IFD 2022 : INFN Workshop on Future Detectors

17-19 October 2022 Bari- Italy

Innovations in the design of thin silicon sensors for extreme fluences

V. Sola, R. Arcidiacono, P. Asenov, G. Borghi, M. Boscardin, N. Cartiglia, M. Centis Vignali, T. Croci, M. Ferrero, S. Giordanengo, L. Menzio, V. Monaco, A. Morozzi, F. Moscatelli, D. Passeri, G. Paternoster, F. Siviero, M. Tornago

Fisica Torino Dipartimento di Eccellenza

FONDAZIONE BRUNO KESSLER

ISTITUTO OFFICINA DEI MATERIALI

Bari - Lungomare Rotonda

The Challenge

At present, difficult to operate silicon sensors above 10^{16} n_{eq}/cm^2

The goals

- ➢ Measure the **properties of silicon sensors** at fluences above 10^{16} n_{eq}/cm^2
- ➢ Design **planar silicon sensors** able to work in the fluence range $10^{16} - 10^{17}$ n_{eq}/cm^2
- ➢ Estimate if such sensors generate **enough charge** to be used in a detector exposed to extreme fluences

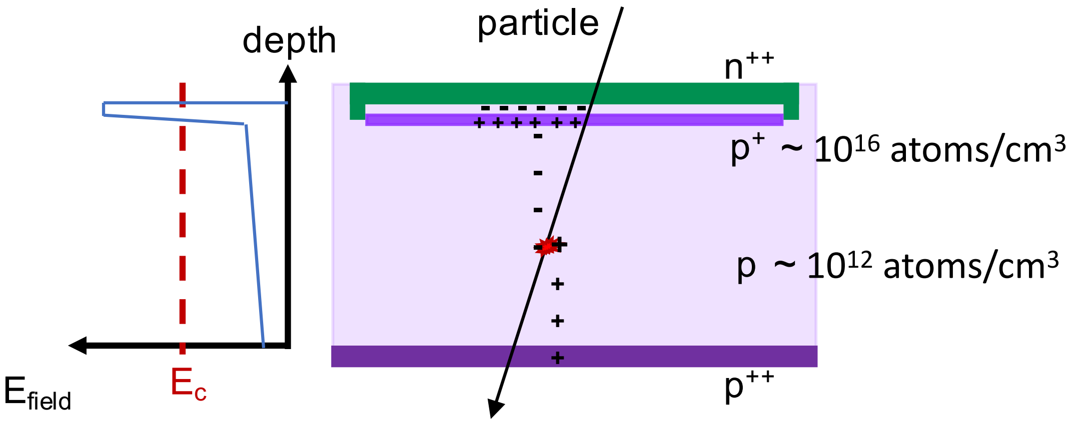
The strategy

To overcome the present limits above 10^{16} n_{eq}/cm^2 we exploit:

1. **Saturation** of the radiation damage effects above $5 \cdot 10^{15}$ n_{eq}/cm^2
2. The use of **thin** active substrates (20 – 40 μm)
3. **Extension** of the charge carrier multiplication up to 10^{17} n_{eq}/cm^2

