Simulation of Radiation Effects on Semiconductors

Design of Low Gain Avalanche Detectors

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- **Ionization Damage Simulation**
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  - ✓ **Silicon oxide**
- **Displacement Damage Simulation**
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  - ✓ **Gain simulation**
  - ✓ **Design of active region**
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  - ✓ **Fabrication and Experimental results**

General Considerations

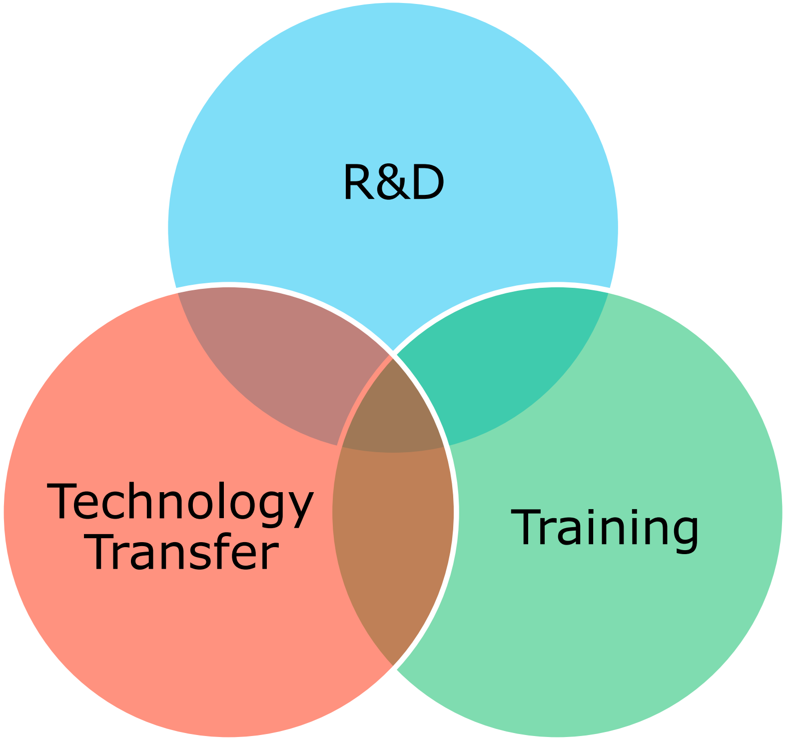
Centro Nacional de Microelectrónica

Centre Nacional de Microelectrònica IMB

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Centro Nacional de Microelectrónica

IMB-CNM Main Pillars & R&D Activity



- **Semiconductor Devices**
- **Power Devices**
- **Integrated Circuits and Systems**
- **Sensors, Actuators and MEMS**
- **Nanoscale Devices and Actuators**
- **Lab-on a chip, Polymer devices**

Centro Nacional de Microelectrónica

Integrated Micro and Nano Fabrication Clean Room

Main CR

- 1,500 m^2
- Class 100-10,000
- CMOS integrated circuits
- Microsystems processes
- Nanolithography and nanofabrication

Back-end CR

- 40 m^2
- Class 1000-10,000
- Chip packaging
- Hybrid circuit assembly

General Considerations

- **TCAD Software for (Power) semiconductors**
  - ✓ **Silvaco**
  - ✓ **Sentaurus**
  - ✓ **SRIM (TRIM Monte Carlo simulation)**

SILVACO

SYNOPSYS®

- **Previous knowledge:**
  - ✓ **<u>Power semiconductor devices</u>: Design, optimisation and fabrication**
  - ✓ **Silvaco tools for process technology simulation and Clean Room control**
  - ✓ **Sentaurus tools for structure optimisation (selection of optimum geometrical and technological parameters)**
  - ✓ **Advanced simulation of device degradation (hot carriers, hot spots, etc.)**
  - ✓ **Performance degradation after irradiation of commercial power lateral MOSFETs**
  - ✓ **Design and application of <u>Silicon tracking detectors</u> (ATLAS)**

General Considerations

- **What do we need to simulate / emulate ?**
  - ✓ **Radiation hardness of (power) semiconductor devices**
    - **Post-irradiation damage**
    - **Technological modifications to enhance robustness**
  - ✓ **Single Event Effects (logic circuits and memories)**
    - **Generated charge profiles**
    - **Transient simulations of complex 3D structures**
  - ✓ **Charge generation and evolution in Silicon detectors**
    - **Transient or quasi-static simulation?**
    - **Strategies**
  - ✓ **Gain simulation in Silicon detectors**

General Considerations

- **The interaction between radiation and materials (of a semiconductor device) is based on the moment and energy transfer**
  - ✓ **Ionisation damage**
  - ✓ **Displacement damage**

Tipo	Energía	Interacción	Secundarios	Daño Primario	Daño Secundario
e^-	< 150 keV	cortical	e^-	ionización	ionización
	> 150 keV				
		nuclear	iones	desplazamiento	
p^+, α, Iones	$>$ MeV	cortical	e^-, iones	ionización	ionización
		nuclear	iones	desplazamiento	
n	< 100 keV	nuclear	iones	desplazamiento	ionización y desplazamiento
	térmicos	captura inelástica	α, productos de fision y γ		
γ	< 50 keV	fotoeléctrico	e^-	ionización	ionización
	> 50 keV < 20 MeV	Compton	e^-, γ		ionización y desplazamiento
	> 20 MeV	prod. pares	e^-, e^+ y γ		

General Considerations

- **Relation between absorbed dose and energy transfer**
  - ✓ **Flux (Φ):** Number of incident particles ($cm^{-2} \cdot s^{-1}$)
  - ✓ **Integrated Flux or Fluence (Φ):** Total number of incident particles (cm^{-2})
  - ✓ **Dose (D):** Absorbed energy per unit mass (Gray: 1 Gy = 100 $J \cdot Kg^{-1}$) (rad; 1 rad = 100 $erg \cdot s^{-1}$)

$$D = S\Phi$$

  - ✓ **Stopping Power (S):** Energy transfer, normalised to the material density ($MeV \cdot cm^2 \cdot Kg^{-1}$)

$$S = \frac{1}{\rho}\frac{dE}{dR}$$

$$S = \frac{1}{\rho}\left.\frac{dE}{dR}\right|_{\text{Ionización}} + \frac{1}{\rho}\left.\frac{dE}{dR}\right|_{\text{Desplazamiento}}$$

Ionising Energy Loss (IEL)
Linear Energy Transfer (LET)

Non-Ionising Energy Loss (NIEL)

Total Ionising Dose (TID) $\quad \mathrm{TID} = \mathrm{LET} \times \Phi$

Displacement Damage Dose (DDD) $\quad \mathrm{DDD} = \mathrm{NIEL} \times \Phi$

Ionisation Damage Simulation

Ionisation Damage Simulation

- The incident particle transfer its energy to a cortical electron, creating an electron-hole pair
- The minimum energy to create an electron-hole pair (Shockley theory) is:

$$E_{ion} = E_G + rE_R + 2E_f$$

E_G (gap), E_R (Raman), E_f(Fonons)

- The generation rate accounts for the electron-hole pairs created by a TID_0 = 1 Rad in 1 cm^3

$$g_0 = \rho \frac{\mathrm{TID}_0}{E_{ion}}$$

Material	E_{ion} [eV]	g_0 [ehp/cm^3·rad]
Si	3.6	$4{,}0 \times 10^{13}$
SiO_2	17.0	$8{,}1 \times 10^{12}$
GaAs	~ 4.8	$\sim 7{,}0 \times 10^{13}$
Ge	2.8	$1{,}2 \times 10^{14}$

Ionisation Damage Simulation

- **The damage introduced by the generation of a great amount of electron-hole pairs depends on the transient evolution of the charge and also on the bias and ambient conditions**

  - ✓ **Semiconductors:**
    - **If no bias is applied, charge disappears due to recombination. The process is ruled by the carrier lifetimes and does not degrade the material. No simulation interest**
    - **If bias is applied, mobile charge is accelerated by the electric field in the depletion region and a transient current is observed. Single Event Effects**
    - **Transient simulation.**

  - ✓ **Dielectrics:**
    - **The number of generated electron-hole pairs is much lower than in semiconductors**
    - **The charge mobility is also much lower than in semiconductors**
    - **As a consequence, carrier are trapped and a certain density of fixed charge is created. Critical in active devices**
    - **Quasi stationary simulation**

Ionisation Damage in Semiconductors

Ionisation Damage Simulation in Semiconductors

- **The simulation of ionising particles is only relevant when the density of generated electron-hole pairs is really high (electron-hole plasma)**

  - ✓ **Heavy ions typically create an electron-hole plasma**
  - ✓ **Transport equation in a non-linear regime have to be solved**
  - ✓ **Strong injection conditions are easily reached**

  - ✓ **The Sentaurus Heavy Ion model works properly to emulate the transient evolution of the generated charge (Single Event Effects)**
    - **Simulation of particles with Minimum Ionizing Energy is of great interest since the number of generated electron-hole pairs is perfectly known.**
    - **Transient simulations are time costly if accuracy is expected.**
    - **The distribution of the generated electron-hole pairs in the semiconductor has to be previously determined by using a SRIM/TRIM simulator (Stopping and Range of Ions in Matter)**

Single Event Effects: Experimental Study and Simulation

- **Single Event Effects (SEE):**
  - ✓ **Produced by high energy particle hits on sensitive circuit regions**
  - ✓ **Main topic in reliability and device performance in space applications**
- **Study and prediction of SEE require test in particle accelerator facilities**
  - ✓ **Heavy Ion accelerator provide high energy capabilities**
  - ✓ **High cost and limited availability impose alternative methodologies**
- **Numerical simulation techniques are able to predict device and circuit behaviour after an ion hit**

Single Event Effects: Experimental Study and Simulation

Simulation Techniques: Different Approaches.

- ✓ **Physics of the incident particle and its interaction with matter (SRIM-Stopping and Rang of Ions in Matter):**
  - **Calculations on the energy deposition of ions passing through matter**
  - **Linear Energy Transfer (LET) profile along the particle track can be obtained**

- ✓ **Electric performance of the circuit after the perturbation (CADENCE-SPECTRE):**
  - **Perturbation is replaced by a pulsed current in the affected node**
  - **Single Event evolution can be followed**

- ✓ **Semiconductor solid state physics (Synopsys Sentaurus TCAD):**
  - **Exact reproduction of the charge collection phenomenology**
  - **Accurate consequences over the electrical characteristics can be evaluated**

Ionisation Damage in Oxides

Case Study: Power LDMOS Transistor

Ionisation Damage Simulation in Oxides

- **Two approaches can be contemplated:**

1. **Simulation of the defect evolution**
   - **Transport, anneal and recombination models**
   - **Transient simulation (time costly)**
   - **Continuity equations are not solved in oxides**
     - **"Oxide as semiconductor" option has to be selected and a correct set of parameters have to be introduced (good knowledge of the dielectric)**

2. **Simulation of the permanent damage using Sentaurus Fixed Charge and Traps models**
   - **Quasi-static simulation**
   - **Average final values necessary**

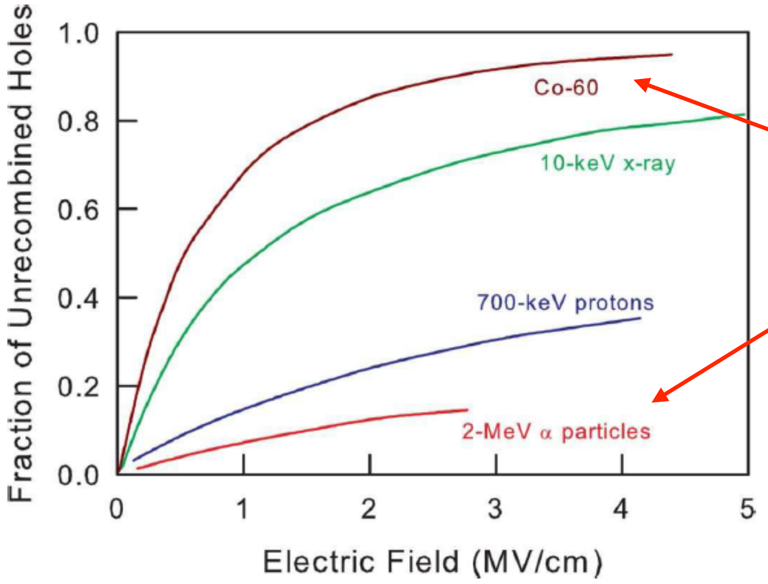
✓ **A relation between defects and Dose (TID) is needed**

- **Generation of fixed charge (N_{ot}) and interface traps (N_{it})**
- **Energy distribution of traps (D_{it})**
- **Strong electric field dependence (irradiation bias conditions to be emulated)**

Ionisation Damage Simulation in Oxides

❑ Calculation of the recombination efficiency (f_y)

- ✓ Efficiency of the recombination process (f_y) is the ratio between surviving holes and total generated holes
- ✓ Recombination strongly depends on the ionising particle



X or γ rays (^{60}Co) generate charges in almost all the dielectric volume (Slow recombination)

α particles generate charges in the neighbourhood of their trajectory (Fast recombination)

- ✓ The efficiency of the recombination also depends on the electric field

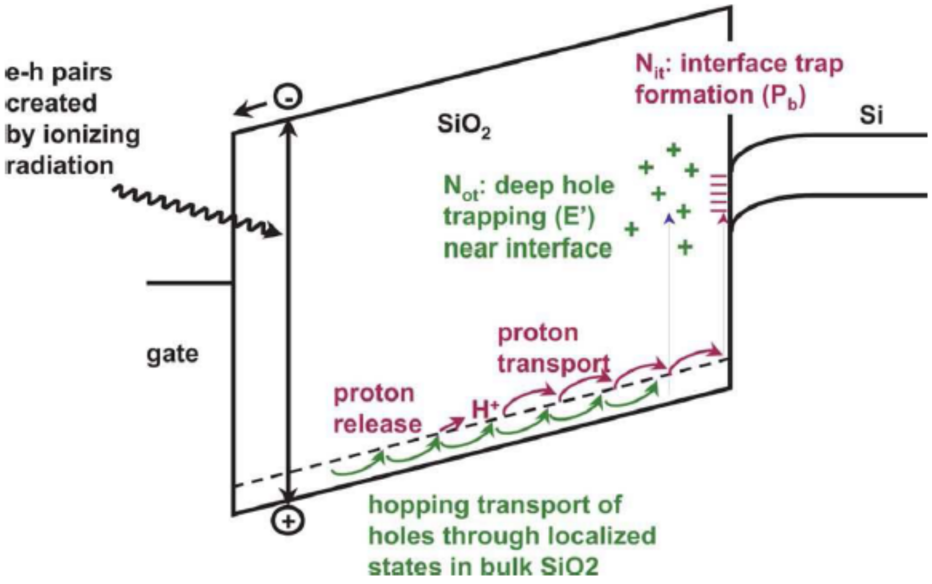
$$f_Y(E_{ox}) = \left(\frac{|E_{ox}|}{|E_{ox}| + E_1}\right)^m$$

For ^{60}Co: m=0.7 and E_1=0.55 MV/cm

Ionisation Damage Simulation in Oxides

Charge generation and evolution in a MOS structure

- Electron-hole pairs suffer an initial recombination (low electric field)
- Under high electric field electrons are immediately removed through the gate electrode
- Holes are also drift by the high electric field, but their mobility is low and take time to reach the Si/SiO_2 interface (hopping transport)
- Some holes are trapped in the deep levels at the region close to the Si/SiO_2 interface creating fixed charges and interface traps



Ionisation Damage Simulation in Oxides

Calculation of the trapping efficiency (f_{ot}) and fixed charges (N_{ot})

