23rd RD50 Workshop

13th-15th Nov 2013 CERN

TCAD for radiation, a review

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Approach

- TCAD as a device physics simulation tool for radiation effects
- **Our approach** makes a physical pre-analysis to design the simulation. Only then we adapt the TCAD radiation operators & models
- Case Studies:
  - Single Event Effects with ad-hoc ionization track
  - Pulsed Laser Effects (800 nm) from ad-hoc ionization track
  - Total Ionization Effects with ad-hoc charge sheets
  - Displacement Damage with ad-hoc trap models

TCAD simulations Track Ionization

- Physics simulations use a finite element approach for solid state physics equations.
- **Drift-Diffusion model:** (short. transients)
- Recombination models (SRH y Auger)

Poisson $$\nabla \cdot \varepsilon \nabla \phi = -q(p - n + N_D - N_A) - \rho_{trap}$$

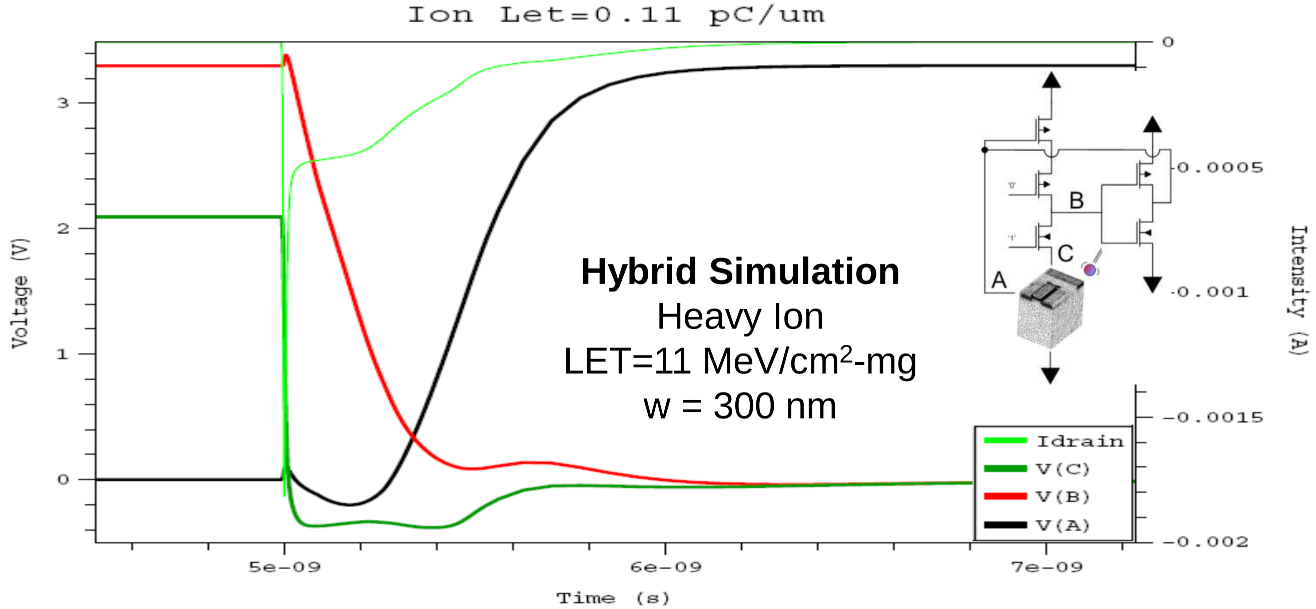
Electron Continuity. $$\nabla . \underline{J}_n = qR_{net} + q\frac{\partial n}{\partial t} \quad \textit{with} \quad \underline{J}_n = q\mu_n \underline{E} + qD_n \nabla n$$

Hole Continuity $$\nabla . \underline{J}_p = qR_{net} + q\frac{\partial p}{\partial t} \quad \textit{with} \quad \underline{J}_p = q\mu_n \underline{E} - qD_p \nabla p$$

- **In particular we use the Heavy Ion Operator for track ionization**: **{z, LET(z),w(z)}**

Simulation methods for ionizing radiation single event effects evaluation. P.Fernández-Martínez, J.M.Mogollón, S.Hidalgo, F.R.Palomo, D.Flores, M.A.Aguirre, J.Nápoles, H.Guzmán-Miranda. **Proceedings of SCDE (Spanish Conference on Electron Devices) 2009 Conference**, Santiago de Compostela, Spain, 10th-13th February , 2009.

TCAD Ionization Track typical simulations

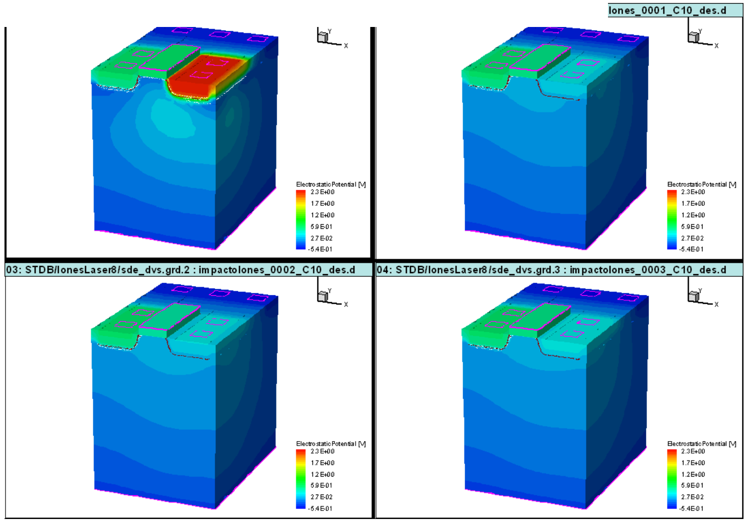


Hybrid Simulation
Heavy Ion
LET=11 MeV/cm^2-mg
w = 300 nm

Possible Calculations:

- Internal State of Device ({n,p},$\vec{J}_n$, $\vec{J}_p$, $\vec{E}$)
- Hybrid simulation: Sentaurus + Spice

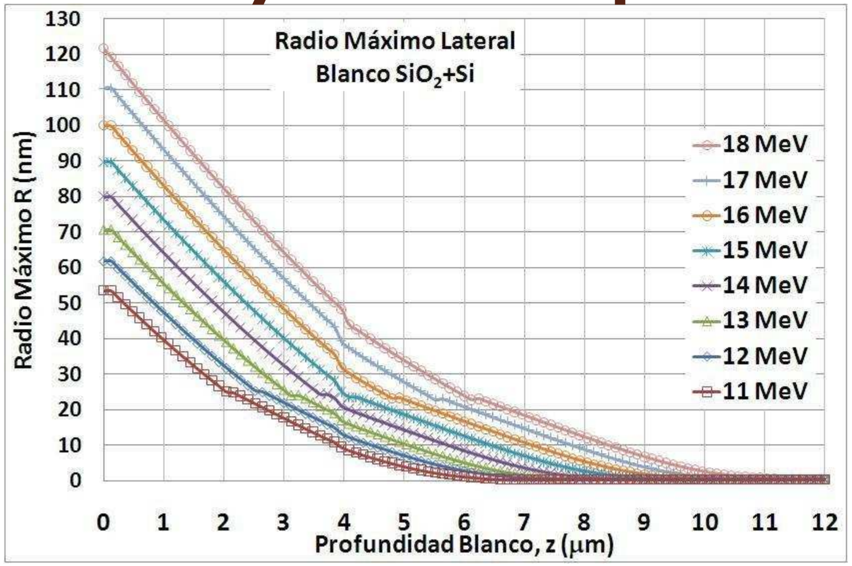
I/V device response curves

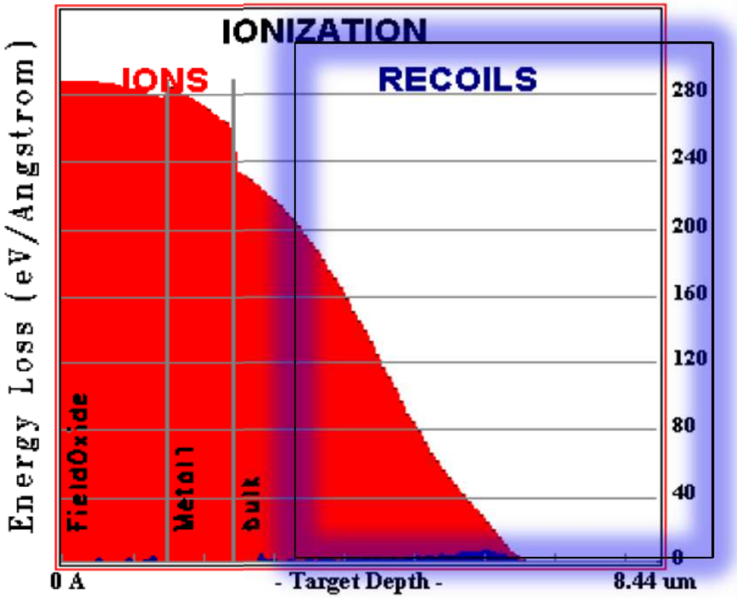


Electric Field Evolution

Simulation methods for ionizing radiation single event effects evaluation. P.Fernández-Martínez, J.M.Mogollón, S.Hidalgo, F.R.Palomo, D.Flores, M.A.Aguirre, J.Nápoles, H.Guzmán-Miranda. **Proceedings of SCDE (Spanish Conference on Electron Devices) 2009 Conference**, Santiago de Compostela, Spain, 10th-13th February , 2009.

