Issues on Segmented Low-Gain Avalanche Detectors (LGAD)

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with

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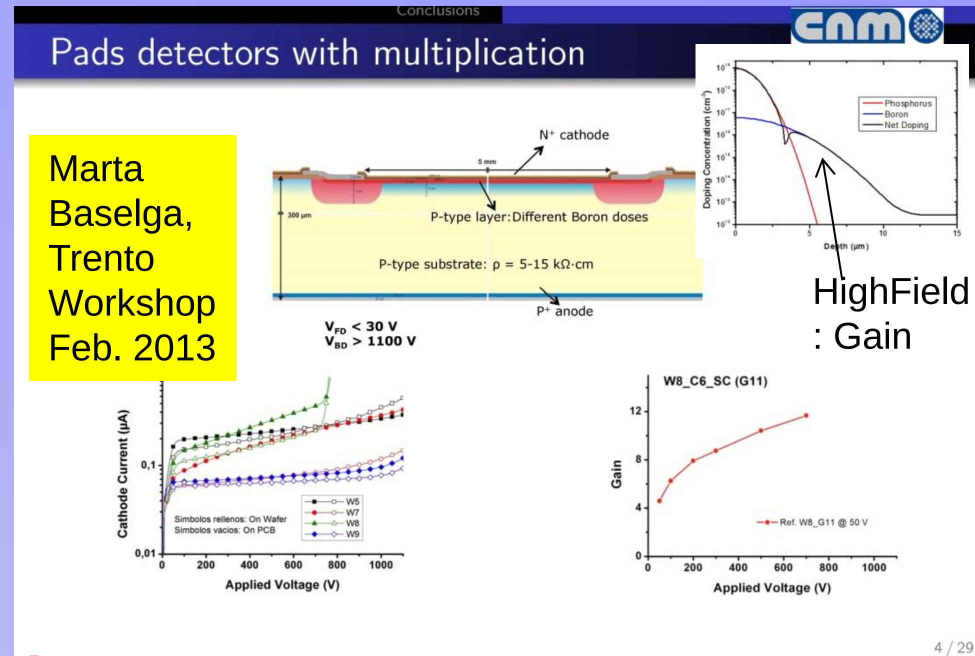
Low-Gain Avalanche Detector (CNM)

Run 6474 2012 (“Pablo”):
Pads 300 um FZ

Run 6827 2013 (“Marta”):
Pads & Strips & Pixels,
10-50 um epi, 300 um FZ

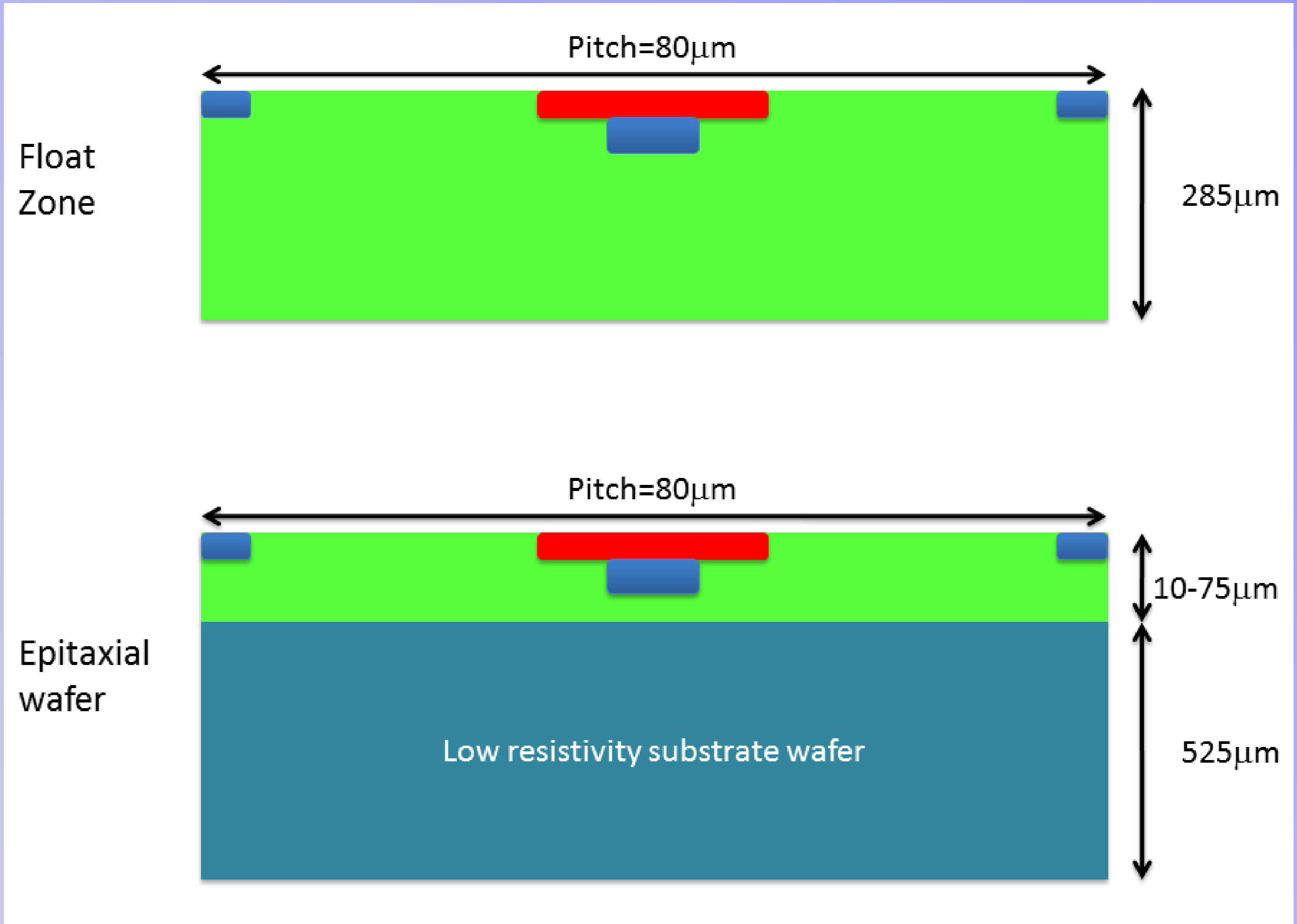
Run 7062 2014 (“Virginia”):
Pads, 300 um FZ



Question: what do we know about charge multiplication on segmented LGAD?

- **Characteristics of Strips from Run 6827**
- **Gain from TCT**
- **Doping Concentration from C-V**
- **Simulations**
- **Explore Alternative Configurations**

Wafer Options Run 6827



W12-W14

W1-W11

Run 6827 LGAD Strips

Pitch p=80 μm

	Strip w [μm]	Metal [μm]	P-implant [μm]	w/p	P-implant /pitch
AC1	24	20	6	0.3	7.5%
AC2	24	24	6	0.3	7.5%
AC3	24	28	6	0.3	7.5%
AC4	48	44	30	0.6	37.5%
AC5	48	48	30	0.6	37.5%
AC6	48	52	30	0.6	37.5%
AC7	62	58	44	0.775	55%
AC8	62	62	44	0.775	55%
AC9	62	66	44	0.775	55%
AC10/AC11/DC	32	40	14	0.4	17.5%

In addition pixels, and pads with and without gain

Breakdown Voltages (strips) Run 6827

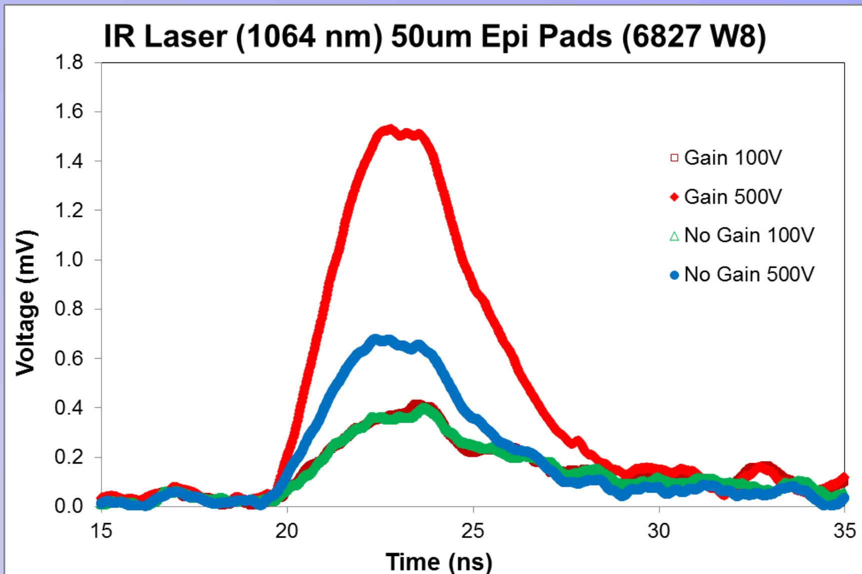
Wafer	1	4	5	6	8	9	10	11	12	13	14
	Epi 10 Sh	Epi 10 St	Epi 50 Sh	Epi 50 St	Epi 50 D	Epi 75 Sh	Epi 75 St	Epi 75 D	FZ 300 Sh	FZ 300 St	FZ 300 D
AC1	5	70	20	60	100	20	5	140	20	200	60
AC2	5	70	25	20	120	25	15	160	20	200	150
AC3	5	10	5	10	160	5	5	110	20	200	150
AC4	5	5	10	10	140	20	5	120	20	140	150
AC5	5	5	5	10	160	20	5	160	20	140	150
AC6	5	5	5	10	160	20	5	150	20	140	60
AC7	5	5	5	10	60	5	5	60	20	80	150
AC8	5	5	5	10	20	5	5	60	20	80	150
AC9	5	5	5	10	40	5	5	60	20	80	150
AC10	5	10	5	10	160	5	5	160	20	5	150
AC11	5	5	5	10	100	20	5	100	20	100	150
FDV					200			450		80	

Epi: 100 Ω-cm, FZ 15 kΩ -cm

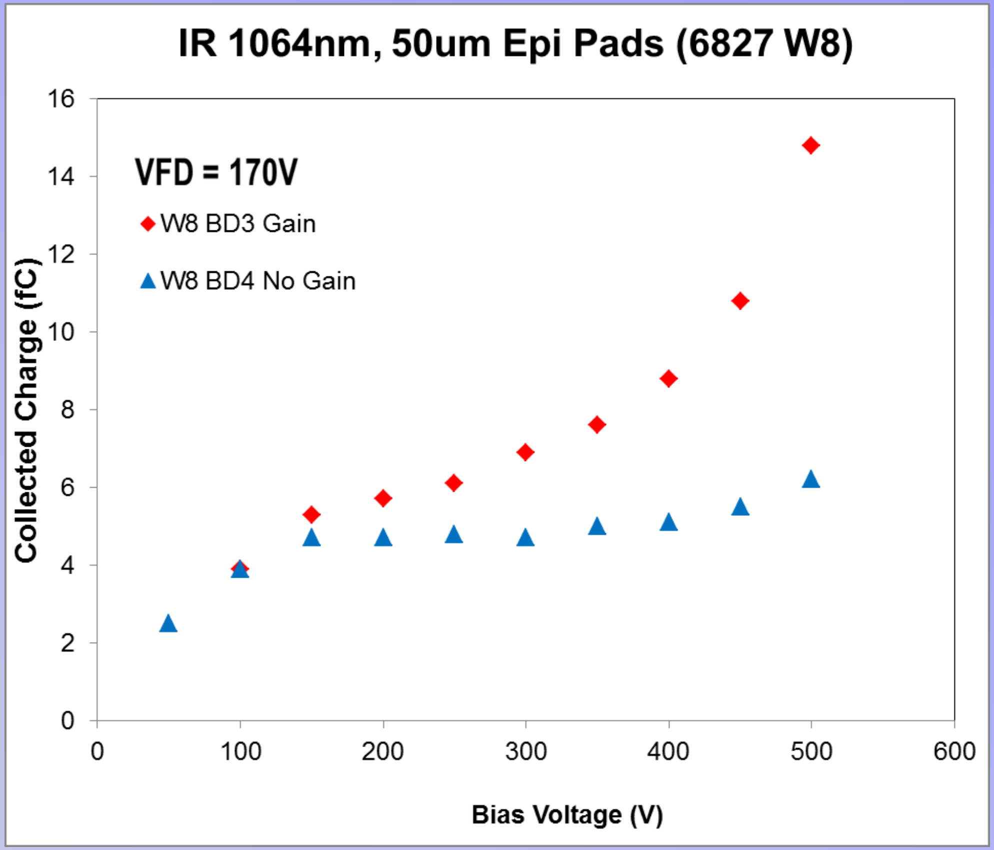
D = Deep implant seems to afford higher break-down voltage, but at same gain?

