Doping Profile of Low-Gain Avalanche Diodes (LGAD) using C-V

Hartmut F.W. Sadrozinski
with
Scott Ely, Vitaliy Fadeyev, Zachary Galloway, Jeffrey Ngo, Colin Parker,
Davi Schumacher, Abe Seiden, Andriy Zatserklyaniy
SCIPP, Univ. of California Santa Cruz
Marta Baselga, Virginia Greco, Salvador Hidalgo, Giulio Pellegrini
IMB-CNM-CSIC
Nicolo Cartiglia, Francesca Cenna
INFN Torino, Torino, Italy

Parts from 2 Runs of Low-Gain Avalanche Diodes
- Pads 2012 (“ Pablo”): 300 um FZ (W8, W7, W13)
- Pads & Strips 2013 (“Marta”): 50 um epi, 300 um FZ

Charge Multiplication

W. MAES, K. DE MEYER* and R. VAN OVERSTRAETEN
Solid-State Electronics Vol. 33, No. 6, pp. 705-718, 1990

Charge multiplication in path length *ℓ* :

$$N(\ell) = N_0 * \exp(\alpha * \ell) = g * N_0$$

$$\alpha_{e,h}(E) = \alpha_{e,h}(\infty) * \exp\left(- \frac{b_{e,h}}{|E|} \right)$$

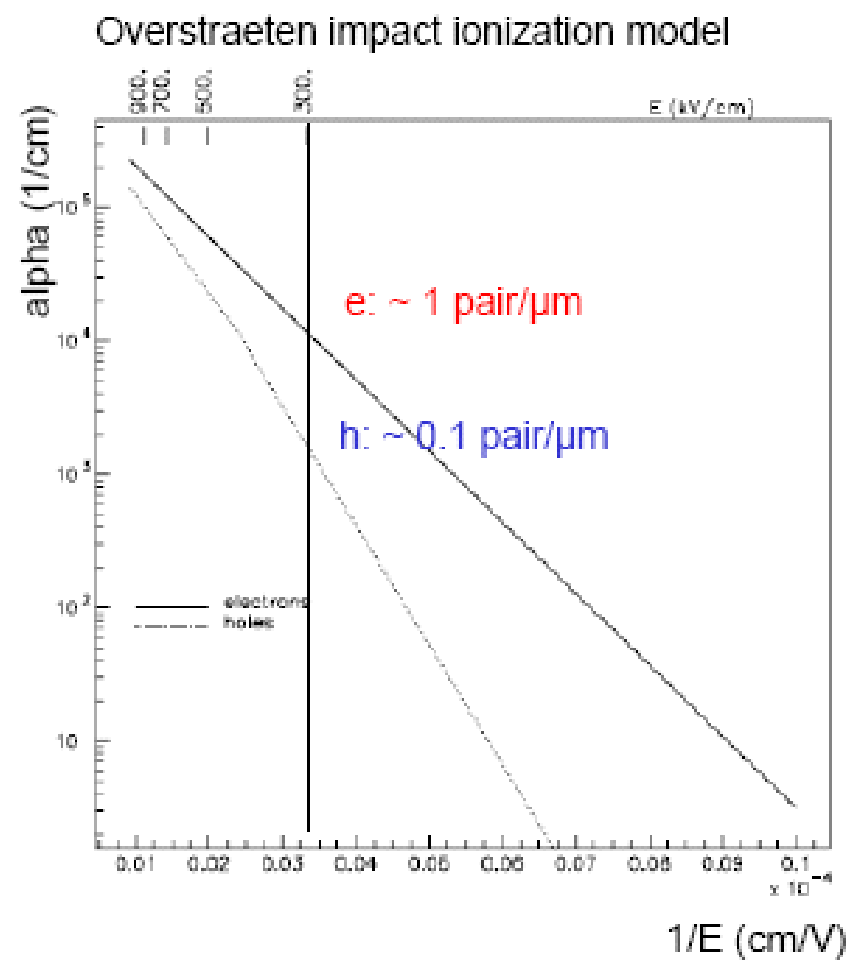
At the breakdown field in Si of 300kV/cm:

$\alpha_e \approx 0.66$ pair/µm

$\alpha_h \approx 0.17$ pair/µm

→ gain g = 27 possible in *l* = 5 µm.

→ In the linear mode (gain ~10), consider electrons only



e: ~ 1 pair/µm

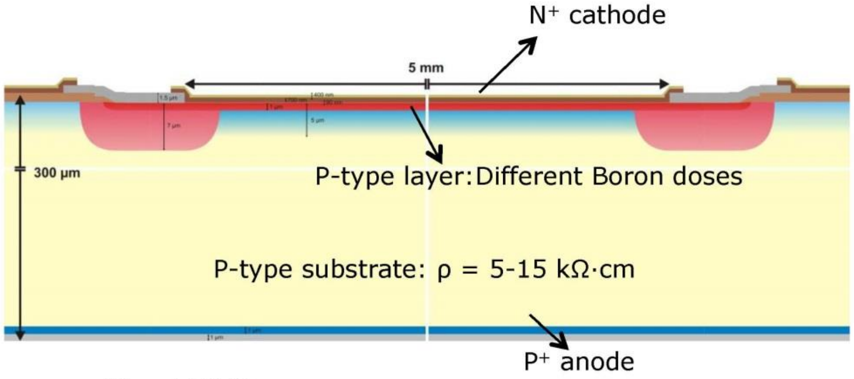
h: ~ 0.1 pair/µm

Need to raise E-field as close to breakdown field as possible for high gain but not too much to prevent breakdown!
Detailed realistic simulation of avalanche required.

Pads detectors with multiplication

Low-Gain Avalanche Detector (LGAD)

