First FBK 50 µm UFSD Production

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OUTLINE

✎ Production
✏ Doping strategies
✏ IV measurements
✏ CV measurements
✏ Doping profiles - Backup

✎ Laboratory Measurements
✏ Gain
✏ Time resolution
✏ Intra-pad inactive region - Backup

✎ Simulation
✏ Gain predictions - Backup

✎ Neutron Irradiated UFSD
✏ CV measurements
✏ c-parameter extraction
✏ Gain
PRODUCTION
## 50µm UFSD Production

<table>
<thead>
<tr>
<th>Wafer #</th>
<th>Dopant</th>
<th>Gain dose</th>
<th>Carbon</th>
<th>Diffusion</th>
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**Production:**
- 18 Silicon-on-Silicon wafers
- 4 different gain layer strategies:
  - **Boron** (Low & High diffusion)
  - **Carbonated Boron** (B High diffusion)
  - **Gallium** (Low diffusion)
  - **Carbonated Gallium** (Ga Low diffusion)
- 4 different doping concentration for Boron implants
- 2 different diffusion temperatures for Boron
- 3 different doping concentration for Gallium implants
- 2 carbon concentration (Low & High)

**Carbonated Boron, Gallium & Carbonated Gallium implants to investigate radiation hardness**

Gallium implant required a complete new simulation, because of implantation energy and diffusion very different from Boron.
IV Curves - Wafer Uniformity

Data from Wafer 2
Boron LD Dose Factor = 1.0
Measurements on wafer

All the 1x1 mm² pads are plotted without any die selection
→ Very high uniformity and low dark current
Boron & Gallium doped sensors show the same behavior

- Low leakage current (10s pA ÷ 10s nA)
- The knee at ~30V indicate the the gain layer depletion voltage
- Exponential growth gives information about the internal gain of the sensors
Different leakage current due to two different wafer production batches

▷ Boron & Gallium doped sensors show the same behavior
▷ Low leakage current (10s pA + 10s nA)
▷ The knee at ~30V indicates the the gain layer depletion voltage
▷ Exponential growth gives an information about the internal gain of the sensors
- Carbon implantation increases the leakage current of the sensors (expected)
- Low Carbon: same trend of the leakage current as in the case without Carbon
- High Carbon: high leakage current (~100nA) hides the information about gain

* Wafers from high $I_{\text{leak}}$ batch
CV Curves - All Wafers

The knee voltage value is proportional to the gain layer doping.

- The knee at ~30V indicates the gain layer depletion voltage
- Boron & Gallium doped sensors show slightly different behavior due to different gain layer width
- Low Carbon: similar depletion voltage as in the case without Carbon
- High Carbon: depletion voltage occurs much earlier than in the case without Carbon
The knee in CV curves matches with the full depletion of gain layer.

- The position of the knee is proportional to the active doping concentration of the gain layer.
- The Carbon reduces the active doping concentration of gain layer:
  - High Carbon effect is relevant both in Boron and Gallium
  - Low Carbon effect is more significant in Gallium than in Boron.
LABORATORY MEASUREMENTS
Gain Measurement

\[ \text{GAIN} = \frac{\text{Signal area LGAD}}{\text{Signal area PiN}} \]

**FBK UFSD2 - Gain**

- **W1**
- **W3**
- **W4**
- **W6**
- **W8**
- **W14**
- **W15**

**TCT Setup from Particulars**
- Pico-second IR laser at 1064 nm
- Laser spot diameter ~ 50 µm
- Cividec Broadband Amplifier (40dB)
- Oscilloscope Lecroy 640Zi
- Room temperature
Beam Test with 180 GeV/C π at CERN SPS
Sensors on INFN-Torino boards
Cividec Broadband Amplifier (40dB)
Oscilloscope Lecroy 640Zi
(40Gsample/s, bandwith 4GHZ)
Room temperature

**Trigger**: CNM 50 µm UFSD sensor on UCSC board + 20dB Cividec Broadband amplifier → $\sigma_t^{\text{trigger}} \sim 35$ ps (subtracted from results)

**Trigger logic**: UCSC & (W1 or W8 or W15)

**Expected $\sigma_t \sim \sigma_j^{\text{jitter}} \oplus \sigma_L^{\text{Landau}} (30$ ps)**

→ W15 in line with predictions, investigating W1 and W8, issue with metal/non metal coverage
(see Backup for details)
Time Resolution from Beam Test

