Evolution of the design of Ultra Fast Silicon Detector to cope with high irradiation fluences and fine segmentation

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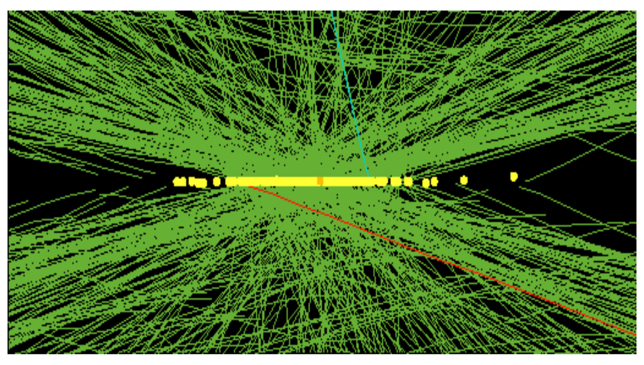
4D tracking motivation



Bunch crossing simulation HL-LHC

Timing-Tracking capability is strongly motivated by high density environments in future hadron collider

Sensors requirements:

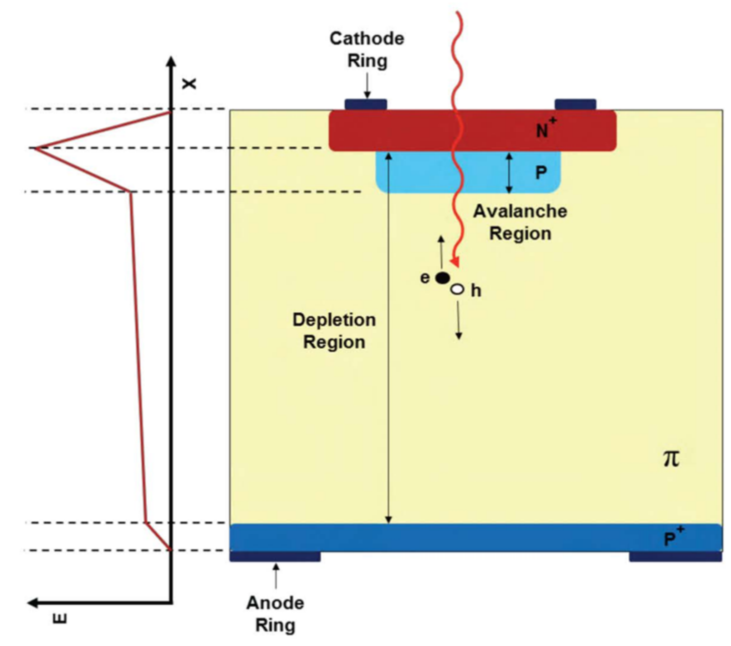
- Radiation hardness
- High fill factor (fraction of active area)

Ultra fast silicon detectors (UFSDs) are suitable for 4D tracking in future experiments at HL-LHC:

- Time resolution of ~ 30ps
- Segmentable electrodes;
- Performances maintained at fluences $\phi > 10^{15}\ n_{eq}/cm^2$

UFSD design based on Low Gain Avalanche diode technology

Low Gain Avalanche Diode (LGAD)



Principle:

Add to n-on-p Silicon sensor a locally enriched p-layer (~10^{16} atoms/cm³) below the junction which increases the E-field so that charge multiplication with moderate gain of 10-50 occurs without breakdown.