→ **The whole research program is performed in collaboration with FBK**

Low-Gain Avalanche Diodes

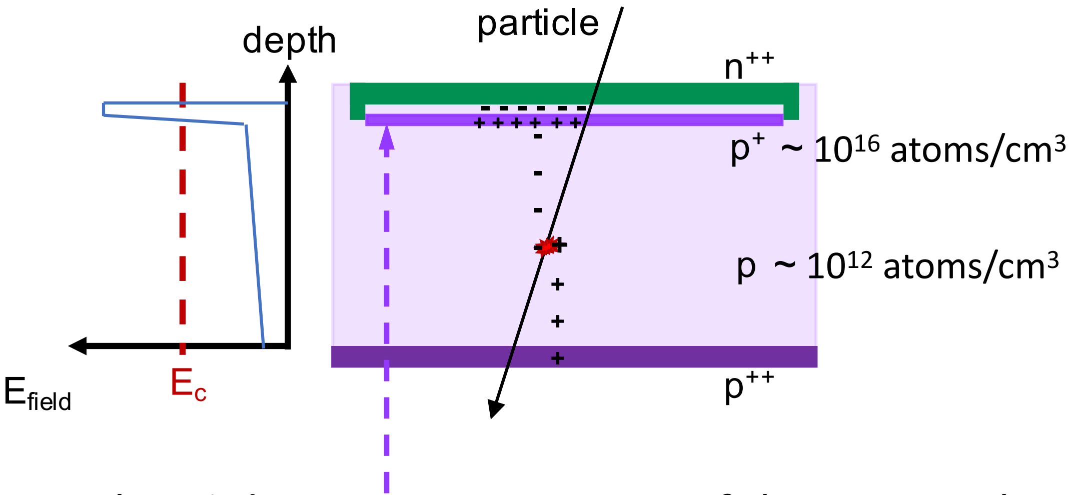


Low-Gain Avalanche Diodes (**LGADs**) are n-in-p silicon sensors

Operated in low-gain regime (~ 20) **controlled** by the external bias

Critical electric field $E_C \sim 20 - 30$ V/µm ⟶ **gain layer region**

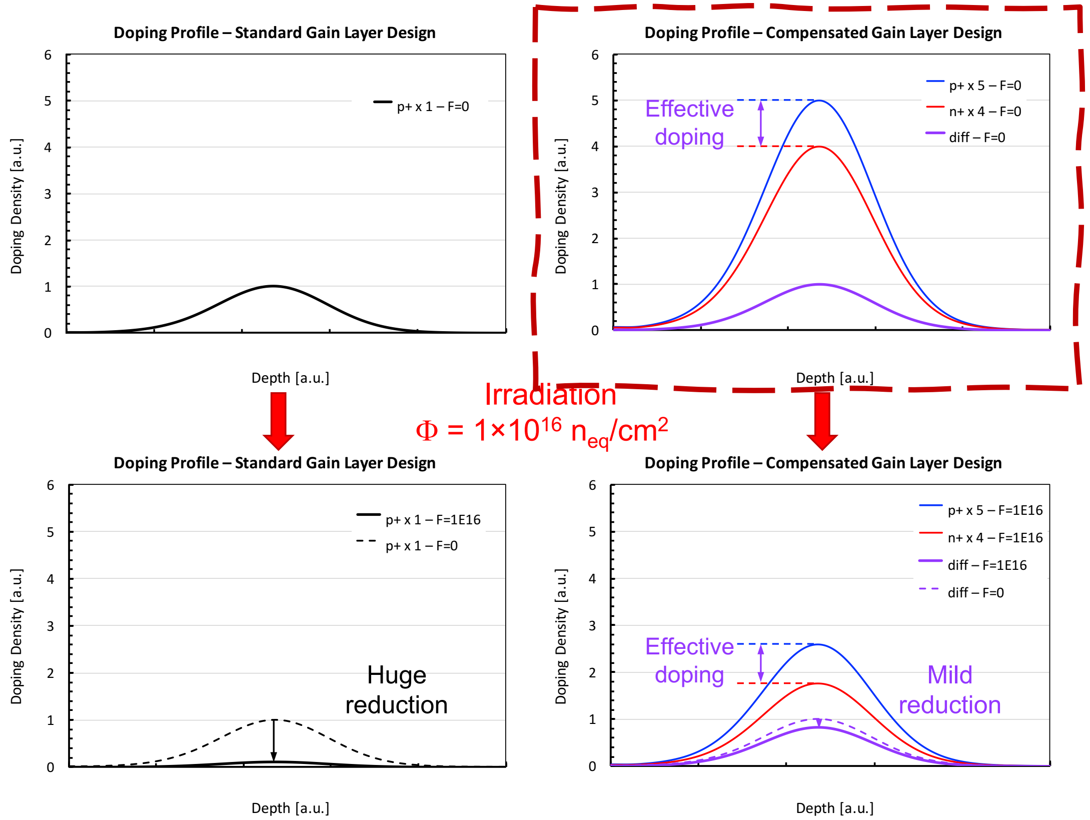
Low-Gain Avalanche Diodes – Innovation



Low-Gain Avalanche Diodes (**LGADs**) are n-in-p silicon sensors

Operated in low-gain regime (~ 20) **controlled** by the external bias

Critical electric field E_C ~ 20 – 30 V/μm → **gain layer region**



The p^{+} dopant concentration of the gain implant gets **reduced** by irradiation and LGADs loose their multiplication power above ~ $3{\cdot}10^{15}\ n_{eq}/cm^2$

An **innovative design** of the gain implant has been designed to extend signal multiplication up to ~ $10^{17}\ n_{eq}/cm^2$