Heavy Ion Operators





```
Physics{
Mobility(Phumob HighFieldsat Enormal)
EffectiveIntrinsicDensity(OldSlotboom)
Fermi
Recombination(SRH Auger)
HeavyIon(
time=5e-9
length=[0 0.09 1.02 2.03 3.05 4.06 4.4]
wt_hi=[0.3 0.3 0.25 0.2 0.2 0.1 0.01]
LET_f=[0.114 0.104 0.087 0.055 0.023 0.001 0]
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Gaussian
```
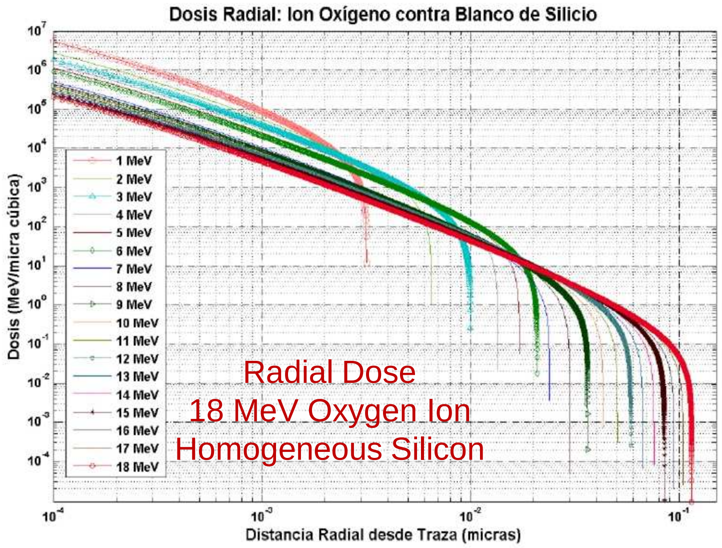
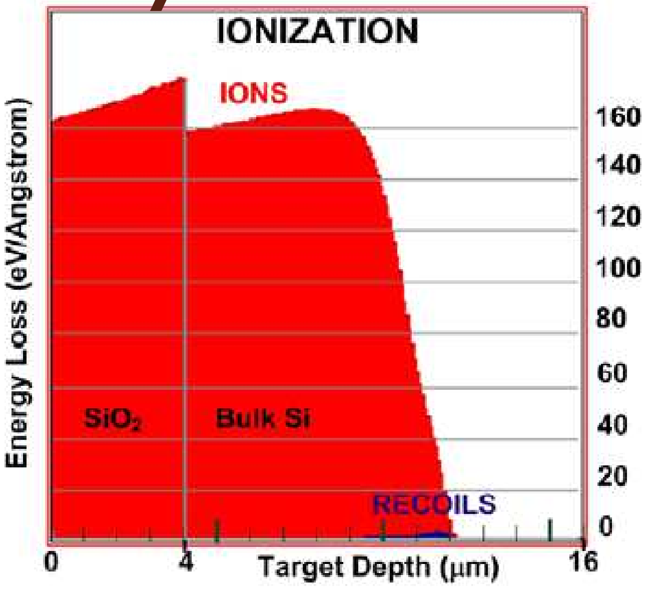

Ionization Model Analysis



Radial Dose
18 MeV Oxygen Ion
Homogeneous Silicon



LET Oxygen Ion, 18 MeV, chip type target

δ electrons radial track:
Katz-Waligorski-Fageeha Model

$$D(r) = \left[\frac{Ne^4}{m_e c^2}\right]\left[\frac{Z^{*2}}{\alpha\beta^2}\right]\left[\frac{\left(1-\frac{r+\theta}{R+\theta}\right)^{\frac{1}{\alpha}}}{r(r+\theta)}\right]$$

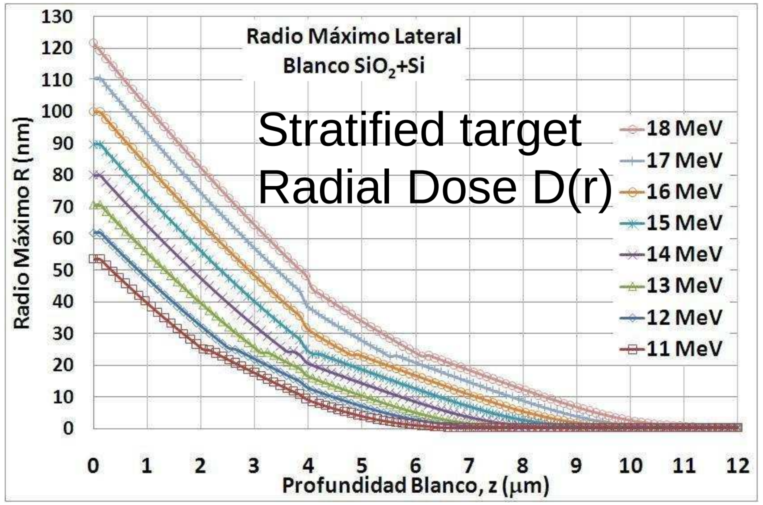
18 MeV Oxygen ion, Si homogeneous:
R=114 nm , D(r)=100 eV/μm^3

D(r) iteration algorithm to consider kynetic energy T reduction with depth z in a chip strata model:

$$T_j = T_{j-1} - LET_{j-1}\Delta z$$

SEU Threshold model and its experimental verification. F.R.Palomo, J.M.Mogollón, Y.Morilla, J.García-López, M.C.Jiménez-Ramos, J.A.Labrador, M.A.Cortés-Giraldo, J.M.Quesada, M.A.Aguirre. **Proceedings of RADECS 2011 Conference.** Sevilla, Spain, 19th-23rd September , 2011.

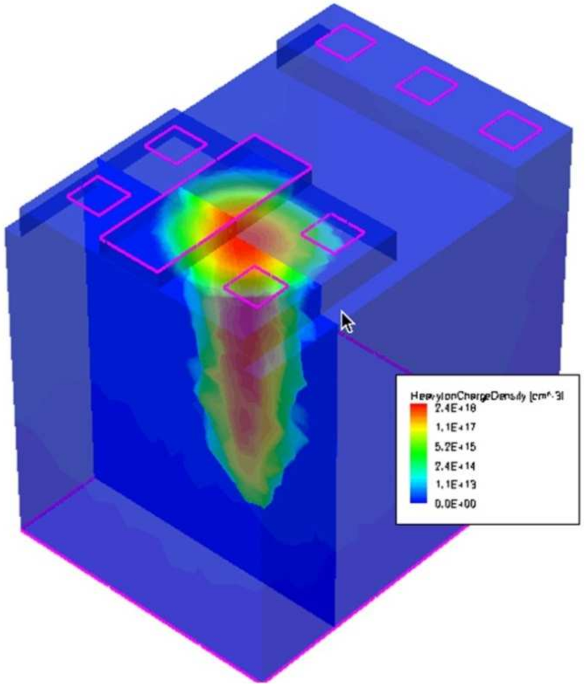
Full Ionization model



Stratified target
Radial Dose D(r)

