Experimental Study of Acceptor Removal in UFSD
(using C-V and charge collection)

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Multiplication in LGADs depends on Electric Field

The multiplication process is governed by the mean free path $\lambda$, the multiplication length.

The probability for multiplication in distance $\Delta x$ is $e^{\Delta x/\lambda}$.

The multiplication length depends approximately exponentially on the inverse of the electric field.

For $\lambda = 1$ $\mu$m, the field needed is about 270 kV/cm and the multiplication happens on the 1 $\mu$m scale.

The E-field in the multiplication is supplied both by the gain layer and the bulk.

**Gain layer:** (amplification of collected charge)

- Adds E-field proportional to doping concentration
- Investigated with C-V measurements:
  - measure voltage to deplete gain layer: $V_{GL}$

**Bulk:** (charge generation and transport),

- Contributes E-field dependent linearly on the bias voltage
- Investigated with charge collection studies
  - measure bias to reach a fixed gain: $V(G=x)$
We would like to make a connection between the charge collection and doping from C-V.

Use 50 um thick sensors from the HPK 1rst prototype:ECX20840. Four sensor types completely identical with the exception of the doping concentration which is changed in 10% steps.

Analyze C-V (R.T.,10 kHz) to extract the

doping profiles and maximum of doping profiles

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<tr>
<td>D</td>
<td>1.06</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.95</td>
<td>0.90</td>
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<tr>
<td>B</td>
<td>0.85</td>
<td>0.80</td>
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<tr>
<td>A</td>
<td>0.75</td>
<td>0.71</td>
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From C-V data the bias voltage $V_{GL}$ to deplete the gain layer is extracted (aka “the foot” (christopher betancourt) since it corresponds to the flat region at low bias in the $1/C^2$ plot).

An alternative way to measure $V_{GL}$ is using the direct bias dependence of the doping concentration, which at high fluences is more stable.

$V_{GL}$ is perfectly correlated with the maximum of the doping density.
Calibration of Doping, Bias, Gain III

Charge collection studies in the $\beta$-source yield the gain vs bias ($G$ vs. $V$) curves.

Gain Curves for LGAD with 10% doping difference are approximately equidistant.

Extract $V(G)$, bias for fixed gain $G$, for $G = 10, 20, 30$

Bias $V(G)$ is perfectly correlated with both doping concentration and $V_{GL}$

Success: Gain-bias curves $\leftrightarrow$ doping concentration!

Rule of thumb: Shift of gain-bias curves is
- about 13V for every 1% shift in doping concentration
- about 37V for 1 V shift in $V_{GL}$
Neutron irradiation lowers the doping in the gain layer through acceptor removal. This lowers the gain layer contribution to the E-field and thus the gain at constant bias. The concurring increase in doping of the bulk does not compensate for this loss. To keep the gain the same level, the bias needs to be increased, increasing the contribution of the bulk to the E-field at the gain layer.

After 6E14 neq the gain of the LGAD 50D (highest doping) matches the pre-rad gain of the LGAD 50A (lowest doping) which has approximately 30% lower doping.
Compare 3 different LGAD with ~ 50µm FZ bulk
- HPK-3.2 (HGTDT): deep and narrow gain layer
- HPK-3.1 (HGTDT): more shallow and wider gain layer
- FBK+C (INFN): very shallow but high gain layer with Carbon

Gain Layer Doping Profile from C-V
- Fluence 0 and 1.5E15 neq

Simple Toy Simulation of E-field
(using the measured doping profile):
- HPK-3.1 & 3.2, FBK+C, prerad, E vs Depth

Gain layer (GL) characteristics -> E-field
- Width -> slope of E(x)
- Depth -> extention of E(x)
Effect of bias on E-Field:
Fixed Gain layer contribution
Increased bulk contribution

Effect of radiation on E-field:
Decreased gain layer contribution
Increased bulk contribution
-> can’t match the pre-rad field unless bias can be raised more.
After Irradiation to 3E15 neq
Typical E-fields and multiplication length $\lambda$

1. Multiplication in the Bulk: $\sim$ 170-200 kV/cm
2. Gain Layer HPK 3.1 - 3.2: $\sim$ 290 – 300 kV/cm
3. Gain Layer FBK: $\sim$ 380 – 400 kV/cm

N.B. In addition the gain depends on their depth $\Delta x$ of the implant!
Acceptor Removal

Dependence of the acceptor removal vs. fluence $\Phi$:

$$V_{GL}(\Phi) = V_{GL}(0)e^{-c\Phi}$$

N.B. at fluence of 3E15, $V_{GL}$ of all three LGAD have become similar. So the bias voltage range of the collected charge is similar.

