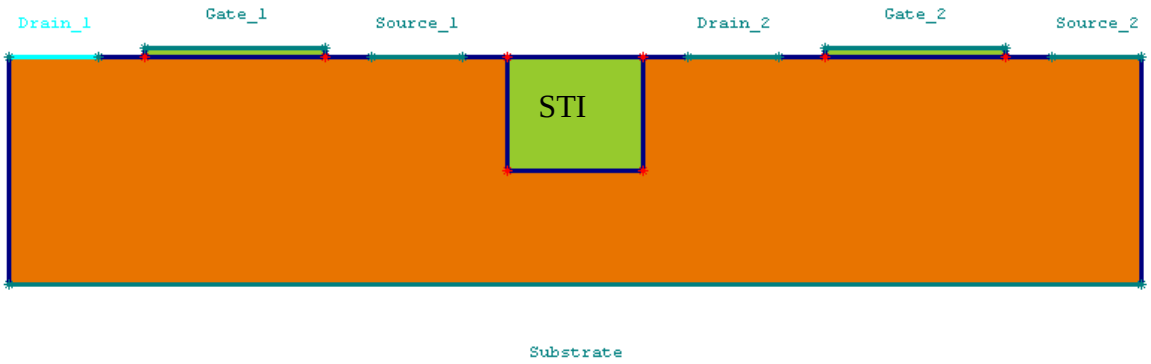


Illustration 23: Schematic view of 2 NMOS transistors separated by an insulating oxide.

.A High electric field in the STI

Copy the device "mosn_mosn_20nm" from "Examples->Lecture->Radiation_effects_2D" in your working directory.

Open the simulation "Id=f(Vgs)" and execute calculation. Check that the Id=f(Vgs) characteristics are the same for both transistors.

Open the simulation "50krad_Vds2_5V". Check the biases applied to the contact during the irradiation.
What will occur inside the STI?

Answer: Since Source_1 is biased at 0V and Drain_2 is biased at +5V, the STI that is between these 2 contacts will have a significant electric field in its volume.

Execute calculation and measure the maximum hole trap density in the STI at the end of irradiation. Observe the evolution of the electron density in the silicon around the STI.
What will occur between Source_1 and Drain_2?

Answer: The electric field in the STI will generate a high density of electron hole pairs because of a value of the yield function close to 1.
$pt_{max}=9.4\ 10^{16}\ cm^{-3}$ in the STI.

Measure the leakage current for V_{gs}=0V for Drain_1 and Drain_2, the threshold voltage for both transistors, and calculate the threshold voltage shift induced by the TID applied.

Answer: $Id1_{Vgs=0V}=1.06\ 10^{-12}$ *A /µm, Vth1=1.24V, ΔVth1=0.13V*
$Id2_{Vgs=0V}=3.55\ 10^{-10}$ *A /µm, Vth2=1.27V, ΔVth2=0.1V*

Alain Michez, RADIAC team
Institut d'Electronique et des Systèmes

Results are slightly different from the one of "nmos_20nm" device because the minimum size of edge length has been corrected to 0.01µm to reduce calculation time.

What is the lower electron density for Vgs=0V around the STI? Compare to the electron density of the pristine device.

Can you explain the high leakage current of the contact Drain_2?

Answer: the positive charge deposited by the irradiation in the STI attract electron around the STI. The lower electron density around the STI is $n=2.5\ 10^{6} cm^{-3}$ for the pristine device and $n=6.9\ 10^{12} cm^{-3}$ after irradiation. Irradiation creates an additional channel between Sources_1 and Drain_2.

For Vgs=0V after irradiation the leakage current for Drain_2 is $3.55\ 10^{-10}$ A/µm and it is $-3.55\ 10^{-10}$ A/µm for Source_1. The leakage current is between those 2 contacts.

.B Low electric field in the STI

Open the simulation "50krad_Vds2_0.1V". Check the biases applied to the contact during the irradiation.

What will occur inside the STI?

Answer: Since Source_1 is biased at 0V and Drain_2 is biased at +0.1V, the STI that is between these 2 contacts will have a low electric field in its volume.

Execute calculation and measure the maximum hole trap density in the STI at the end of irradiation. Observe the evolution of the electron density in the silicon around the STI.

What will occur between Source_1 and Drain_2?

Answer: The electric field in the STI will generate a low density of electron hole pairs because of the low electric field in the STI.

$pt_{max}=6.3\ 10^{16}\ cm^{-3}$ in the STI.

Measure the leakage current for V_{gs}=0V for Drain_1 and Drain_2, the threshold voltage for both transistors, and calculate the threshold voltage shift induced by the TID applied.

Answer: $Id1_{Vgs=0V}=1.06\ 10^{-12}$ A /µm, Vth1=1.24V, ΔVth1=0.13V
$Id2_{Vgs=0V}=1.82\ 10^{-12}$ A /µm, Vth2=1.24V, ΔVth2=0.13V

What is the lower electron density for Vgs=0V around the STI? Compare to the electron density for the irradiation with Vds2=5V.

Can you explain the low leakage current of the contact Drain_2?

Answer: the positive charge deposited by the irradiation in the STI still attract electron around the STI but the electron density is around 100 times lower than for Vds2=5V: $n=10^{10} cm^{-3}$. The additional channel between Sources_1 and Drain_2 generates a leakage current that is only twice the leakage current of the pristine device.

.VI Transient current induced by single particles

A single particle crossing a component triggers a transient current that will propagate along the external circuit. This effect is called Single Event Transient (SET).

Copy the device "pn_2D_SET" from "Examples->Lecture->Radiation_effects_2D" in your working directory.

Open the simulation "Al_10MeV" and execute calculations. It is a 1V reversely biased diode. While it is running take a look at applied biases, ion definition: “PARAM. STIM.→ Stimuli→Irradiation” and have a look at the Linear Energy Transfer (LET) curve and the parameters of the applied ion. What are the sensitive parameters?

