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New developments in Ultra Fast Silicon Detectors at FBK

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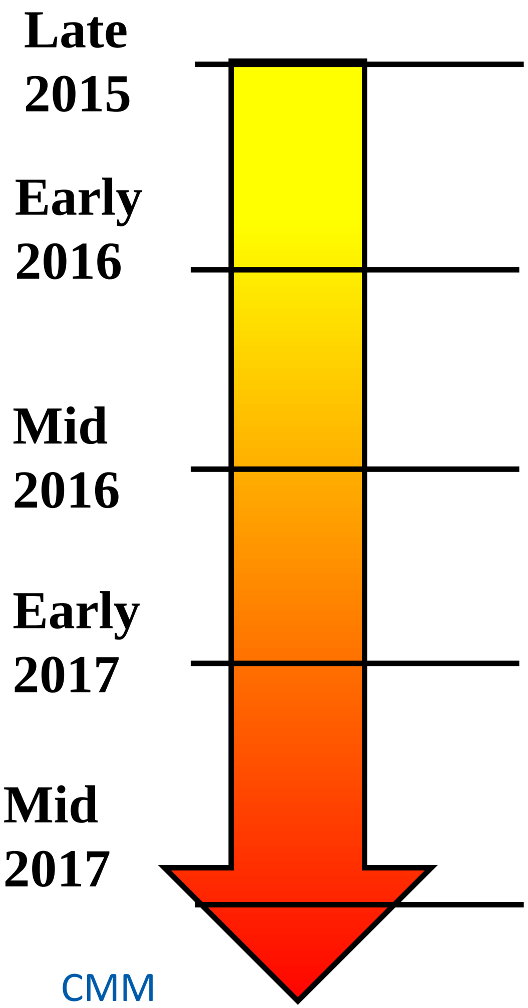
On behalf of
UFSD Collaboration
INFN Torino, Univ. Torino, Univ. Trento, TIFPA, FBK

Summary

1. UFSD technology at FBK
2. UFSD2 Production Batch
3. Techniques to improve the radiation hardness
   - Gallium doping
   - Carbon co-implant
4. UFSD2 Characterization: IV, CV, Gain and Timing
5. Conclusions

UFSD Roadmap at FBK

close collaboration with Uni Turin, Uni Trento and INFN Turin



Late 2015

Fabrication process-flow definition and simulation campaign

Early 2016

1st Batch on 300um Si

- Technology assessment
- Validation of the simulations
- Testing of different segmentation techniques

Mid 2016

1st batch characterization

Early 2017

2nd Batch on 50um Si

- Improving timing performance
- Test new methods to increase the radiation hardness

Mid 2017

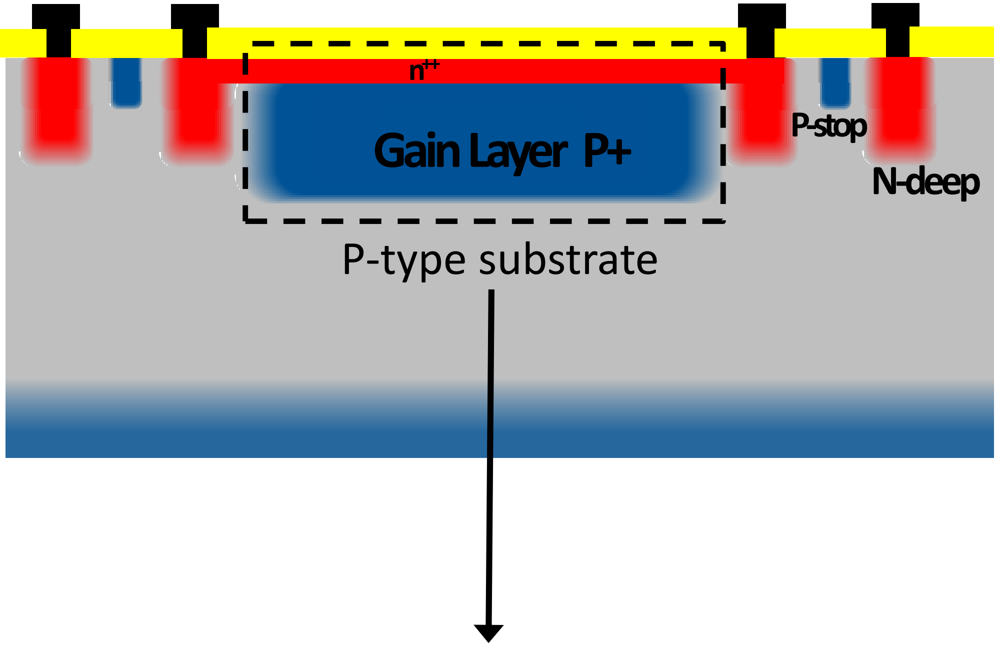
2nd batch characterization

UFSD technology

UFSD = Low Gain Avalanche Diode with Gain in the range ~10 - 20

New challenges:

- Precise tuning of the Gain
- Ultra Fast timing resolution ≈ 10-20 ps
- High spatial resolution: ≈ 10's -100's of µm
- Radiation hardness

