Update on proposal RD50-2023-03: Deep Junction LGAD

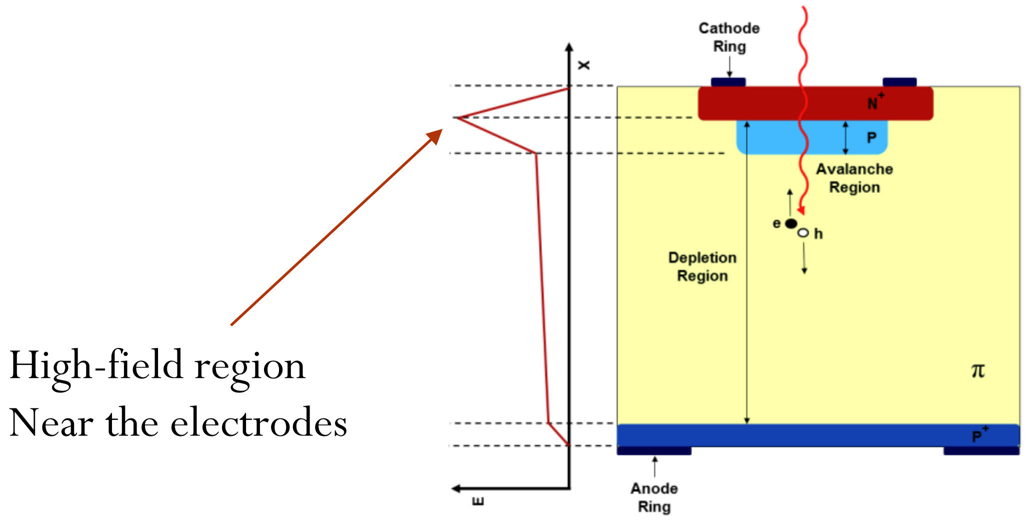
2° DRD3 Workshop (2024, CERN)

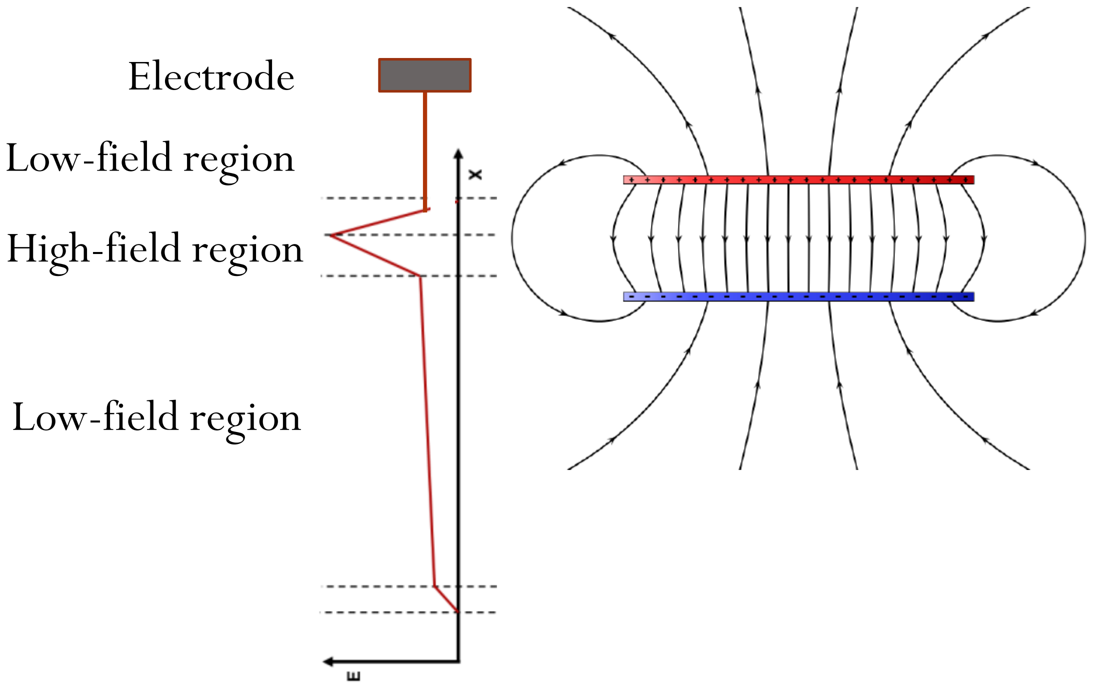
Dr. Simone M. Mazza (SCIPP, UC Santa Cruz)

On behalf of the 13 institutes involved

A new approach: deep junction

- Granularity limit is caused by high field near the electrodes
  - **What if the field is kept low while maintaining gain?**
- Basic inspiration is that of the capacitive field:
  - Large between plates, but surrounded by low-field region beyond the plates
- Use symmetric P-N junction to act as an effective capacitor
- Localized high field in junction region creates impact ionization
- Bury the P-N junction so that fields are low at the surface, allowing conventional granularity
- **→ "Deep Junction" LGAD (DJ-LGAD)**
- Concept presented first at TREDI 2020
- Prototype results presented at previous RD50 workshop
- Project approved after RD50 workshop last year