Beam Test with 180 GeV/C $\pi$ at CERN SPS
Sensors on INFN-Torino boards
Cividec Broadband Amplifier (40dB)
Oscilloscope Lecroy 640Zi
(40Gsample/s, bandwidth 4GHZ)
Room temperature

Trigger:
Trigger logic: UCSC & (W1 or W8 or W15)
Expected $\sigma_t \sim \sigma_t^{\text{jitter}} \oplus \sigma_t^{\text{Landau}} (30 \text{ ps})$
$\rightarrow W15$ in line with predictions, investigating W1 and W8, issue with metal/non metal coverage
(see Backup for details)
NEUTRON IRRADIATED UFSD
Irradiation Strategy

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**Sensors from these wafers sent to Ljubljana and CERN PS for irradiation**

**Neutron irradiation**

Fluence steps:
- $2 - 4 \cdot 10^{14}$ $n_{eq}/cm^2$
- $1.5 - 3 \cdot 6 \cdot 10^{15}$ $n_{eq}/cm^2$
- $1 \cdot 10^{16}$ $n_{eq}/cm^2$

→ Irradiated sensors just arrived in Torino

**24 GeV/c Proton irradiation**

Fluence steps:
- $1 - 6 \cdot 10^{14}$ $n_{eq}/cm^2$
- $1 - 3 - 6 - 9 \cdot 10^{15}$ $n/cm^2$

→ Irradiated sensors on their way to Torino
IV Measurements on Irradiated Sensors

Curvature proportional to gain

Irradiation extends the operating voltage of the sensors up to ~ 750 V

V. Sola
CV Measurements on Irradiated Sensors

Reminder: fluence doubles at each step

The knee voltage value is proportional to the gain layer doping
CV Measurements on Irradiated Sensors

Standard

Carbonated

FBK UFSD2 - W8 B 1.02 H - CV Irradiated

FBK UFSD2 - W14 Ga 1.04 L - CV Irradiated

FBK UFSD2 - W6 B 1.02 H C Low - CV Irradiated

FBK UFSD2 - W15 Ga 1.04 L C Low - CV Irradiated

Capacitance [C]

Reverse Bias [V]

Capacitance [F]

Reverse Bias [V]

Capacitance [F]

Reverse Bias [V]

Capacitance [F]

Reverse Bias [V]
CV Measurements on Irradiated Sensors

Standard

Carbonated

V. Sola

CV Measurements on Irradiated Sensors

**FBK UFSD2 - W8 B 1.02 H - CV Irradiated**

- NEW
- 2e14
- 4e14
- 8e14
- 1.5e15
- 3e15
- 6e15

**FBK UFSD2 - W14 Ga 1.04 L - CV Irradiated**

- NEW
- 2e14
- 4e14
- 8e14
- 1.5e15
- 3e15
- 6e15

**FBK UFSD2 - W6 B 1.02 H C Low - CV Irradiated**

- NEW
- 2e14
- 4e14
- 8e14
- 1.5e15
- 3e15
- 6e15

**FBK UFSD2 - W15 Ga 1.04 L C Low - CV Irradiated**

- NEW
- 2e14
- 4e14
- 8e14
- 1.5e15
- 3e15
- 6e15

V. Sola

CV Measurements on Irradiated Sensors

**Standard**

- **FBK UFSD2 - W8 B 1.02 H - CV Irradiated**
- **FBK UFSD2 - W14 Ga 1.04 L - CV Irradiated**

**Carbonated**

- **FBK UFSD2 - W6 B 1.02 H C Low - CV Irradiated**
- **FBK UFSD2 - W15 Ga 1.04 L C Low - CV Irradiated**

```
Capacitance [F]
Reverse Bias [V]
```

- NEW
- 2e14
- 4e14
- 8e14
- 1.5e15
- 3e15
- 6e15

**Preliminary**
CV Measurements on Irradiated Sensors

Standard

Carbonated
CV Measurements on Irradiated Sensors

FBK UFSD2 - W8 B 1.02 H - CV Irradiated

FBK UFSD2 - W14 Ga 1.04 L - CV Irradiated

FBK UFSD2 - W6 B 1.02 H C Low - CV Irradiated

FBK UFSD2 - W15 Ga 1.04 L C Low - CV Irradiated

Capacitance [F] vs Reverse Bias [V] for different irradiation levels.
The B+C and Ga+C gain layers are more radiation resistant than those with B or Ga.
Acceptor Removal Coefficient

