Experimental Study of Acceptor Removal in UFSD

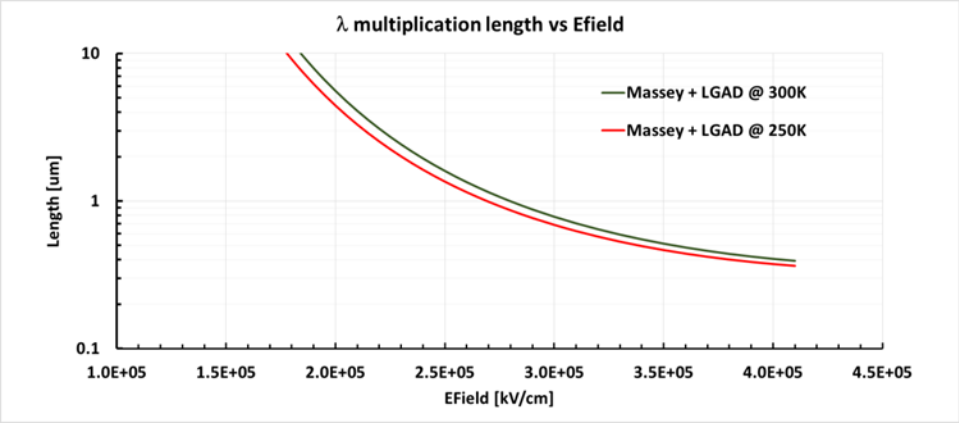
(using C-V and charge collection)

Hartmut F.-W. Sadrozinski
SCIPP – UC Santa Cruz
for the UFSD Collaboration

Multiplication in LGADs depends on Electric Field

The multiplication process is governed by the mean free path λ, the multiplication length.
The probability for multiplication in distance Δx is $e^{\Delta x/\lambda}$,

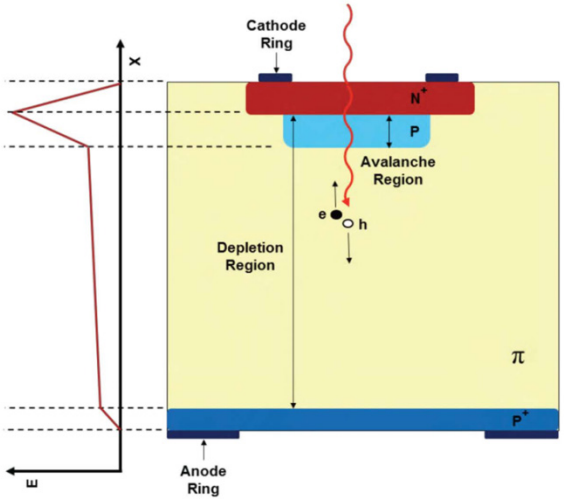
The multiplication length depends approximately exponentially on the inverse of the electric field.
For λ = 1 µm, the field needed is about 270 kV/cm and the multiplication happens on the 1 µm scale.



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)



