13th Trento Workshop on Advanced Silicon Radiation Detectors

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Production and design of LGAD with high radiation resistance

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On behalf of
UFSD Collaboration
INFN Torino, Univ. Torino, Univ. Trento, TIFPA, FBK

INFN

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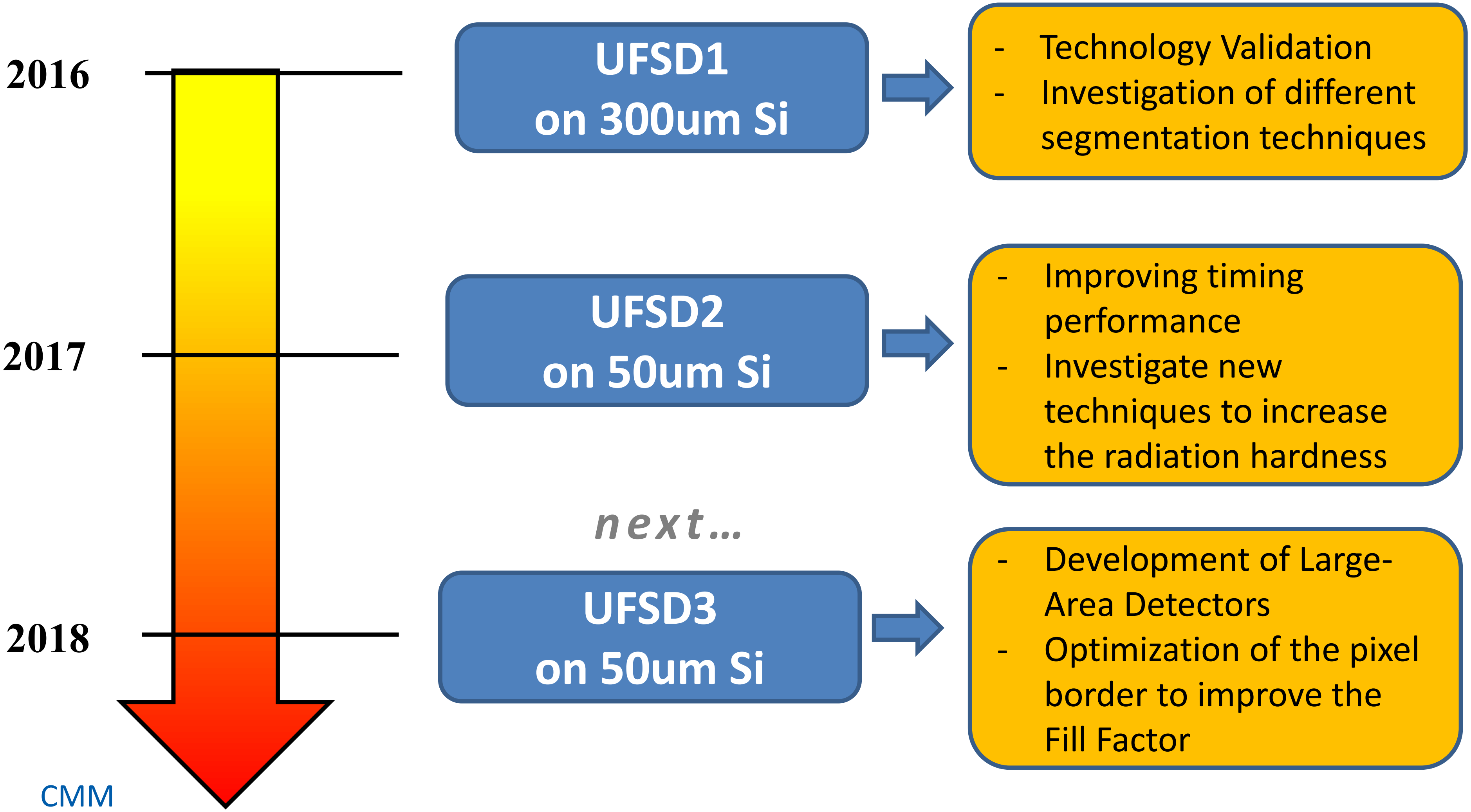
BRUNO KESSLER

Summary

1. LGAD technology at FBK
2. Techniques to improve the radiation hardness (UFSD2)
   - Gallium doping
   - Carbon co-implant
   - Gain-layer shaping
3. UFSD2 Batch pre-irradiation characterization: IV, CV, Gain and Timing
4. Next developments
5. Conclusions

UFSD Collaboration Roadmap

UFSD Collaboration: FBK, Univ. Trento and Turin, INFN Turin



2016

UFSD1
on 300um Si

- Technology Validation
- Investigation of different segmentation techniques

2017

UFSD2
on 50um Si

- Improving timing performance
- Investigate new techniques to increase the radiation hardness

next…

2018

UFSD3
on 50um Si

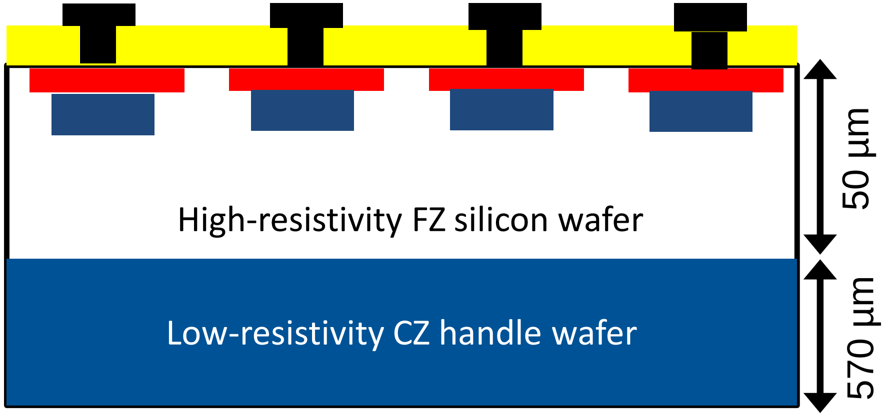
- Development of Large-Area Detectors
- Optimization of the pixel border to improve the Fill Factor

UFSD2 Batch

Last production batch on 50 µm thick substrates

Goals of the new production:

- Increasing **timing performance**-> using 50 µm thick Silicon
- Testing new techniques to **increase the radiation hardness** (avoid gain reduction after irradiation):
  1. **Gallium doping**
  2. **Carbon co-implant**



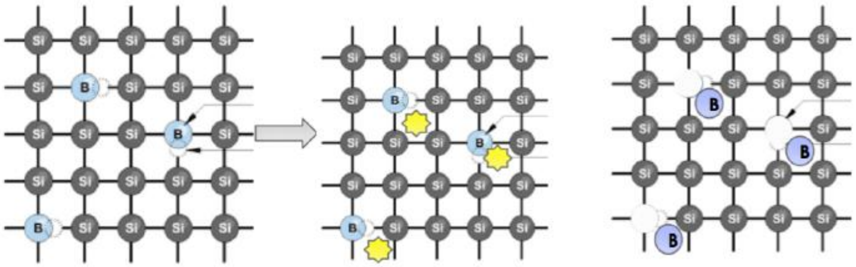
Si-on-Si wafers with 50um of active thickness.