N.B: Break-down voltage of pad sensors > 500V typically

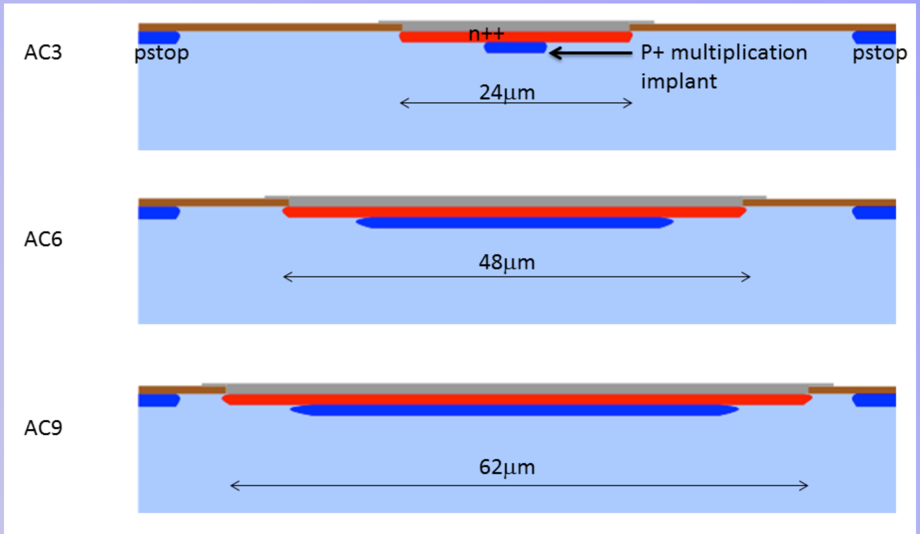
IR Laser Injection in epi 50 µm pads



Comparison of LGAD and no-gain pads reveals gain starts at bias of 150V. This is close to the break-down voltage of the strip sensors!



Issues for 6827 Strip LGAD



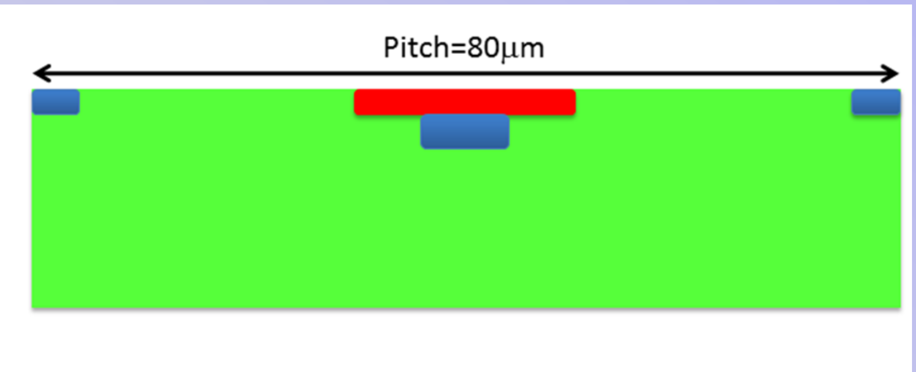
W13 300 μm FZ Break-Down Voltage [V]

200

140

80

Issue of field at strip edge?

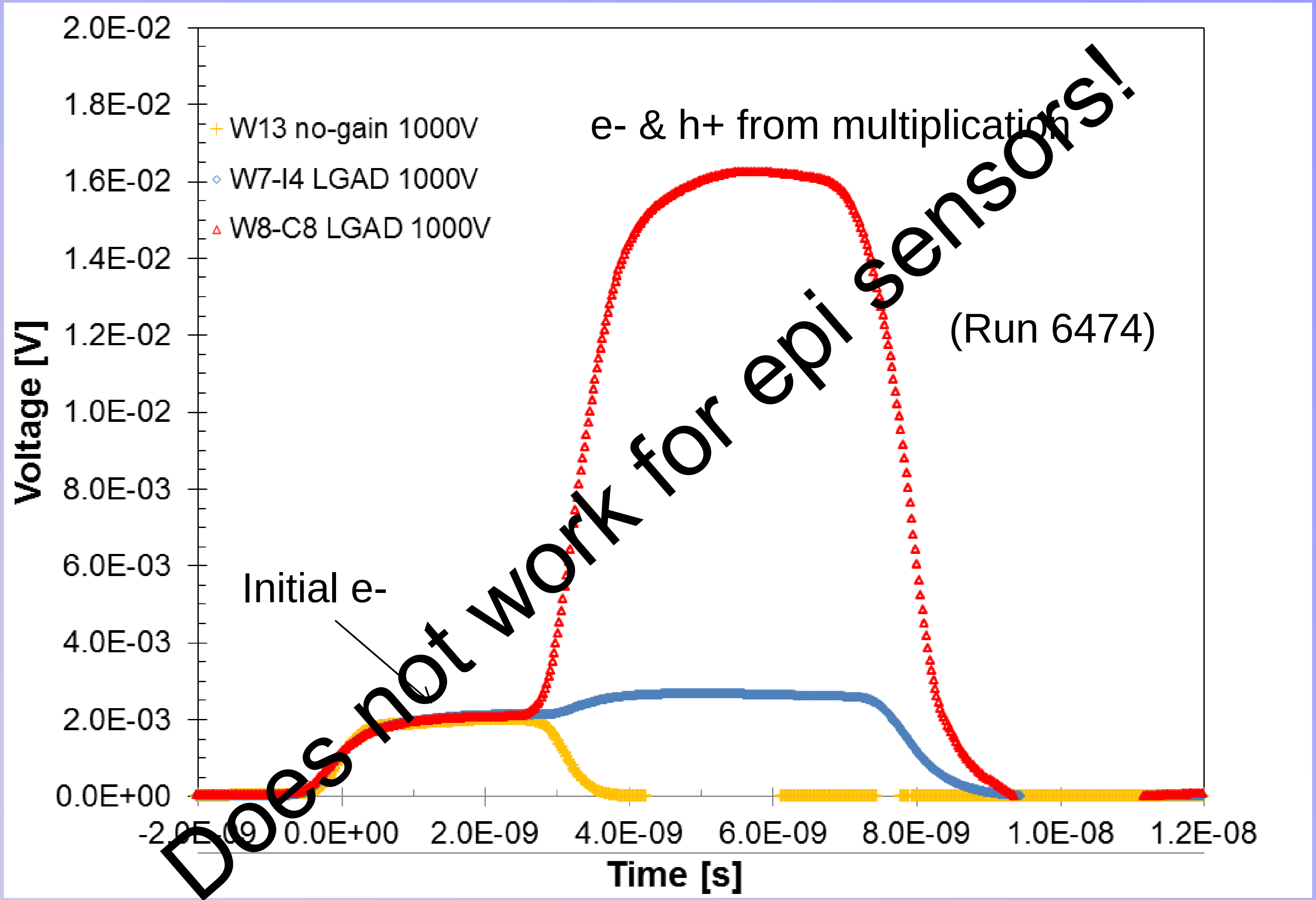


Uniformity of Response
(p-layer covers between 7.5% and 55% of pitch: what fraction of e- are traversing it and are multiplied?)

Simulations

Charge collection

LGAD Pulse – shape analysis with α TCT



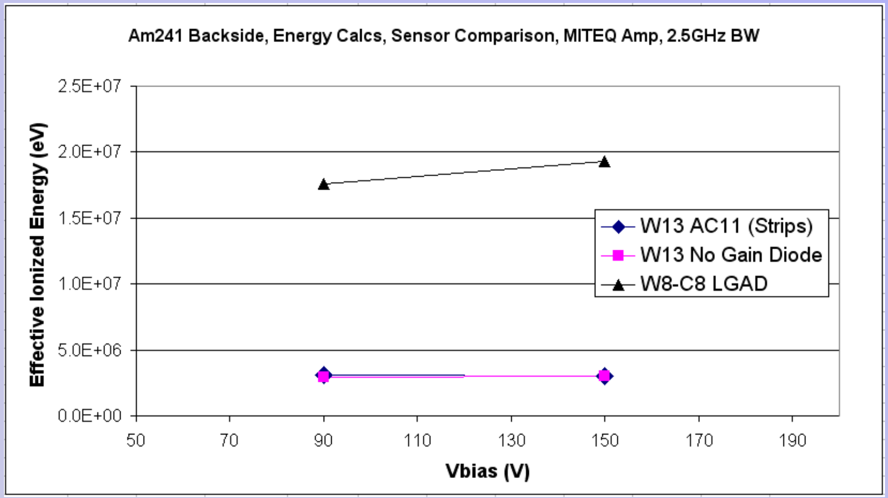
Gain = Total pulse area / Initial Pulse Area

Gain is characterized by late collection of holes from multiplication

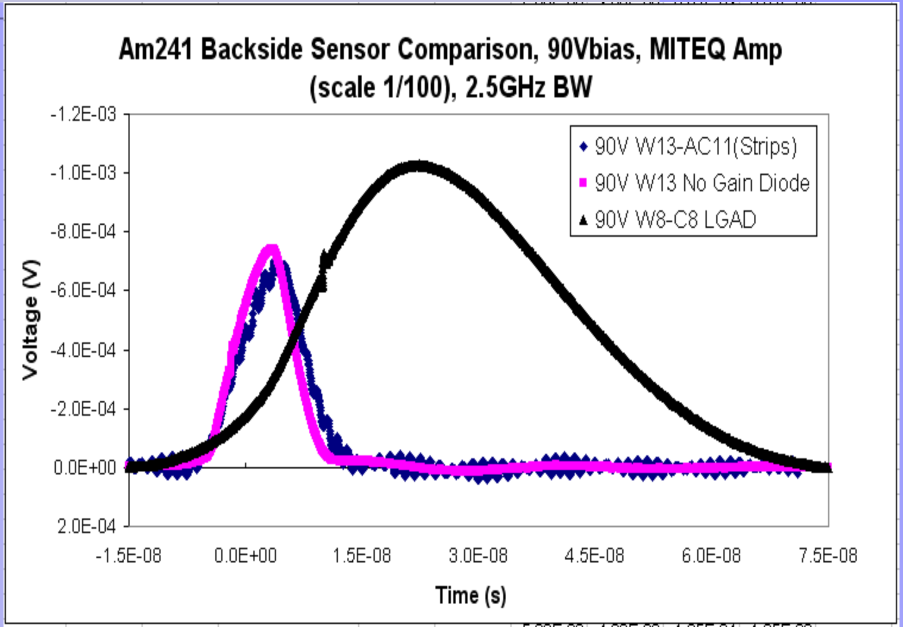
Sensor Comparison 6474 vs. 6827

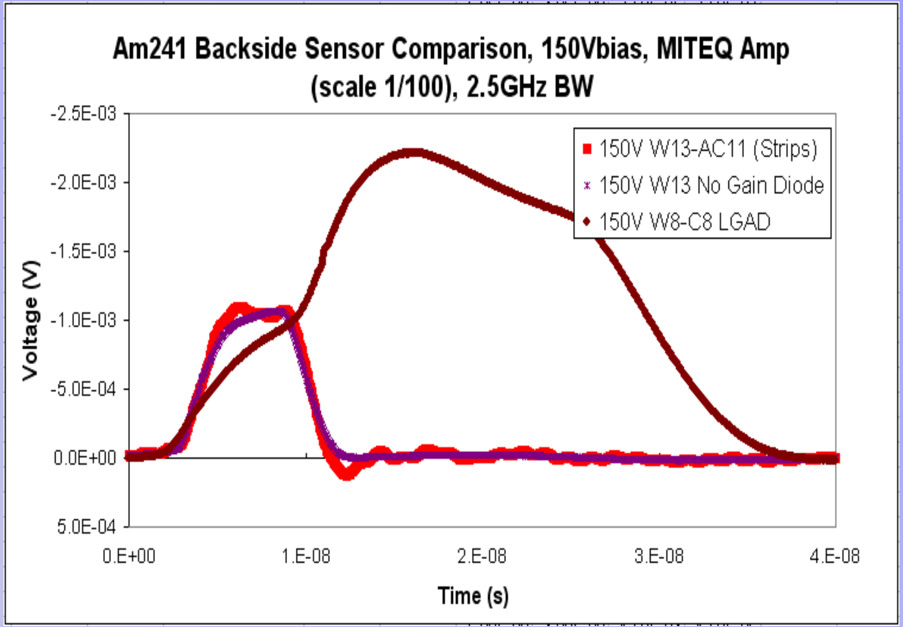
Pulse shapes for 6827-W13 are comparable for no-gain pads and “gain” strip sensor -> No gain observed!