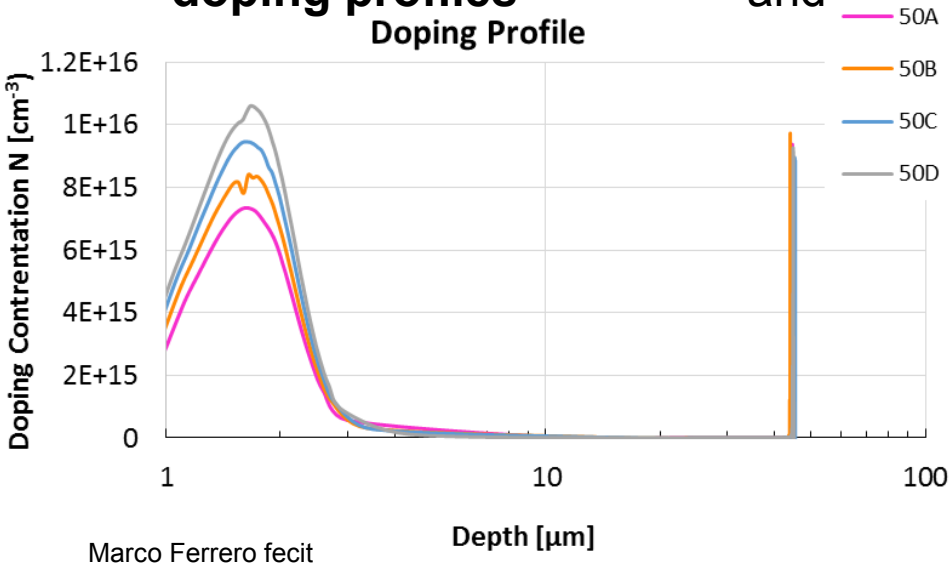
Calibration of Doping, Bias, Gain I

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**

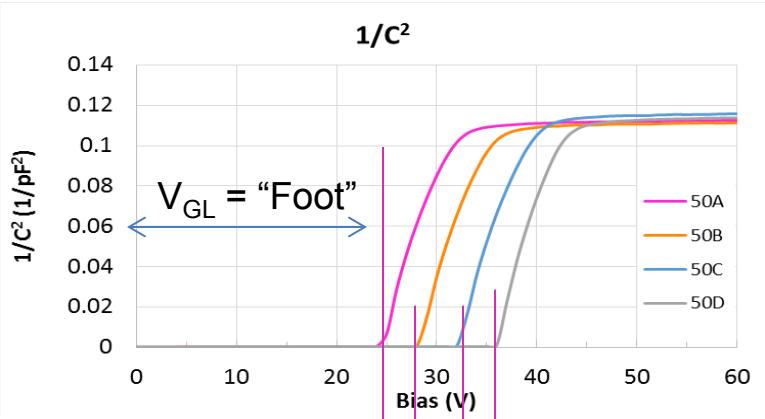


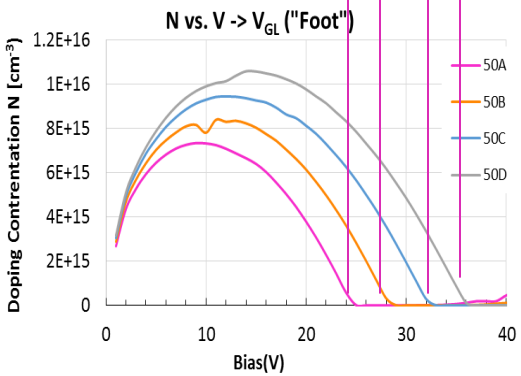
Marco Ferrero fecit

	x1E16	
D	1.06	1
C	0.95	0.90
B	0.85	0.80
A	0.75	0.71

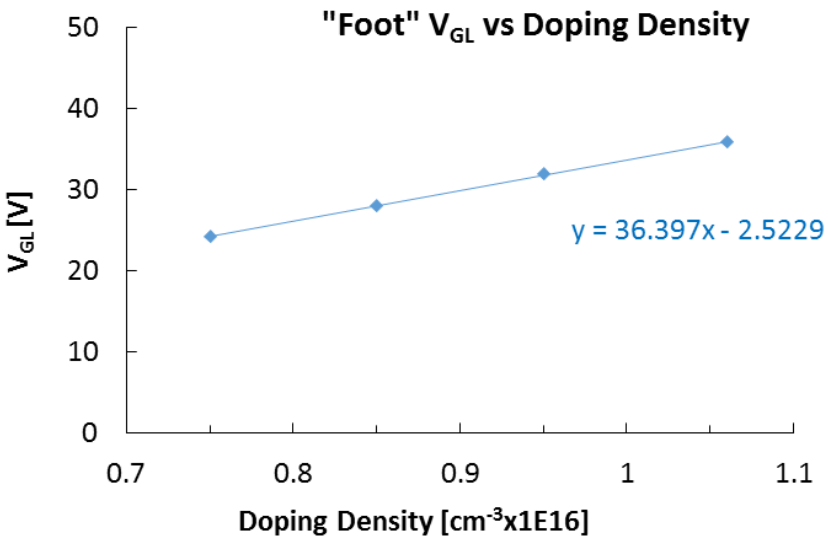
Calibration of Doping, Bias, Gain II

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. .





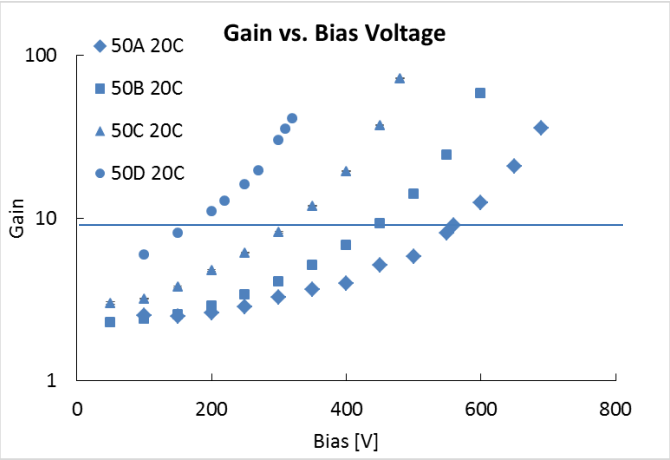
V_{GL} is perfectly correlated with the maximum of the doping density



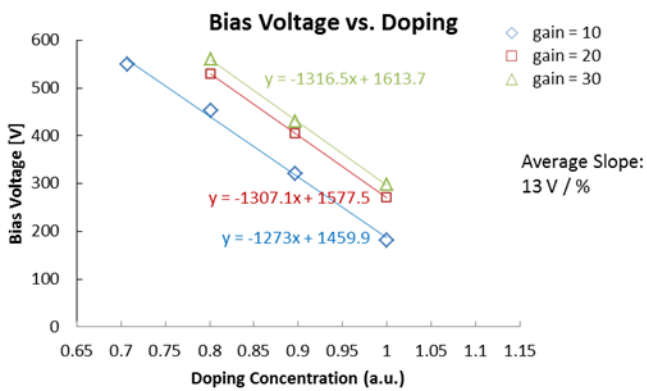
Calibration of Doping, Bias, Gain III

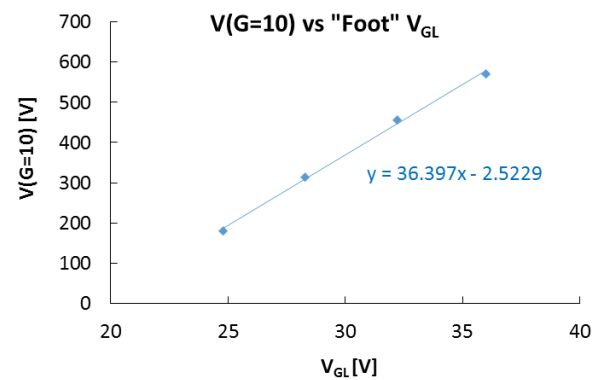
Charge collection studies in the β-source yield the gain vs bias (G vs. V) curves.