Si-Si wafers are a good compromise in terms of:

- High Silicon quality (FZ)
- Customization of silicon resistivity and thickness

Design of Radiation Resistant LGAD

It has been shown in previous studies that the Boron-doped gain layer in LGAD is susceptible to inactivation when exposed to neutrons and protons irradiations. (G. Kramberger). **INITIAL ACCEPTOR REMOVAL EFFECT**



BORON

Radiation induced defects could inactivate Boron

$I + B_s \rightarrow B_i$

In UFSD2 batch we investigated some strategies to mitigate the initial acceptor removal effect

1. GALLIUM Doping (instead of Boron)
2. Carbon co-implantation
3. Gain Layer doping profile shaping

Design of Radiation Resistant UFSD

1. GALLIUM Doping (instead of Boron)

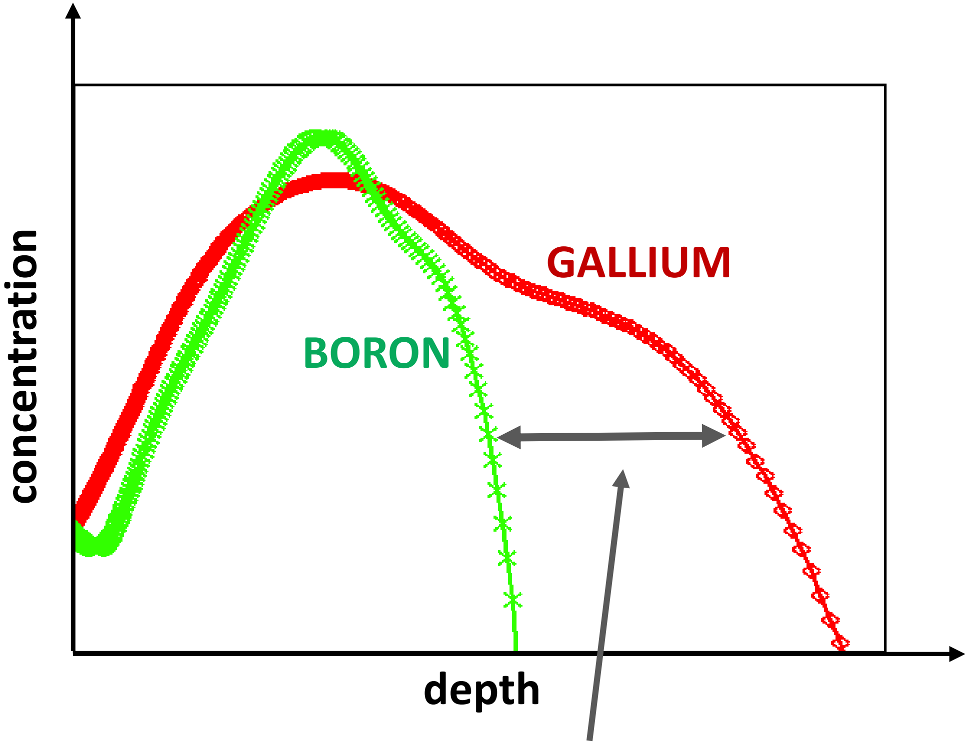
Gallium could be less prone to be inactivated with respect to Boron

- **Gallium is much heavier than B –>**

High energy ion implantation (>> 1MeV) has to be used to reach the same depth as Boron

- **Gallium diffusion coefficient in Silicon is one order of magnitude higher than Boron –>**

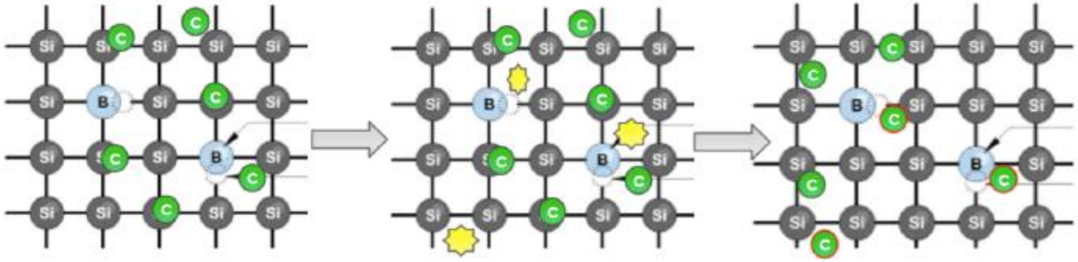
thermal budget has to be strongly reduced



Gallium concentration profile is wider with respect to Boron due to both higher energy and diffusion coefficient

Design of Radiation Resistant UFSD

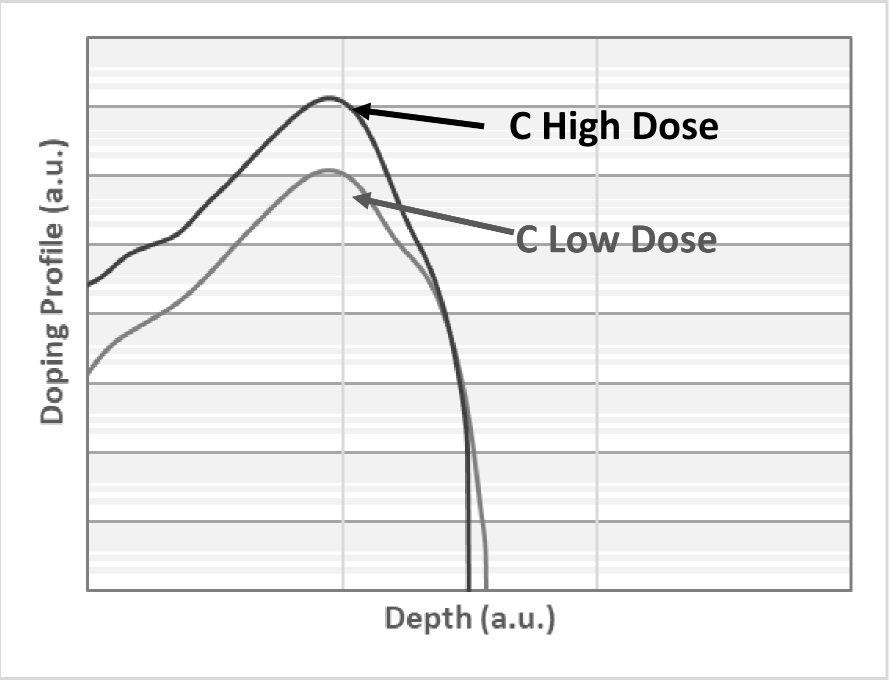
2. Carbon co-implantation



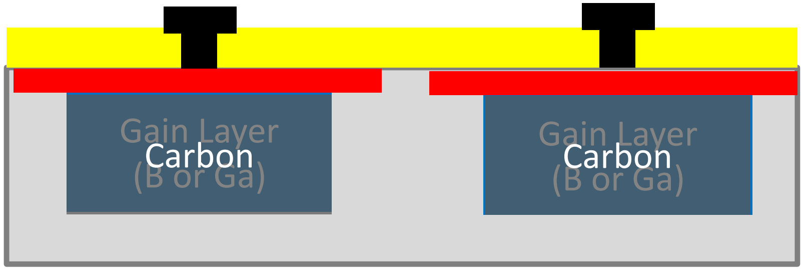
C competes with B in filling interstitial defects