High Doping Concentration equal High Field

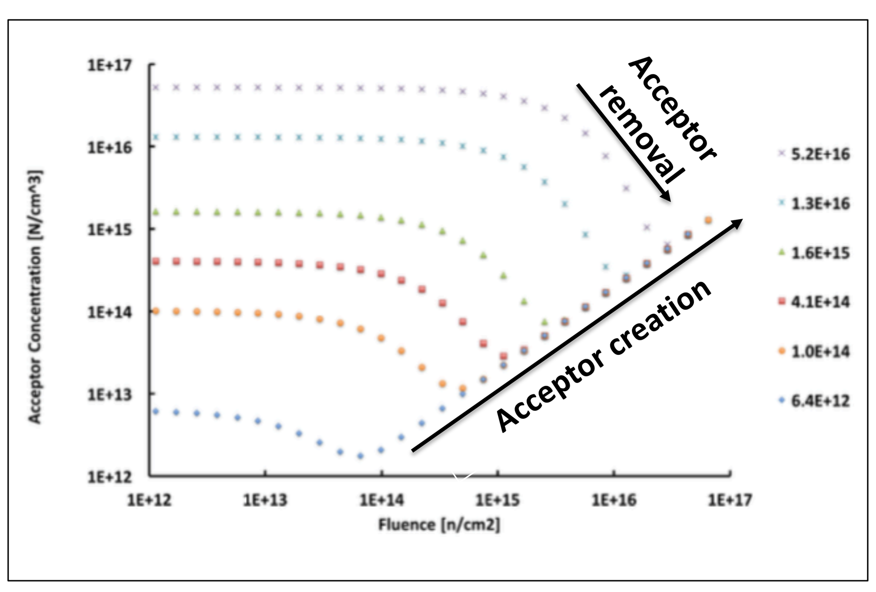
Ultra Fast Silicon Detector (UFSD) is a thin LGAD (~50µm thick) optimized to achieve a time resolution of ~ 30ps

Radiation effects

$$N_A(\emptyset) = g_{eff}\emptyset + N_A(0)e^{-c(N_A(0))\emptyset}$$

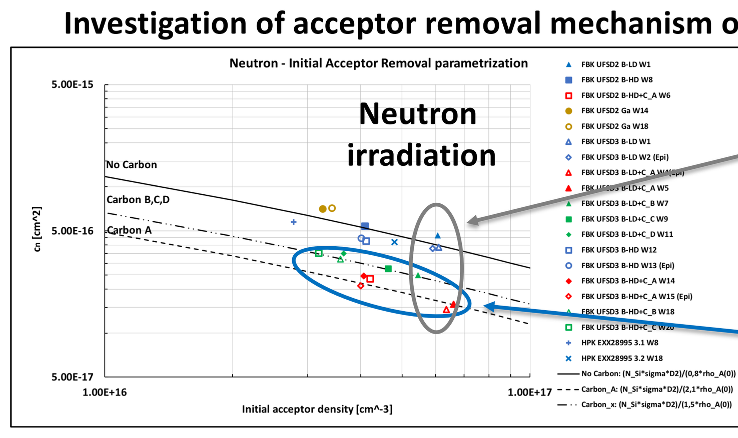
Acceptor creation (bulk effect)
$g_{eff} \sim 0.02\ cm^{-1}$

Acceptor removal (gain layer effect)
$c(N_A(0))$ acceptor removal coefficient



Acceptor removal

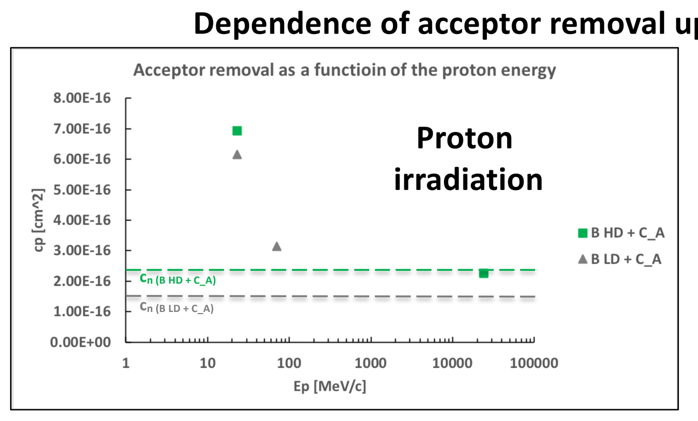
Investigation of acceptor removal mechanism on different gain layer flavors