Marta Baselga,
Trento Workshop
Feb. 2013



N+ cathode

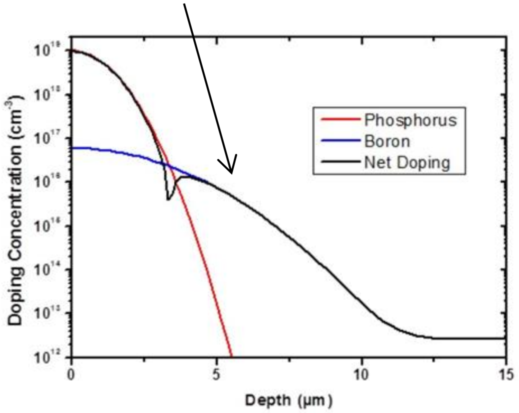
P-type layer: Different Boron doses

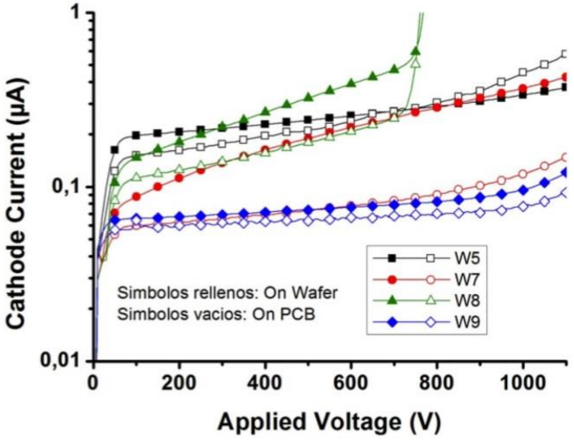
P-type substrate: ρ = 5-15 kΩ·cm

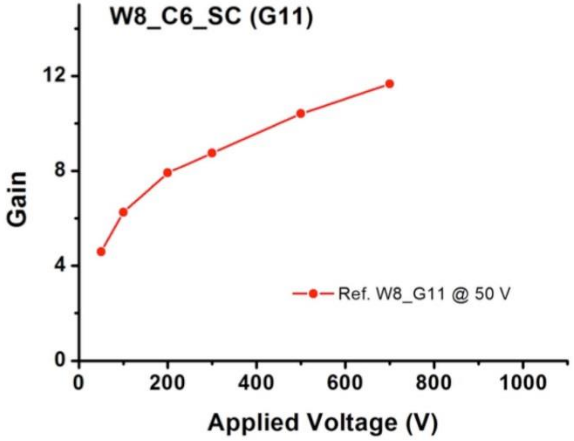
P+ anode

V_{FD} < 30 V
V_{BD} > 1100 V

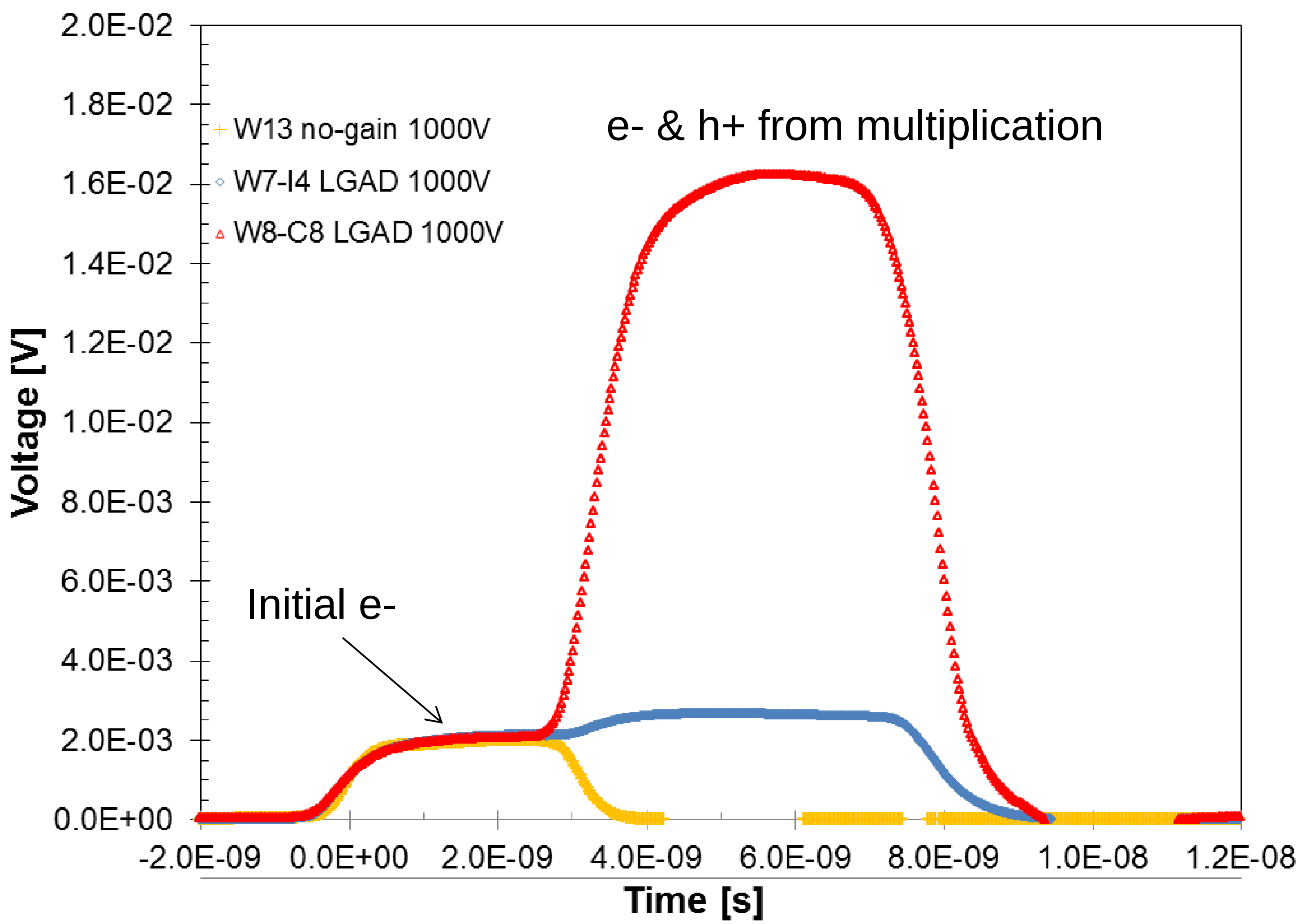
High-Field: Gain







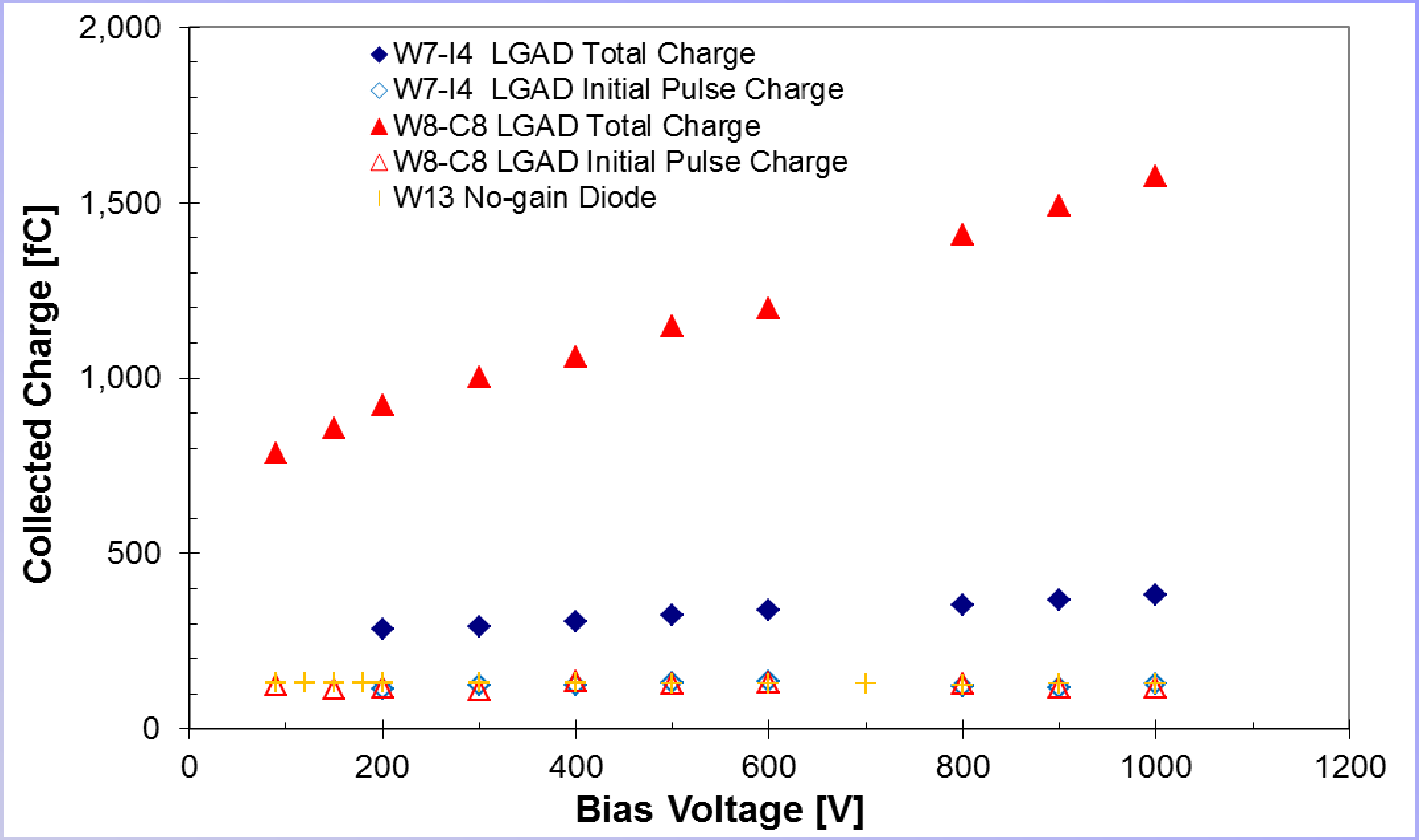
Pulse – shape analysis with α TCT



Gain = Total pulse area / Initial Pulse Area

Charge collection well described by simulations (Francesca's talk)

Total charge & initial Pulse charge



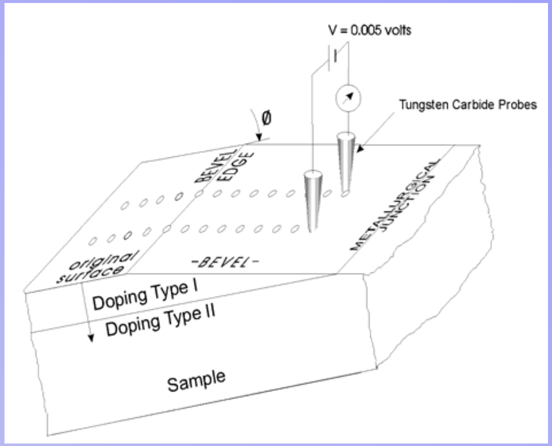
The initial pulse charge is identical for two different LGAD’s (after correction) and a no-gain diode: Reflects the initial electron drift.