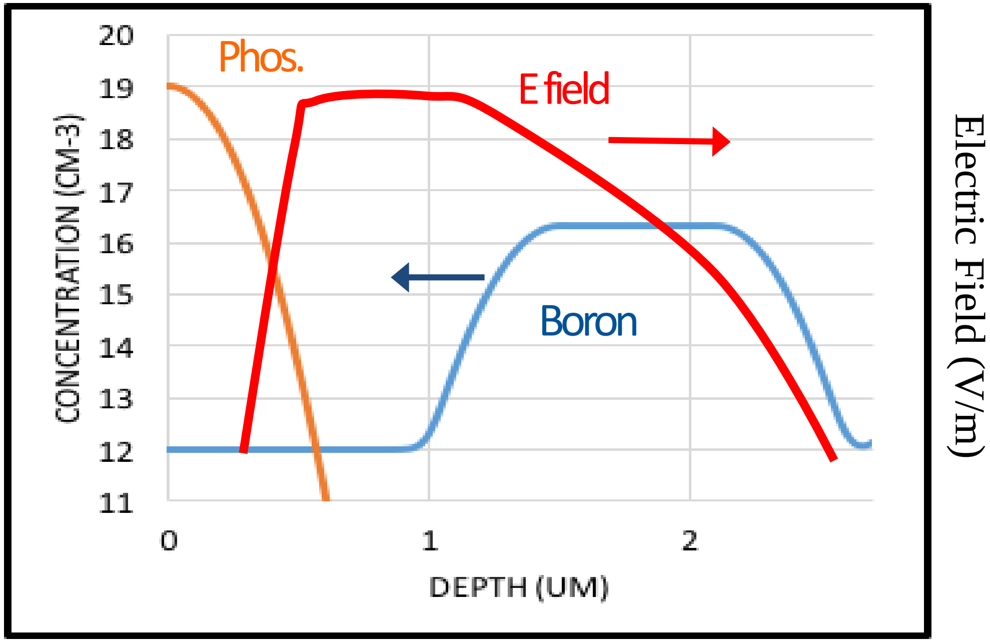


Introduction of an High-Field region:

Electric Field > 2e5 to activate the impact ionizing multiplication

Design of the Gain Layer

The doping profile of the Gain layer controls the shape of the Electric Field



The Gain layer is obtained by means of high energy ion implantation.
-> The Gain layer is implanted in depth in the substrate

This approach has several advantages:

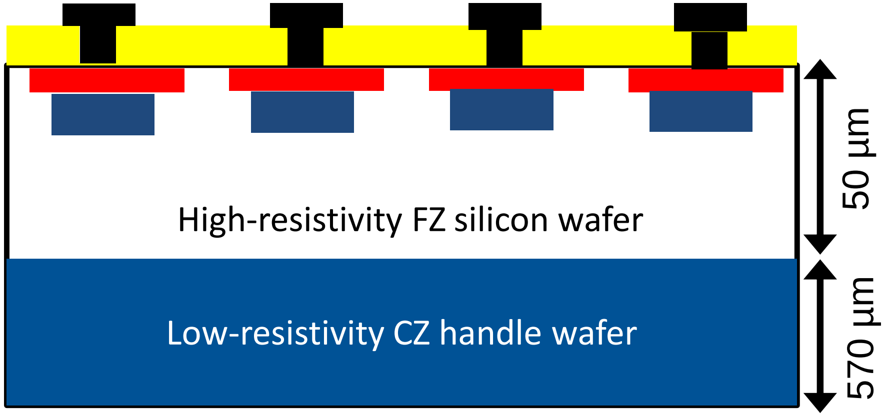
- Is more reliable (gain almost independent of thermal diffusion and of doping compensation effects)
- It takes under control the shape of the E field, avoiding any peaks -> less field enhanced noise generation

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**



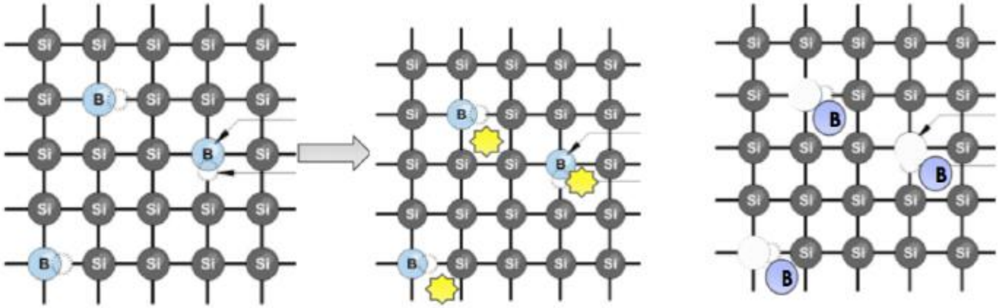
Si-on-Si wafers with 50um of active thickness.