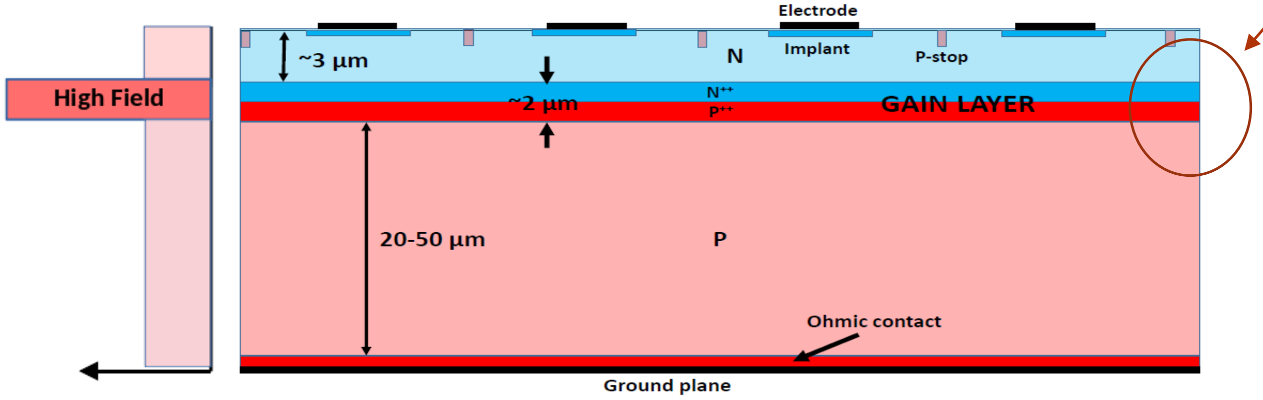


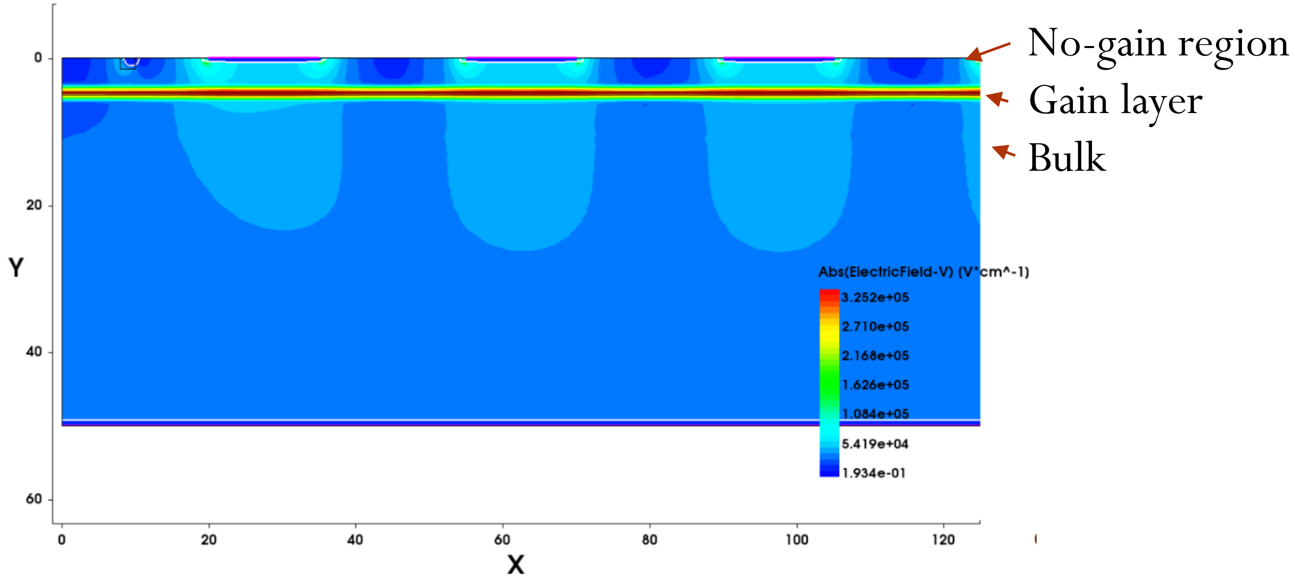


Dr. Simone M. Mazza

DJ-LGAD

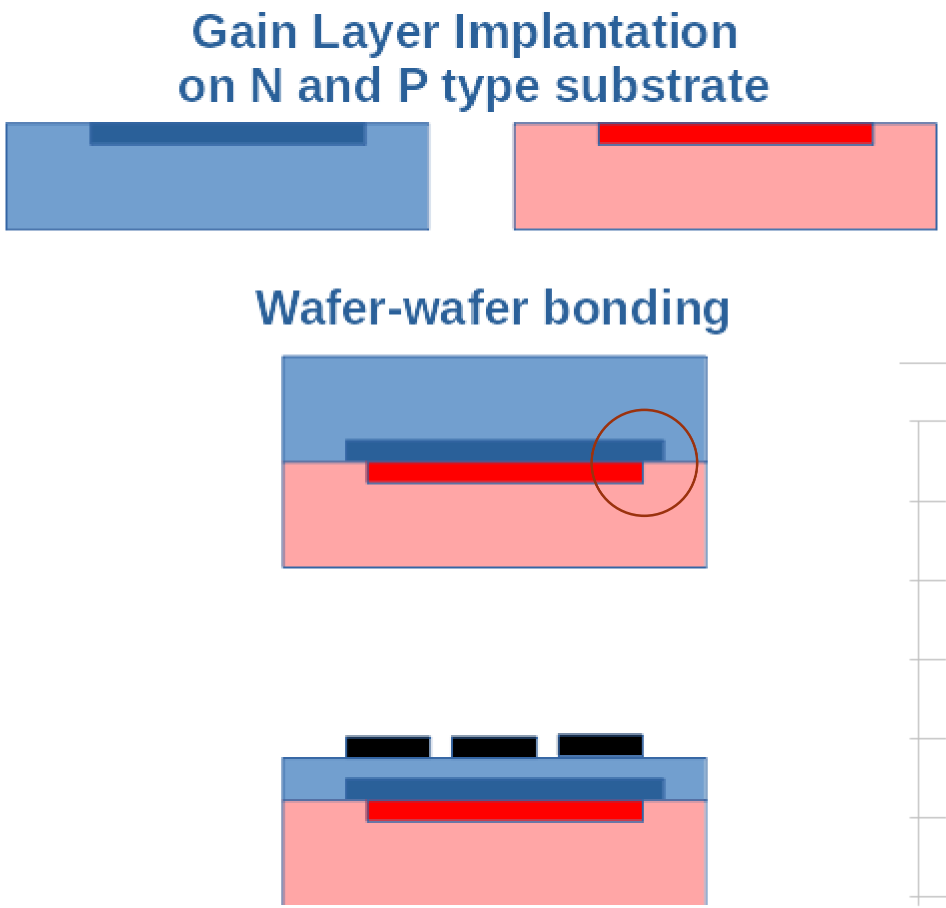
Termination of the gain layer was studied in the first production





- **P++ gain layer is paired with a N++ layer that lowers the field**
  - Junction is buried ~5 um inside the detector
- Tuning of N+ and P+ parameters important
  - Low field outside of the electrodes while maintaining sufficient gain
  - No need for a JTE
  - Different termination of the gain layer designed
- DJ-LGAD design studied with TCAD Sentaurus
  - First production in collaboration with BNL and CACTUS completed and results presented