- **Two Carbon Doses Tested**

Carbon Profiles



- To avoid useless Carbon (which can increase the noise), **only the gain layer region is enriched with C**



Boron + Carbon

Gallium + Carbon

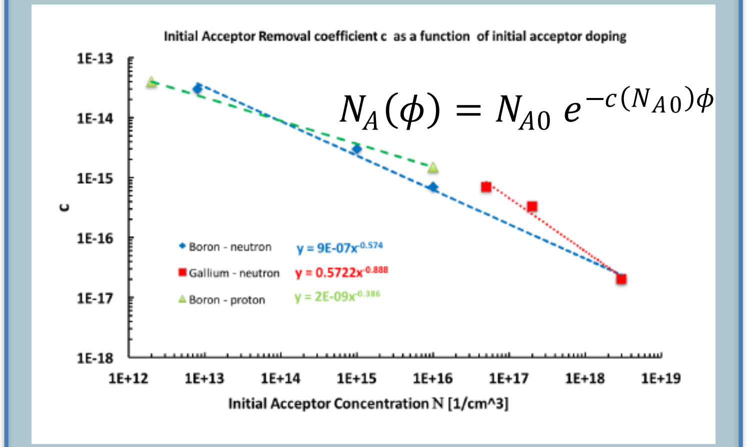
Design of Radiation Resistant UFSD

3.

Gain Layer doping profile shaping

Narrower doping profiles with high concentration peak (Low Thermal Diffusion) could be less prone to be inactivated

higher doping densities are less affected by acceptor removal

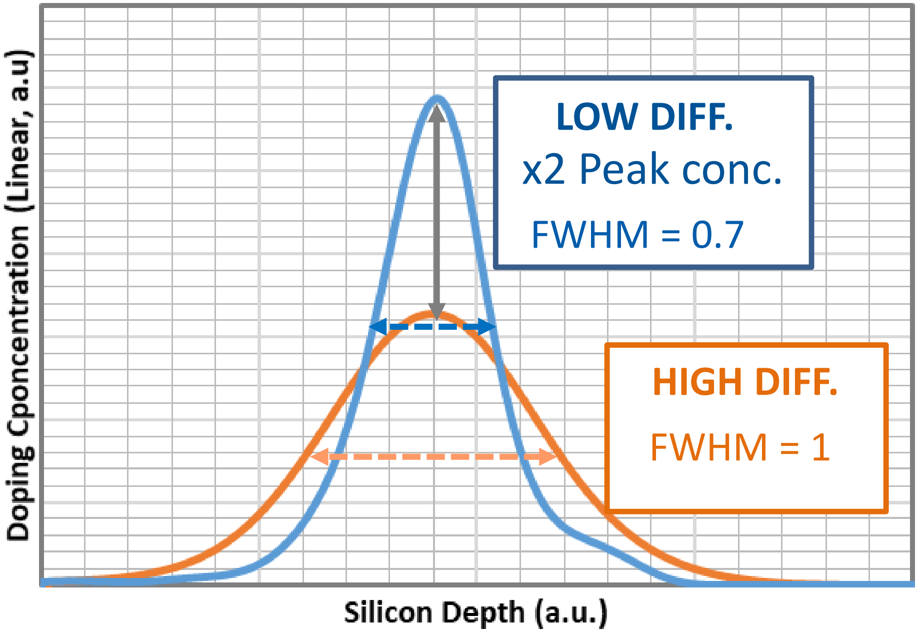


Initial Acceptor Removal coefficient c as a function of initial acceptor doping

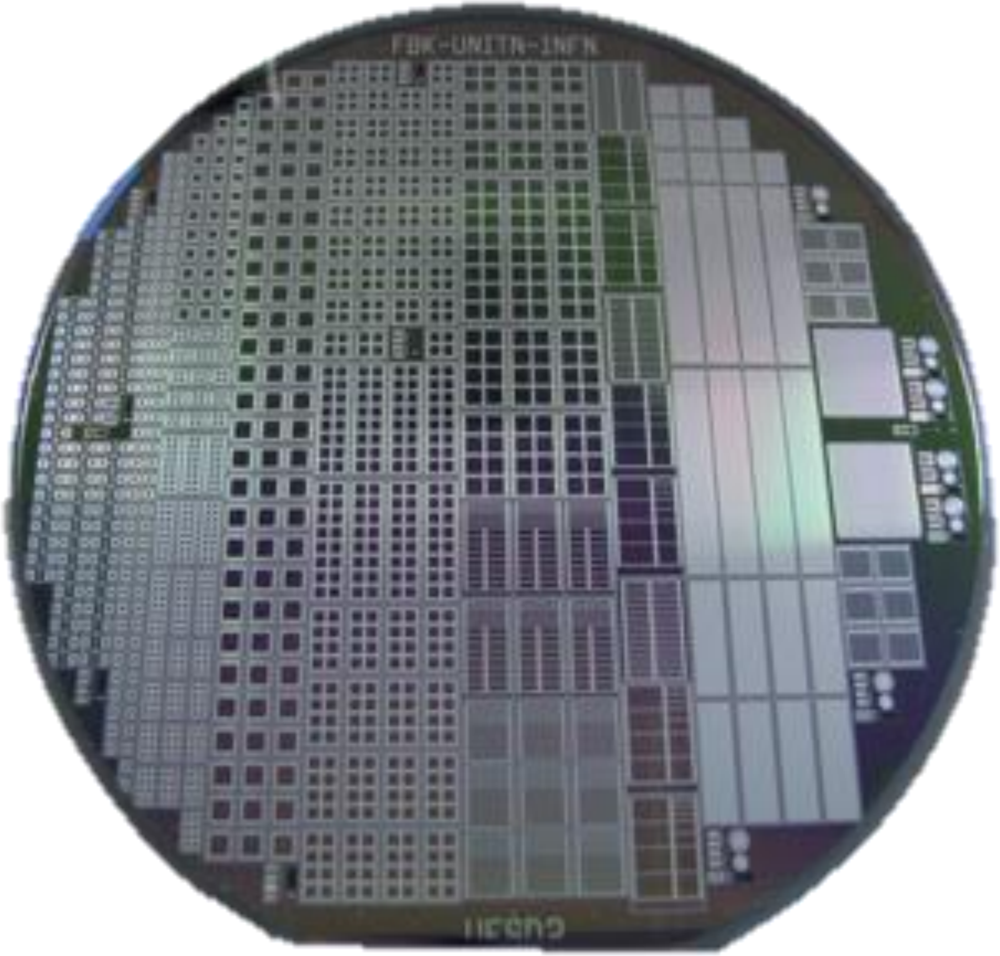
$$N_A(\phi) = N_{A0}\, e^{-c(N_{A0})\phi}$$

