Novel Strategies for Fine-Segmented LGADs

G. Paternoster, G. Borghi, M. Centis Vignali, F. Ficorella, M. Boscardin
(FBK, TIFPA)
(INFN To and University of To)
G.-F. Dalla Betta, L. Pancheri
(University of Trento, TIFPA)

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1. Segmentation Issues in LGADs
Segmentation in PIN Planar Sensors

Inter-pixel region hosts the isolation and termination structures:
- P-stop
- Junction Termination Extension (JTE)

In p-i-n sensors the charge is shared between adjacent pixels, but the total charge is a constant.
Segmentation in LGADs

Pixel 1

Pixel 2

n+

n+

p-substrate

p-stop

Metal pads

JTE

px1

px2
Segmentation in LGADs

- **p-stop**
- **Metal pads**
- **n⁺ pgain implant**
- **n⁺ pgain implant**
- **JTE**
- **Pixel 1**
- **Pixel 2**
- **p⁻ substrate**

(px1) (px2)
Segmentation in LGADs

The pixel border is a dead-region. The carriers generated in this area are not multiplied.

Nominal NO-GAIN region
(PGAIN-PGAIN distance defined by layout)
Segmentation in LGAD

The collection and drift mechanisms also play a role in the no-gain region.

➢ Some carriers, generated at the periphery of the gain implant, are collected by the dee JTE and do not pass through the gain layer.

➢ These carriers are multiplied with reduced gain

Effective inter-pad width

G=50%

G=1

Effective interpad width

>=

nominal no-gain
Segmentation in LGAD

The nominal no-gain width depends on:
- **Fabrication technology**
- **Physical limits** (maximum E fields) to fulfill operational requirements ($V_{BD}$, etc.)

<table>
<thead>
<tr>
<th>Layout</th>
<th>No-gain width</th>
</tr>
</thead>
<tbody>
<tr>
<td>UFSD 2 – Super Safe</td>
<td>66 um</td>
</tr>
<tr>
<td>UFSD 3 - Safe</td>
<td>31 um</td>
</tr>
<tr>
<td>UFSD 3 - Medium</td>
<td>20.5 um</td>
</tr>
<tr>
<td>UFSD 3 Aggressive</td>
<td>11 um</td>
</tr>
</tbody>
</table>

HPK (LGAD 3.1 2019) => 60um

There is an **intrinsic limit in reducing the inter-pad region**. A too small distance between n-doped regions and p-stop leads to early edge-BD and popcorn noise.
New Segmentation Strategies under development at FBK and INFN

Trench-Isolated LGADs (TI-LGAD)

- DC readout
- Patterned p-gain
- Compact isolation structure based on Deep Trench Isolation technology

Resistive AC-coupled Silicon Detectors (RSD) (M. Mandurrino INFN To)

- Metal Pads AC-coupled to the resistive n+ via dielectric coupling layer
- Not-segmented PGAIN -> virtually 100% FF
2. Trench-Isolated LGADs (TI-LGADs)
Deep Trench Isolation technology

➢ JTE and p-stop are replaced by a single trench.
➢ Trenches act as a drift/diffusion barrier for electrons and isolate the pixels.

- The trenches are a few microns deep and < 1um wide.
- Filled with Silicon Oxide
- The fabrication process of trenches is compatible with the standard LGAD process flow.
A TCAD simulations campaign was carried out in order to optimize the TI-LGAD design in terms of:

- Trench geometry (1 trench, 2 trenches)
- Trench depth

### Layouts

<table>
<thead>
<tr>
<th>Layout</th>
<th>Nominal no-gain width</th>
</tr>
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<tbody>
<tr>
<td>1 Trench</td>
<td>~ 4 um</td>
</tr>
<tr>
<td>2 Trenches</td>
<td>~ 6 um</td>
</tr>
</tbody>
</table>
Deep Trench Isolation technology

Two-fold advantage with respect to standard LGADs:

- Trenches are much smaller wrt JTE and p-stop => smaller nominal no-gain region (from 20-60 um to 4-6um)
- The E-field at the pixel border could be optimized to reduce the transition region width

Smaller gain-loss region is expected
1\textsuperscript{st} Test Run of TI-LGADs (RUN 0)

First test run of TI-LGADs produced at FBK in 2019.

Sensor geometry:
- 2x1 pixels (250 µm × 375 µm)

Layout splits (~30):
- Trench layout (1T and 2T)
- Pixel Lateral border (trench-multiplication region distance)

Process splits:
- trench fabrication process.
- Trench depth
- PGAIN implant doses
TI-LGAD Parametric Characterization (IV)

First IV curves show expected behaviour of TI-LGAD sensors:

- Gain “knee” @ ~ 25 V
- Breakdown > 300 V

Breakdown due to multiplication divergence above 300 V
TI-LGAD Parametric Characterization (IV)

TI-LGAD vs STD LGADs (produced in the same batch with the same junction technology)

- Electrical behavior is compatible with STD LGADs
- Same knee Voltage and BD Voltage
- Difference in dark current is not significant

- STD PIN breakdown at 420 Volts (most likely at the pixel border).
- NO BD in TI-PIN up to 500V
TI-LGAD inter-pad Characterization (TCT laser Setup)