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}





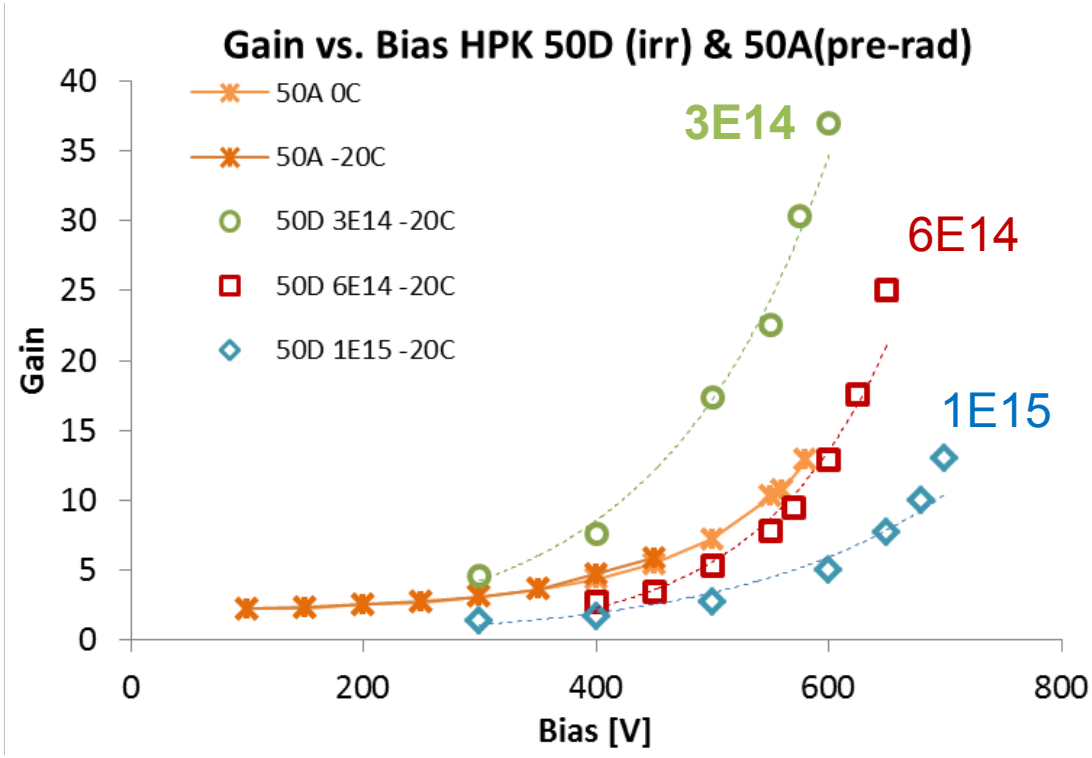
Success: Gain-bias curves ←→doping concentration!

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}

Bias Dependence of Gain after Irradiation

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.

G vs. V curve after irradiation
=
G vs. V for lower initial doping



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.

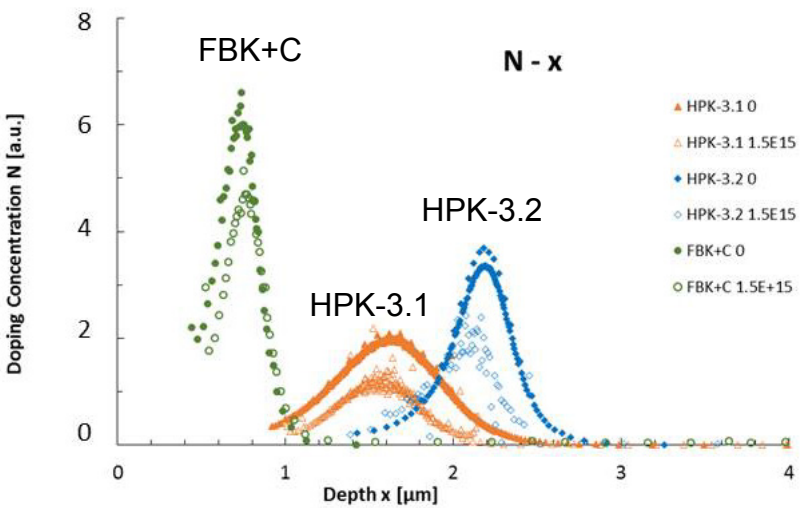
UFSD Doping -> E-field

Compare 3 different LGAD with ~ 50µm FZ bulk

HPK-3.2 (HGTD) : deep and narrow gain layer
HPK-3.1 (HGTD) : more shallow and wider gain layer
FBK+C (INFN): very shallow but high gain layer with Carbon

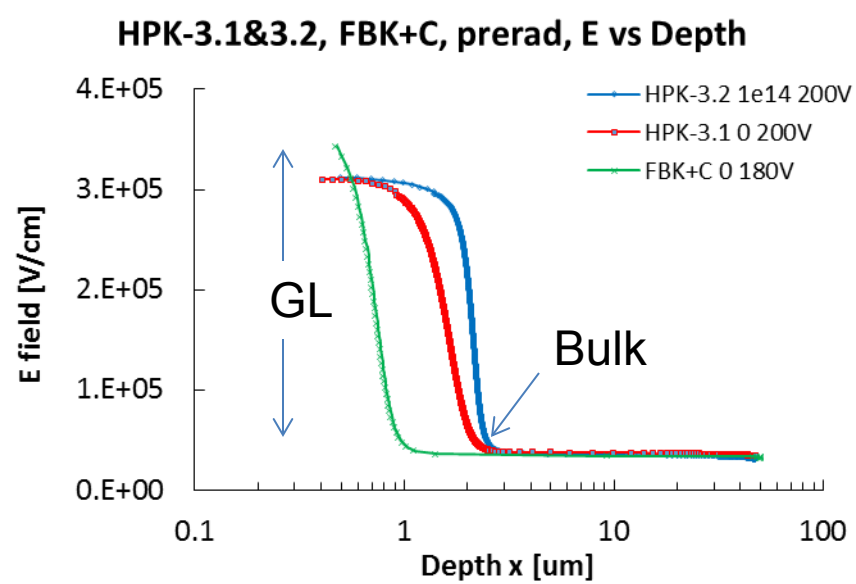
Gain Layer Doping Profile from C-V

Fluence 0 and 1.5E15 neq



Simple Toy Simulation of E-field

(using the measured doping profile):



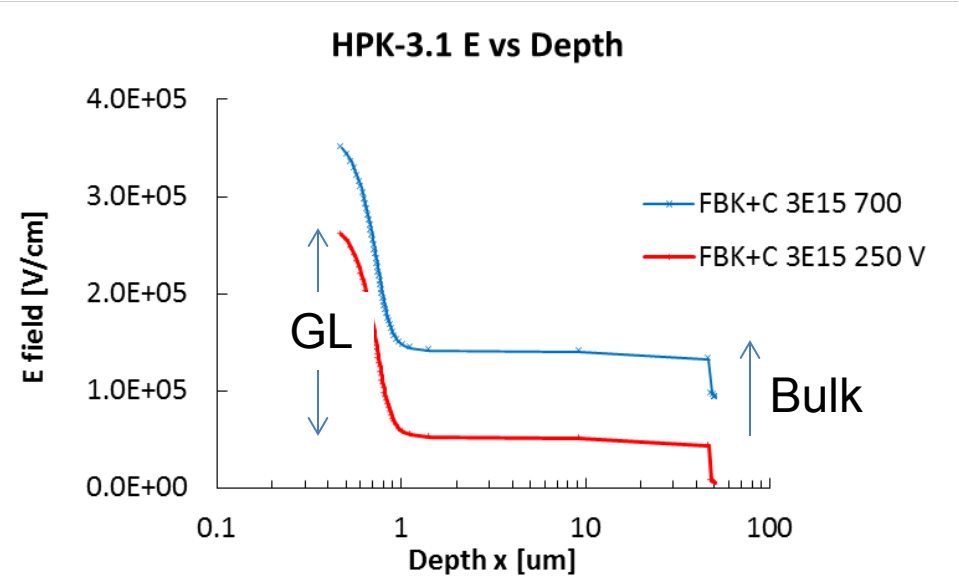
Gain layer (GL)characteristics -> E-field