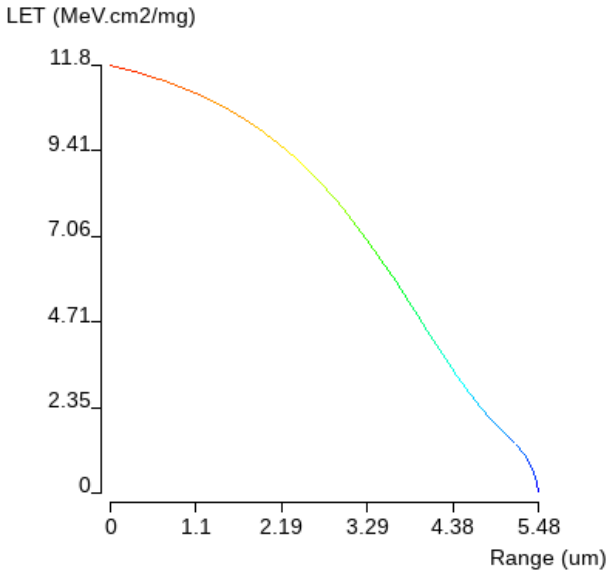


Illustration 24: Linear Energy Transfert of the ion crossing the component.

Answer: An Al ion with a 10 MeV initial energy is applied. It crosses the junction in the middle of the Anode contact and has a 5.48 µm range. Its direction is vertical, going from the Gate to the substrate. Since the junction is 10 µm along the Y axis, this ion does not fully cross the device. It stops in the middle of the diode.

Calculations are long. To save time for the next exercise, copy the simulation “Al_10_MeV” to “Al_30_MeV”. In this new simulation change the ion energy: 30 MeV. As you can see, this ion will fully cross the device. Launch calculations and go back to the “10_MeV_Al” simulation analysis.

When calculations are finished, observe the evolution of potential in the volume as function of time (simulation “Al_10MeV”).

For a better understanding, you can create an animation. Use a delay time between steps that gives you time to read the curve between steps (100 ms is a good value).

Display with an animation the electron and hole densities (don’t forget to fix and adjust the n and p scales).

Display the Cathode current as a function of time. Two peaks are observed. Using your understanding of the animations, explain those two peaks. The noise observed between the two peaks is induced by the mesh change. Don't take it into account, it a nearly no effect on the result.

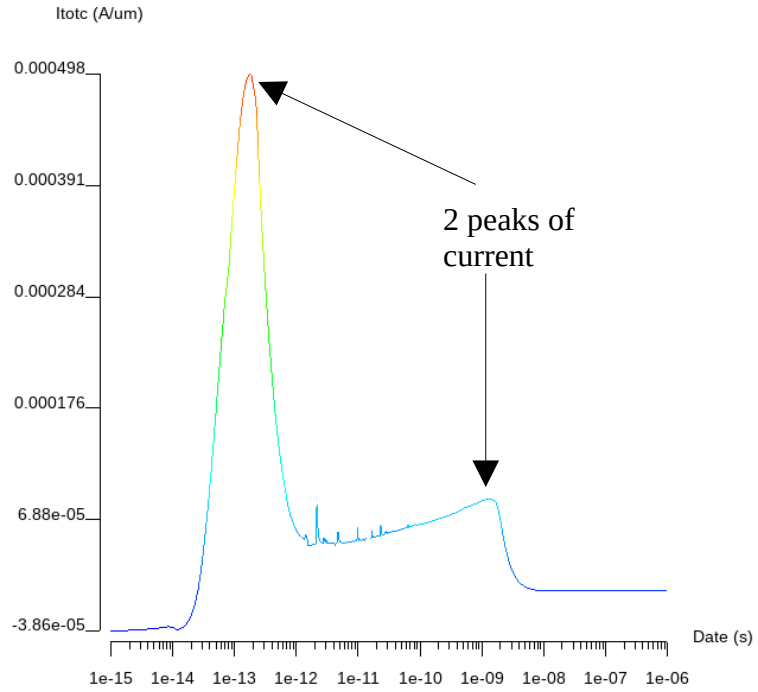


Illustration 25: Cathode current as a function of time after 10 MeV Al ion crossing at X=5 µm and Y=10µm.

Answer: This is a well known result. Because the ion does not fully cross the device, electron and hole are separated by the electric field. However after a while, a counter-electric field appears, which opposes to the electric field induced by the bias. The potential along the track collapses and carriers can not be separated anymore. This induces the first peak of current.

After a while, the track diffuses toward the Cathode. When electron-hole pairs are close enough, the charge separation can restart, electrons being collected to the cathode and hole to the Anode.

To highlight this mechanism, display the hole density as a function of time at point X=5 µm Y=3 µm. The maximum hole density is reached around 1.47 ns. Compare this time with the second peak of current maximum time. Conclusion?

Answer: the maximum value for the second peak is around 1.2 ns, close to this one. The two values are not exactly the same because the current also depends on the electric field that is maximum at that point at 1.2 ns and has decreased at 1.5 ns.

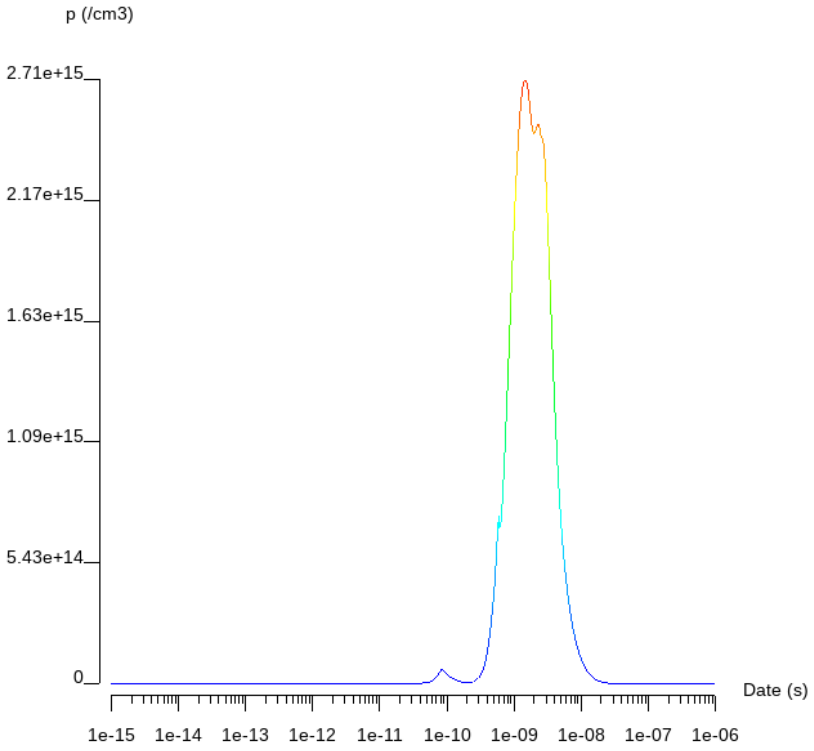


Illustration 26: Hole density as a function of time after 10 MeV Al ion crossing the diode.