Narrow and high-peak-concentration gain layer profiles are more radiation resistance

Acceptor removal mechanism is mitigated by co-implantation of carbon into gain layer

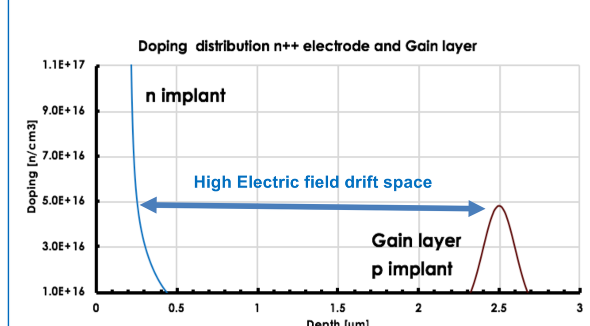
Dependence of acceptor removal upon the proton energy



Proton irradiation induces more or equal acceptor removal than Neutron

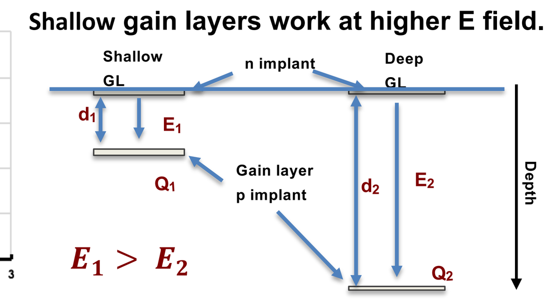
Effect of Proton energy: acceptor removal is faster for lower Proton energy

LGAD gain mechanism



Gain: exp(field * distance) $G \propto e^{\alpha \cdot d}$

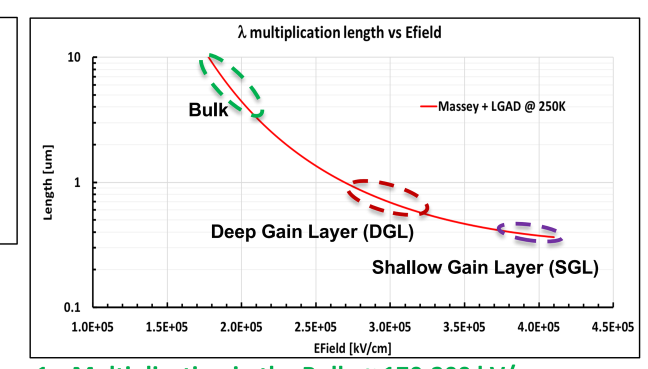
Shallow gain layers work at higher E field.



The position of the GL determines the field working point: **the deeper it is, the lower the field is**

Different manufacturers have different gain layer strategies:

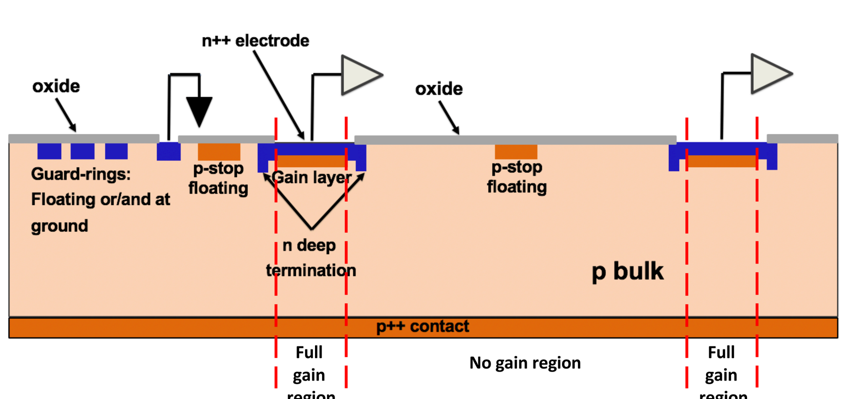
- **FBK:** shallow implant
- **HPK:** deep implant