Large difference to LGAD pad (6474-W8) which exhibits the characteristic late hole signal.



6474-W8 pulses are huge compared to W13 ones, even at low bias (fields).





Investigation of the Doping Profile from C-V

(strictly correct only for pad sensors and uniform doping density!!)

Bias Voltage V – Depleted Region x :
$$V = \frac{qN}{2\varepsilon\varepsilon_0} x^2$$

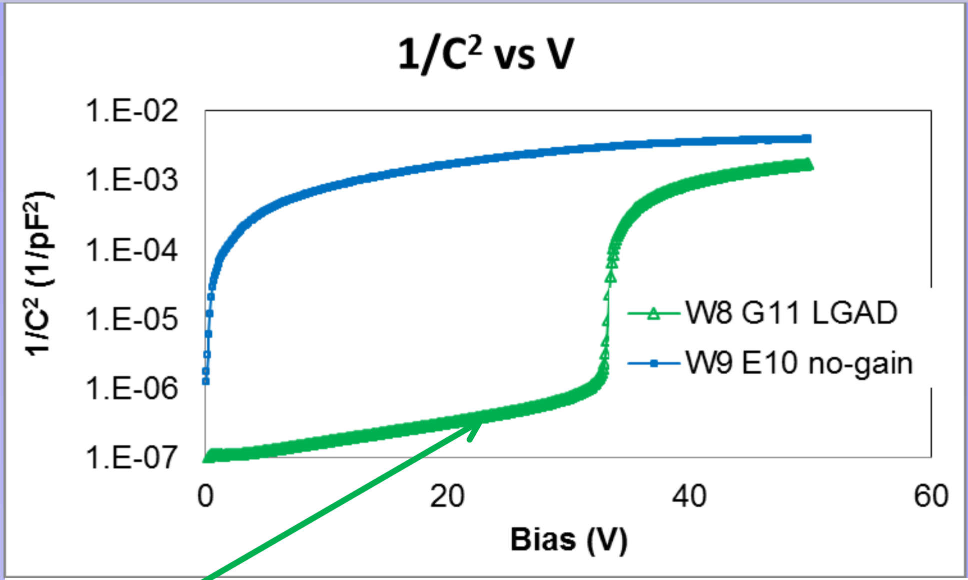
Resistivity ρ – Doping density N :
$$\rho = \frac{1}{q\mu N}$$

Capacitance C – Depl. Region x :
$$C(x) = \varepsilon\varepsilon_0 \frac{A}{x} = A\sqrt{\frac{\varepsilon\varepsilon_0 qN}{2V}}, \Rightarrow x = A/C$$

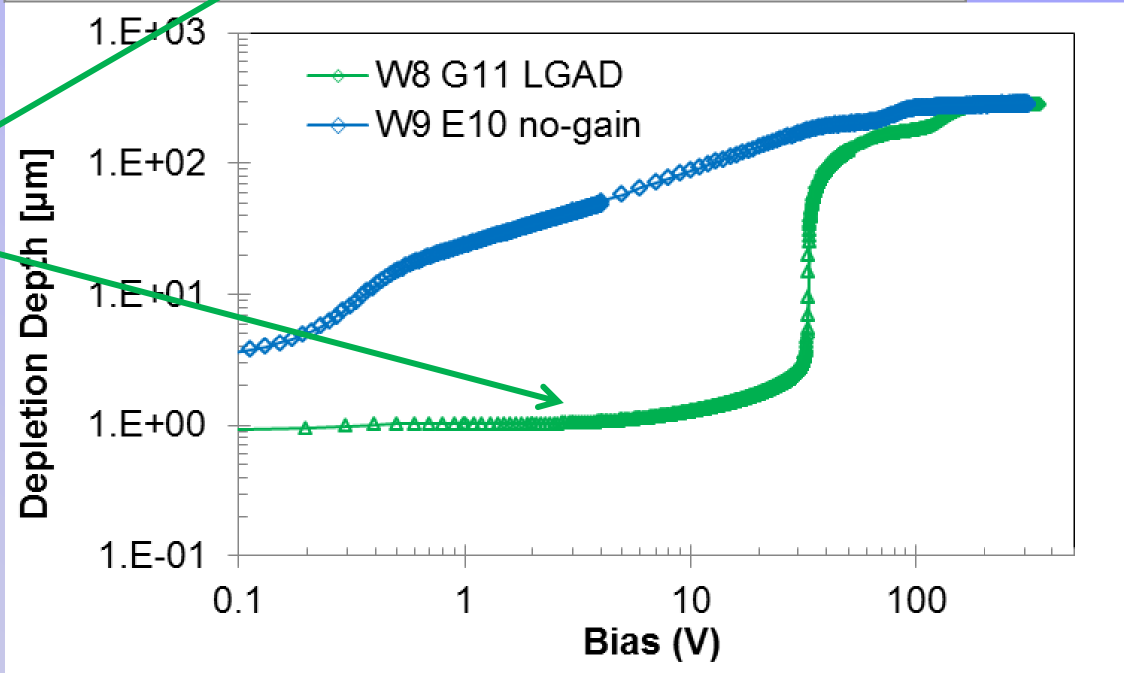
Doping Density:
$$N = \frac{2}{\frac{d(1/C^2)}{dV}} \bullet \frac{1}{\varepsilon\varepsilon_0 qA^2} = \frac{2}{\frac{d(1/C^2)}{dV}} \bullet \frac{1}{1.6\cdot 10^{-7} A^2}$$

Large C-V Difference LGAD/no-gain at low Bias

Run 6474
Example on pads
W8G11: LGAD
W9E10 no-gain

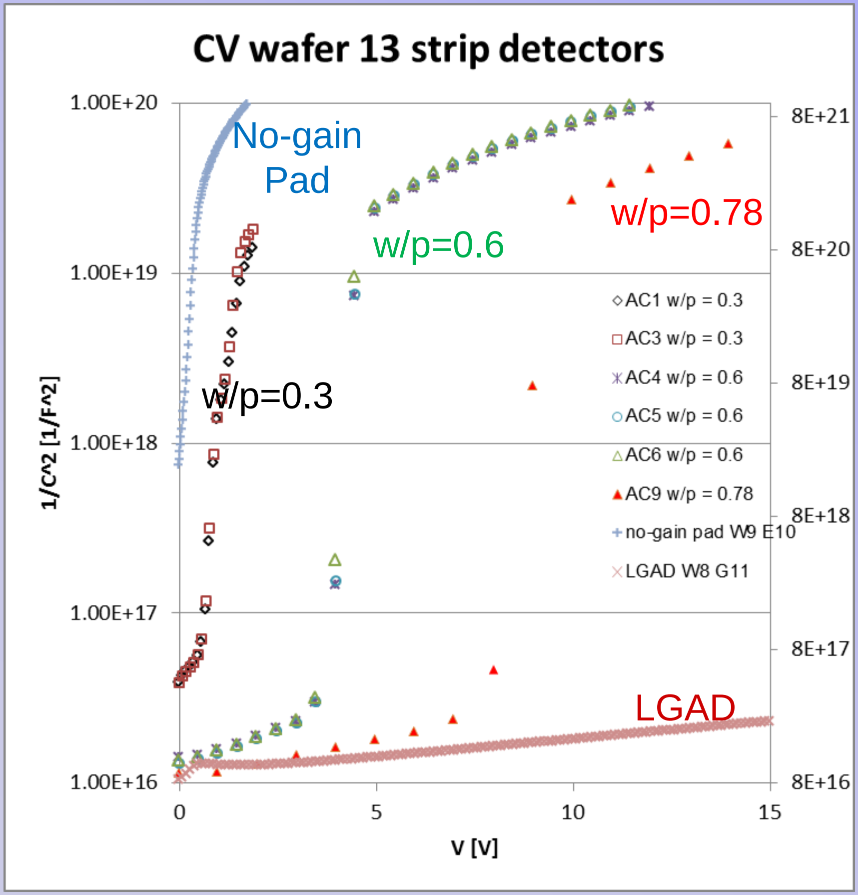


Important:
Take voltage steps
of 0.1V below 50 V
(below the **"foot" / "lag"**).

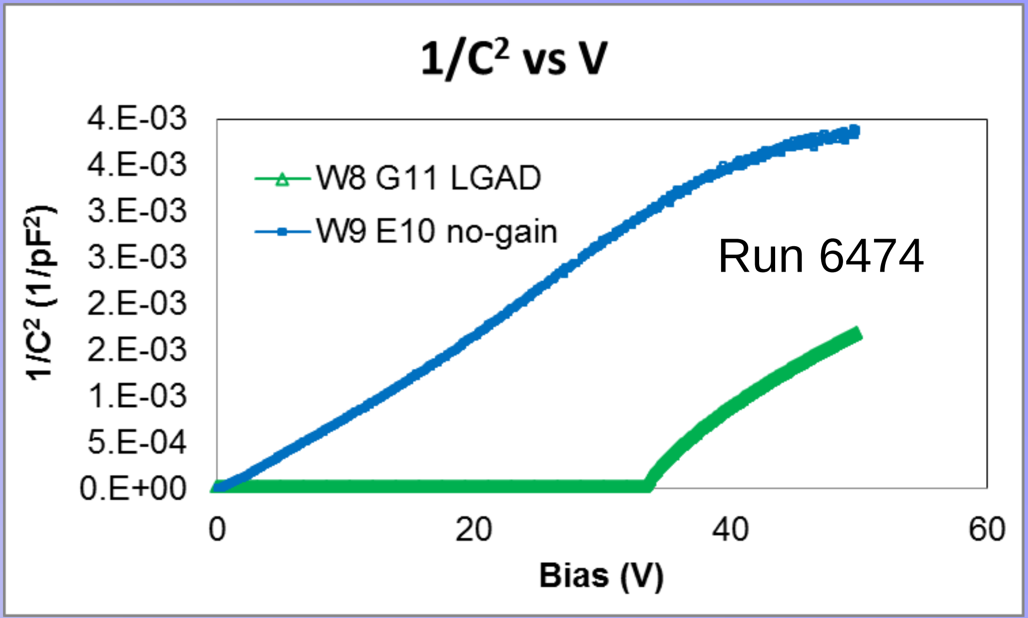


Large Voltage "Lag" due to Strip Geometry

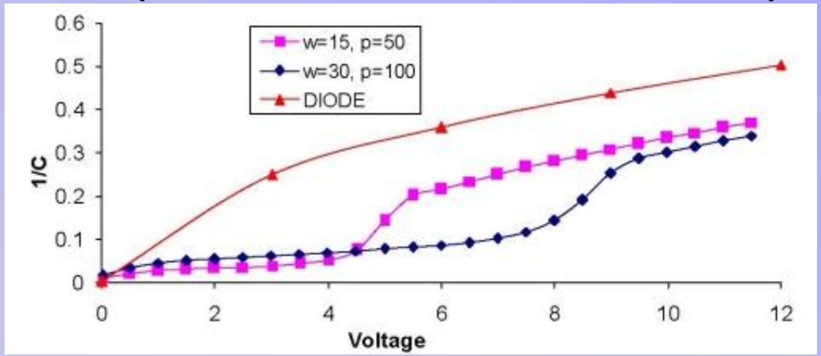
Careful: "foot" indicates gain only with pads!
FZ strips gain?/no-gain?