Measurements performed in Torino Silicon Lab (University of Torino - INFN)
F. Siviero – 35th RD50 Workshop, November 2019
TI-LGAD inter-pad Characterization (TCT laser Setup)

Measurements performed in Torino Silicon Lab (University of Torino - INFN)
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3. Resistive AC-Coupled Silicon Sensors (RSD)
Resistive AC-coupled Silicon Detectors

Main Technological Features

- Not-segmented p-gain implant
- Resistive n+ implant
- AC Metal pads
- Segmentation of the AC pads defines the pitch
- Thin coupling dielectric layer under the AC pads
First production of RSD at FBK

First RSD Production delivered in Q2 2019

Layout Splits:
- Pad arrays (from 50 to 500 um pitch)
- Strips
- ALTIROC arrays

Process Splits:
- Sheet resistance of the n+ implant
- PGain Implant Dose
- Coupling Dielectric Layer Thickness
RSD: Parametric Characterization

- Electrical behavior is compatible with STD LGADs
- High BD Voltage (~450 Volts)
- Very good homogeneity

- Full-depletion of the pgain implant at ~ 25V

M. Tornago – 35th RD50 Workshop, November 2019
The signal spreads on several pads, with **amplitude inversely proportional to the hit distance**

**Note:** the amplitudes on far away pads is much larger than what is predicted by direct induction
RSD: Spatial resolution

The signal spreads on several pads, with amplitude inversely proportional to the hit distance.

Note: the amplitudes on far away pads is much larger than what is predicted by direct induction.

TCT Measurements with IR Laser Setup

Channel 0

Channel 2

CC1

Entries: 200400
Mean: 28.98
Mean y: 0.593
Std Dev: 2.887
Std Dev y: 5.057

CC2

Entries: 200400
Mean: 28.98
Mean y: 0.593
Std Dev: 2.887
Std Dev y: 5.057

CC3

Entries: 200400
Mean: 28.98
Mean y: 0.593
Std Dev: 2.887
Std Dev y: 5.057

Courtesy of N. Cartiglia
RSD: Spatial resolution

Study of signal projections along a scan line (in red) for two neighboring pads

2x2 Pixels 300 um pitch

M. Tornago – 35th RD50 Workshop, November 2019
RSD: Spatial resolution

The position of the hit is obtained as:

\[(\text{amplitude} > 10 \text{ mV})\]

100um pitch Array:

- x resolution: 6 um, with an offset of 1 um

\[x_{\text{hit}} = \frac{\sum_{i=1}^{4} x_{\text{pad}}(i) \cdot \text{Amp}(i)^{\text{Cor}}}{\sum_{i=1}^{4} \text{Amp}(i)^{\text{Cor}}}\]

\[x_{\text{hit}} - x_{\text{Laser}}\]

Courtesy of N. Cartiglia
RSD: Spatial resolution

The position of the hit is obtained as:

\[ x_{\text{hit}} = \frac{\sum_{i=1}^{4} x_{\text{pad}}(i) \times Amp(i)_{\text{Cor}}}{\sum_{i=1}^{4} Amp(i)_{\text{Cor}}} \]

\[ x_{\text{hit}} - x_{\text{Laser}} \]

100um pitch Array:
x resolution: 6 um, with an offset of 1 um

<table>
<thead>
<tr>
<th>Resolution [um]</th>
<th>X Resolution [um]</th>
<th>Y Resolution [um]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 um</td>
<td>4-6</td>
<td>4-6</td>
</tr>
<tr>
<td>200 um</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>500 um</td>
<td>19</td>
<td>18</td>
</tr>
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</table>

Courtesy of N. Cartiglia
Conclusions

➢ The segmentation issues of the Standard LGAD technology has been presented. Inter-pad width is > 30 um

➢ Two development strategies have been introduced (TI-LGADs & RSD)

➢ First Samples of Trench-isolated LGAD have been successfully produced at FBK

➢ Preliminary electrical measurements showed the expected behavior in terms of knee Voltage, BD voltage, and IV-CV shapes

➢ TCT Characterization shows that the Interpad of TI-LGADs is reduced down to 7-9 um.

➢ Promising results also from RSD development. The RSD shows a sub-pixel spatial resolution down to 6 um (sigma).
Thank you for your attention

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- RD50 Collaboration, CERN
- Fondazione Bruno Kessler, Trento, ITALY
BACKUP Slides
TCAD simulation of the pixel border in a UFSD2 structure (left) and UFSD3-intermediate structure (right).

G. Borghi – October 31st, 2019 – IEEE NSS MIC
TCAD Simulated laser scan at the inter-pixel region (1um wide IR laser spot)

Signal Bump close to the trench

Design optimization trade-off between minimization of the gain-loss region and reduction of E-field at the border.

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<td>~3 um</td>
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➢ Even if 2T Layout has larger nominal no-gain region the effective gain-loss width is less wrt to 1T layout
➢ 2T layout shows increased signals at the border (high local E-field)
The induced charge shape depends on the pitch and the AC pad size in the DUTs
Waveforms change with the sensors RC, depending on n+ dose, oxide thickness and also AC pad size and pitch.