From the *pn* junction to the UFSD design

The role of numerical simulation

9.05.2019

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Summary

I. Overview of semiconductor devices
  - The *pn* junction
  - Low Gain Avalanche Detectors (LGAD)

II. Electronic device modeling
  - Analytical description
  - Numerical implementation

III. LGAD design using numerical simulations

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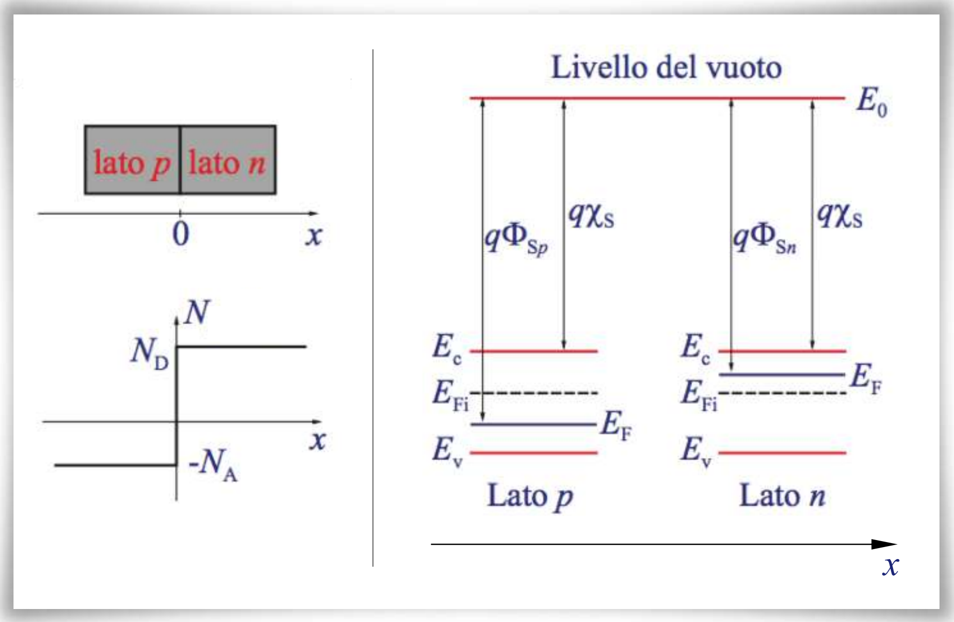
Characteristic equations of the *pn* junction

- **Definition:** the *pn* junction is a semiconductor region where a *p*-type and an *n*-type doped materials are placed side by side.
- **Example:** the *abrupt junction* of two *uniformly doped* semiconductors.



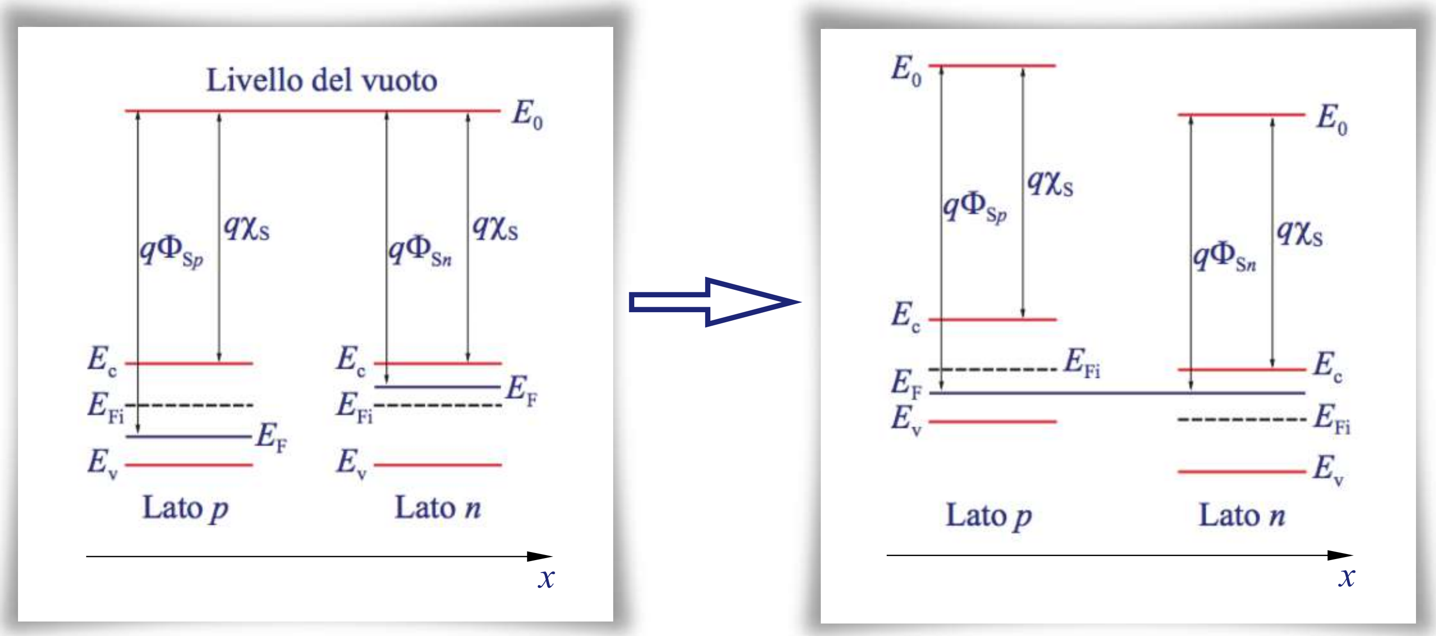
$q\chi$ is the electronic affinity (~4.05 eV in Si)
$q\Phi$ is the semiconductor work function

$$q\Phi_{Sp} = q\chi_S + E_g - (E_F - E_v) = q\chi_S + E_g - k_B T \ln \frac{N_v}{N_A}$$

$$q\Phi_{Sn} = q\chi_S + (E_c - E_F) = q\chi_S + k_B T \ln \frac{N_c}{N_D}$$

Characteristic equations of the *pn* junction

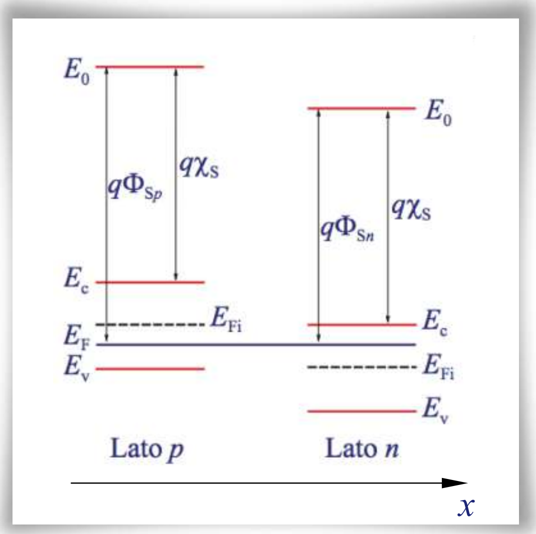
- **Golden-rules to compute the final band-diagram:**
  1. E_g and $q\chi$ are **conserved** by definition;
  2. E_F must be **constant** across the junction;



  3. E_0 and bands must be **continuous** functions (in space *x*).

Characteristic equations of the *pn* junction

- The gradient of carriers concentration produces a **transient**, in which **electrons travel from the *n*-side to the *p*-side** (the vice-versa holds for holes). This mechanism behaves as a **diffusion-like dynamics**
- The diffusion of free charges **depletes a zone** across the junction, called **space-charge region** (**SCR**), where **fixed charges** (ionized atoms) **are no more compensated by free charges** ($\rho \neq 0$). Far from the junction, we still have compensation (**neutral regions**, $\rho = 0$)

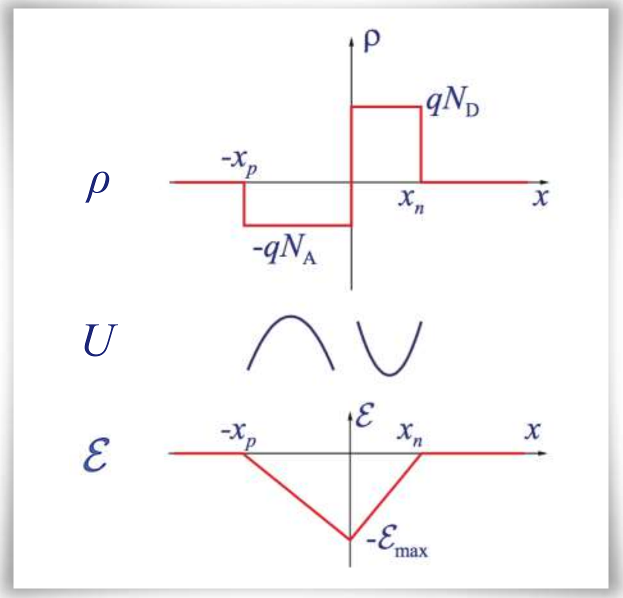


Characteristic equations of the *pn* junction

- **Within the space-charge region** ($\rho \neq 0$) **the field is not a constant** and **bands are no more straight lines**. In particular, due to the **Poisson equation** of semiconductors

$$\frac{\mathrm{d}^2 U}{\mathrm{d}x^2} = q\frac{\rho}{\epsilon}$$

where $U = -q\varphi$ is the *potential energy* felt by free charges, we have



by definition of space-charge region

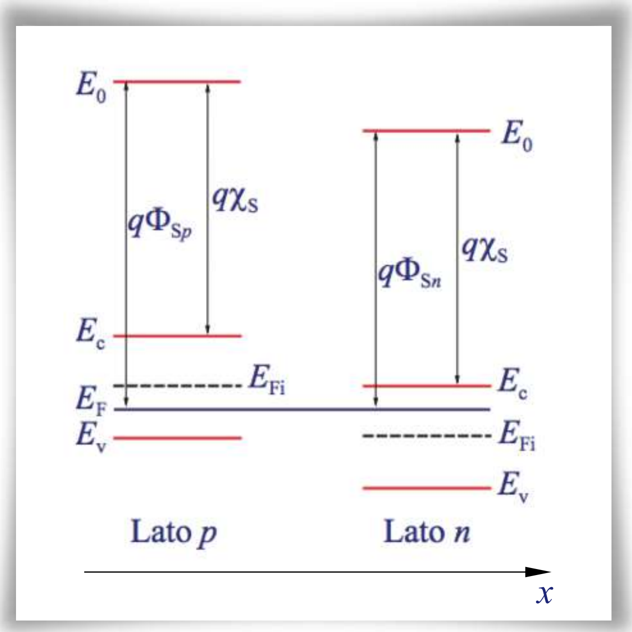
directly from the Poisson eq.

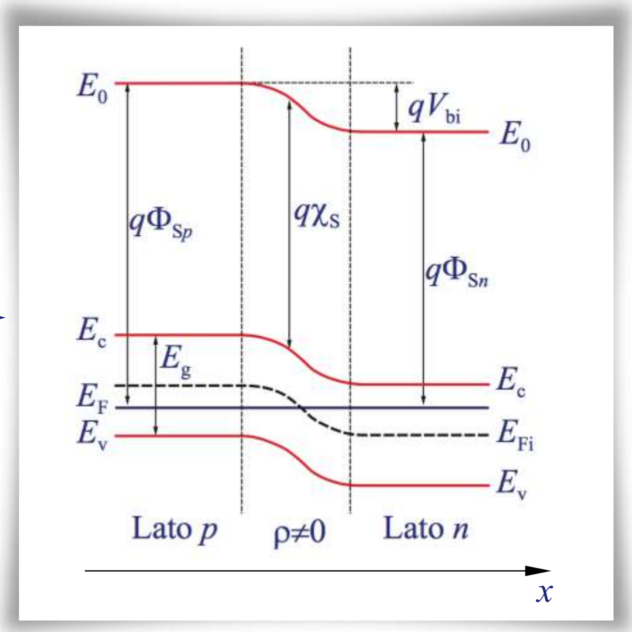
by 1st x-integration of the Poisson eq.:

$$\frac{\mathrm{d}\mathcal{E}}{\mathrm{d}x} = \frac{\rho}{\epsilon}$$

Characteristic equations of the *pn* junction

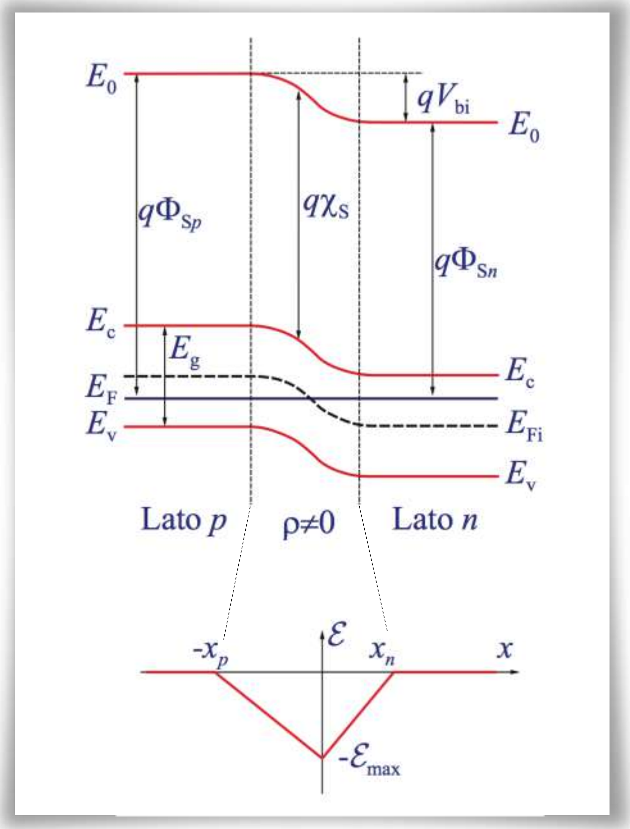
- So, finally we have:





Characteristic equations of the *pn* junction

What we concluded has several important physical implications:



1. $\mathcal{E} \neq 0$ implies the onset of a **drift current** of carriers tending to **compensate the diffusion** of free charges such that $J = 0$;
2. A **built-in potential** $qV_{\rm bi}$, created across the junction, represents an additional **barrier for the diffusion** of electrons towards the *p*-side (and holes in the *n*-side)

$$\begin{aligned} qV_{\rm bi} &= q\Phi_{{\rm S}p} - q\Phi_{{\rm S}n} = E_{\rm g} - k_{\rm B}T \ln \frac{N_{\rm v}N_{\rm c}}{N_{\rm A}N_{\rm D}} \\ &= k_{\rm B}T \ln \frac{N_{\rm v}N_{\rm c}}{n_{\rm i}^2} - k_{\rm B}T \ln \frac{N_{\rm v}N_{\rm c}}{N_{\rm A}N_{\rm D}} \\ &= k_{\rm B}T \ln \frac{N_{\rm A}N_{\rm D}}{n_{\rm i}^2} \end{aligned}$$