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

≥ 6 Methods for Extraction of Doping Profile

C-V

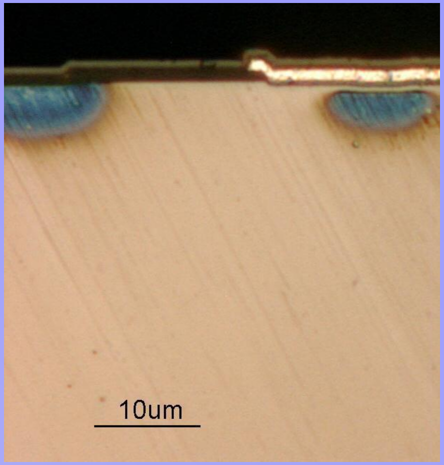
(used here)



SRP

Spreading Resistance Profiling

N. Dinu, Sept 2013 PPS



Micro-section + Etch

Salvador Hidalgo, 22nd RD50

see Marta’s talk

SIM

Secondary Ion Mass Spectroscopy

XPS (ESCA)

X-ray photoelectron spectroscopy

Question: applicable for our range : $N = 10^{12} - 10^{17}\ \mathrm{cm}^{-3}$?

6th Method to extract N(x) of LGAD

Terahertz Imaging

"Terahertz imaging of silicon wafers"

M. Herrmann at al, JAP 91,3, 1 (2002)

2 J. Appl. Phys., Vol. 91, No. 3, 1 February 2002

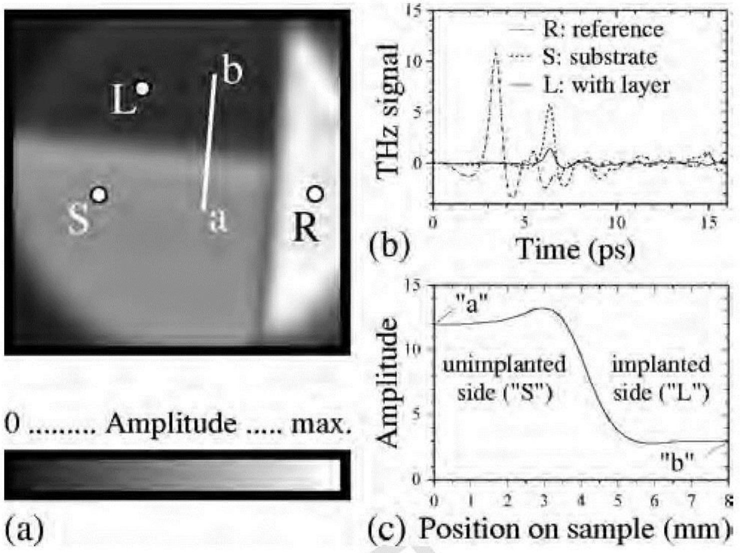


FIG. 1. (a) THz image of a Si sample with a 5×10^{15} cm^{-2} implanted layer: reference region (R, no sample), substrate region (S, not implanted) and layer region (L, implanted and strongly absorbing). The image size is 20 mm×20 mm. The dark areas in the edges are shadows from the sample holder. (b) THz time-domain wave forms taken in the regions R, S, and L. (c) Pulse maxima along the line $a-b$ in (a) (from a separate measurement). There are refraction effects resulting in a maximum and a minimum at the border between the implanted and unimplanted regions.

Exploits relationship between permittivity and refractive index:

$$\varepsilon(\omega) = (n+ik)^2$$

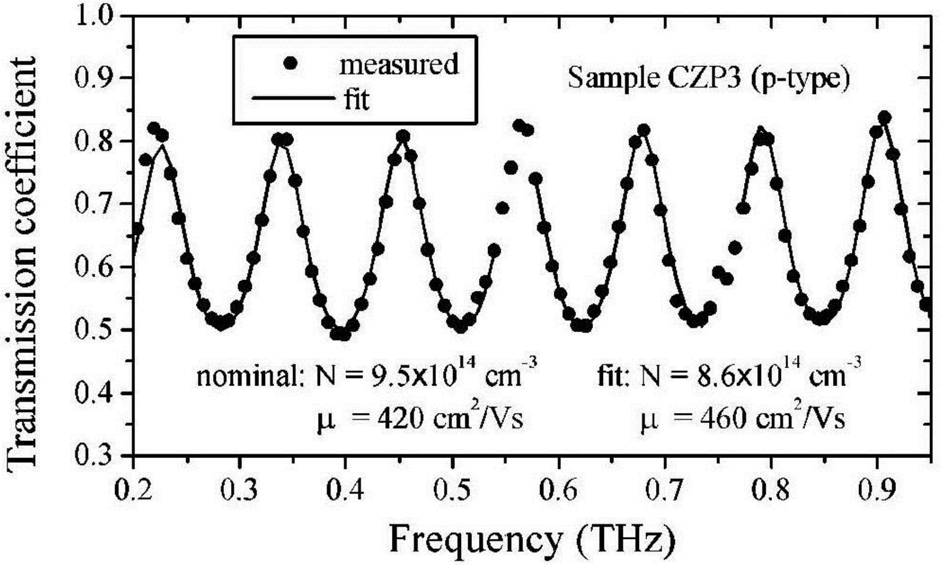


FIG. 2. Transmission spectrum of a p-type Si sample, and its best fit.

Like C-V, potentially not invasive?
Contact with Frauenhofer Institute

Deriving the Doping Profile from C-V

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

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

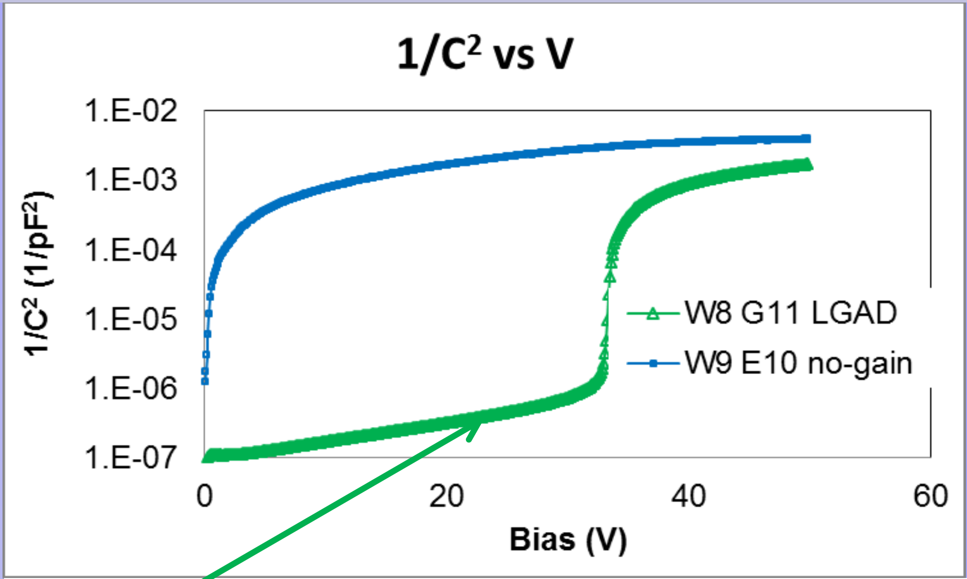
Resistivity ρ – Doping density N : $$\rho = \frac{1}{q\mu N}$$