The simulation “Al_30MeV” should be finished. Display the Cathode current as a function of time. Only one peak appears. Explain this using all methods used with previous simulation.

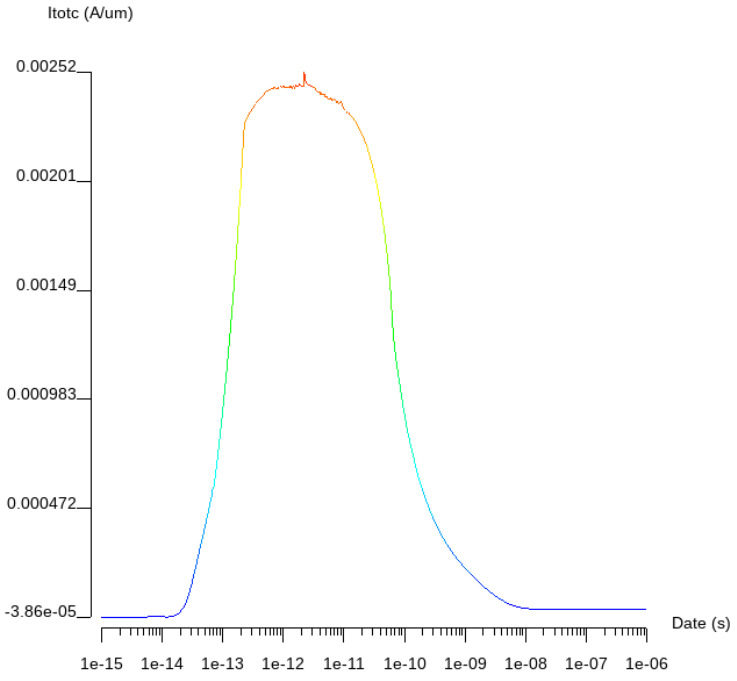


Illustration 27: Cathode current as a function of time after 10 MeV Al ion crossing at X=5 µm and Y=10µm.

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Answer: The animation of potential as a function of time shows that the potential does not fully collapses as it does for the 10 MeV Al ion (switch between those 2 simulations to check it). This is because the 30 MeV Al ion fully cross the device and the counter-electric field is much lower. Indeed electron and hole are collected at the contact as and when the separation proceeds.

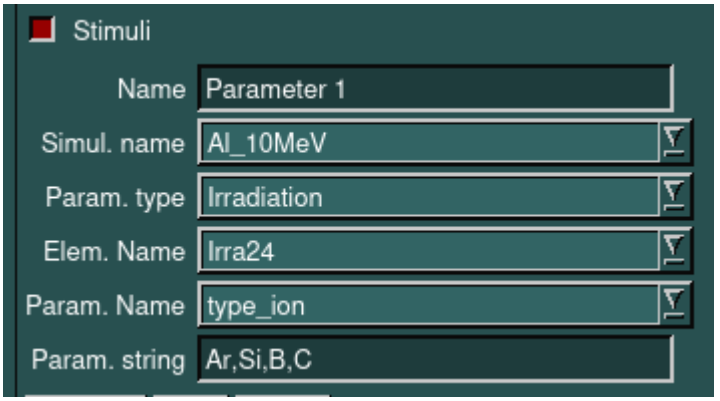
The type of ion also has a significant effect on the transient current.
To study this effect you will create an optimization.

Change the skill level of the user, from beginner to advanced.
Create a new optimization: "File->New optimization"

Create a new "Calculated results"

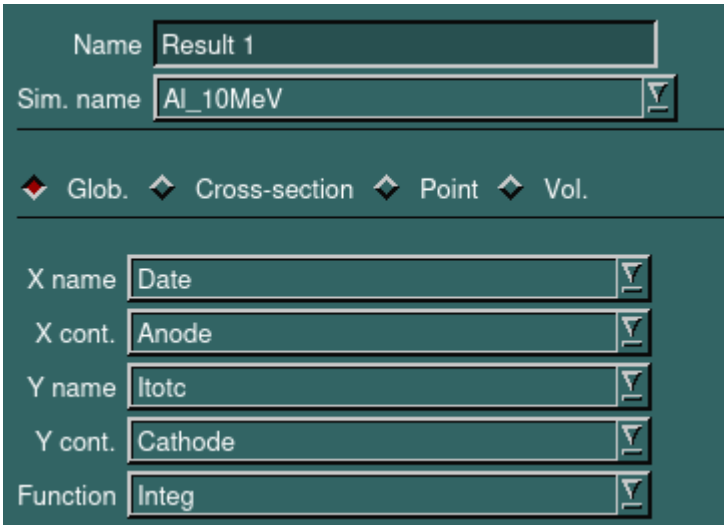
Create a new parameter for the electron interface trap density, check the button “Stimuli”.

Fill the parameter values as defined here:
Explain.

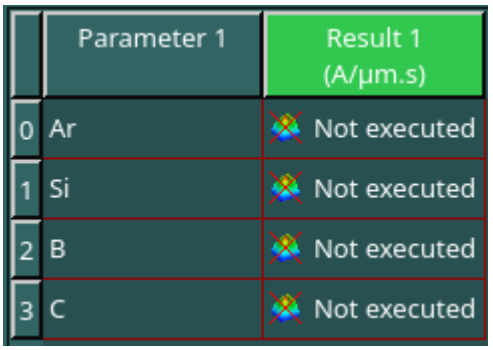


Create the result you want to calculate:

For each value of the parameters, the optimizer will calculate the characteristics Id=f(Vgs) and extract the collected charges.



You should obtain this display that resumes the parameter values and the results that will be calculated.



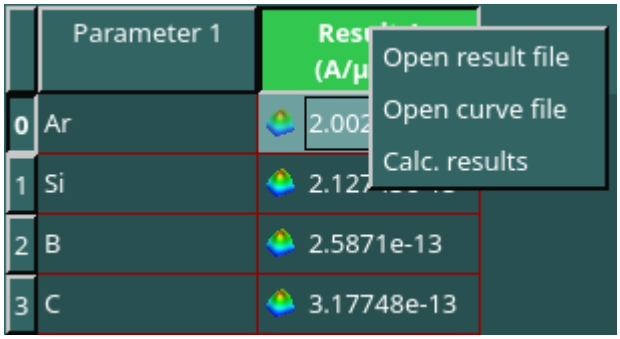
Execute the calculation with 2 processors by process. Optimization name: “QCollected_function_ion_type”

You obtain these results.