1. Multiplication in the Bulk: ~ 170-200 kV/cm
2. Deep Gain Layer: ~ 290 – 300 kV/cm
3. Shallow Gain Layer: ~ 380 – 400 kV/cm

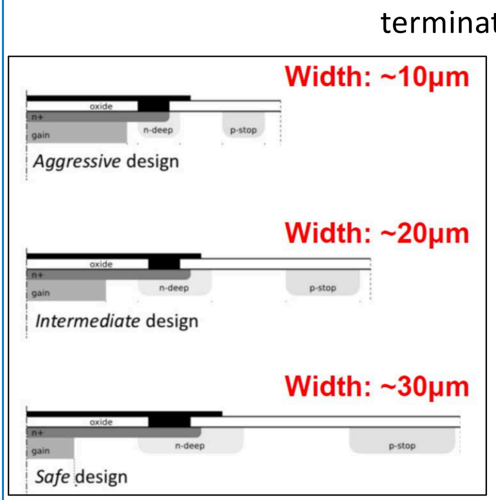
At high field the mean free path is saturated, so the "recovering power" of bias is much reduced. At lower field, bias is more effective

UFSD standard design

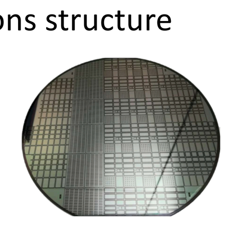


Transversal cut of a standard multi pad UFSD sensor

FBK UFSD3 production (2018)- reducing the border dimensions in terminations structure



FBK-UFSD3 inter-pad layout (in scale)

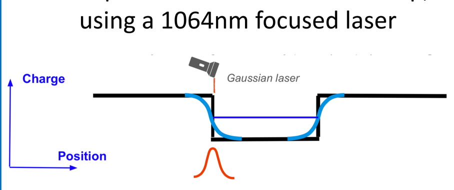


UFSD3 Wafer layout

Three different inter-pad designs, with a different nominal distance between gain layers:

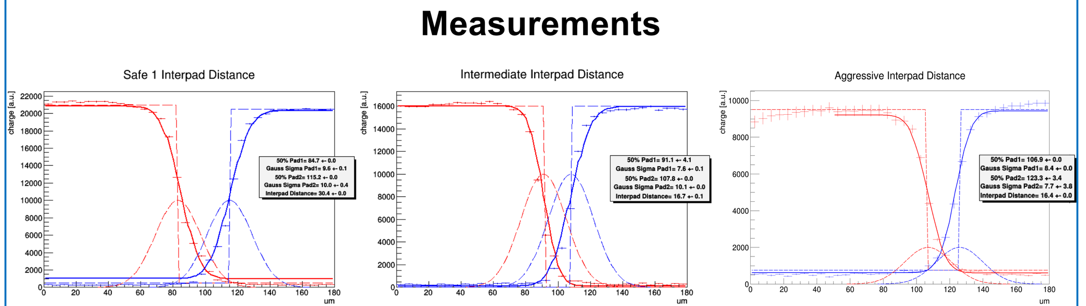
- Safe design ~ 30µm
- Intermediate design ~ 20µm
- Aggressive design ~ 10µm

Inter-pad measured with TCT setup, using a 1064nm focused laser



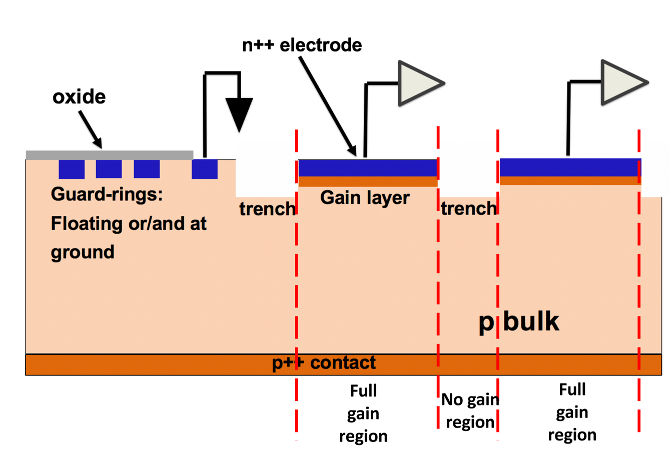
Design	Nominal distance (µm)	Measured distance (µm)
Safe	31	30.4
Intermediate	20.5	16.7
Aggressive	11	16.4