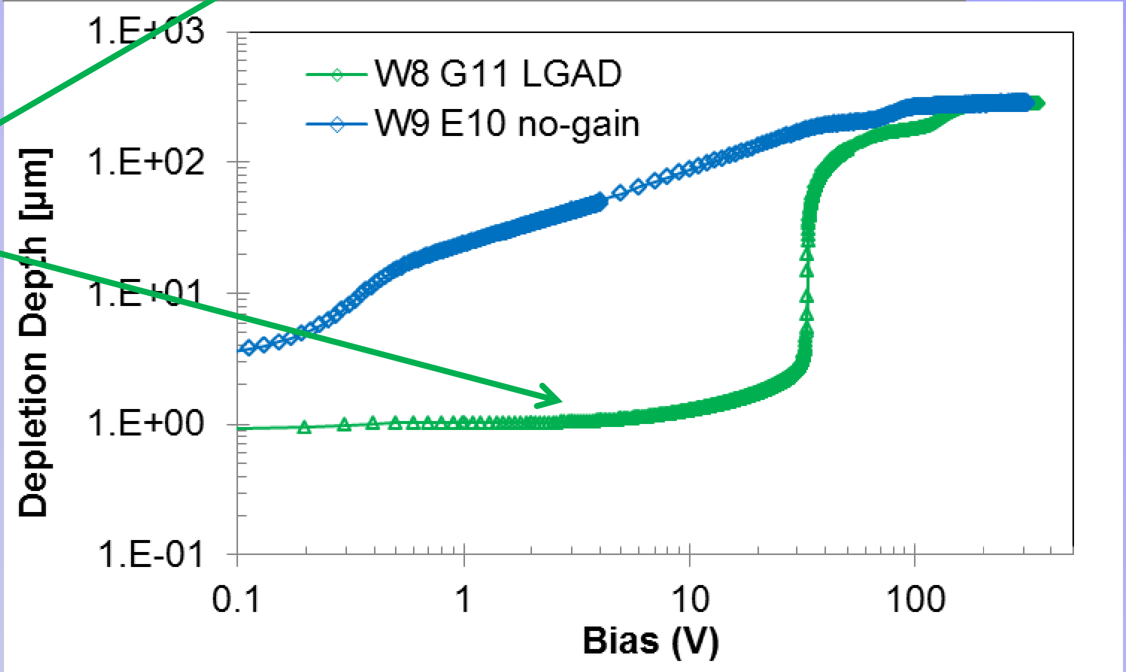
Capacitance C – Depl. Region x : $$C(x) = \varepsilon\varepsilon_0 \frac{A}{x} = A\sqrt{\frac{\varepsilon\varepsilon_0 qN}{2V}}, \Rightarrow x = A/C$$

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

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

Example on pads
W8G11: LGAD
W9E10 no gain

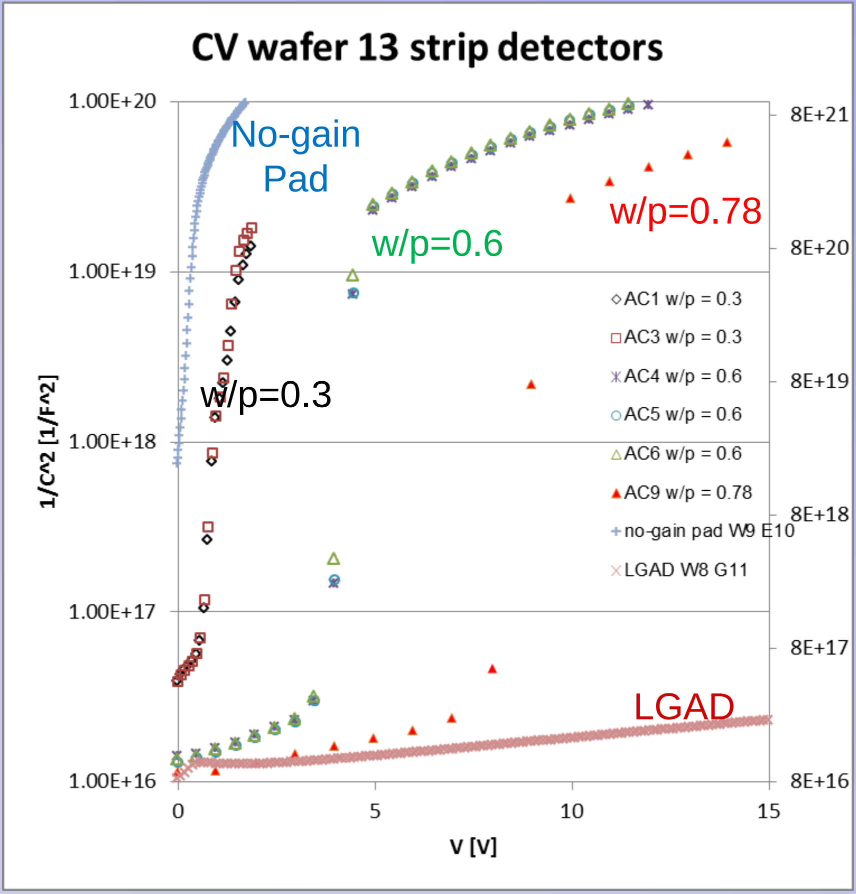




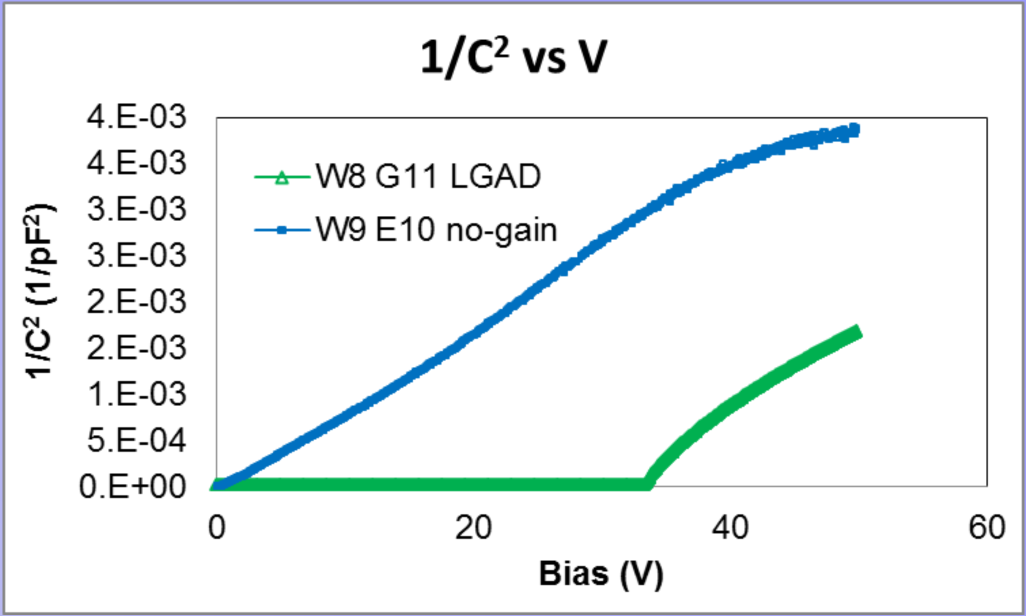
Important:
Take voltage steps
of 0.1V below 50 V
(below the **“foot” / “lag”**).