	Parameter 1	Result 1 (A/µm.s)
0	Ar	2.00263e-13
1	Si	2.12743e-13
2	B	2.5871e-13
3	C	3.17748e-13

Calculates again the results by clicking on

This creates the excel files.



Display the curves for all simulations. Right click on “Results 1” and select “Open curve file”. An excel file appears.

Apply a log scale for X axis from 10^{-15} to 10^{-6}s

The curves for Ar and Si are very similar and the one for B and C are also similar. Explain.

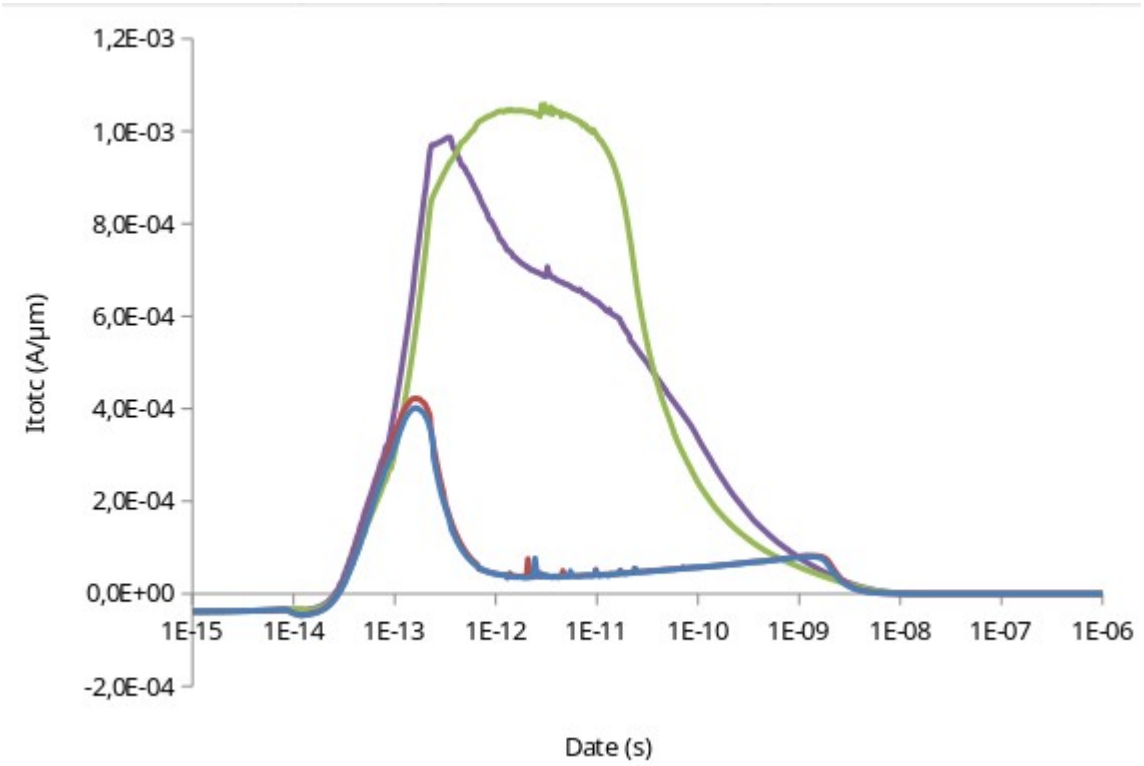
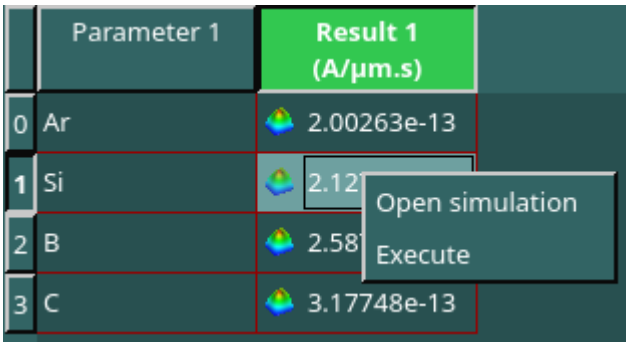


Illustration 28: Cathode Current as a function of time for Ar, Si, B and C 10 MeV ions.

Answer: The range for Ar and Si ions are lower than the diode thickness: Ar 4.7 µm and Si 4.79 µm. Thus, 2 peaks appear on the I=f(V) characteristics. On the other hand, the B and C ion fully cross the device, so only one peak appears on the characteristic.

To check this, open the simulation for each ion:
right click on the result of the ion and select
"Open simulation"
and check the range of each ion.



Copy the device "mosn_SET" from "Examples->Lecture->Radiation_effects_2D" in your working directory. This device is very similar to the one defined in section II. What is the difference?

Answer: This device is exactly the same except it has a 2µm substrate thickness.

Do the same study than the previous one using the 1 MeV Al ion.

.VII PDSOI NMOS transistor

To be done

.VIII FDSOI NMOS transistor

To be done

.IX LATCHUP on thyristor structure

Components used in power devices and integrated circuits may contain parasitic PNPN junctions (thyristor structure) that can trigger a short circuit between 2 contacts (Anode and Cathode) when a single particle hits the device.

To understand this phenomena you will study the effect of a single particle on a thyristor component.

Copy the device "Thyristor" from "Examples->Bipolar" in your working directory.

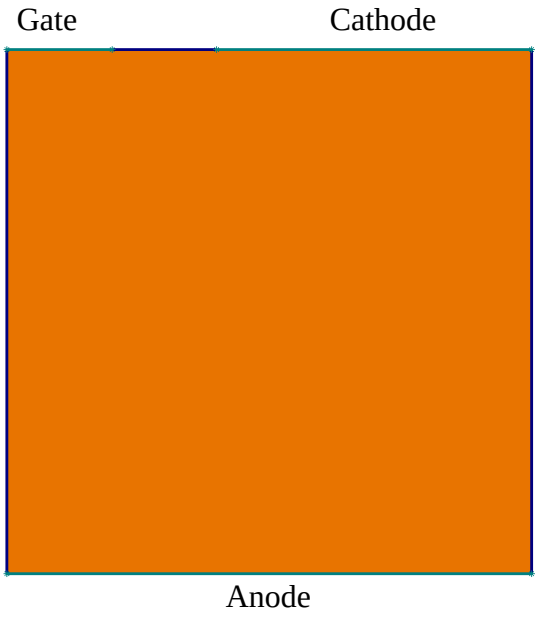


Illustration 29: Schematic view of the thyristor without doping.