Characteristic equations of the *pn* junction

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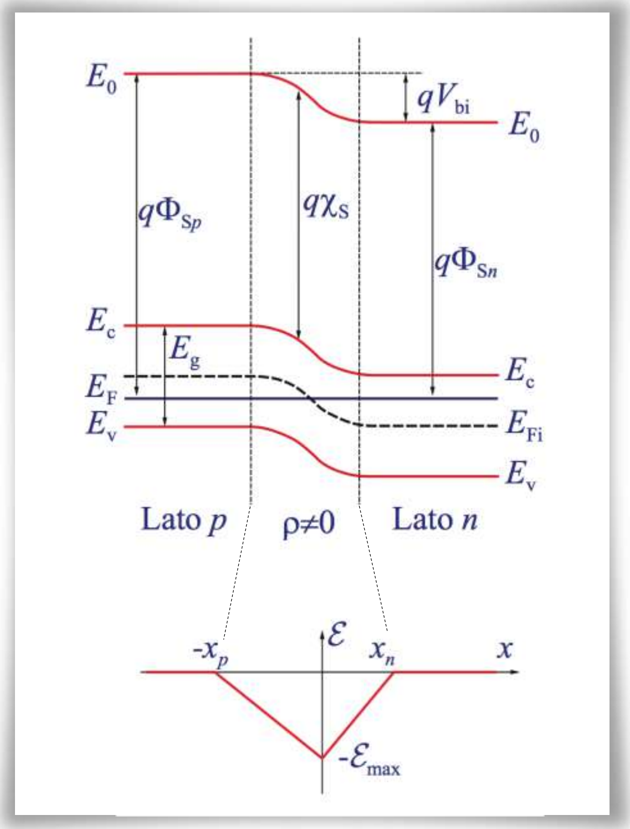


3. By integrating the Poisson equation, and thanks to the *neutrality law* $N_A x_p = N_D x_n$, one has

$$\mathcal{E}(x) = \begin{cases} -\frac{qN_A}{\epsilon}(x+x_p) & -x_p \le x < 0 \\ \frac{qN_D}{\epsilon}(x-x_n) & 0 \le x < x_n \end{cases}$$

and

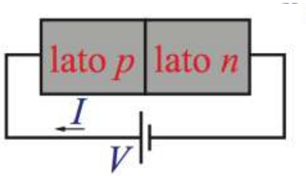
$$\mathcal{E}_{max} = \frac{qN_A}{\epsilon}x_p = \frac{qN_D}{\epsilon}x_n$$

4. In the same way:

$$\varphi(x) = \begin{cases} \frac{qN_A}{2\epsilon}(x+x_p)^2 & -x_p \le x < 0 \\ -\frac{qN_D}{2\epsilon}(x-x_n)^2 + \frac{qN_A}{2\epsilon}x_p^2 + \frac{qN_D}{2\epsilon}x_n^2 & 0 \le x < x_n \end{cases}$$

Characteristic equations of the *pn* junction

- **What happens if the junction is no more at equilibrium?**



Direct polarization

- $V > 0, I > 0$
- J_{diff} dominates
- electrons from *n*- to *p*-side
- holes from *p*- to *n*-side
- $qV < qV_{\text{bi}}$

Reverse polarization

- $V < 0, I < 0$
- J_{drift} dominates
- electrons from *p*- to *n*-side
- holes from *n*- to *p*-side
- $qV > qV_{\text{bi}}$

Characteristic equations of the *pn* junction

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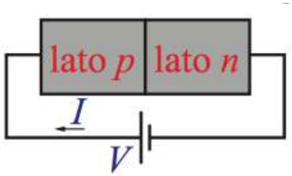
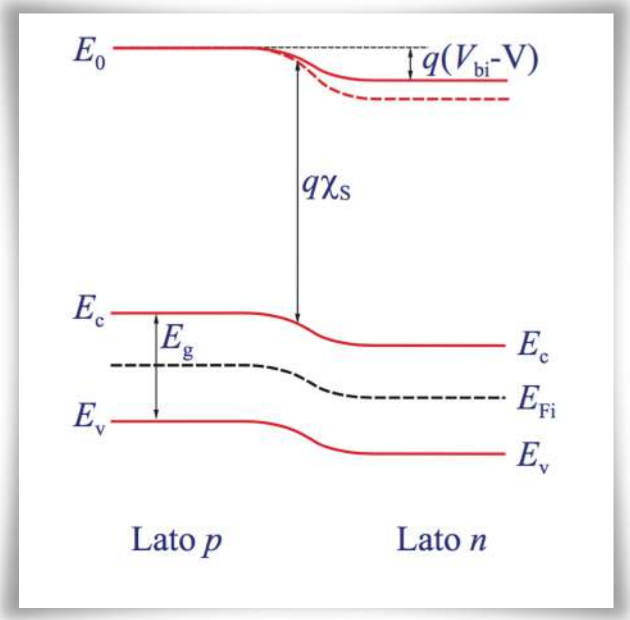
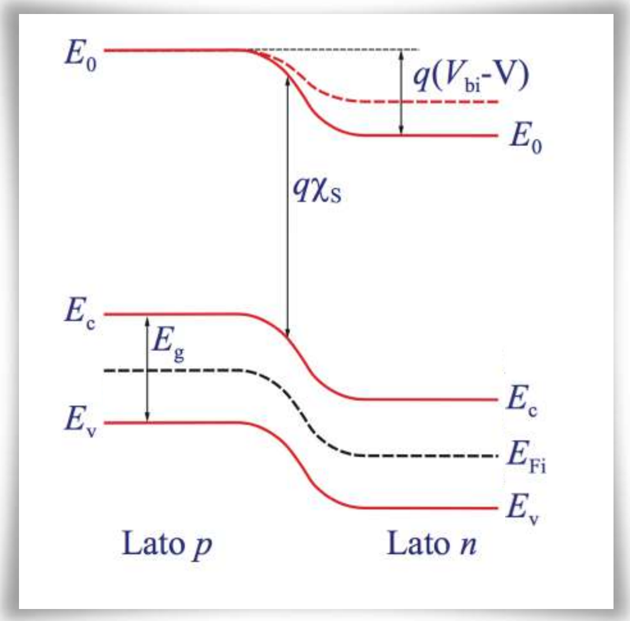


Direct polarization



Reverse polarization



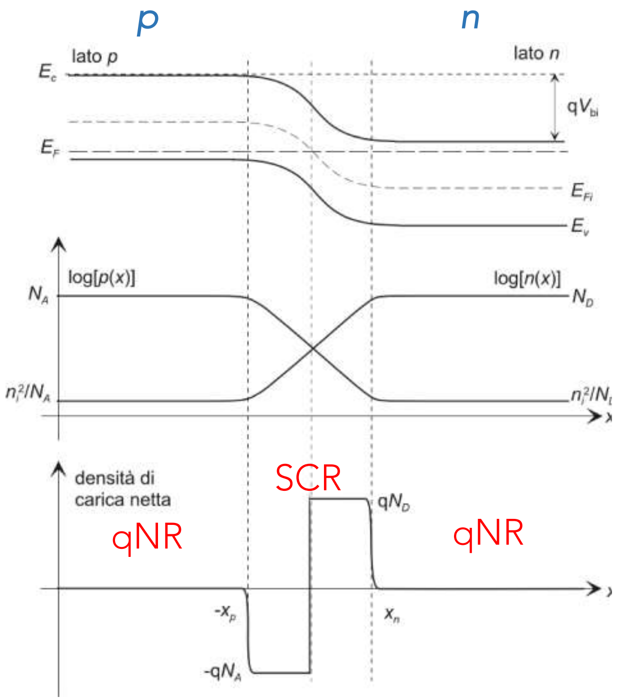
Characteristic equations of the *pn* junction

- *pn* junction at **equilibrium**:

$$V_{\text{bi}} = V_T \log \frac{N_{\text{A}} N_{\text{D}}}{n_{\text{i}}^2}$$

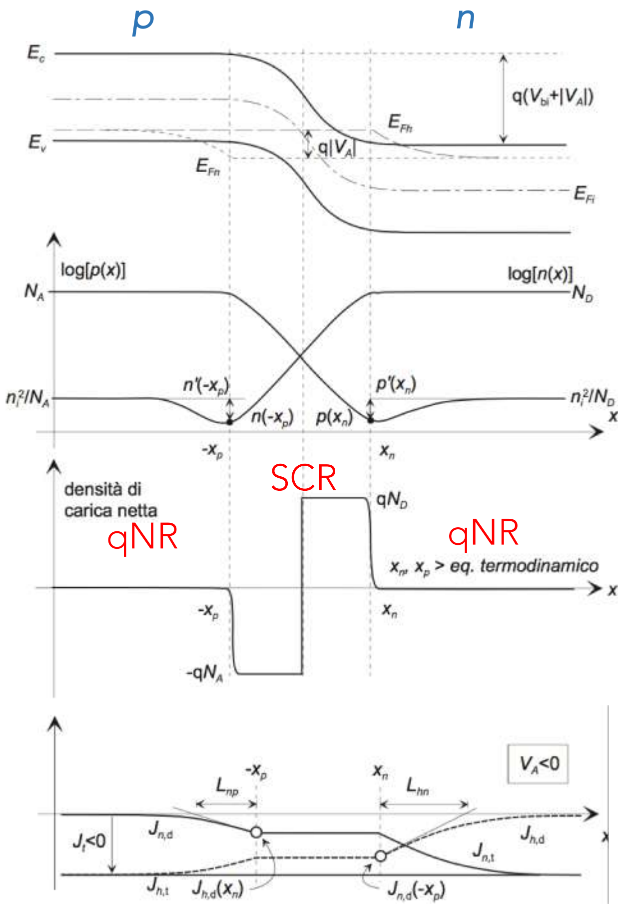
$$p_{p0}(-x_p) = N_{\text{A}} \qquad p_{n0}(x_n) = n_{\text{i}}^2 / N_{\text{D}}$$

$$n_{n0}(x_n) = N_{\text{D}} \qquad n_{p0}(-x_p) = n_{\text{i}}^2 / N_{\text{A}}$$



Characteristic equations of the *pn* junction

- *pn* junction in **reverse polarization**:

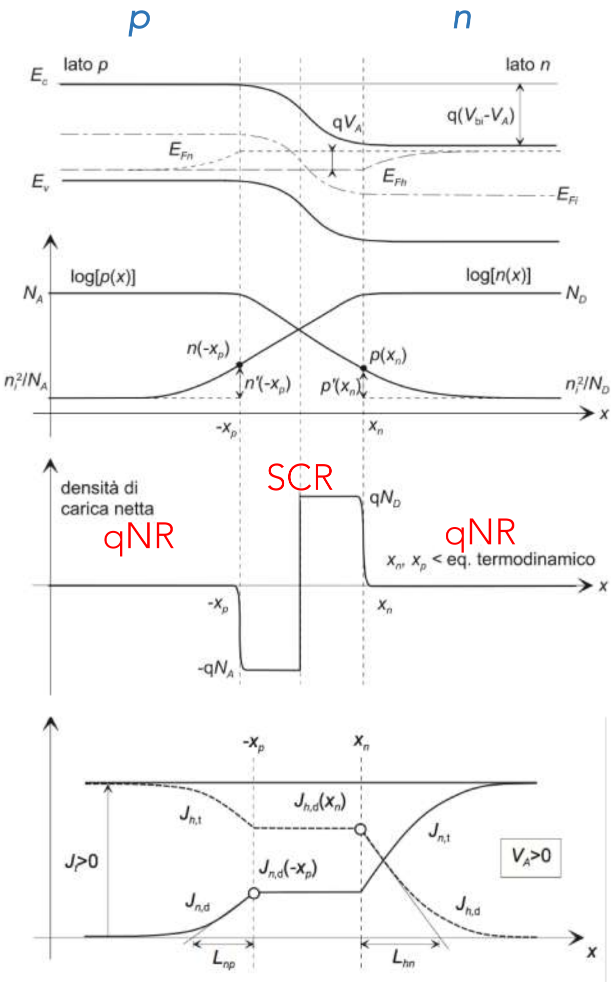


$$n'_p = n_p - n_{p0} \qquad p'_n = p_n - p_{n0} \qquad < 0$$

- $V_{bias} < 0$, $I < 0$
- J_{drift} dominates
- electrons from *p*- to *n*-side
- holes from *n*- to *p*-side
- $qV_{bias} > qV_{bi}$

Characteristic equations of the *pn* junction

- *pn* junction in **forward polarization**:



$$n'_p = n_p - n_{p0} \qquad p'_n = p_n - p_{n0} \qquad > 0$$

- $V_{\text{bias}} > 0$, $I > 0$
- J_{diff} dominates
- electrons from *n*- to *p*-side
- holes from *p*- to *n*-side
- $qV_{\text{bias}} < qV_{\text{bi}}$

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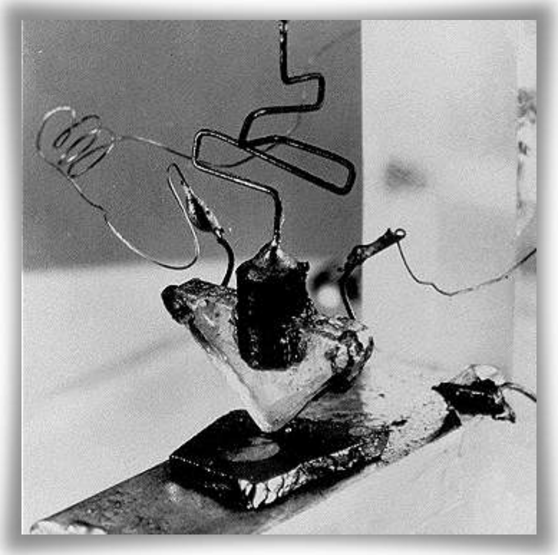
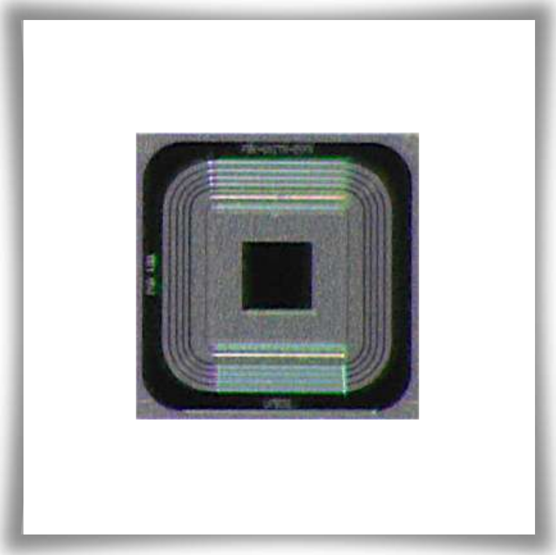
Towards a technological step…

first *n*-*p*-*n* “tip”-transistor



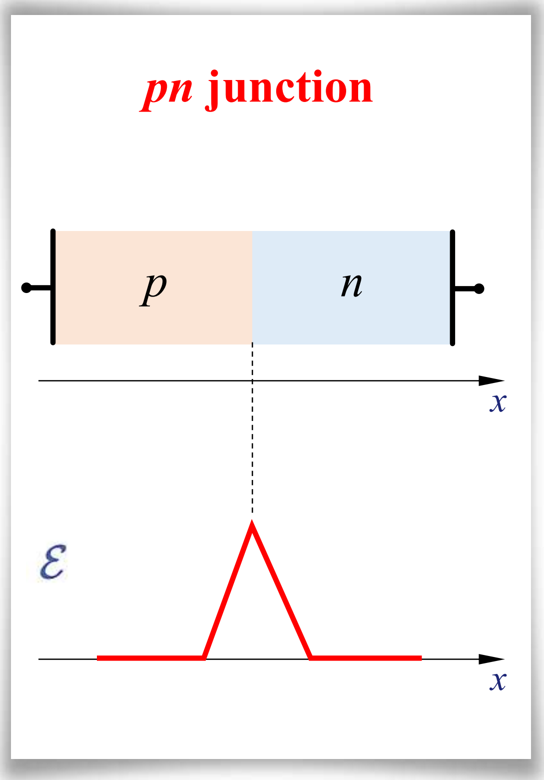
J. Bardeen, W. Brattain, W. Shockley
Bell Labs. - NJ
(1948)