- ✓ Survivor holes (to the eventual initial recombination) travel through the oxide
- ✓ Holes can be trapped in their way to the oxide interface
- ✓ The efficiency of the trapping process (f_{ot}) is the ratio between trapped holes and surviving holes
  - The trapping efficiency depends on the electric field and on the oxide quality
  - If the oxide thickness is lower than 15 nm, holes are completely removed by tunneling effect (f_{ot}=0)
- ✓ Finally:
  - The fixed charges are described by $N_{ot} = g_0 \mathrm{TID} f_Y f_{ot}$

Initially generated

Ionisation Damage Simulation in Oxides

Calculation of the Interface traps

- ✓ **Traps in the Si/SiO_2 interface are related with the H^+ density in the oxide (depends on the growth process) and are identified as P_b**
  - **Incident particles release H^+ which are drift to the Si/SiO_2 interface where they create dangling bonds (traps)**

- ✓ **Finally:**
  - **The <u>interface traps</u> (N_{it}) are described by** $N_{it} = a_{it}[p]$

    (where a_{it} is the kinetic constant and p is the H^+ concentration)

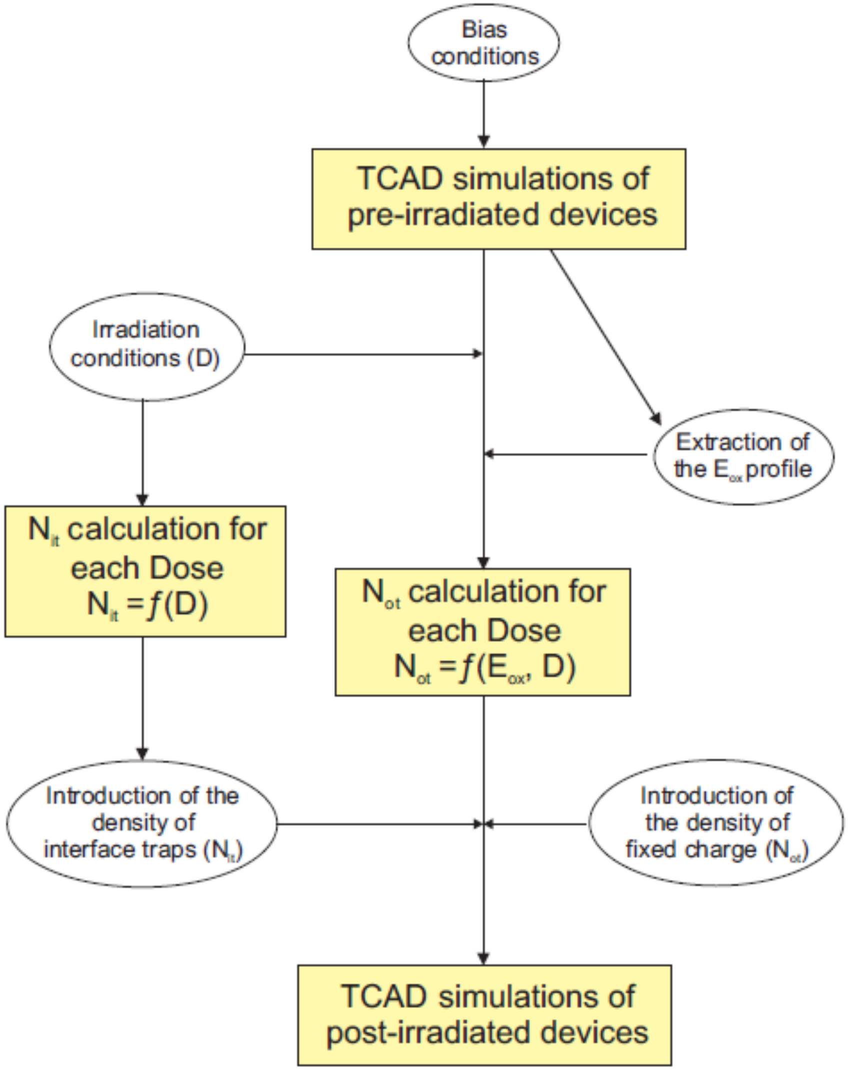
  - **N_{it} can also be expressed as a function of the ionising dose (TID) as**

$$N_{it} = a_{it}\mathrm{TID}^{b_{it}}$$

    (where b_{it} depends on the process technology and is determined by performing tests on capacitors. Typically b_{it}~1)

- ✓ **Only two energy levels are considered: E_V+0.3 eV (acceptor) and E_v+0.8 eV (donor)**

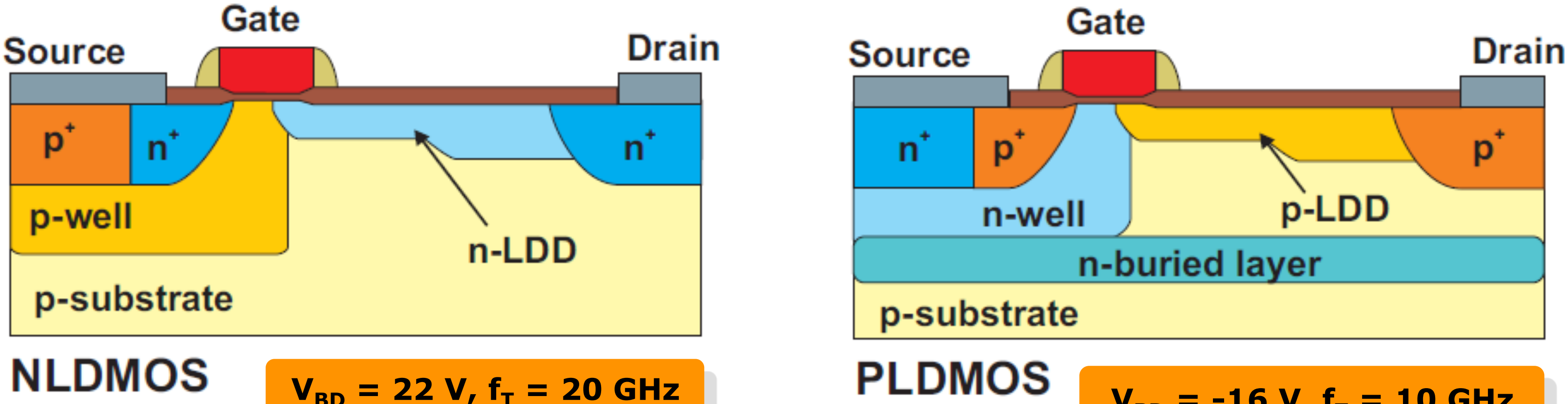
Ionisation Damage Simulation Procedure in Oxides



- ✓ **Fixed charge (N_{ot}) is introduced in Sentaurus by setting the <u>*charge* parameter</u>**
- ✓ **Traps in the Si/SiO_2 interface are set by:**
  - **The two energy levels (E_V+0.3 eV and E_V +0.8 eV)**
  - **The superficial trap concentration (N_{it})**
  - **Capture cross-section of electrons and holes**

Ionisation Damage in LDMOS Transistors

- LDMOS transistors will be used in DC-DC converters for the HL-LHC upgrade



V_{BD} = 22 V, f_T = 20 GHz

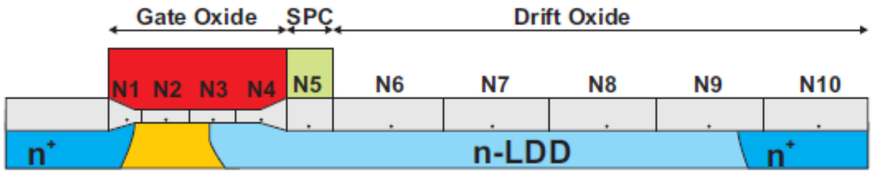
V_{BD} = -16 V, f_T = 10 GHz

- ✓ Transistors from IHP Microelectronics (DE) (0.25 µm SGB25V GOD SiGe BiCMOS)
- ✓ Submitted to neutron irradiation (0.5, 5 and 10 Mrad)

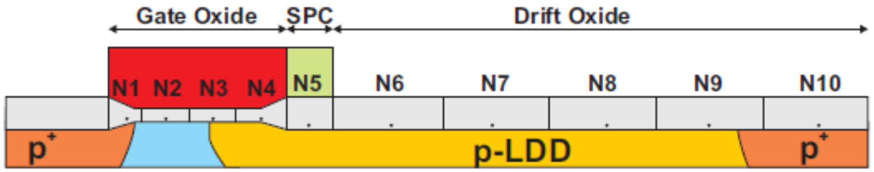
- First step: Technological and electrical simulation of basic cell and fitting with experimental data
- Second step: Electric field distribution (oxides and semiconductors)

Ionisation Damage in LDMOS Transistors

- **Third step: Definition of oxide blocks for fixed charge and interface traps**



NLDMOS



PLDMOS

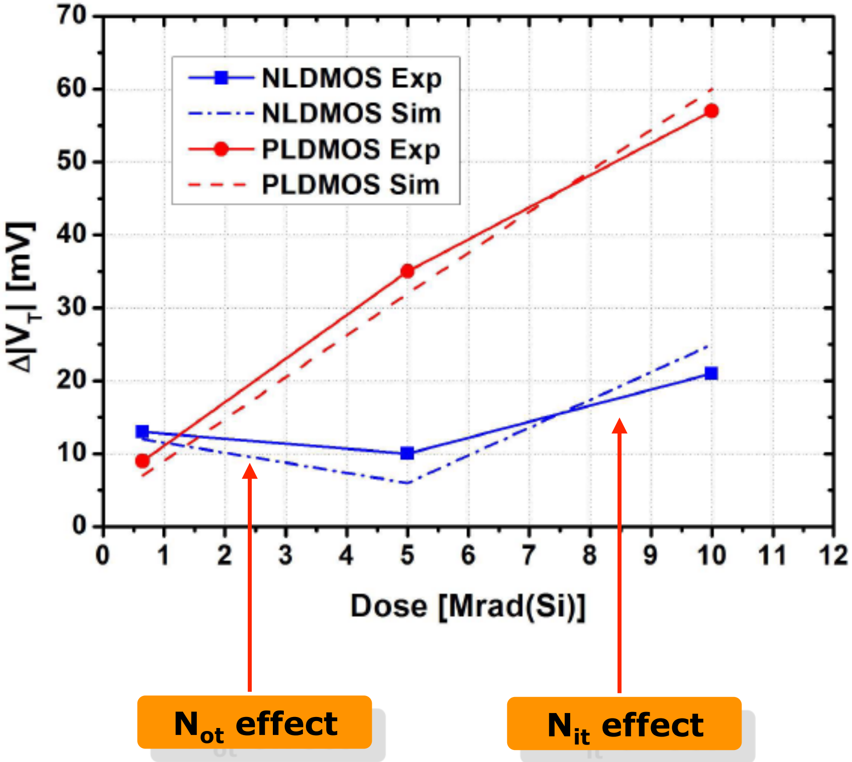
- **Fourth step: Calculation of recombination efficiency $f_y(E_{ox})$ and fixed charges N_{ot} (f_{ot} has to be tuned with available irradiation data)**
  - ✓ **N_{ot} values are introduced in Sentaurus as fixed charges in each oxide block**

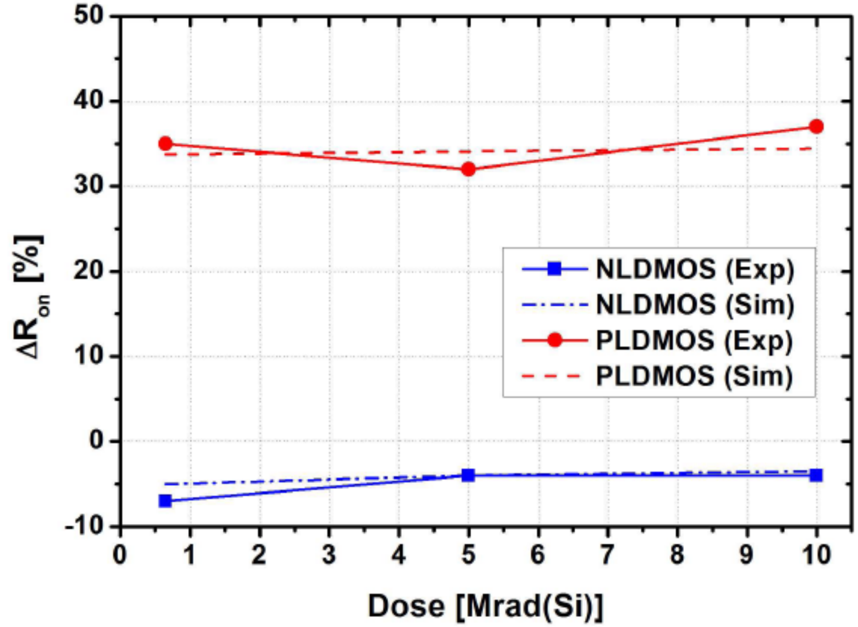
- **Fifth step: Calculation of interface traps N_{it} according to:** $N_{it} = a_{it}\text{TID}$ **(a_{it} has to be tuned with available irradiation data)**

Parámetro	NLDMOS	PLDMOS
f_{ot} [1] (gate oxide)	0.01	0.01
f_{ot} [1] (drift oxide)	0.2	0.2
a_{it} [cm^{-2}rad^{-1}]	$1{,}7 \times 10^4$	$2{,}5 \times 10^4$

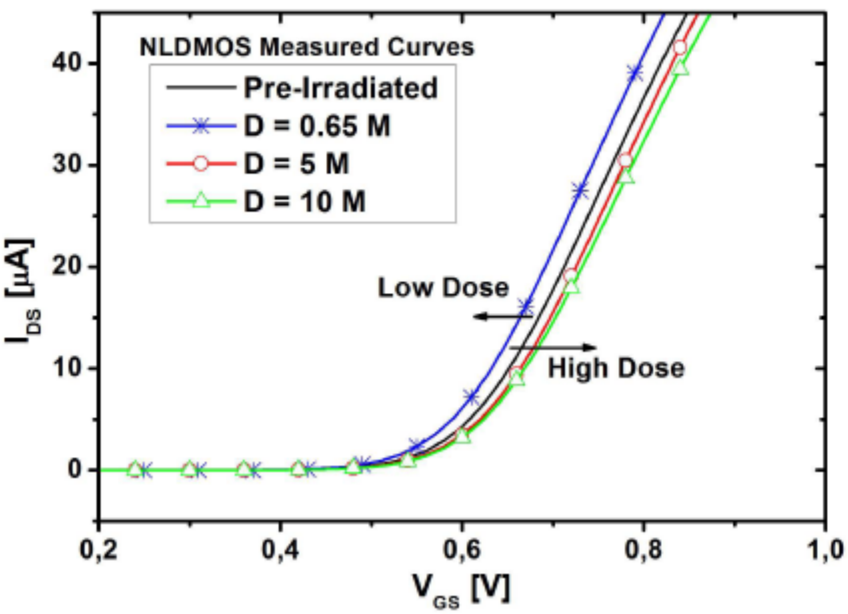
f_{ot} and a_{it} values according to available irradiation data