HIGH DIFF. Less peaked and broader doping profile

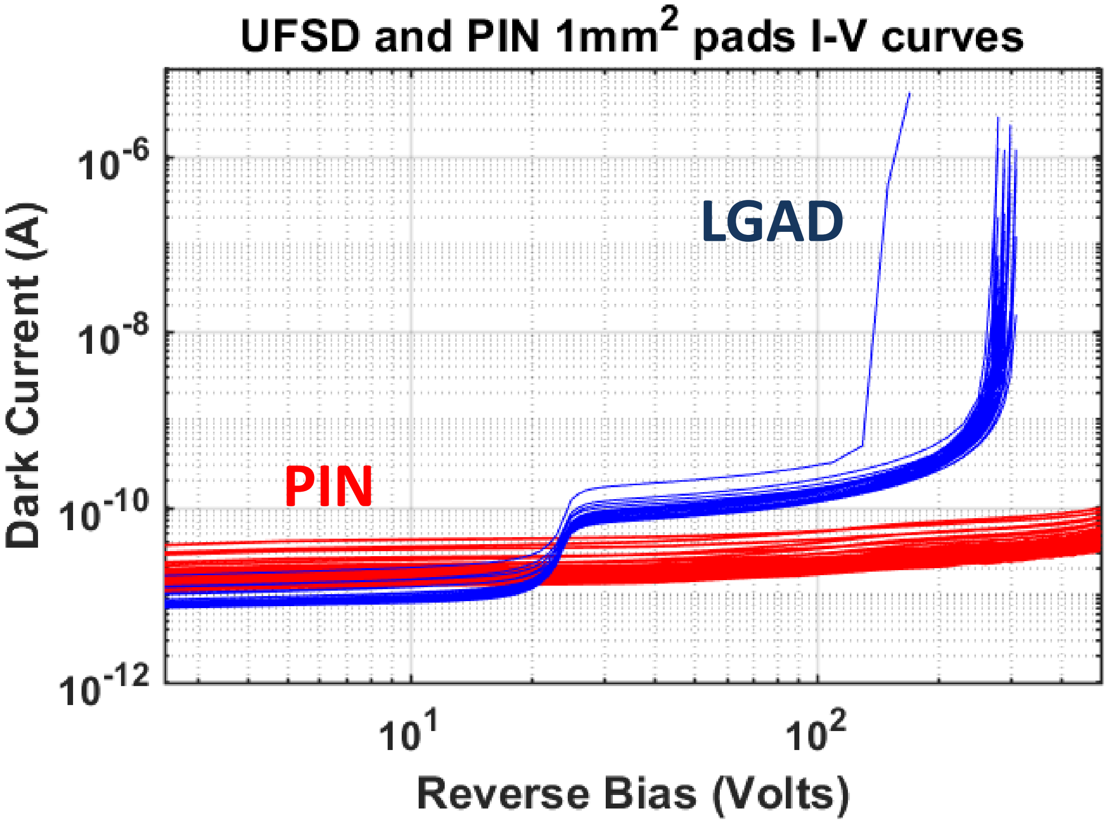
LOW DIFF. More peaked and narrower doping profile

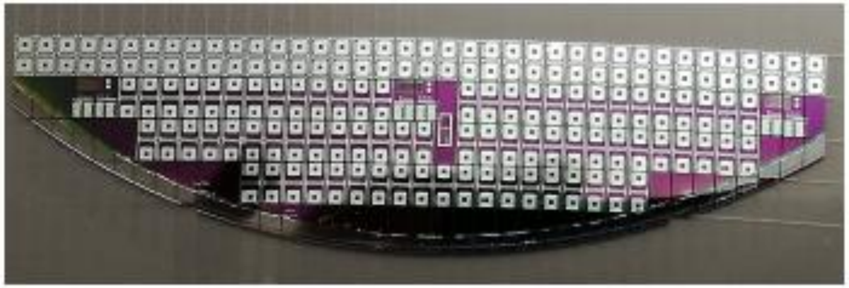


UFSD 2 – Characterization



UFSD 2: Characterization

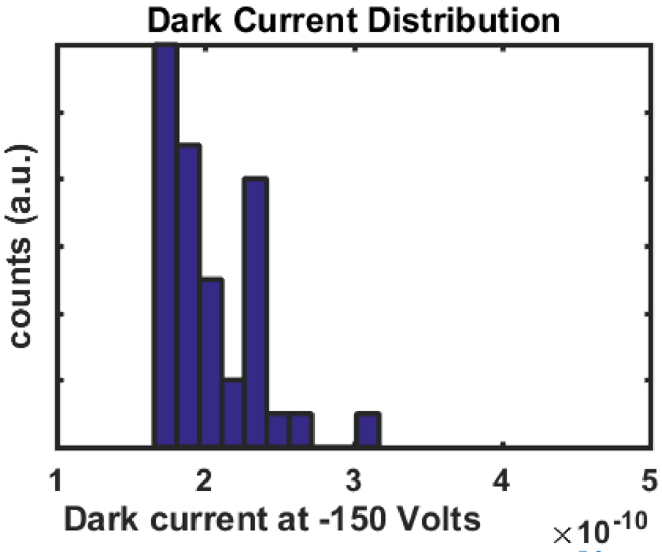

UFSD and PIN 1mm^2 pads I-V curves



Data from Wafer 2
Boron Dose Factor = 1.0

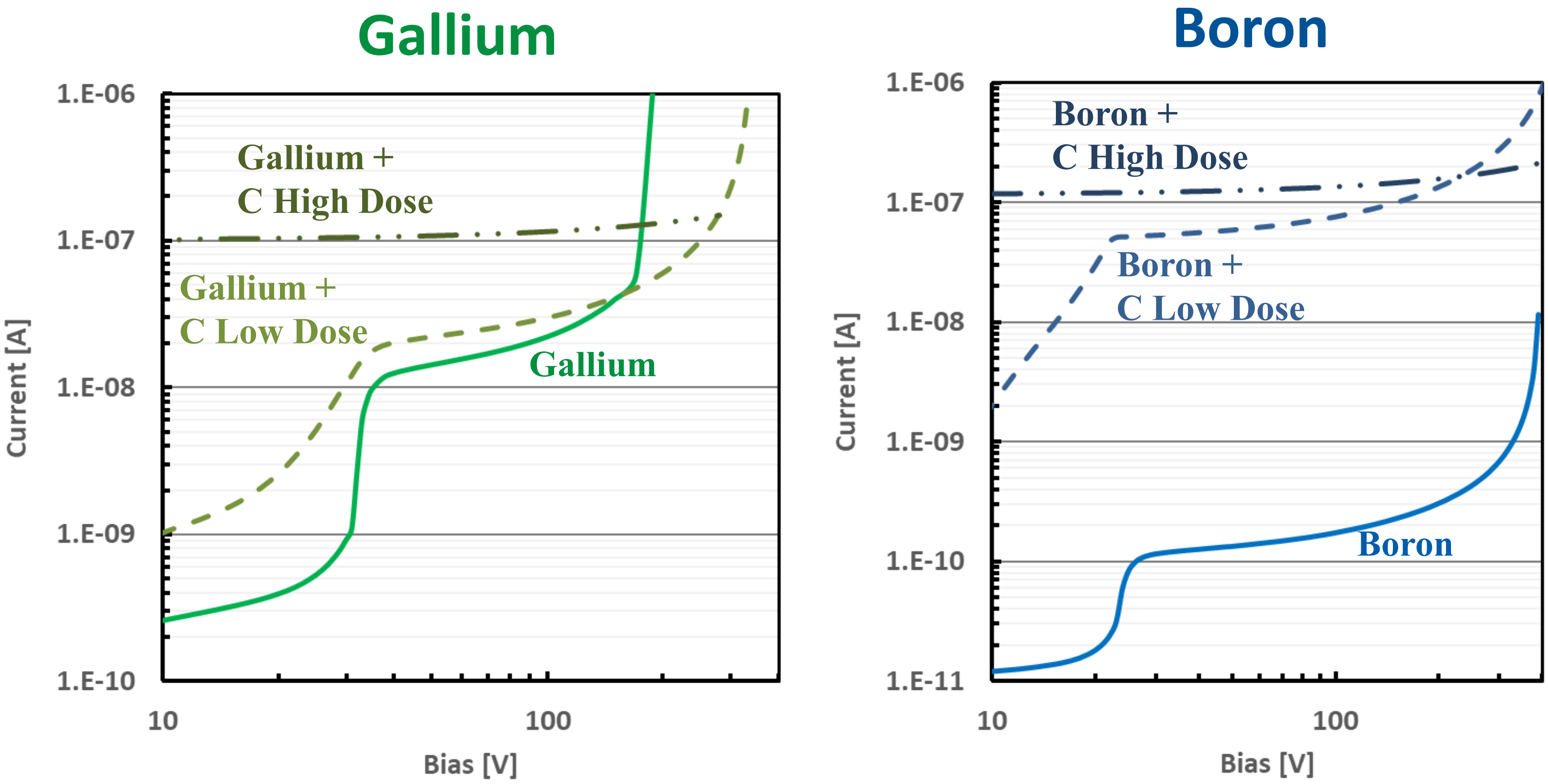
All the 1x1 mm^2 pads are plotted w/o any die selection