Ultra Fast Silicon Detector

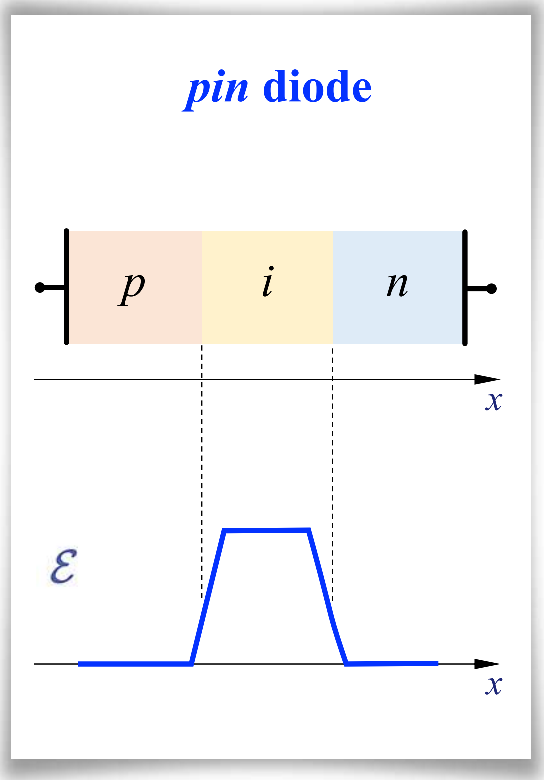


UFSD Group
INFN Torino and FBK Trento
(2018)

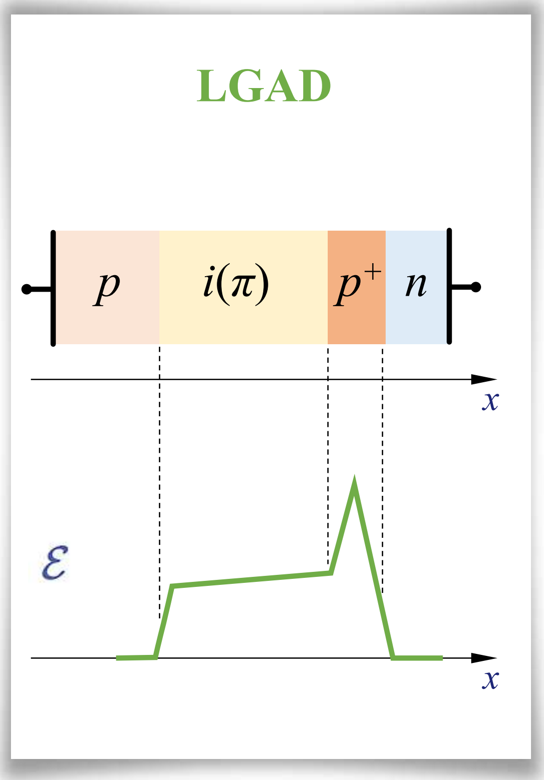
Extending our application domain to other systems



***pn* junction**



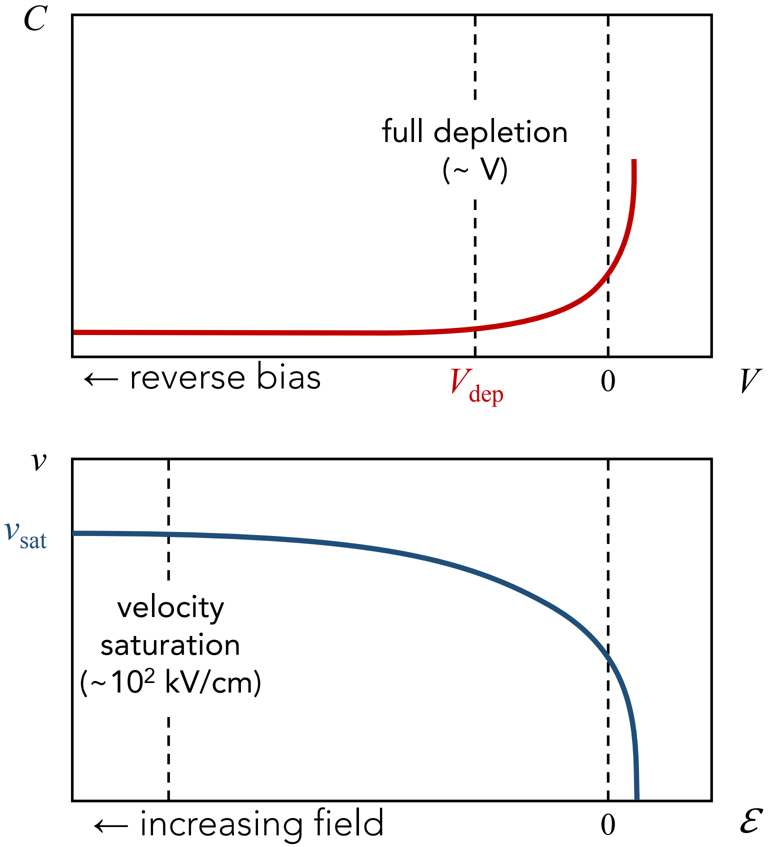
***pin* diode**



LGAD

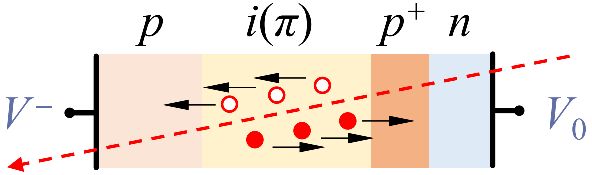
Working principles of an LGAD

- How large the **external biasing voltage** has to be?



Working principles of an LGAD

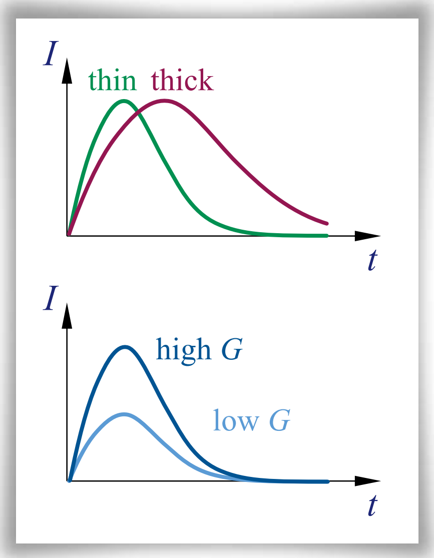
➤ **What is charge multiplication in LGAD?**



- **Primary charges** (electron/hole pairs) are produced **by ionization**, while the particle is crossing the sensor;
- Due to the **reverse field**, electrons **drift** towards the *n*-side and holes towards the *p*-side;
- When electrons travel along the $\boldsymbol{p^+}$ **region** (the *gain*- or *multiplication*-layer) they experience an **high field**;
- This field is responsible for the **impact ionization**, which produces an avalanche **multiplication of secondary charges**;
- Now the **total current** is due to the **additional avalanche contribution**.

Working principles of an LGAD

➤ Why using LGAD to detect particles at CERN?



I. We need **charge multiplication**:

1. LGAD exploit the so-called **avalanche multiplication**, a process which belongs to the class of **generation/recombination (GR) mechanisms**;
2. Charge multiplication allows to obtain **large and fast signals**:
   - the **thinner** the sensor, the **faster** the signal;
   - the **higher** the **gain**, the **larger** the signal.

II. We need a good **S/N**:

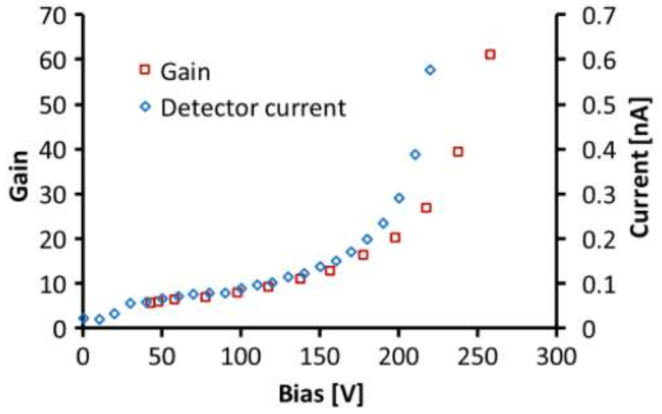
1. Also the **noise** related to the current signal is **proportional to the gain**
2. The **gain** ***G*** has to be kept as **low** as required by electronics ($G \sim$ 10-20)

Working principles of an LGAD

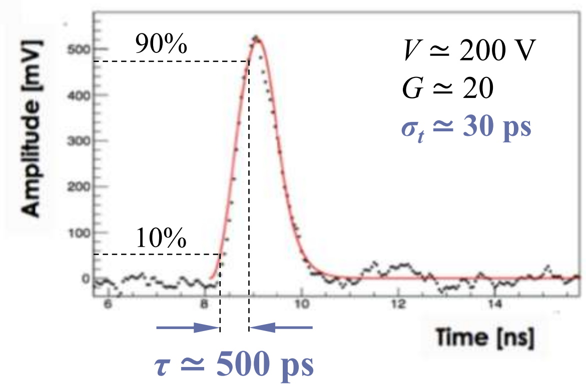
- **Why using LGAD to detect particles at CERN?**

Examples of 50 μm LGAD performance:

reverse current & gain versus bias *V*



current signal (test beam @ CERN-H8)



$V \simeq 200$ V
$G \simeq 20$
$\sigma_t \simeq 30$ **ps**

$\tau \simeq 500$ **ps**

Working principles of an LGAD

- **Can we predict the avalanche contribution to the total current?**

Let’s introduce a bit of physical-mathematatics…

1. The **avalanche** process is modeled via its **ionization coefficient** α, i.e. the **inverse of the electron/hole mean free path** (cm^{-1});
2. In the literature, several **expressions of *α*** are available. In general, all of them are based on the **Chynoweth’s theory** (1958), according to which:

$$\alpha_{n,p}(\mathcal{E}) = \gamma\, A_{n,p} \exp\left(-\gamma \frac{B_{n,p}}{\mathcal{E}}\right)$$

3. Once the coefficient has been obtained, one has to evaluate the **net avalanche generation rate** U_{aval}, i.e. the **number of multiplied e$^-$/h$^+$ pairs per volume** (cm^{-3}) **per unit time** (s^{-1}), as:

$$U_{\text{aval}} = \frac{\mathrm{d}n}{\mathrm{d}t} = \frac{\mathrm{d}p}{\mathrm{d}t} = \alpha_n n v_n + \alpha_p p v_p$$

… Now we need a complete description of the system!

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Electronic device modeling - I

- We recall the **twofold nature of the current** in a semiconductor device:
  a. **Drift current**, driven by the *electric field*;
  b. **Diffusion current**, due to the density gradient of *free charges*.

$$J_{n,\text{dr}} = qn\mu_n\mathcal{E} \qquad J_{p,\text{dr}} = qp\mu_p\mathcal{E}$$

$$J_{n,\text{diff}} = qD_n\frac{\partial n}{\partial x} \qquad J_{p,\text{diff}} = -qD_p\frac{\partial p}{\partial x}$$

$$J = \underbrace{J_{n,\text{diff}} + J_{n,\text{dr}}}_{J_n} + \underbrace{J_{p,\text{diff}} + J_{p,\text{dr}}}_{J_p}$$

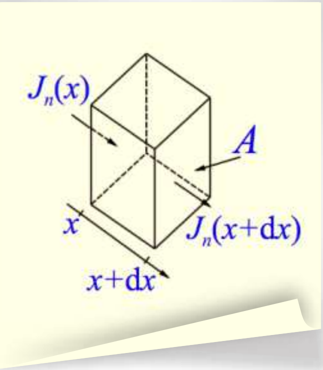
- Then we introduce (all) the **GR mechanisms** through their **net rates *U***:

$$U_n = R_n - G_n \approx \frac{n-n_0}{\tau_n} = \frac{n'}{\tau_n} \qquad U_p = R_p - G_p \approx \frac{p-p_0}{\tau_p} = \frac{p'}{\tau_p}$$

Electronic device modeling - I

- To derive the **global current density** (field + charge + GR):
  1. in a volume $\mathrm{d}V = A\mathrm{d}x$ the **time variation of the electron density** (similarly for holes) is

$$\frac{\partial n}{\partial t}A\mathrm{d}x = \overbrace{\frac{J_n(x)}{-q}A - \frac{J_n(x+\mathrm{d}x)}{-q}A}^{\text{field + charge}} + \overbrace{G_n A\mathrm{d}x - R_n A\mathrm{d}x}^{\text{GR}}$$



  2. by using the 1st-order Taylor series expansion

$$J_n(x+\mathrm{d}x) \approx J_n(x) + \frac{\partial J_n}{\partial x}\mathrm{d}x$$

and assuming $\mathrm{d}x \longrightarrow 0$, we obtain the **continuity equations**:

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} - U_n \qquad \frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} - U_p$$

Electronic device modeling - I

- Since the drift component depends on the **electric field**, we need a third equation to close the system, the **Poisson equation**, which connects the *field* to the *charge densities*.
  The final (1D) mathematical framework is:

continuity eqs.