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

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

UFSD Batch 2 – Gallium Doping

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) – Acceptor removal effect

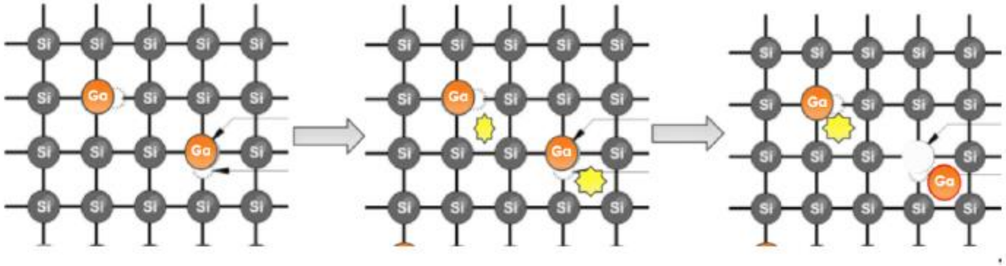


BORON

Radiation induced defects could inactivate Boron

$I + B_s \rightarrow B_i$

B_iO_i complex can also play a role



GALLIUM

Probably is less prone to be inactivated with respect to Boron

UFSD Batch 2 – Gallium Doping

Gallium Gain layer

Some concerns in using Gallium doping in the gain layer

- Gallium is much heavier than B –>

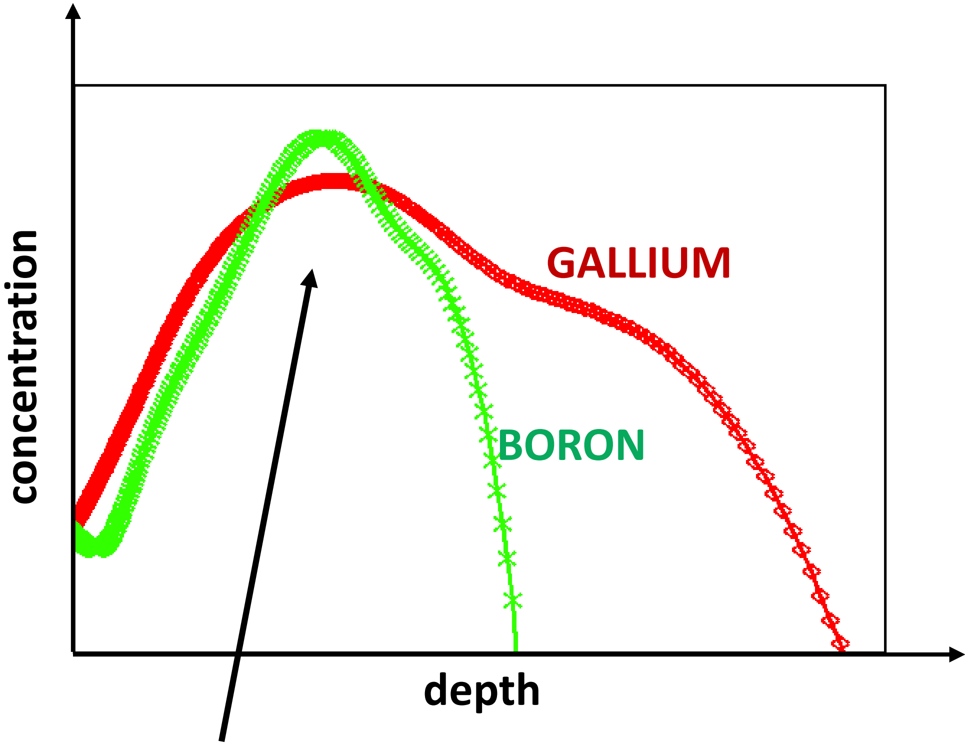
Implantation energy (>> 1MeV) has to be used to reach the same depth as Boron

- The diffusion coeff. in Silicon is one order of magnitude higher than Boron –>

the thermal budget has to be strongly reduced

- Thermal diffusion of Gallium is not well modelled by TCAD software. –>

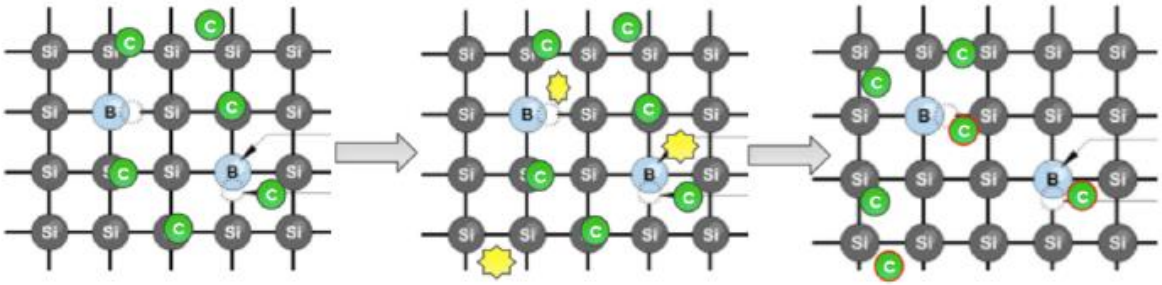
The deep gain layer technology helps in limiting the dependence of the gain on the profile reshaping due to diffusion



Gallium implantation energy has be tuned to reach the same depth of Boron. After all a difference in the tails is unavoidable.

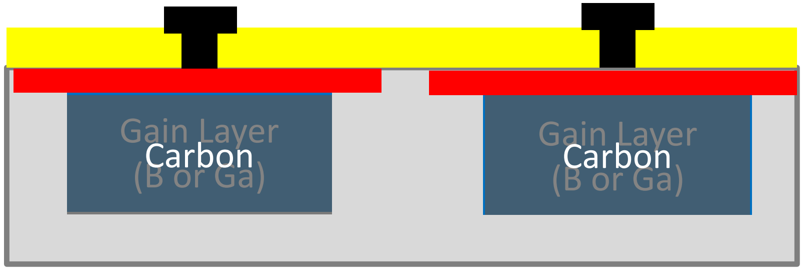
*same dose for both Boron and Gallium

UFSD2 – Carbon co-implant



CARBON

C competes with B in filling interstitial defects



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

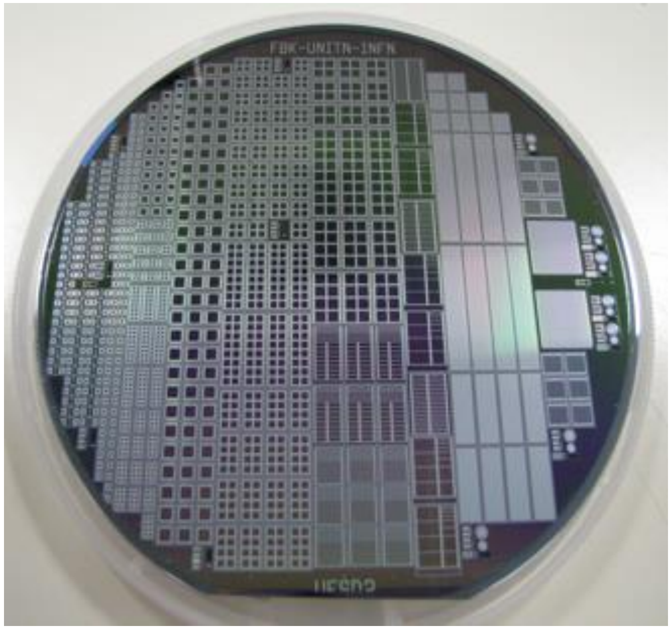
Boron + Carbon
Gallium + Carbon

Two Carbon Doses Tested:

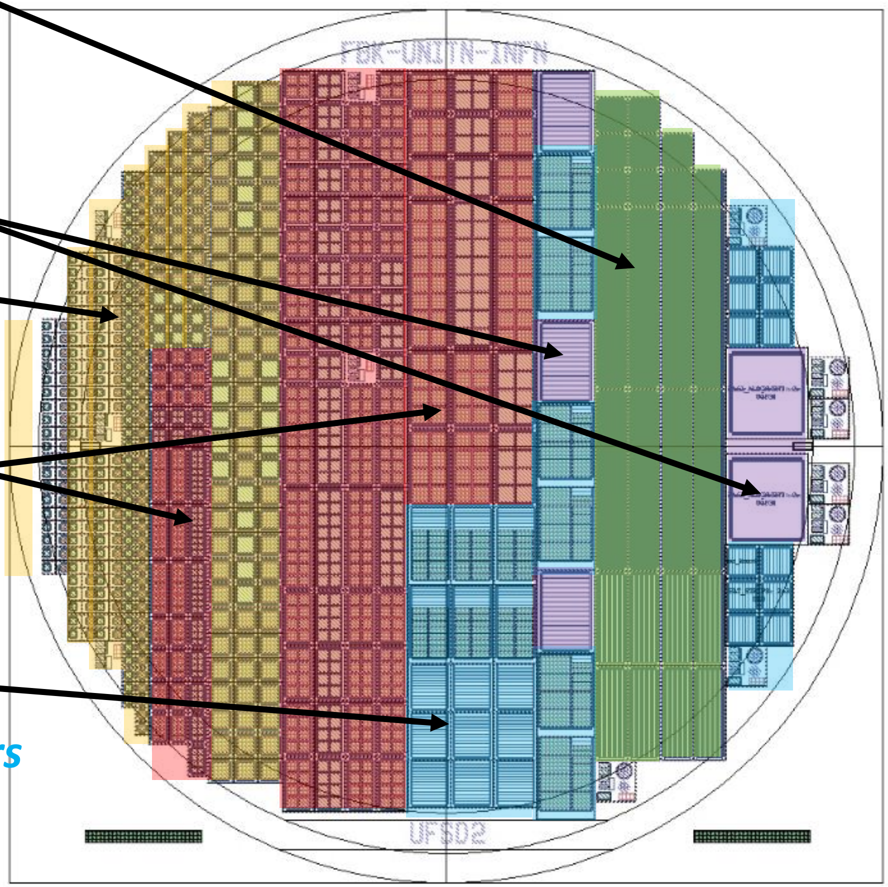
- **Low Dose**
- **High Dose**

UFSD 2 – Split Table

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	



UFSD2 Batch - Layout



STRIPS

TOTEM
NA62

Single Pads

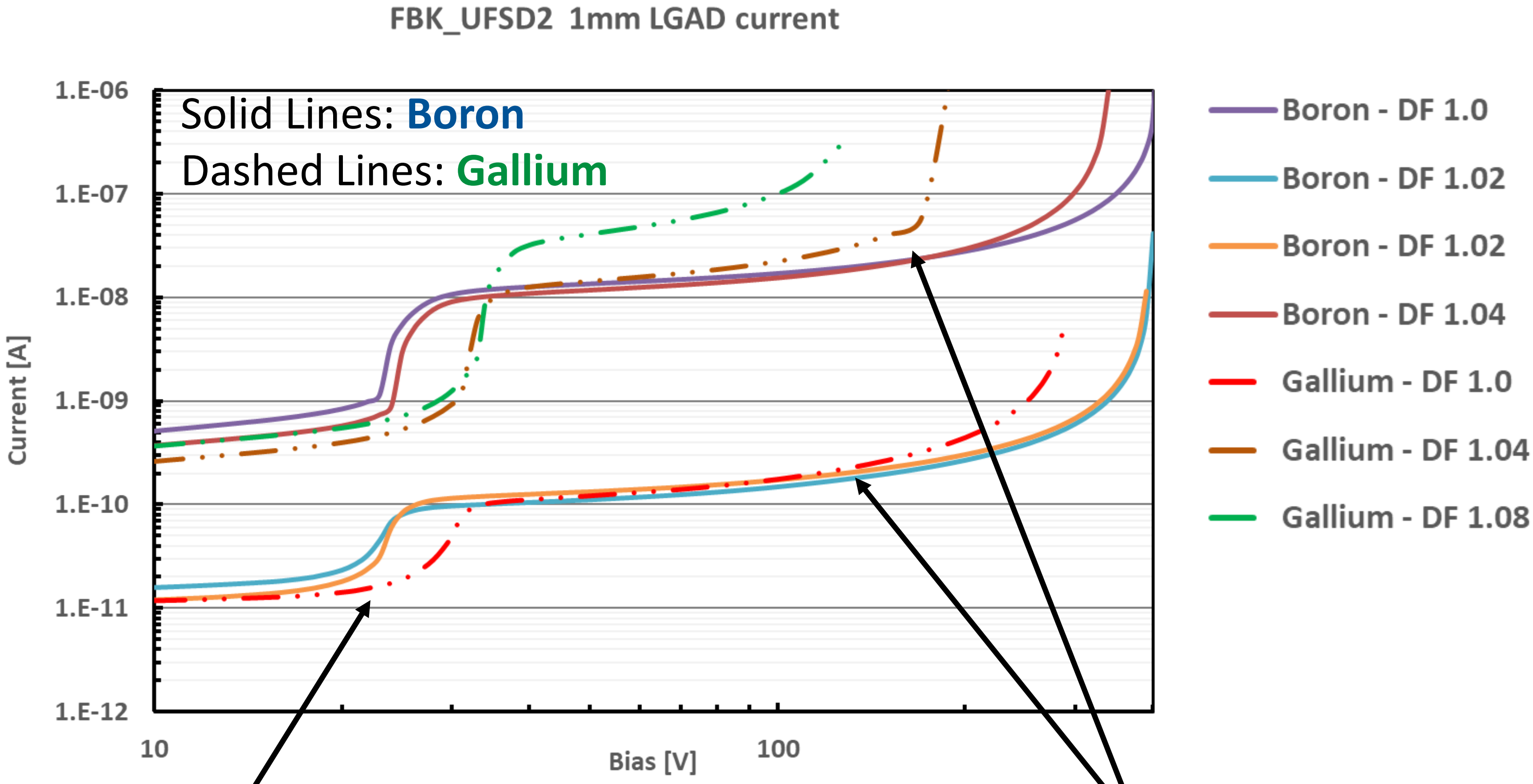
Pad Arrays

FAT STRIPS
CT PPS Sensors

Multilayout:
Single pads,
Pad arrays;
Strips;
Other pixelated detectors….