Very high uniformity and low dark current


Dark Current Distribution

UFSD 2: Characterization

Effect of Carbon co-implantation on IV curves

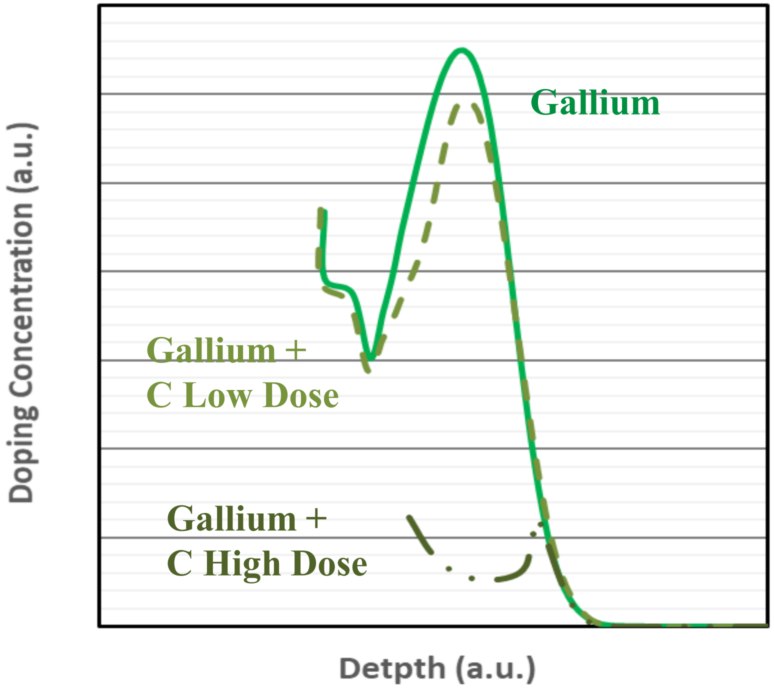


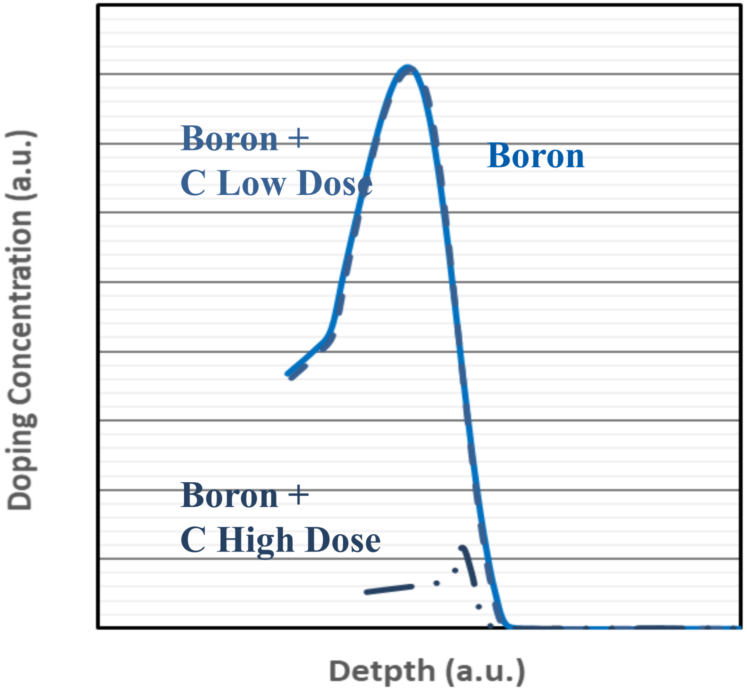
- **Carbon co-implantation increases the leakage** current of the sensor;
- **Carbon Low Dose**: similar trend of the leakage current as in the lack of carbon ;
- **Carbon High Dose**: very high leakage current (~100nA/mm^2), the exponential growth vs Bias is strongly reduced