Poisson eq.

$$\begin{cases} \dfrac{\partial n}{\partial t} = \dfrac{1}{q}\dfrac{\partial J_n}{\partial x} - U_n \\[2ex] \dfrac{\partial p}{\partial t} = -\dfrac{1}{q}\dfrac{\partial J_p}{\partial x} - U_p \\[2ex] \dfrac{\partial \mathcal{E}}{\partial x} = \dfrac{\rho}{\epsilon} \end{cases}$$

DRIFT-DIFFUSION MODEL (DD)

where $J_n = q\mu_n n\mathcal{E} + qD_n\dfrac{\partial n}{\partial x}$, $J_p = q\mu_p p\mathcal{E} - qD_p\dfrac{\partial p}{\partial x}$

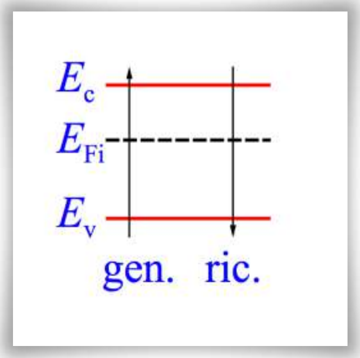
TRANSPORT EQS.

and $\mathcal{E} = -\dfrac{\partial \varphi}{\partial x}$, $\rho = q\left(p - n + N_{\mathrm{D}}^{+} - N_{\mathrm{A}}^{-}\right)$.

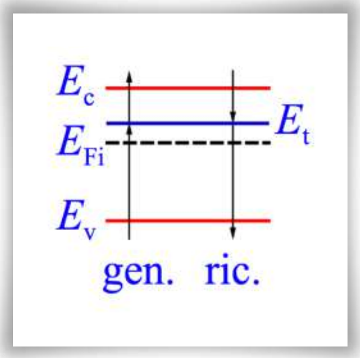
Electronic device modeling - I

- Avalanche generation is not the only **GR mechanism** occurring in silicon devices. In general, we have to account for **two different families**:

A. **Band-to-band** generation/recombination
  - *Auger*
  - *direct tunneling*
  - …



B. **Defect-assisted** generation/recombination
  - *Shockley-Read-Hall* (*SRH*)
  - *trap-assisted tunneling*
  - …



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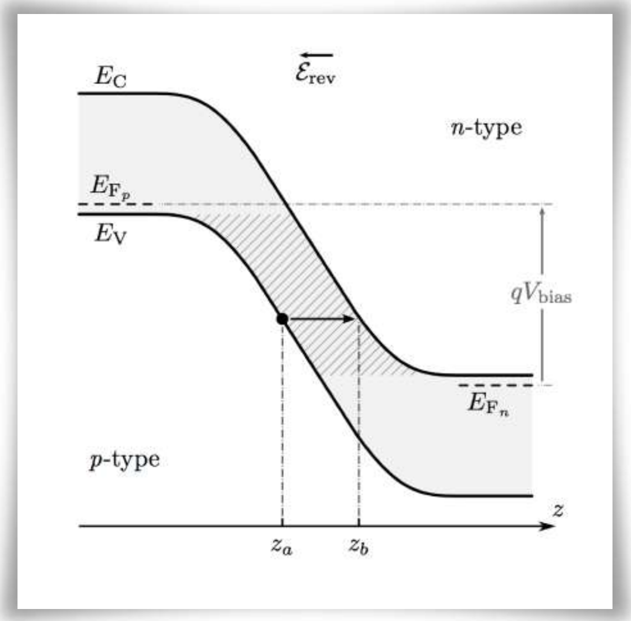

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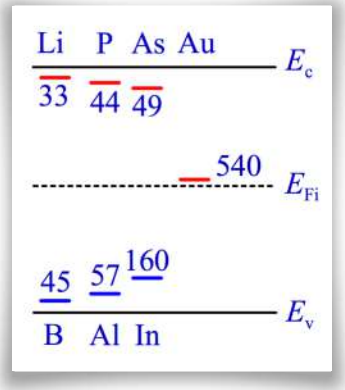

Electronic device modeling - I

- **SRH** processes are determined by such a net rate statistics

$$U_{\mathrm{SRH}} = \frac{np - n_i^2}{\tau_p \left(n + n_i \, \mathrm{e}^{\frac{E_{\mathrm{trap}} - E_{\mathrm{F}_i}}{k_{\mathrm{B}}T}} \right) + \tau_n \left(p + n_i \, \mathrm{e}^{\frac{E_{\mathrm{F}_i} - E_{\mathrm{trap}}}{k_{\mathrm{B}}T}} \right)}$$

  where $\tau_{n,p}$ are proper **electron/hole lifetimes**, i.e. the average time interval (~10^{-7}-10^{-9} s) between two consecutive scattering processes originating (or annihilating) e^-/h^+ pairs.

- Moreover, **band-to-band tunneling** is modeled with the usual Kane expression (1961)

$$U_{\mathrm{tunn}} = A\,\mathcal{E}^2 \cdot \exp\left(-B/\mathcal{E}\right)$$

  with A and B (V/cm) material-dependent parameters.

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Electronic device modeling - II

- **We need a method to compute the DD model**

$$\begin{cases} \dfrac{\partial n}{\partial t} = \dfrac{1}{q}\dfrac{\partial J_n}{\partial x} - U_n \\ \dfrac{\partial p}{\partial t} = -\dfrac{1}{q}\dfrac{\partial J_p}{\partial x} - U_p \\ \dfrac{\partial \mathcal{E}}{\partial x} = \dfrac{\rho}{\epsilon} \end{cases}$$

where φ is the input function, n, p and $\mathcal{E}$ are the unknowns of the continuity equations and where the Poisson equation closes the system.

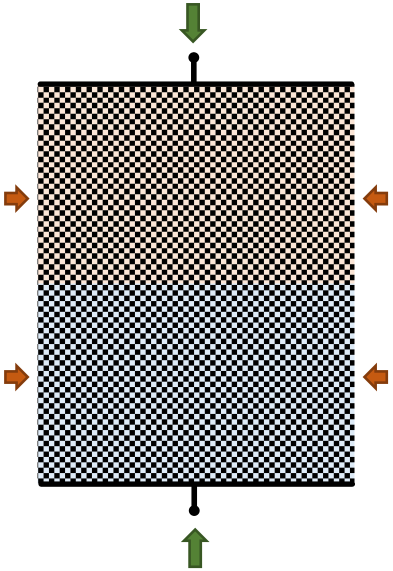
- **We have to solve a set of *non-linear*, *secondary-order* PDEs, in *space* and *time*, for the whole device!**

Electronic device modeling - II

- **The strategy**

- Dynamics (bias ramps, transients, …) is treated as a sequence of *small* increments between stationary states at equilibrium: the **quasi-stationary process**;

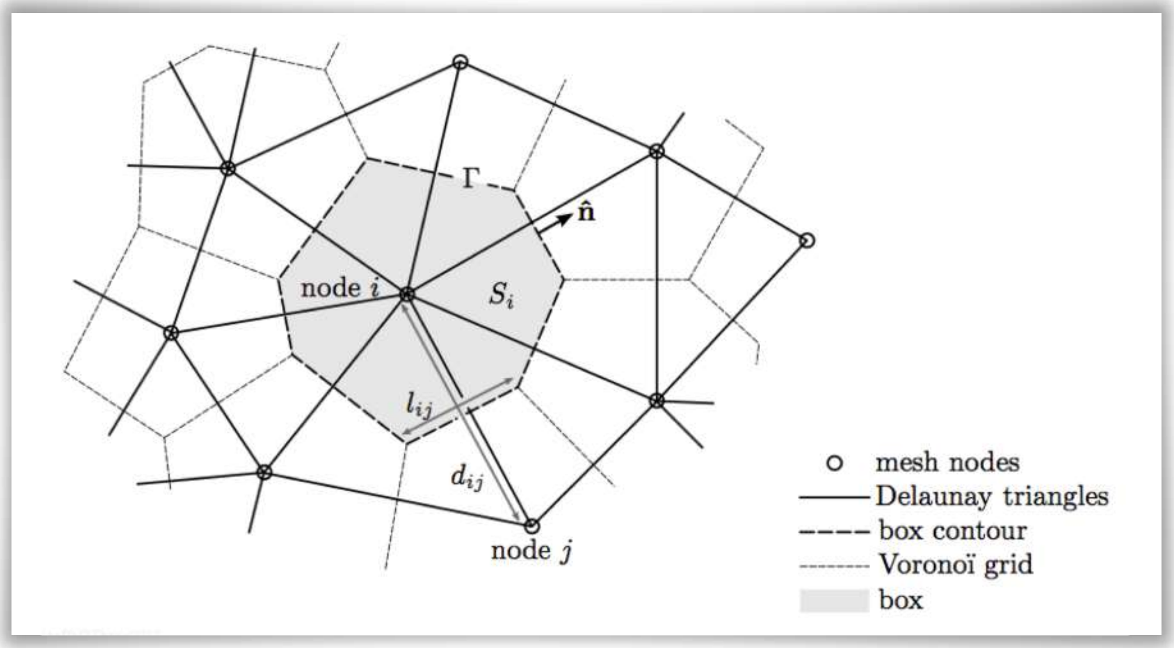
- At each quasi-stationary step the mathematics has to be simplified through proper approximations and algorithms:



1. the **geometry** is **discretized** (e.g.: Delaunay-Voronoï procedure)
2. DD system is rewritten and adapted to the mesh grid
3. PDEs are linearized and transformed into **ODEs** (**FD schemes**)
4. **I.C.** and **B.C.** are defined
5. the *new* DD model is solved via **iterative methods** (Newton) in all mesh nodes

Electronic device modeling - II

1. The **geometry** is **discretized** (e.g.: **Delaunay-Voronoï procedure**)



design of **nodes**

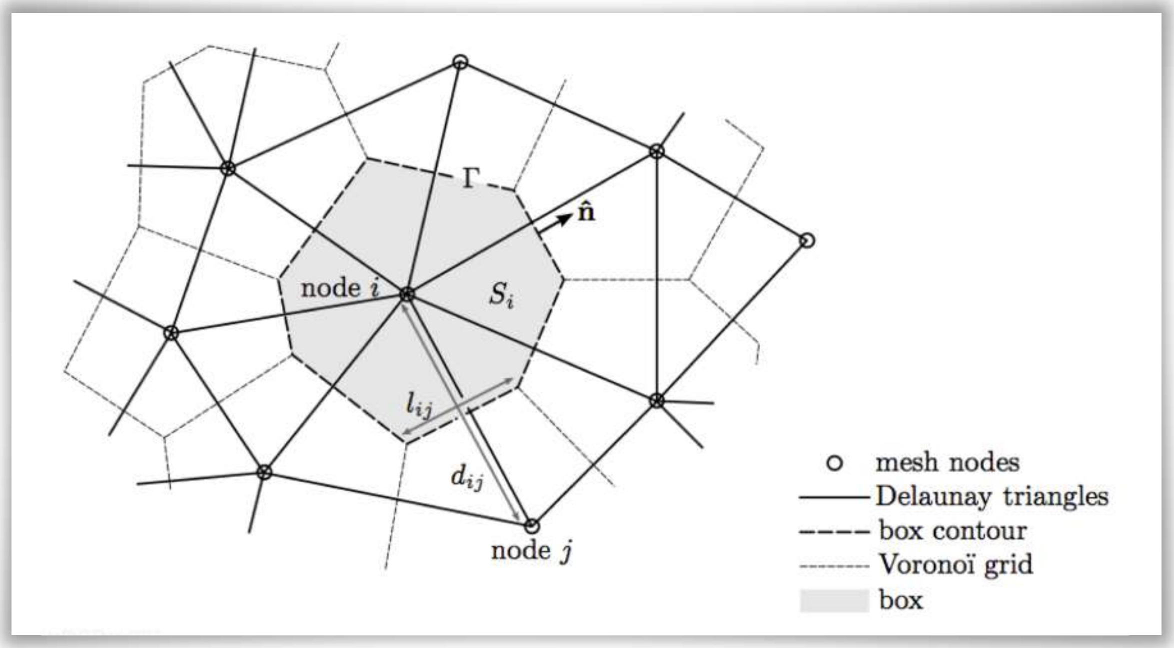
creation of
non-obtuse triangles

creation of **boxes**

$\mathbf{J}_{\perp n,p}$ are conserved
at boxes interfaces

Electronic device modeling - II

2. **Drift-Diffusion system** is rewritten and **adapted** to the **mesh grid**



scalar/vector operators and **constants** are transformed:

$$\frac{\partial}{\partial t}\int_S x\,\mathrm{d}s \Rightarrow \frac{\partial x_i}{\partial t} S_i$$