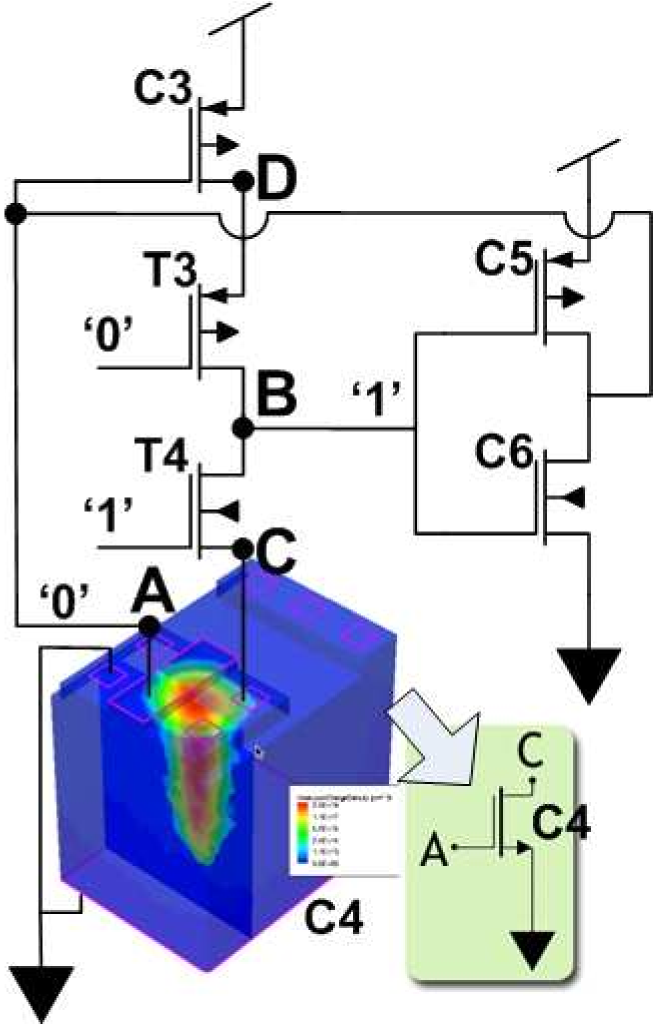
Considering the whole model in the strata layered target ($4\ \mu m\ SiO_2 + Si$) we got the ionization profile

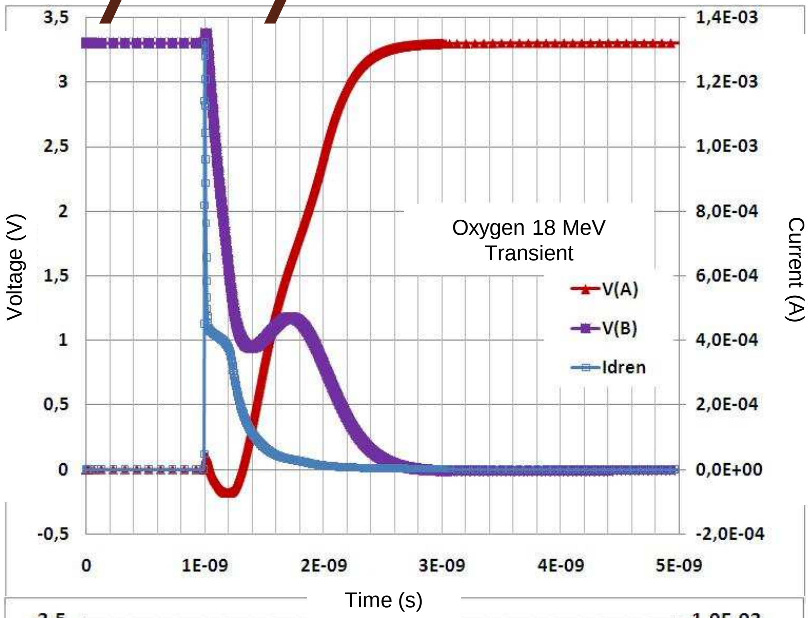
Programming the TCAD operators {z, LET(z), w(z)} de Sentaurus we obtain the “true” track geometry. This particular study considered oxygen ions with energies from 11 to 18 MeV.

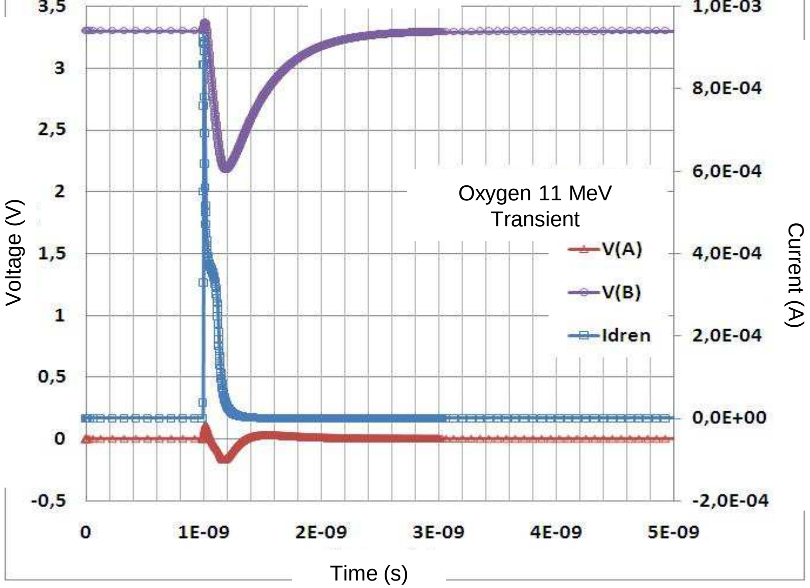


SEU Threshold model and its experimental verification. F.R.Palomo, J.M.Mogollón, Y.Morilla, J.García-López, M.C.Jiménez-Ramos, J.A.Labrador, M.A.Cortés-Giraldo, J.M.Quesada, M.A.Aguirre. **Proceedings of RADECS 2011 Conference.** Sevilla, Spain, 19th-23rd September , 2011.

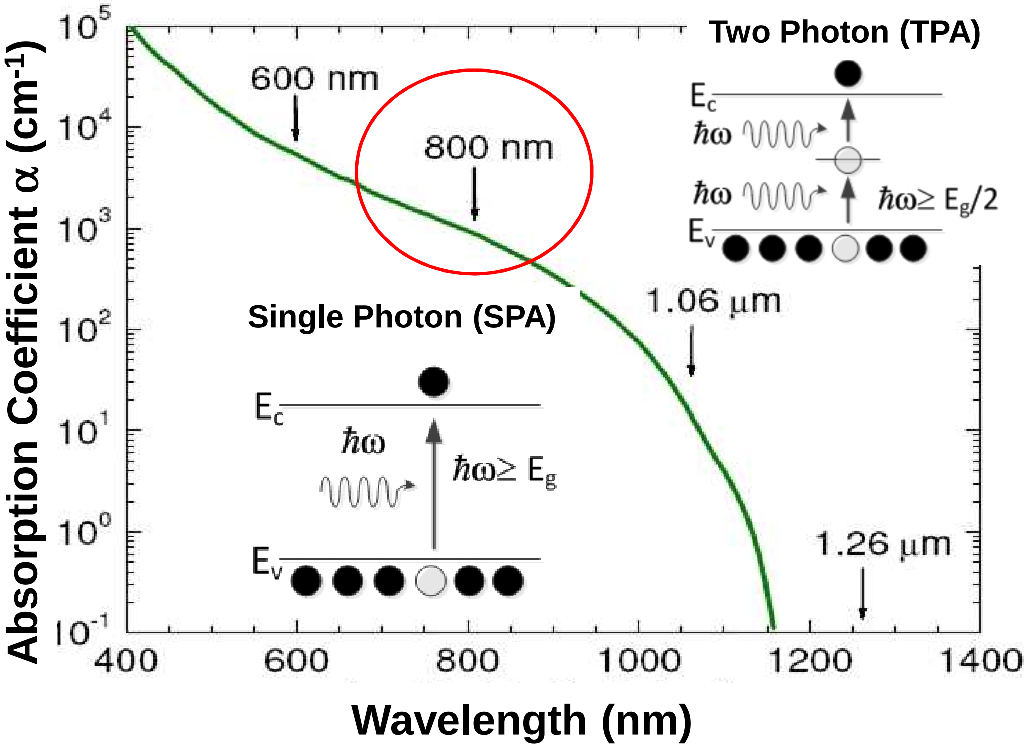
Another possibility: hybrid sim.