Open the simulation "Pulse_on" and execute calculation. While the execution is running, go in “PHYS. MOD.→Functions” and make a diagram of the doping functions to highlight the PNPN structure. Have a look at the bias applied on the contacts, explain.

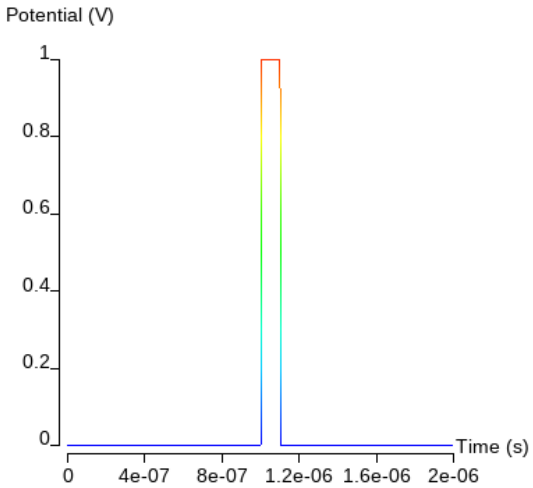


Illustration 30: Bias applied on the Gate contact as a function of time

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Answer: The gate receive a 0V to 1V pulse with rise and fall time of 1 ns and a pulse duration of 0.1 µs. The pulse starts at 1 µs. The Anode receive a constant 2V bias.

Display the current at the Anode as a function of time. Explain the shape of this current. Why a small peak of current that appears around 1 µs? Measure the leakage current.

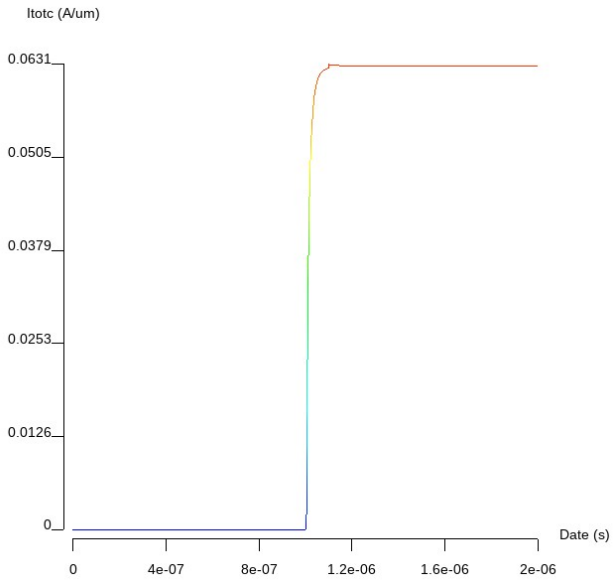

Illustration 31: Anode current as a function of time (linear scale).

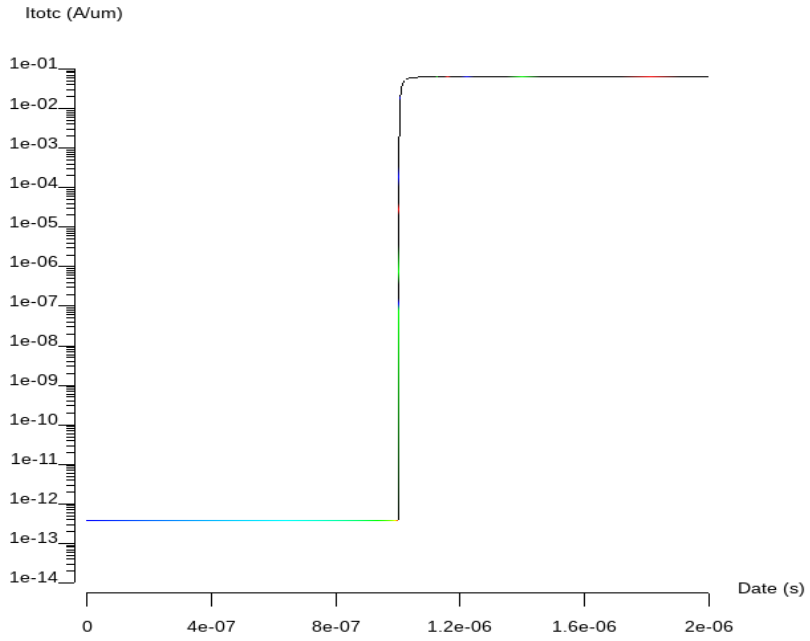

Illustration 32: Anode current as a function of time (logarithmic scale).

Answer: From to 1 µs, the gate is biased to 0V. At 1 µs a ramp from 0 V to 1V is applied on the Gate. This ramp last 1 ns. The current at the Anode starts to increase. Then this bias stays constant (1V) during 0.1µs. During that time, the current at the Anode increases, the

thyristor is turned on . Finally the bias fall from 0V to 1V during 1 ns then stays to 0V. The current stays at the maximum value. It is not turned off even when the Gate bias returns to 0V.

The small peak appears at 1.101 µs. It is exactly the time where the bias on the Gate starts switching from 1V to 0V. This peak stops exactly at 1.002 µs that is the end of the Fate switch from 1V to 0V. So this peak is induced by this ramp.

Leakage current: 3.83x10^{-13} A/µm

Observe the evolution of potential in the volume as function of time. At t=0 s identify the area that lock the current. Observe the potential at the end of the simulation. Explain.

For a better understanding, you can create an animation. Lock the Psi axis from -5 to -2 and use a delay time between steps that gives you time to read the curve between steps (100 ms is a good value). Display with an animation the electron and hole densities (don't forget to adjust the n and p scales).

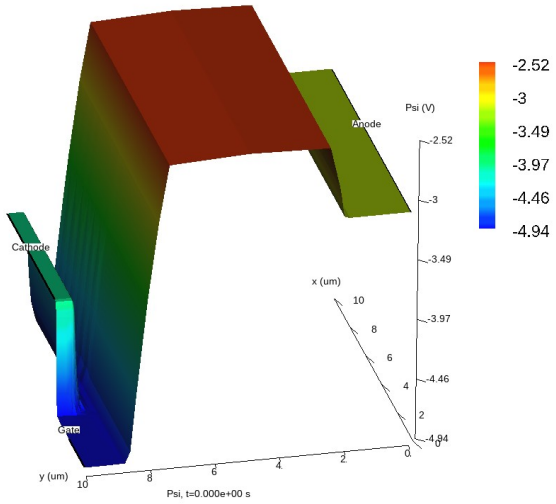

Illustration 33: Off-state potential distribution in the thyristor.