Width -> slope of E(x)

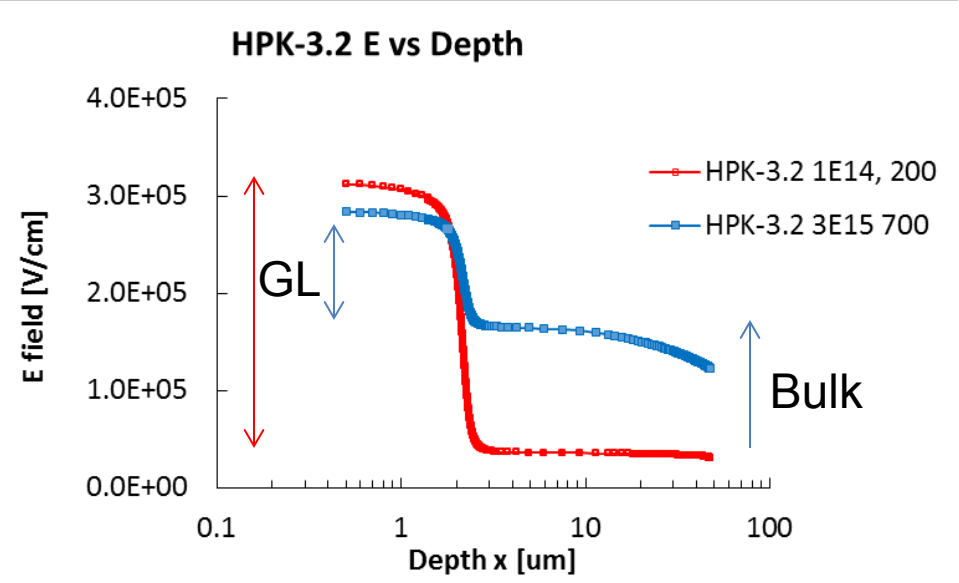
Depth -> extention of E(x)

UFSD Doping -> E-field

Effect of bias on E-Field:
Fixed Gain layer contribution
Increased bulk contribution



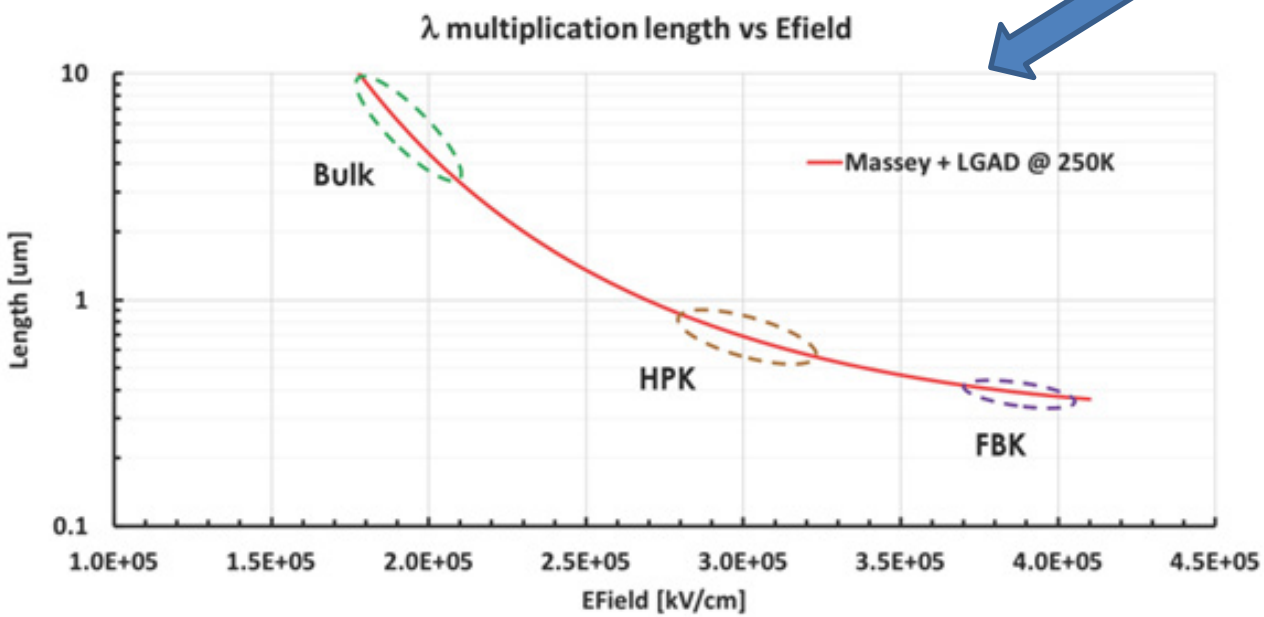
Effect of radiation on E-field:
Decreased gain layer contribution
Increased bulk contribution
-> can't match the pre-rad field
unless bias can be raised more.