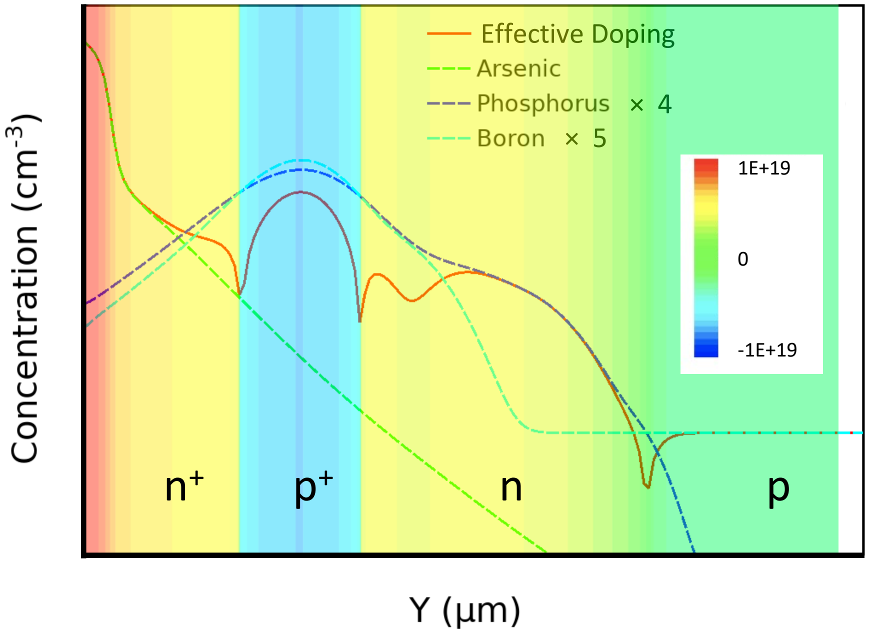
→ **Complensated LGAD**

From Simulation to Production

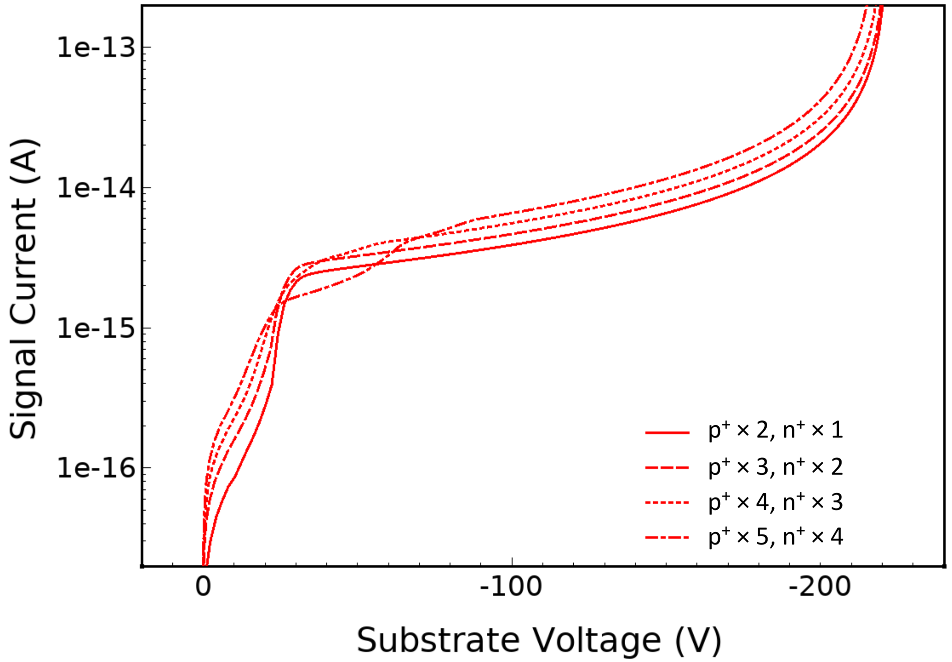
Process simulations of Boron (p^+) and Phosphorus (n^+) implantation have been performed

The electrostatic simulation shows that it is possible to optimise the production process to replicate the operation conditions of standard LGADs

Doping Profiles from Process Simulation



I-V from Simulation



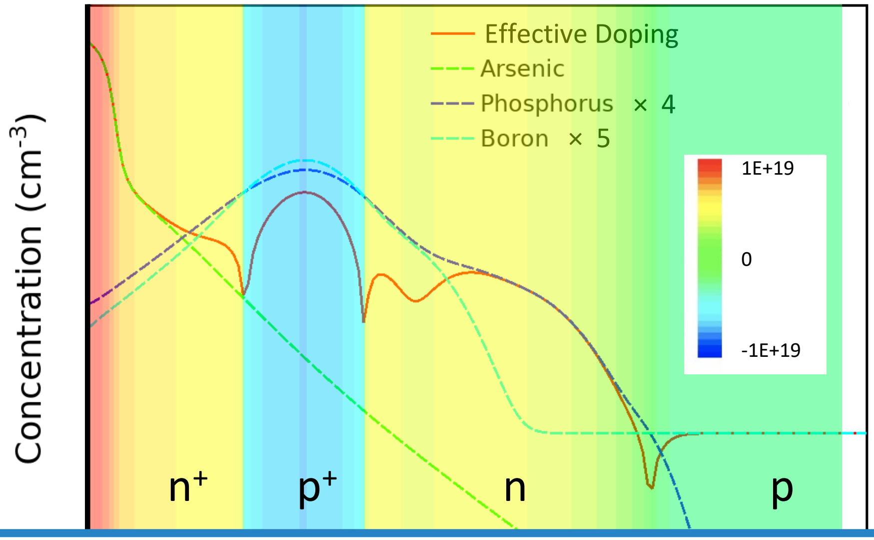
→ The first batch of compensated LGAD is about to be delivered by FBK