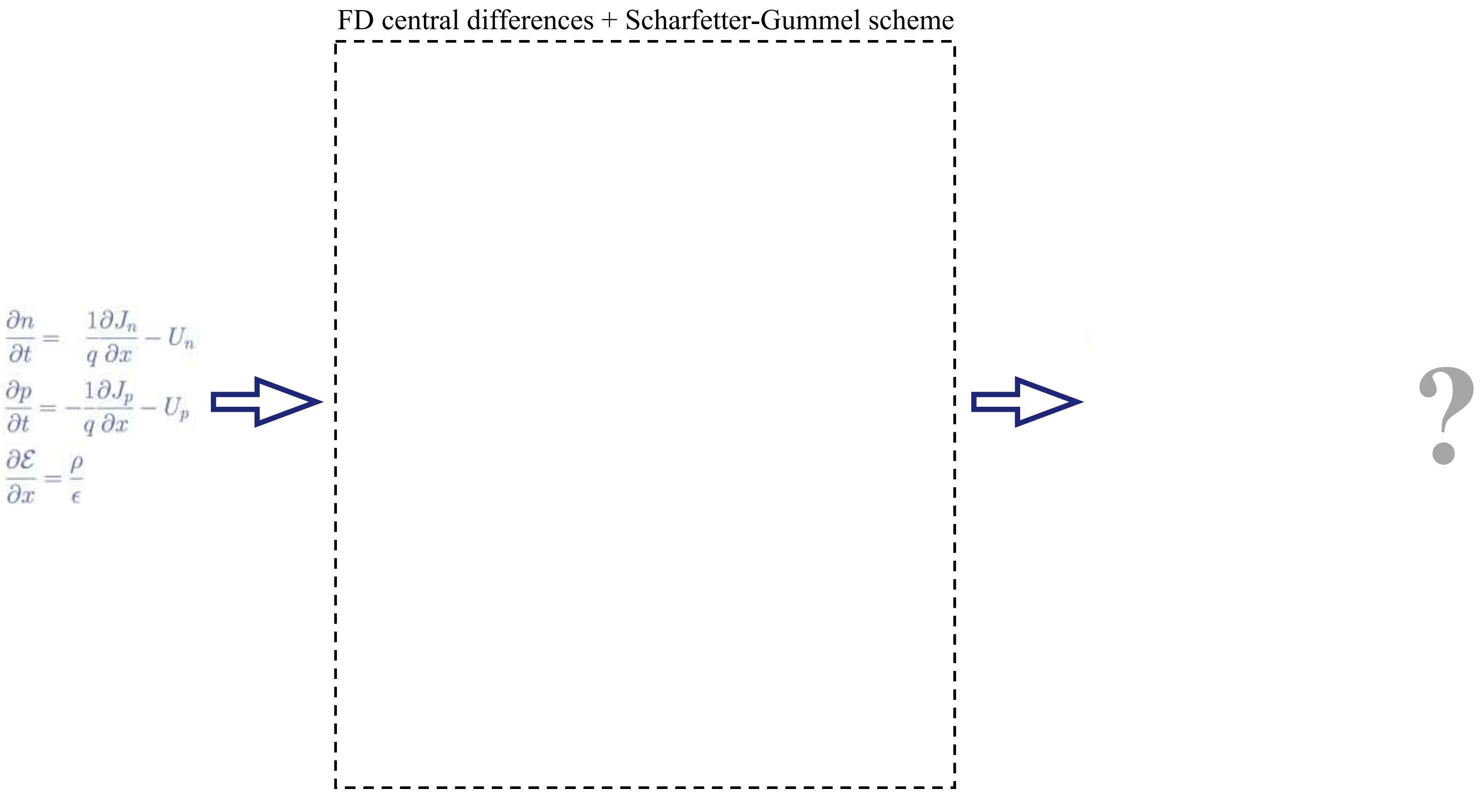
$$\oint_\Gamma \mathbf{F}_\perp\,\mathrm{d}\gamma \Rightarrow \sum_j l_{ij}\,\langle \mathbf{F}_\perp \rangle_{ij}$$

$$\int_S c\,\mathrm{d}s \Rightarrow c_i\,S_i$$

by **averaging** the **in/out quantities** at each box side, they are computed at **nodes**

Electronic device modeling - II

3. PDEs are linearized and transformed into **ODEs (FD schemes)**



FD central differences + Scharfetter-Gummel scheme

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} - U_n$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} - U_p$$

$$\frac{\partial \mathcal{E}}{\partial x} = \frac{\rho}{\epsilon}$$

Electronic device modeling - II

4. **I.C.** and **B.C.** are defined

Initial Conditions: starting polarization at contacts

Boundary Conditions:

$$\frac{\partial n(\mathbf{r},t)}{\partial \hat{\mathbf{n}}} = 0\,, \quad \frac{\partial p(\mathbf{r},t)}{\partial \hat{\mathbf{n}}} = 0 \quad \text{and} \quad \frac{\partial \phi(\mathbf{r},t)}{\partial \hat{\mathbf{n}}} = 0$$

Neumann *homogeneous* (insulators, external edges,…)

$$\begin{cases} n(\mathbf{r},t)\,\mu_n \dfrac{\partial \phi(\mathbf{r},t)}{\partial \hat{\mathbf{n}}} = D_n \dfrac{\partial n(\mathbf{r},t)}{\partial \hat{\mathbf{n}}} \\ p(\mathbf{r},t)\,\mu_p \dfrac{\partial \phi(\mathbf{r},t)}{\partial \hat{\mathbf{n}}} = -D_p \dfrac{\partial p(\mathbf{r},t)}{\partial \hat{\mathbf{n}}} \\ \epsilon_\mathrm{s} \left. \dfrac{\partial \phi(\mathbf{r},t)}{\partial \hat{\mathbf{n}}} \right|_\mathrm{s} = \epsilon_\mathrm{diel} \left. \dfrac{\partial \phi(\mathbf{r},t)}{\partial \hat{\mathbf{n}}} \right|_\mathrm{diel} \end{cases}$$

Neumann *non-homogeneous* (dielectrics)

$$\begin{cases} n(\mathbf{r},t) = \dfrac{1}{2}\left(\sqrt{\displaystyle\sum_k C_k^{\pm 2}(\mathbf{r},t) + 4n_i^2} + \displaystyle\sum_k C_k^{\pm}(\mathbf{r},t)\right) \\ p(\mathbf{r},t) = \dfrac{1}{2}\left(\sqrt{\displaystyle\sum_k C_k^{\pm 2}(\mathbf{r},t) + 4n_i^2} - \displaystyle\sum_k C_k^{\pm}(\mathbf{r},t)\right) \\ \phi(t) = V_\mathrm{bias}(t) + \mathrm{const.} \end{cases}$$

Dirichlet *non-homogeneous* (contacts)

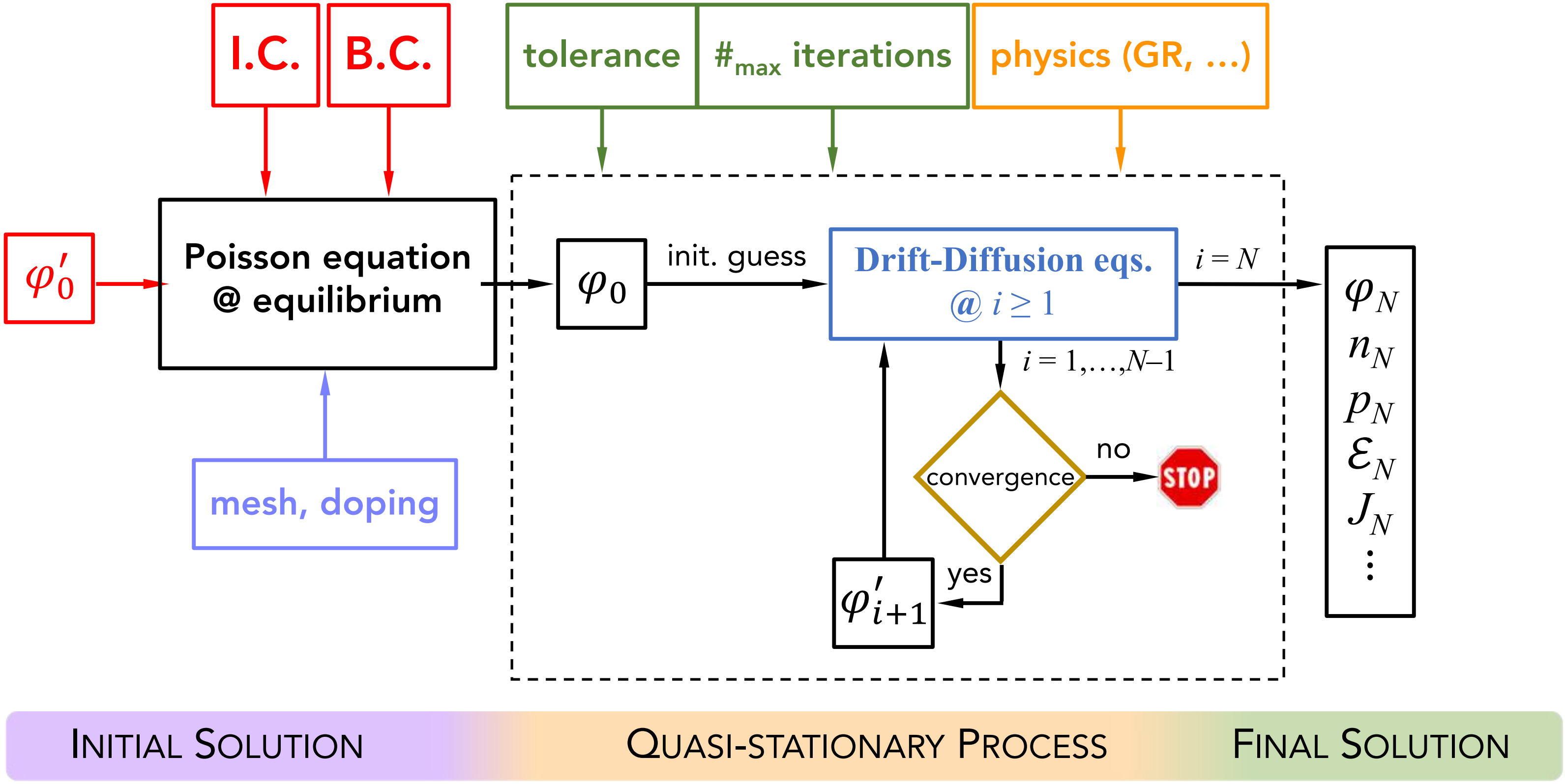
Electronic device modeling - II

- TCAD procedure for each node:
  a) Choose a **maximum number of iterations $\#_{max}$** and a **tolerance ε**
  b) Impose proper **I.C.** and **B.C.**
  c) Start from an **initial guess φ_0'** for the **electrostatic potential**
  d) The **equilibrium solution φ_0** is obtained by **solving only the Poisson equation** with the **I.C.** and **B.C.**

- If we have to perform a **voltage ramp** or a **transient**:
  d) each step i of the ramp (with $i = 1,\ldots,N$) is treated as a **quasi-stationary state**. The potential resulting from the Poisson solution at equilibrium φ_0 is used as initial guess for solving the **DD equations** at steps $i \geq 1$

- If the **solution** is found **within the maximum number of iterations $\#_{max}$** and with an **error smaller than the tolerance ε**, then **the system converges** and the scheme go further, otherwise:
  - The **pitch** of the steps Δi is **decreased**
  - The **tolerance** ε is **increased**
  - If the alternatives above fails, then the method is **aborted**

Electronic device modeling - II



Summary

I. Overview of semiconductor devices
  - The *pn* junction
  - Low Gain Avalanche Detectors (LGAD)

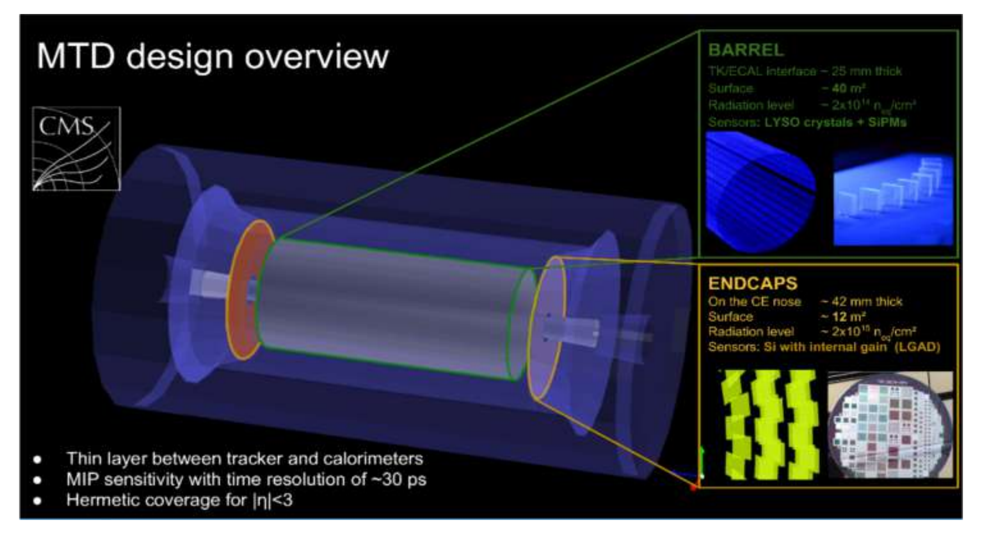
II. Electronic device modeling
  - Analytical description
  - Numerical implementation

III. LGAD design using numerical simulations

Design and simulation of LGAD

➤ Why LGAD are so innovative?

- **Large signals** coupled with **low Gain** ⟹ **high S/N**
- **Fast signals** ⟹ **high time resolution**
- **Simple design** ⟹ **low production cost**
- **Huge ongoing R&D** ⟹ **radiation hardness**

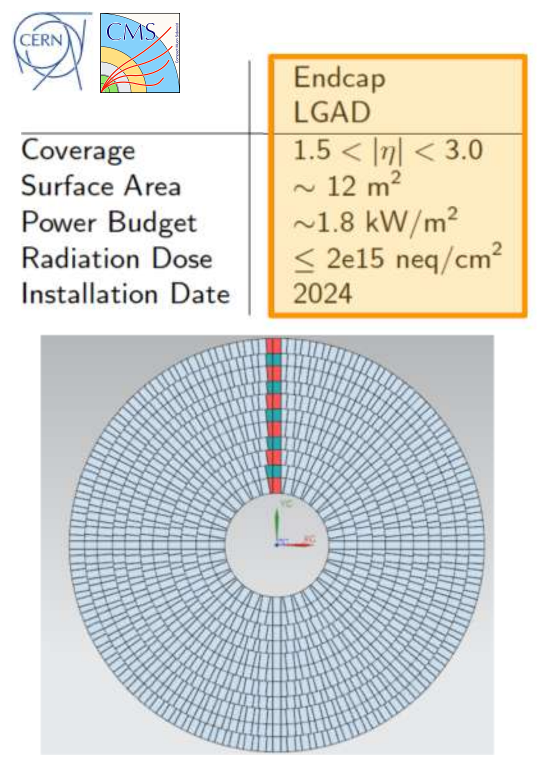


MTD design overview

BARREL
TK/ECAL interface ~ 25 mm thick
Surface ~ 40 m^2
Radiation level ~ 2x10^{14} n$_{eq}$/cm^2
Sensors: LYSO crystals + SiPMs

ENDCAPS
On the CE nose ~ 42 mm thick
Surface ~ 12 m^2
Radiation level ~ 2x10^{15} n$_{eq}$/cm^2
Sensors: Si with internal gain (LGAD)