Large voltage "Lag" due to strip geometry

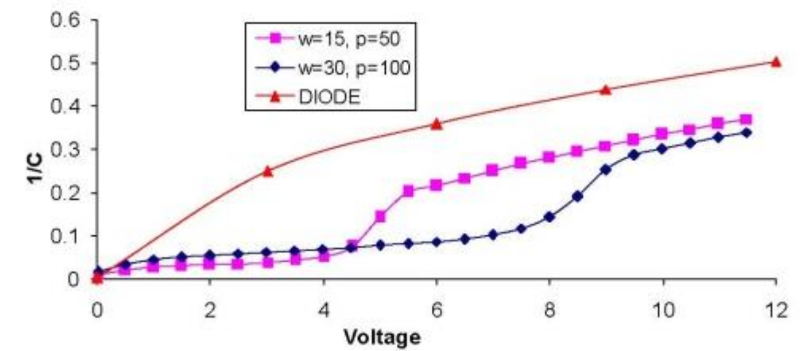
Careful: "foot" indicates gain only with pads!
FZ strips gain?/no-gain?



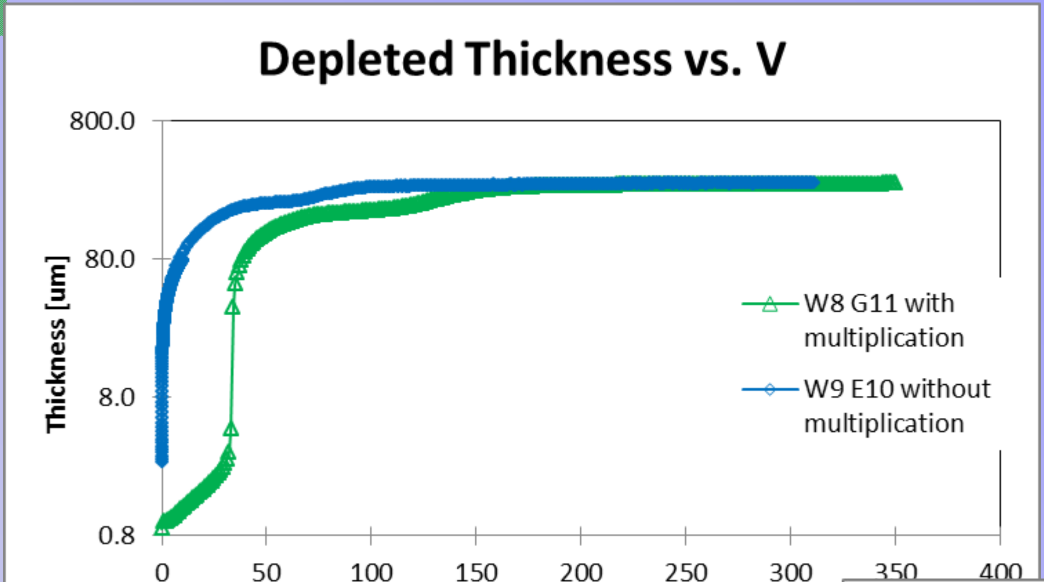
Example of "Foot" on pads



Lateral depletion in no-gain SMART FZ strips (Chris Betancourt M.S. Thesis)

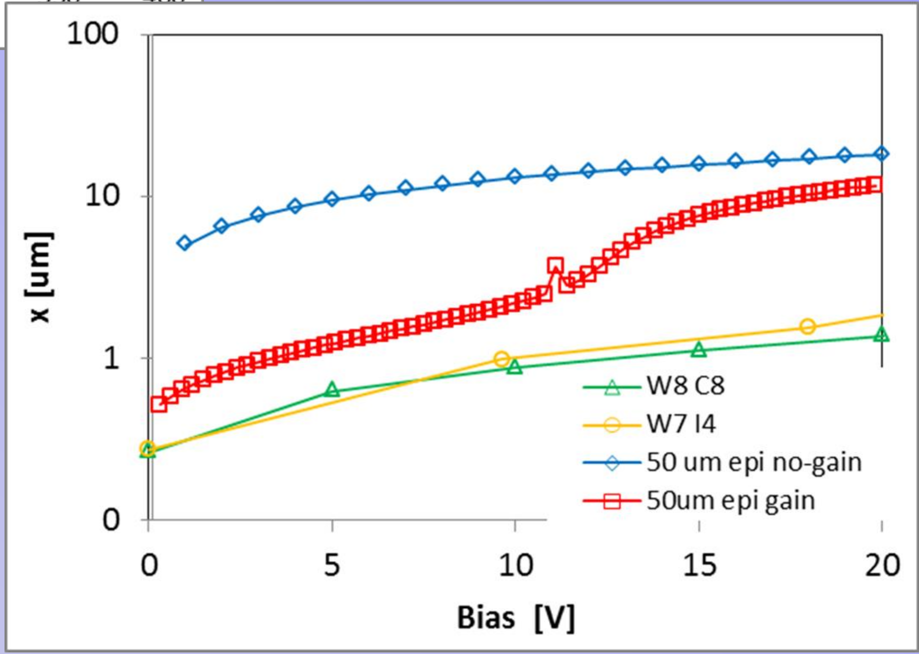


Depleted thickness x vs. V



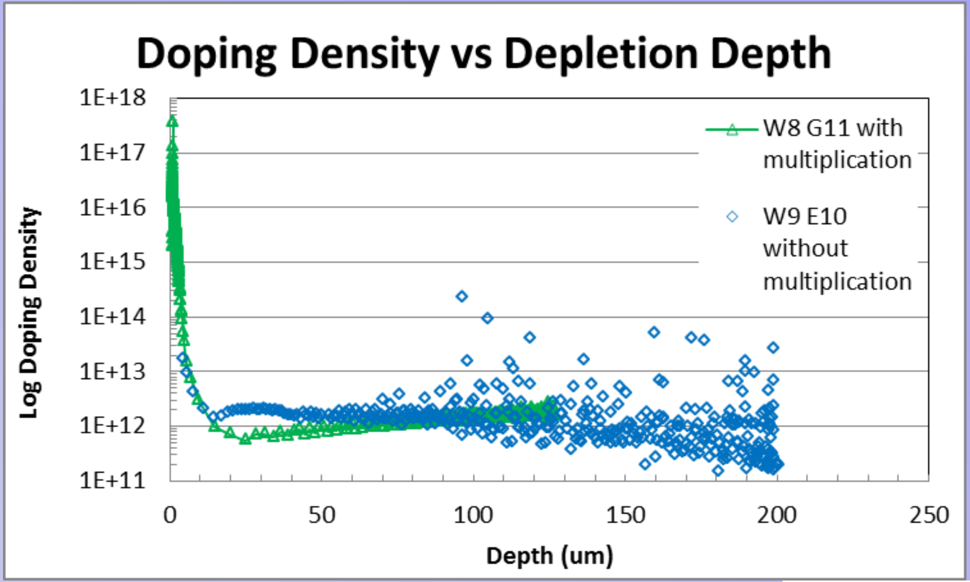
$$x = A / C$$

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

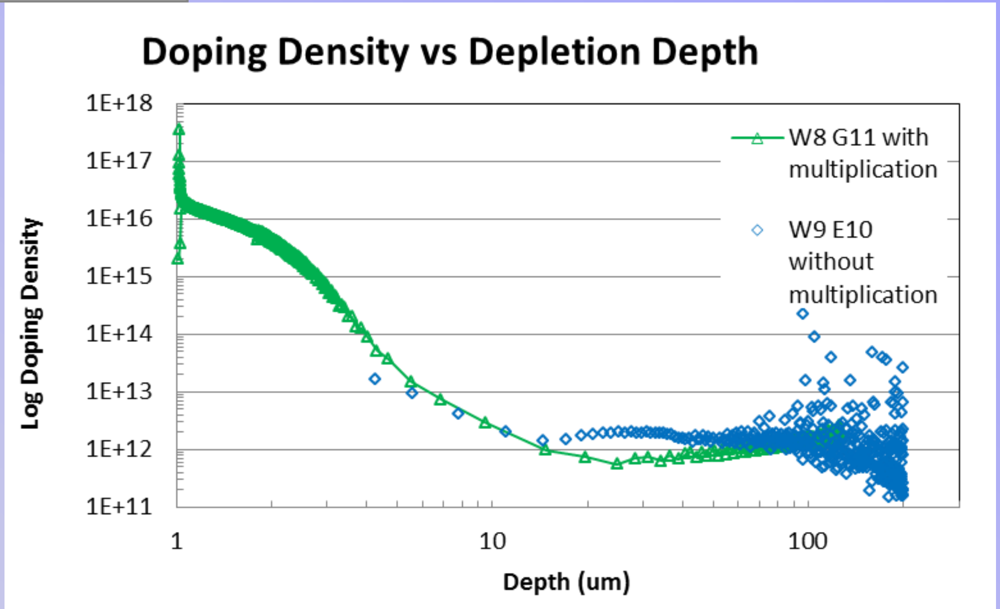


- Saturates at x ≈ 250um as expected
- Shows large voltage lag for LGAD

Doping Density Profile N(x)