Fabrication process for first prototype run



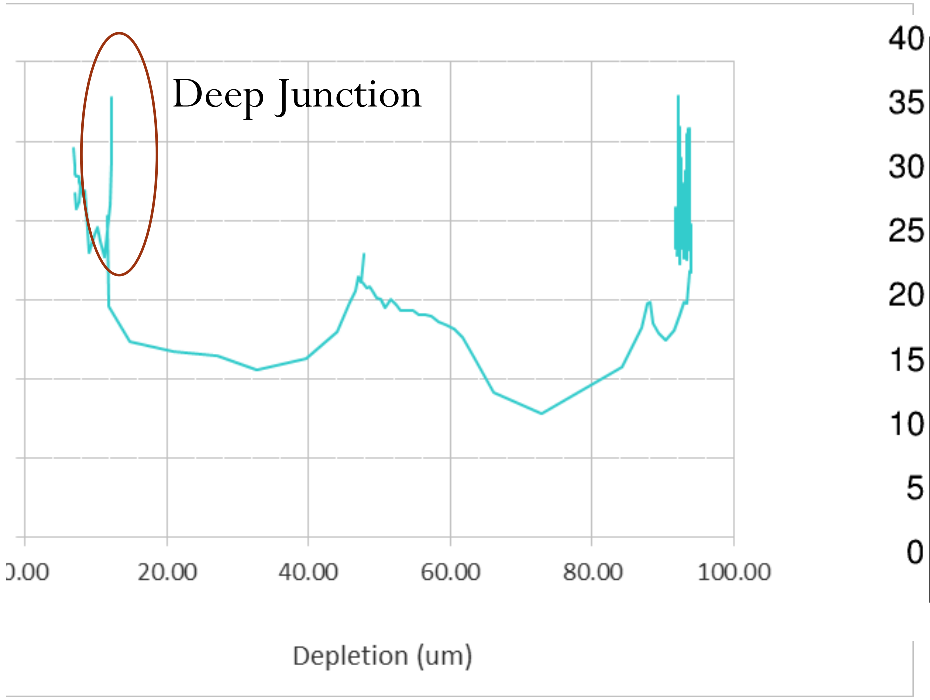
Production SCIPP, BNL, Cactus Materials, funded by SBIR

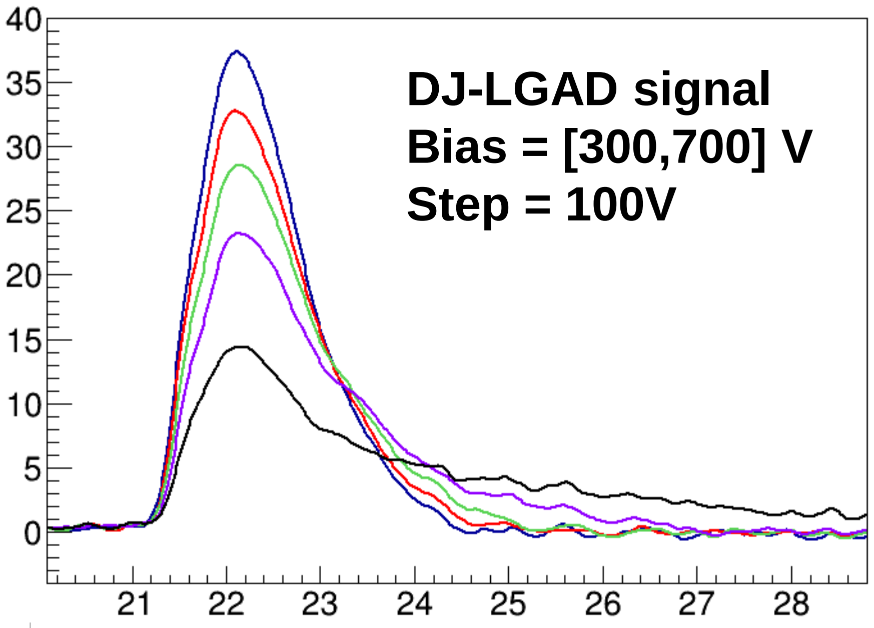
Prototypes work with moderate gain (~5)

2x1 arrays were also produced and show minimal IP gap

However the production had some issues

- Lengthy and complex
- Low yield (wafers easily break)
- High current in prototypes

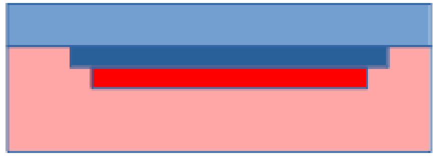




Fabrication process for epitaxial prototype

Gain Layer Implantation
Similar to Conventional LGAD, but with higher energy

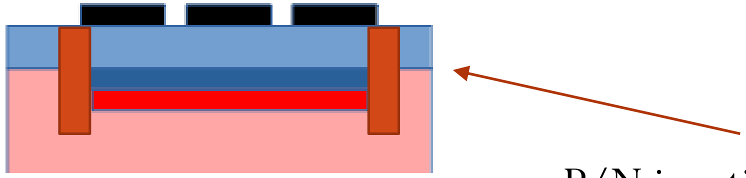
Epitaxial growth of high resistivity N type layer



Deposit electrodes and implants

- Proposed next fabrication using epitaxial growth
- Gain layer terminated with asymmetric N+ and P+ profiles
  - or terminated with deep trenches
- **Demonstration of the process and production of finely pixelated arrays**