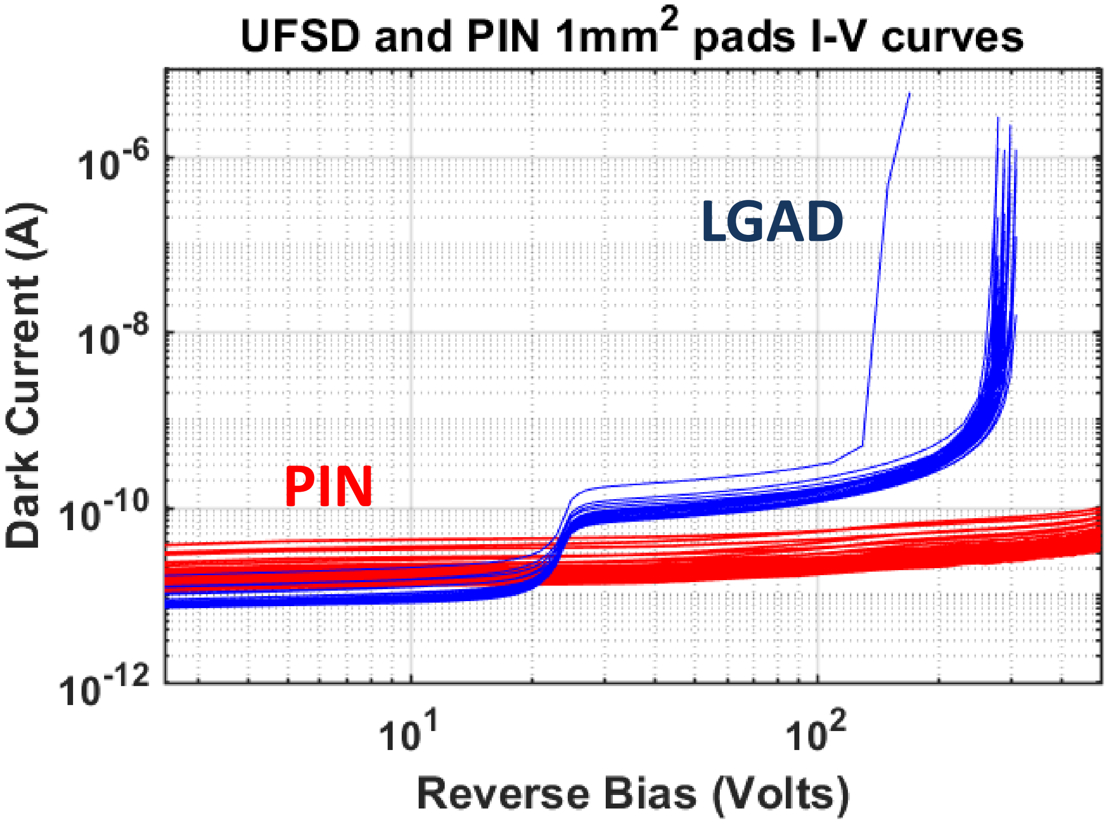
Only N-side segmentation
(single side processing)

