Studies of the breakdown in R&D structures of the FBK UFSD3 production

33rd RD50 Workshop, CERN, Geneva, 27th November 2018

Outline

➢ The UFSD3 Production: I(V) curves and Breakdown
➢ Breakdown studies with the TCT Setup
➢ Breakdown studies with a CCD camera
➢ An unwanted effect: Pop-Corn noise
The UFSD3 production

➢ UFSD3: 3rd production of Ultra-Fast Silicon Detectors by Fondazione Bruno Kessler (FBK)
➢ Wide range of strip and pad arrays
➢ 4 solutions for the inactive area between gain layers (pads/strips):
The UFSD3 production

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- **4 solutions for the inactive area** between gain layers (pads/strips):
  1) “SUPER-SAFE” - similar to UFSD2

*UFSD3 (2018)*
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  1) “SUPER-SAFE” - similar to UFSD2
  2) “AGGRESSIVE”
  3) “MEDIUM”
  4) “SAFE”

R&D structures: Narrower inactive area width than UFSD2
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UFSD3 R&D Structures (in scale)

Width: ~30μm
Width: ~20μm
Width: ~10μm
Largest width: ~40μm
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What is the impact of the design of the gain termination area on the sensor properties?
Tested Sensors

- 3 pad sensors (1x3 mm$^2$ pads): “SAFE”, “MEDIUM” and “AGGRESSIVE”
- Strip sensor “SUPER-SAFE” (600 $\mu$m pitch)
- Strip sensor “MEDIUM” (300 $\mu$m pitch)

→ All devices are pre-irradiation

One of the 2x2 pad sensors tested
**Different Breakdowns**

- **“SUPER-SAFE”**
  - Breakdown Voltage \( V_{BD} > 300V \)
  - \( I(V) \) exponential
  - Breakdown due to internal gain
  - This is the kind of Breakdown we like

\[ I \text{(uA)} \]
\[ V \]

~200 - 300V is the voltage range we’d like to operate the sensors
Different Breakdowns

“SUPER-SAFE”

● Breakdown Voltage ($V_{BD}$) > 300V

● $I(V)$ exponential

➔ Breakdown due to internal gain

➔ This is the kind of Breakdown we like

R&D Structures

● $V_{BD} < 300V$

● $I(V)$ is not an exponential

➔ Early Breakdown, not due to the gain
Hundreds of pads tested → **Same $V_{BD}$ within few volts for all R&D structures**

“**SUPER-SAFE**” design uniform as well (see M. Tornago talk)
Breakdown Voltage vs Width

V_{BD} strongly dependent on the width of the inactive area

This is close to what we want, but not yet ok

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Inactive Area Studies

- The DUTs Breakdown (BD) strongly depends on:
  - Design of the inactive area
  - Inactive area width
Inactive Area Studies

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  - Design of the inactive area
  - Inactive area width

Two main tools to perform this study:
1. Mapping of the sensors using the Transient Current Technique (TCT) Setup
2. Observation of the sensors hot spots with a CCD camera

Measurements performed in Torino Silicon Lab (University of Torino - INFN)
TCT

TCT Setup in Torino

Particulars TCT setup:
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- IR pulsed laser (1060 nm) → 10-15 μm spot
- xy-stage with sub-μm precision
- Stage control and DAQ via Labview software
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- IR pulsed laser (1060 nm) → 10-15 μm spot
- xy-stage with sub-μm precision
- Stage control and DAQ via Labview software
- **Automatic xy-scan + Small laser spot:**
  → Very precise mapping of the DUT
A preliminary measurement: Interpad

- We measured the inactive area width* of the tested sensors with the TCT

* Inactive area width = Interpad (Interstrip) width
A preliminary measurement: Interpad

- We measured the inactive area width of the tested sensors with the TCT
- **Get the width** by scanning two nearby pads (strips) → charge vs position

![Diagram](width_diagram.png)
A preliminary measurement: Interpad

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Result with a point-like spot → our spot is 10-15 μm with a gaussian shape
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→ The real profile is a convolution of the step function with a gaussian (= s-curve)
A preliminary measurement: Interpad