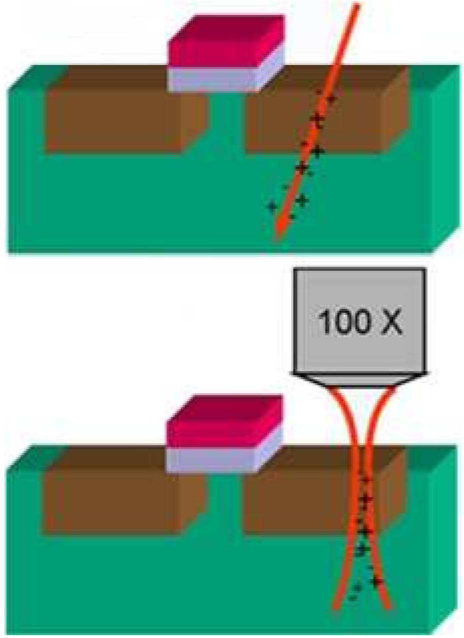






Track Ionization and Pulsed Laser





- **Ionizing particle**
- **Coulombian interaction**

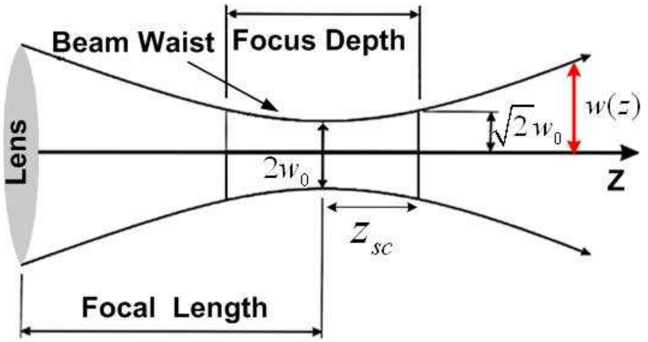
- **Pulsed Laser**
- **Photoelectric Effect**

Charge < 1 pC
Duration < 1 ps

Track Ionization and Pulsed Laser

- We modify the Sentaurus ion track model to get a full 3D simulation of a SRAM cell under femtosecond pulsed laser, reproducing even the optical Rayleigh Profile:

$$\omega(z) = \omega_0\sqrt{1+(\frac{z}{z_{sc}})^2}$$



$$g_{las}(r,z,t) = \left[\frac{T_{trans}E_{laser}}{\pi^2 E_\gamma}\frac{\alpha}{\omega_0^2}\frac{\omega_0^2 e^{-\alpha z}}{w^2(z)}\right]\left[e^{\frac{-2r^2}{w^2(z)}}\right]\left[\frac{2e^{-\frac{t^2}{\tau_{las}^2}}}{\tau_{las}\sqrt{\pi}}\right]$$

Pulsed laser photoelectric carrier generation rate

Track Ionization and Pulsed Laser

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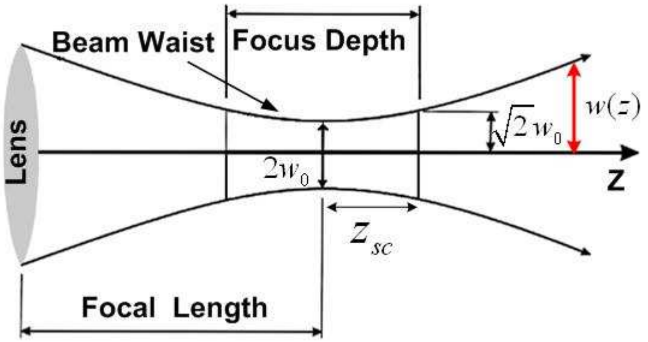
$$\omega(z) = \omega_0\sqrt{1+(\frac{z}{z_{sc}})^2}$$



$$G(z,w,t) = G_{LET}(z)R(r,z)T(t)$$

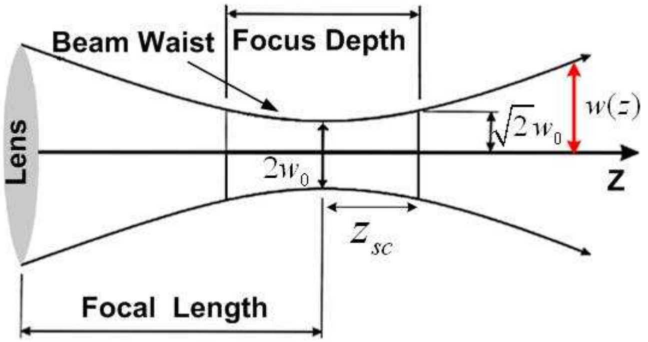
$$\begin{aligned} G_{LET}(z) &= a_1 + a_2 z + a_3 e^{a_4 z} + \\ &+k'[c_1(c_2+c_3 z)^{c_4} + LET_f(z)] \\ R(r,z) &= e^{\frac{-r^2}{w_t^2(z)}} \\ T(t) &= \frac{2\,e^{-\frac{(t-t_0)^2}{s_{hi}^2}}}{s_{hi}\sqrt{\pi}\,(1-erf(\frac{t_0}{s_{hi}}))} \end{aligned}$$

TCAD generic track ionization carrier generation rate

Track Ionization and Pulsed Laser

- We modify the Sentaurus ion track model to get a full 3D simulation of a SRAM cell under femtosecond pulsed laser, reproducing even the optical Rayleigh Profile:

$$\omega(z) = \omega_0 \sqrt{1 + (\frac{z}{z_{sc}})^2}$$

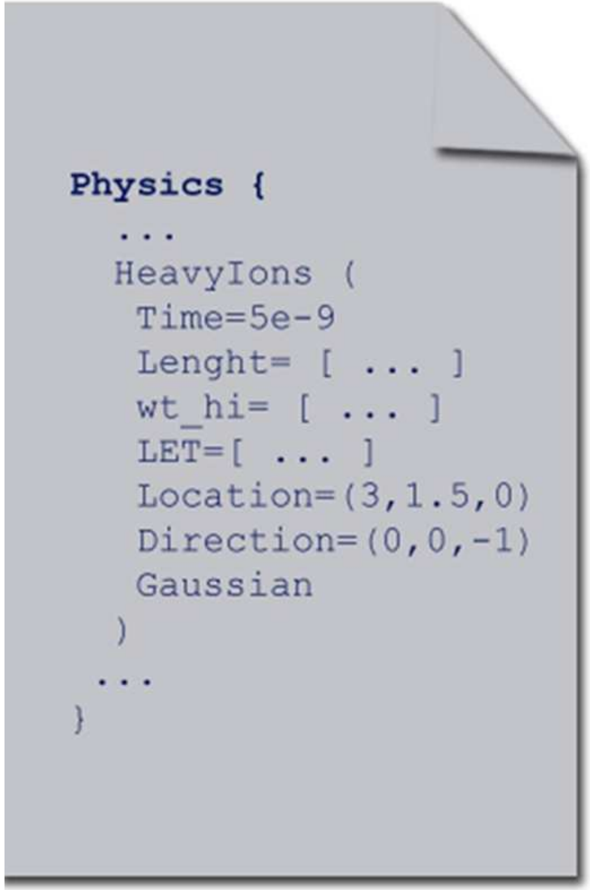


$$\begin{aligned} k' &= \frac{T_{trans} E_{laser}}{\pi^2 E_\gamma} \\ LET_f(z) &= \frac{\alpha}{\omega_0^2} \frac{\omega_0^2 e^{-\alpha z}}{\omega^2(z)} \\ \omega_t(z) &= \frac{\omega(z)}{\sqrt{2}} \\ s_{hi} &= \tau_{las} \end{aligned}$$