Measurements



Trench Isolated LGADs

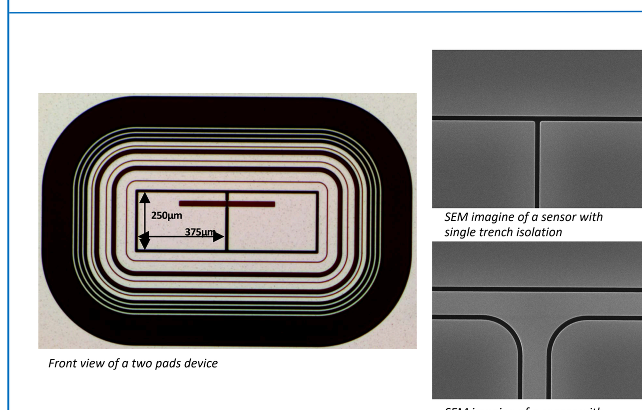
Trench isolation technology successfully used in FBK SiPMs



Transversal cut of a trench isolated UFSD sensor

Trench isolation could reduce inter-pad border region down few µm:

- Typical trench width < 1µm
- Trench filling with dielectric material



Front view of a two pads device

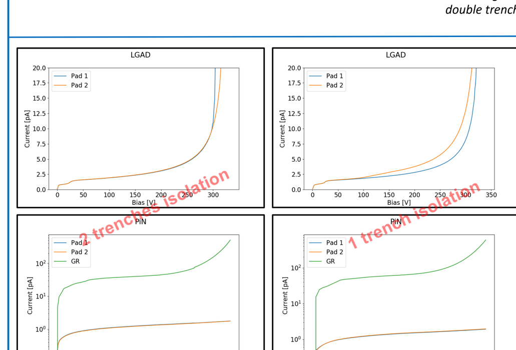
SEM imagine of a sensor with single trench isolation

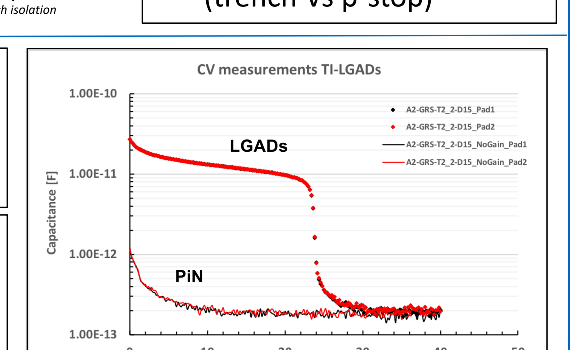
SEM imagine of a sensor with double trench isolation

FBK started a first development run of TI-LGADs in 2019 to demonstrate feasibility of technological process

Layout splits:

- n of trenches (1-2 trenches)
- Guard ring isolation (trench Vs p-stop)



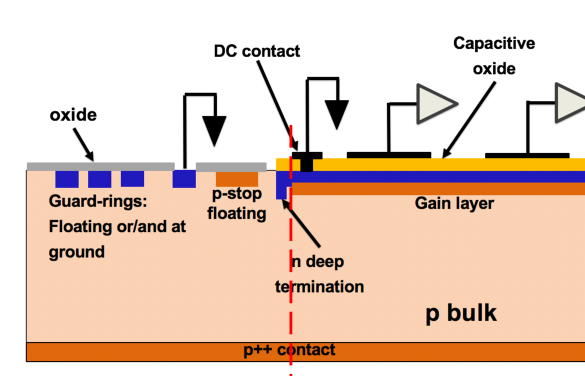


- Very low current <100pA;
- Breakdown due to internal gain at ~ 300V;
- No Breakdown up to 500V in sensors without gain;