From Simulation to Production

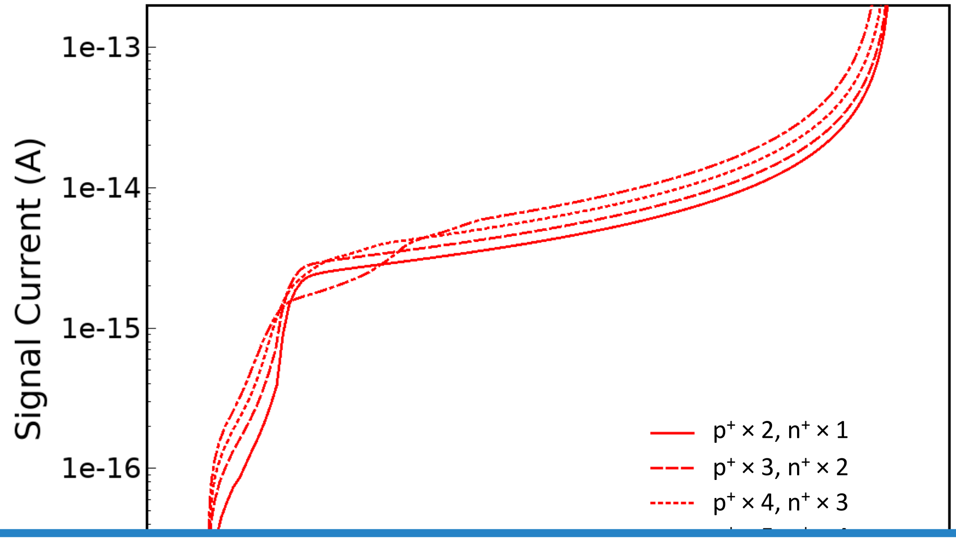
Process simulations of Boron (p^+) and Phosphorus (n^+) implantation have been performed

The electrostatic simulation shows that it is possible to optimise the production process to replicate the operation conditions of standard LGADs

Doping Profiles from Process Simulation



I-V from Simulation



→ A 3 years project has been accepted for funding by AIDAinnova as Blue Sky R&D to investigate and develop the compensated LGAD design

Acknowledgements

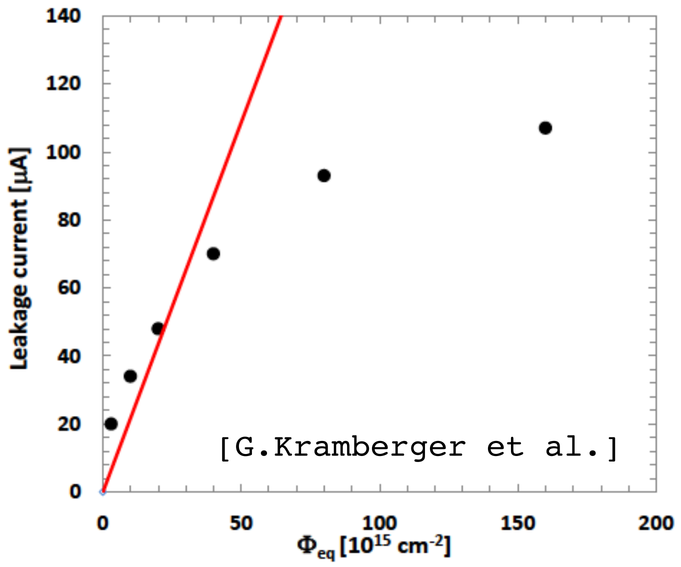
We kindly acknowledge the following funding agencies and collaborations:

- INFN CSN5
- Ministero della Ricerca, Italia, FARE, R165xr8frt_fare
- Ministero della Ricerca, Italia, PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- MIUR, Dipartimenti di Eccellenza (ex L. 232/2016, art. 1, cc. 314, 337)
- Università deli Studi di Torino, Grant for Internationalization – SOLV_GFI_22_01_F
- European Union’s Horizon 2020 Research and Innovation programme, Grant Agreement No. 101004761
- AIDAinnova, WP13
- RD50, CERN

Backup

Radiation Effect Saturation

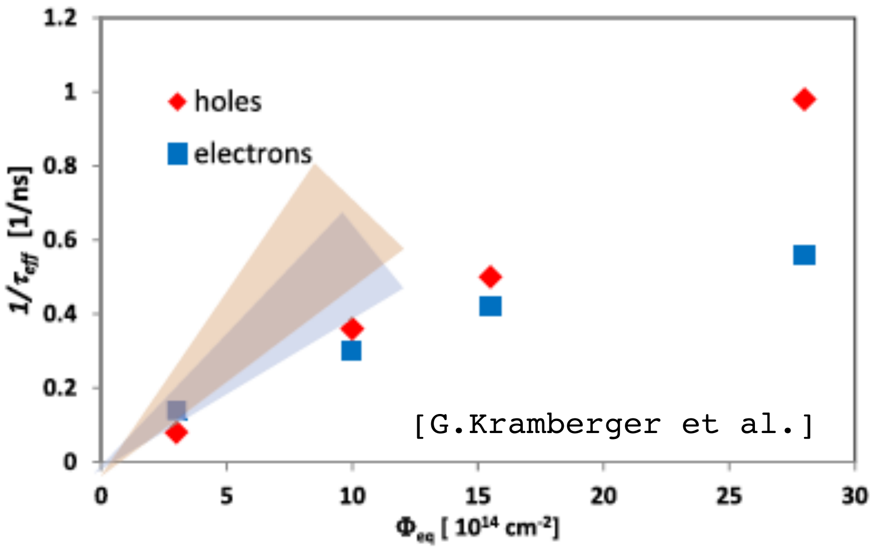
At fluences above $5 \cdot 10^{15}$ cm^{-2} → **Saturation of radiation effects observed**