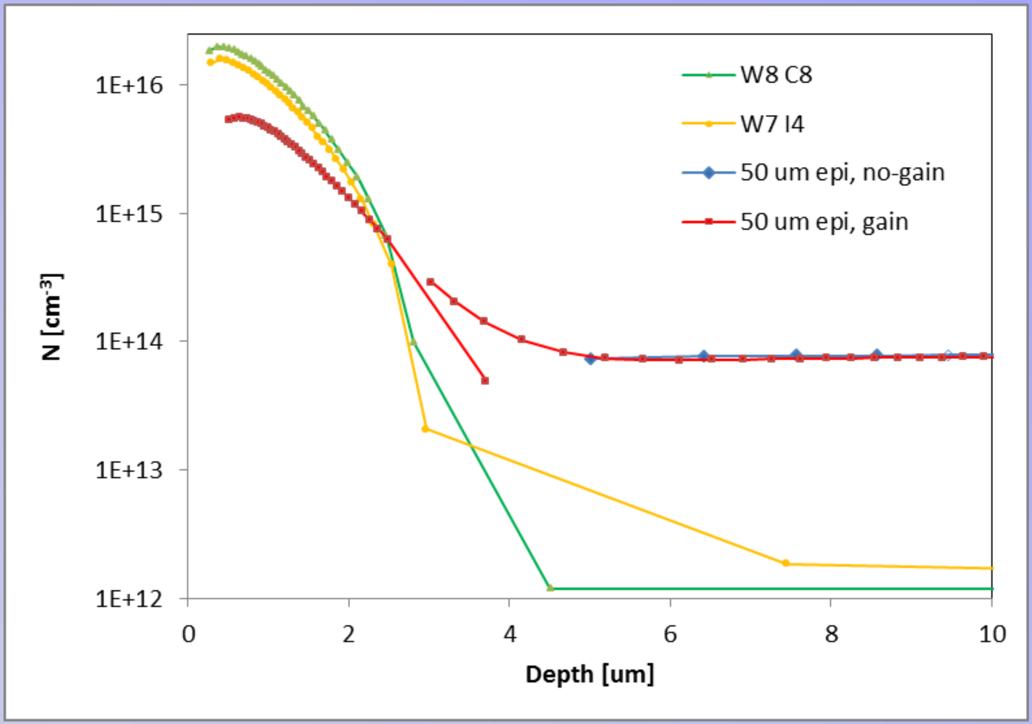
Example of "Foot" on pads

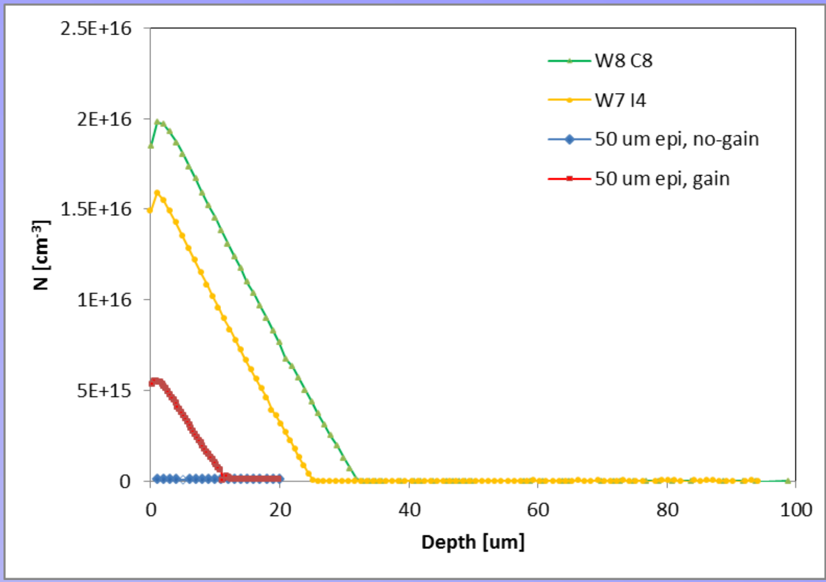


Example of "Foot" in no-gain SMART FZ strips due to lateral depletion (Chris Betancourt M.S. Thesis)



Doping Density Profile

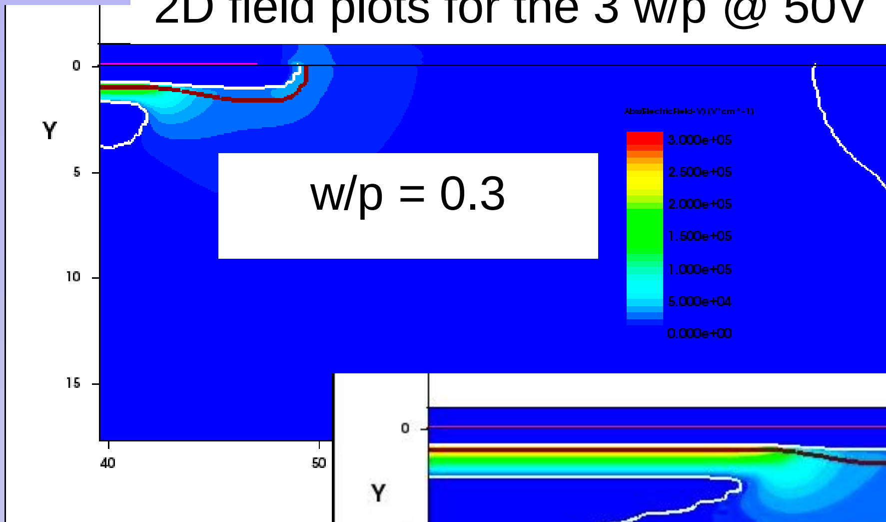


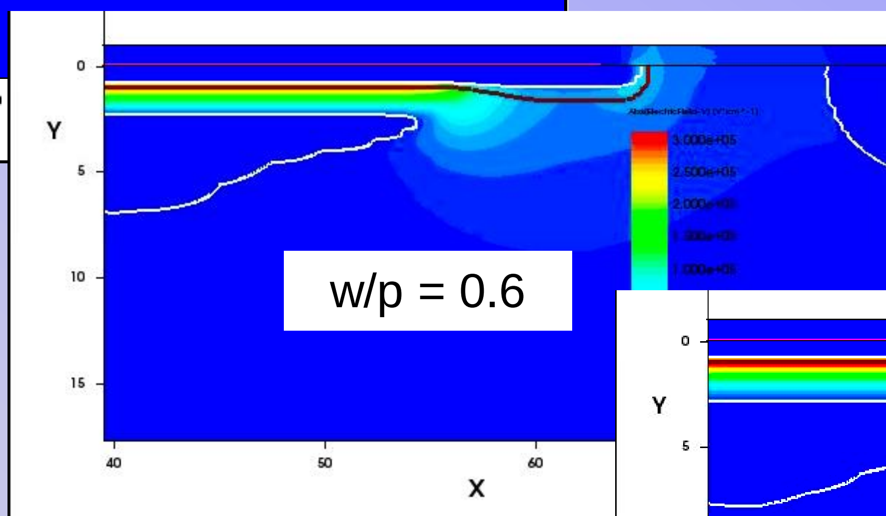


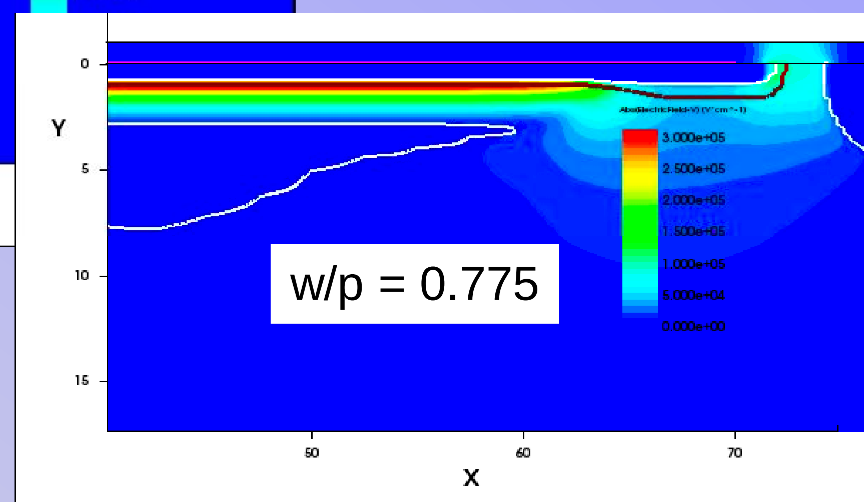
Device	Voltage Lag [V]	N_{max} [cm^{-3}]	N_{Bulk} [cm^{-3}]	Gain (400V)
W8 C8 FZ (6474)	35	2.0e16	1.6e12	8
W7 I4 FZ (6474	29	1.6e16	1.6e12	2.5
50um epi (gain)	14	0.6e16	7e13	~ 1.7
50um epi (no-gain)	< 1	7e13	7e13	1

2D Field Simulation -> Gain Uniformity

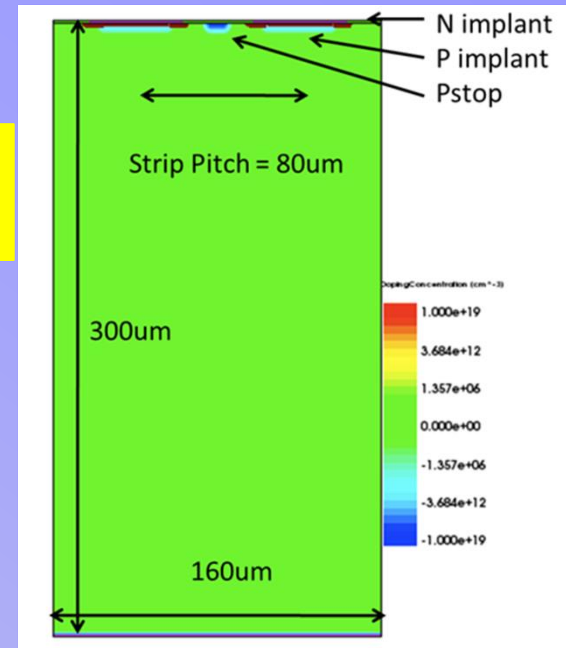
2D field plots for the 3 w/p @ 50V





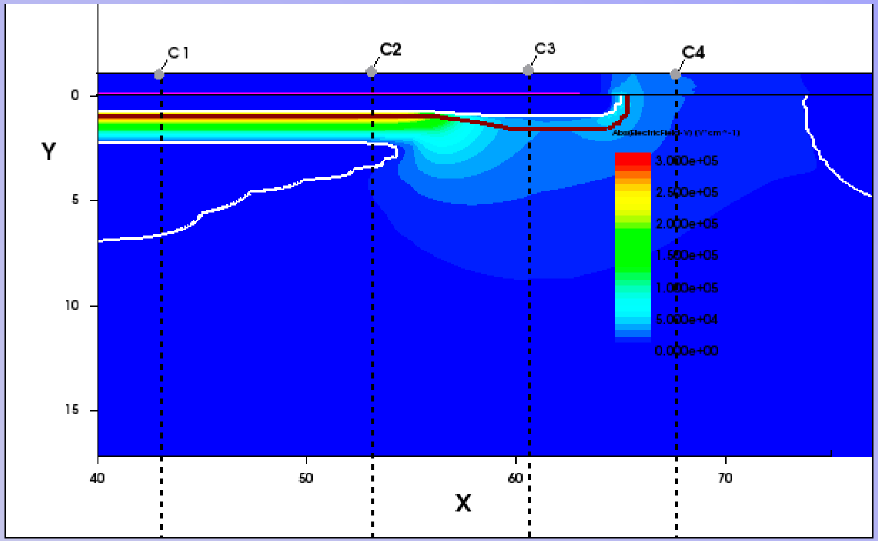


Marta Baselga & Colin Parker



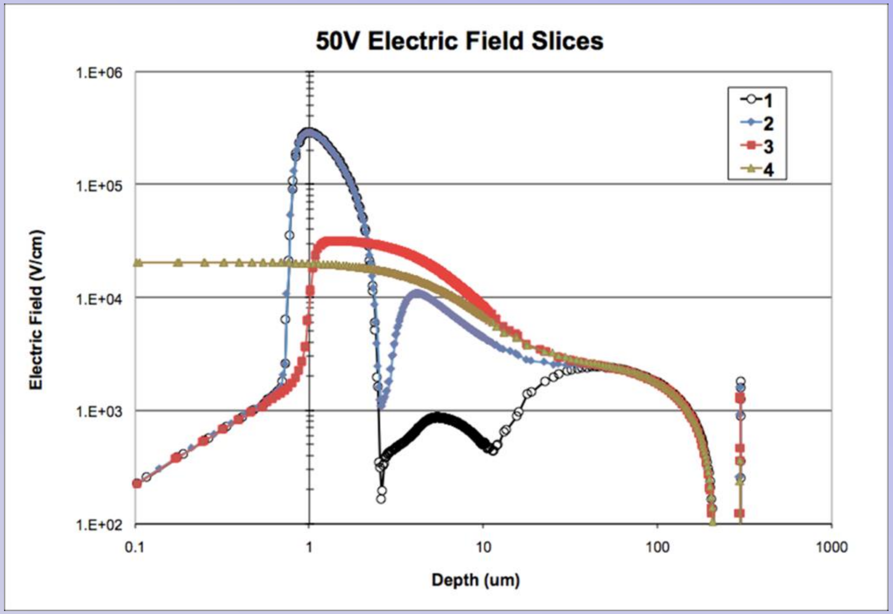
More gain coverage appears for larger w/p, outside of implant area no large field extension.