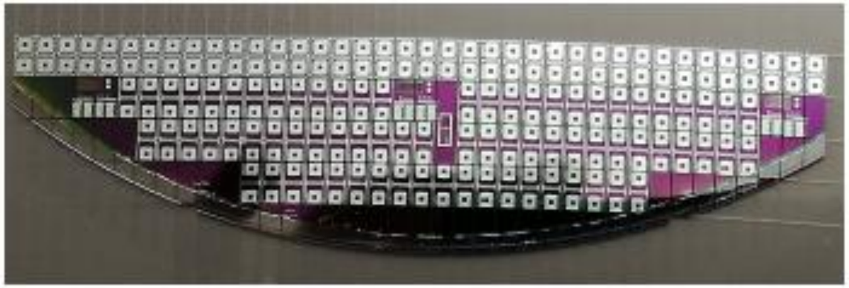
UFSD 2 –IV



- 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

UFSD 2 – IV

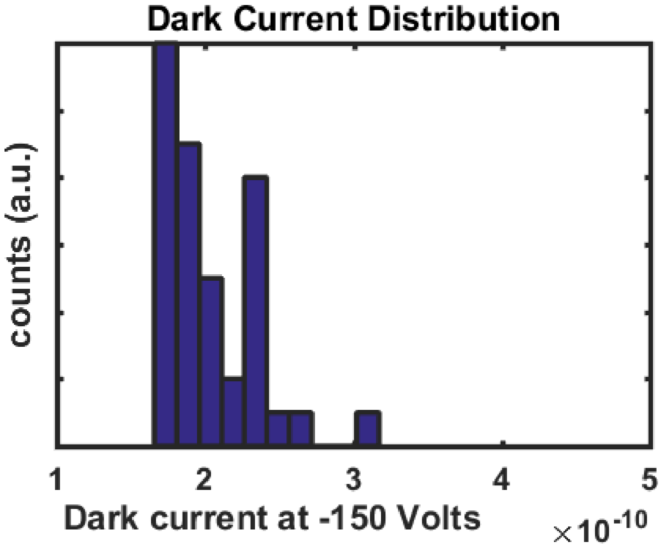




Data from Wafer 2
Boron Dose Factor = 1.0

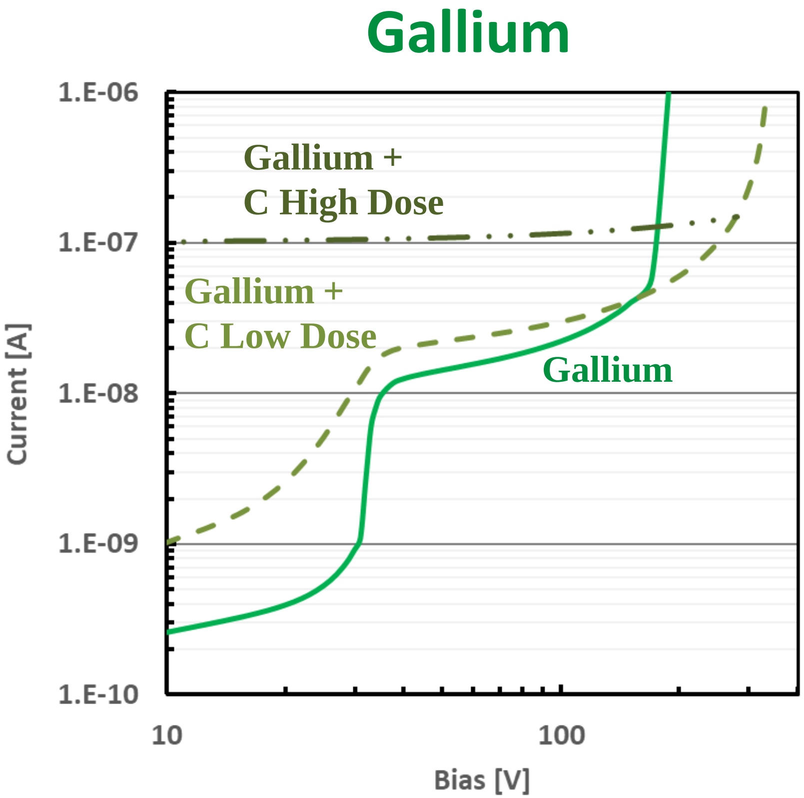
All the 1x1 mm^2 pads are plotted w/o any die selection

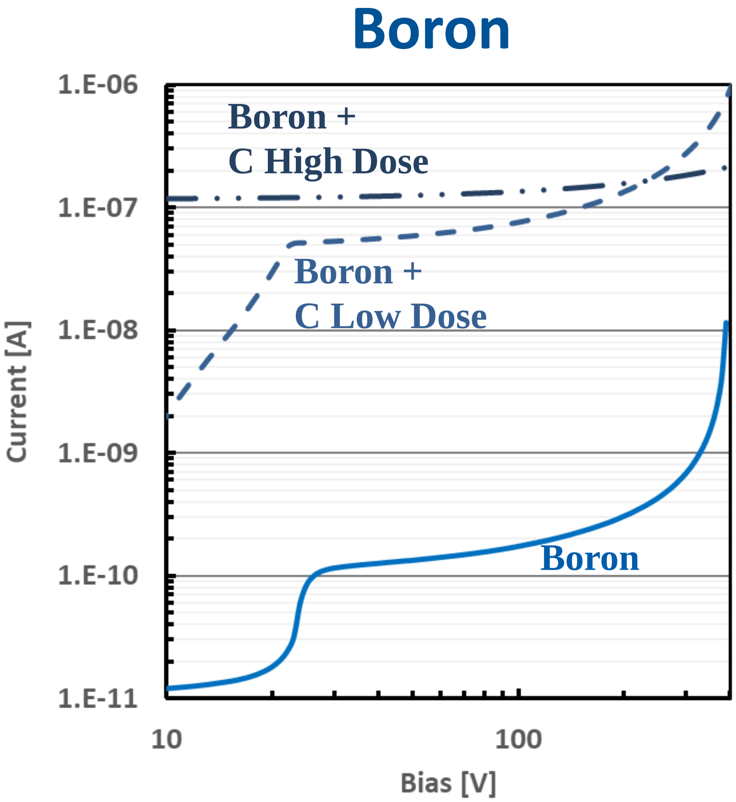
Very high uniformity and low dark current