Deep trenches for gain layer termination

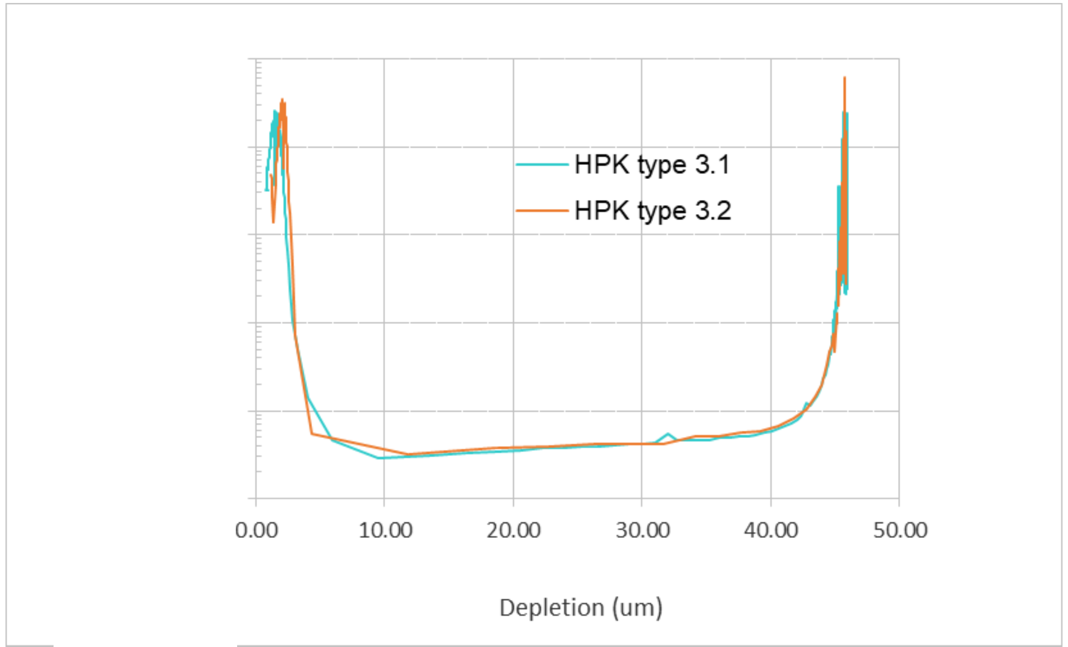


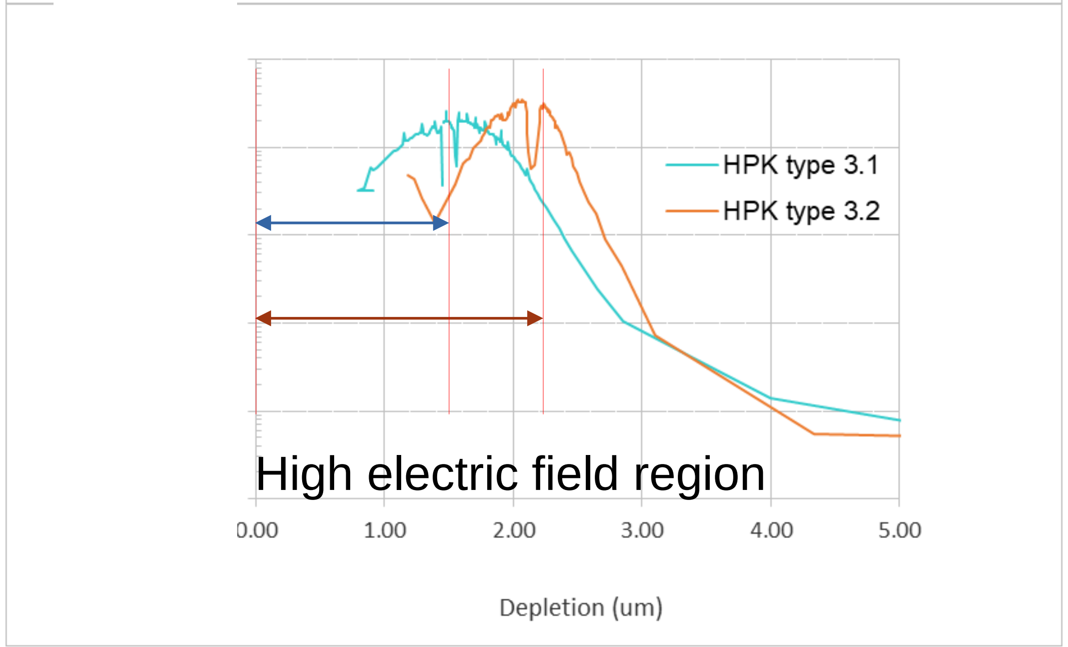
P/N junction at the edge, needs very sharp dicing or trenches as well

“Adaptive” gain layer

Using the deep Junction to push radiation hardness

Deep gain layer LGAD effect (HPK sensor examples)