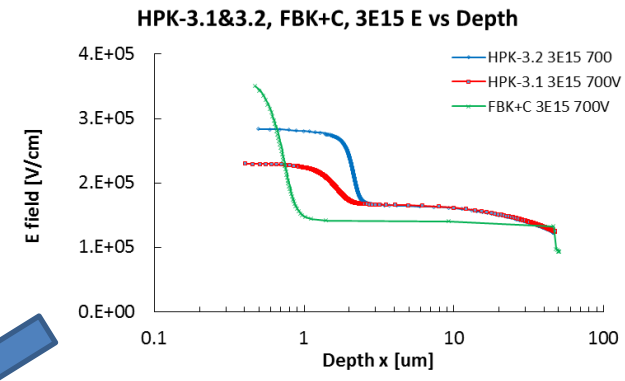


UFSD Doping -> E-field -> Multiplication

After Irradiation to 3E15 neq
Typical E-fields and multiplication length λ

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





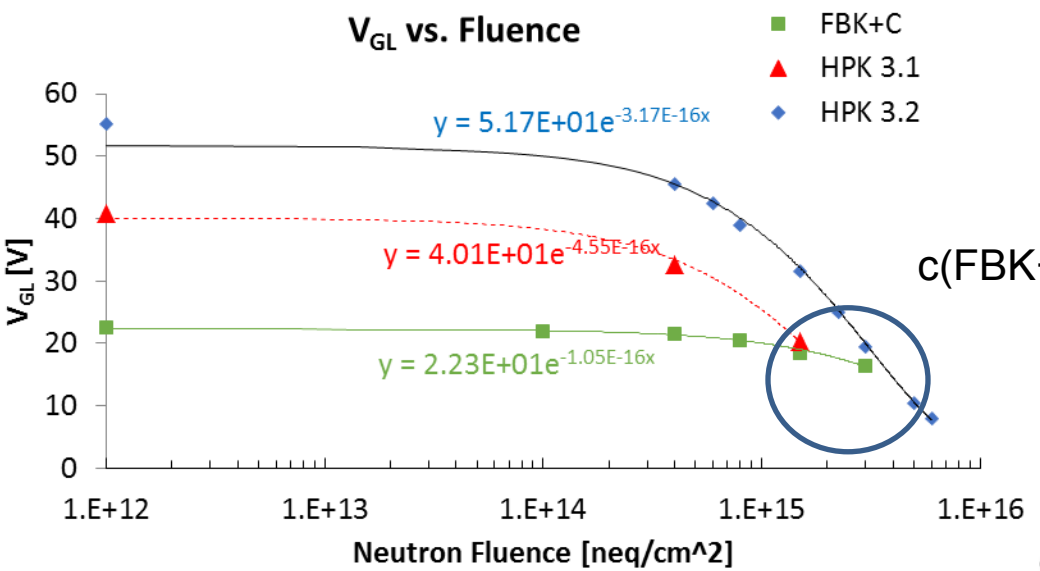
Nicolo Cartiglia (WF2) fecit

N.B. In addition the gain depends on their depth Δx of the implant!

Acceptor Removal

Dependence of the acceptor removal vs. fluence Φ:

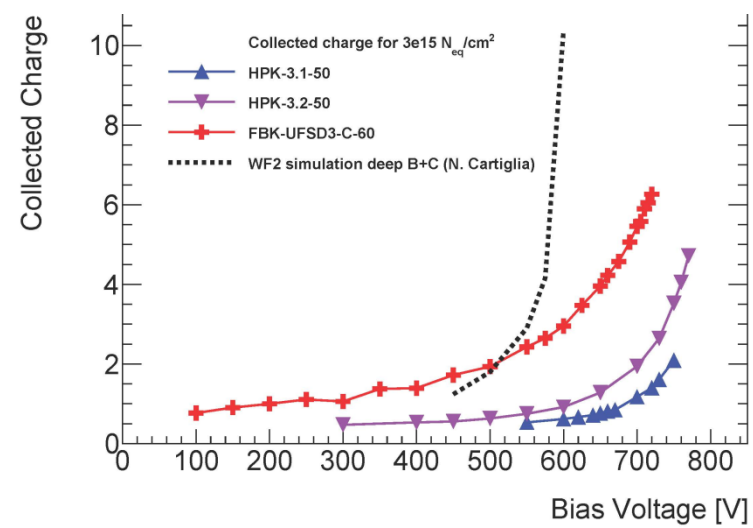
$$V_{GL}(\Phi) = V_{GL}(0)*e^{(-c*\Phi)}$$



Different pre-rad V_{GL}
and
"Acceptor removal coefficient c"
c(FBK+C) : c(HPK-3.2) : c(HPK-3.1) = 1 : 3 : 5