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![Diagram showing charge vs position with a Gaussian laser and an s-curve]

Result with a point-like spot → our spot is 10-15 μm with a gaussian shape
→ The **real profile** is a convolution of the step function with a gaussian (= **s-curve**
Interpad Measurement: “Medium”

Intermediate Interpad Distance

Measured width
## Interpad Summary

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<thead>
<tr>
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UFSD2 Interpad width: ~ 60µm
TCT: Mapping a 2x2 sensor

2x2 SAFE @200V

2D Map of the collected charge
- 4 pads read out
- Collected charge = Sum of the charges collected by 4 pads

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TCT: Mapping a 2x2 sensor

2D Map of the collected charge
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Pads metallized on the front
→ Signal only in the inactive area

Inactive area, no front metallization
TCT: Mapping a $2\times2$ sensor

2D Map of the collected charge

- 4 pads read out
- Collected charge = Sum of the charges collected by 4 pads

Pads metallized on the front
→ Signal only in the inactive area

Let’s now consider only the charge collected by Pad 1
TCT: Charge vs Bias

- Charge collected by Pad 1 at 3 different voltages
- \( V_{BD} \sim 250 \text{V} \)
- Coloured scale is different from the previous slide
TCT: Charge vs Bias

- The collected charge should be constant (inactive area = no gain)
TCT: Charge vs Bias

- The collected charge should be constant (inactive area = no gain)
- Instead, the charge increases with the bias → strong indication of charge multiplication in that region (gain)

![Graphs showing charge vs. bias at different voltages](image-url)
Consider the X-projection for a fixed y (Black line)
Consider the X-projection for a fixed $y$ (Black line)

- Clear dependence of the collected charge on $V_{\text{BIAS}}$ → Gain shows up near BD
- Effect more evident in the corners
“MEDIUM” & “AGGRESSIVE”

- **Gain** present near BD in “MEDIUM” and “AGGRESSIVE” as well
  - Present both in pad and strip sensors

MEDIUM strip

MEDIUM strip: Y-projection

Y-projection at fixed x

270 V
200 V
250 V

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“MEDIUM” & “AGGRESSIVE”

- **Gain** present near BD in “MEDIUM” and “AGGRESSIVE” as well
  - Present both in pad and strip sensors

What about the “SUPER-SAFE” sensor? (Which has a different design of the inactive area)
TCT: mapping the “SUPER-SAFE” strip

- “SUPER-SAFE” strip @300V
- Metallization on the front

SUPER-SAFE Strip @300V

Metal (no signal)

Inactive Area
TCT: Charge vs Bias

- Charge collected by the strip at 3 different voltages
- \( V_{BD} \approx 320 \text{V} \)
- Coloured scale is different from the previous slide
Y-Projections

Consider the Y-projection for a fixed x (Black line)

No dependence on the bias voltage → no gain in the inactive area for the “SUPER-SAFE” design, no sign of early BD
Y-Projections

Consider the Y-projection for a fixed x (Black line)

SUPER-SAFE strip: Y-projection

Now we repeat the measurements with a CCD camera

➢ No dependence on the bias voltage → no gain in the inactive area for the “SUPER-SAFE” design
Hamamatsu C11090-22B

- EM-CCD Camera working with visible light
- 1024 x 1024 pixels
- Ultra-Low light Imaging:
  - Able to detect the hot spots* of the DUT when it is in BD

* Gain = high current densities
  → emit visible photons
  → Hot Spot
Hamamatsu C11090-22B

- The camera is mounted on a probe station
- 2 pictures of the sensor are taken:
  - A conventional picture taken with an external source of light
  - A picture taken in complete darkness (probe station closed) with the DUT in BD
- The 2 pictures are then overlapped to show in which area the hot spots come out

We focused on the corners of the inactive area
2x2 “SAFE”: The Hot Spots

- 2x2 SAFE @200V
- No Hot Spots
2x2 “SAFE”: The Hot Spots

Breakdown: Hot Spots in the curved regions!
2x2 “SAFE”: The Hot Spots

Breakdown: Hot Spots in the curved regions!