And the c_n's and a_n's constants identically zero

Track TCAD Operator

```
  Physics {
       Mobility(Phumob HighFieldsat Enormal)
  EffectiveIntrinsicDensity(OldSlotboom)
  Fermi
  Recombination (SRH Auger)
  #Simulacion Laser Pulsado
  HeavyIon(
  time=5e-9
  length=
[0        0.125e-4 0.250e-4 0.375e-4 0.500e-4 0.625e-4 0.750e-4
 0.875e-4 1.000e-4 1.125e-4 1.250e-4 1.375e-4 1.500e-4 1.625e-4
 1.750e-4 1.875e-4 2.000e-4 2.125e-4 2.250e-4 2.375e-4 2.500e-4
 2.625e-4 2.750e-4 2.875e-4 3.000e-4 3.125e-4 3.250e-4 3.375e-4
 3.500e-4 3.625e-4 3.750e-4 3.875e-4 4.000e-4 4.125e-4 4.250e-4
 4.375e-4 4.500e-4 4.625e-4 4.750e-4 4.875e-4 5.000e-4 5.125e-4
 5.250e-4 5.375e-4 5.500e-4 5.625e-4 5.750e-4 5.875e-4 6.000e-4]
  wt_hi=
[7.071e-5 7.075e-5 7.085e-5 7.103e-5 7.128e-5 7.160e-5 7.199e-5
 7.244e-5 7.297e-5 7.356e-5 7.421e-5 7.492e-5 7.569e-5 7.653e-5
 7.741e-5 7.836e-5 7.935e-5 8.040e-5 8.149e-5 8.264e-5 8.382e-5
 8.505e-5 8.632e-5 8.764e-5 8.898e-5 9.037e-5 9.179e-5 9.324e-5
 9.472e-5 9.623e-5 9.777e-5 9.934e-5 1.009e-4 1.026e-4 1.042e-4
 1.059e-4 1.075e-4 1.092e-4 1.110e-4 1.127e-4 1.145e-4 1.163e-4
 1.181e-4 1.199e-4 1.217e-4 1.235e-4 1.254e-4 1.272e-4 1.291e-4]
       LET_f=
[2.252e11 2.187e11 2.120e11 2.051e11 1.980e11 1.908e11 1.835e11
 1.762e11 1.689e11 1.616e11 1.543e11 1.472e11 1.402e11 1.334e11
 1.267e11 1.202e11 1.140e11 1.079e11 1.021e11 9.659e10 9.127e10
 8.619e10 8.134e10 7.674e10 7.236e10 6.822e10 6.429e10 6.057e10
 5.706e10 5.375e10 5.062e10 4.768e10 4.490e10 4.229e10 3.983e10
 3.751e10 3.534e10 3.329e10 3.137e10 2.956e10 2.786e10 2.627e10
 2.477e10 2.336e10 2.204e10 2.079e10 1.962e10 1.852e10 1.749e10]
  Location=(3,1.5,0)
  Direction=(0,0,-1)
  Gaussian)
  }
```

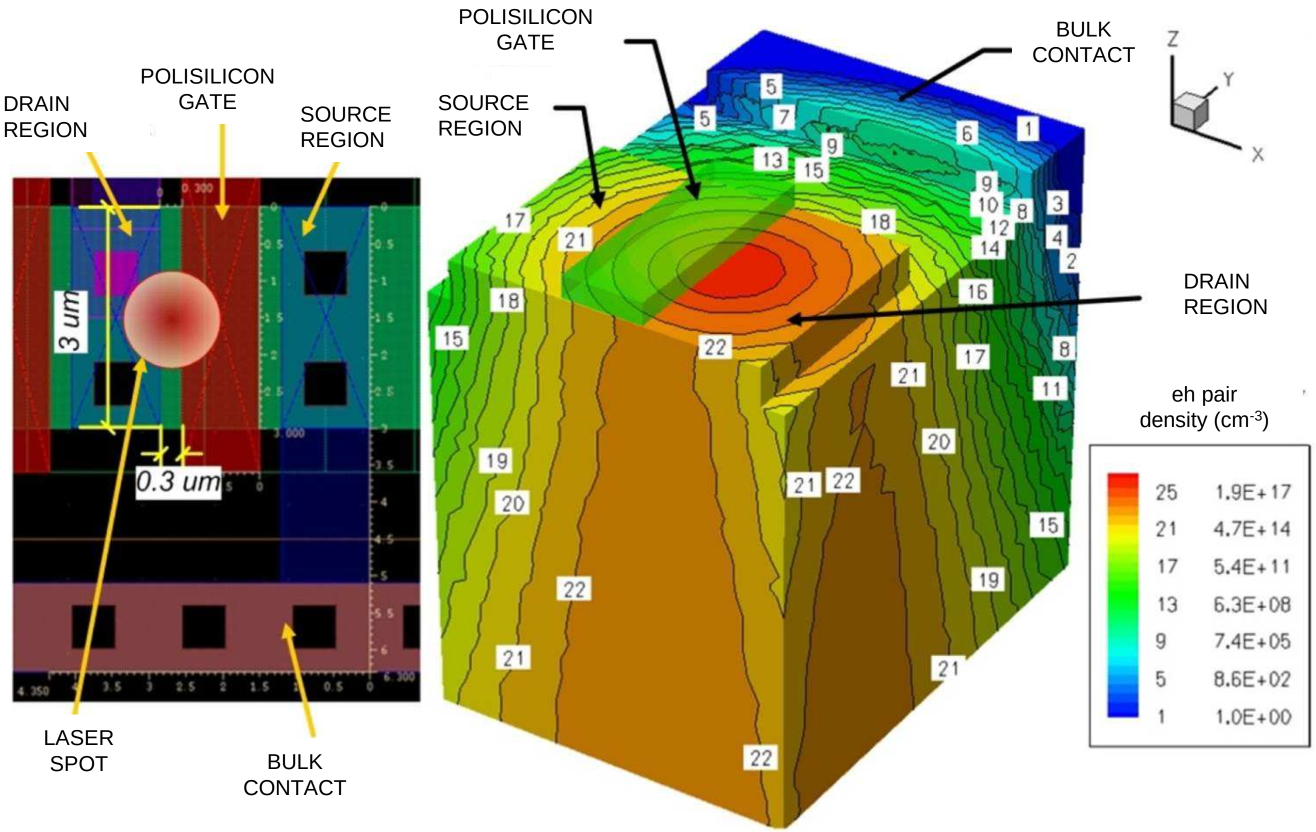


```
Physics {
  ...
  HeavyIons (
   Time=5e-9
   Lenght= [ ... ]
   wt_hi= [ ... ]
   LET=[ ... ]
   Location=(3,1.5,0)
   Direction=(0,0,-1)
   Gaussian
  )
 ...
}
```