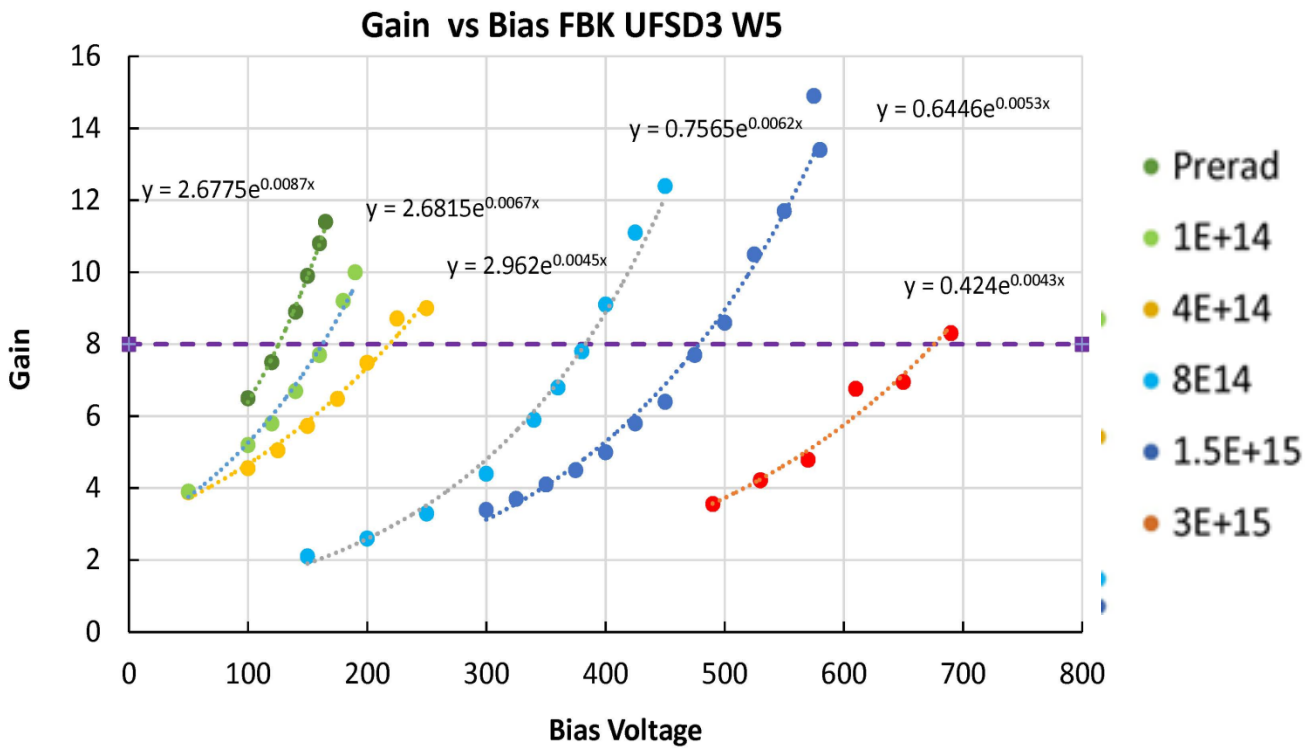
N.B. post-rad C-V at R.T. 1kHz

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



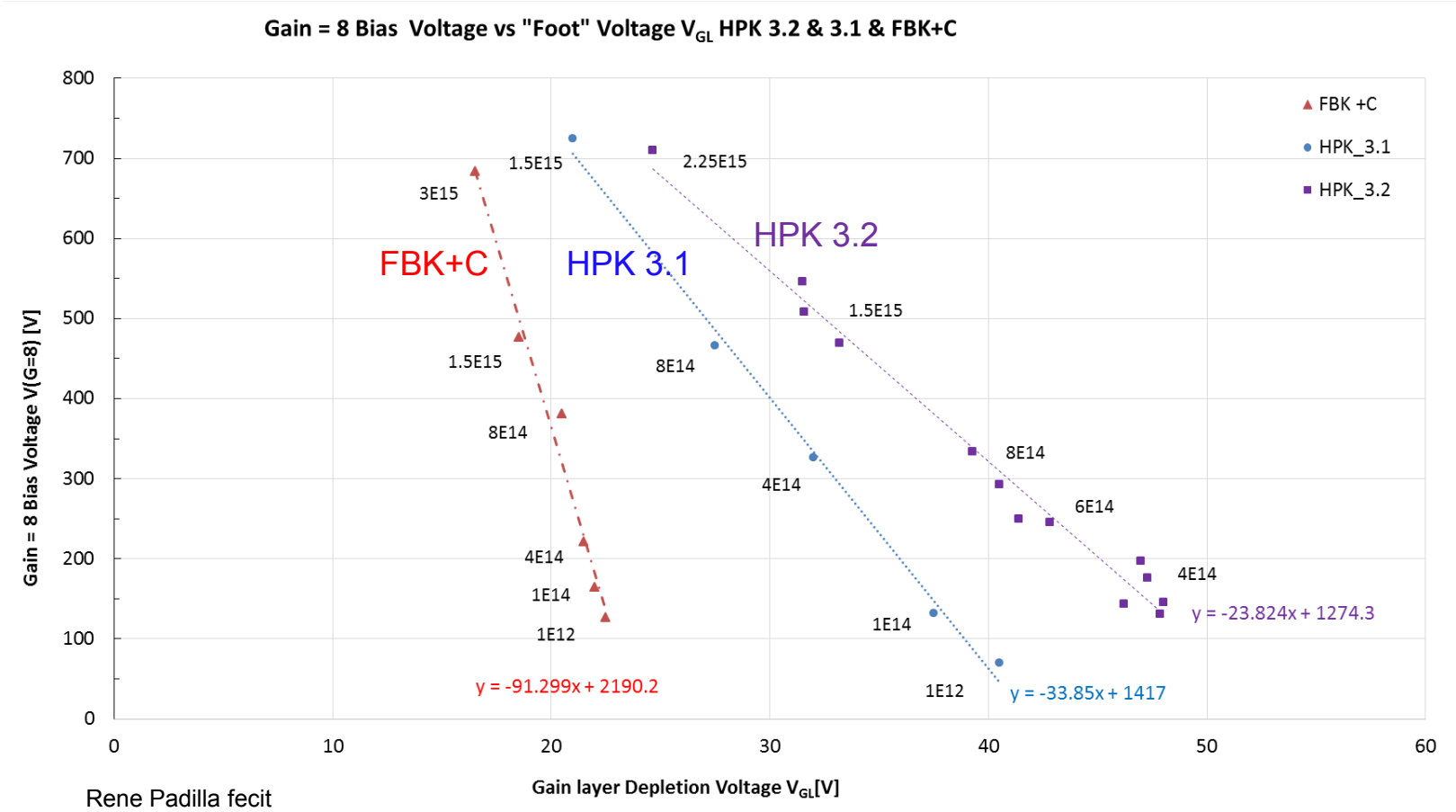
Determination of Bias for Gain = 8: V(G=8)

For comparison of the gain of different LGAD, determine the bias for a gain G=8 at different fluence levels.



Combine Charge Collection and C-V : V(G=8) vs V_{GL}

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.

