Study and characterization of Low Gain Avalanche Diodes

Marco Ferrero for the UFSD Group (FBK – Torino – Trento – UCSC)

INFN Torino (Italy)
Outline

- Hamamatsu 50&80µm Production:
  - IV and CV measurements;

- CNM 50µm production:
  - Test of UFSDs production for CTPPS experiments;
Hamamatsu LGADs

- Two different Thickness: 50µm and 80µm;
- 4 gain layer doses implantation (A/B/C/D)
  
  Dose A < Dose B < Dose C < Dose D
- Single pad sensors;
- Sensors active area ~1mm²

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Doping implant</th>
<th>Sensor Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>50µm</td>
<td>A</td>
<td>ECX20840_Single_80-A_STD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECX20840_Single_80-A_GR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECX20840_Single_80-A_GBGR</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>ECX20840_Single_80-B_STD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECX20840_Single_80-B_GR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECX20840_Single_80-B_GBGR</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>ECX20840_Single_80-C_STD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECX20840_Single_80-C_GR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECX20840_Single_80-C_GBGR</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>ECX20840_Single_80-D_STD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECX20840_Single_80-D_GR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECX20840_Single_80-D_GBGR</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Doping implant</th>
<th>Sensor Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>80µm</td>
<td>A</td>
<td>ECX20840_Single_80-A_STD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECX20840_Single_80-A_GR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECX20840_Single_80-A_GBGR</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>ECX20840_Single_80-B_STD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECX20840_Single_80-B_GR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECX20840_Single_80-B_GBGR</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>ECX20840_Single_80-C_STD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECX20840_Single_80-C_GR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECX20840_Single_80-C_GBGR</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>ECX20840_Single_80-D_STD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECX20840_Single_80-D_GR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECX20840_Single_80-D_GBGR</td>
</tr>
</tbody>
</table>
IV measurements (laboratory setup)

Key sight
B1505A Power Device Analyzer / Curve Tracer

Modules
- High Voltage SMU: Max Range (±3000V, ±4mA);
  Min Range (200V, 1nA);
- Medium Power SMU: Max Range (±100V, ±100mA);
  Min Range (0,5V, 1nA);

The electric contacts was made with coaxial needles

Marco Ferrero, INFN Torino, 12th Trento Workshop – Trento, February 21, 2017
I-V Measurements (50µm)

Gain dose A $\rightarrow V_{\text{breakdown}} \approx 650V$
Gain dose B $\rightarrow V_{\text{breakdown}} \approx 600V$
Gain dose C $\rightarrow V_{\text{breakdown}} \approx 450V$
Gain dose D $\rightarrow V_{\text{breakdown}} \approx 300V$

Leakage current is hundreds of pA

Sensors STD (without guard ring) have earlier breakdown.
Sensors STD (without guard ring) have earlier breakdown

Gain dose A $\rightarrow V_{\text{breakdown}} > 900\text{V}$
Gain dose B $\rightarrow V_{\text{breakdown}} > 800\text{V}$
Gain dose C $\rightarrow V_{\text{breakdown}} \approx 650\text{V}$
Gain dose D $\rightarrow V_{\text{breakdown}} \approx 400\text{V}$

Leakage current is hundreds of pA
C-V Measurements

RESULTS & CONSIDERATIONS:

- Same Depletion Voltages of gain layer for 50µm and 80µm thickness:
  
  Dose A = ~24 Volt
  Dose B = ~28 Volt
  Dose C = ~31,5 Volt
  Dose D = ~35,5 Volt

- Expected same Doping profile for 50µm and 80µm thickness;

- Uniformity of the gain dose implant (Very good overlap of the CV curves about sensors with same gain implant);
Results & Considerations:

- Sensors Voltage Depletion varies with the gain layer doping:
  - between 35 V and 45 V for 50µm thickness;
  - between 80 V and 90 V for 80µm thickness;

- Bulk depletion of 80µm sensors is slower in voltage compared to 50µm sensors;
  - Expected an higher bulk resistivity for 50µm sensors than 80µm ones;

- Voltage necessary to deplete the p-bulk:
  - ~ 10 for the 50µm thickness sensors;
  - ~ 55 for the 80µm thickness sensors;
The $1/C^2$ slope is decreasing with $V_{bias}$.

There is a relationship between the parallel plate capacitor area and the $V_{bias}$.

The correction factor is therefore negative and increase with $V_{bias}$.

It is expected a linear dependency between $1/C^2$ and the $V_{bias}$.

It isn’t the case of the HPK sensors.

\[
\frac{1}{C^2} = \frac{2}{N_A q \varepsilon} \frac{1}{A} V_{Bias} \implies \frac{\partial (1/C^2)}{\partial V} = \frac{2}{N_A q \varepsilon} \frac{1}{A} - \frac{2}{N_A q \varepsilon} \frac{1}{A^2} V_{Bias} \frac{\partial A}{\partial V}
\]

It’s expected a linear dependency between $1/C^2$ and the $V_{bias}$.