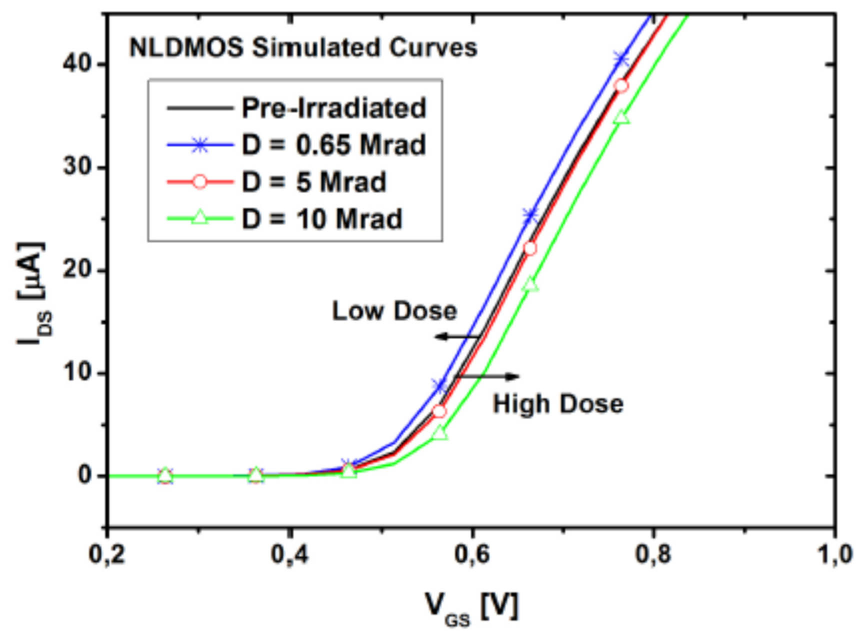
Ionisation Damage in LDMOS Transistors





Ionisation Damage in LDMOS Transistors



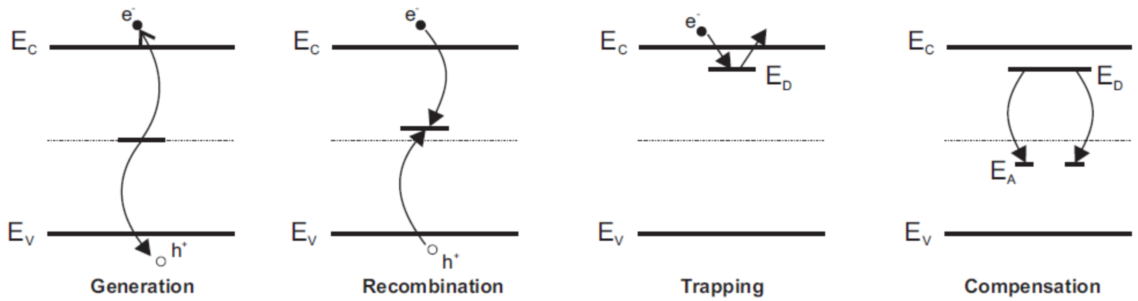


Accurate fitting between simulated and measured I_{DS} versus V_{DS} curves

Displacement Damage

Displacement Damage Simulation

- ❑ **Displacement damage in oxides is not relevant (only optical effects)**
- ❑ **Displacement damage in semiconductors creates energy levels in the gap**



	Si	Ge	GaAs		SiC	
			Ga	As	Si	C
E_{despl}[eV]	13-21	15-27.5	7-11		21.8 (C)	
$E_{despl-th}$ (e^-)[keV]	166-268	492-903	188-275	200-292	220	108
$E_{despl-th}$ (p^+) [keV]	0.1-1.16	0.28-0.51	0.12-0.19	0.13-0.21	0.15	0.65

E_{displ} = Minimum energy for atomic dislocation

$E_{displ-th}$ = Minimum energy for relevant displacement damage

- ✓ **Minority carrier lifetime reduction**
- ✓ **Reduction of carriers (n or p)**
- ✓ **Mobility degradation**

Displacement Damage Simulation Procedure

- **Sentaurus includes a model for Semiconductor Traps**
- **Typical traps in Float Zone substrates for Silicon detectors are perfectly determined**

Type	E(eV)	Trap	$\sigma_e(\mathrm{cm}^{-2})$	$\sigma_h(\mathrm{cm}^{-2})$	$\eta(\mathrm{cm}^{-1})$
Aceptor	E_C-0.42	VV	9.5×10^{-15}	9.5×10^{-14}	1.613
Aceptor	E_C-0.46	VVV	5.0×10^{-15}	5.0×10^{-14}	0.9
Donador	E_V+0.36	CiOi	3.23×10^{-13}	3.23×10^{-14}	0.9

University of Peruggia model, including Pennicard corrections

- ✓ **The total trap concentration (N_t) is the added contribution of filled (n_t) and empty (p_t)**

$$N_t = n_t + p_t \qquad N_t = \eta \cdot \Phi$$

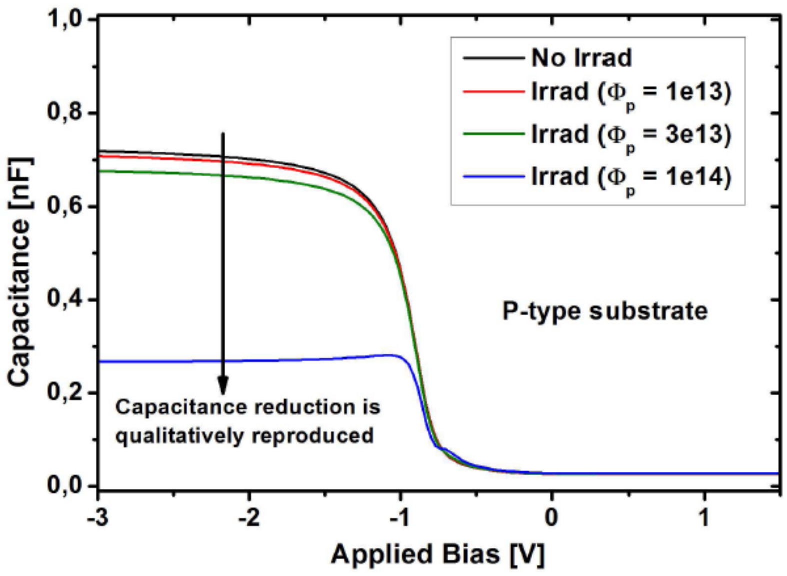
(where η is the introduction rate, determined by DLTS measures)

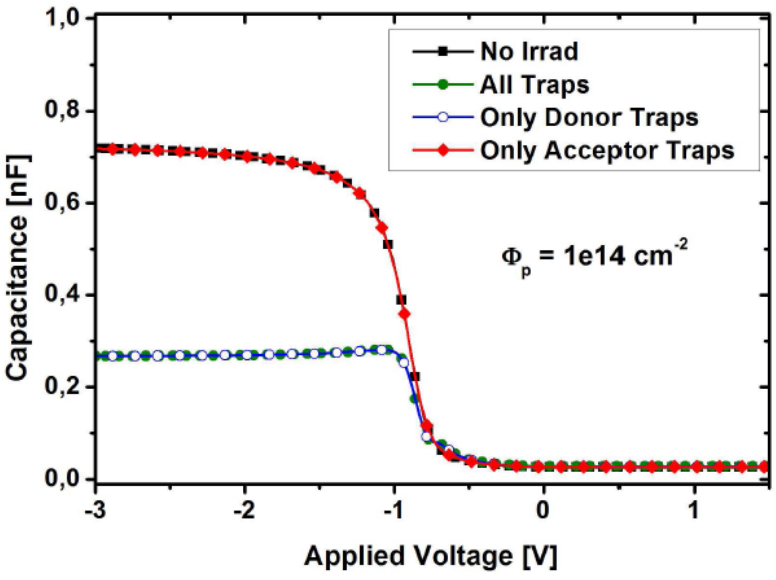
- ✓ **The effective doping concentration in the P-type substrate is finally given by:**

$$N_{eff} = N_D - N_A + \sum_{donadores} p_t - \sum_{aceptores} n_t$$

Displacement Damage in MOS Capacitors

- **Simulation of displacement damage in MOS capacitors under 24 GeV proton irradiation conditions**
  - ✓ **The introduction rate (η) is calculated for the equivalent 1 MeV neutrons. Hence, the fluence has to be corrected according to the 24 GeV protons**





Boron concentration = 8e14 cm^{-3}
Oxide thickness = 10 nm

Case Study: Design of Low Gain Avalanche Photodetectors

Silicon Detectors with Internal Gain and Proportional Response

Tracking Detectors

- **PiN Diodes**
  - ✓ Proportional response
  - ✓ Good efficiency
  - ✓ Good spectral range
  - ✓ Segmentation is technologically available (strip and pixel detectors).

After Irradiation

- ✗ Worse signal to noise ratio (lower quality signal + noise increment)
- ✗ Increment of the power consumption (leakage current increase)
- ✗ Ionisation damage (relevant on n-on-p structures)

Internal Gain →

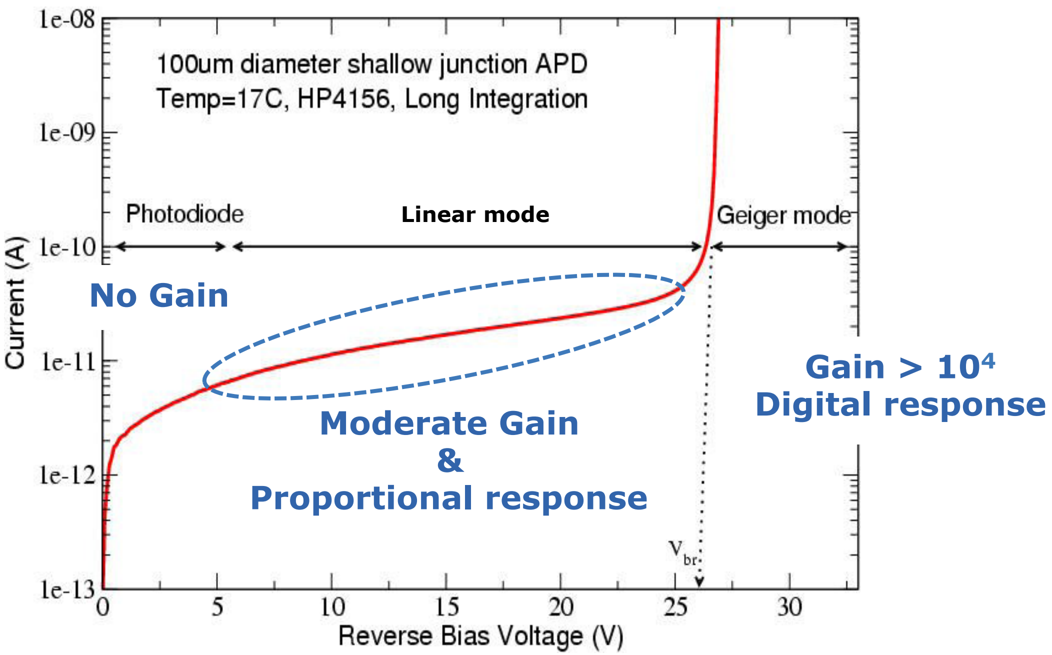
- **Low Gain Avalanche Detectors (LGAD)**
  - ✓ Proportional response (linear mode operation)
  - ✓ Good efficiency
  - ✓ Good spectral range
  - ✓ Better sensibility (Gain)
  - ✓ Thin detector integration with the same signal and higher collection efficiency
  - ✓ Better signal/noise ratio

After Irradiation

- ✓ Similar pre & post irradiation signal (higher quality signal + lower noise increase)
- ✓ Power consumption slightly increased
- ✗ Ionisation damage in oxides (relevant on n-on-p structures)

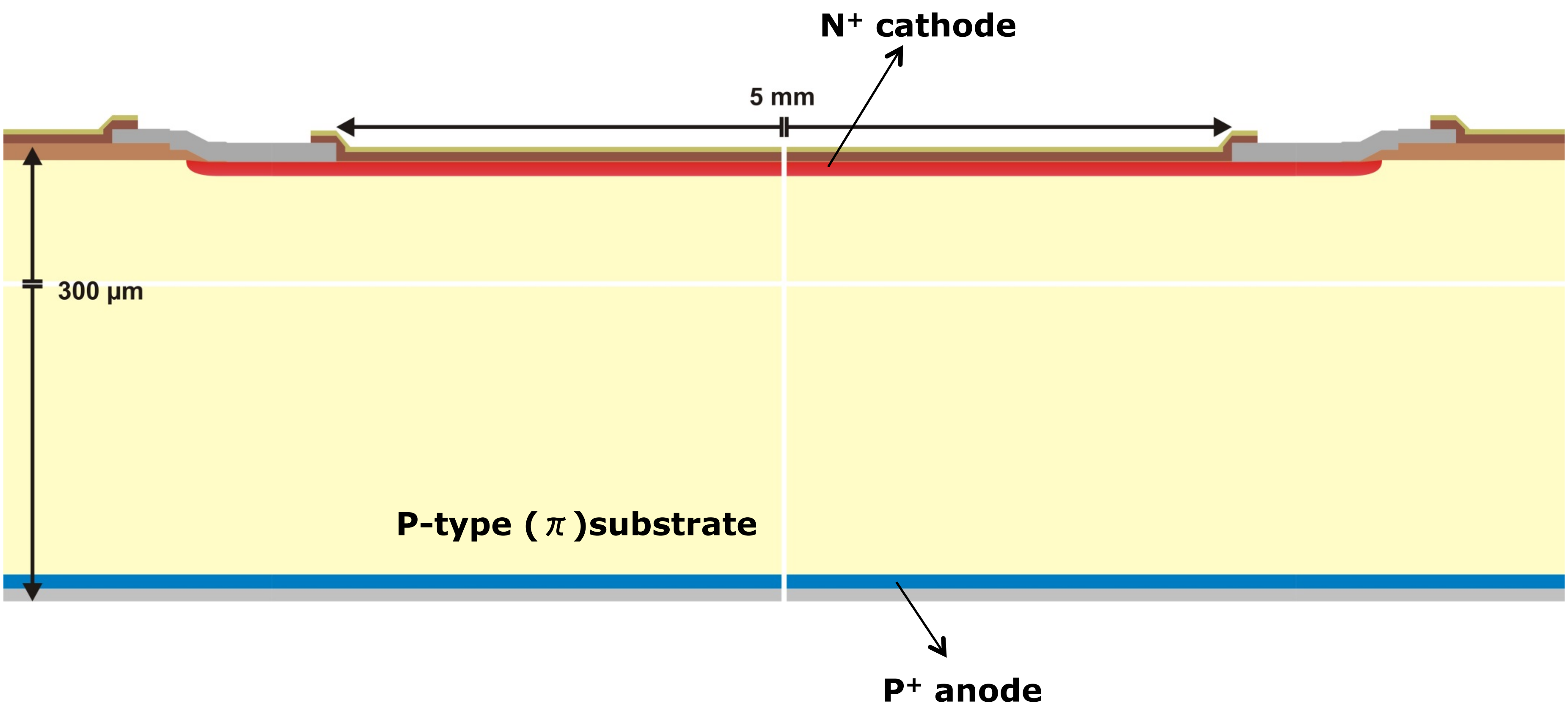
Linear Mode Operation. Gain Definition

- **Diodes with multiplication can operate in Linear or Geiger mode**
  - ✓ **Linear mode: Moderate gain: Proportional response to the deposited energy**
  - ✓ **Geiger mode: Very high gain: Digital response (detection or not detection)**