Leakage current saturation

$I = \alpha V \Phi$

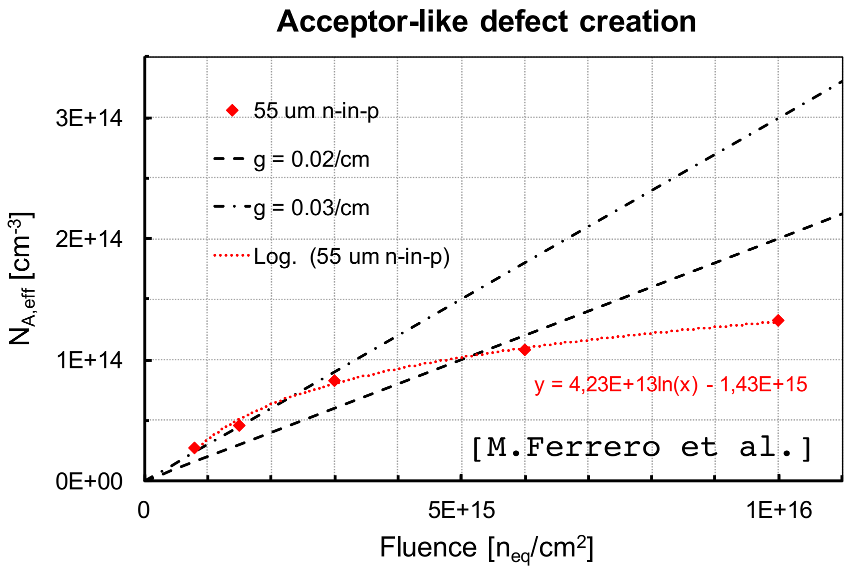
α from linear to logarithmic



Trapping probability saturation

$1/\tau_{eff} = \beta \Phi$

β from linear to logarithmic



Acceptor creation saturation

$N_{A,eff} = g_c \Phi$

g_c from linear to logarithmic

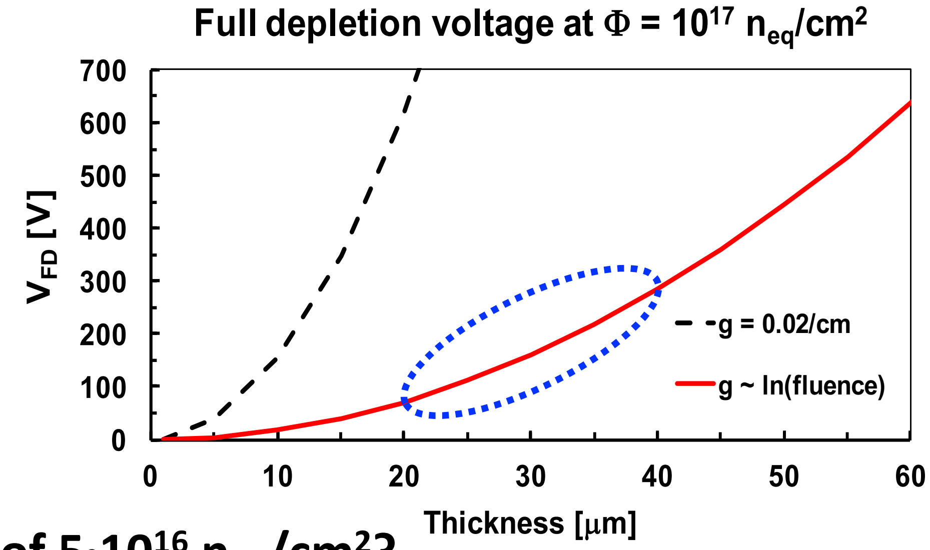
Silicon detectors irradiated at fluences 10^{16} – 10^{17} n_{eq}/cm^2 do not behave as expected → They behave better

Thin Substrates

$V_{FD} = e|N_{eff}|d^2/2\varepsilon$

Saturation → N_{eff} **Reduce thickness** → d^2

At high fluences, only thin substrates can be fully depleted



What does it happen to a 25 μm sensor after a fluence of $5 \cdot 10^{16}$ n_{eq}/cm^2?

- It can still be depleted
- Trapping is limited (small drift length)
- Dark current is low (small volume)

However: charge deposited by a MIP ~ 0.25 fC

→ This charge is lower than the minimum charge requested by the electronics (**~ 1 fC** for tracking, $\gtrsim$ **5 fC** for timing)

→ **Need a gain of at least ~ 5** in order to efficiently record a hit

Optimal candidate: LGAD sensors

A new Sensor Design

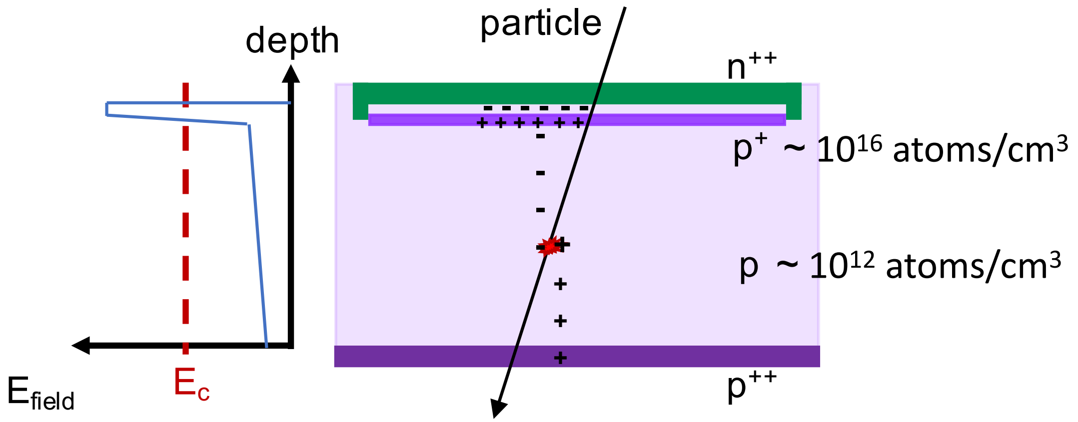
Difficult to operate silicon sensors above 10^{16} n_{eq}/cm^2 due to:

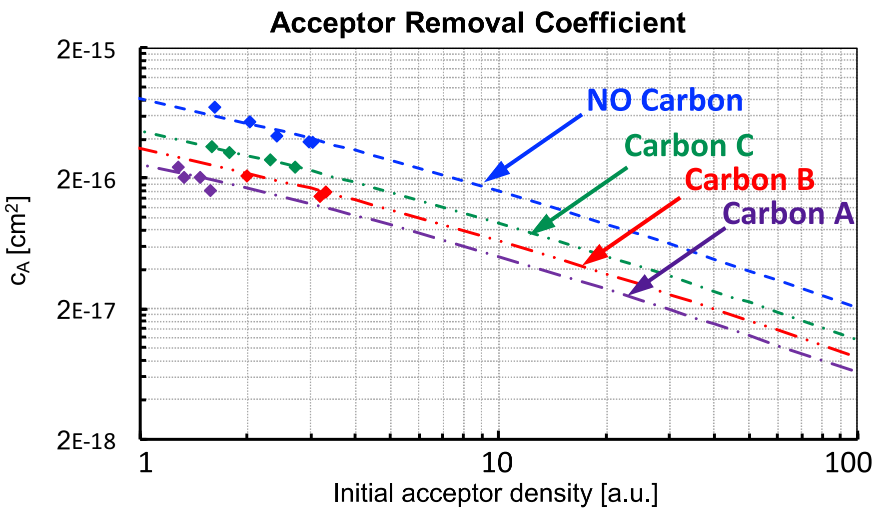
- defects in the silicon lattice structure → increase of the dark current
- trapping of the charge carriers → decrease of the charge collection efficiency
- change in the bulk effective doping → impossible to fully deplete the sensors

The ingredients to overcome the present limits above 10^{16} n_{eq}/cm^2 are:

1. **saturation** of the radiation damage effects above $5 \cdot 10^{15}$ n_{eq}/cm^2
2. the use of **thin** active substrates (20 – 40 μm)
3. **extension** of the charge carrier multiplication up to 10^{17} n_{eq}/cm^2

Gain Removal Mechanism in LGADs





The acceptor removal mechanism deactivates the p^+-doping of the **gain layer** with irradiation according to

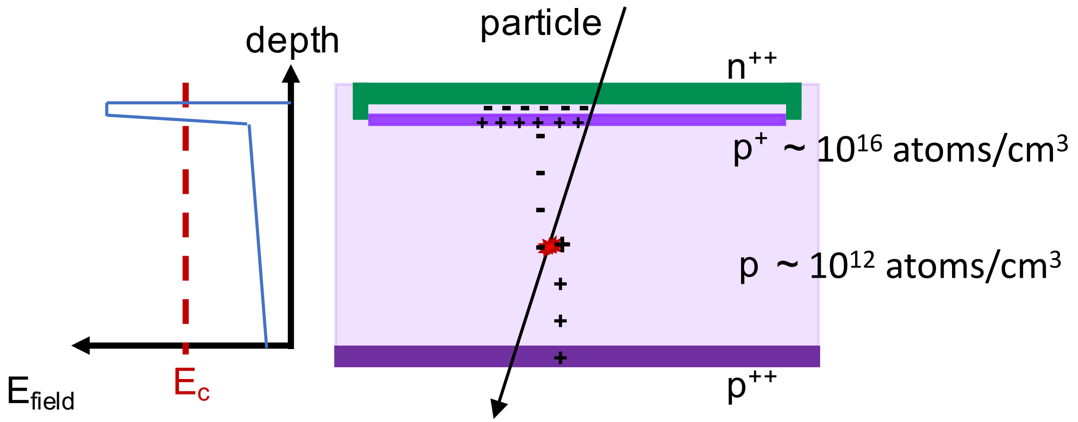
$$p^+(\Phi) = p^+(0) \cdot e^{-c_A \Phi}$$

where c_A is the acceptor removal coefficient

c_A depends on the initial acceptor density, $p^+(0)$, and on the defect engineering of the gain layer atoms

[M. Ferrero et al., doi:10.1016/j.nima.2018.11.121]