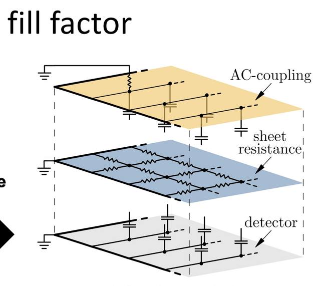
- Full depletion capacitance ~ 0.2pF, as expected;
- Perfect pads electrical insulation;

Resistive AC-Coupled Silicon Detectors (RSD)

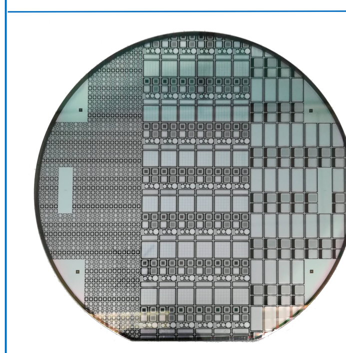
Silicon particle detector with 100% fill factor



Transversal cut of a RSD sensor



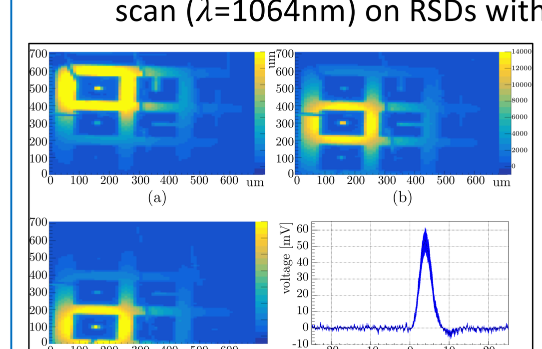
Simplified model



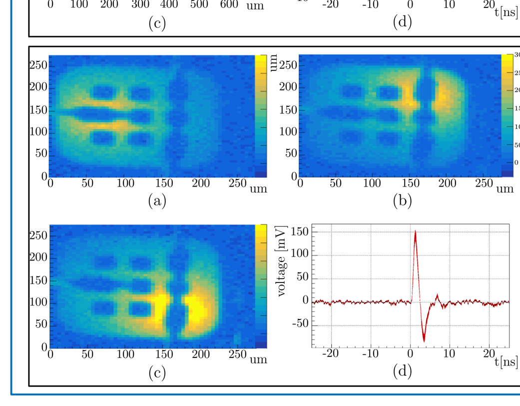
RSD1 production:

- Si-Si Float Zone (FZ) and epitaxial (Epi) substrates;
- three n++ doses;
- two capacitive oxide thickness;
- pads matrix with 50x50 to 500x500 µm² pitch and different pad sizes;

2D maps of integrated charge and signal waveform induced with TCT laser scan (λ=1064nm) on RSDs with different pitches and pad sizes



- 3x3 pad matrix;
- 200µm x 200µm pitch;
- 150µm x 150µm pad size;
- Integration time of 5ns;



- 3x3 pad matrix;
- 50µm x 50µm pitch;
- 25µm x 25µm pad size;
- Integration time of 2.7ns;

Conclusion

- **Ultra-Fast Silicon Detectors are being realized in form of thin Low-gain Avalanche Diodes**
- **Radiation hardness improved by co-implantation of carbon into the gain layer**
- **The interplay of acceptor removal and the capability to recover the effect of fluence with Bias will determine the more radiation resistance designs.**
- **16-17µm is the minimum inter-pads distance measured in multi-pad sensors**
- **Trench isolated and Resistive AC-coupling detectors are the two technological solution to improve the inactive inter-pad region in multi-pad sensors**

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