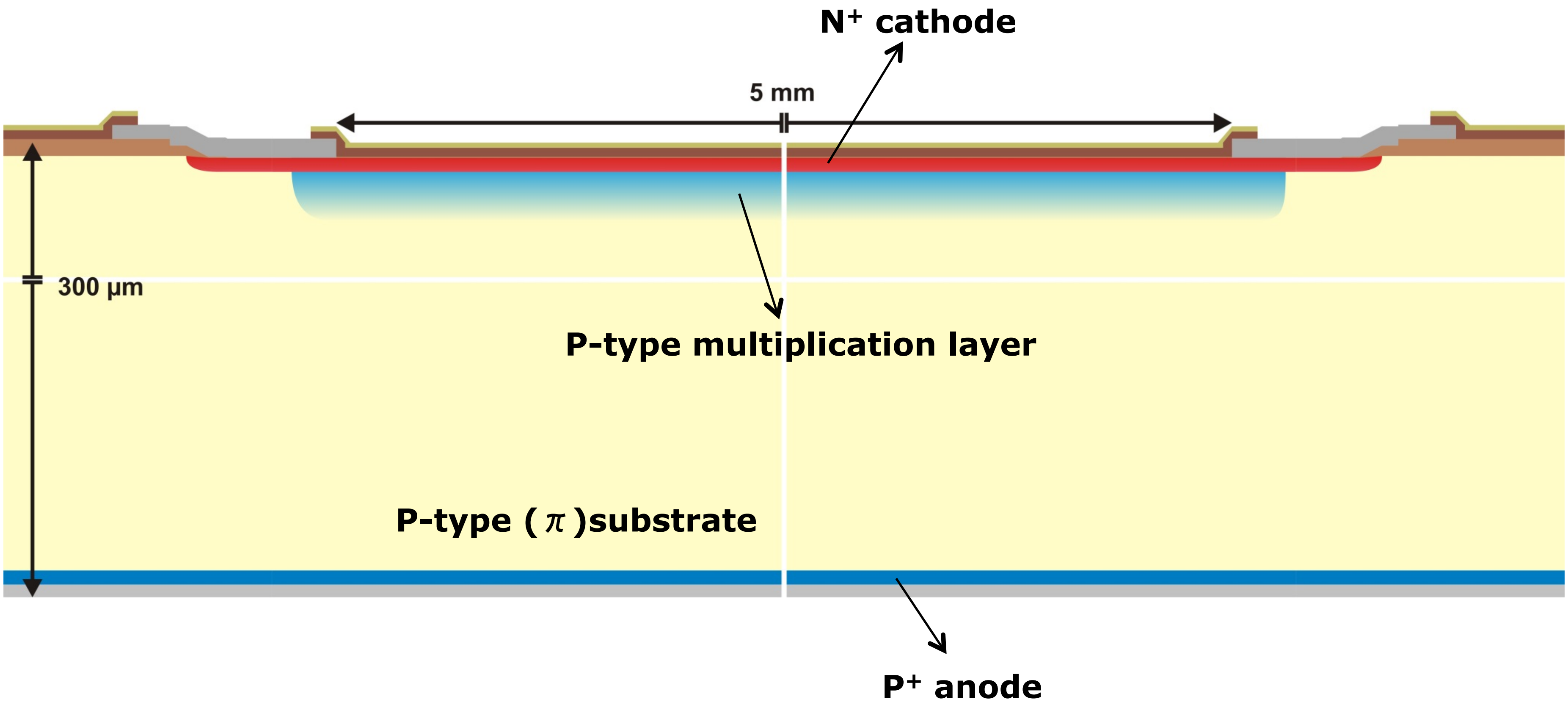
[1] A.G. Stewart et al. in Proc. of SPIE, Vol. 6119, 2006

PiN Diode (No Gain)



- **Abrupt N^+P junction with trapezoidal electric field profile (linearly decreasing in the P substrate)**
  - ✓ **Electrons are accelerated towards the N^+ region until they reach the saturation velocity**
  - ✓ **Since the electric field is much lower than E_{crit}, electrons can not generate new carriers (no impact ionisation and no gain)**

Pad Diode with internal Gain



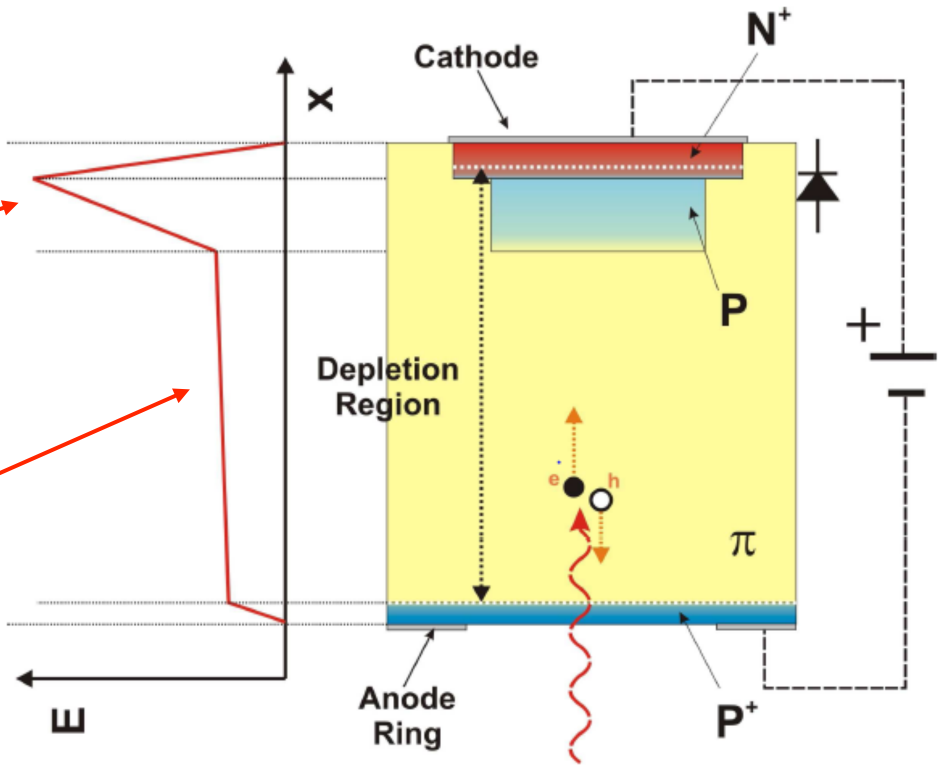
- **Gaussian N^+P junction where the P-multiplication layer becomes completely depleted at a very low reverse voltage**
  - ✓ **Electrons are accelerated towards the N^+ region until they reach the saturation velocity**
  - ✓ **The electric field in the P layer is close to the E_{crit}, value (impact ionisation and gain)**

Conditions for Gain

- **Impact ionisation requires a minimum electric field of 1e5 V/cm in the P layer**
  - ✓ **Full depletion of the P-type substrate is needed to avoid recombination**
  - ✓ **The E_{crit} value (~3e5 V/cm) can not be reached in the N^+P junction (reverse breakdown)**

Impact ionisation region

Electrons traveling at their saturation velocity (good for signal uniformity)



Gain Definition and Usage

- **The Gain can be defined in two equivalent ways and is identical whatever the incident particle is**

$$\mathrm{Gain}|_{Curr} \equiv \frac{\text{corriente multiplicada}}{\text{corriente no multiplicada}}$$

$$\mathrm{Gain}|_{Char} \equiv \frac{\text{carga recolectada}}{\text{carga depositada}}$$

If no impact ionisation is contemplated (Equivalent PiN diode.)

- ✓ **A known radiation source has to be used to calibrate the gain**
  - **Collected charge is determined by integrating the current waveform**
  - **The total number of generated electron-hole pairs in Silicon is determined by the type of radiation source**

- **Once the Gain is calibrated, the detector can be used to identify the incident radiation by simply measuring the collected charge**

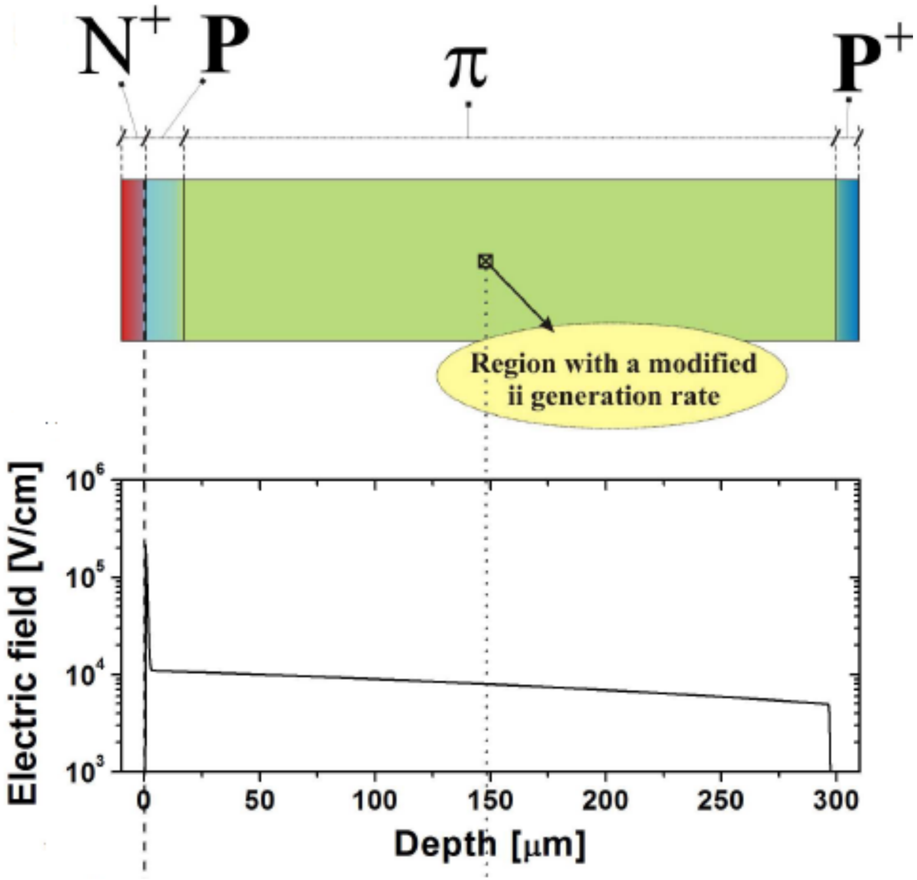
Gain Simulation

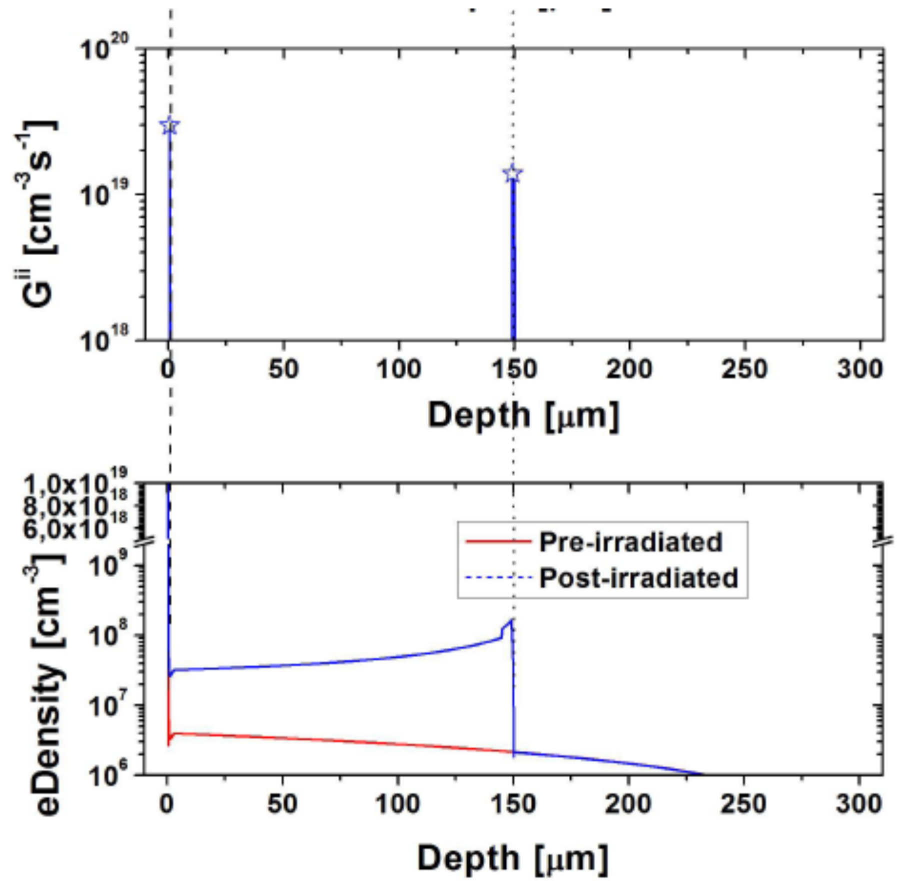
- **Gain simulation considering generated and collected charge**
  - ✓ **An initial charge distribution has to be introduced in the Sentaurus Heavy Ion model**
  - ✓ **The evolution of the generated charge is calculated by transient simulations**
  - ✗ **We have not been able to observe any transient current increase**
    - **Impact ionisation is an statistic concept while transient simulation considers the evolution of each single electron…**

- **Gain simulation considering multiplied and non-multiplied current (alternative method)**
  - ✓ **Ionisation coefficients are modified in a very small volume of the P-type substrate (3 orders of magnitude greater) to create a know number of electron-hole pairs (3000)**
  - ✓ **Quasi static simulations are performed with and without the generated charge**
    - **The PiN diode is simulated to determine current increase due to the generated charge (no impact ionisation is present)**
    - **Then, the LGAD counterpart is simulated with and without charge (impact ionisation is present)**
    - **Finally, the simulated Gain corresponds to the ratio between PiN and LGAD currents when charge is generated**

$$M(V) = \frac{I_{APD}|_{Charge}(V) - I_{APD}|_{NoCharge}(V)}{I_{PiN}|_{Charge}(V) - I_{PiN}|_{NoCharge}(V)}$$

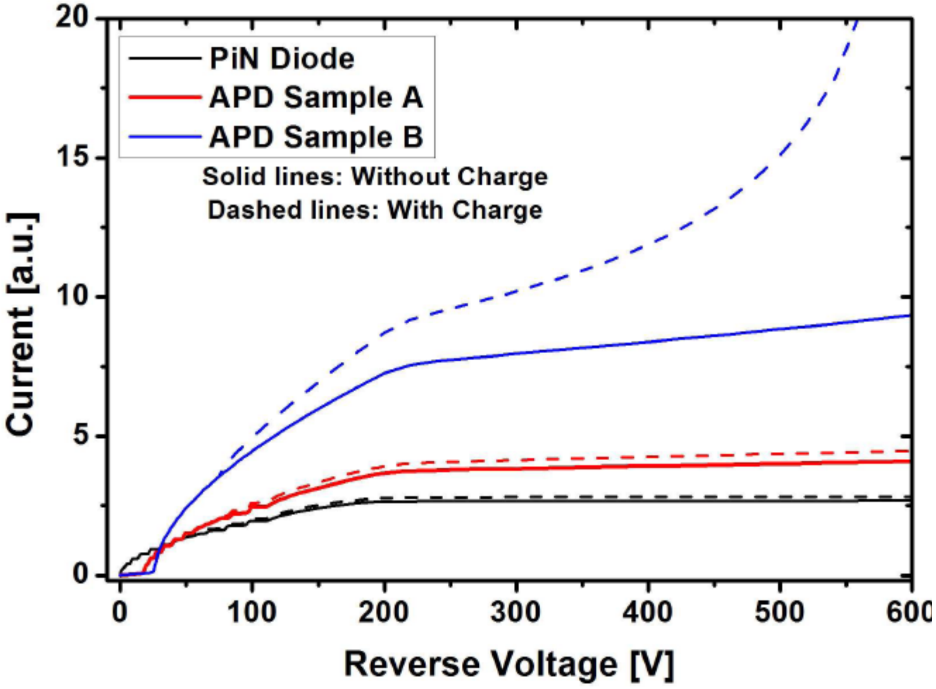
Gain Simulation

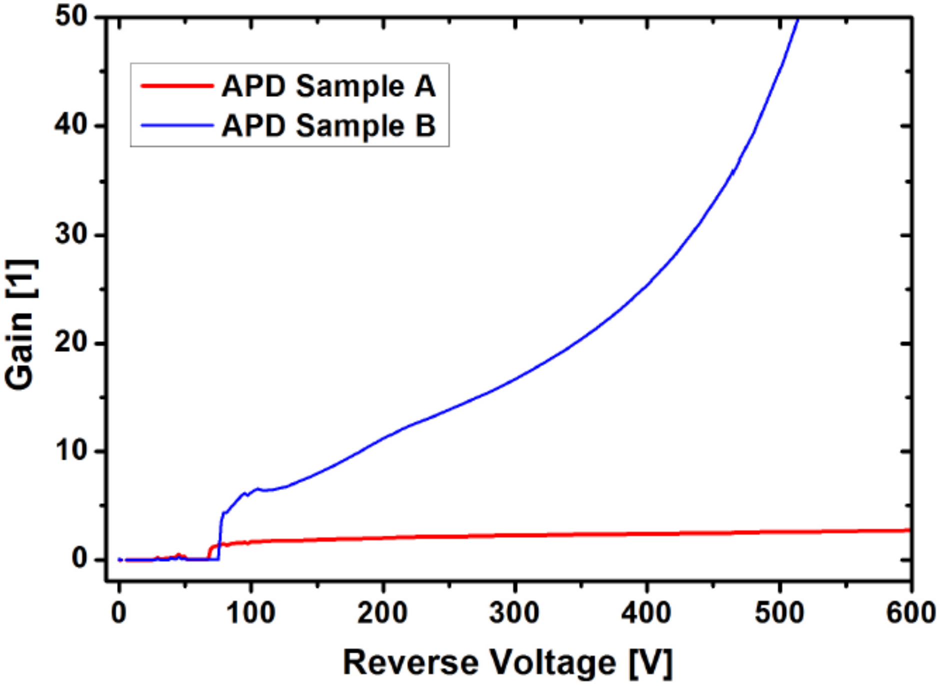




Gain Simulation

- ✓ **Local charge generation equivalent to the absorption of a 30 KeV X-ray**
- ✓ **The doping of the sample B P-multiplication layer is higher than the A sample (high Gain)**