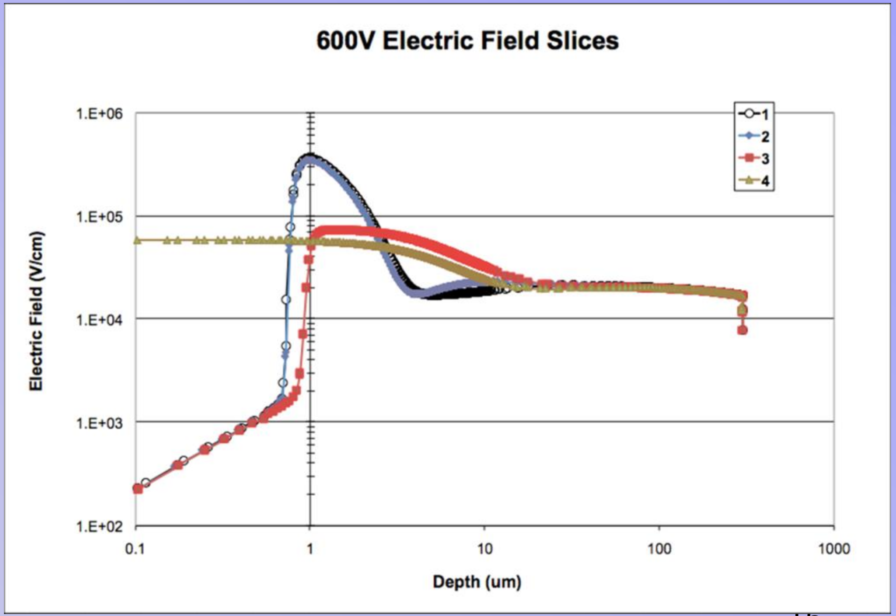
Field Slices for w/p =0.6



Electric field magnitude along 4 slices show large differences in the electric field across the pitch, suggesting also large difference in gain in those areas.

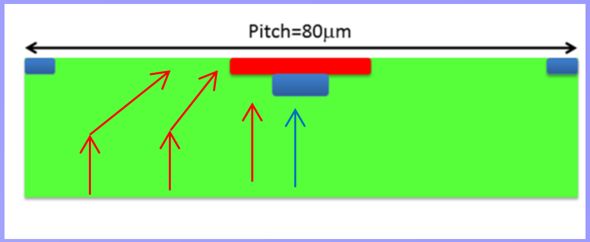
Marta and Colin are working on extracting the 2D field map to predict the electric field vectors and the charge multiplication along different electron paths (to be merged with “Weightfield”).

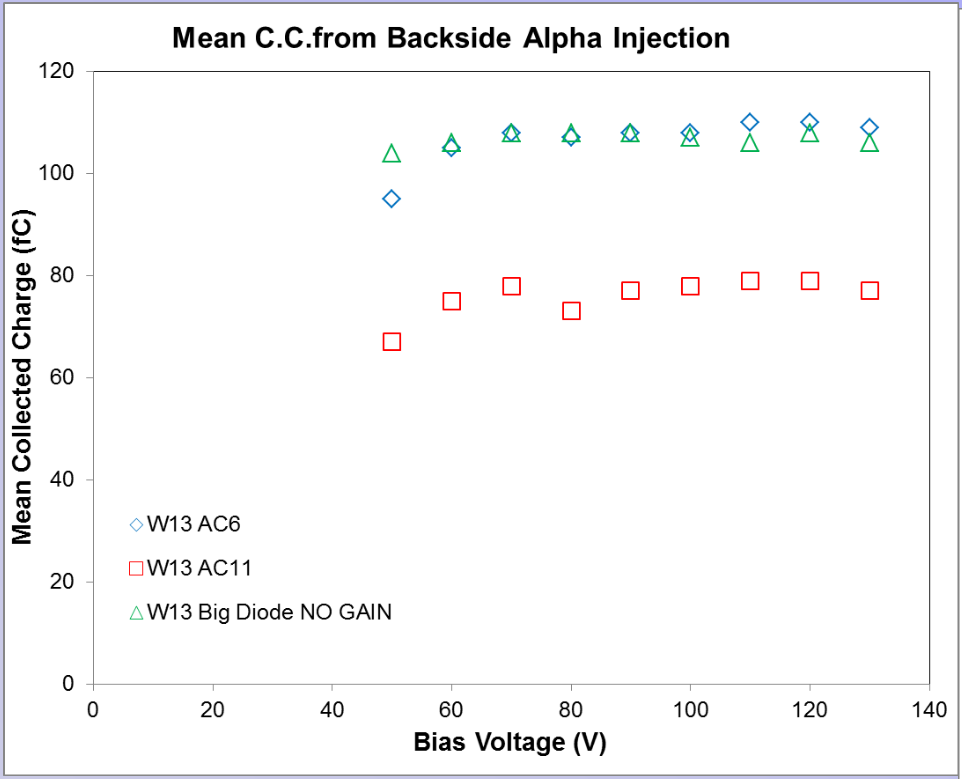


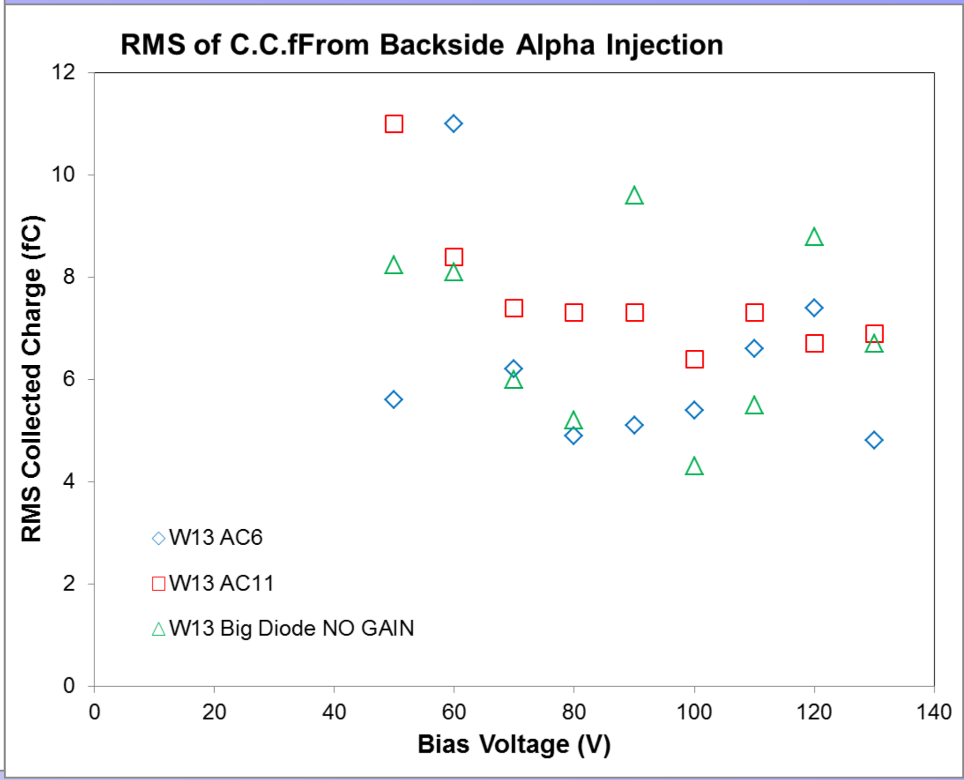


Two types of pulses: gain/no-gain?

Partial coverage of the strip with the p+ multiplication layer should lead to two distinct pulse shapes:
Turn-on of multiplication with bias should increase both the mean and the RMS of the collected charge.

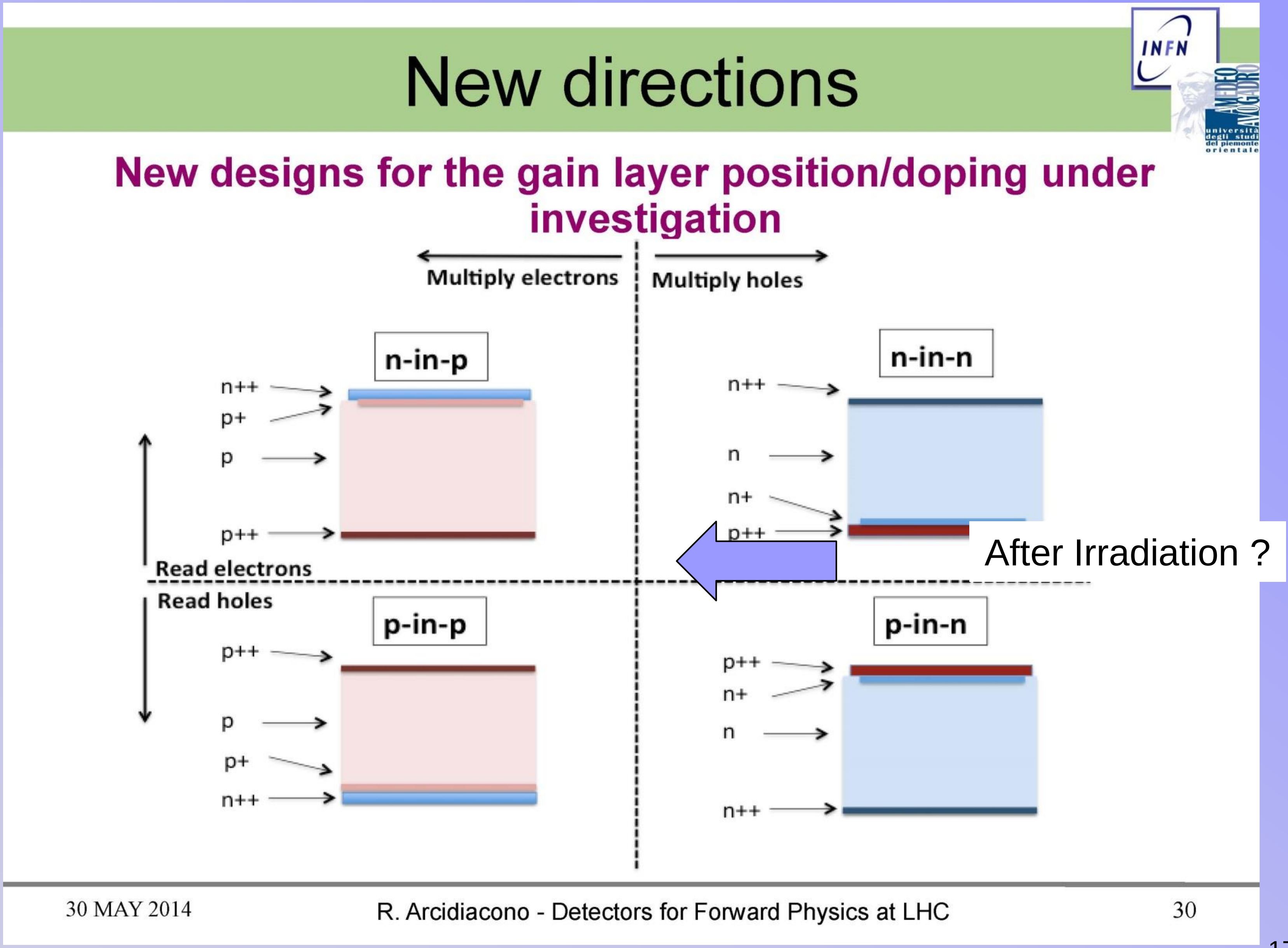






No increase in pulse mean and RMS observed for strips: no observable gain before breakdown.

Separate the Collection and the Gain



Pulse Simulations with “Weightfield”

Pulse shapes for the 4 types of sensors with gain

4 sensor types: n & p bulk and n & p strip implants.
Combine two things which are proven to work:
Gain is always on an **non-segmented p-n junction** (like LGAD pads)
Charge collection is on the **segmented ohmic side** (like n-on-n strips)

Use **Weightfield** 2.1 settings, MIP
3 strips, pitch = 80 µm, width 30 µm
“gain” = 2 and 3, h/e = 0.03
Scope BW = 2.5 GHz (black curves)

Developed by
Nicolo Cartiglia.