Same hot spots in “MEDIUM” & “AGGRESSIVE”
“SUPER-SAFE” strip: No Hot Spots
“SUPER-SAFE” strip: No Hot Spots

300 V

320 V

330 V

No hot spots observed
Summary on Breakdown

- **R&D Structures**: Breakdown occurs in the inactive region due to the **high electric field** between JTE and p-stop
- **Weakest spot** identified in the **corners** of the pad
- Narrower inactive area → earlier $V_{BD}$ (since JTE and p-stop are closer)

- **“SUPER-SAFE”: different design** of the inactive area → higher $V_{BD}$
  → Gain avalanche in the pad happens before breakdown in corners
Pop-Corn Noise

An undesired effect related to the new inactive area design:

- **Pop-Corn Noise**: micro-discharges (spikes) that appear at a certain voltage
  - the sensor can still be operated, but the noise worsens a lot
- Already observed in the previous **UFSD2** but always **few Volts before BD**
  → Not an issue in **UFSD2**, it is just an indication that BD is going to start
- Several **UFSD3** sensors show Pop-Corn at voltages **much lower than V_{BD}**
  → Important issue, we cannot operate the sensors at the appropriate voltage
Pop-Corn Noise

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- **Pop-Corn Noise**: micro-discharges (spikes) that appear at a certain voltage
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- Several UFSD3 sensors show Pop-Corn at voltages **much lower than \( V_{BD} \)** → **Important issue**, we cannot operate them at the appropriate voltage

- Example of **Pop-Corn (Yellow)**
- Pink is “normal” noise of another device of the same type, shown for comparison

**Taken 100V before \( V_{BD} \)**
The electrons under the oxide create an “inversion layer”, acting as n-doped Silicon: this layer with the p-stop creates a p-n junction.

- The more doped is the p-stop, the shorter is the p-n junction, and the higher is the electric field.
- According to literature: pop-corn noise is generated when this p-n junction is too sharp.
UFSD3 Pop-Corn

- UFSD3 has been produced using the “stepper” technique instead of the “mask aligner” technique.
- The stepper is able to create much sharper images, much better defined edges, higher uniformity and process speed.
- Unforeseen consequence on the p-stop: much sharper images → much sharper pn junction → Pop-Corn noise
- We believe that the Pop-Corn noise is due to: use of the stepper + p-stop too doped
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● We believe that the Pop-Corn noise is due to: use of the stepper + p-stop too doped

→ A possible fix to this issue: use a less-doped p-stop, in order to get a less sharp pn junction

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Summary & Conclusions

- UFSD3 has 2 designs of the inactive area:
  - UFSD2 like “SUPER-SAFE”: BD due to internal gain → the sensor can be operated at the proper voltage (~ 300V)
  - 3 R&D structure: BD due to high gain in the inactive area → sensor cannot reach 300V
- The inactive area design determine the type of BD and therefore the voltage that can be reached → Key point for future productions
- Pop-Corn Noise: micro-discharges that appear much before BD → Likely due to the “stepper” technique + highly doped p-stop
Thank You!
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Backup
I(V) Curves

I(V) curves of the 5 sensors tested

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Strip Breakdown

$V_{BD}$ is strongly dependent on the width of the inactive area

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Interpad: SAFE & SUPER-SAFE

Safe 1 Interpad Distance

Safe 2 Interpad Distance

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Larger discrepancy if the width is narrow because of the laser spot.
“AGGRESSIVE” Hot Spots

90 V  
100 V  
110 V
“MEDIUM” Hot Spots

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Figure 6: Section from T-CAD simulation of the V2 sample with a high p-stop doping concentration. The simulation was performed for $T = 253$ K and $V_{bias} = -600$ V. The asymmetry between the p-stops is due to the chosen mesh density.

Figure 7: Maximum electric field strength distribution between two strips as a result from T-CAD simulations. The parameters correspond to the values listed in Figure 6. (The asymmetry between the p-stops is due to the choice of the mesh parameter.)

Martin Printz, KiT