UFSD 2 – IV

Effect of Carbon co-implant on IV curves


Gallium

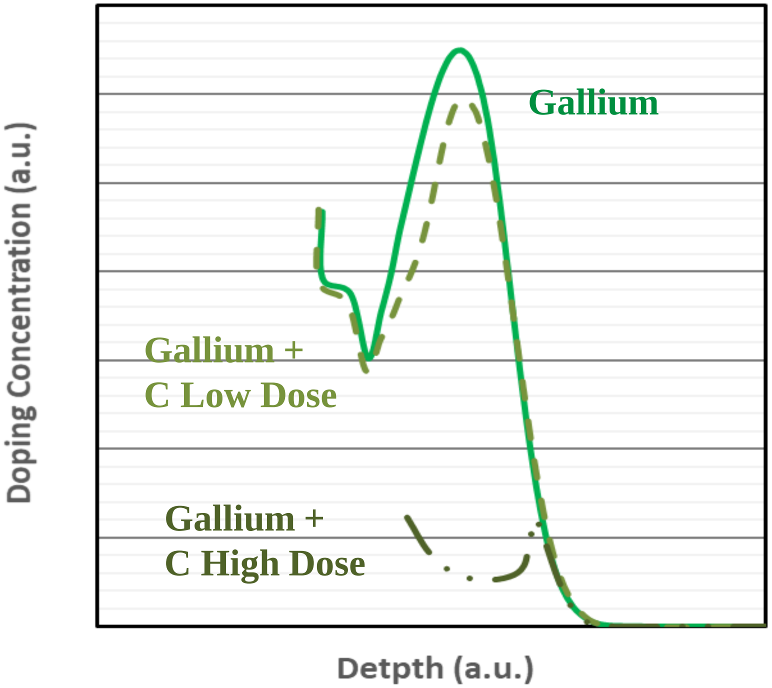

Boron

- **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

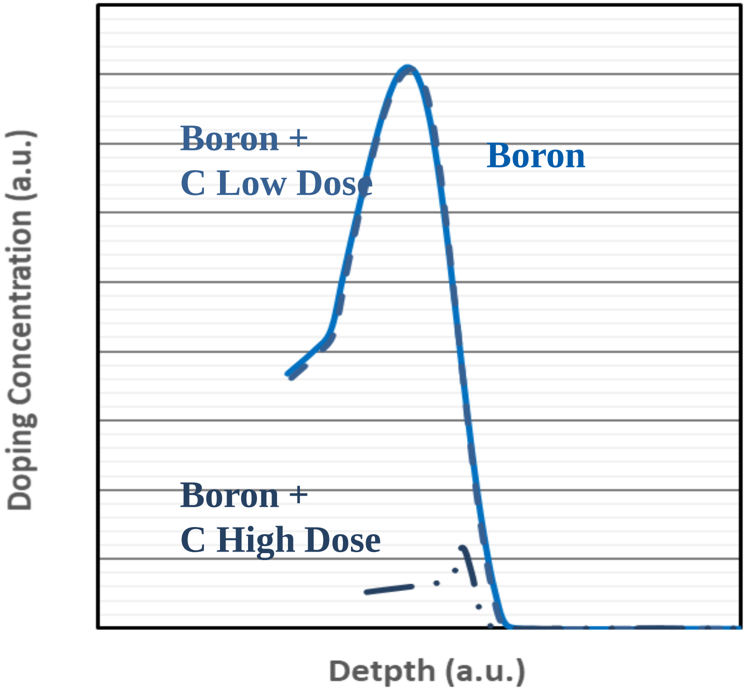
UFSD 2 - CV

Effect of Carbon co-implant on IV curves

Gallium

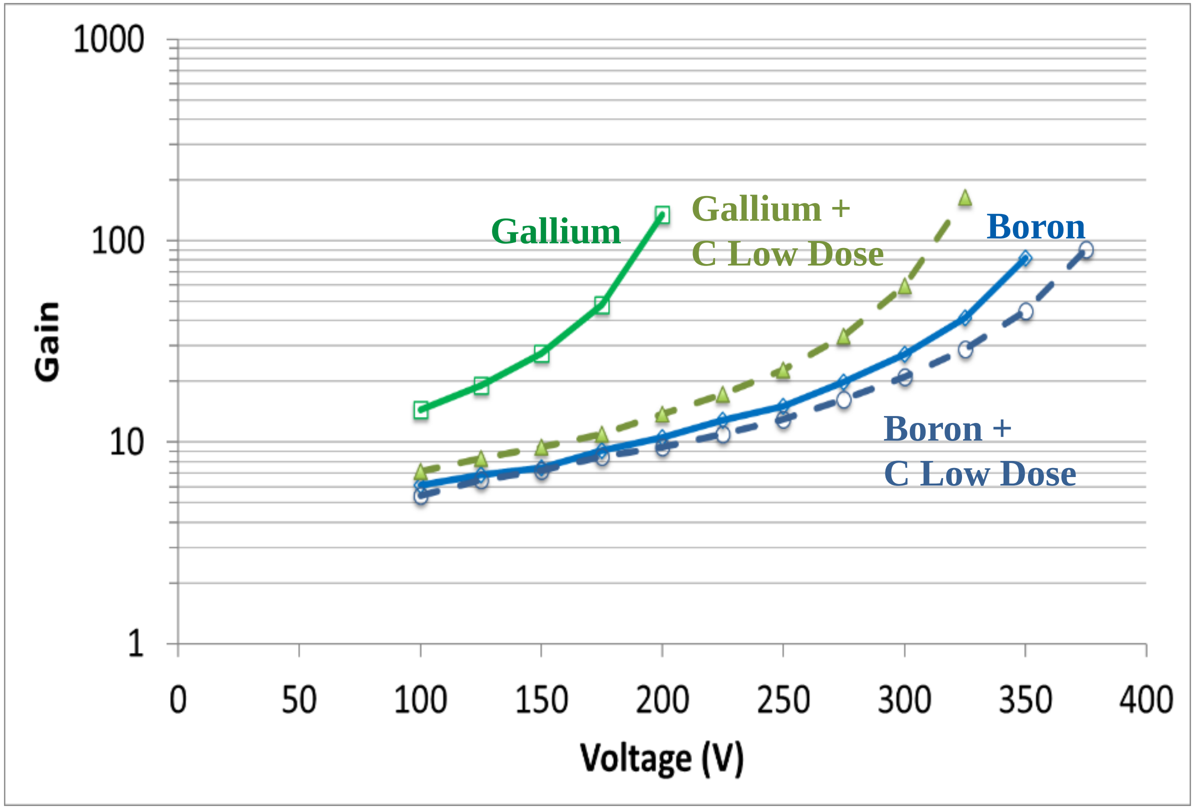


Boron



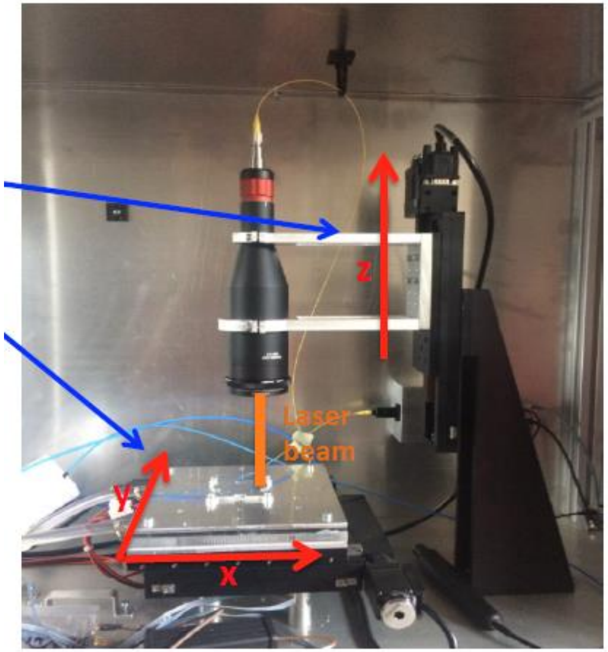
- **The Carbon reduces the active doping concentration of the gain layer**
- **High Carbon** effect is relevant for both Boron Gallium;
- **Low Carbon** effect is more pronounced in Gallium than in Boron;