Towards a Radiation Resistant Design

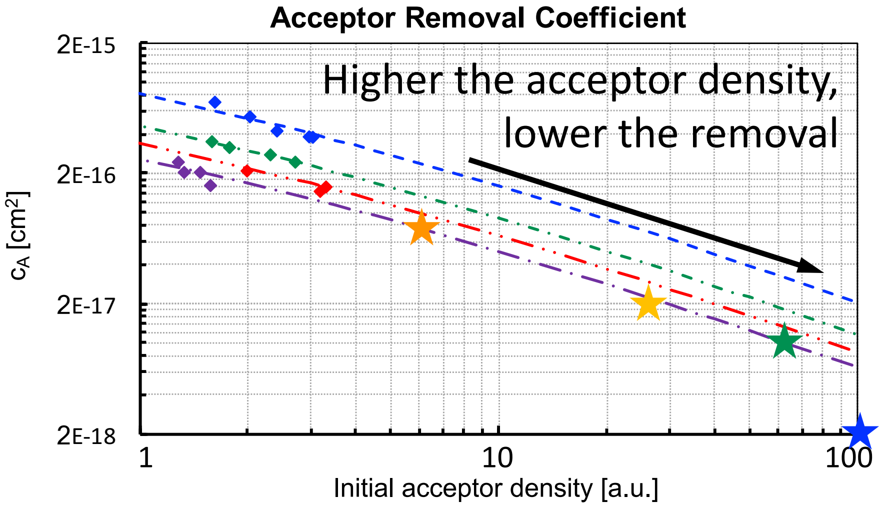


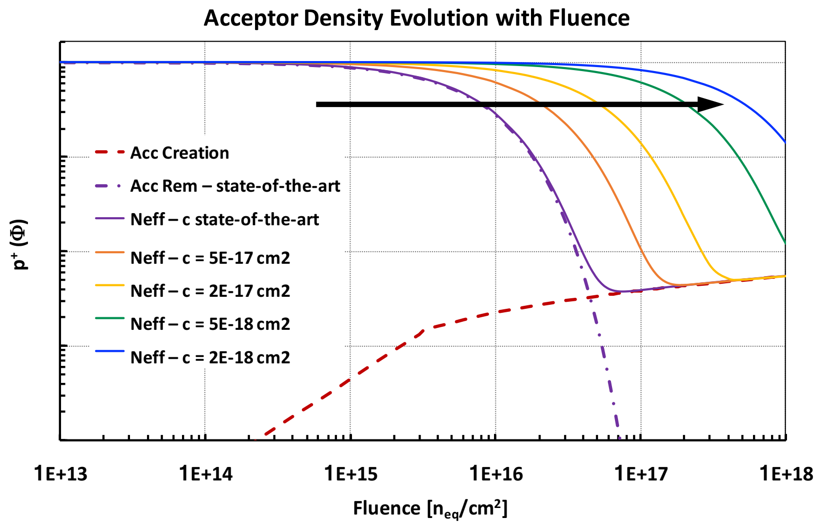
The acceptor removal mechanism deactivates the p^+-doping of the **gain layer** with irradiation according to

$$p^+(\Phi) = p^+(0)\cdot e^{-c_A\Phi}$$

where c_A is the acceptor removal coefficient

c_A depends on the initial acceptor density, $p^+(0)$, and on the defect engineering of the gain layer atoms