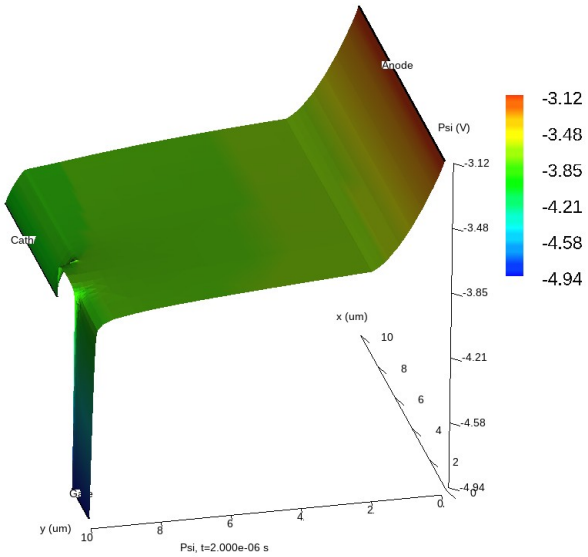

Illustration 34: On-state potential distribution in the thyristor.

To turn off this thyristor, 0V must be applied on the Anode. Open the simulation "Pulse_off_after_pulse_on" and execute calculation. You may notice that this simulation starts from the last step of the “Pulse_on” simulation so the thyristor is on at the beginning of the calculation. Have a look at the bias applied on the contacts, explain.

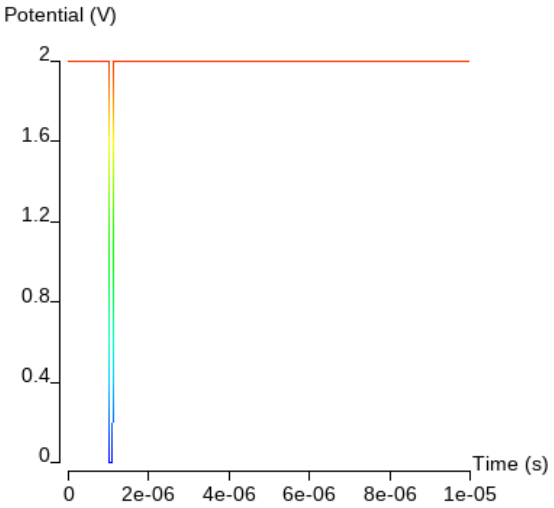

Illustration 35: Bias applied on the Drain contact as a function of time

Answer: The drain receive a 2V to 0V pulse with rise and fall time of 1 ns and a pulse duration of 0.1 µs. The pulse starts at 1 µs.

Display the total current (Itotc) at Anode contact as a function of time (Date).

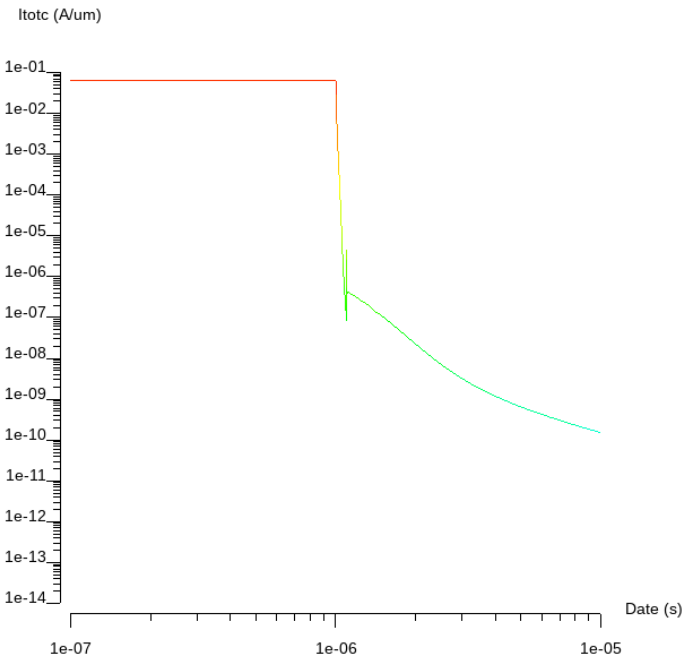

Illustration 36: Total current crossing the Anode contact as a function of time.

The leakage current at the end of the calculation (10-5 s) is $1.52x10^{-10}$ A/µm. By analyzing the volume results, explain.

Answer: At 10^{-5} s the carriers injected during the on-state are not fully removed. Measuring the hole density at position Y=5 µm gives:

- *off-state "Pulse_on", step 0: $4x10^{8}$ cm^{-3}*
- *off-state "Pulse_off_after_pulse_on", last step: $2x10^{11}$ cm^{-3}*

This is confirmed by the potential measurement:

- *off-state "Pulse_on", step 0: -2.52 V*
- *off-state "Pulse_off_after_pulse_on", last step: -2.68 V*

Create a copy of the simulation "Pulse_off_after_pulse_on" and rename it "Pulse_off_after_pulse_on_1s".

Change the analysis duration: 1s and execute the calculations.

Display the Anode current as a function of time. What is the leakage current? Measure the hole density and potential at Y=5 µm.

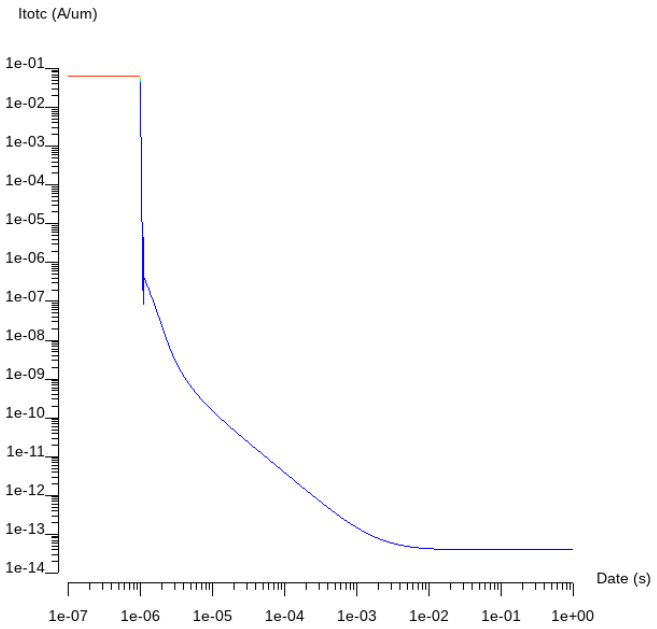

Illustration 37: Anode current as a function for a 1s analysis.