Pulsed Laser and TCAD

- In a silicon device, pulsed laser and ion tracks have similar effects

$$\int g_{ion}(r,z,t)dV\,dt = \int g_{las}(r,z,t)dV\,dt$$



DRAIN
REGION

POLISILICON
GATE

SOURCE
REGION

LASER
SPOT

BULK
CONTACT

POLISILICON
GATE

SOURCE
REGION

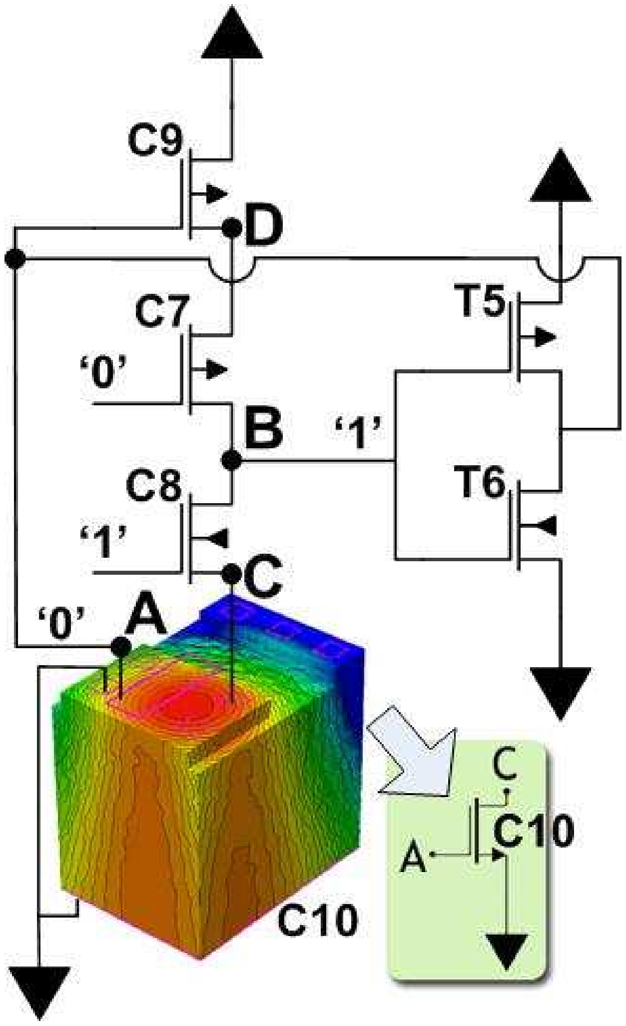
BULK
CONTACT

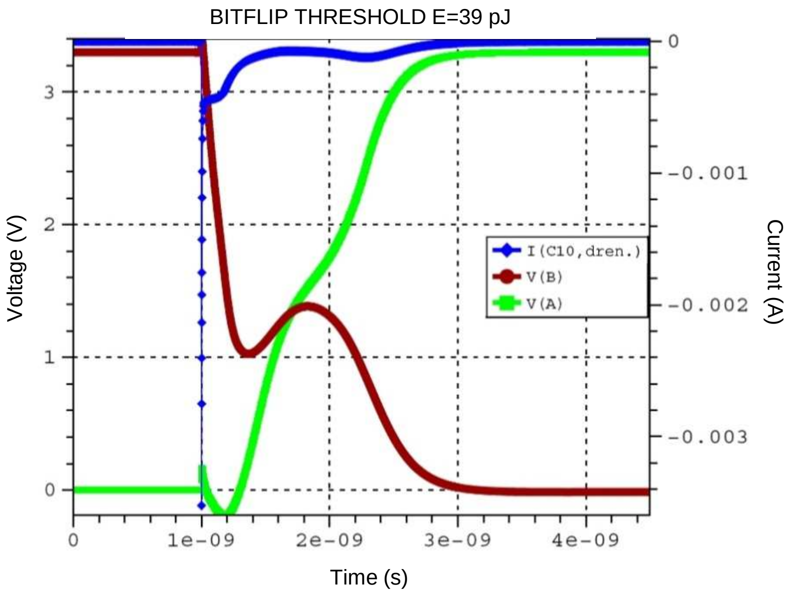
DRAIN
REGION

eh pair
density (cm^{-3})

Simulations of femtosecond pulsed laser effects on MOS electronics using TCAD Sentaurus customized models. F.R.Palomo, P.Fernández-Martínez, J.M.Mogollón, S.Hidalgo, M.A.Aguirre, D.Flores, I.López-Calle, J.A de Agapito. **International Journal on Numerical Modelling: electronic networks, devices and fields, 23(4-5):379-399, 2010.**

Results Laser Simulation





Pulse Energy (pJ)	Transmitted Energy (pJ)	Bitflip?	Q_{drain} (fC)
42	8.0	Si	245.3
41	7.8	Si	249.4
40	7.6	Si	254.8
39	7.4	Si	267.2
38	7.2	No	274.4
37	7.0	No	263.0
36	6.8	No	257.0
35	6.6	No	249.5

Equivalence Criterium:

$$\int I_{dren,ion}dt = \int I_{dren,las}dt$$

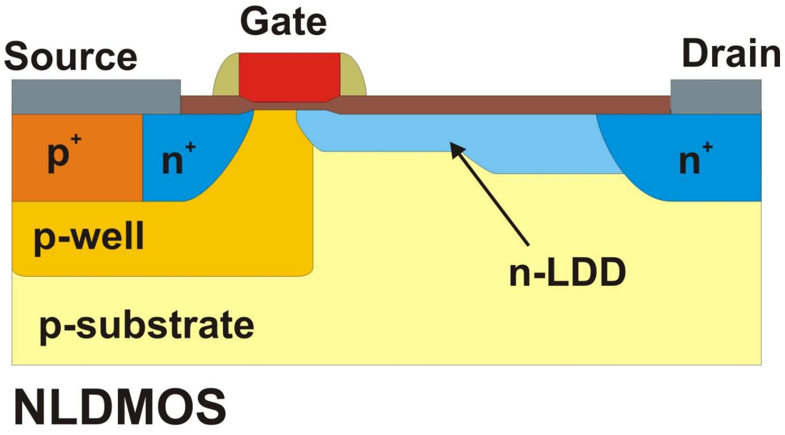
$$Q_{dren,39pJ,19\%} = 267.2 \text{ fC}$$

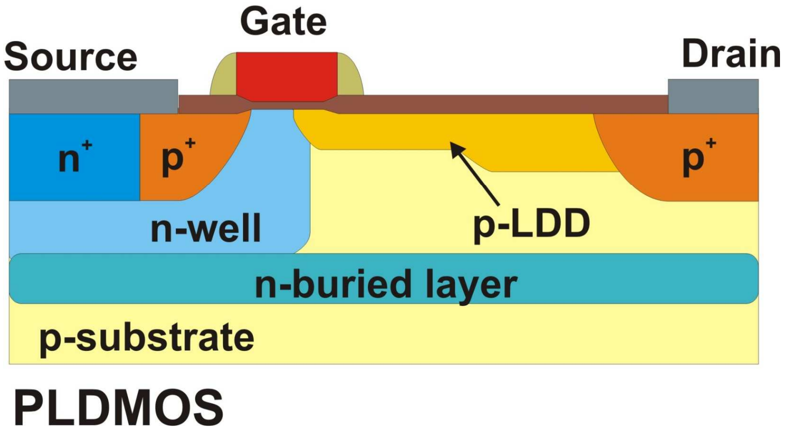
$$Q_{dren,15MeV,O} = 268.8 \text{ fC}$$

Mixed-mode simulations of bitflip with pulsed laser . F.R.Palomo, J.M.Mogollón, J.Nápoles, M.A.Aguirre. **IEEE Transactions on Nuclear Science, 57(4):1884-2991, 2010.**

TCAD Mixed-mode simulations of bitflip with pulsed laser . F.R.Palomo, J.M.Mogollón, J.Nápoles, M.A.Aguirre. **Proceedings of RADECS 2009 Conference**, Brugge, Belgium, 14th-18th September , 2009.

TID in TCAD





- LDMOS transistors are second-generation devices from the GOD LDMOS mo dule implemented in the SGB25V 0.25 µm SiGe BiCMOS technology from IHP microelectronics
  - Gamma Irradiation

    0.65, 5 and 10 Mrad

✓ Focus on the LDMOS Drift and Gate Oxides

Simulation methodology for dose effects in lateral DMOS transistors, P.Fernández-Martínez, F.R.Palomo, S.Díez, S.Hidalgo, M.Ullán, D.Flores, R.Sorge, Microelectronics Journal 43(1), 2012, pp 50-56

Simulation of Total Ionising Dose in MOS capacitors, P.Fernández-Martínez, F.R.Palomo, I.Cortés, S.Hidalgo, D.Flores, Proceedings of the 8th Spanish Conference on Electron Devices, CDE 2011

Study of the Dose Induced Breakdown in LDMOS and LUDMOS devices P.Fernández-Martínez, F.R.Palomo, I.Cortés, S.Hidalgo, D.Flores, Proceedings of RADECS 2010

TID in TCAD

- For Total Ionization Dose effects:

1.We calculate the N_{ot} and N_{it} density from analytical models

2.N_{ot} is simulated as a fixed charge sheet in the oxide;

N_{ot} calculation is tricky because it depends in the E field

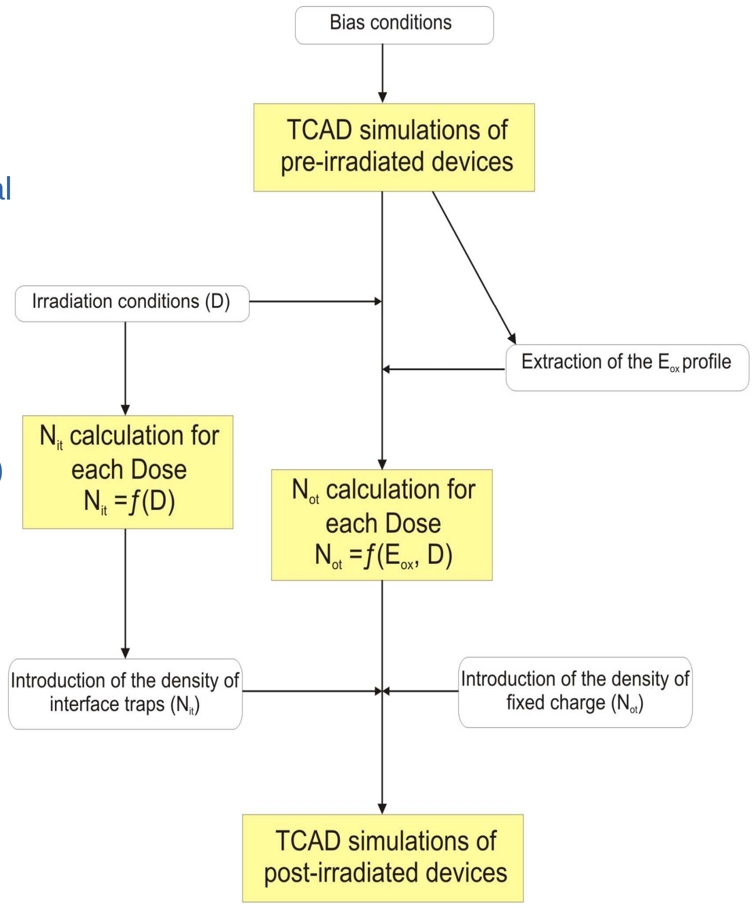
3.N_{it} is simulated with a TCAD trap model (Pb defects two discrete levels at 0.3 and 0.8 eV from Valence band)

