Gain suppression mechanism observed in Low Gain Avalanche Detectors

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Outlook

- Motivation: better understanding of gain and timing studies performed with TCT IR-laser and Sr-90 source.

- Comparison between IR-laser and Sr-90 measurements.

- Gain suppression mechanism with IR-laser.

- Gain suppression mechanism with Sr-90 source.

- Summary.
**Motivation: understand the differences between Sr-90 and IR-laser measurements**

IR-laser at different power intensities vs Sr-90 source

HPK2-W31-LGAD (1.3x1.3 mm² x 50 um)

~1 MIP

LGADs:
- Can we compare IR-laser measurements with Sr-90 ones: charge, gain, timing ...?
- Is there any IR-laser setting that will induce the same charge than the Sr-90 source?

LGADs used:
HPK2 and CNM-12916 (1.3x1.3 mm² x 50 um)
Gain and timing measurements with Sr-90

27 MBq$^{90}$Sr

CIVIDEC C2-amp

2 sensor stack

Set-up inside a RF cage and Climate Chamber

System time resolution:

$$\sigma^2_{sys} = \sigma^2_{dut} + \sigma^2_{ref}$$

Gain definition:

$$G(V) = \frac{Q(V)_{LGAD}}{Q_{PIN}}$$

$Q_{PIN}$ measured: ~ 0.5 fC for a 50 um thick PIN.

$Q(V)_{LGAD}$ is the MPV of the charge distribution.

Feb 17, 2021
Gain and timing measurements with IR-laser

- **Time standard**: constant time interval between two picosecond IR laser pulses (1060 nm)
- Fixed time interval between laser pulses generated by optical splitting and delayed recombination of a single laser pulse.
- **External time reference is not needed.**

Gain definition: \( G(V) = \frac{Q(V)_{LGAD}}{Q_{PIN}} \)

* \( Q_{PIN} \) and \( Q_{LGAD} \) are measured in the same conditions.
* IR-laser intensity calibrated to have 1 MIP equivalent: \( Q_{PIN} (V>V_d) \approx 0.5 \) fC for a 50 um thick PIN.

System time resolution:
\[
\sigma_{sys}^2 = \sigma_{t1}^2 + \sigma_{t2}^2
\]
\[
\sigma_{dut}^2 = \frac{1}{2} \sigma_{sys}^2
\]
Are IR-laser and Sr-90 measurements comparable?

**Initial idea:** IR laser in TCT tuned to ~ 1 MIP to compare with Sr-90.

**Samples:** HPK2 and CNM 12916 (50 um thick devices of 1.3x1.3 mm² active area).

**Problems found:**

- Two identical sensors measured under the same conditions in TCT and RS-90 show different gain curves.
- Also the jitter measured in TCT is much lower than the time resolution measured in Sr-90.
Differences between IR-TCT (~ 1 MIP) and RS:

We generate the same amount of charge in both, but inside a different volume in the bulk:

- With Sr-90 we have a much higher charge density because the ionizing path is narrower.
- With the IR-laser we have less charge density, the ionizing “path” is wider: around 10 μm in FWHM when focused.

Hypothesis

- Low charge density in the GL will lead to a higher gain: there will be a negligible gain suppression.
- High charge density in the GL will lead to a reduction in the gain: drop in the GL E-field (less amplification).
Increasing laser intensity in TCT:

- T: +20 °C
- Averaging: 1024
- No amplifier
- IR shutter aperture:
  - 3.0 (~ 5 MIPs)
  - 3.2 (~10 MIPs)
  - 3.4 (~20 MIPs)
  - 3.6 (~30 MIPs)

**Graph:**
- **HPK2-W31-S2-LGAD-L15P9**
- **Gain**: $G(V) = \frac{Q(V)_{\text{LGAD}}}{Q_{\text{PIN}}}$

**Plot Data:**
- **Charge [MIPS]**: 0, 5, 10, 15, 20, 25, 30, 35, 40
- **Shutter aperture [mm]**: 3, 3.2, 3.4, 3.6, 3.8

**Legend:**
- ~ 5 MIPs
- ~ 10 MIPs
- ~ 20 MIPs
- ~ 30 MIPs
Decreasing laser intensity in TCT:

T: +20 °C
Averaging: 1024
Amplifier
IR shutter aperture:
- 3.0 (~ 5.0 MIPs)
- ...
- 2.5 (~ 0.4 MIPs)

\[ G(V) = \frac{Q(V)_{LGAD}}{Q_{PIN}} \]
Out-of-focus measurements

Charge density inside the detector can be changed by defocusing the laser.