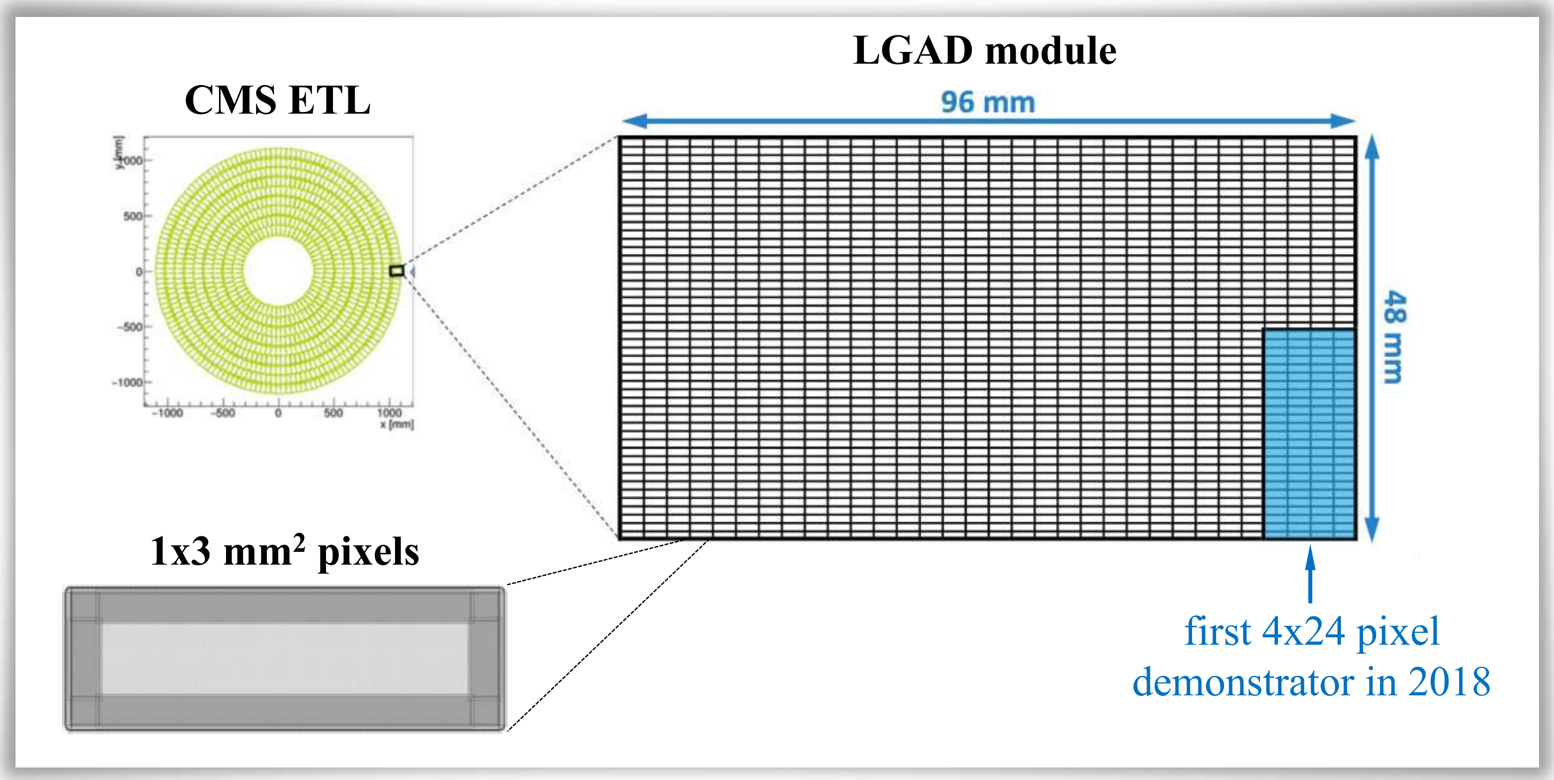
- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of ~30 ps
- Hermetic coverage for |η|<3



	Endcap LGAD
Coverage	$1.5 < \|\eta\| < 3.0$
Surface Area	$\sim$ 12 m^2
Power Budget	$\sim$1.8 kW/m^2
Radiation Dose	$\leq$ 2e15 neq/cm^2
Installation Date	2024

Design and simulation of LGAD

- **How a real LGAD module is made?**



CMS ETL

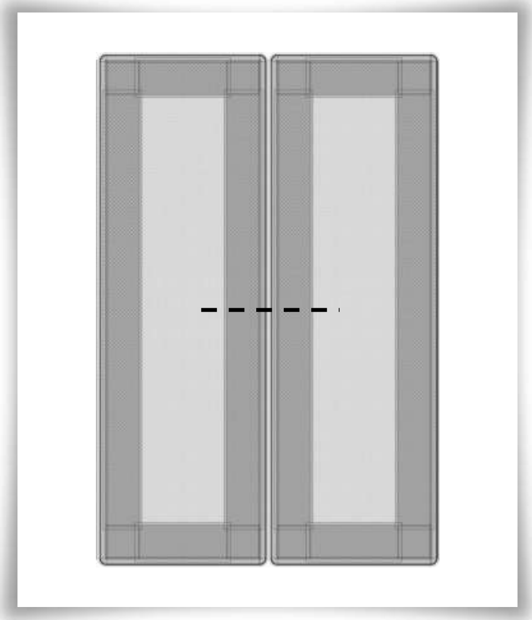
LGAD module

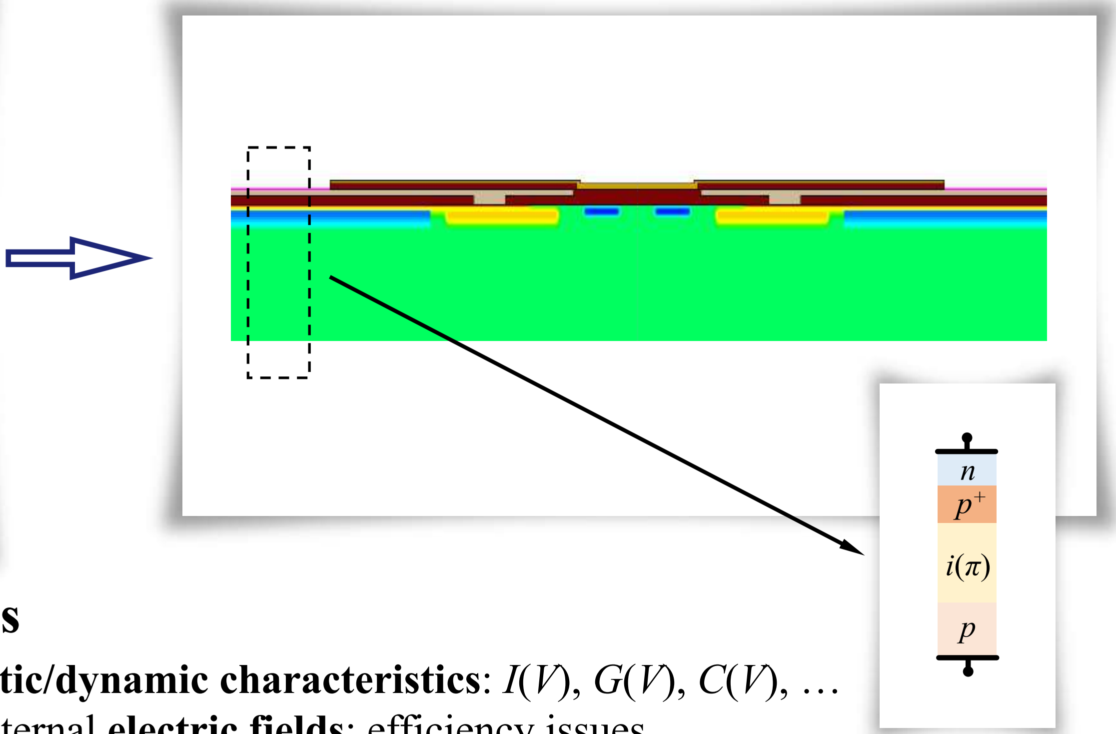
1x3 mm^2 pixels

first 4x24 pixel demonstrator in 2018

Design and simulation of LGAD

- **How a real LGAD module is made?**



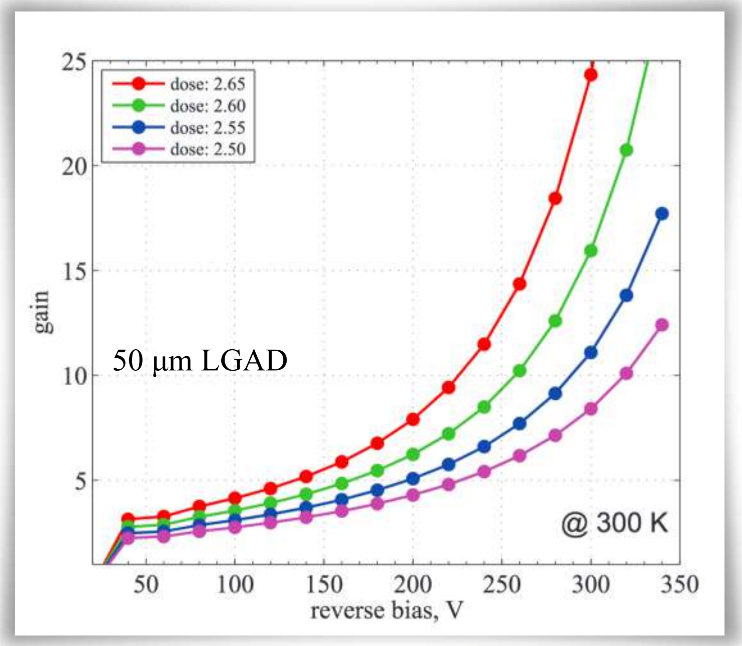


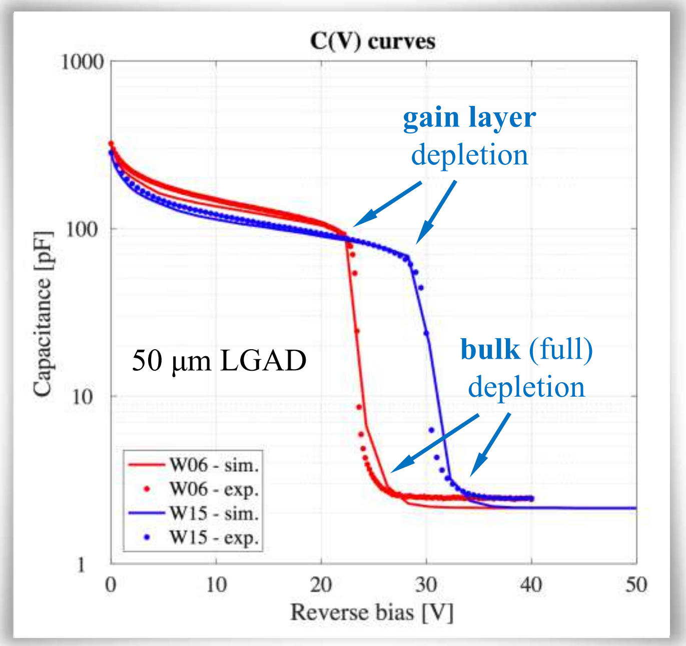
Three main R&D areas

1. Study of detector **static/dynamic characteristics**: $I(V)$, $G(V)$, $C(V)$, …
2. Analysis about the internal **electric fields**: efficiency issues, …
3. **Radiation tolerance**

Design and simulation of LGAD

1. Study of detector **static/dynamic characteristics**: *I*(*V*), *G*(*V*), *C*(*V*), …

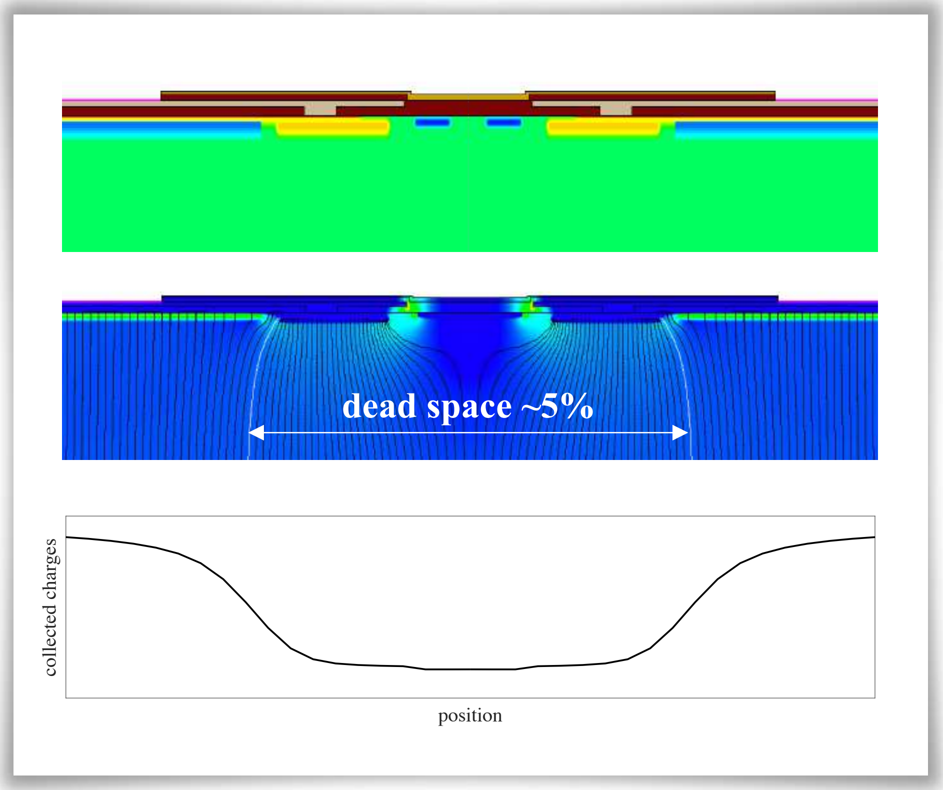




$$\alpha_{n,p}(\mathcal{E}) = \gamma\, A_{n,p} \exp\left(-\gamma \frac{B_{n,p}}{\mathcal{E}}\right)$$

Design and simulation of LGAD

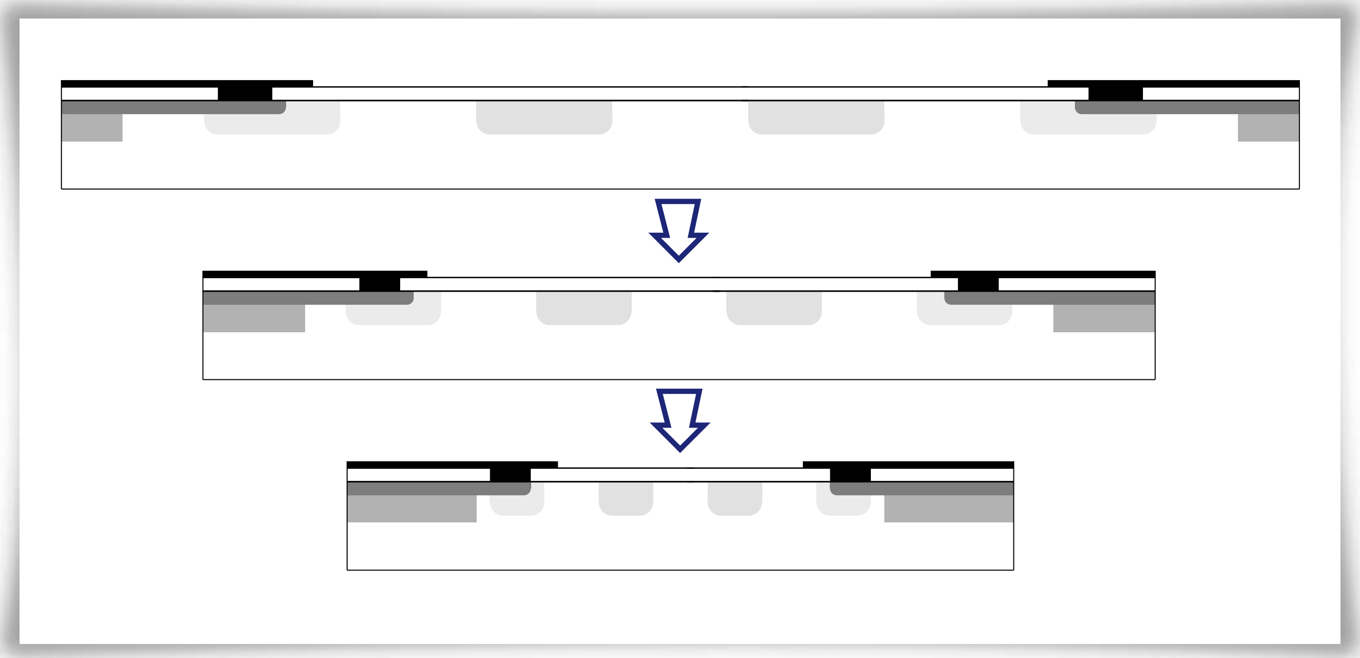
2. Analysis about the internal **electric fields**: efficiency issues, …



