Radiation hardness studies of HAB HPK sensors

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Motivation

➢ Acceptor removal limits radiation hardness of LGAD devices
   ➢ B₃ + Si → B₁ ; B₁ + O → B₁O (the complete mechanism not yet fully explained)

➢ Different ways to mitigate acceptor removal
   ➢ Dope gain layer with carbon – approach for ATLAS HGTD and CMS ETL
   ➢ Narrow B implantation (e.g. HPK-P2)
   ➢ Partial activation of boron - this talk

➢ HPK has produced a Half Activated Boron (HAB) run of LGAD devices
   ➢ Part of boron is implanted, but not electrically activated in the gain layer
   ➢ Not activated boron could “protect” substitutional boron
   ➢ Early results show potential improvement of radiation hardness (K. Hara, 18th Trento Workshop)
HPK samples

- HPK provided three sample flavours which were characterized at JSI
  - Reference (full boron activation)
  - 0.5 HAB (same activated boron concentration as reference + non activated boron 0.5x reference)
  - 1 HAB (same activated boron as reference + non activated boron 1x reference)

- Samples were 2x2 LGAD arrays of 1.3x1.3 mm² and 50 μm thickness. Each pad had opening in metallization for light injection, but no opening was available in the inter-pad region.

- Samples irradiated with neutrons at JSI TRIGA reactor
  - Equivalent fluences of 8e14, 1.5e15, 2.5e15 cm⁻²
  - annealed before the measurements to 80 min at 60 °C
  - Majority of samples sent to the AIDAINNOVA test beam in June and September and are still being analysed (still working on analysis tools)

- Techniques used in this work : CV-IV, CC/timing performance, TCT
Acceptor removal constant

Every result we show now is preliminary!

In irradiated samples measured $V_{gl}$ values after FIRST application of bias voltage different from all subsequent measurements. Here showing results after second biasing.

Acceptance removal coefficients
- $c_{(REF)} = 3.8 \times 10^{-16}$ cm$^2$
- $c_{(1B05H)} = 3.4 \times 10^{-16}$ cm$^2$
- $c_{(1B1H)} = 2.6 \times 10^{-16}$ cm$^2$

Small effect of HAB on acceptor removal
Measurements with Sr90

- JSI “Timing” setup with Sr90
- DUT cooled to -30 °C
- Coincidence trigger on PMT + reference LGAD -> DUT doesn’t take part in trigger!
- Measurement of charge and time resolution as function of voltage
- Measurements done with fluences 0e14, 15e14, 25e14 cm^{-2}
  - at 25e14 signal peak can not clearly separated from pedestal in the spectrum
  - a single pad was measured with the rest at GND

GR grounded
grounded
connected to amp
90Sr: collected charge

- CC is correlated with $V_{gl}$ (also the break down voltage) as expected – the 1B1H breaks down early
- Collected charge significantly degraded at $15e14 \text{ cm}^{-2}$ – results compatible with $V_{gl}$ measured after this fluence
- Sample with highest implanted boron (1HAB) shows lowest degradation (10 fC at 550 V), but has also the highest initial $V_{gl}$
- For beam operation the highest safe voltage is $\sim 550$ V (11 V/$\mu$m) – single event burnout
Expected behavior for non-irradiated sensors:
- due to early break-down 1B1H doesn’t get close to Landau fluctuation limited time resolution
- small gain of 1B05H prevents better time resolution
- after $15\times10^{14}$ cm$^{-2}$ achievable time resolution just below 50 ps is reached for 1B1H -> corresponds to highest gain
- Leakage current of irradiated samples confirms smaller gain for 1B05H and reference
TCT measurements

- TCT setup at IJS with focused infrared light
- Test method: top-TCT in both Interpad and pad region
- Measurements on non-irradiated and 15e14 cm⁻² samples

- Measuring charge as function of voltage in inter-pad region / in 4 pads (2x2 array of pads)
  - Similar to method for ATLAS-HGTD irradiation test during QC
  - Inter-pad region behaviour similar to PIN diode without gain
  - Room temperature measurements (the correlating with low T has been shown for numerous ATLAS-HGTD samples)