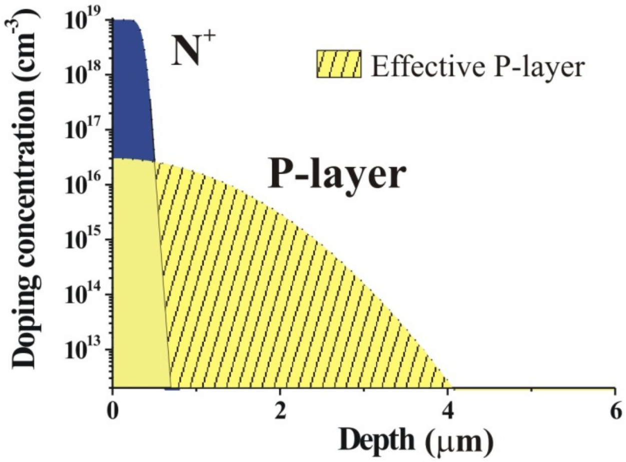


Design of the P-Multiplication Region

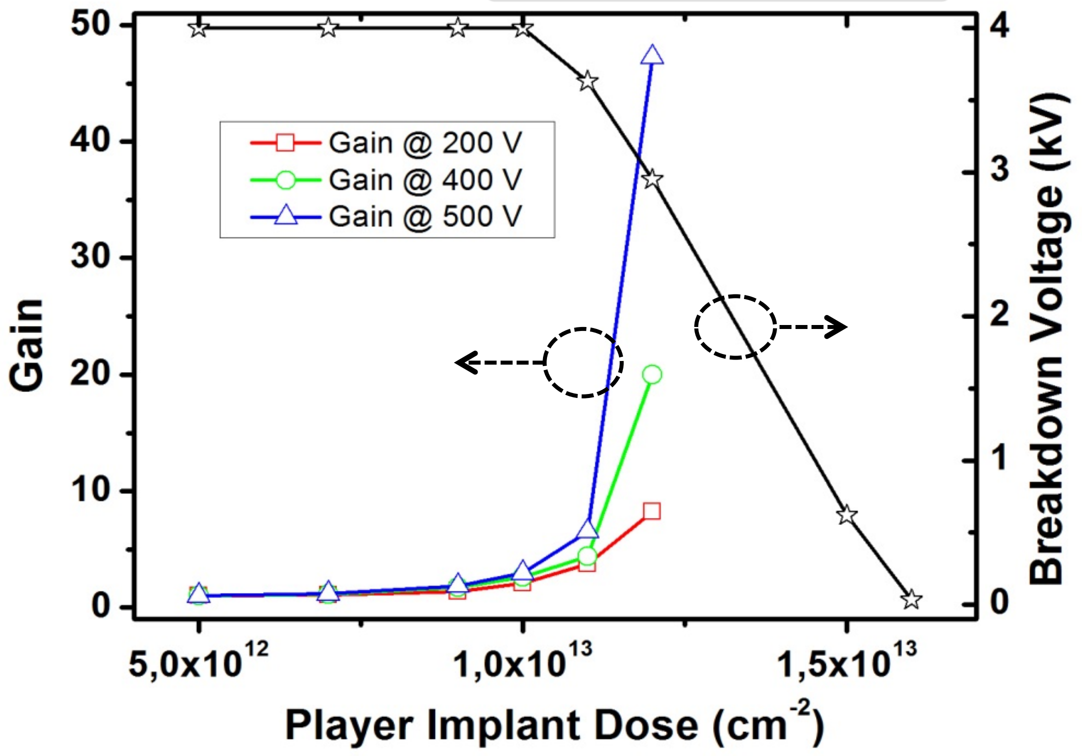
- ❑ **Doping profile of the P-multiplication layer is critical**

Gain/V_{BD} trade-off

✓ If implant dose increases:
- Gain increases
- V_{BD} decreases



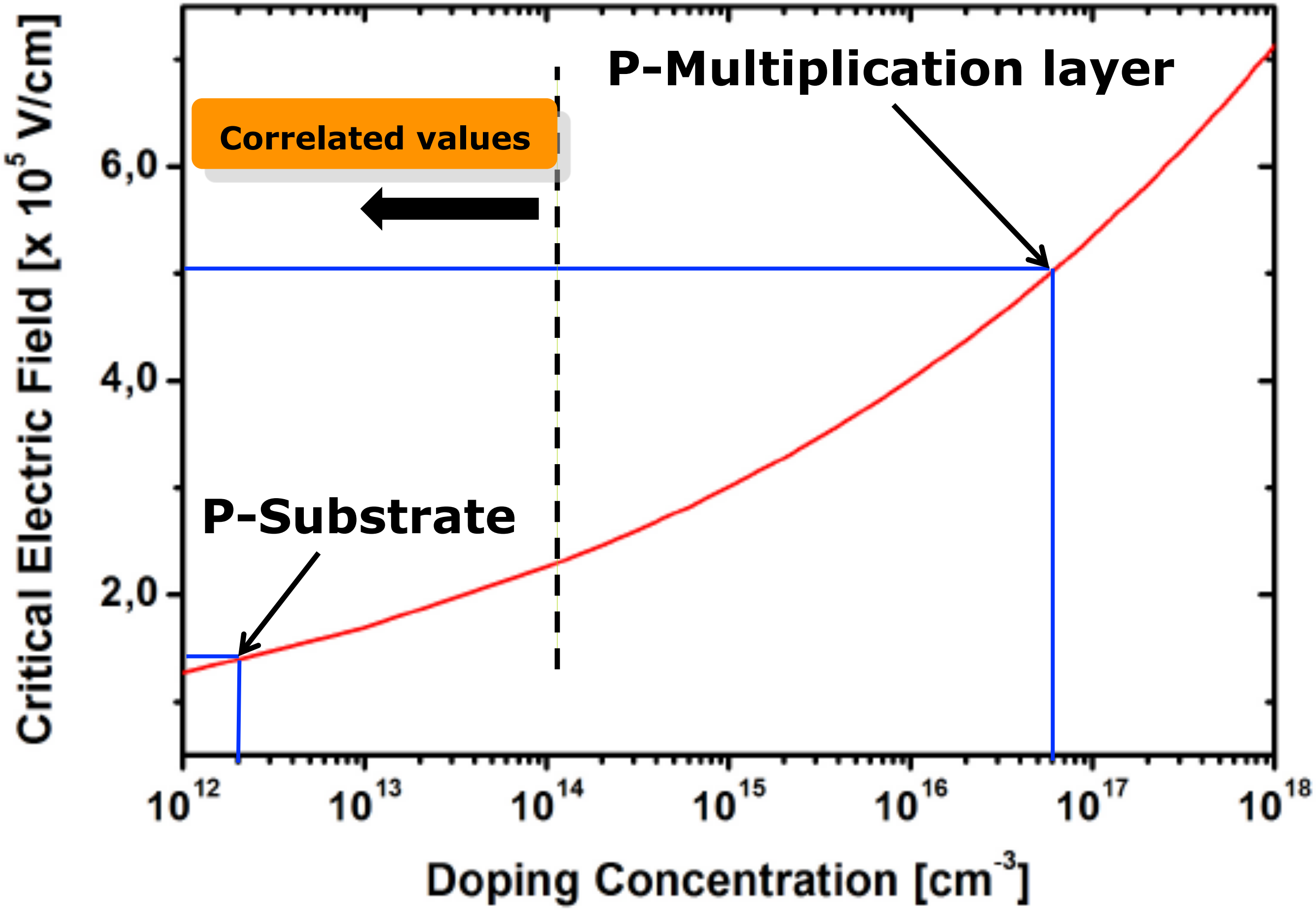
1D Simulation @ Pad Centre



Small modifications in the Boron implant dose (~ 2×10^{12} cm^{-2}) induce great changes in Gain and V_{BD}

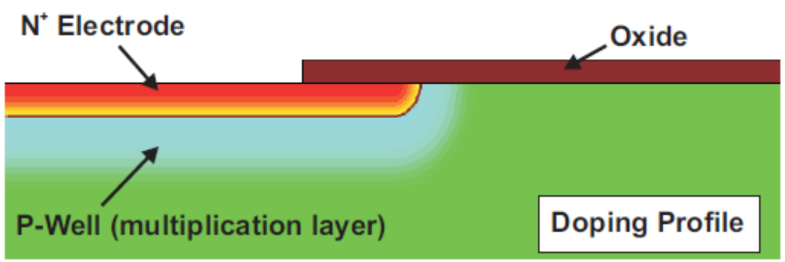
Design of the Edge Termination

- **The optimisation of the edge termination is ruled by the electric field at the multiplication layer (not by the maximum voltage capability, as in the case of power devices)**

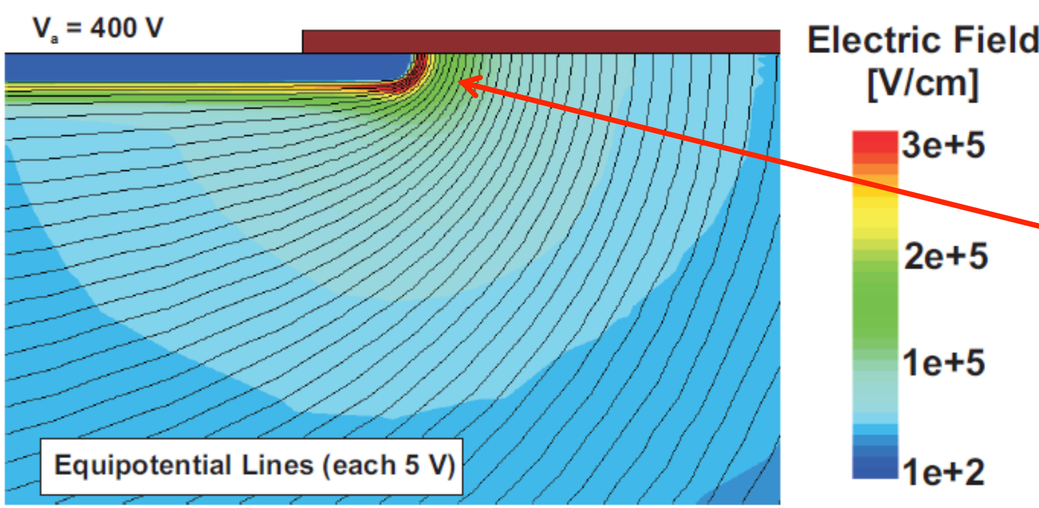


Edge Termination: Why is needed?

- **The N^+ shallow contact and the P-multiplication layers have to be locally created with a lithography mask**
  - ✓ **The electric field at the curvature of the N^+/P junction is much higher than that of the plane junction (where Gain is needed)**
  - ✓ **Avalanche at the N^+/P curvature at a very low reverse voltage (premature breakdown)**