Fixed Charges

$$\begin{cases} N_{ot} = g_0 \cdot f_Y(E_{ox}) \cdot f_{ot} \cdot D \\ g_0 = 7.88\times10^{12}\left[rad^{-1}\cdot cm^{-3}\right] \\ f_Y(E_{ox}) = \left(\dfrac{|E_{ox}|}{|E_{ox}+E_1|}\right)^m \\ E_1 = 0.55\left[MV/cm\right] \\ m = 0.7 \end{cases}$$

Interface Traps $N_{it} = a_{it} \cdot D$

✓ f_{ot} and a_{it} are considered simulation fitting parameters



Bias conditions

TCAD simulations of pre-irradiated devices

Irradiation conditions (D)

Extraction of the E_{ox} profile

N_{it} calculation for each Dose $N_{it} = f(D)$

N_{ot} calculation for each Dose $N_{ot} = f(E_{ox}, D)$

Introduction of the density of interface traps (N_{it})

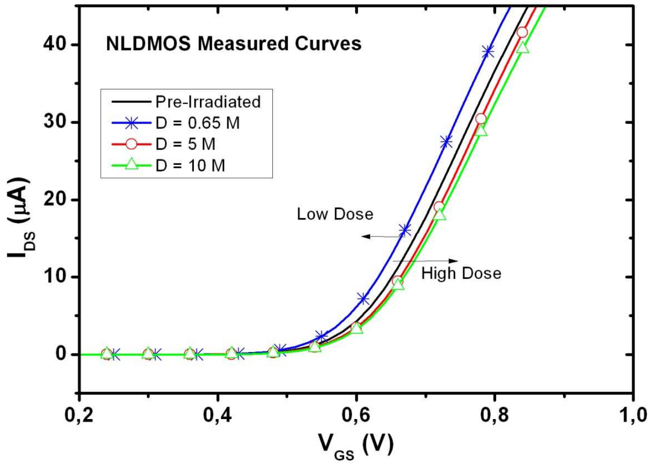
Introduction of the density of fixed charge (N_{ot})

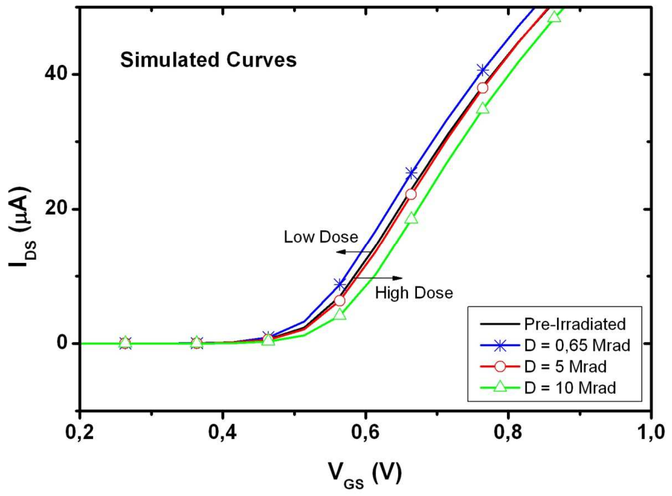
TCAD simulations of post-irradiated devices

	NLDMOS	PLDMOS
f_{ot} Gate Ox	0.01	0.01
f_{ot} Drift Oxide	0.2	0.2
a_{it} (rad^{-1} cm^{-2})	1.7×10^4	2.5×10^4

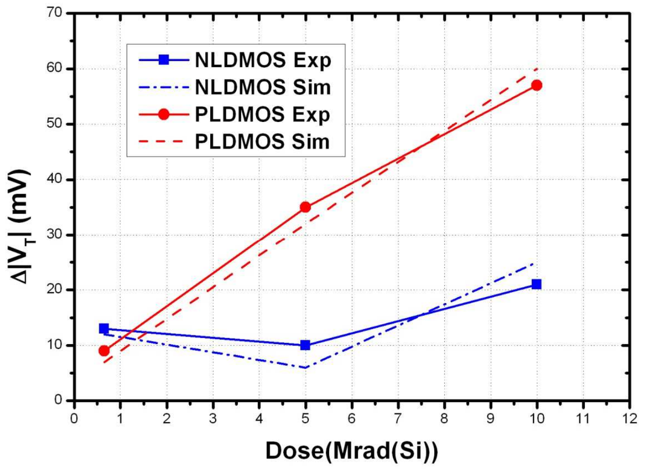
TID in TCAD

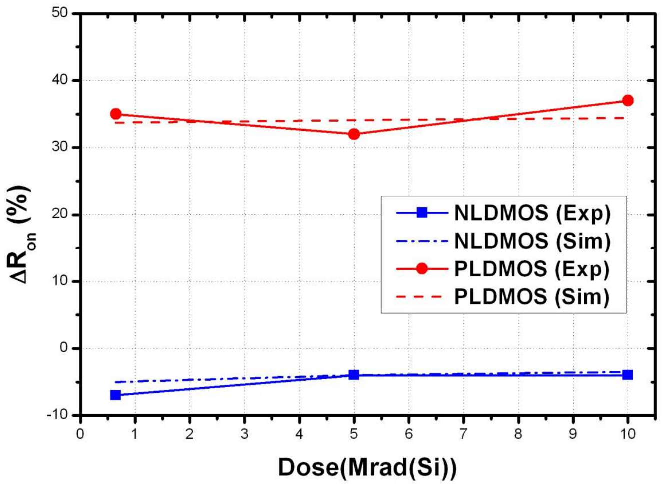
NLDMOS post-irradiated curves





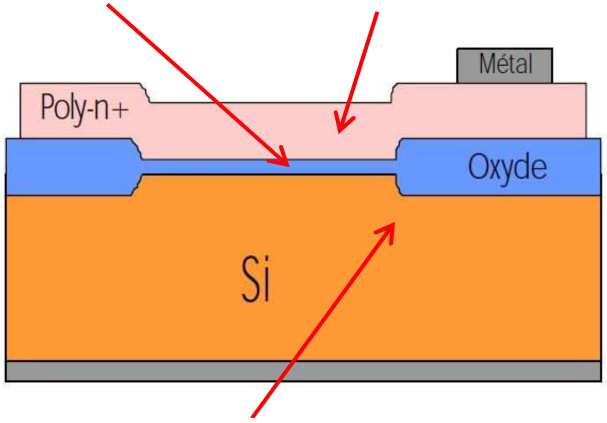
- Shifts on the I-V curves as a function of increasing Dose values are simulated in accordance with the experimental results for the LNDMOS transistor. Also consider relative shifts in of V_{th} and R_{on} , even the rebound effect in N-type transistors





Displacement Damage in TCAD

- In order to reproduce displacement damage we make two steps:
  - We make sweep simulations of device parameters known to be related to DD
  - We propose and adapt the TCAD model to the observables
  - In this particular study, a MOS capacitor, the substrate Resistance was the key device parameter



T_{ox} ranges at the nanometric scale (3-10 nm)