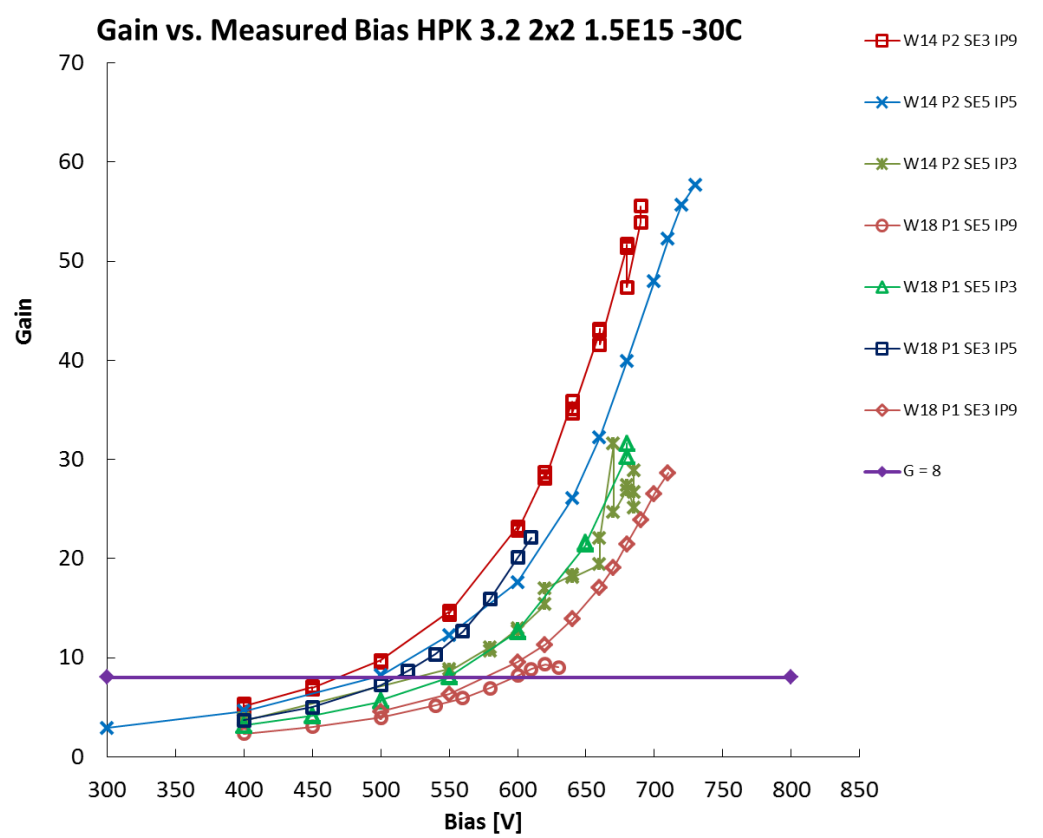


Rene Padilla fecit

Correlation of charge of V(G=8) and V_{GL} for all sensors with different slopes

Variation of V(G=8) at 1.5E15 Neq

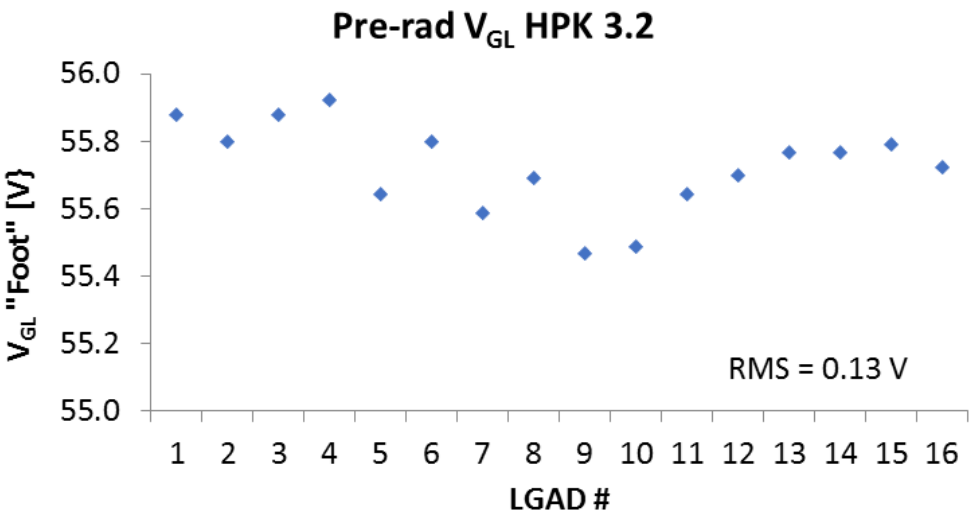
We observe large variations in gain curves vs. bias for the same fluence.
Select a sub-set of data of HPK 3.2, 2x2 arrays, irradiated to 1.5E15 to investigate
No systematic correlation with sensor geometry.



Variation of V(G=8) ≈ 120V ! If caused by variation in doping, would be > 10% !

Variation in pre-rad V_{GL}

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.



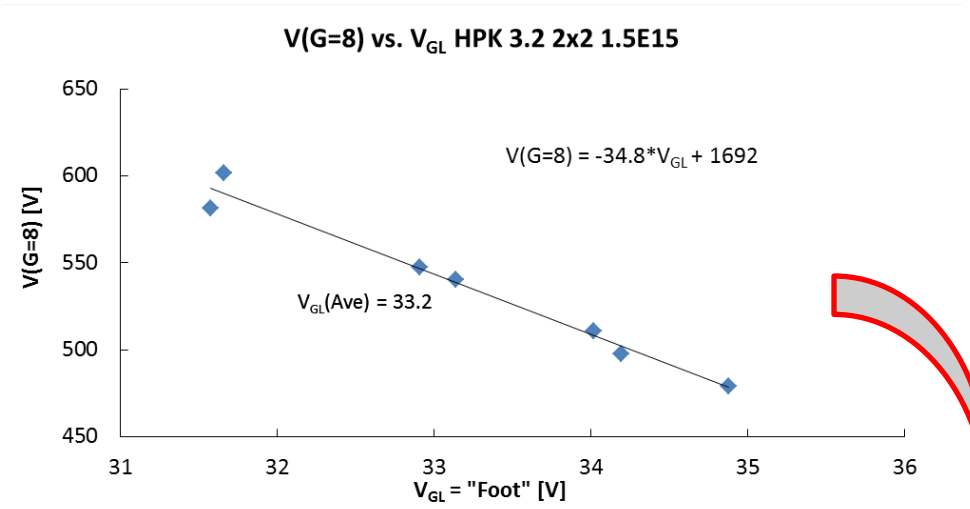
Pre-rad V_{GL} has very small spread (here 0.2%)