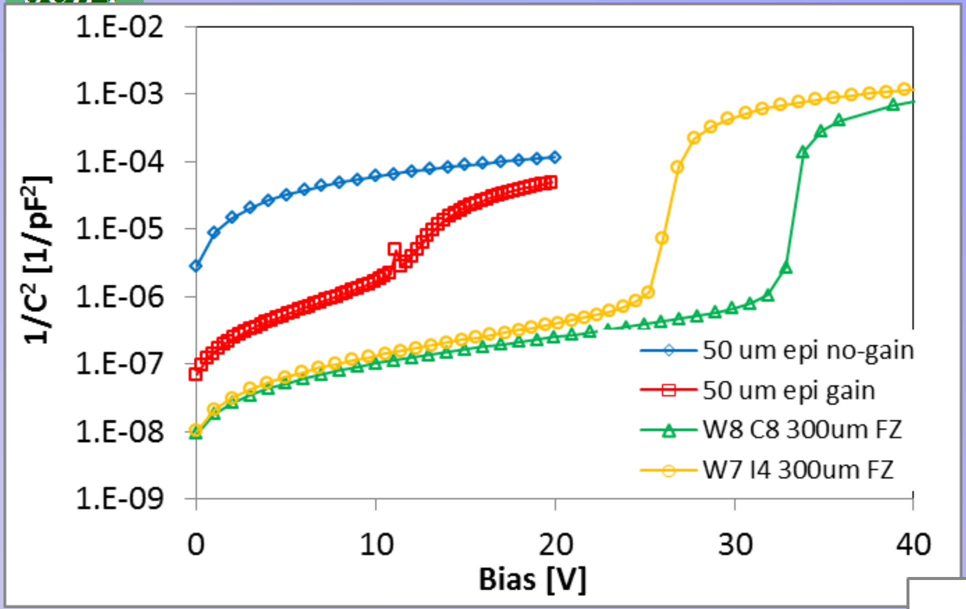


$$N = \frac{2}{\frac{d(1/C^2)}{dV}} \bullet \frac{1}{\varepsilon q A^2}$$



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

Voltage Lag (“Foot”) in $1/C^2$ vs V



lag of depletion in gain diodes:

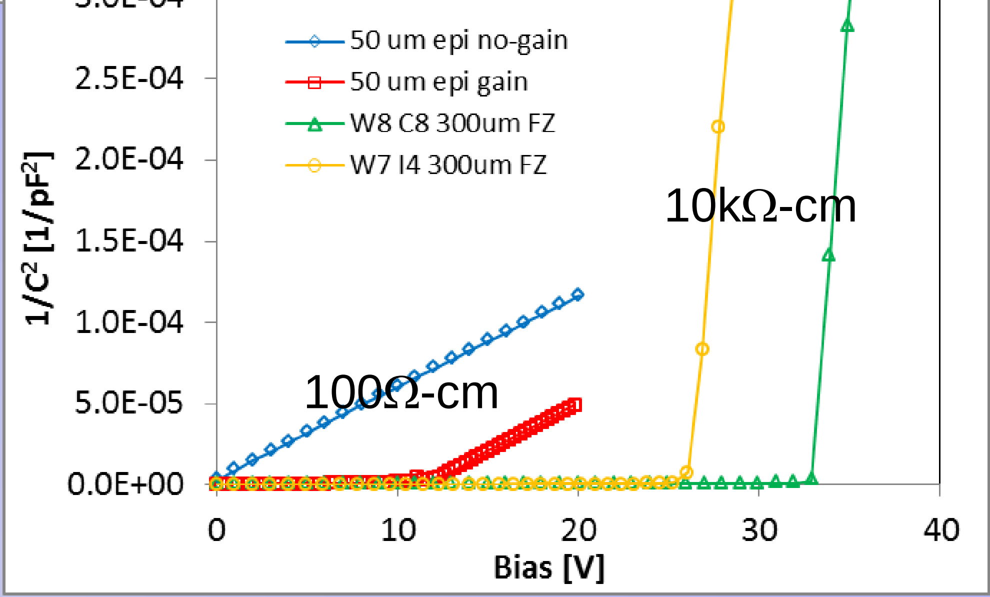
W8 C8 : 33V,

W7 I4 : 26V,

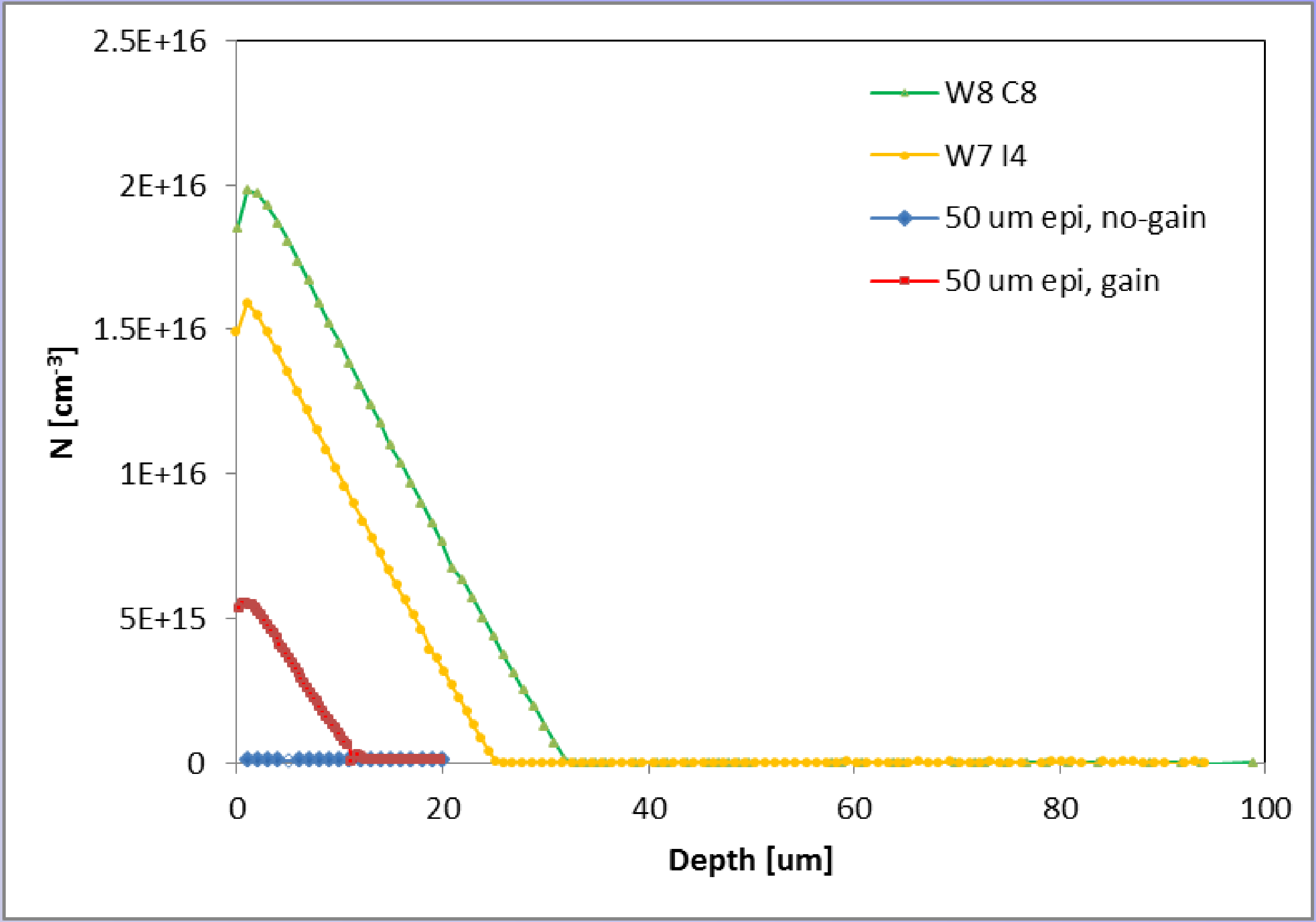
(W13, W9 : < 1V)