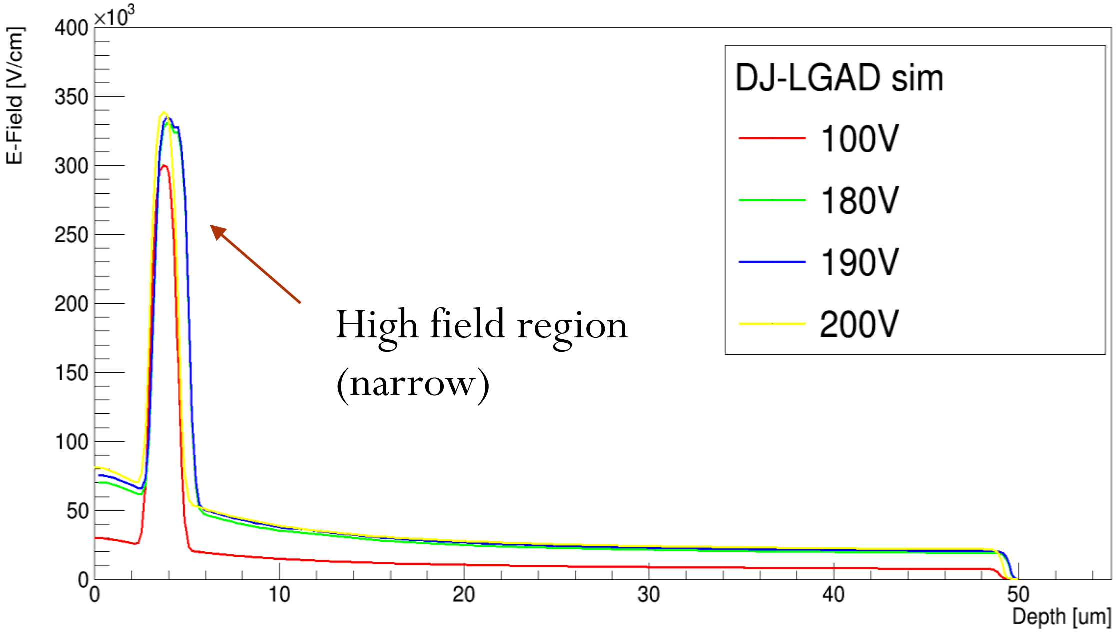




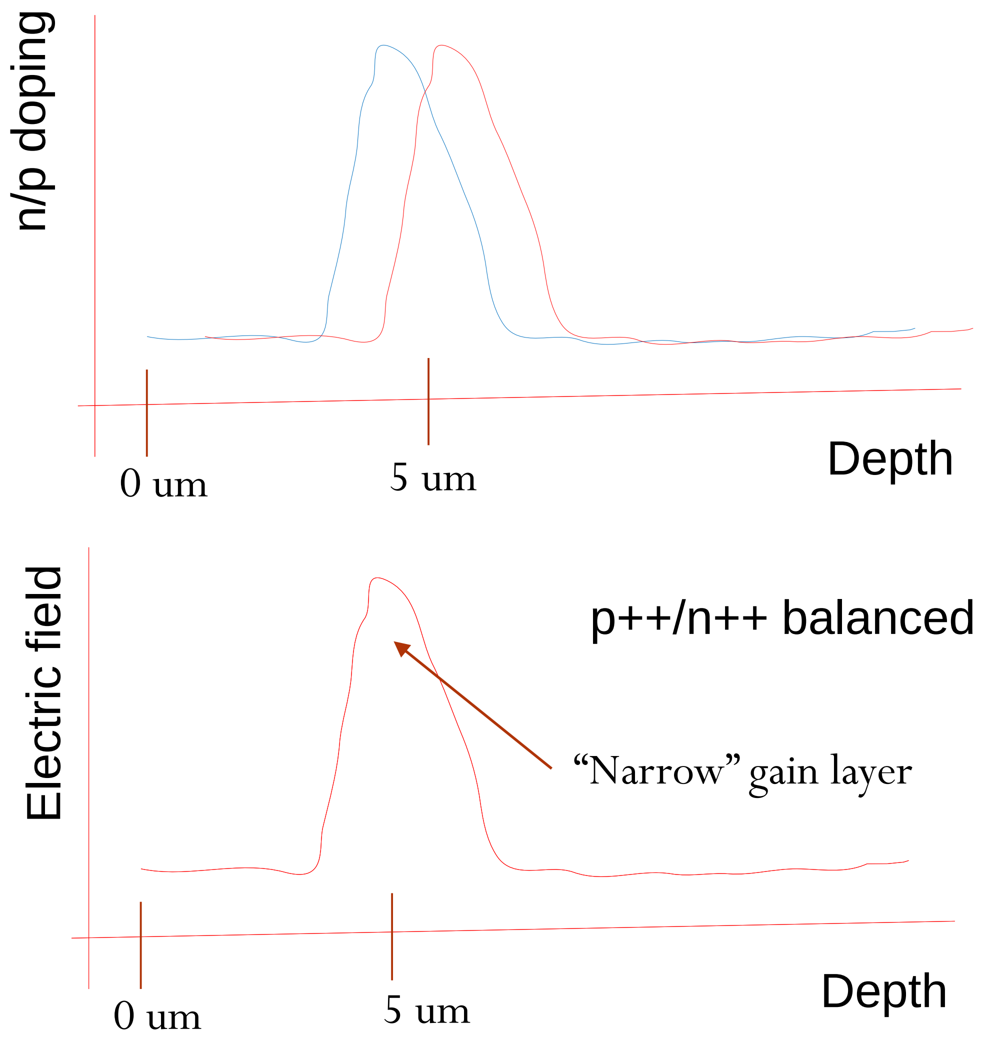
Deep gain layer increases electric field region, makes bias voltage increase after irradiation more effective in recuperating the gain

However doping concentration can't be too high or it would cause early breakdown and bad time resolution

With DJ-LGAD the junction is inside the device, but the field is high only for a narrow region