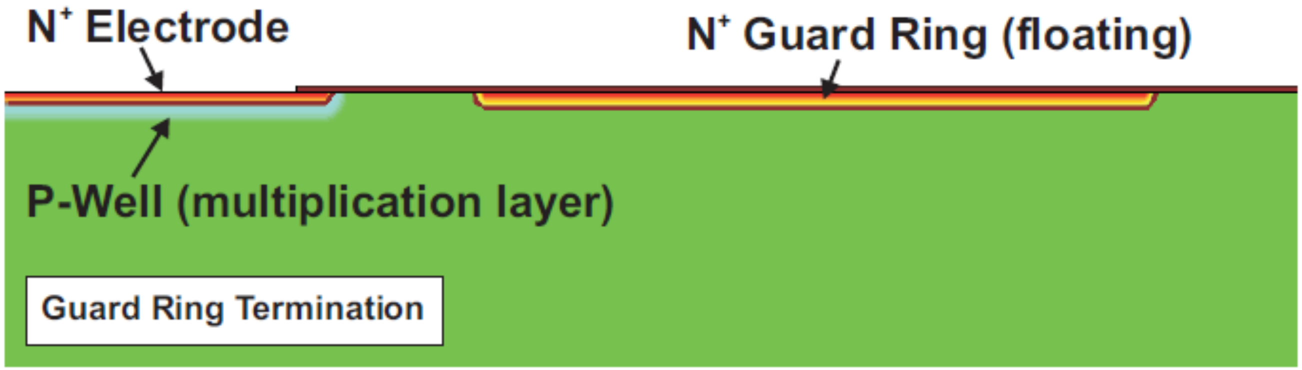


Shallow N^+ and P-multiplication layers self aligned

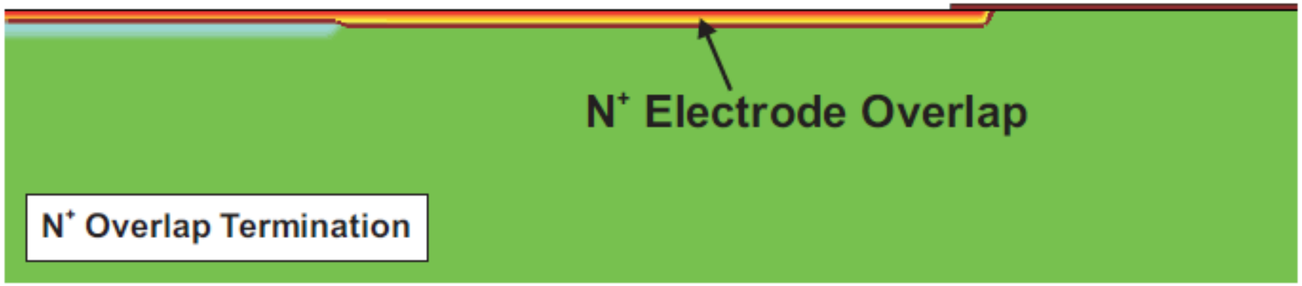


High electric field peak at the curvature

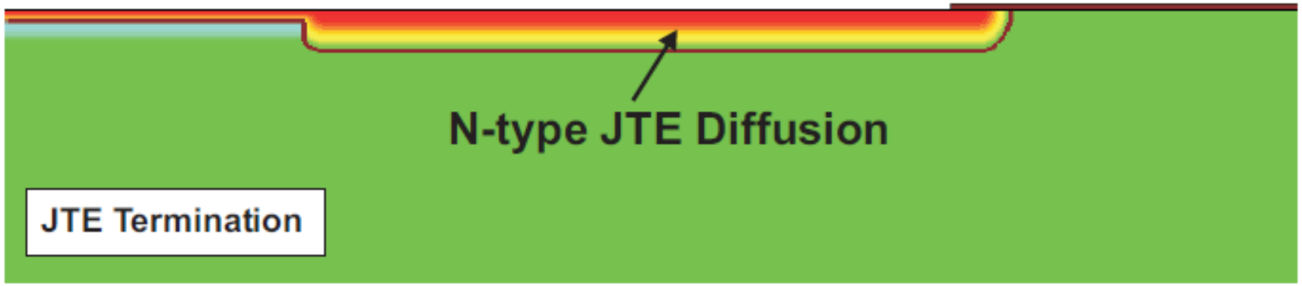
Compatible Edge Termination Techniques



Maximum efficiency of 80%



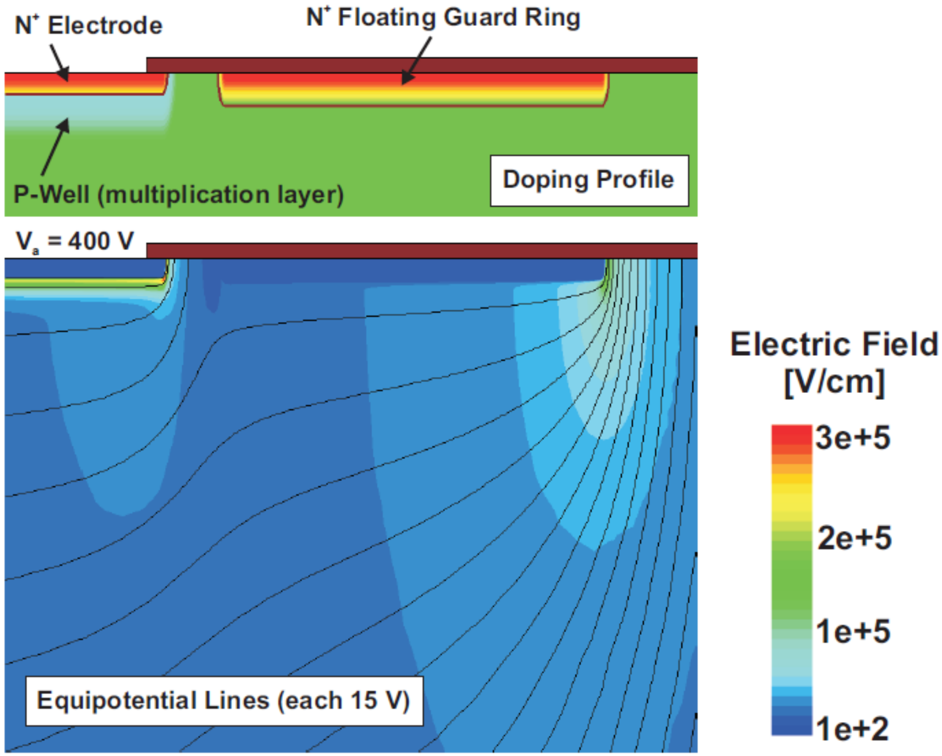
Maximum efficiency of 60%

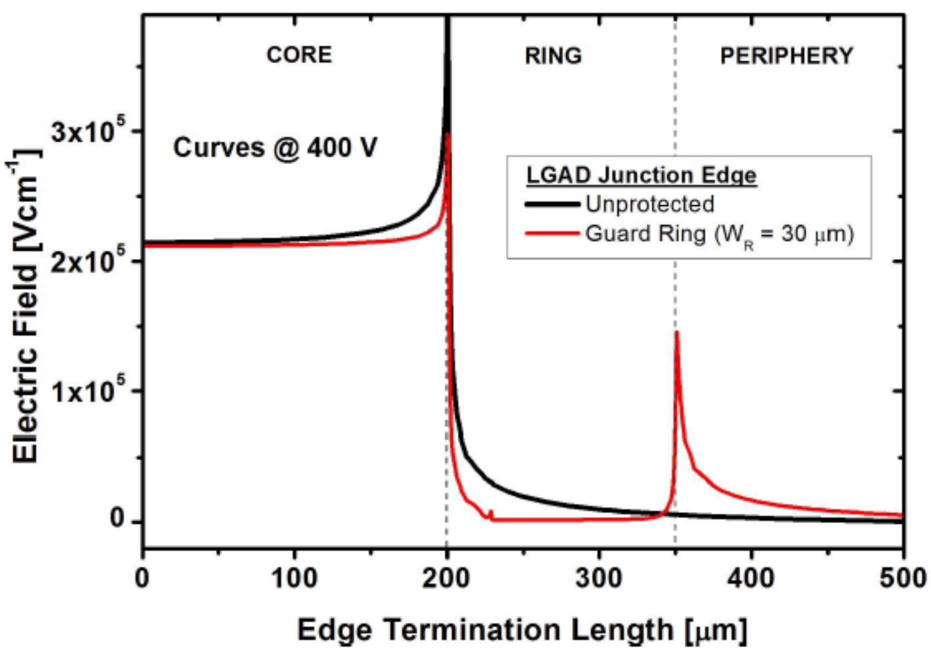


Maximum efficiency of 90%

Edge Termination with Guard Ring

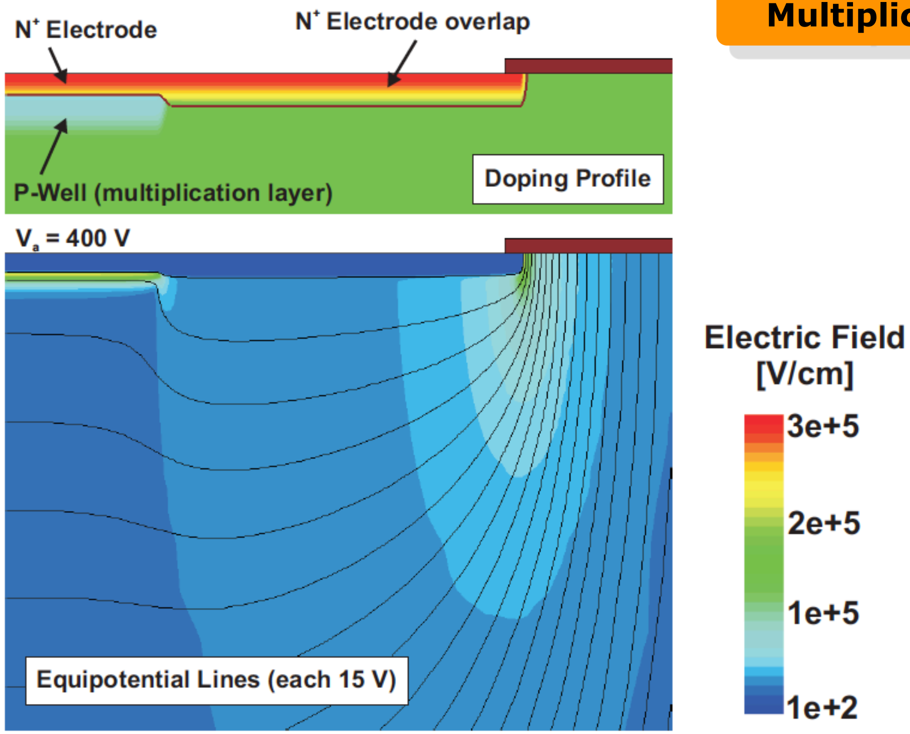
- **The N^+ shallow diffusion is used to implement a floating guard ring**
  - ✓ **The lateral electric field distribution is smoothed leading to two peaks (main junction and floating guard ring)**
  - ✓ **The electric field peak and the risk of avalanche breakdown at the curvature of the main junction is reduced. Optimisation of the guard ring location is needed**

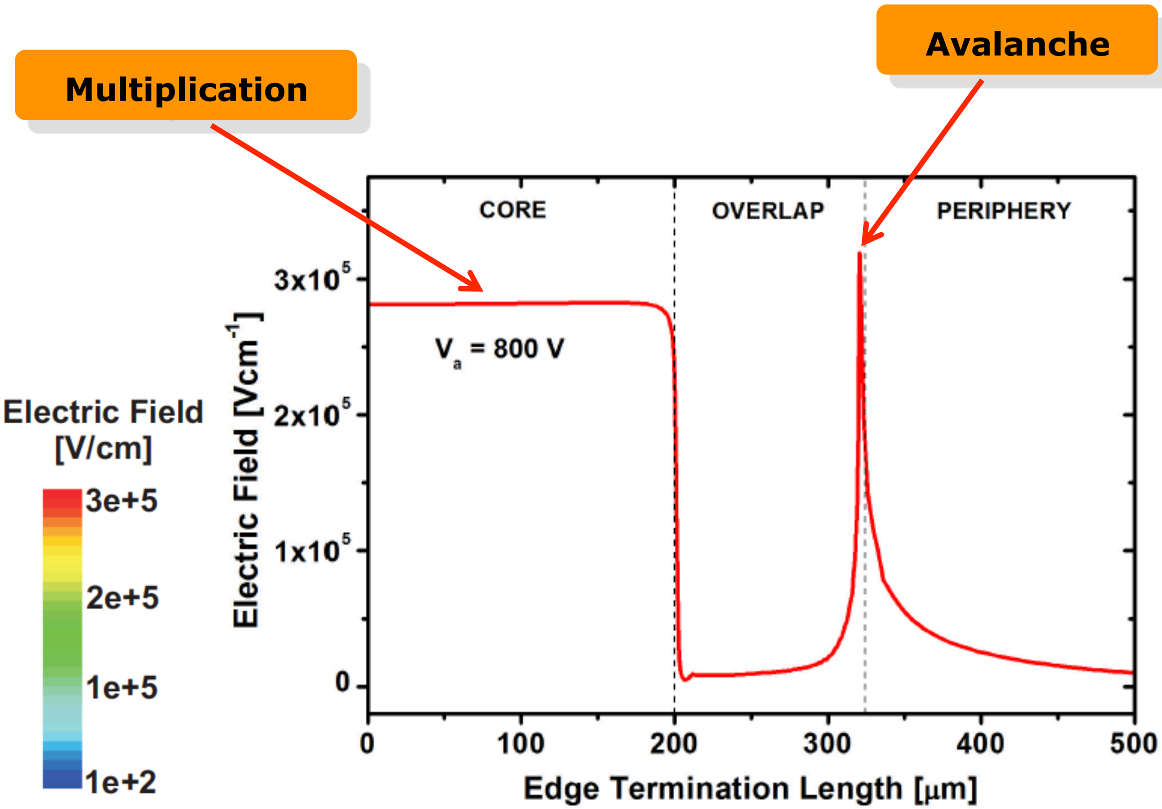




Edge Termination with N^+ Extension

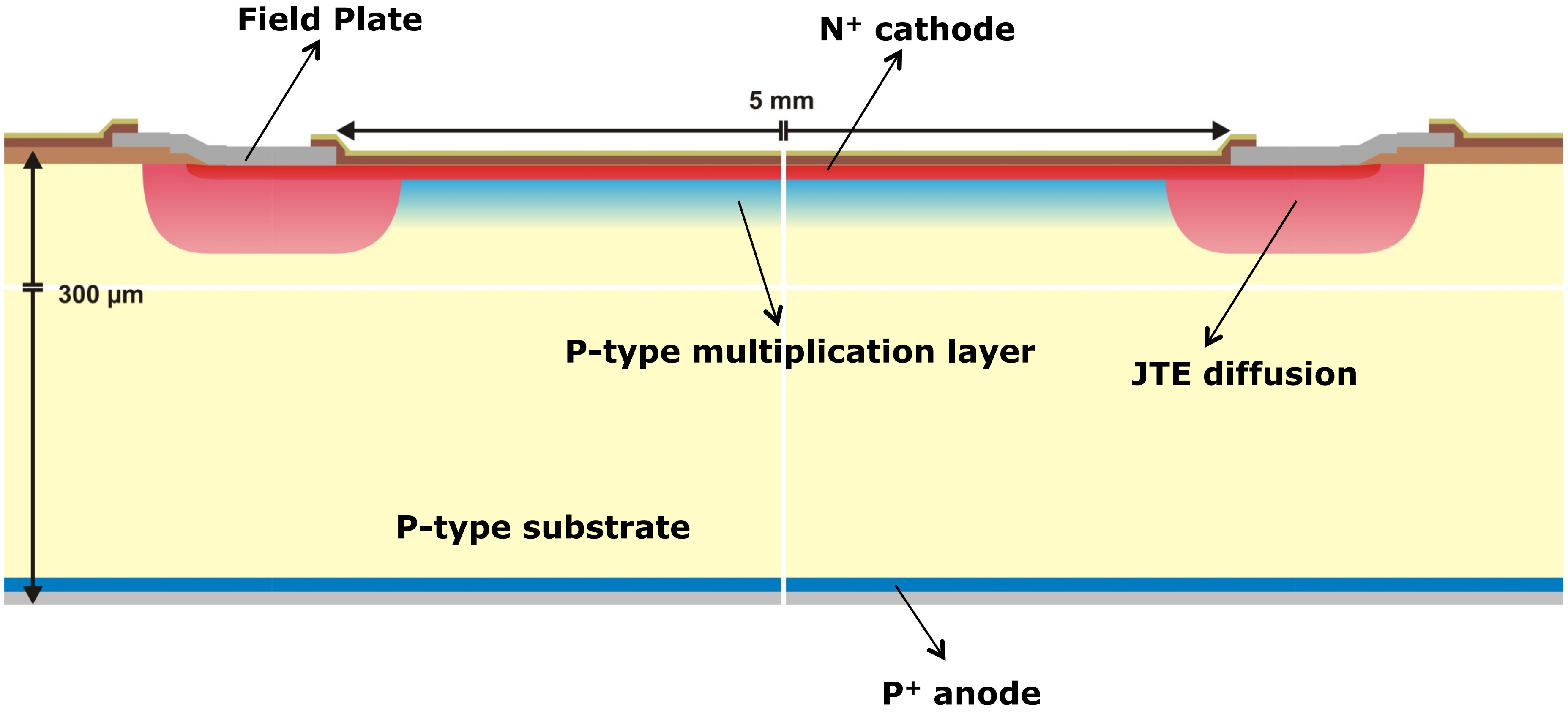
- **The N^+ shallow diffusion is used to extend the N^+ beyond the edge of the multiplication layer**
  - ✓ **Phosphorous diffuses more in the very low doped substrate (higher curvature radius and voltage capability)**
  - ✓ **The electric field rapidly increases at the plain junction (multiplication)**
  - ✓ **At high reverse voltage the electric peak at the extended N^+ diffusion leads to avalanche breakdown**





Edge Termination with Junction Termination Extension

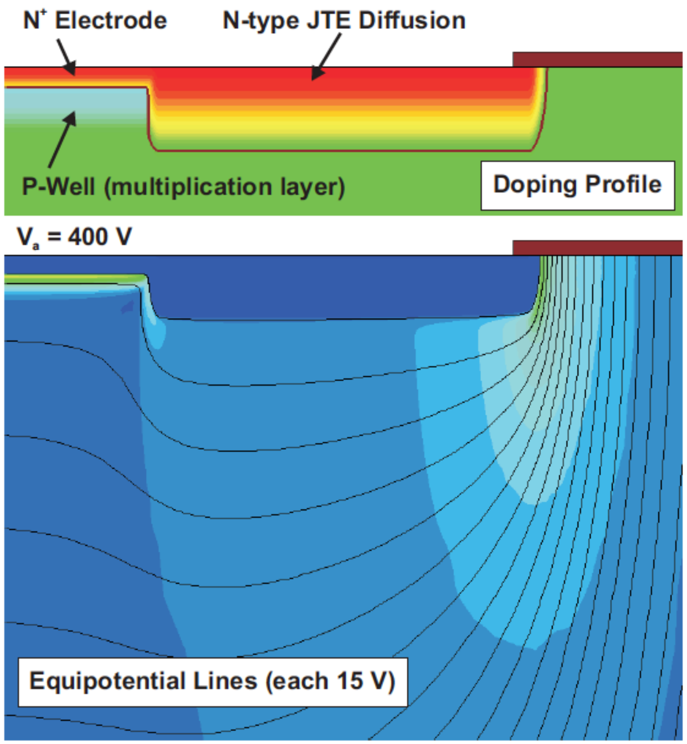
- **Junction Termination Extension (JTE) with an additional deep N diffusion**
  - ✓ **Additional photolithographic step with high energy Phosphorous implantation**
  - ✓ **A field plate can also be implemented for additional electric field smoothing**