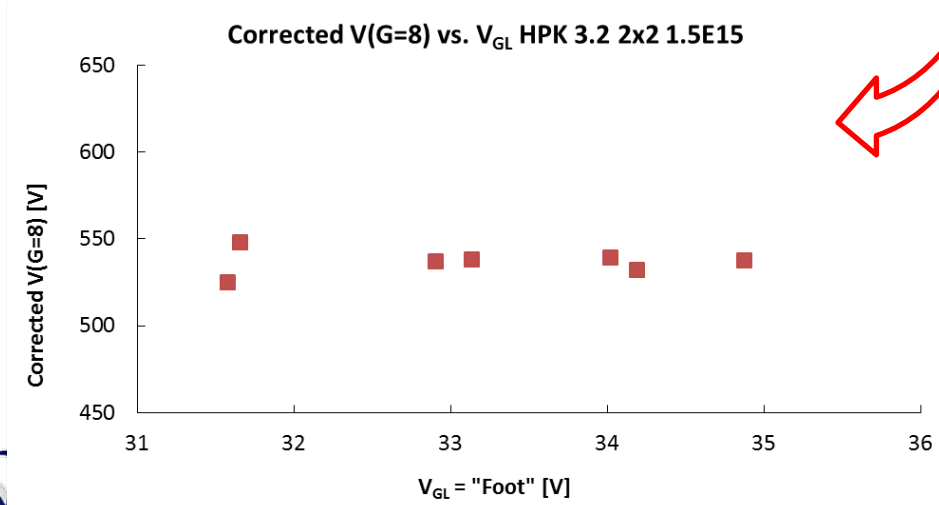
CMS study over many wafers: V_{GL} varies 1-2 %

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





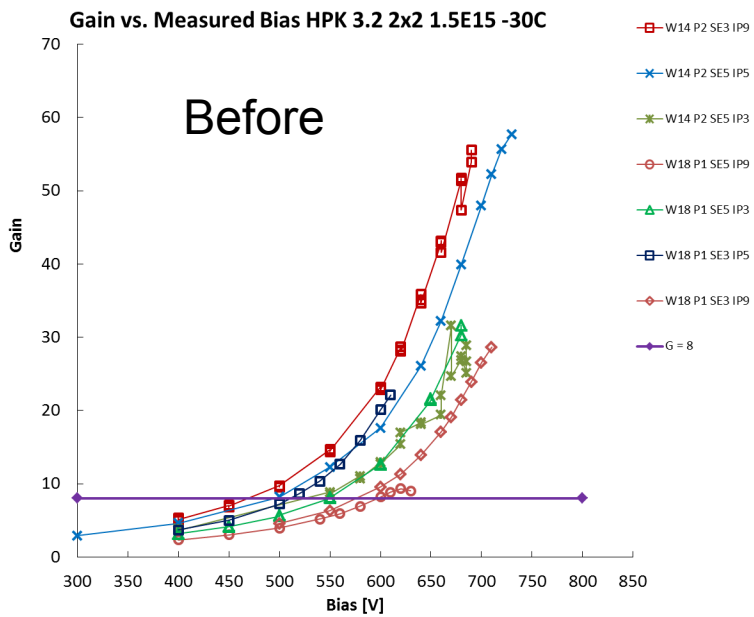
Strong correlation between V(G=8) and V_{GL}
(as shown earlier)
1% doping change results in bias voltage shift of 10 – 13 V)

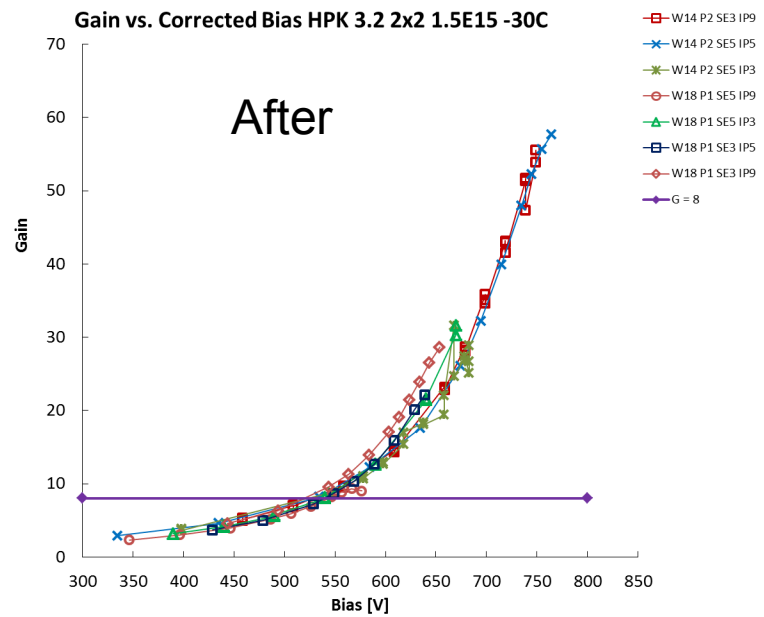
Use correlation to correct V(G=8) using the V_{GL} measured value.

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.





	Measured Bias	Shifted Bias
Average (V(G=8))	536 V	536 V
RMS (V(G=8))	**45 V = 8.3%**	**7 V = 1.3%**
		(this value is close to the pre-rad variation!)

A likely root-cause is fluence uncertainty which is estimated to be ~10%.

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 (~ 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.

Contributors

S. Christie, Z. Galloway, **C. Gee, C. Labitan,** S. Mazza, F. Martinez-Mckinney, **R. Padilla, H. Ren,** H. F.-W. Sadrozinski, B. Schumm, A. Seiden, M. Wilder, **Y. Yin, Y. Zhao**
SCIPP, Univ. of California Santa Cruz, CA 95064, USA

R. Arcidiacono, N. Cartiglia, **F. Cenna, M. Ferrero,** A. Staiano, V. Sola
Univ. of Torino and INFN, Torino, Italy

G. Pellegrini, S. Hidalgo, **M. Baselga, M. Carulla, P. Fernandez-Martinez,** D. Flores, A. Merlos, D. Quirion
Centro Nacional de Microelectrónica (CNM-CSIC), Barcelona, Spain

V. Cindro, G.Kramberger, I. Mandić, M. Mikuž, M. Zavrtanik
Jožef Stefan Inst. and Dept. of Physics, University of Ljubljana, Ljubljana, Slovenia

K. Yamamoto, S. Kamada, A. Ghassemi, K. Yamamura
Hamamatsu Photonics (HPK), Hamamatsu, Japan

M. Boscardin, G-F. Della Betta et al
Fondation Bruno Kessler, Trento

*Students in **bold***

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