PIN: charge is $z$-invariant

For an LGAD measured in IR-TCT the collected charge depends on beam waist position (focusing)

The laser beam is always inside the opening window in the metallization. 100x100 um$^2$
Sr-90 measurements: DUT tilted at different angles

DUTs positioned at different angles: 0, ~7, ~14 deg
- HPK-P2-LGAD-W31-S2
- CNM-12916-W4-DB02

HPK-P2-LGAD-W42-S4: always the same sensor, not tilted and same Vbias = 180 V.

Temperature constant at 20.0 deg

Narrow ionizing “area” under the gain layer.

Larger ionizing “area” under the gain layer → less charge density in the amplification layer.

$e^-$ will cross $d$ um

$e^-$ will cross $h = d / \cos(\alpha)$ um

(charge deposition increases due to a larger ionizing path)
Set-up picture at 14 deg

- Low Gain (low Vbias) → low E-fields: low effect and we should be close to the 3.0% increase in the signal
- High Gain (high Vbias) → high E-fields: high effect and we should see an increase in the charge higher that 3.0%

**DUT plane: 14 deg line**

**SR-90 plane**

**REF plane**

<table>
<thead>
<tr>
<th>HPK</th>
<th>Bulk thickness $d$: 48 um</th>
<th>$h = d / \cos(14)$: 49.47 um (+ 3.0 %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNM</td>
<td>Bulk thickness $d$: 42 um</td>
<td>$h = d / \cos(14)$: 42.28 um (+ 3.0 %)</td>
</tr>
</tbody>
</table>
Clear effect in the gain observed

Remarkably more charge collected by tilting the sample than expected by simple geometry.

Expected increase by only geometrical aspects marked with dotted lines:

- 3.0% for 14° and 1.0% for 7°.
Effect in the timing performance

RS set-up still not optimized for low noise measurements. Not easy to measure because of the noise fluctuation between measurements:

- We have noise fluctuations between different measurements of almost 10%.
- We can only measure the time resolution of the whole system (DUT+REF) and it was dominated by REF.
- The timing resolution of the REF has to be much lower than the DUT one.
- Move to a three sensor configuration.

Best case scenario
Effect in the timing performance

Measuring in a three sensors configuration!

It is possible to get directly the time resolution of the DUT. It is less affected by noise fluctuations in the system in a two sensors configuration (DUT + REF).

\[
\delta_{\text{time}} \propto \frac{\delta_{\text{noise}}}{|dV/dt|} \propto \frac{\Delta t}{\Delta V} \times \delta_{\text{noise}} = \frac{\delta_{\text{noise}}}{SR}
\]

Higher noise!

With noise correction

\[
(\delta_{\text{time}})_i^c = (\delta_{\text{time}})_i \times \frac{(\delta_{\text{noise}})_{\text{ref}}}{(\delta_{\text{noise}})_i}
\]

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Effect in the timing performance and charge

Summarizing Sr-90 results:

- Clear increase in the **charge collected** by tilting the sample.
- Clear improve in the **time resolution** by tilting the sample.

**DUT: HPK2-W31-S2**

**Increase in Charge**

- **14°**
- **7°**
- **3.0%**
- **1.0%**

**Decrease in Time Resolution**

- **0°**
- **7°**
- **14°**
1-dim TCAD simulation: origin of the damping process?

- Carrier generation by impact ionization leads to reduction of Field strength
- Reduction of Field strength leads to reduction of impact ionization coefficient
- Reduction of impact ionization coefficient leads to less gain (i.e. signal reduction)

Beware: very conservative! 1-dim model for a clearly 3-dim problem!
Summary

- Discrepancies between IR-TCT and RS-90 were observed.

- They can be explained by the gain reduction produced for different charge densities inside the bulk under different conditions. This is affecting the impact ionization process in the gain layer:
  - RS generates a higher charge density → lower gain than IR-TCT.
  - Lower gain implies less charge collected → worse SNR and worse time resolution.

- Measurements in TCT and RS modifying the charge density were carried out to confirm it.

- Comparison of Gain and Charge measurements between TCT and RS set-ups is not straightforward.

- New parameter to keep under control: charge density. Especially important during the TCT measurements.
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Thank you for your attention