Design and simulation of LGAD

2. Analysis about the internal **electric fields**: efficiency issues, …

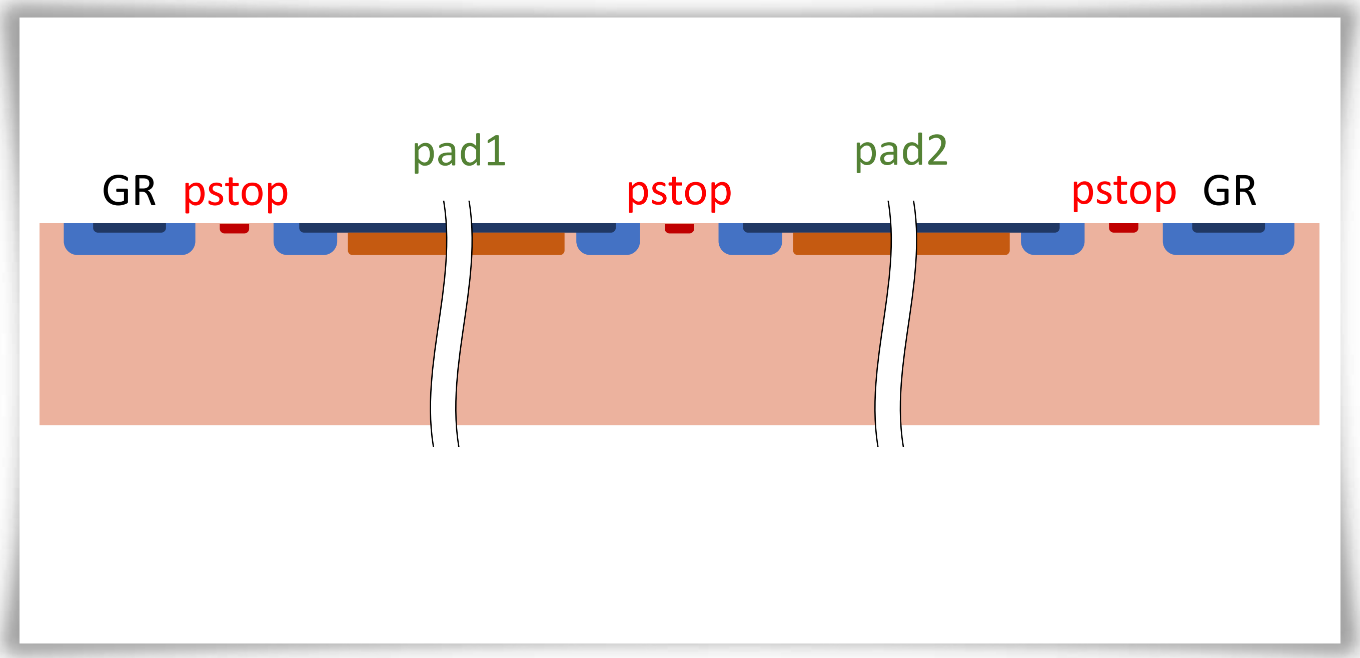
- **Two main strategies:**
  - *a. layout scaling*



Design and simulation of LGAD

2. Analysis about the internal **electric fields**: efficiency issues, …

- **Two main strategies:**
  - *a. layout scaling*

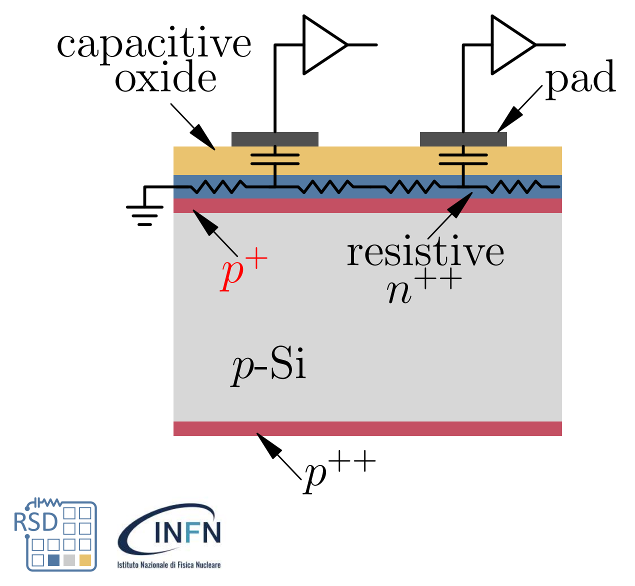


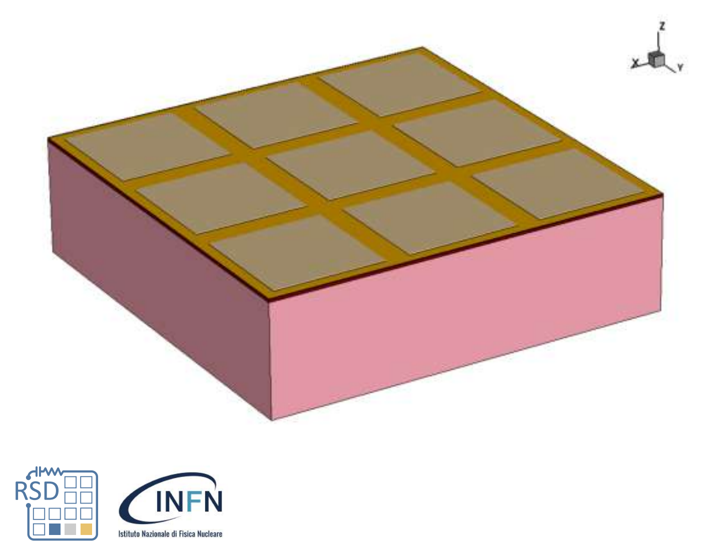
Design and simulation of LGAD

2. Analysis about the internal **electric fields**: efficiency issues, …

- **Two main strategies:**

  b. implement a new readout approach





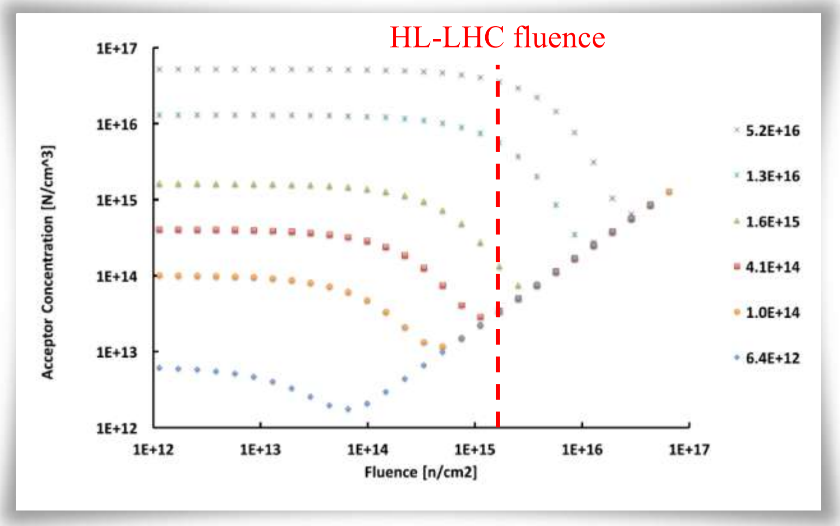
Design and simulation of LGAD

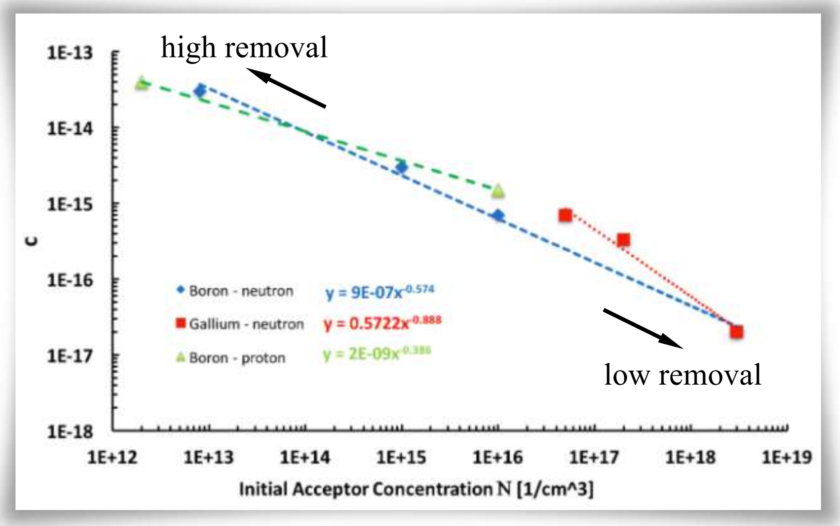
3. **Radiation tolerance**

empirical **acceptor removal/creation** law

$$N_\mathrm{A}(\phi, x) = g_\mathrm{eff}\,\phi + N_\mathrm{A}(0,x)\,\mathrm{e}^{-c(N_\mathrm{A}(0,x))\phi}$$

$$c\,(N_\mathrm{A}(0,x)) = \alpha\,N_\mathrm{A}(0,x)^{-\beta}$$





Design and simulation of LGAD

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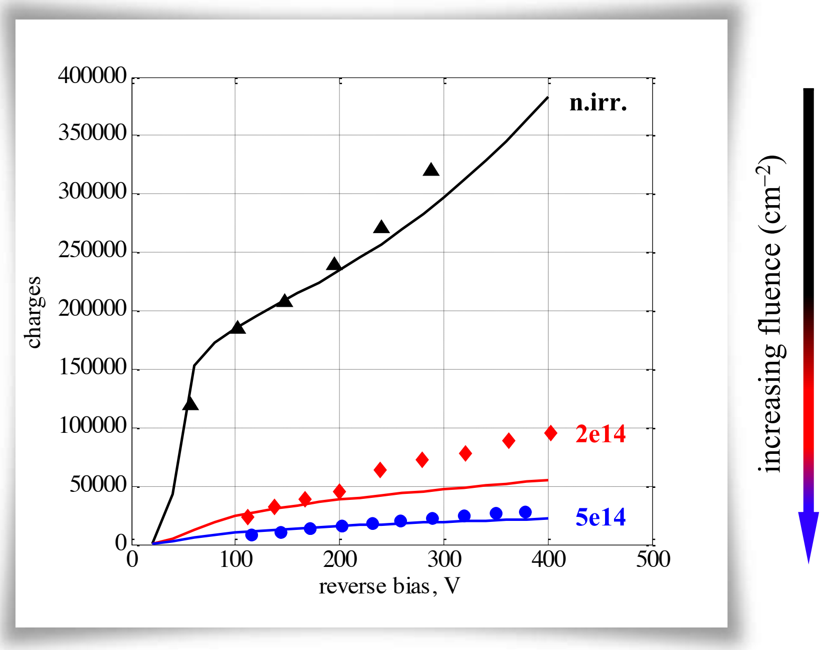
$$N_A(\phi, x) = g_{\text{eff}}\,\phi + N_A(0, x)\,\mathrm{e}^{-c(N_A(0,x))\phi} \qquad c\,(N_A(0, x)) = \alpha\, N_A(0, x)^{-\beta}$$



Design and simulation of LGAD

1. Study of detector **static/dynamic characteristics**: $I(V)$, $G(V)$, $C(V)$, …

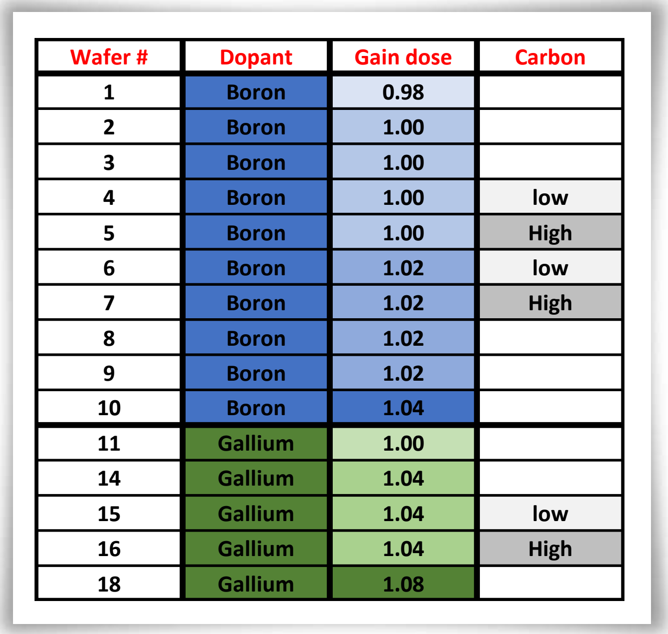
+

2. Analysis about the internal **electric fields**: efficiency issues, …

+

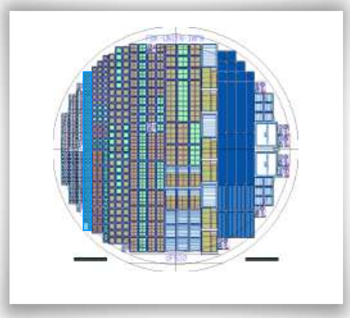
3. **Radiation tolerance**

1. + 3.