UFSD 2: Characterization

Effect of Carbon co-implantation on CV curves

Gallium **Boron**

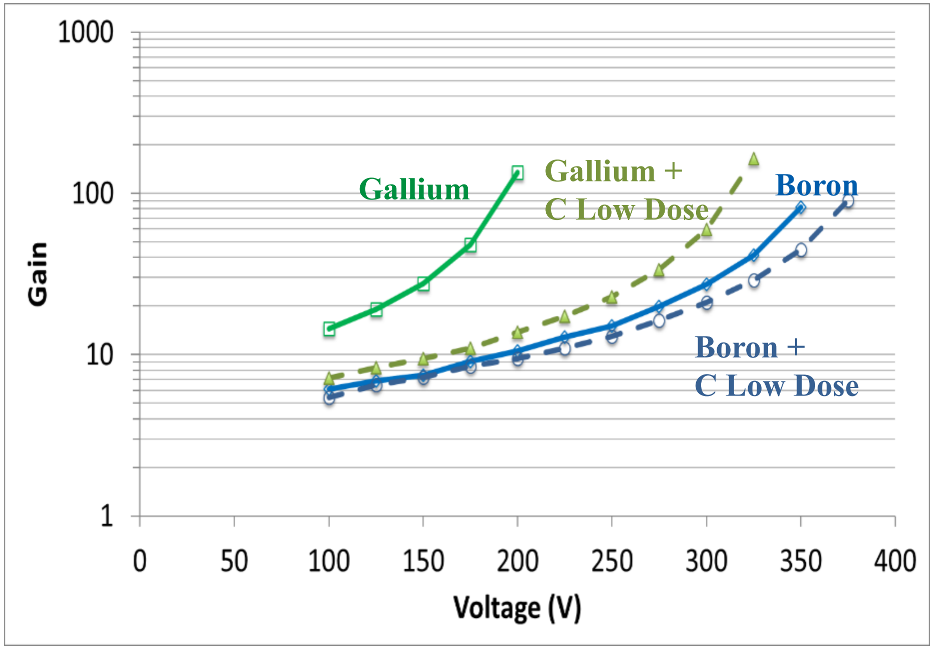




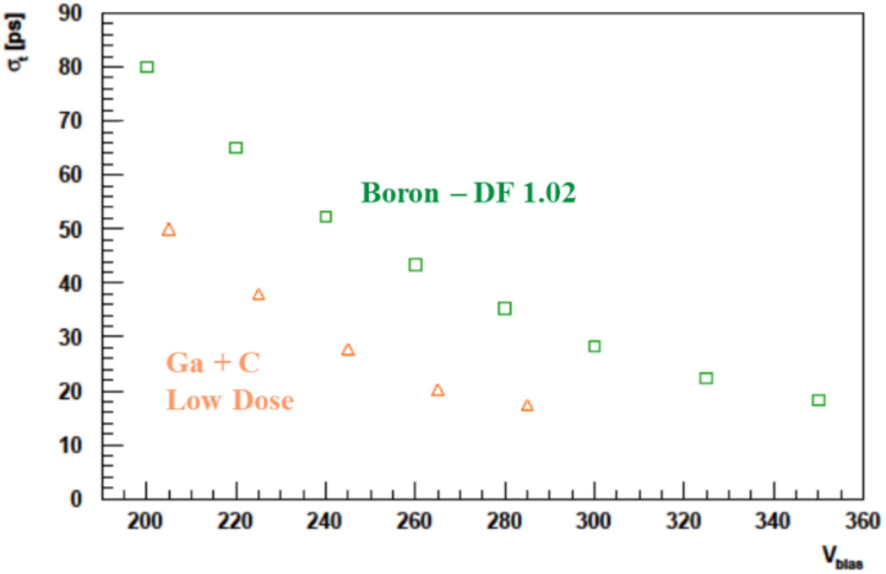
- **The Carbon reduces the active doping concentration of the gain layer**
- **High Carbon** effect is relevant for both Boron Gallium;
- **Low Carbon** effect is more pronounced in Gallium than in Boron;

UFSD Batch 2 – Gain an Timing

Gain



Time Jitter



- **Both carbon co-implantation and Gallium doping does not affect Gain and timing jitter in not-irradiated samples**

UFSD characterization after irradiation will be shown in next talk by Arcidiacono

Next Activities

Next Batch (expected in summer 2018)

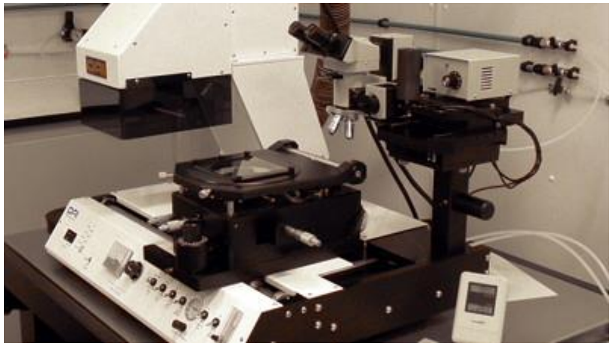
UFSD3
on 50um Si

GOALS

1. Optimization of carbon co-implantation to further improve the radiation hardness
2. Development of Large-Area Detectors up to 1.2x2.4 cm^2
3. Optimization of the pixel border to improve the Fill Factor

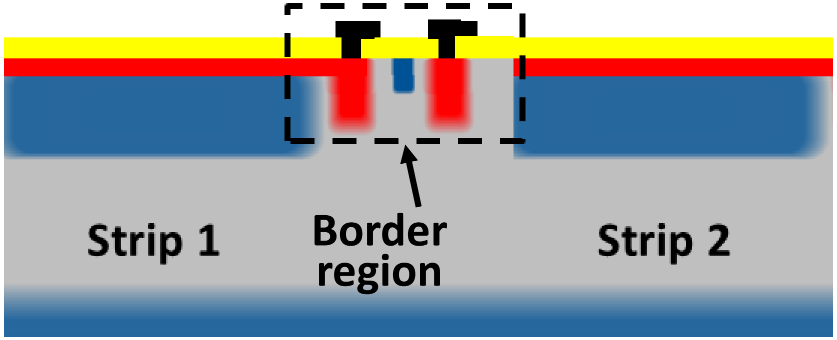
Strategies to increase Fill Factor

Standard technology (UFSD1 & 2)
Based on Mask Aligner



Resolution=1um.
Critical Size = 2um
Border width = 66um

Current technology UFSD2



New technology (UFSD 3)
Based on Stepper

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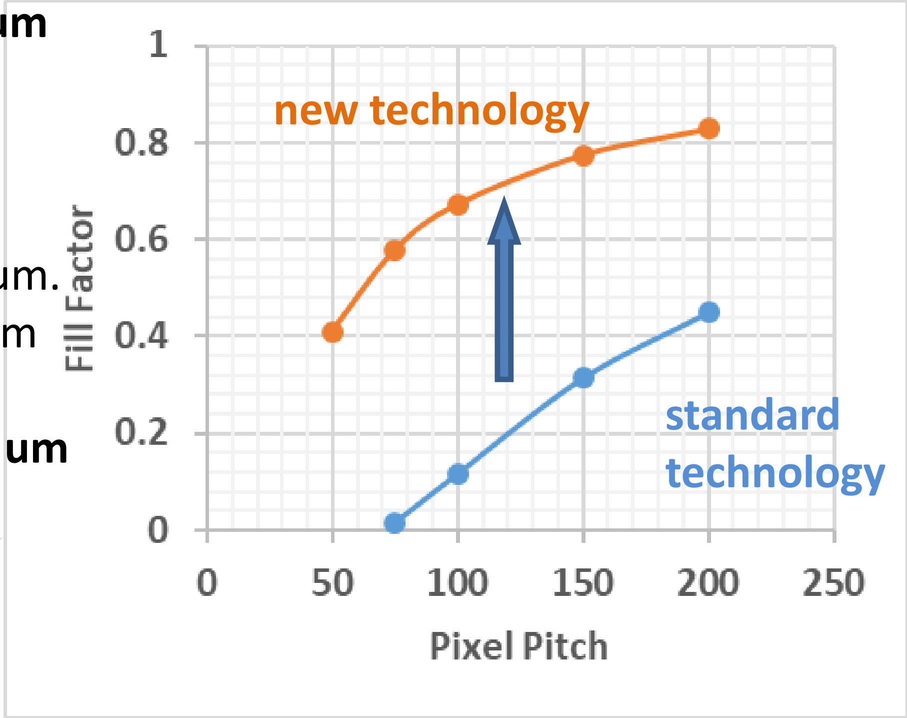
Resolution = 0.35 um.
Critical Size = 0.5 um

Border width ~ 20 um

Nominal Pixel Fill Factor



Conclusions

- UFSD 2 batch has been produced at FBK based on 50um thick Si-on Si wafers

- Different techniques to improve the radiation hardness have been explored:
  - Substitution of Boron with Gallium in the Gain Layer
  - Carbon co-implantation
  - Gain-layer doping profile shaping

- UFSD with Gallium and Carbon co-implantation are perfectly working. Gallium and Carbon do not affect gain and timing performance.