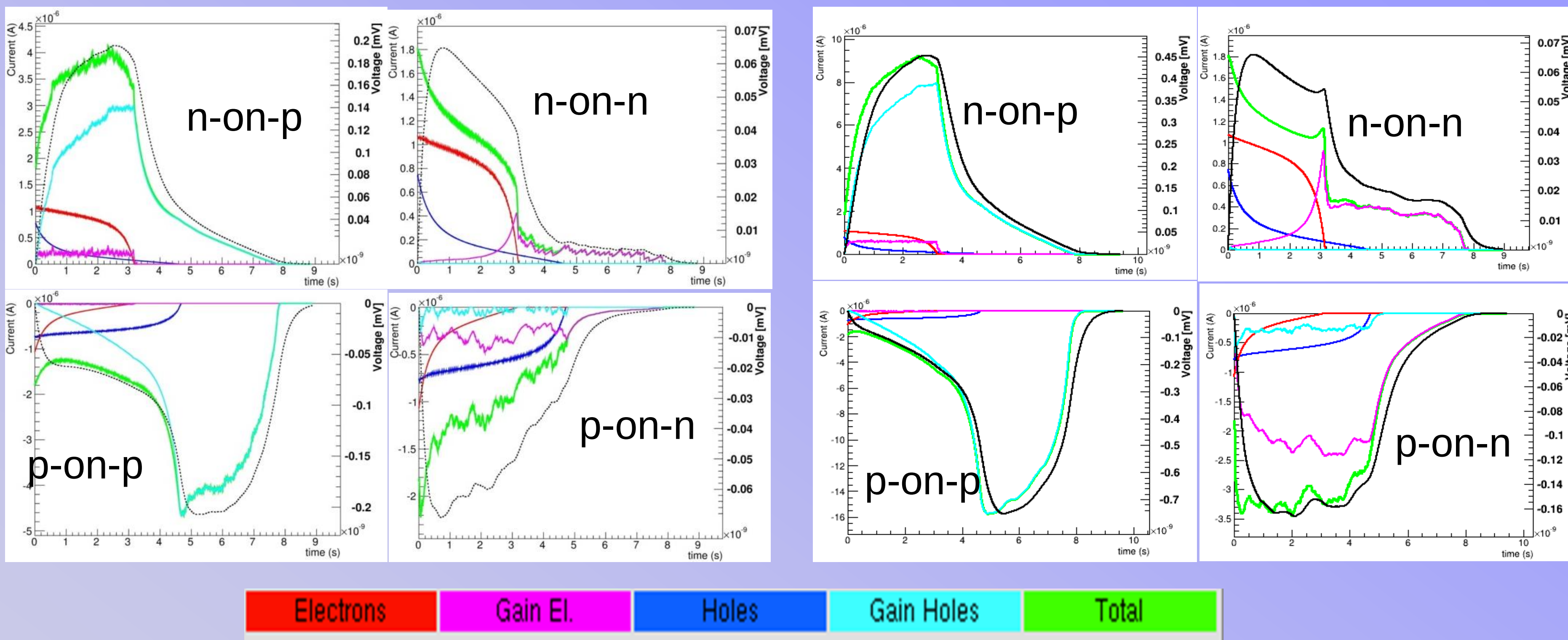
Need to merge it with
2D field simulations.

Thickness
30 µm: bias = 100, 150V, VFD = 20V
50 µm: bias = 200, VFD =30V
300 µm: bias = 1000, VFD = 80V

Investigate the relation between gain and slew rate for timing.

Pulse shapes for MIP in 300 µm LGAD

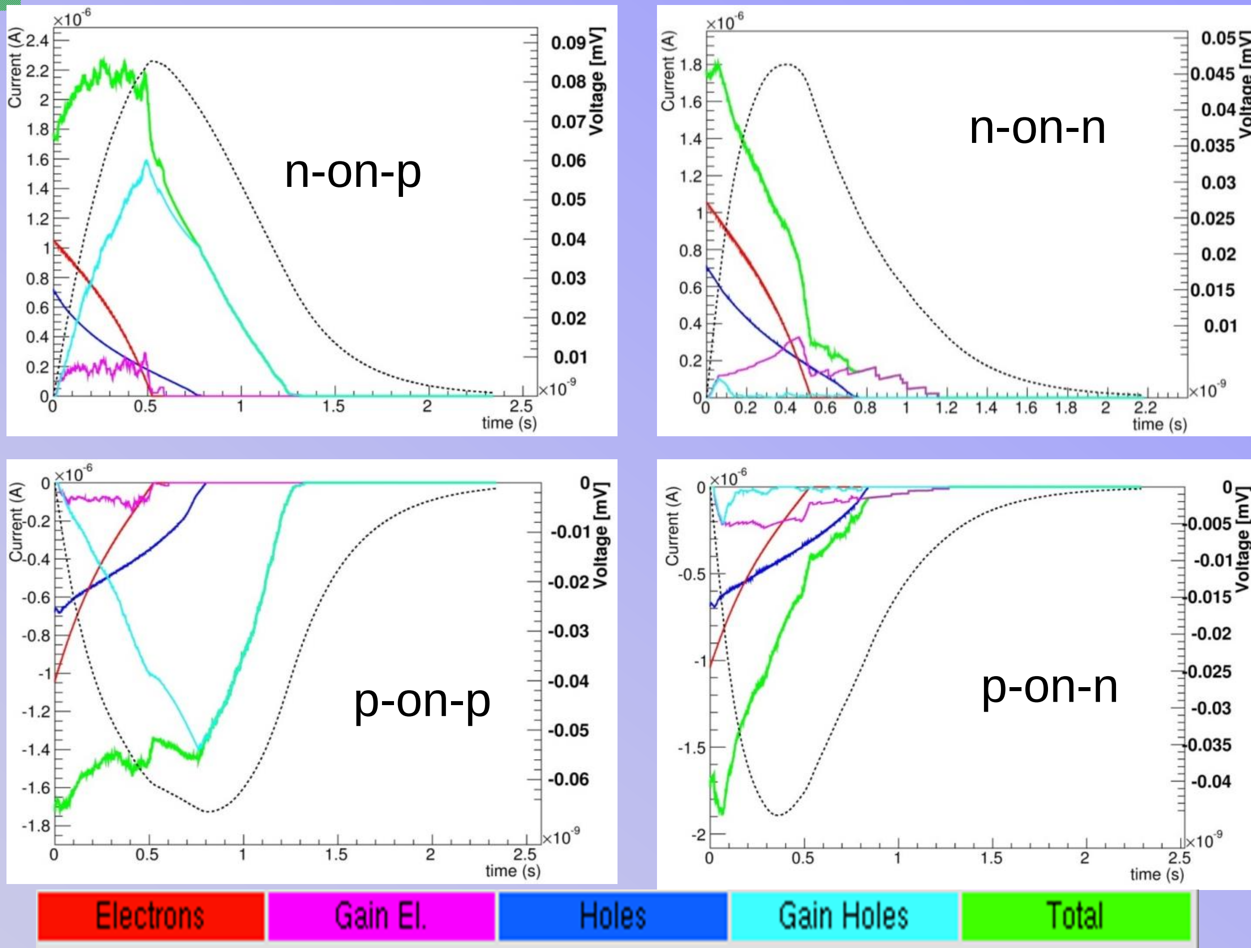
gain = “2” **gain = “3”**



Thick p-type LGAD rely on late hole collection: p-on-p not viable.
Thick n-type LGAD rely on much smaller hole multiplication
(with a fast p-on-n).

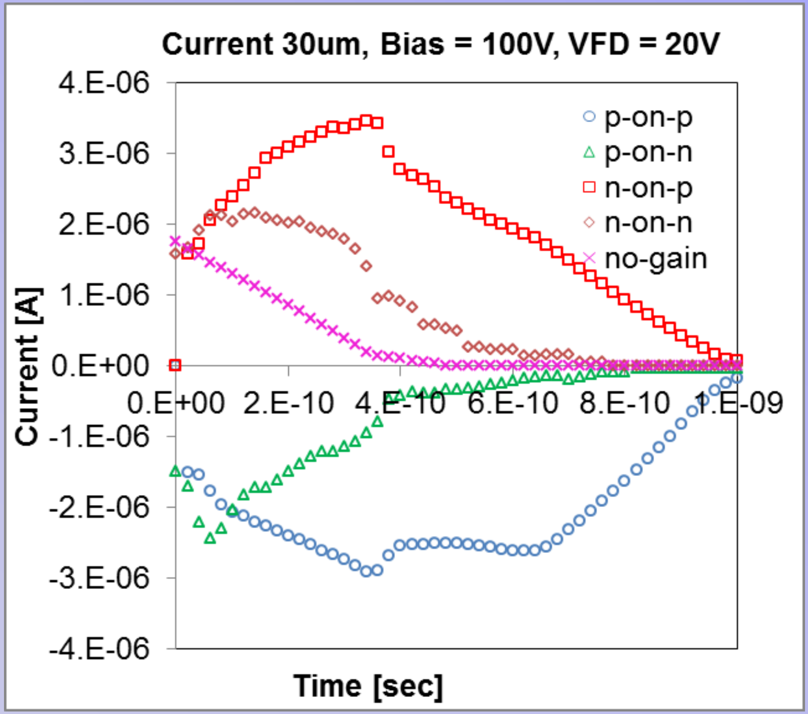
Pulse shapes for MIP in 50 µm LGAD

Bias = 200 V
VFD = 30 V



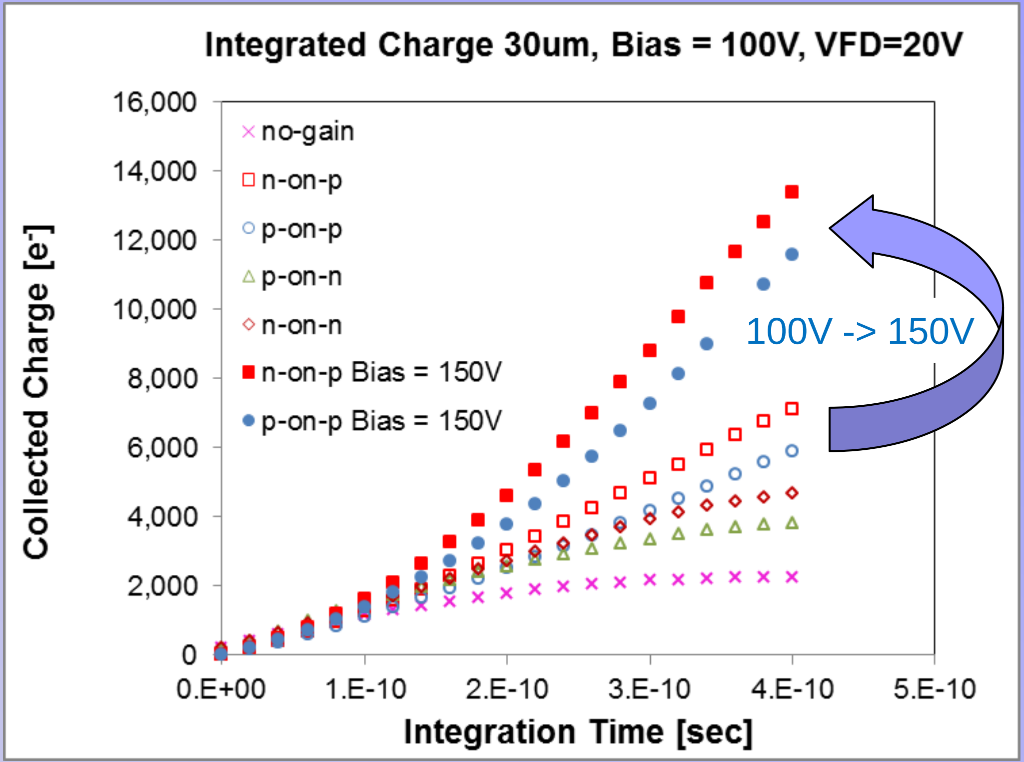
The no-gain pulse (sum of red and dark blue) is very fast.
A thin LGAD needs a fair amount of gain to improve on the fast no-gain pulse!
Thin p-on-p LGAD might be viable, although the holes are more delayed than in n-on-p.

Slew Rate dQ/dt is F.o.M. for Time Resolution



Gain:

Bias:	100V	150V
n-on-n	2.3	
p-on-n	1.9	
p-on-p	5.5	11.5
n-on-p	5.2	10.5



Thin p-on-p LGADs look viable, especially with large gain:

Charge [ke$^-$] within 400ps:

Bias:	100V	150V
p-on-p	5.9	11.6
n-on-p	7.1k	13.4
n-on-n	2.3 (no-gain)	

Conclusions from Run 6827

- Segmented sensors from Run 6827 show very low gain attributable to low doping density of the p-implant layer and the low breakdown voltages.
- The important question how uniform the response is (i.e. how much the gain differs for electrons arriving at different regions of the strip) could therefor not be answered. We need a simulation program to estimate this information using 2D simulations, taking into account the doping profile.
- Scans across the strips of “Spaghetti” diodes implemented in the next run are expected to allow answering this question on a variety of strip geometries.

- To achieve uniformity of response and high bias operation in thin segmented sensors, a spatial separation of the charge collection and the gain mechanism combines two aspects which have proven to work at high bias voltage:

  a) LGAD pads and b) strips on the ohmic side.
- Simulations with ”Weightfield” indicate that for very thin sensors, i.e. very fast charge collection, p-on-p is a viable option.
- Since most of the signal from charge multiplication is late, a large gain (>10) is needed for fast collection in thin sensors.