From the fraction of gain layer surviving the radiation, it is possible to extract the acceptor removal coefficient $c$.

$$N_A = N_{A0} - N_c \cdot (1 - \exp(-c \cdot \Phi_{eq}))$$

$$dN_A = -\sum_i c_i \cdot N_A \, d\Phi, \quad c = \sum_i c_i ([O],[C],[B])$$

$y = 9.9E-01e^{-2.1E-16x}$
$y = 9.7E-01e^{-2.7E-16x}$
$y = 9.8E-01e^{-4.1E-16x}$
$y = 1.0E+00e^{-5.5E-16x}$
$y = 9.5E-01e^{-5.5E-16x}$
$y = 1.0E+00e^{-6.9E-16x}$
$y = 9.6E-01e^{-7.7E-16x}$
$y = 1.0E+00e^{-8.5E-16x}$
$y = 1.0E+00e^{-1.1E-15x}$
Carbonated sensors have a factor ~ 3 better acceptor removal coefficient

Among not carbonated sensors, low diffusion Boron has the better response to irradiation

HPK data courtesy of G. Kramberger
Carbonated sensors have a factor ~ 3 better acceptor removal coefficient

Among not carbonated sensors, low diffusion Boron has the better response to irradiation

→ Will be Boron LD + Carbon the most rad-hard option?

HPK data courtesy of G. Kramberger
Carbonated sensors have a similar acceptor removal coefficient.

Strong \( c \) dependence on the doping layer width for sensors without Carbon.
Gain of Irradiated Sensors

\[ \text{GAIN} = \frac{\text{Signal area LGAD}}{\text{Signal area PiN}} \text{ irradiated at the same fluence} \rightarrow \text{only from gain layer} \]

\(\text{Gain}_{\text{layer}} = \frac{\text{Gain}}{\text{Bias}}\)

\(\text{Wafer 8 (Boron)}\)

\(\text{Wafer 14 (Gallium)}\)

\(\text{Wafer 6 (Boron-Carbon Low)}\)

\(\text{Wafer 15 (Gallium-Carbon Low)}\)

\(\Delta \) Carbonated Boron at ~ 600 V maintains factor 2 higher gain than standard Boron
SUMMARY

➤ First 50 µm UFSD production from FBK of very high quality
  ▶ Different strategies for the gain layer implant have been pursued
  ▶ IV measurements show good uniformity along wafer
  ▶ CV measurements allow extraction of doping concentration profiles
  ▶ Sensors with low Carbon dose show similar behaviour to not carbonated ones

➤ Laboratory measurement
  ▶ Well controlled moderate gain for all wafers
  ▶ Good timing performances

➤ Radiation tolerance
  ▶ Acceptor removal coefficient increases with gain implant width
  ▶ Carbon underneath the gain implant halves acceptor removal effect

→ Will be Boron LD + Carbon the most rad-hard option?
We kindly acknowledge the following funding agencies, collaborations:

- INFN - Gruppo V
- Horizon 2020, grant UFSD669529
- Horizon 2020, grant INFRAIA
- Ministero degli Affari Esteri, Italy, MAE, “Progetti di Grande Rilevanza Scientifica”
- U.S. Department of Energy grant number DE-SC0010107
- RD50, CERN
BACKUP
Doping Strategy Motivation

Different types of gain layer implant to study the radiation effects on the gain layer

- **Boron**
  - Radiation creates interstitial defects that inactivate the Boron

- **Gallium**
  - From literature, Gallium has a lower possibility to become interstitial

- **Carbon**
  - Interstitial defects filled with Carbon instead of with Boron and Gallium

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From RD50 Collaboration
Leakage current scales with the temperature (expected a factor 2 for every 7°C)

- Expected a gain inversely proportional to the temperature
- Internal Breakdown shift towards lower voltage due to the temperature decreasing

\[ \Delta T = 48\, ^\circ C \rightarrow \text{Current}(24^\circ C)/\text{Current}(-24^\circ C) \approx 100 \rightarrow \text{Result expected} \]
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
### Jitter Measurement

**Jitter from laser FBK-UFSD2**

- **Jitter Wafer 1 (CFD 70%)**
- **Jitter Wafer 8 (CFD 70%)**
- **Jitter Wafer 15 (CFD 70%)**