50um epi (gain): 12V

50um epi (no-gain): < 1V



Estimate of Doping Density Profile



Nmax :

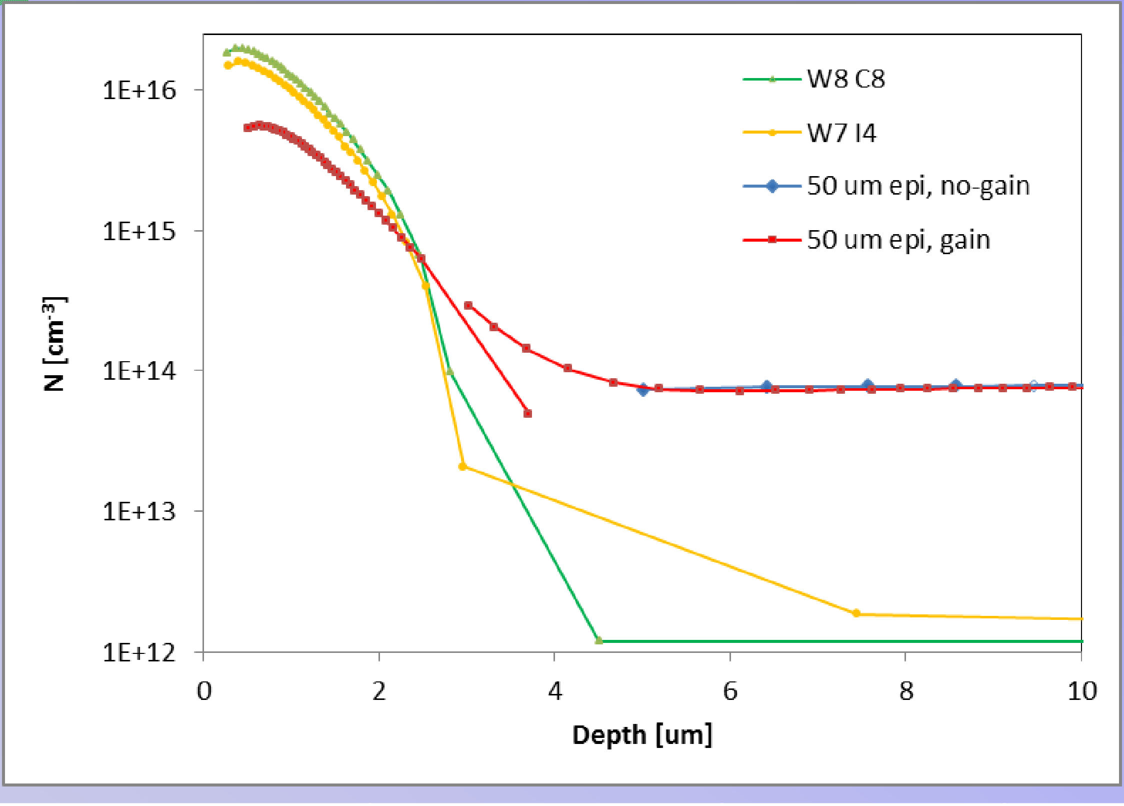
W8 C8 : 2.0e16

W7 I4: 1.6e16

50um epi (gain): 0.6e16

50um epi (no-gain): 7e13

Doping Density Profile



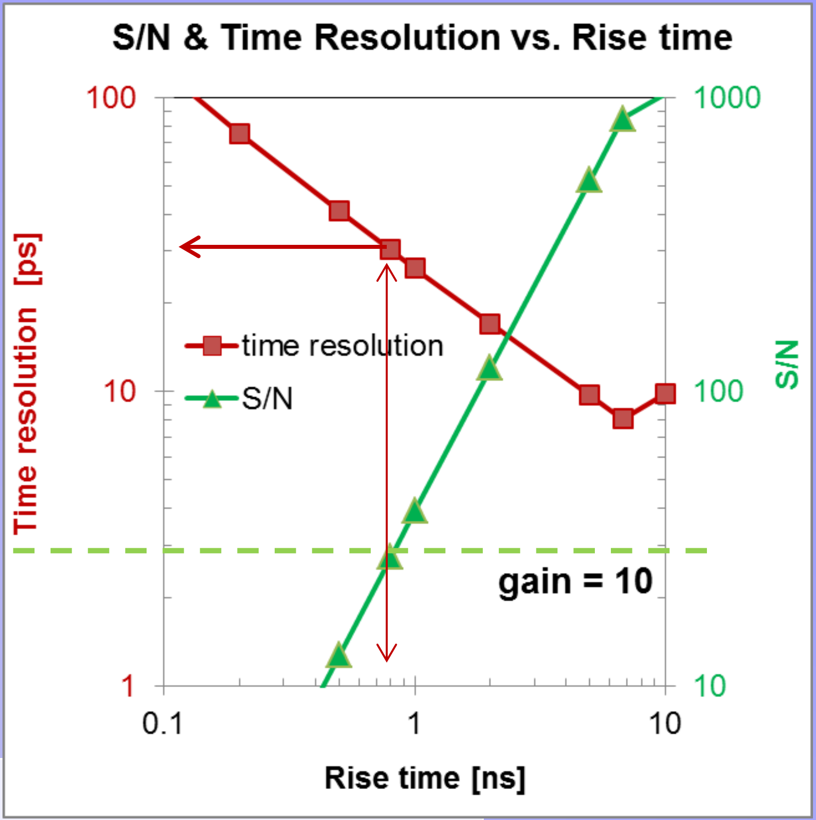
Device	Voltage Lag [V]	N_{max} [cm^{-3}]	N_{Bulk} [cm^{-3}]	Gain (400V)
W8 C8 FZ	35	2.0e16	1.6e12	8
W7 i4 FZ	29	1.6e16	1.6e12	2.5
50um epi (gain)	14	0.6e16	7e13	~ 1
50um epi (no-gain)	< 1	7e13	7e13	~ 1

Rise Time, Thickness, S/N, Time Resolution

$$\sigma_t(CFD) = \tau_R \frac{1}{\left(S/_N\right)} \left[1 + \left(CFD \cdot 10 \frac{\Delta S}{S} \right)^2 \right]^{1/2}$$

Rise rime ≈ Collection time
(~Thickness)