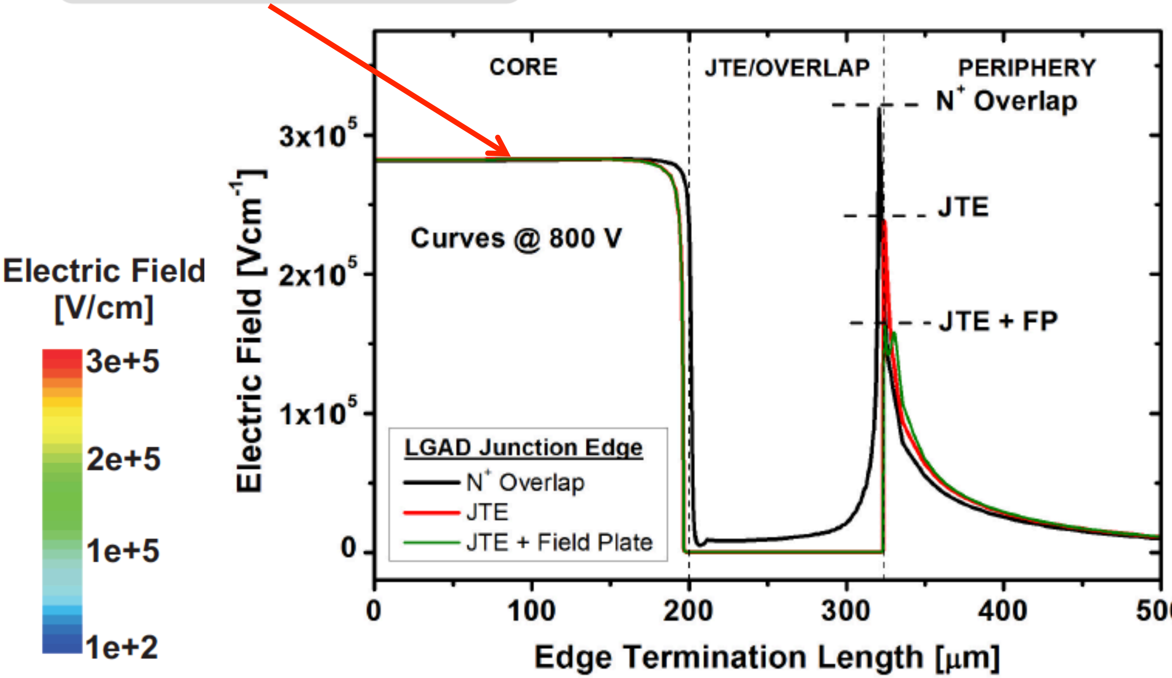


Edge Termination with Junction Termination Extension

- ✓ **Deep N diffusion with high curvature radius (long anneal process)**
- ✓ **Reduced electric field peak at the JTE diffusion**
- ✓ **Highest electric field at the plane junction (gain control) $V_{BD\ plane} < V_{BD\ JTE}$ (Gain control)**

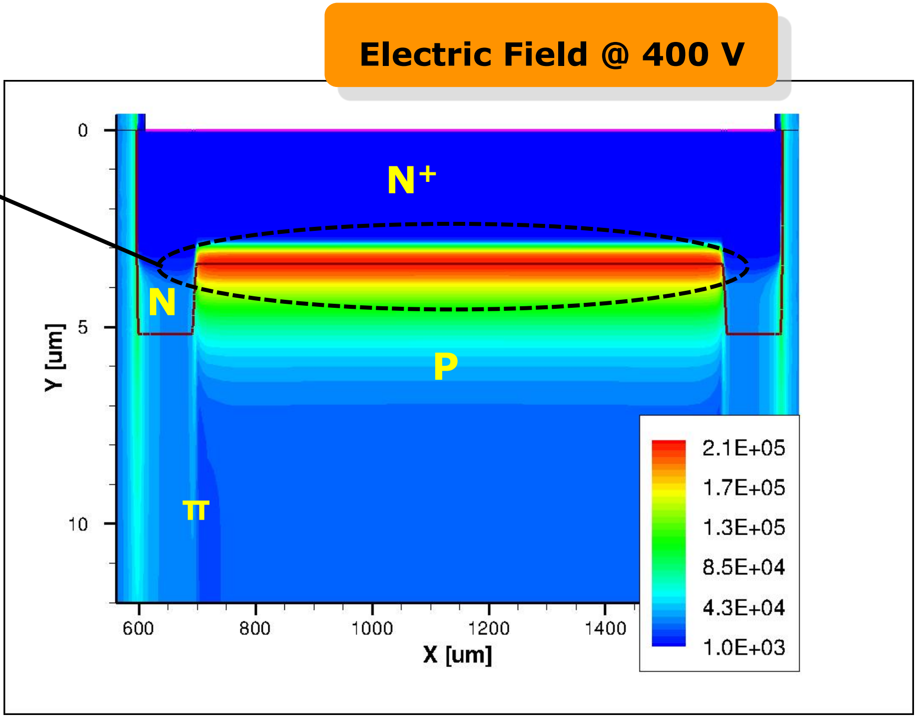
Multiplication and avalanche control





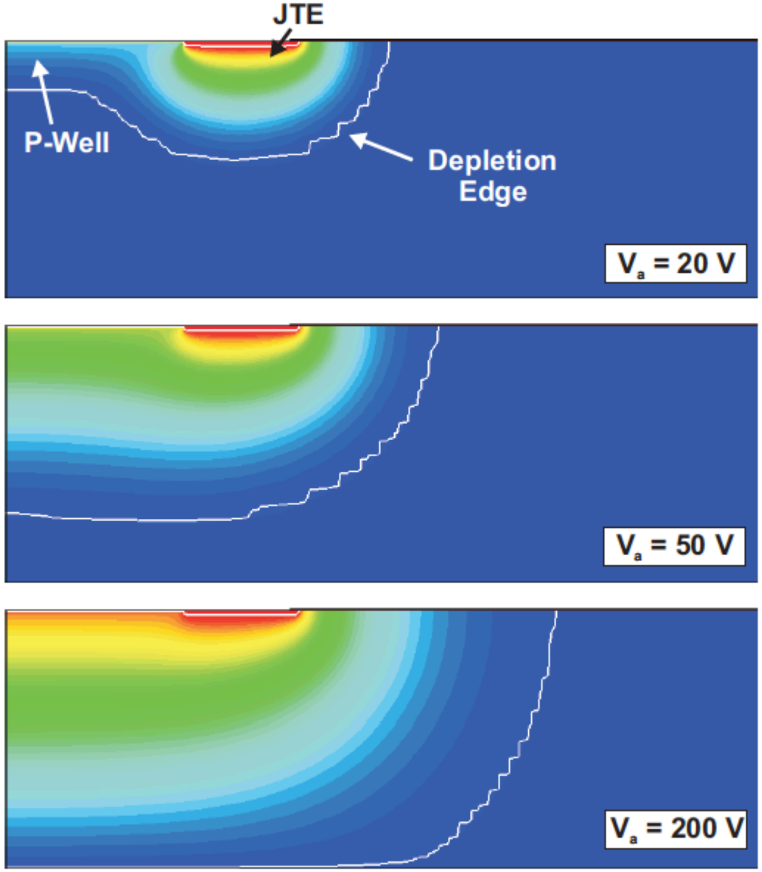
Edge Termination with Junction Termination Extension

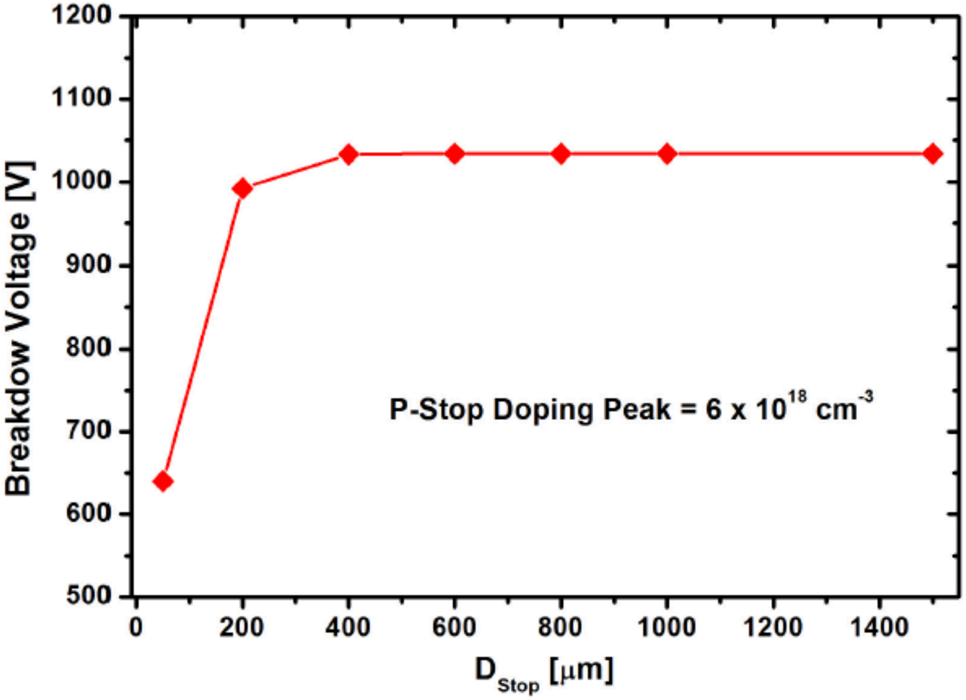
Planar and uniform electric field distribution, high enough to activate charge multiplication



Design of the Device Periphery

- ✓ **Full depletion below 100 V reverse bias**
- ✓ **Fast lateral depletion of the low doped substrate (A deep P⁺ diffusion –P stop- is needed in the die periphery to avoid the depletion region reaching the unprotected edge**

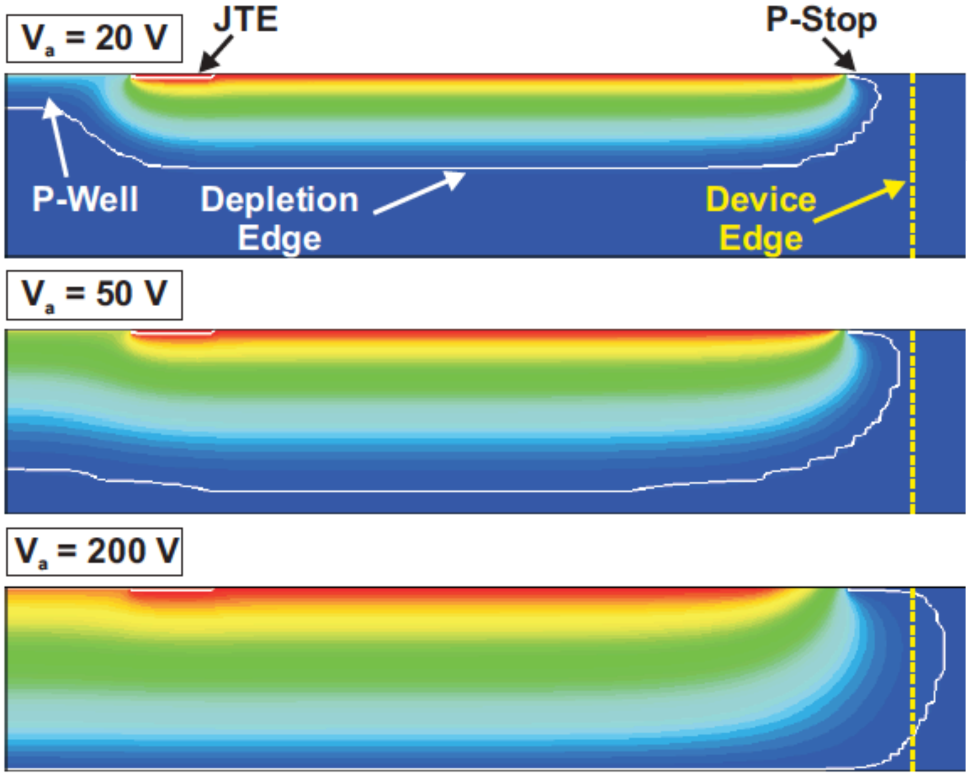


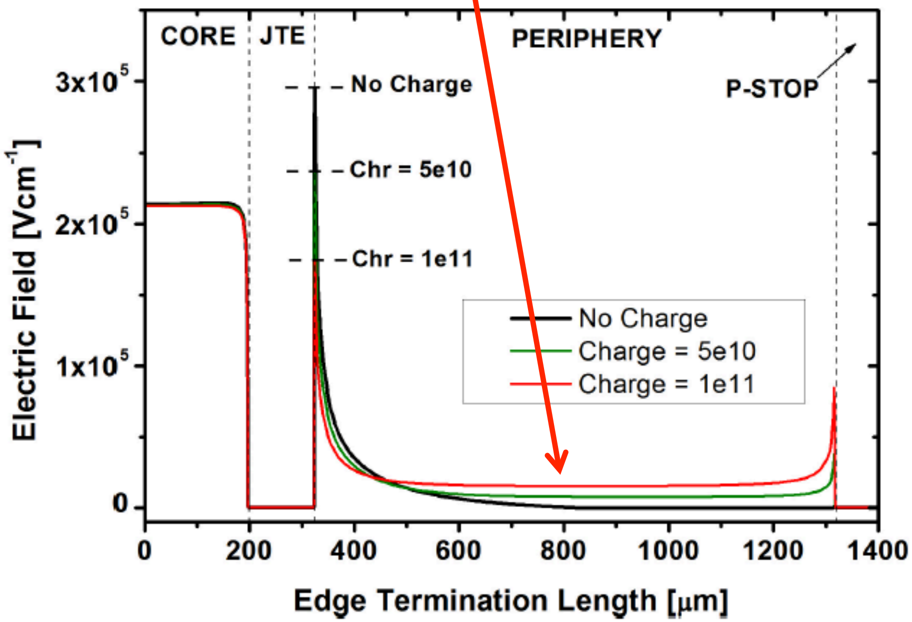


What about the Inherent Positive Oxide Charges?