Answer: The leakage current at 1 s is $4.08x10^{-14}$ A/µm. It is lower than the one at step 0 for "Pulse_on" simulation because the meshes of these simulations are different (650 and 777 nodes). Measuring hole density and potential at position Y=5 µm gives:

- *hole density: $7.27x10^{6}$ cm-3*
- *potential: -2.41 V*

Again, these values are slightly different from the "Pulse_on" step 0 values because of the different meshes. To remove these differences we need to use more precise meshes but this will induce longer calculation time.

To resume, a 1V pulse on the gate turn the thyristor on and a 0V pulse on the Anode turn the thyristor off. When used in radiative environment, the thyristor can also be turned on by a single particle crossing the component. This particle generates a high electron-hole pair

density along its track. This electron-hole density acts as a pulse on the gate and may turn the thyristor on depending on its initial energy and impact position.

Open the simulation "Al_2MeV_x=7µm" and execute calculations. While the execution is running, go to “PARAM. STIM.→Stimuli→Irradiation” and have a look at the Linear Energy Transfer (LET) curve and the parameters of the applied ion. What are the sensitive parameters?

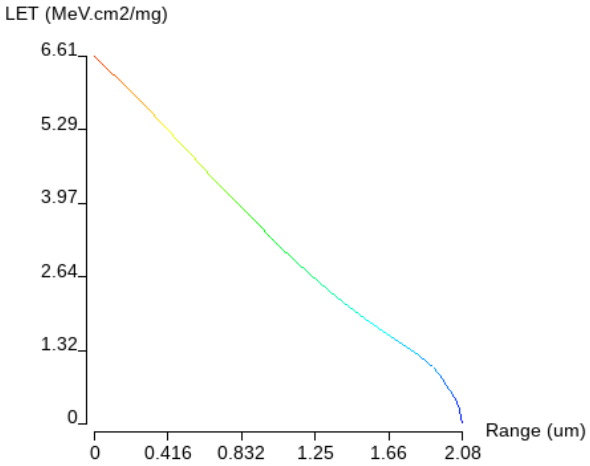

Illustration 38: Linear Energy Transfert of the ion crossing the component.

Answer: An Al ion with a 2 MeV initial energy is applied. It crosses the thyristor in the middle of the Cathode contact and has a 2.08 µm range. Its direction is vertical, going from the Cathode to the Anode. Since the thyristor is 10 µm along the Y axis, this ion do not fully cross the device.

Display the Anode current as a function of time. The ion impact the thyristor at 10^{-14}s. At what time can we consider the thyristor is turned on?

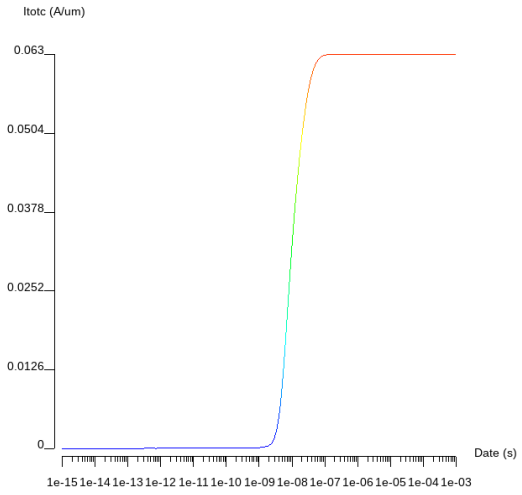

Illustration 39: Anode current as a function of time after 2 MeV Al ion crossing at X=7µm.

Answer: The Anode current reaches the maximum current around 0.1 µs. So this time can be considered as the one needed to turn the thyristor on after Al ion crossing.

Launch an animation to display evolution of the potential, electron and hole densities as a function of time using 100 ms for the interval time. Don't forget to lock and adjust the Potential scale. A jump of the potential occurs around step 35. Explain.

Answer: At step 35, the maximum potential in the volume is -2.54V. At step 36, it abruptly jump to -1.77V. Because the electron-hole diffuse in the direction of the Anode contact they reach the 10^{15} cm^{-3} donor doping area. Then the mesh needs to be refined in this layer. At step 35 the number of node is 1162 while it is 1254 at step 36. This significant change of the mesh is responsible for the jump of the potential observed for those 2 steps.

The condition for triggering the latchup also depend on the impact position of the ion. Open the simulation "Al_2MeV_x_2.5µm" and execute the calculations. While the execution is running, have a look at the parameters of the applied ion. What is the difference width the previous ion?

Answer: The only difference is the impact point of the ion. It is located at X=2.5 µm, between the gate and the Cathode.

Display the Anode current as a function of time.

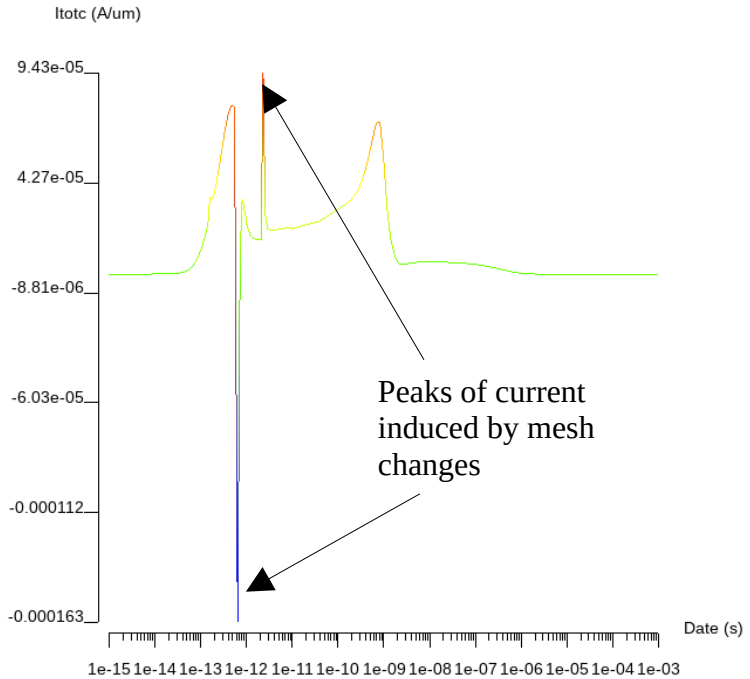

Illustration 40: Anode current as a function of time after 2 MeV ion crossing, impact point located at X=2.5 µm.