Hamamatsu Sensors 50 μm
On the $1/C^2$ slope (1)

The slope of $1/C^2$ tells us if the sensors active area is getting larger or smaller as a function of depletion depth.

Increasing steepness:

The area is decreasing as a function of $V_{bias}$

$$\frac{\partial A}{\partial V} < 0$$

Decreasing steepness:

The area is increasing as a function of $V_{bias}$

$$\frac{\partial A}{\partial V} > 0$$

CONCLUSION
Since in the measurement of the HPK diode the $1/C^2$ slope is decreasing, the area of the depleted area is increasing with thickness.
UFSD, CTPPS sensors (50µm CNM production)

- 3 gain layer dose implants
  - 1.8 \times 10^{13} \text{cm}^{-2} (Low gain)
  - 1.9 \times 10^{13} \text{cm}^{-2} (Medium gain)
  - 2.0 \times 10^{13} \text{cm}^{-2} (High gain)

- Two Groups of pads:
  - Small pads (#16) \rightarrow \text{Active area} = 1.5 \text{mm}^2
  - Big pads (#16) \rightarrow \text{Active area} = 3 \text{mm}^2

- Pads surrounded by a Guard Ring;

- Each pads is surrounded by a JTE;

Gain and time resolution of 50µm LGADs before and after irradiation.
Joern Lange, 29th RD50 Workshop, CERN
CTPPS sensors, Guard Ring Current

- $I_{guardring}$ allows to select good sensors;
- Good sensors $\Rightarrow V_{\text{breakdown}} > 150\text{V}$ ($150\text{V}$ is the voltage necessary to saturation the free charge drift velocity in 50µm silicon sensors);
- Most of the sensors have a $V_{\text{BD}}$ above 200V;
CTPPS sensors, Pads leakage Current

Gain | $V_{\text{breakdown}}$
--- | ---
Low | $> 250$ V
Medium | $\sim 250$ V
High | $\sim 75$ V

Sensors chosen to install in CTPPS are the medium and low gain ones
CTPPS sensors, CV measures (High gain)

HIGH GAIN

- Gain Layer Voltage depletion ~ 37 V;
- Full Depletion Voltage ~ 41 V; (Only 4 V are necessary to deplete the p-bulk);
- Pad Capacitance:
  \[ C_{\text{Big Pad}} = 8.2 \, \text{pF} \]
  \[ C_{\text{Small Pad}} = 4.1 \, \text{pF} \]

Measures Performed at 3kHz
RESULTS & CONSIDERATIONS:

- No effective active area correction in these measurements;
- Implant width peaks at the n++ /p+ junction, depth is about 3-4µm;
- p-bulk doping concentration ~$10^{12}$;
Guard Ring: measurements from HPK devices suggest that the presence of the guard ring is helpful to prevent earlier Breakdown

Segmented LGAD structures:

We have successfully tested multipad structures from CNM. Large statistics show that it is possible to have segmented silicon sensors with internal gain. The characteristics that we find important are:

1. The leakage current in each pad should be low, otherwise it will cause a breakdown due to the internal gain
   ==> Small pads are less prone to breakdown due to internal gain;
   ==> Large pads are often in breakdown before reaching good operation voltage

2. Multipad sensors where the pads are isolated from each other by an edge protection are more reliable, with large number of pads well behaving
References

➢ M. Carulla et al. , First 50μm thick LGAD fabrication at CNM, 28th RD50 Workshop, Torino, (June 7th, 2016);

➢ G. Pellegrini et al. , Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications, NIMA 765 (2014) 24;

➢ J.Lange et al. , Study of Ggain and time resolution of 50μm LGADs before and after irradiation, 29th RD50 Workshop, CERN (November 22th, 2017);
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
CV measurements (laboratory setup)

Keysight B1505A Power Device Analyzer / Curve Tracer

Modules
- High Voltage SMU: Max Range (±3000V, ±4mA);
  Min Range (200V, 1nA);
- LRC Module;

The electric contacts were made with coaxial needles.

High Voltage SMU

LRC Module

Bias T

Probe station chuck

coaxial needle

Guard Ring

n++
p+
p

p++

p bulk

Probe station

Marco Ferrero, INFN Torino, 12th Trento Workshop – Trento, February 21, 2017
1/C²-V Curves considerations

Gain layer depletion

Linear trend (Constant active area)
CT-PPS: CMS TOTEM Precision Proton Spectrometer

A proton spectrometer to study central exclusive production at the LHC

CT-PPS consists a silicon tracking system to measure the position and direction of the protons, and a set of timing counters to measure their arrival time.
Timing for CT-PPS – Why?

At each bunch crossing there will be many interactions (up to 50 in 2016-2018)

A precision of $\sim 20$ ps on the arrival time of each proton will determine the vertex position with a precision of $\sim 4.2$ mm

‘z-by-timing’ resolution $\Delta z = c \Delta(t_1-t_2)/2$