Lowering c_A extends the gain layer survival up to the highest fluences

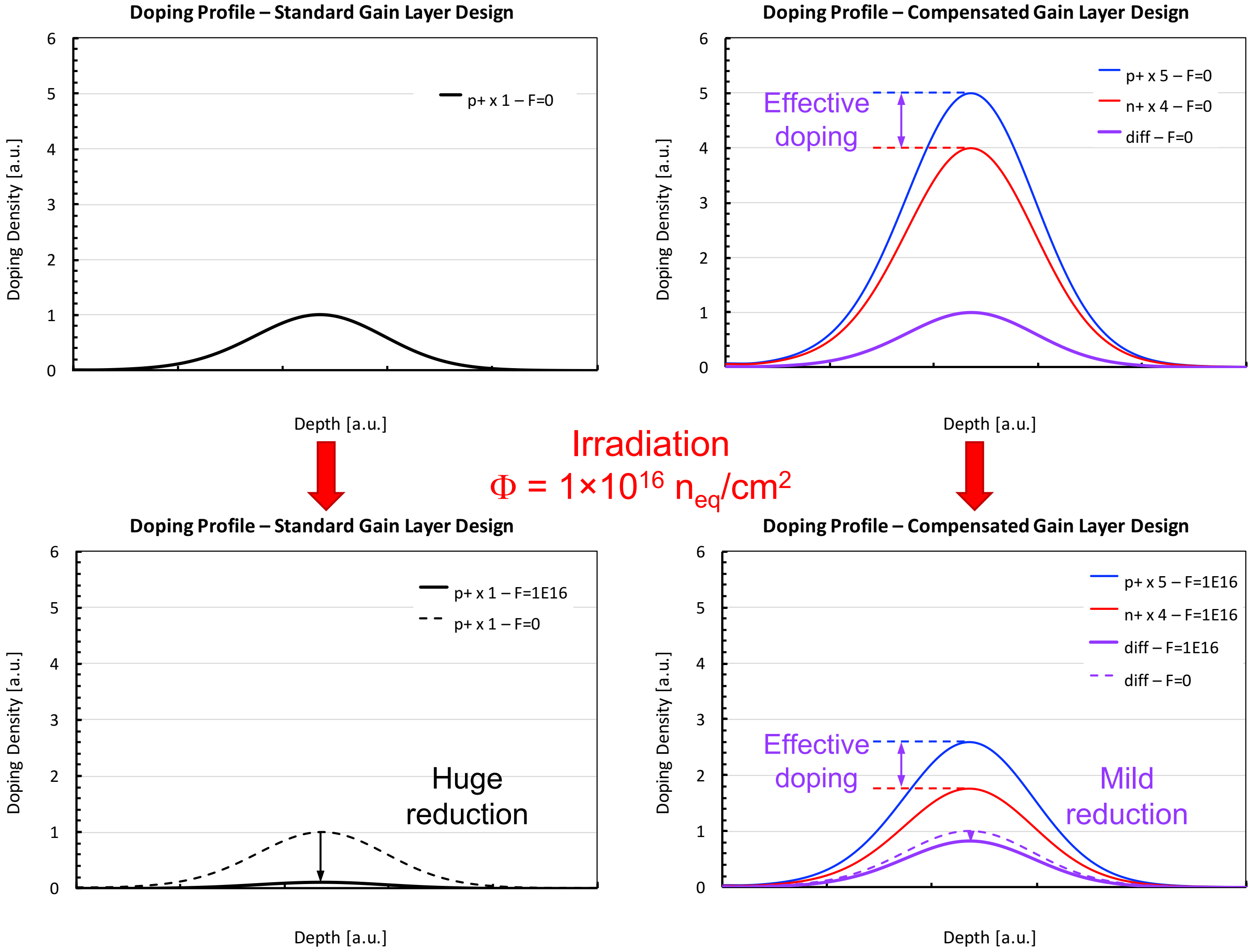
A new Paradigm – Compensation

Impossible to reach the design target with the present design of the gain layer

Use the interplay between acceptor and donor removal to keep a constant gain layer active doping density

Many unknown:

- ▻ donor removal coefficient, from $n^{+}(\Phi) = n^{+}(0) \cdot e^{-c_D \Phi}$
- ▻ interplay between donor and acceptor removal (c_D vs c_A)
- ▻ effects of substrate impurities on the removal coefficients



Compensation – Doping Evolution with Φ

Three scenarios of net doping evolution with fluence are possible, according to the acceptor and donor removal interplay:

1. **$c_A \sim c_D$**

   p^+ & n^+ difference will remain constant $\Rightarrow$ unchanged gain with irradiation

   $\rightarrow$ **This is the best possible outcome**

2. **$c_A > c_D$**

   effective doping disappearance is slower than in the standard design

   $\rightarrow$ **Co-implantation of Carbon** atoms mitigates the removal of p^+-doping

3. **$c_A < c_D$**

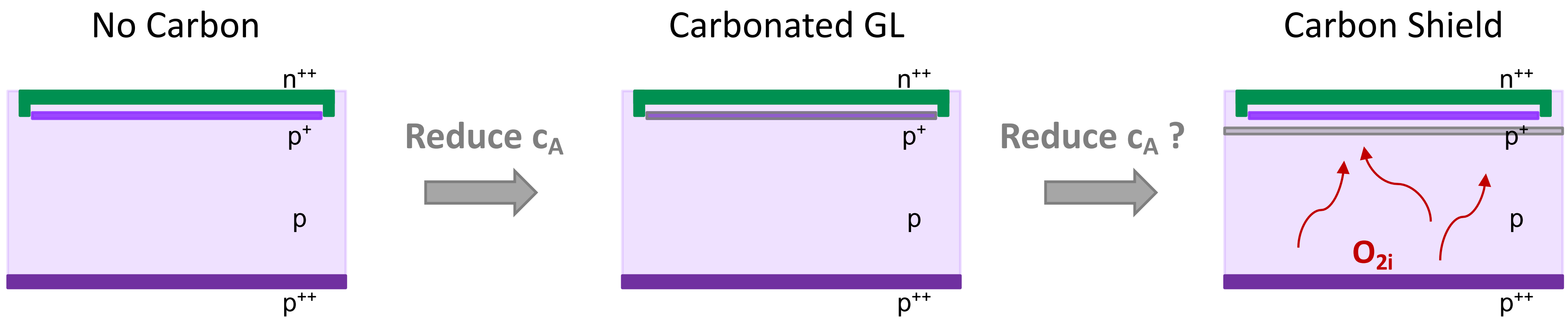
   n^+-atoms removal is faster $\Rightarrow$ increase of the gain with irradiation

   $\rightarrow$ **Co-implantation of Oxygen** atoms might mitigate the removal of n^+-doping

A Carbon Shield to further improve c_A

Defect engineering strategy to enhance the gain layer radiation tolerance

→ A **Carbon shield** will be infused below the gain layer volume to protect the gain layer from the diffusion of defect complexes from the bulk region and the support wafer



A spray of Carbon will be introduced below the gain layer region to protect the gain layer atoms from defects moving towards the n^{++} electrode during process thermal loads or exposure to particle radiation

→ Oxygen dimers can be captured by the Carbon atoms, preventing the removal of acceptors