- A next batch (UFSD3) is going to be designed. In this batch we are going to produce for the first time large-area detectors and to optimize the pixel border region and the FF.

Thank you for your attention!

UFSD Collaboration

INFN Torino, Univ. Torino, Univ. Trento, TIFPA, FBK

Acknowledgements:

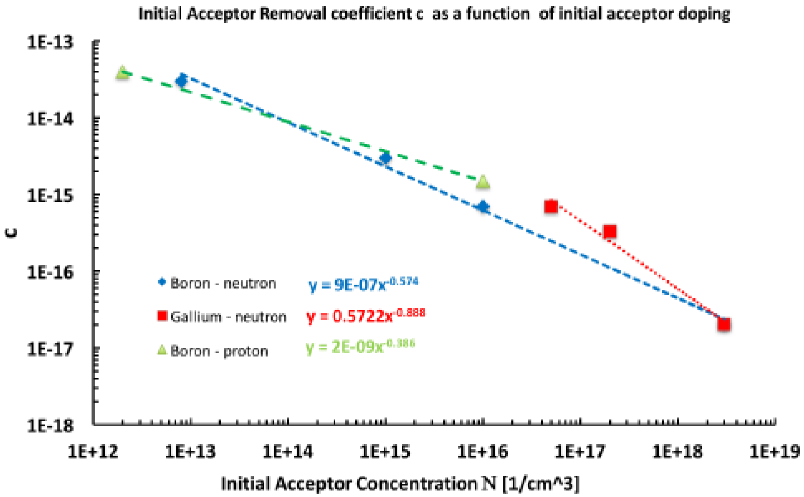
" Part of this work has been financed by the European Union's Horizon 2020 Research and Innovation funding program, under Grant Agreement no. 654168 (AIDA-2020) and Grant Agreement no. 669529 (ERC UFSD669529), and by the Italian Ministero degli Affari Esteri and INFN Gruppo V."

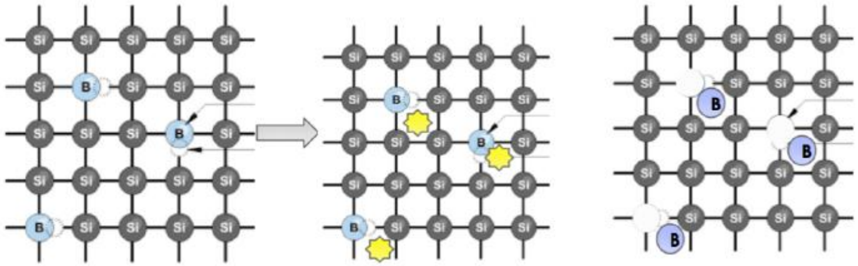
Backup Slides

Acceptor Removal Effect

It is well known that the gain of UFSD strongly degrades after irradiation and it completely disappears at fluences higher than 1e15 cm^{-2}.
This effect could be explained with an effective N_{eff} reduction (G. Kramberger)

$$N_A(\phi) = N_{A0}\, e^{-c(N_{A0})\phi}$$





BORON

Radiation induced defects could inactivate Boron

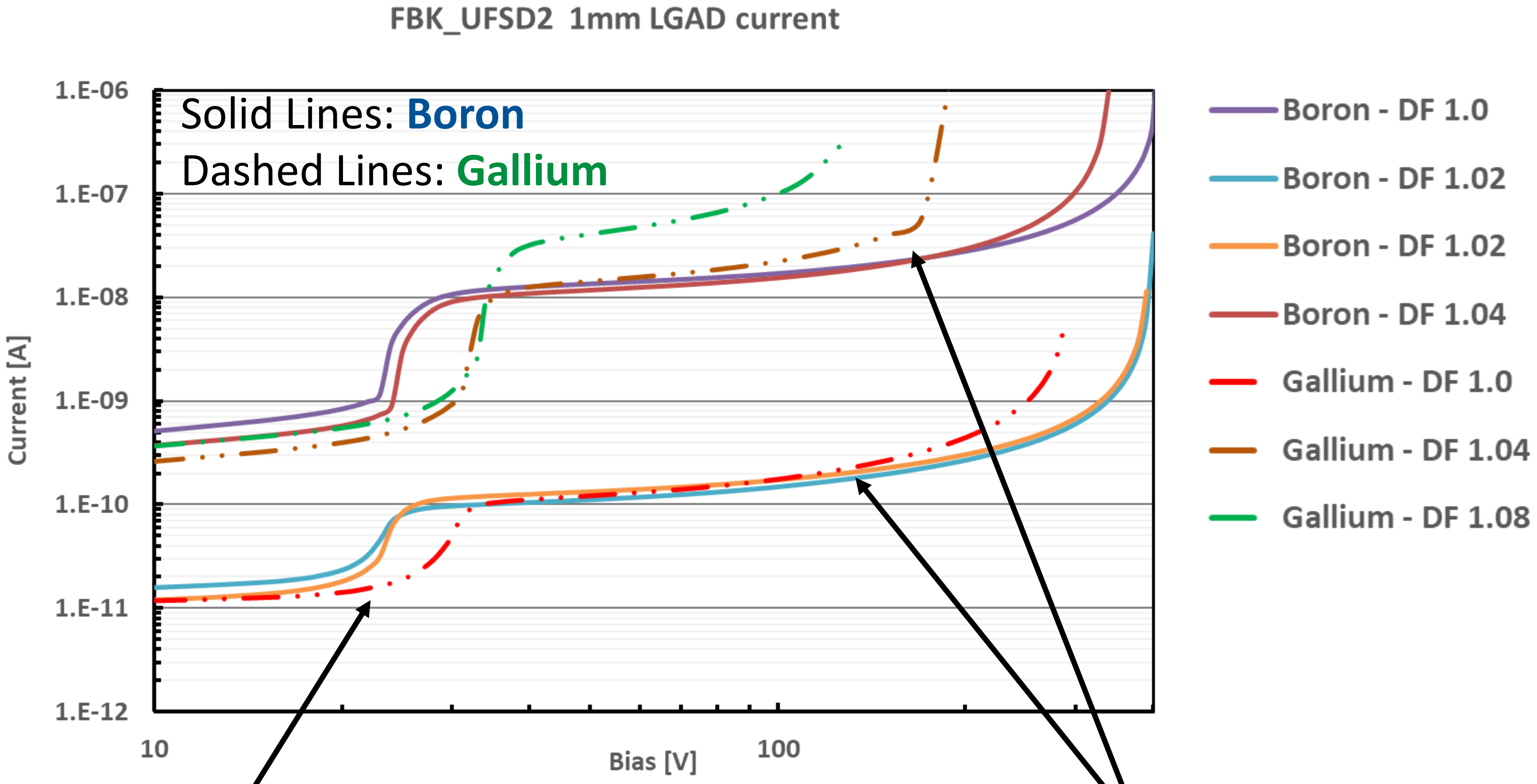
$I + B_s \rightarrow B_i$

B_iO_i complex can also play a role

It depends on the initial Acceptor concentration!