Highly doped n-type polysilicon gate electrode

P-type silicon <100> substrate with boron doping concentration = 10^{15} cm^{-3}

Proton Irradiation on MOS Capacitors

Φ_p [cm^{-3}]	E [GeV]
1×10^{13}	24
3×10^{13}	24
1×10^{14}	24

Low ionising Conditions

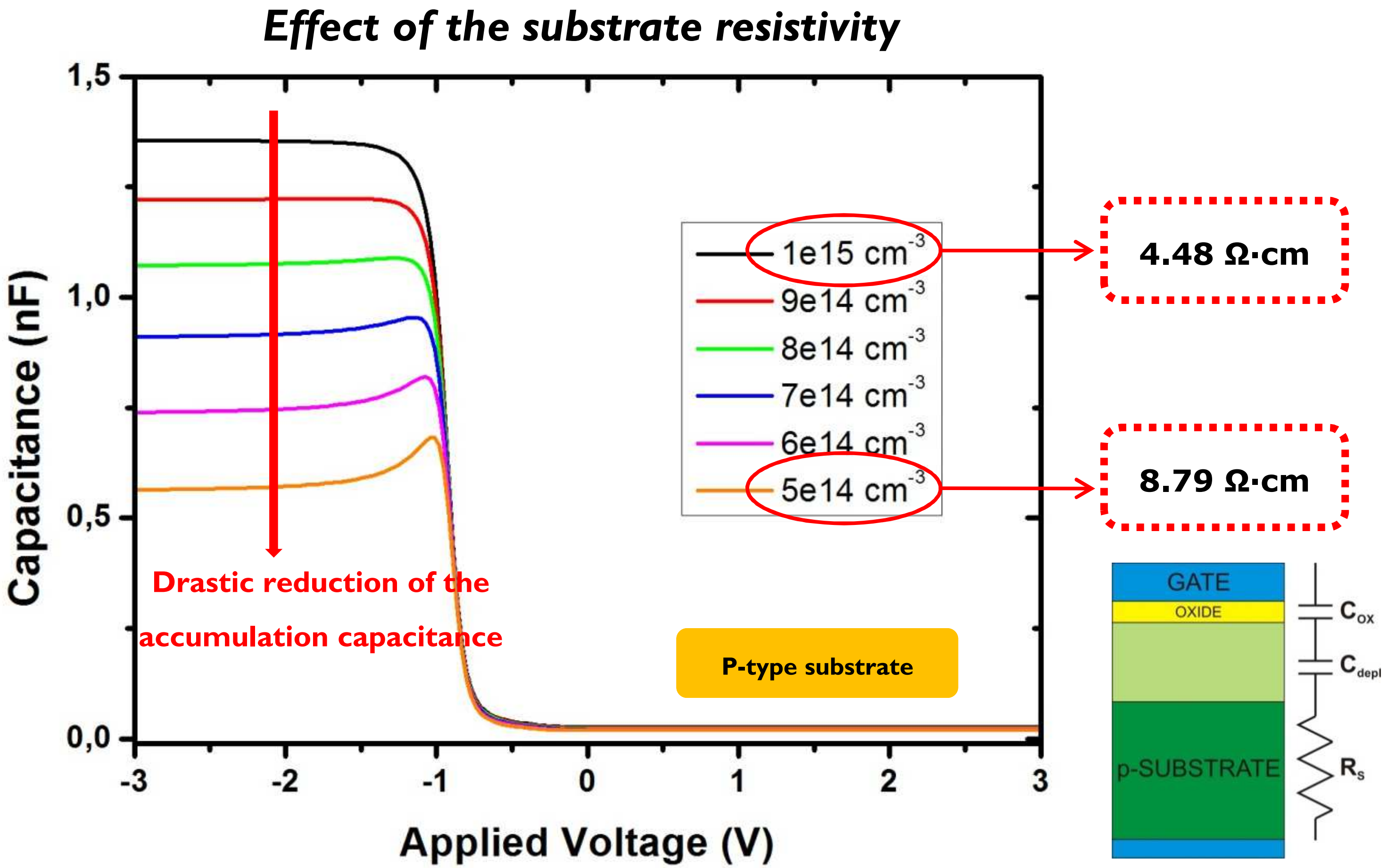
- **24 GeV protons are MIPs with reduced ionising capability**
- **Generated N_{ot} densities drain out the nanometric oxide by tunneling processes**
- **Low N_{it} densities are expected in low-hydrogen containing nm-thin oxides**
- **Interface does not play the most relevant role in MOS capacitor C-V characteristics**

Analysis of displacement damage effects on MOS capacitors, P.Fernández-Martínez, F.R.Palomo,S.Hidalgo, C.Fleta, F.Campabadal, D.Flores, NIMA 730 (2013) pp 91-94

MOS Capacitor displacement damage dose (DDD) dosimeter, P.Fernández-Martínez, F.R.Palomo,S.Hidalgo, C.Fleta, F.Campabadal, D.Flores, Proceedings of RESMDD 2012

Displacement Damage in TCAD

- For a MOS capacitor, R_{subs} is the key parameter affected by Displacement Damage, so we make exploratory simulations by parameter sweeping.



Effect of the substrate resistivity

Drastic reduction of the accumulation capacitance

P-type substrate

4.48 Ω·cm

8.79 Ω·cm

Displacement Damage in TCAD

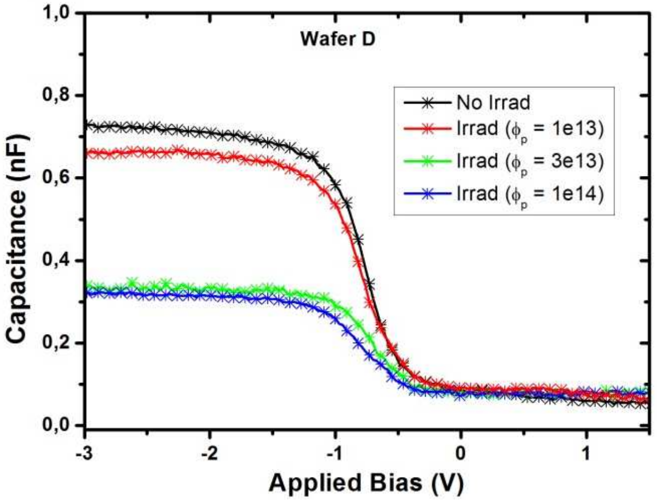
University of Perugia trap model

- DDD defects are emulated by localised traps within the band-gap, with fluence dependent density: $Conc(cm^{-3}) = \Phi_{eq}\eta$

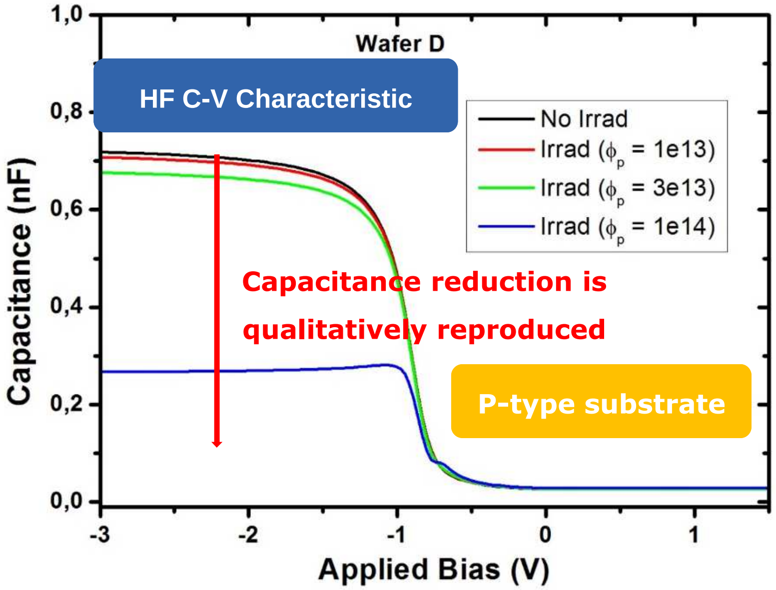
P-type (FZ)

Type	Energy [eV]	Trap	σ_e [cm^2]	σ_h [cm^2]	η [cm^{-1}]
Acceptor	$E_C - 0.42$	VV	9.5×10^{-15}	9.5×10^{-14}	1.613
Acceptor	$E_C - 0.36$	VVV	5.0×10^{-15}	5.0×10^{-14}	0.9
Donor	$E_C + 0.36$	CiOi	3.23×10^{-13}	3.23×10^{-14}	0.9

Modified cross sections to match trapping times



Experimental Results



HF C-V Characteristic

Capacitance reduction is qualitatively reproduced

P-type substrate

Thanks for your attention

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