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

- Fabrication process-flow definition and simulation campaign
  - 1st Batch on 300um Si
  - Technology assessment
  - Validation of the simulations
  - Testing of different segmentation techniques
  - Improving timing performance
  - Test new methods to increase the radiation hardness

Timeline:
- Late 2015: Fabrication process-flow definition and simulation campaign
- Early 2016: 1st batch characterization
- Mid 2016: 2nd Batch on 50um Si
- Early 2017: 2nd batch characterization
- Mid 2017: 1st 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
It is well known that the gain of UFSD strongly degrades after irradiation and it completely disappears at fluences higher than $1 \times 10^{15}$ cm$^{-2}$. This effect could be explained with an effective $N_{\text{eff}}$ 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
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

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<th>Carbon</th>
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</table>
UFSD2 Batch - Layout

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

**Only N-side segmentation**
(single side processing)
- Solid Lines: **Boron**
- Dashed Lines: **Gallium**

- 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.
Data from Wafer 2

Boron Dose Factor = 1.0

All the 1x1 mm² pads are plotted w/o any die selection

Very high uniformity and low dark current

Dark Current Distribution
Effect of Carbon co-implant 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/mm²), the exponential growth vs Bias is strongly reduced.
UFSD 2 - CV

Effect of Carbon co-implant on IV curves

- 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;

Gallium

- Gallium + C Low Dose
- Gallium + C High Dose

Boron

- Boron + C Low Dose
- Boron + C High Dose
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 ($\sim$1e18 cm$^{-2}$) does not affect the timing performance.

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**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.
Thank you for your attention!

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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."

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