**TCT Setup from Particulars**
- Pico-second IR laser at 1064 nm
- Laser spot diameter ~ 50 µm
- Cividec Broadband Amplifier (40dB)
- Oscilloscope Lecroy 640Zi (40Gsample/s, bandwidth 4GHZ)
- Room temperature
- Sensors on INFN-Torino boards (not optimised for timing measurement)

→ **Ga+C sensor has same timing performaces as B ones**

**REMINDER:**
- W1 = B 0.98 LD
- W8 = B 1.02 HD
- W15 = Ga 1.04 + C Low
Beam Test Setup at CERN SPS

**REMINDER:**

- \( W_1 = B \ 0.98 \ L \)
- \( W_8 = B \ 1.02 \ H \)
- \( W_{15} = Ga \ 1.04 + C \ \text{Low} \)

**Trigger logic:**

- UCSC
- \( (\ W_1 \ \text{or} \ W_8 \ \text{or} \ W_{15} \ ) \)

**180 GeV/c \( \pi \) beam**
Data analysis:

- Distribution of the time distance between trigger signal and each sensors signal
- Using Constant Fraction Discriminator (CFD) at 25% for trigger and optimised for sensors
- $\sigma_t$ is trigger subtracted ($\sigma_t^{\text{trigger}} \sim 35$ ps)

REMINDER:

- W1 = B 0.98 L
- W8 = B 1.02 H
- W15 = Ga 1.04 + C Low

Time Resolution - FBK UFSD2 W1

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<tr>
<td>Sigma</td>
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$V_{\text{bias}} = 300$ V
Gain = 41
$\sigma_t = 48$ ps

Time Resolution - FBK UFSD2 W8

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$V_{\text{bias}} = 350$ V
Gain = 46
$\sigma_t = 45$ ps

Time Resolution - FBK UFSD2 W15

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$V_{\text{bias}} = 265$ V
Gain = 39
$\sigma_t = 40$ ps
Edge TCT to investigate Hole Effect

ToA and signal amplitude measurements using edge TCT
W15 board 20 - same as August TB
Laser spot = 9 µm
Edge TCT - Signal Amplitude

integral of the coll charge @250V

mean Amp (mV)

0 20 40 60 80 100

y(1bin = 10um)

V. Sola

Edge TCT - Signal Amplitude ZOOM

integral of the coll charge @250V

mean Amp (mV)

-380
-375
-370
-365
-360
-355
-350

y(1bin = 10um)

0 20 40 60 80 100
Edge TCT - Signal Amplitude

integral of the coil charge @250V
Edge TCT - Time of Arrival

Events crossing the hole region arrive ~ 25 ps later than the events underneath the metal region.
Edge TCT - Time of Arrival
Intra-Strip Inactive Region

**Edge TCT measurement to investigate the intra-structure inactive region**

- Pico-second IR laser at 1064 nm
- Laser spot diameter ~ 10 µm
- Multistage readout board by Pilsen University
- Oscilloscope Lecroy 640Zi
- Room temperature

eTCT scan on 2 adjacent strip

W8  \( V_{\text{bias}} = 230 \text{ V} \)

→ The inactive region between two adjacent strips has been measured to be ~ 60 µm
Doping Profile Parametrisation

Data by H. Sadrozinski (UCSC)
Doping concentration profile from CV measurements on Wafer 6
CV measurements give doping concentration profile starting from the n++ contact, simulations need doping concentration starting from the junction (~ hundreds nm offset)
Doping concentration profile extracted by CV measurement has ~ % level uncertainty on the peak value
→ A very precise fine tuning is necessary in order to have reliable predictions

Simulation with Synopsys TCAD based on Massey model for gain generation

[Graphs showing gain vs reverse bias with different doping and dose levels]
Gain Evolution with Temperature

Data by H. Sadrozinski (UCSC)
Different models for gain generation have been tested
Different tuning of the doping concentration profile extracted for each model
No corrective factors are accounted for in simulation

→ A precise prediction of the gain generation and evolution with temperature is crucial to design new UFSD productions

For more details: M. Mandurrino el al., Numerical simulation of charge multiplication in Ultra-Fast Silicon detectors and comparison with experimental data, N-03-173, IEEE 2017, Atlanta (USA)
Gain of Irradiated Sensors

\[ \text{GAIN} = \frac{\text{Signal area LGAD}}{\text{Signal area PiN}} \text{ irradiated at the same fluence} \rightarrow \text{only from gain layer} \]

- Boron low diffusion shows an higher gain than Boron high diffusion