Acknowledgements

Part of this work has been performed in the framework of the CERN RD-50 collaboration and (partially) financed by the Spanish Ministry of Education and Science through the Particle Physics National Program (FPA2010-22060-C02-02 and FPA2010-22163_C02-02).

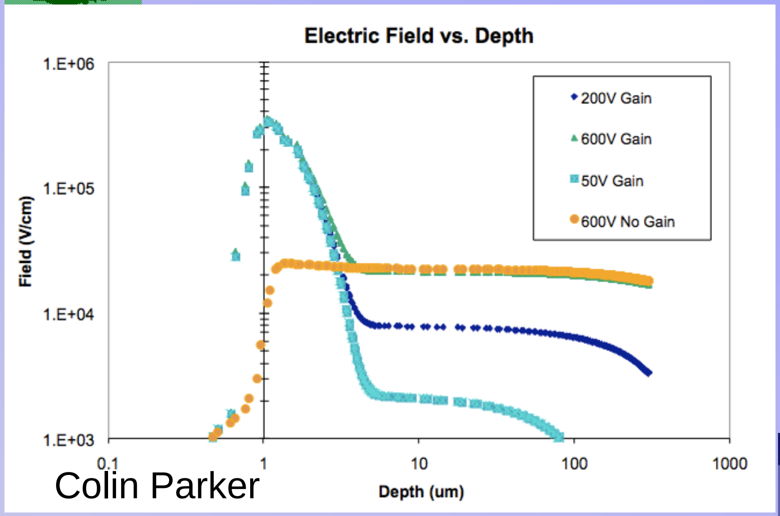
Marta Baselga acknowledges a stipend from the Spanish Ministry of Science and Innovation (FPA2010-22060-C02-02).

This research was carried out with the contribution of the Ministero degli Affari Esteri, “Direzione Generale per la Promozione del Sistema Paese” of Italy.

The work at SCIPP was partially supported by the United States Department of Energy, grant DE-FG02-04ER41286.

Back-up

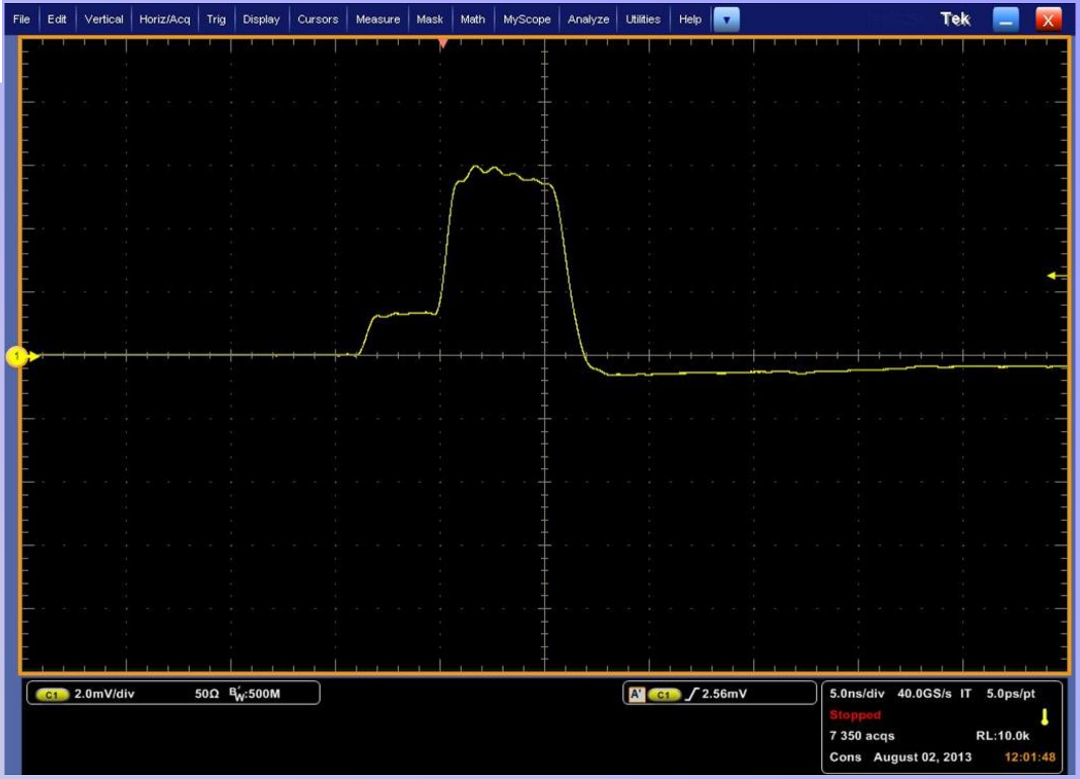
Charge Collection with α's from Am(241)



α's

Am(241)

illuminating the back side, range ~ few um's "electron injection" signal drifts and is then amplified in high field

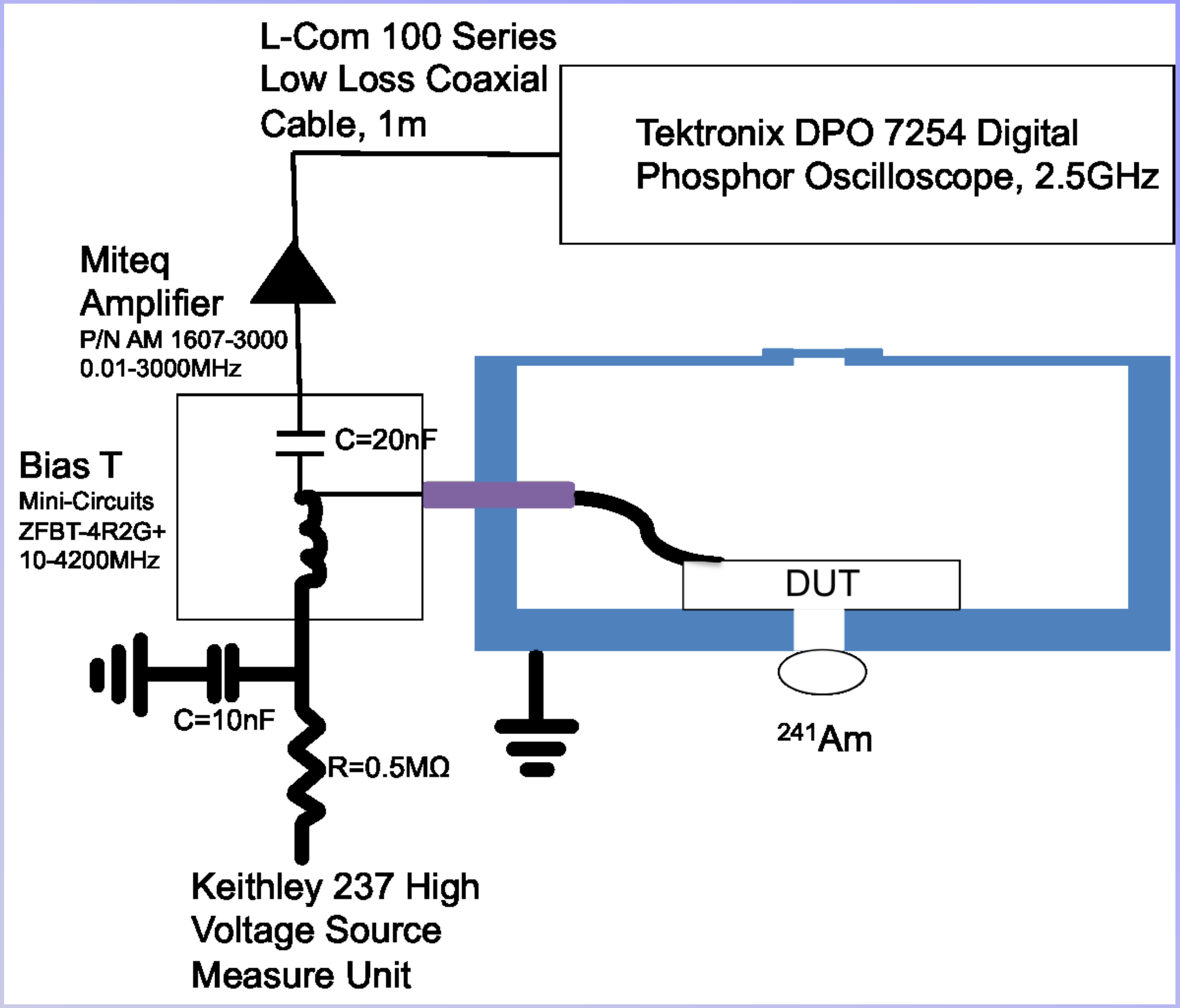


Fast signals!

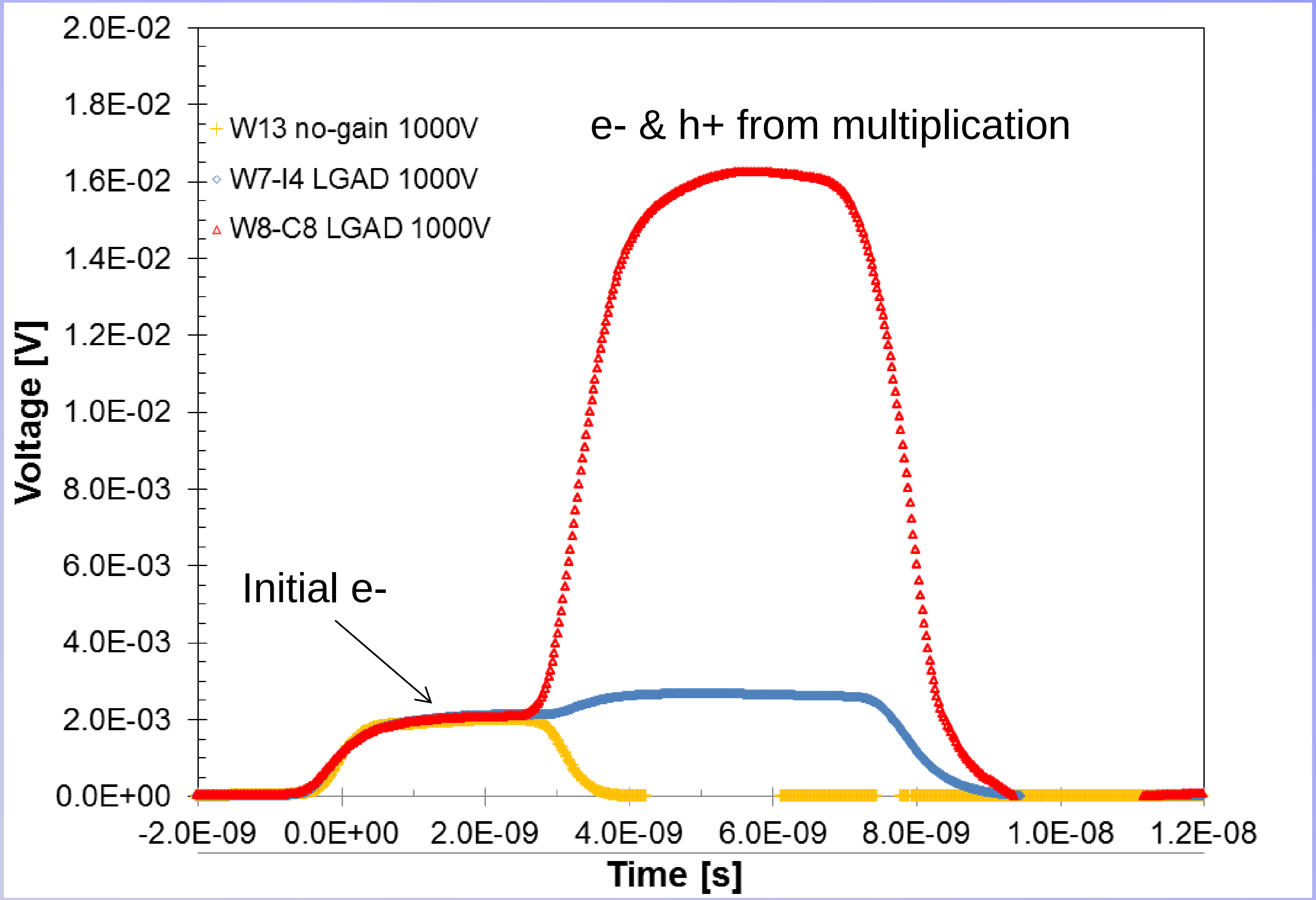
Observed rise times ≈ 400 ps allowing time-resolved current transient (TCT) analysis .

Don't know yet where the lower limit is, since we are still improving the BW of the system.