As you can see, at the end of the simulation, the thyristor is still off. The low ion energy and the deposited electron-hole pairs did not trigger the latchup.

The current peaks are induced by the mesh change over steps. To correlate these peaks with the mesh changes, display the number of node as a function of time (NbNo).

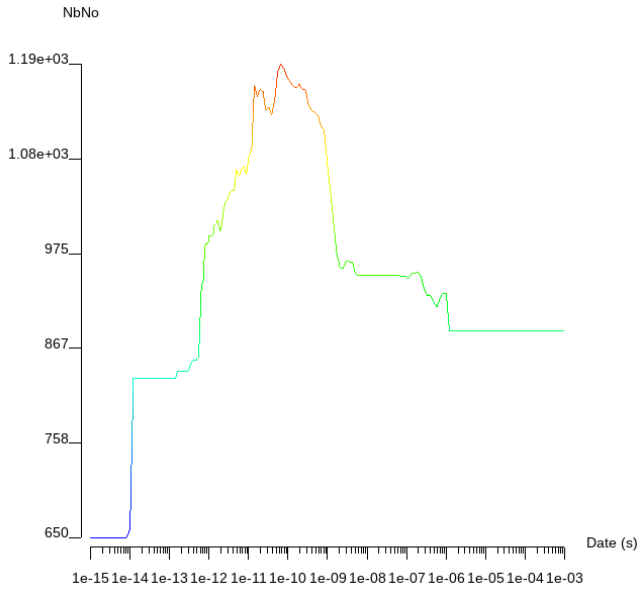

Illustration 41: Number of nodes as a function of time after 2 MeV Al ion crossing, impact point located at X=2.5 µm.

These peaks can be reduced by improving the mesh. Open the simulation "Al_2MeV_x_2.5µm_precise" and launch the calculations. Take a look at the mesh parameters: "PARAM. STIM.→ Mesh". The only difference is the "Space precision", 0.005 for the precise simulation and 0.02 for the previous one.

Display the Anode current as a function of time.

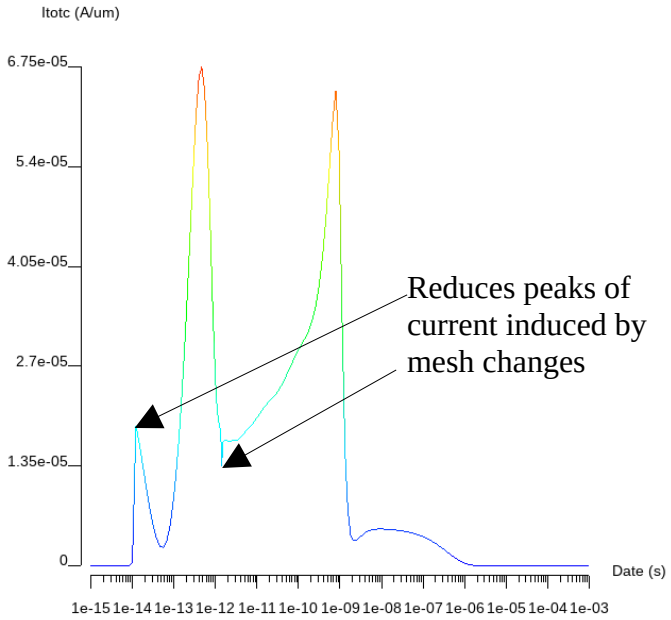

Illustration 42: Anode current after 2MeV ion crossing, impact point located at X=2.5 µm, space precision 0.005

Only 2 peaks still appear and they are strongly reduced compared to the 0.02 space precision modeling.

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Add on the same excel file the number of nodes as a function of time for the 2 simulations. Note the calculation time given at the end of log files. Conclusion?

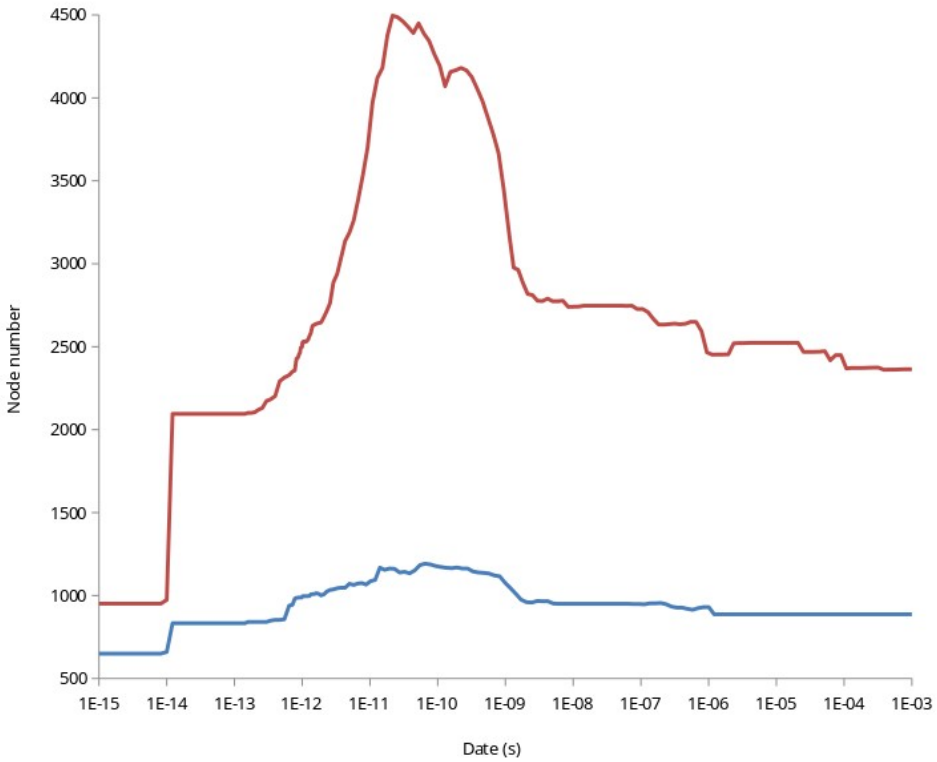

Illustration 43: Number of nodes as a function of time after 2MeV Al ion crossing, impact position located at 2.5 µm, space precision 0.02 (blue curve) and 0.005 red curve.

Answer: The number of nodes is about 4 times higher for the precise simulation. The reduction of the mesh induced peaks is at the cost of a more than 4 times higher calculation time.

Calculation time:

- *space precision 0.02: 4 min 43 s*
- *space precision 0.005: 18 min 32 s*

That's all folks

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