higher doping densities are less affected by acceptor removal

UFSD 2: Characterization



- The knee at ~30V indicates the depletion of the gain layer;
- Similar trend of the leakage current for both Boron and Gallium doped wafers
- Different leakage current due to two different substrates production batches

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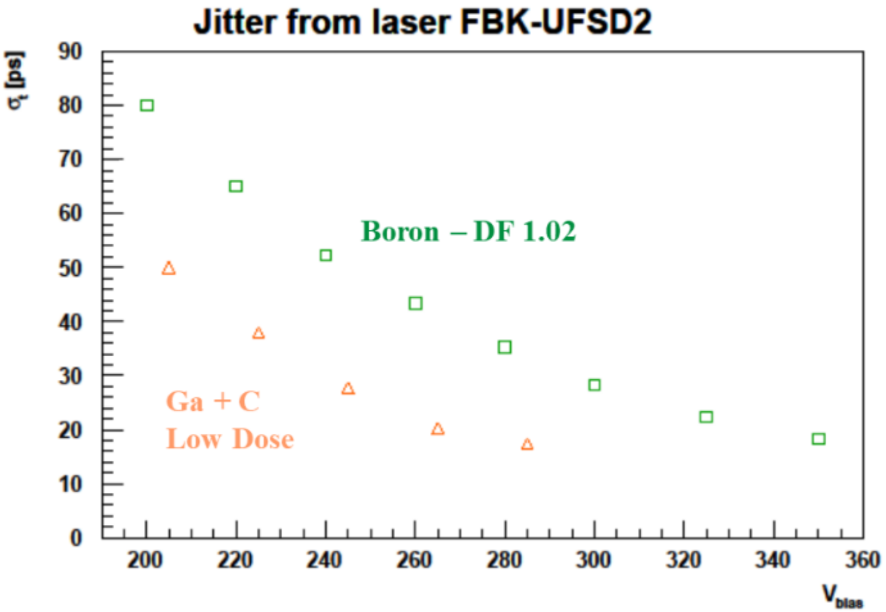
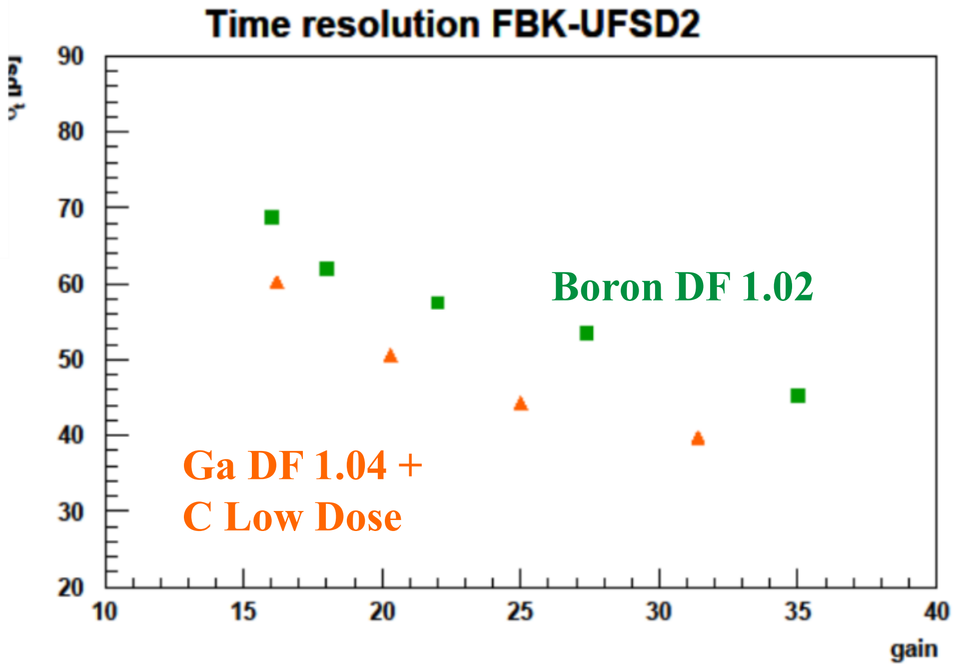
UFSD Batch 2 –Timing



- Excellent Jitter measured with laser setup;
- Doping element of the gain layer doesn’t affect the sensor performance
- Carbon updoes not affect the timing performance

Time resolution from Beam Test



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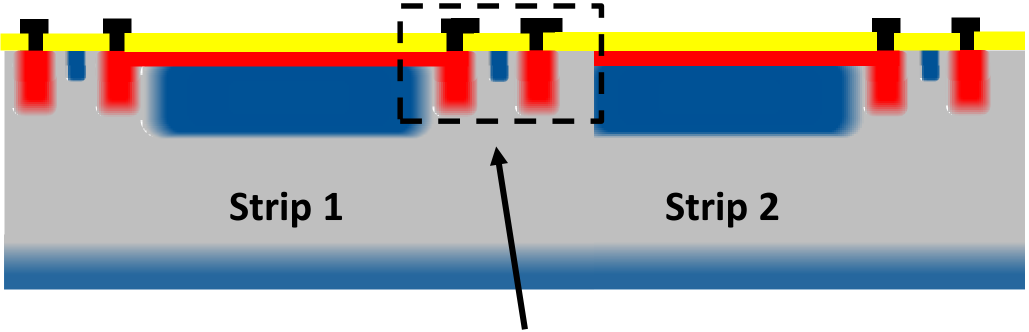
Data from V. Sola

Effect of pixel (strip) border region

Current technology UFSD2

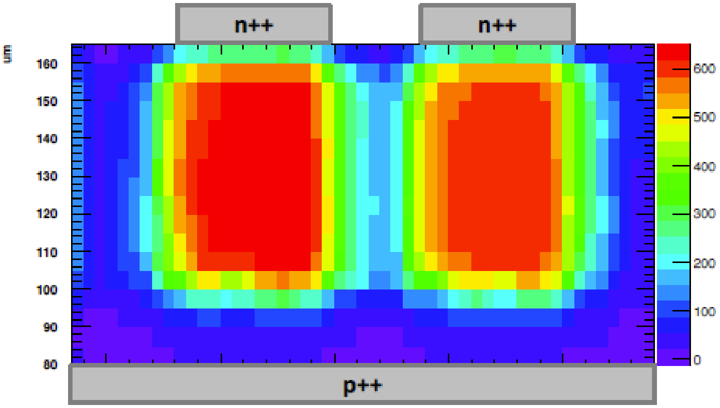
Design:
66 um dead Border (mainly limited by microfabrication technology constraints).



Experimental:
(Edge TCT Measurement)

Inactive region between two adjacent strips has been measured to be ~60um.
Comparable to the design

2D scan of two adiacent strip edge



Signal amplitude projection - 2 strips