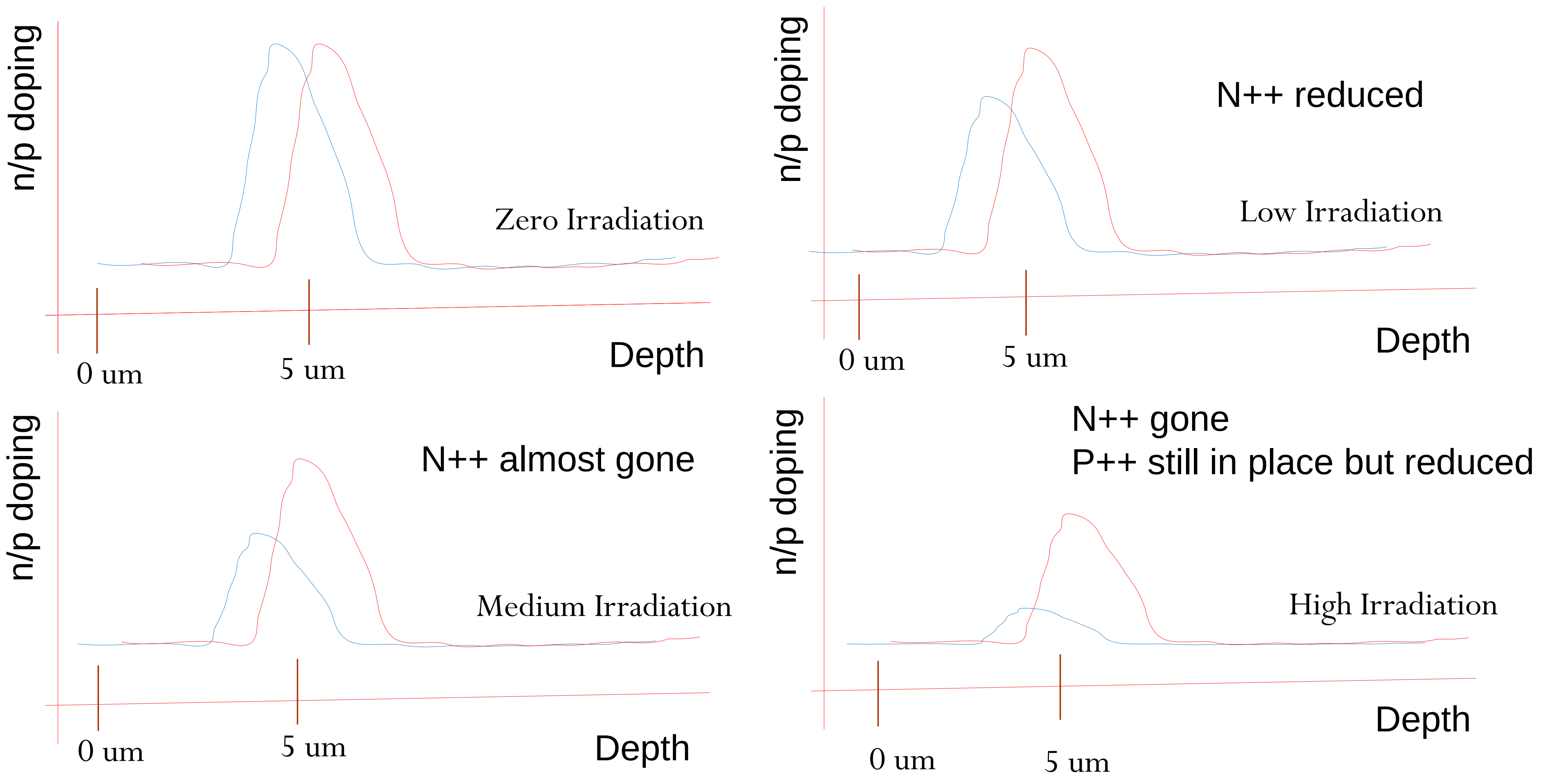


Adaptive gain layer

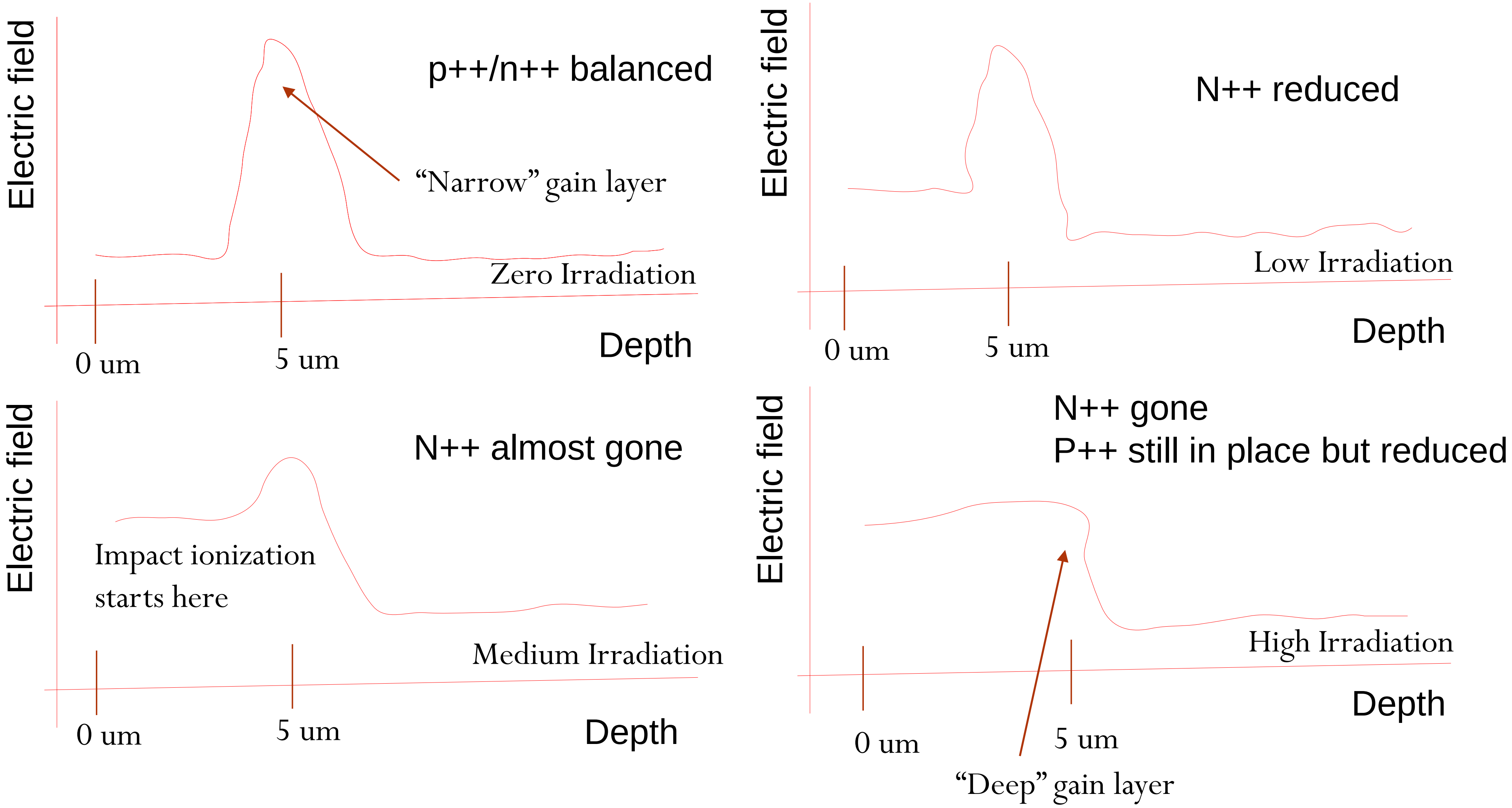


- P++ and N++ regions ramp up and down the E field
  - When new the layers are balanced so the electric field in the n region is low
- **Before irradiation n++ and p++ can be very high since the gain layer can be narrow**
  - The breakdown is under control because they balance out
- But after irradiation **if N++ goes down faster than P++** the electric field in the region is increased
  - From literature N is more affected by acceptor removal
  - Ratio of acceptor removal can be adjusted with Carbon (P) and Oxygen (N) co-implantation
- After irradiation the n++ "shielding" goes away and the gain layer adapts to a "deep" one in a controlled way
- **Good performance before and after irradiation!**

Adaptive gain layer - doping

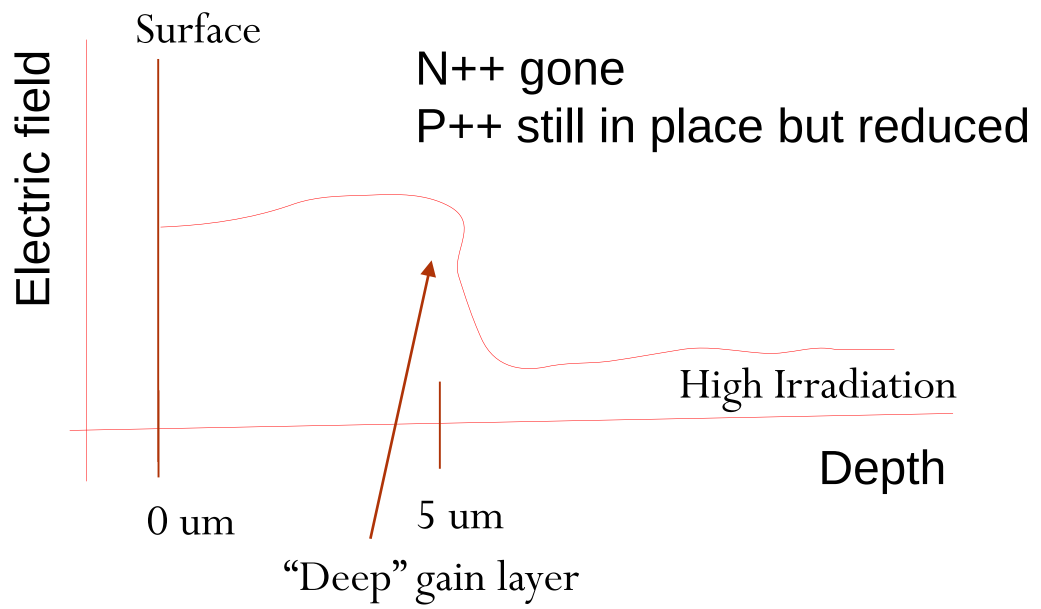


Adaptive gain layer – Electric field



Adaptive gain layer – Top surface field

- After irradiation the high electric field "leaks" to the surface
- The fine pixelation advantage of DJ-LGAD is gone
- Need either AC-coupling of trenches for arrays
  - But that's an issue for another day…