- ✓ **Field oxides grown in wet conditions (H_2+O_2) typically have a positive charge density in the range of 5e10 cm^{-2}**
- x **Surface inversion and modification of the depletion region, reaching the deep P-Stop peripheral diffusion**

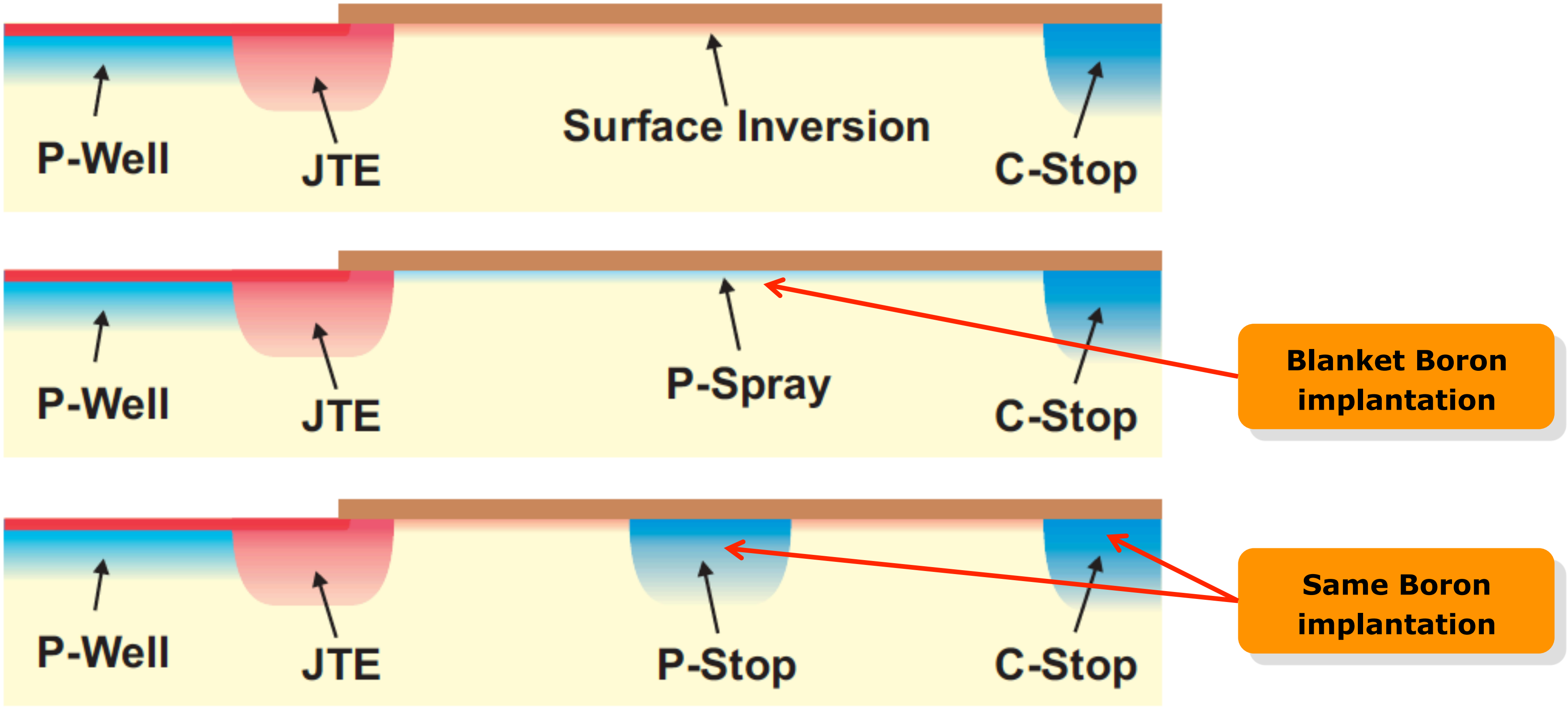
Surface inversion + fast depletion + electric field peak at deep P-stop+ <u>SURFACE LEAKAGE CURRENTS</u>





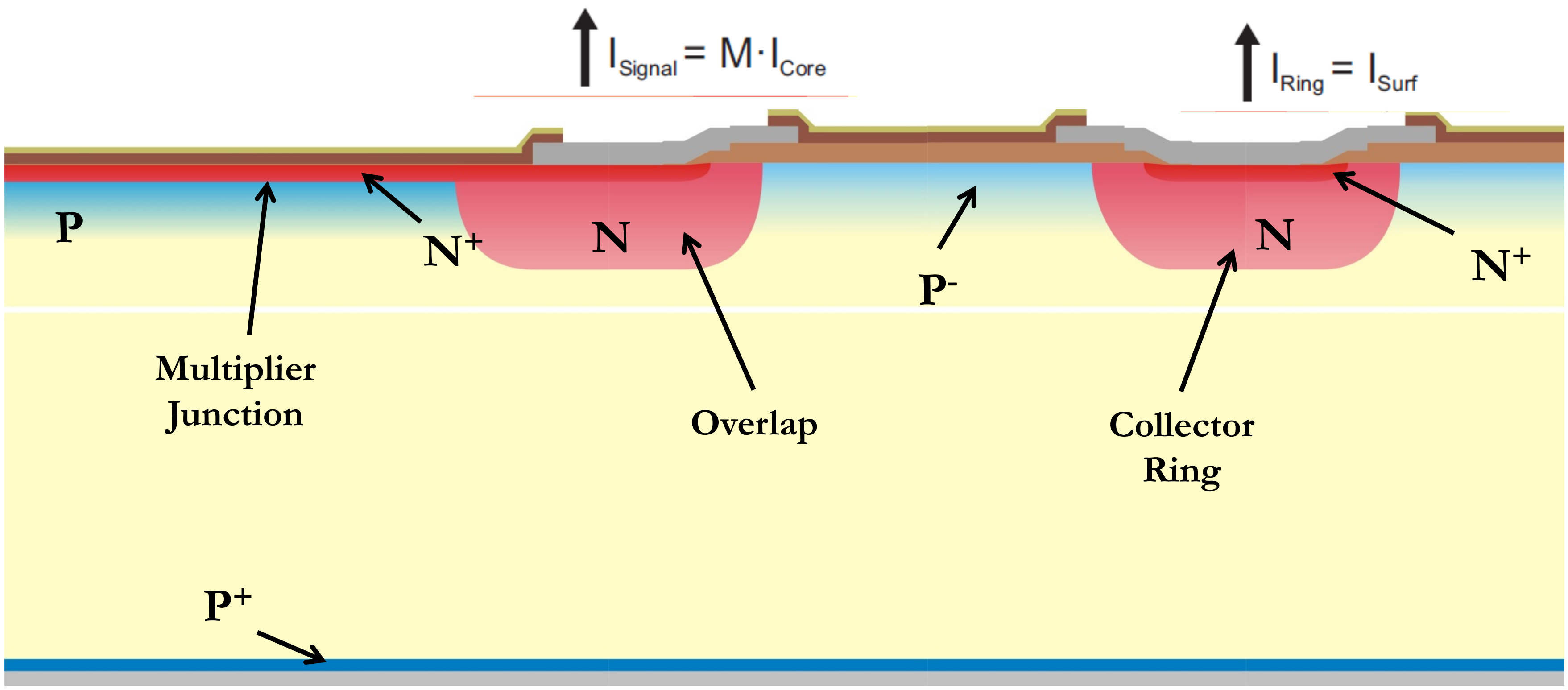
How to Protect the Surface, Limiting the Current Leakage?

- **Oxide positive charges create a surface inversion layer (electron path towards the cathode electrode, masking the charge collection when used as a detector)**
  - ✓ **A shallow P-type diffusion (P-Spray) can be used to compensate the surface inversion**
  - ✓ **A deep P$^+$ diffusion can be placed close to the JTE to eliminate the electron surface current**



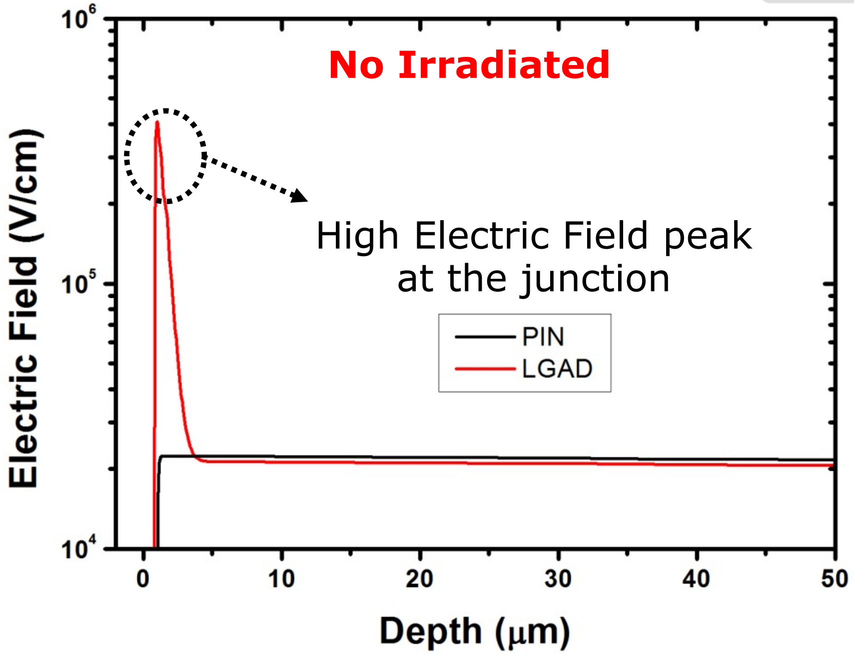
How to Protect the Surface, Limiting the Current Leakage?

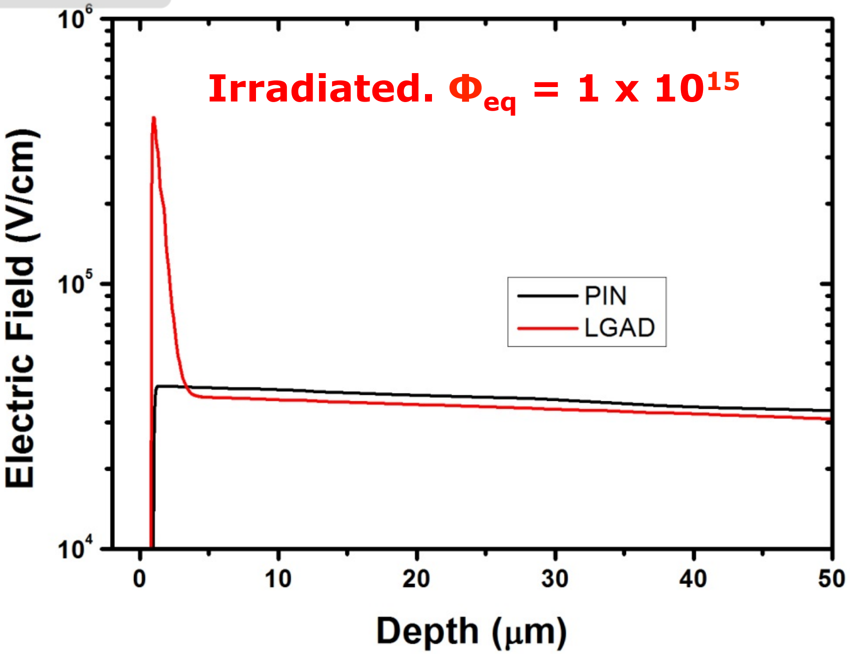
- **An additional N-type ring is implemented by using the deep JTE diffusion**
  - ✓ **The N ring has to be placed close to the JTE to avoid a premature breakdown at the JTE**
  - ✓ **The P-spray diffusion has to be efficient (to avoid short circuit through the inversion layer)**
  - ✓ **The voltage capability is not degraded since the junction to be protected is now the right edge of the added ring (identical than the JTE)**



Simulation of the Irradiated Devices

Curves @ 600 V





- **PiN**: electric field strength at the junction increases after irradiation
- **LGAD**: electric field strength at the junction is almost equal after irradiation

- **Irradiation Trap Model (Perugia Model)**

Acceptor;	E= E_c + 0.46 eV;	η=0.9	$\sigma_e = 5 \times 10^{-15}$	$\sigma_h = 5 \times 10^{-14}$
Acceptor;	E= E_c + 0.42 eV;	η=1.613	$\sigma_e = 2 \times 10^{-15}$	$\sigma_h = 2 \times 10^{-14}$
Acceptor;	E= E_c + 0.10 eV;	η=100	$\sigma_e = 2 \times 10^{-15}$	$\sigma_h = 2.5 \times 10^{-15}$
Donor;	E= E_v - 0.36 eV;	η=0.9	$\sigma_e = 2.5 \times 10^{-14}$	$\sigma_h = 2.5 \times 10^{-15}$

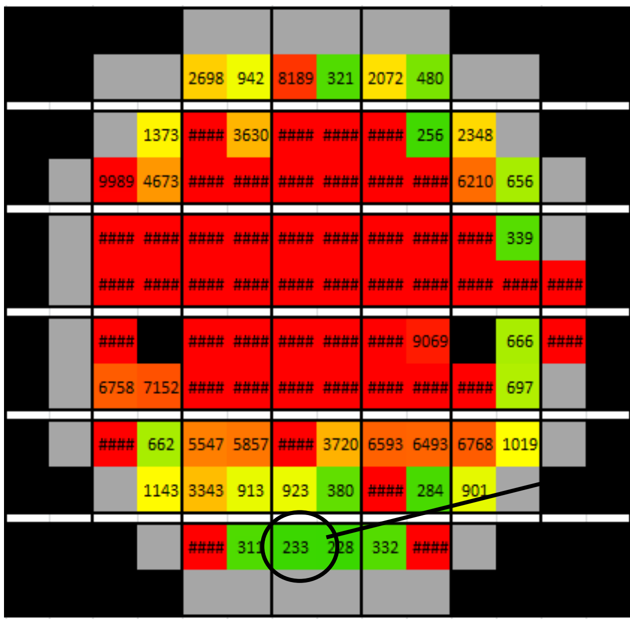
- **Impact Ionization Model (Univ. of Bolonia)**

Experimental Results

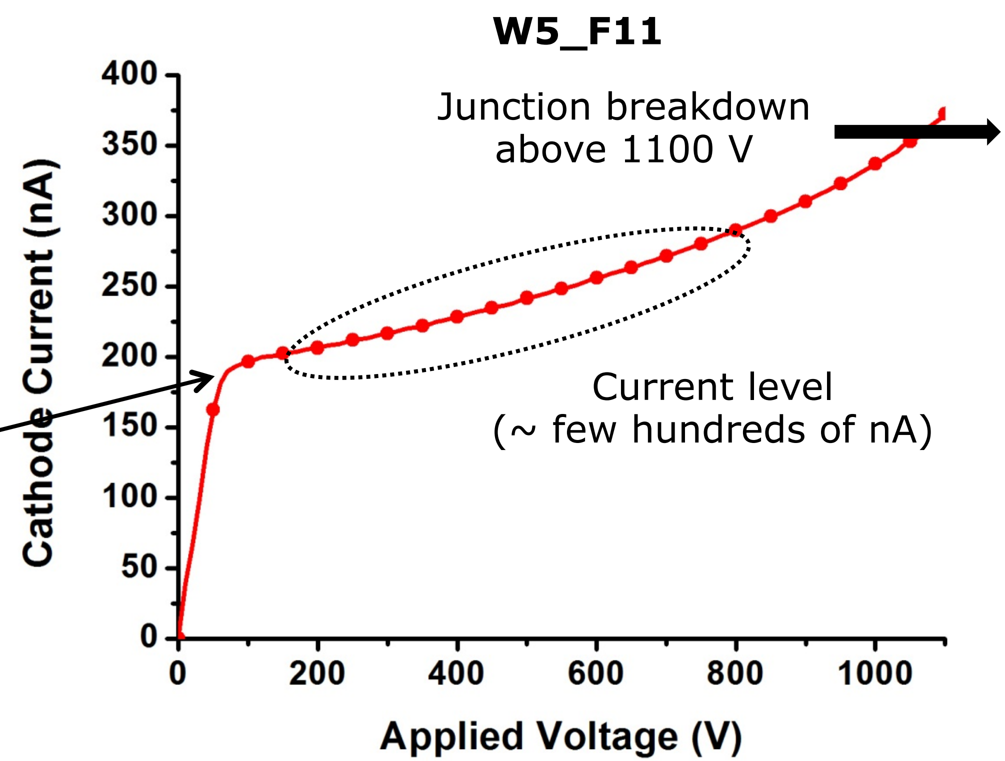
✓ Static Performance

→ **Current levels below 1 μA thorough the whole voltage range**

→ **Junction breakdown above 1100 V**



Wafer 5 (1.4×10^{13} cm^{-2})



Experimental Results

- **Multiplication factor has been tested with tri-alpha (^{239}Pu/^{241}Am/^{244}Cm) source.**
  - ✓ **Irradiation through the anode (back side, 1 µm Aluminum):**