- Extracted Parameters: \( V_{gl} \), \( V_{fd} \) and Gain
- HPK sample for TCT is wire-bonded with all pads together, GR floating

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https://indico.cern.ch/event/1270076/contributions/5461468/attachments/2670554/4629315/Skomina_RD50_MNE.pdf
TCT measuring method – example for 15e14 cm$^{-2}$ 1B05H

Measurement method:
- QV in LGADs
- QV in Inter-pad (PIN like behaviour)

$Gain(V) = \frac{Q(LGAD)}{Q(PIN)}$
Gain-unirradiated HPK samples

- For unirradiated HPK samples we observe rapid increase in gain
- Here is depicted gain for single pad for all 3 flavors
- Minimal fluctuations between four pads
- Somewhat more problematic behavior of 1B05H sample

<table>
<thead>
<tr>
<th>Vgl (V)</th>
<th>TCT/CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>30/29.7</td>
</tr>
<tr>
<td>0.5 HAB</td>
<td>29.89/30</td>
</tr>
<tr>
<td>1 HAB</td>
<td>37.6/38</td>
</tr>
</tbody>
</table>

not clear why the gain is much smaller than in Sr90
Gain-irradiated HPK samples -1.5e15 neq/cm²

- At full depletion voltage gain approximately 1.5
- Gain increases to 2.5 at 350 V (max. achievable voltage with this method)
  - Leakage current scales the same – good indication of gain
  - Modest gain
- Extracted Vgl indicates significant acceptor removal/gain degradation

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</tr>
<tr>
<td>1 HAB</td>
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Conclusion

➢ Investigated HPK samples with partially activated boron as a way to mitigate acceptor removal by CV/IV, CC/Timing and TCT measurements

➢ Measured samples were irradiated to fluences of 0e14, 15e14 and 25e14 cm\(^{-2}\) (IJS TRIGA neutrons)

➢ CV/IV measurements:
  ➢ acceptor removal constant shows improvement with respect to older runs, but the values are around 3x larger than that of best C-enriched gain layer designs (>2.5e-16 cm\(^{-2}\))
  ➢ partial activation of boron shows only marginal improvement of radiation hardness
  ➢ leakage current and CV of the samples don’t exhibit any unexpected features

➢ Timing Sr90 measurements:
  ➢ Significant degradation of collected charge after irradiation – compatible with Vgl measurements
  ➢ Due to highest doping before irradiation the best performance after 15e14 cm\(^{-2}\) is measured for 1B1H sample, but the performance is comparable with HPK-P2 (ATLAS/CMS prototype run from 2020), while 1B05H and reference samples are worse
  ➢ The collected charge below 600 V can not be separated from the noise peak/pedestal at 25e14 cm\(^{-2}\)

➢ TCT analysis:
  ➢ Extracted V\(_{\text{gl}}\) and Gain from TCT in LGAD/inter-pad region – gain can be measured at lower bias voltages and room temperature
  ➢ Only marginal gain up to 350 V for irradiated samples showing not sufficient radiation hardness
  ➢ Measurements of Vgl compatible with CV

Samples with partially activated boron have slightly improved radiation hardness, but not on the level required for e.g. ATLAS-HGTD.
BACKUP
CC-Timing results

**HPK_HAB_1B+0.5HAB_0e14**

![Graph showing CC-Timing results for HPK_HAB_1B+0.5HAB_0e14](image1)

**HPK_HAB_1B+1HAB_G5_15e14**

![Graph showing CC-Timing results for HPK_HAB_1B+1HAB_G5_15e14](image2)
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TCT results for HPK samples

- Vgl 1/2/3/4- voltages for gain layer depletion for first/2nd/3rd/4th pad
- Vfd 1/2/3/4-voltages for depletion of the bulk

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Fluence (neq/cm²)</th>
<th>Vgl1 (V)</th>
<th>Vfd1 (V)</th>
<th>Vgl2 (V)</th>
<th>Vfd2 (V)</th>
<th>Vgl3 (V)</th>
<th>Vfd3 (V)</th>
<th>Vgl4 (V)</th>
<th>Vfd4 (V)</th>
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</thead>
<tbody>
<tr>
<td>HPK_HAB-1B+05HAB_G5</td>
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