Ongoing RD50/DRD3 production

Fabrication of DJ-LGAD in RD50

- Fabrication within RD50 of DJ-LGAD at FBK (providing in-kind contribution)
  - Project cost ~100k
  - 12 participating institutions

Project cost	
Starting wafers (40 epitaxial wafers)	3.800 €
Fabrication of both short loops (deep junction and trench)	8.000 €
Epi growth for short loop (external service)	9.600 €*
High energy implantation for short loop (external service)	3.000 €
Photolithographic masks (for trench short loop and sensor batch)	7.200 €
Wafer processing for sensor batch	43.000 €
Epi growth for sensor batch (external service)	9.600 €*
High energy implantation for sensor batch (external service)	3.000 €†
SIMS	4.800 €
On-wafer electrical measurements	7.200 €
Dicing	2.400 €
Total Cost	101.600 €

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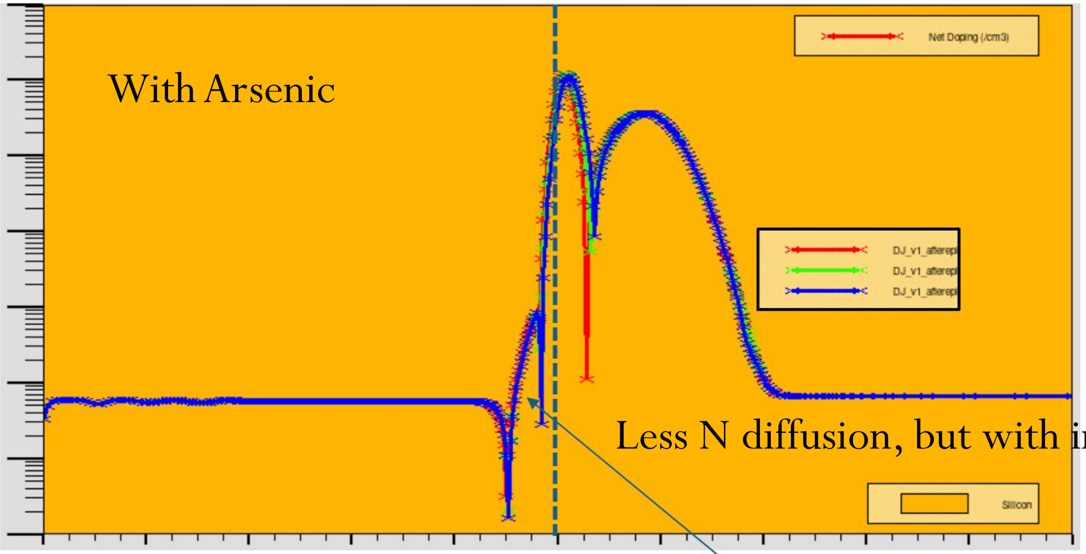
Institutes	1. University of California Santa Cruz (S.M. Mazza, B. Schumm) 2. FBK (M. Boscardin, M. Centis Vignali, G. Paternoster) 3. CERN (M. Moll, V. Kraus, M. Wiehe, M. Fernandez Garcia, N. Sorgenfrei) 4. UNM (S. Seidel, J. Si, R. Novotny, J. Sorenson, H. Farook, A. Gentry) 5. KIT (M. Caselle, A. Dierlamm) 6. PSI (J. Zhang, A. Bergamaschi, M. Carulla) 7. HEPHY (T. Bergauer, A. Hirtl, M/ Dragicevic) 8. UCG (G. Lastovicka-Medin, V. Backovic, I. Bozovic, J. Doknic) 9. Nikhef (M. van Beuzekom, F. Filthaut, M. Wu, H. Snoek) 10. UZH (B. Kilminster, A. Macchiolo, M. Senger) 11. IHEP Beiking (Z. Liang, M. Zhao, Y. Fan) 12. Manchester (O.A. De Aguiar Francisco, E. Ejopu, M. Gersabeck, A. Oh)
Total project	101.600 €
RD50 request	50.000 €

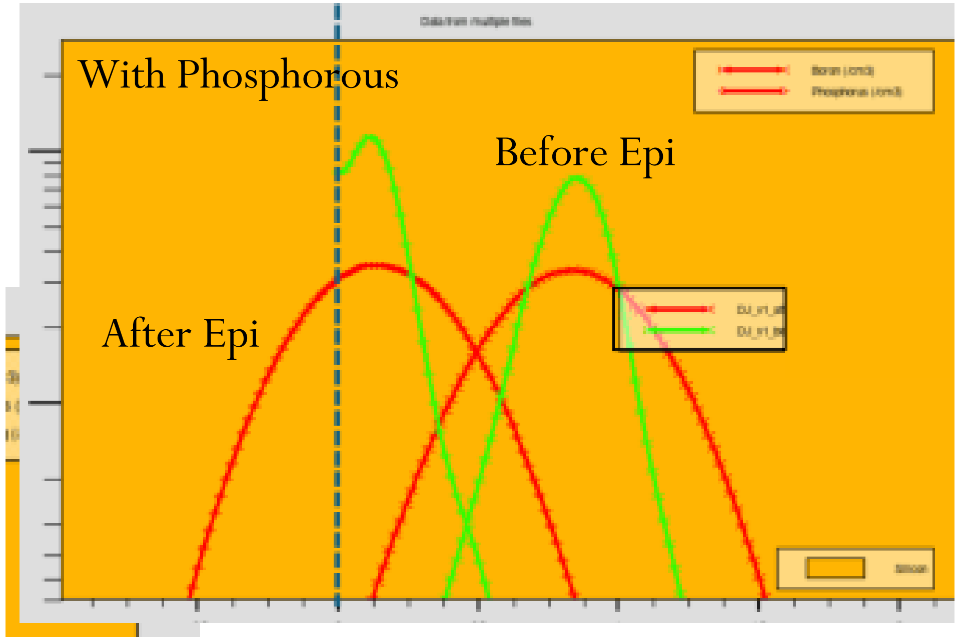
Project status

- The project started somewhat slowly due to patenting issues and setting up the CERN order to start gathering funds
- Due to Epi temperature issues with outgassing and diffusion to understand
  - Considering As for N doping to reduce diffusion
- The first short loops to study the effect of gain layer implantation and Epitaxial growth is almost done
  - Next: SIMS to understand the doping profile change
- Support from UCSC and KIT on TCAD simulation to understand the sensor behavior after diffusion
- Epi growth with 'standard' FBK contractor with atmospheric pressure, another vendor with low-pressure/low-temperature process considered but more expensive