High BW α TCT Set-up



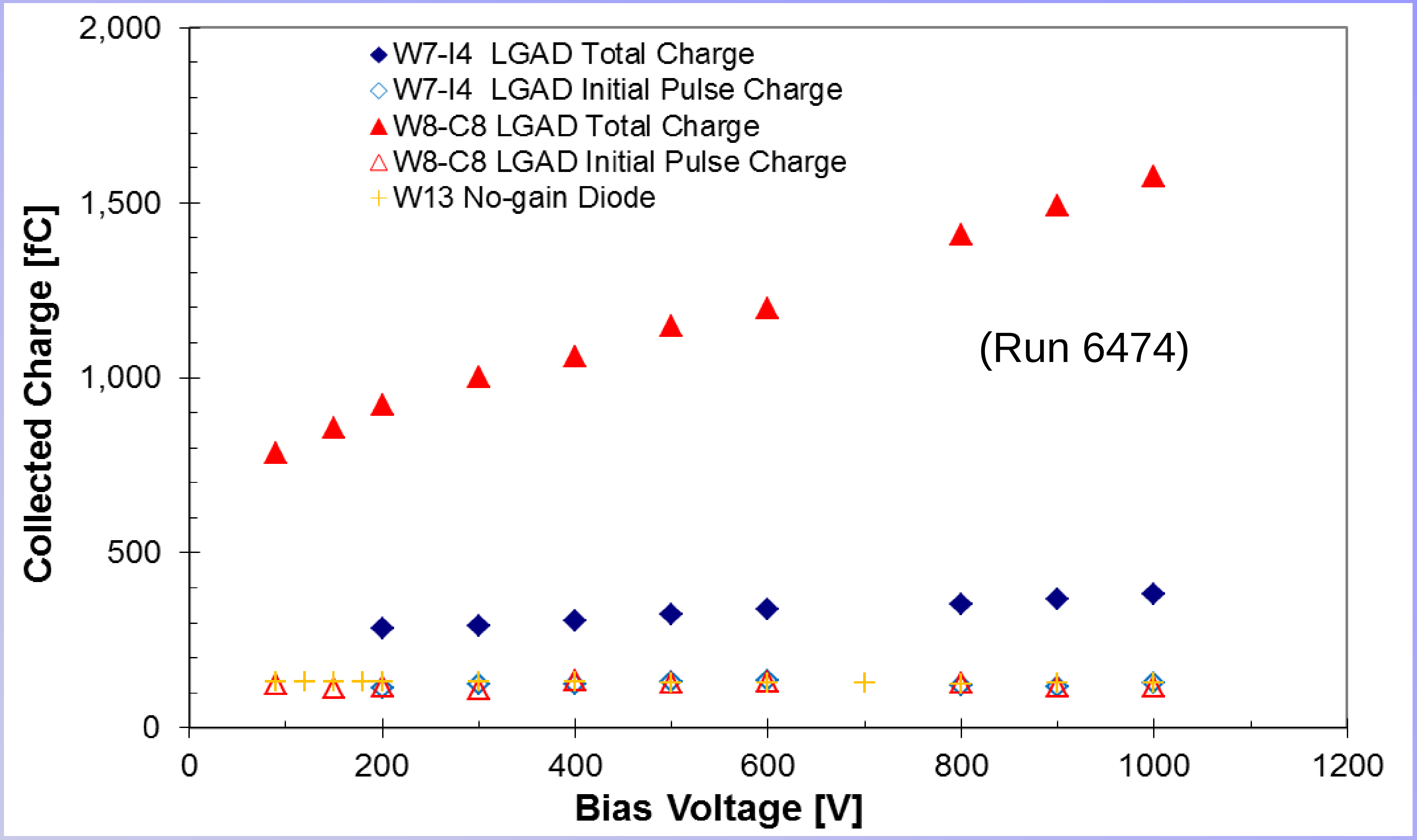
Pulse – shape analysis with α TCT



Gain = Total pulse area / Initial Pulse Area

Charge collection well described by simulations

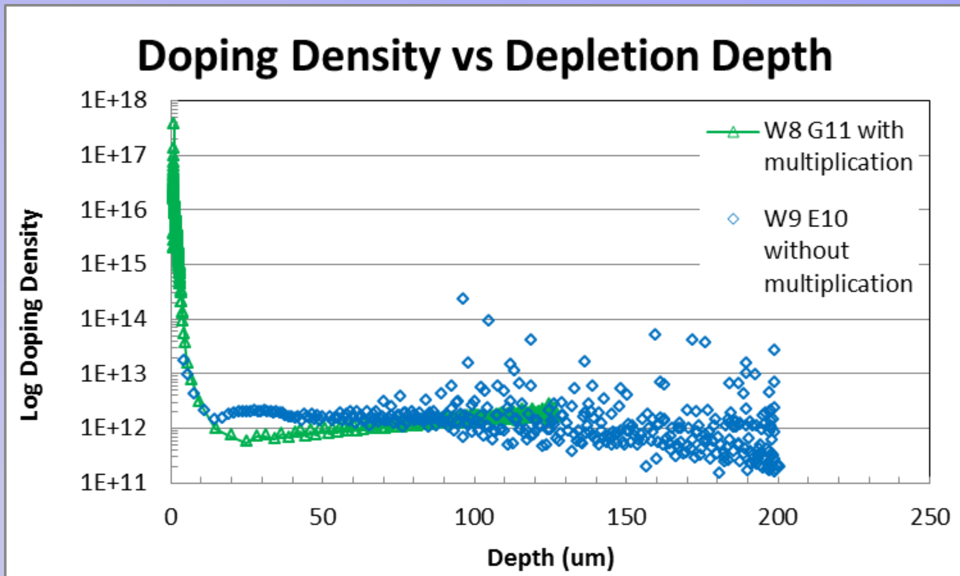
Total charge & initial Pulse charge



The initial pulse charge is identical for two different LGAD's (after correction) and a no-gain diode: Reflects the initial electron drift.

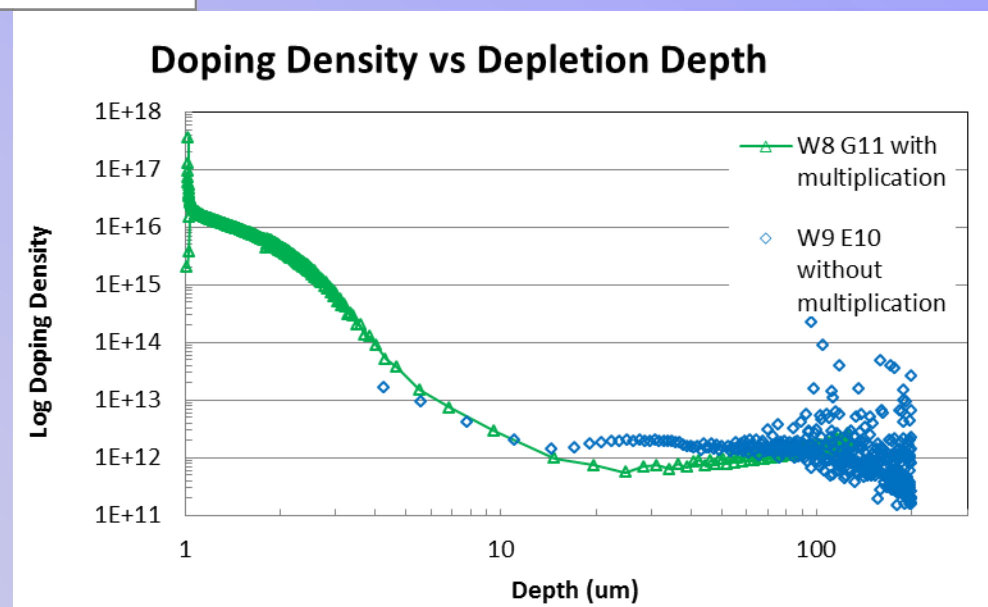
Large gain differences: G(W8-C8)/G(W7-I4) ≈ 4 at 1000V bias.
Original idea: correlation with high leakage current, turns out to be wrong

Doping Density Profile N(x)

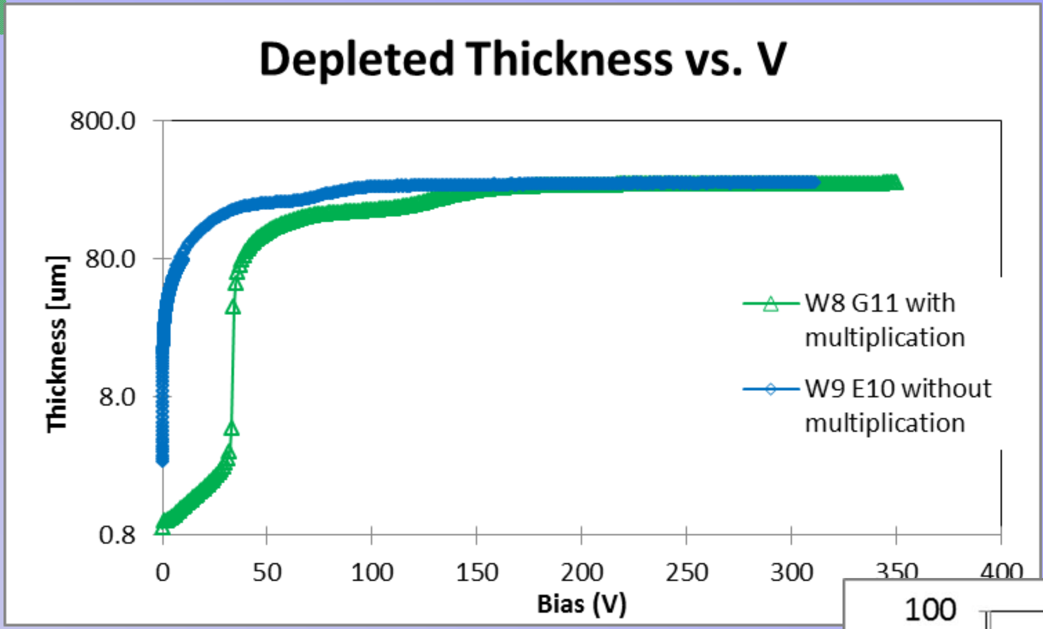


$$N = \frac{2}{\frac{d(1/C^2)}{dV}} \bullet \frac{1}{\varepsilon q A^2}$$

LGAD and no-gain diode have same doping profile far away from gain region!

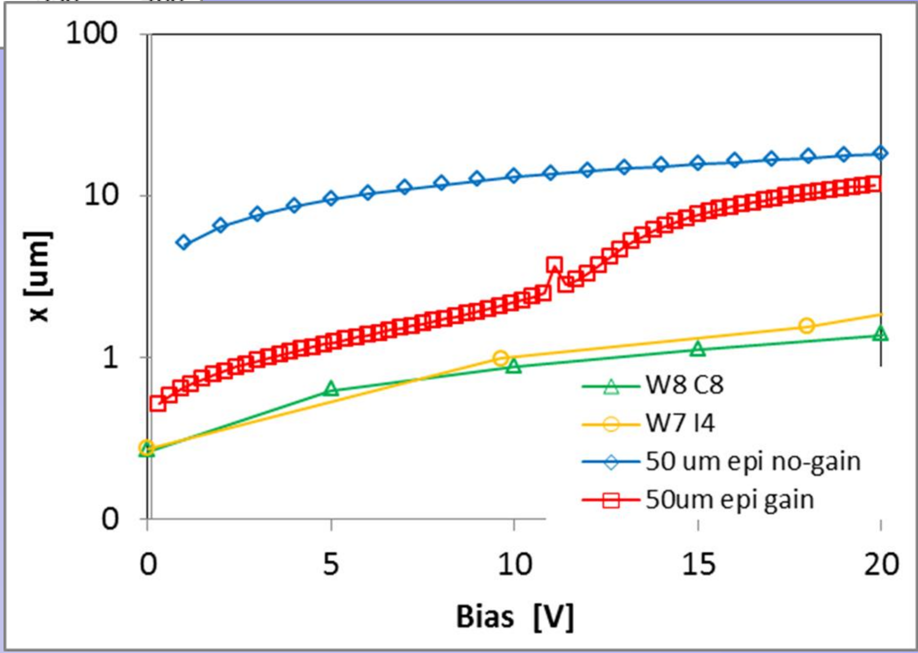


Depleted thickness x vs. V



$$x = A / C$$

Conversion of
capacitance C(V) -> C(x)
doping density N(V) -> N(x)
resistivity ρ(V) -> ρ(x)



- Saturates at x ≈ 250um as expected
- Shows large voltage lag for LGAD

Structure Screenshot