UFSD Batch 2 – GAIN



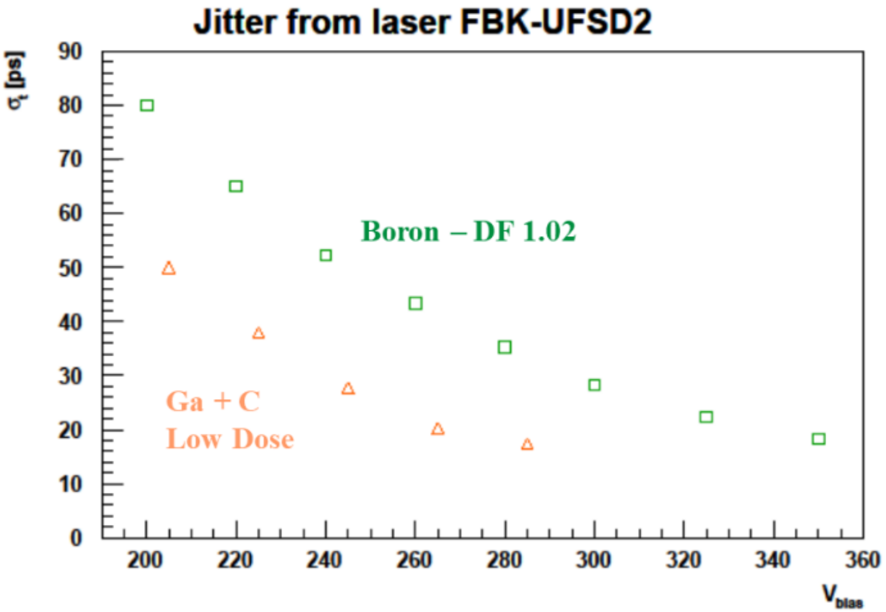
TST Setup

Pico-second IR laser
at 1064 nm
Laser spot diameter ~50um
Broadband Amplifier
Room temperature



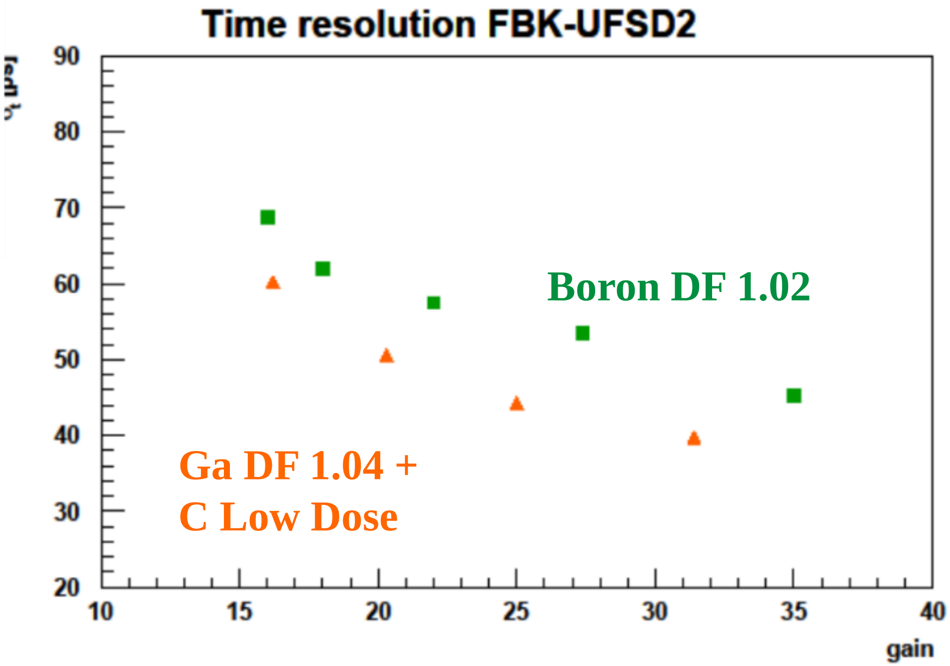
Presented by M. Ferrero @ IEEE NSS 2017

UFSD Batch 2 –Timing



- Excellent Jitter measured with laser setup;
- Doping element of the gain layer doesn’t affect the sensor performance
- Carbon up to (~1e18 cm^{-2}) does not affect the timing performance

Time resolution from Beam Test



Data from V. Sola

Conclusions 1/2

- A new UFSD 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

- The UFSD2 batch showed very promising results in terms of:
  - Low dark current; uniformity and technology reliability.
  - Gain value
  - Very high timing resolution

Conclusions 2/2

- UFSD with Gallium are perfectly working. Gallium does not affect the noise, gain and timing performance.
- Carbon co-implanted UFSDs are working, although Carbon increases the dark current.
- Carbon in lower concentrations slightly reduces the gain but it does not affect the detector timing performance.
- Carbon in higher doses de-activates the Dopant (both Gallium and Boron) and strongly reduce the gain.

FONDAZIONE
BRUNO KESSLER

Thank you for your attention!

UFSD Collaboration

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

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