Activity	Institutes	Duration
Short loop for deep junction	FBK	6 months†
Short loop for trench filling	FBK	3 months
Simulation and detector design	FBK, UCSC (partially parallel to short loops)	3 months
Batch production	FBK	9 months†
On-wafer testing	FBK	2 months
Electrical characterization	UCSC, HEPHY, CERN, UNM, KIT, Nikhef, UZH, IHEP, Manchester	2 months
Functional characterization	UCSC, HEPHY, CERN, UNM, KIT, PSI, UCG, Nikhef, UZH, IHEP, Manchester	4 months
Sensor irradiation	UNM	TBD
Post-irradiation characterization	UCSC, CERN, UNM, UCG, Nikhef, UZH, IHEP, Manchester	4 months

Table 1: Time allocation for project activities. † Note that these times are susceptible to the lead time for external services.





Short loop status

- 24 short loop wafer, should be done soon
- Testing both Phosphorous and Arsenic
- Different implantation energies for different depth
- Some have markers to test alignment after growth
- Using past LGAD mask to study the effect of growth in implanted regions
- 10x doses for SIMs studies
- 1x dose for SRP measurements

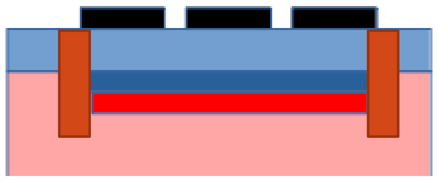
W#	Litho&Markers	PGAIN E	PGAIN D	NGAIN Spc	NGAIN E	NGAIN D	Proc Ther Budget	Scope
1	NO	1	1	Phosphorus	0.47	1		SRP/sims
2	YES	1	1	Phosphorus	0.47	1		alignment test
3	NO	1	10	Phosphorus	0.47	10		SRP/sims
4	NO	1	10	Phosphorus	0.47	10	NO	SRP/sims
5	NO	1	1	Phosphorus	0.7	1		SRP/sims
6	YES	1	1	Phosphorus	0.7	1		alignment test
7	NO	1	10	Phosphorus	0.7	10		SRP/sims
8	NO	1	10	Phosphorus	0.7	10	NO	SRP/sims
9	NO	1	1	Phosphorus	1	1		SRP/sims
10	YES	1	1	Phosphorus	1	1		alignment test
11	NO	1	10	Phosphorus	1	10		SRP/sims
11	NO	1	10	Phosphorus	1	10	NO	SRP/sims
13	NO	1	1	Arsenic	0.7	1		SRP/sims
14	YES	1	1	Arsenic	0.7	1		alignment test
15	NO	1	10	Arsenic	0.7	10		SRP/sims
15	NO	1	10	Arsenic	0.7	10	NO	SRP/sims
17	NO	1	1	Arsenic	1	1		SRP/sims
18	YES	1	1	Arsenic	1	1		alignment test
19	NO	1	10	Arsenic	1	10		SRP/sims
19	NO	1	10	Arsenic	1	10	NO	SRP/sims
21	NO	1	1	Arsenic	1.3	1		SRP/sims
22	YES	1	1	Arsenic	1.3	1		alignment test
23	NO	1	10	Arsenic	1.3	10		SRP/sims
24	NO	1	10	Arsenic	1.3	10	NO	SRP/sims

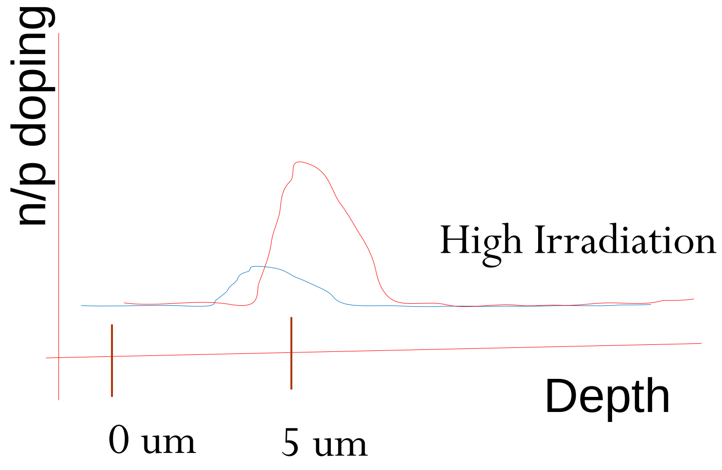
Reference wafers that do not do epi (other batch)

W#	Litho&Markers	PGAIN E	PGAIN D	NGAIN Spc	NGAIN E	NGAIN D	Proc Ther Budget	Scope
1	NO	1	1	Phosphorus	0.47	1	NO	SRP/sims
2	NO	1	10	Phosphorus	0.47	10	NO	SRP/sims
3	NO	1	1	Phosphorus	0.7	1	NO	SRP/sims
4	NO	1	10	Phosphorus	0.7	10	NO	SRP/sims
5	NO	1	1	Phosphorus	1	1	NO	SRP/sims
6	NO	1	10	Phosphorus	1	10	NO	SRP/sims
7	NO	1	1	Arsenic	0.7	1	NO	SRP/sims
8	NO	1	10	Arsenic	0.7	10	NO	SRP/sims
9	NO	1	1	Arsenic	1	1	NO	SRP/sims
10	NO	1	10	Arsenic	1	10	NO	SRP/sims
11	NO	1	1	Arsenic	1.3	1	NO	SRP/sims
12	NO	1	10	Arsenic	1.3	10	NO	SRP/sims

Conclusions

- DJ-LGAD: a device with deep gain layer
  - Avoid high field near the electrodes while maintaining gain
  - Fine pixelation of the top surface
  - First working DJ-LGAD prototype demonstrated but with some issues
- **Adaptive gain layer can increase greatly the radiation hardness** capabilities of LGADs
  - Adaptive gain layer can be combined with compensated gain layer and Carbon co-implantation
- **Current RD50 (DRD3) production with FBK using Epitaxial growth**
  - First short loop to study the effect of Epi growth to the implanted gain layer almost done





Acknowledgements

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- This work is supported by RD50/DRD3 funds