Different pre-rad $V_{GL}$ and

"Acceptor removal coefficient $c$"

$c$(FBK+C) : c(HPK-3.2) : c(HPK-3.1) = 1 : 3 : 5

N.B. post-rad C-V at R.T. 1kHz
Determination of Bias for Gain = 8: V(G=8)

For comparison of the gain of different LGAD, determine the bias for a gain G=8 at different fluence levels.
Correlation of $V(G=8)$, the bias for gain $G=8$, and the gain layer depletion voltage $V_{GL}$ for the sensors HPK 3.1, 3.2 and FBK+C for the fluences indicated. This gain can be reached up to a fluence of $3E16$ neq at bias voltages close to 700V.

Correlation of charge of $V(G=8)$ and $V_{GL}$ for all sensors with different slopes
Variation of $V(G=8)$ at $1.5\times10^{15}$ Neq

We observe large variations in gain curves vs. bias for the same fluence. Select a sub-set of data of HPK 3.2, 2x2 arrays, irradiated to $1.5\times10^{15}$ to investigate.

No systematic correlation with sensor geometry.

Variation of $V(G=8) \approx 120\text{V}$! If caused by variation in doping, would be $>10\%$!
Can the variation in the post-rad gain originate in pre-rad differences in doping? The gain layer depletion voltage $V_{GL}$ has been measured carefully before irradiations using C-V.

Given the small spread in pre-rad doping, it is difficult to explain the observed variation in the post-rad gain by a variation in the sensor doping.
Use Correlation $V(G=8)$ and $V_{GL}$

Post-rad the GL depletion voltage $V_{GL}$ shows the same variation as $V(G=8)$. Apply correlation of $V(G=8)$ with $V_{GL}$ to find a root-cause of variations.

**Strong correlation between $V(G=8)$ and $V_{GL}$**

(as shown earlier)

1% doping change results in bias voltage shift of 10 – 13 V)

Use correlation to correct $V(G=8)$ using the $V_{GL}$ measured value.

The same shift in the bias values will then be applied to the gain vs. bias curves of each sensor.
Small $V(G=8)$ Variation when Bias corrected by $V_{GL}$

Shifting the bias using the observed variation in the doping of the gain layer reduces the variation of the bias dependence of the collected charge.

A likely root-cause is fluence uncertainty which is estimated to be $\sim 10\%$. 

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<th>Before</th>
<th>After</th>
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<tr>
<td>Average $(V(G=8))$</td>
<td>536 V</td>
<td>536 V</td>
</tr>
<tr>
<td>RMS $(V(G=8))$</td>
<td>$45 V = 8.3%$</td>
<td>$7 V = 1.3%$</td>
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(this value is close to the pre-rad variation!)
Lessons Learned

• The large variation $V(G=8)$, the bias at which the gain $= 8$, observed in charge collection studies on irradiated LGAD, can be overcome with a correction derived from C-V measurements of $V_{GL}$, the bias voltage to deplete the gain layer $V_{GL}$.

• This correction results in a shift of the bias voltage of the gain curves such that the data from different sensors overlap nicely.

• A likely cause of the variation is the variation of the fluence which influences both gain and doping profile.

• The correction requires that charge collection studies (cold) and C-V measurements (warm) are both performed on the same sensor.

• A benefit of the correlation between gain and doping might be that room temperature C-V can be used over a small range of low bias ($\sim 50V$) to estimate the gain.
Conclusions

• Combining C-V and charge collection data permits to get insight into acceptor removal due to the correlation of the bias to deplete the gain layer and the bias to reach a certain gain.
• The correlation between C-V and charge collection data is a powerful tool to verify the internal consistency of the data and find the root cause of observed variations.
• The prospect to predict the post-rad gain from low-bias room temperature C-V measurements warrants further investigations.
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This work was supported by the United States Department of Energy, grant DE-FG02-04ER41286.
Part of this work has been financed by the European Union’s Horizon 2020 Research and Innovation funding program, under Grant Agreement no. 654168 (AIDA-2020) and Grant Agreement no. 669529 (ERC UFSD669529), and by the Italian Ministero degli Affari Esteri and INFN Gruppo V.
This work was partially performed within the CERN RD50 collaboration.
The next generation was meeting next door