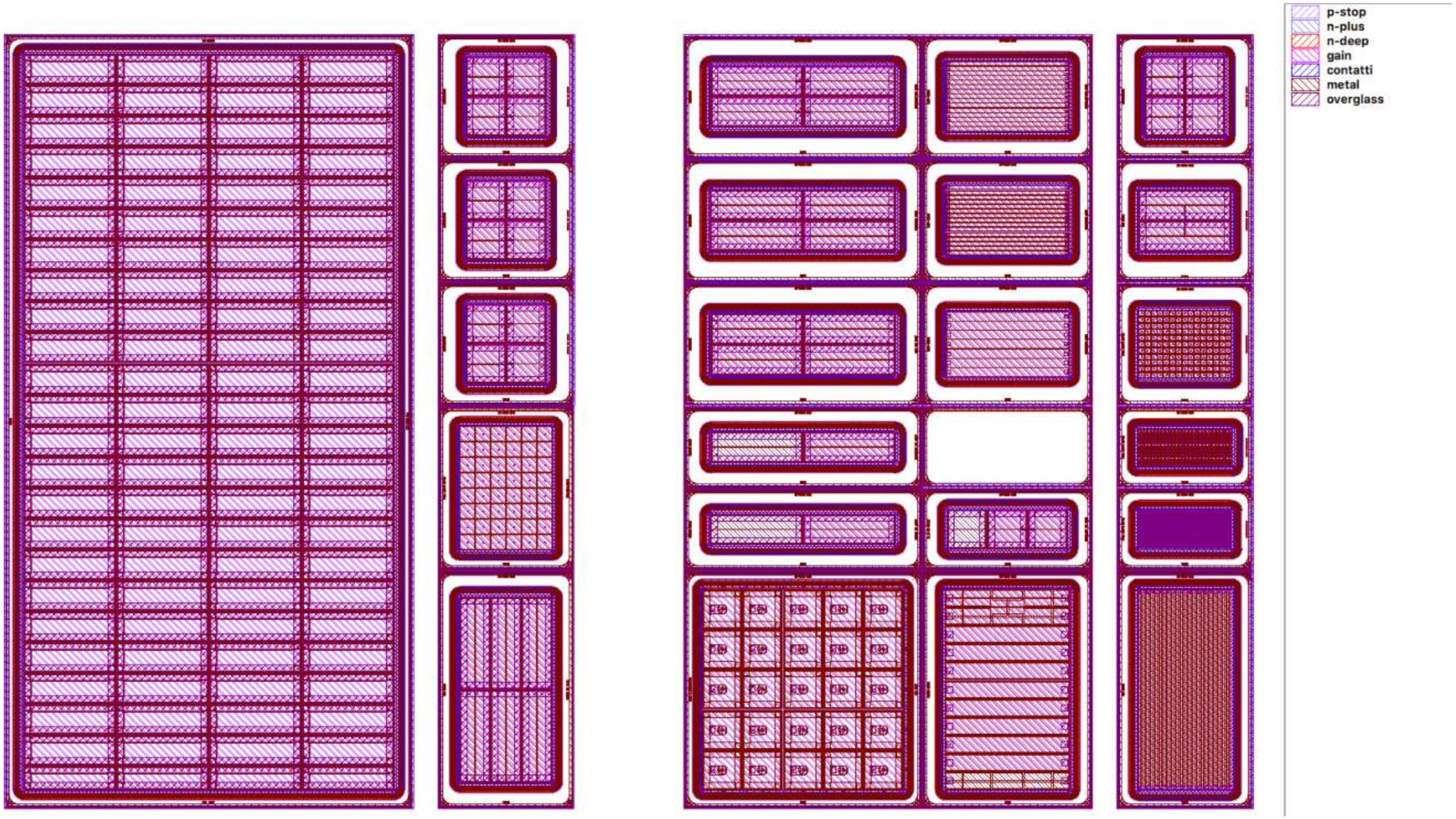


Wafer #	Dopant	Gain dose	Carbon
1	Boron	0.98	
2	Boron	1.00	
3	Boron	1.00	
4	Boron	1.00	low
5	Boron	1.00	High
6	Boron	1.02	low
7	Boron	1.02	High
8	Boron	1.02	
9	Boron	1.02	
10	Boron	1.04	
11	Gallium	1.00	
14	Gallium	1.04	
15	Gallium	1.04	low
16	Gallium	1.04	High
18	Gallium	1.08	

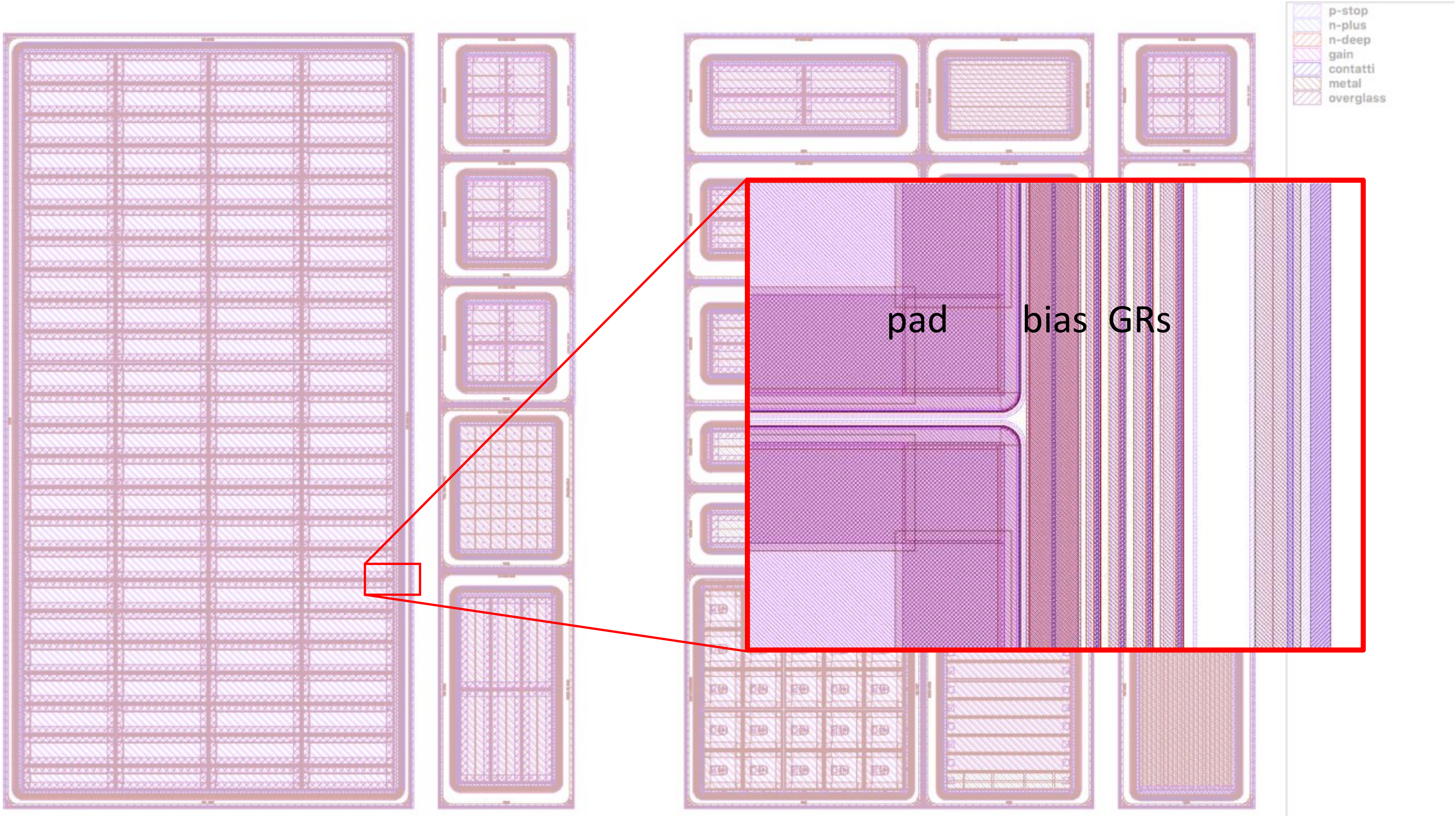
2.



Design and simulation of LGAD



Design and simulation of LGAD



Design and simulation of LGAD

1. Study of detector **static/dynamic characteristics**: *I*(*V*), *G*(*V*), *C*(*V*), …

+

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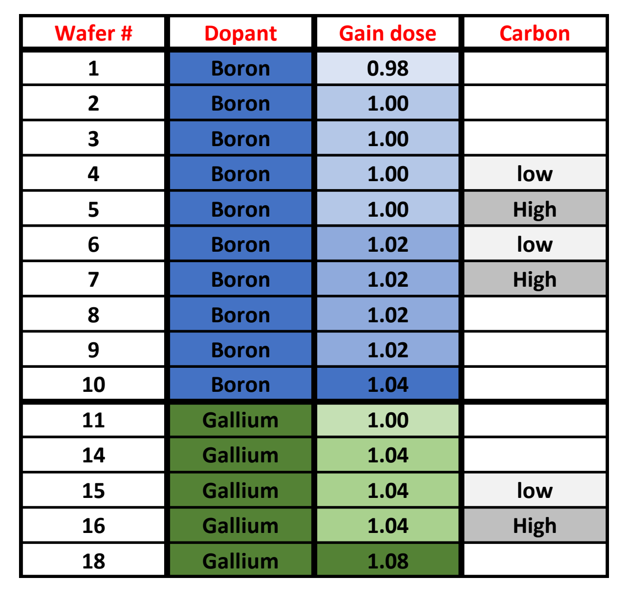
+

3. **Radiation tolerance**

1. + 3.



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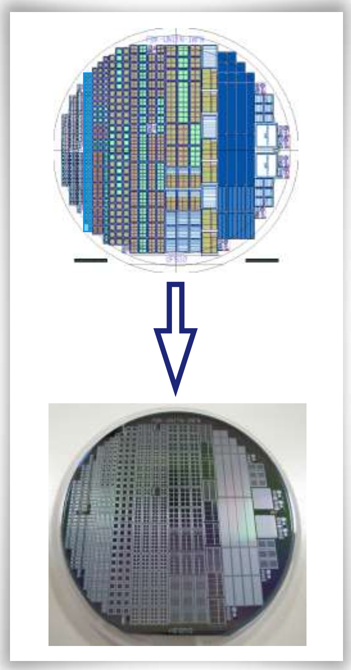
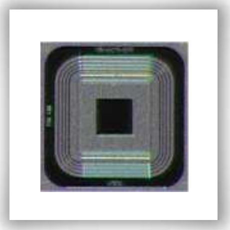
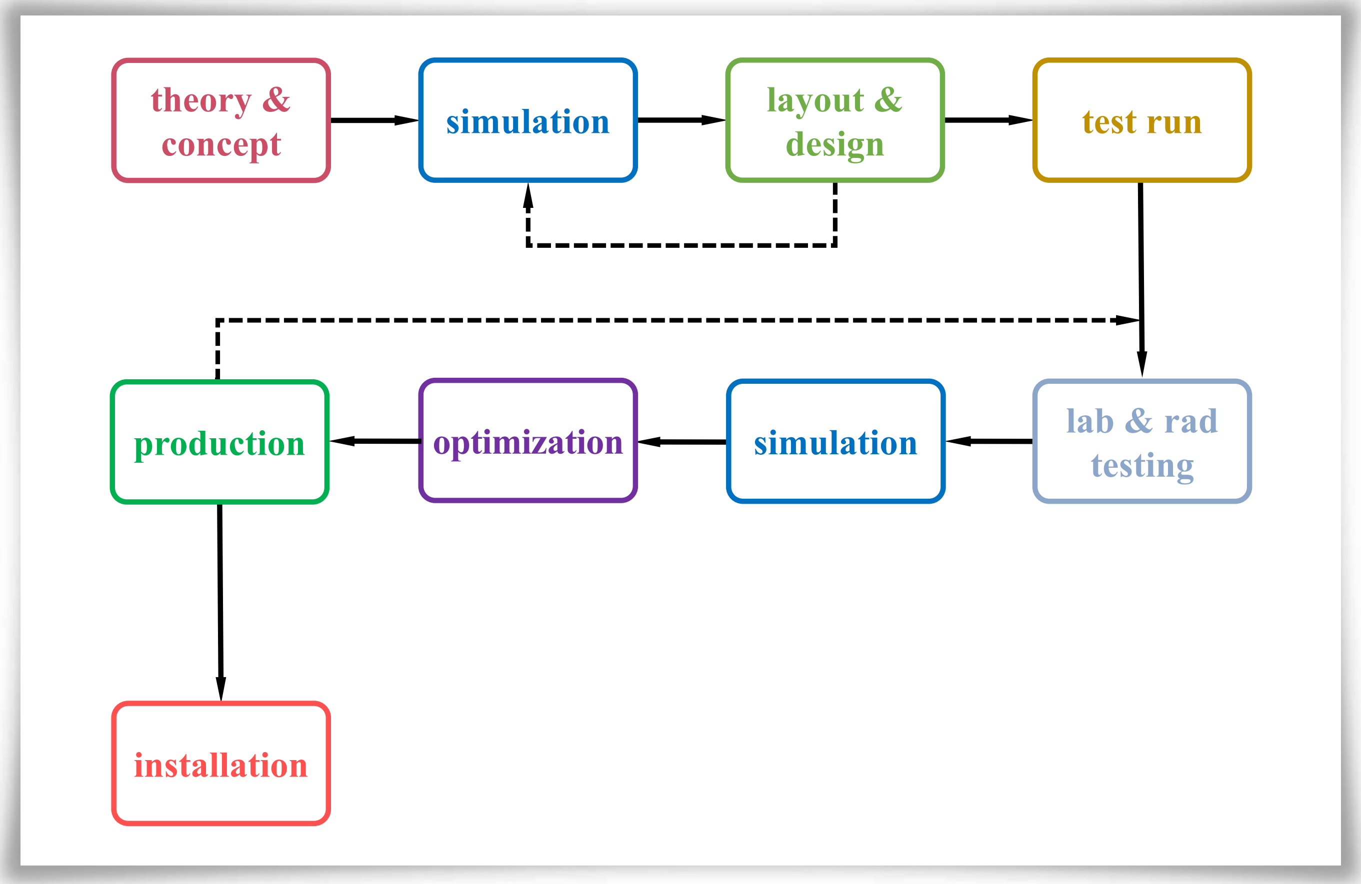
9	Boron	1.02	
10	Boron	1.04	
11	Gallium	1.00	
14	Gallium	1.04	
15	Gallium	1.04	low
16	Gallium	1.04	High
18	Gallium	1.08	

2.





LGAD production: the complete workflow!



Contacts and Info

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⇒ To download this presentation and for more info about simulation: http://personalpages.to.infn.it/~mandurri/teaching.html
⇒ About the RSD experiment: http://personalpages.to.infn.it/~mandurri/rsdproject.html
⇒ Master Thesis Proposal: http://personalpages.to.infn.it/~mandurri/teaching/Proposta_di_Tesi_LM_RSD.pdf