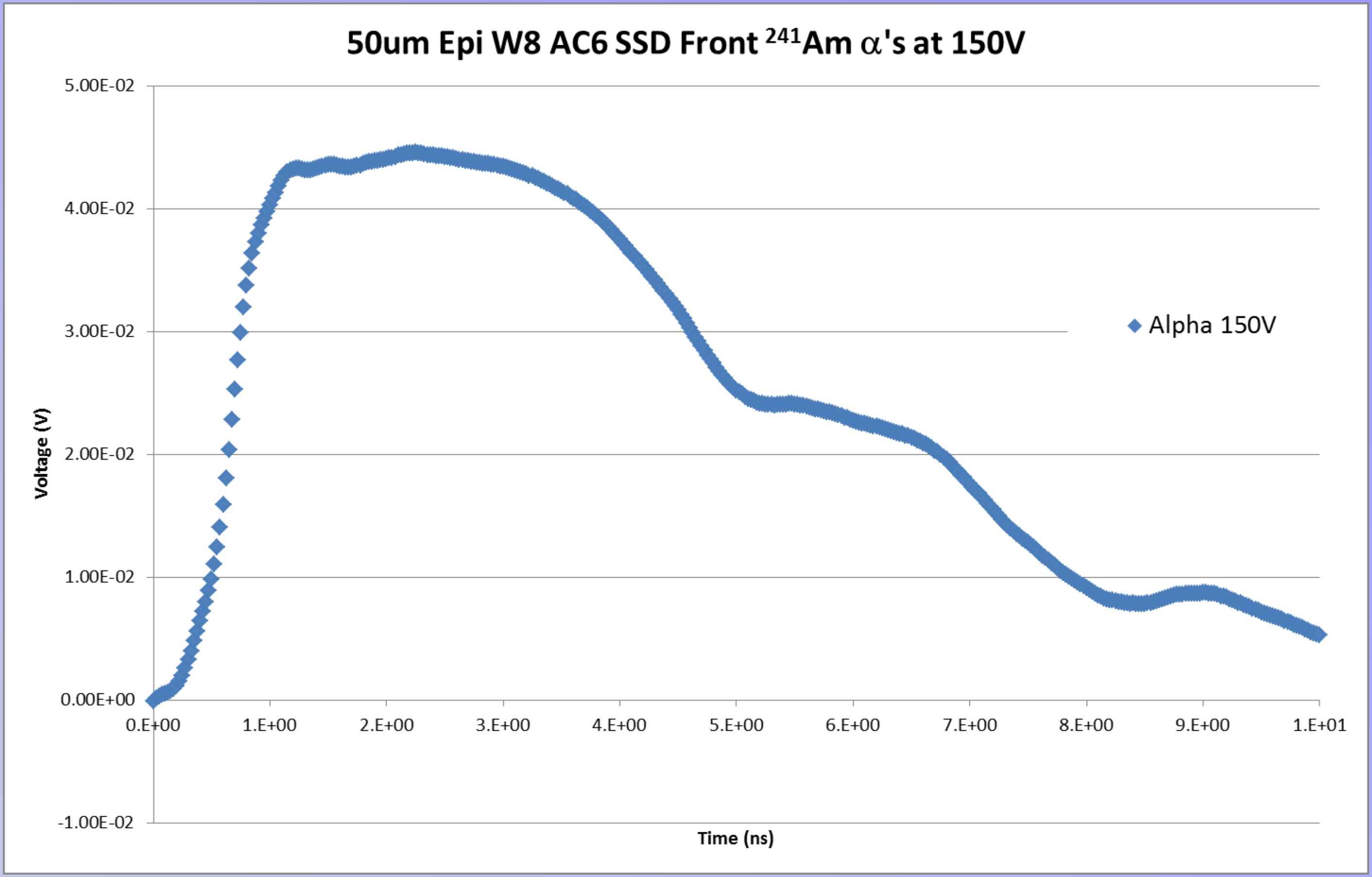
Need S/N >30



Gain G	τ_R [ps]	Thickness [μm]	Time resolution [ps]			
			no CDF	CFD=1/10	CFD=1/5	CFD=1/3
1	3000	130	282	132	139	154
10	800	36	85	30	33	40
100	200	9	29	7.5	9.0	11.6

(like ~50um thick sensors..but see Nicolo's talk)

Front-side α TCT on 50um epi strip sensors



Limited by early breakdown at ½ of VFD = 270 V (100Ω-cm!)
Need high resistivity bulk and high breakdown voltage on thin sensors

Excess Noise in Sensors with Gain

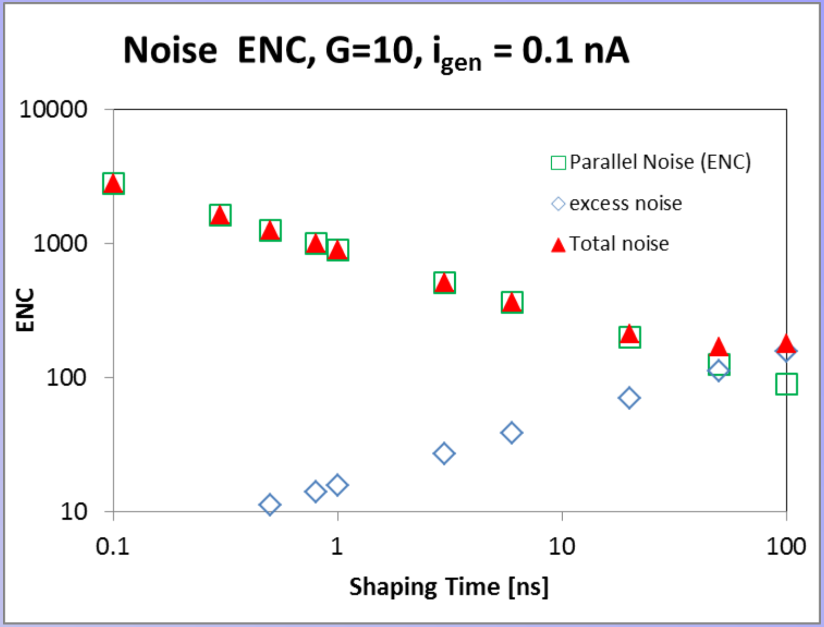
Charge multiplication in silicon sensors allows increasing the signal-to-noise ratio S/N as long as the excess noise due to the multiplication process is small.

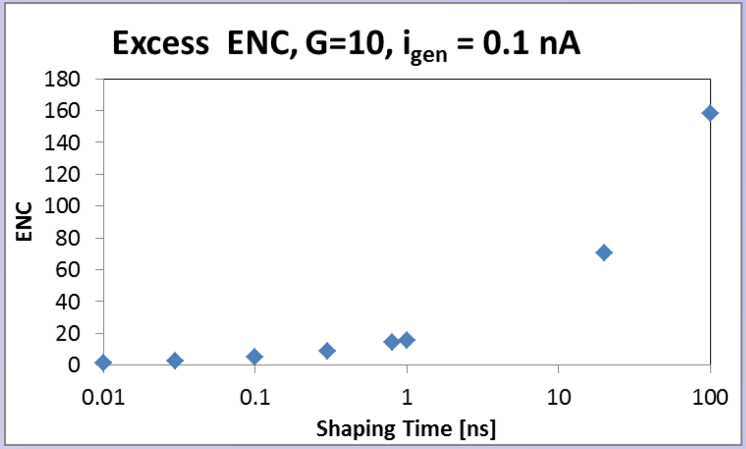
ENC=$\sqrt{2 \cdot e \cdot i_{gen} \cdot \tau} \cdot \sqrt{F} \cdot G$ (M. Mikuz, HSTD9, Sept. 2013)

F(G=1) =1, F(G>>1) =2 (R. J. McIntyre, IEEE TED13(1966)164)

For LGAD:
Current i_{gen} = 10 µA/cm^2
-> current per pixel i=1nA , i_{gen}=0.1nA
Gain = 10, F=2

-> excess Noise at τ=800 ps: 14 e$^-$
-> extcess Noise at τ= 20 ns : 70 e$^-$





Conclusions

- Extraction of doping density value for the bulk agrees with expected value for both FZ and epi.
- Comparing values for the doping density N of the gain region of LGAD's shows the sensitivity of the gain:

  Factor 3 in gain for 20% difference in N!
- "Marta's" gain diodes have ~30% of N of the "Pablo's" diodes:

  ⇨ Marta
- Have a run with higher doping density and higher resistivity bulk ⇨ Virginia
- Simulations describe observed pulse shapes reliably

  ⇨ Francesca
- Simulation of time resolution including e-h statistics in thin sensors ⇨ Nicolo
- Always worry about radiation damage ⇨ Gregor

Pulse shapes on LGAD using α's and lasers

Hartmut Sadrozinski, Vitaliy Fadeyev, Abe Seiden,, Zac Galloway, Jeff Ngo

SCIPP, UC Santa Cruz

Nicolo Cartiglia, Francesca Cenna

INFN Torino

Marta Baselga

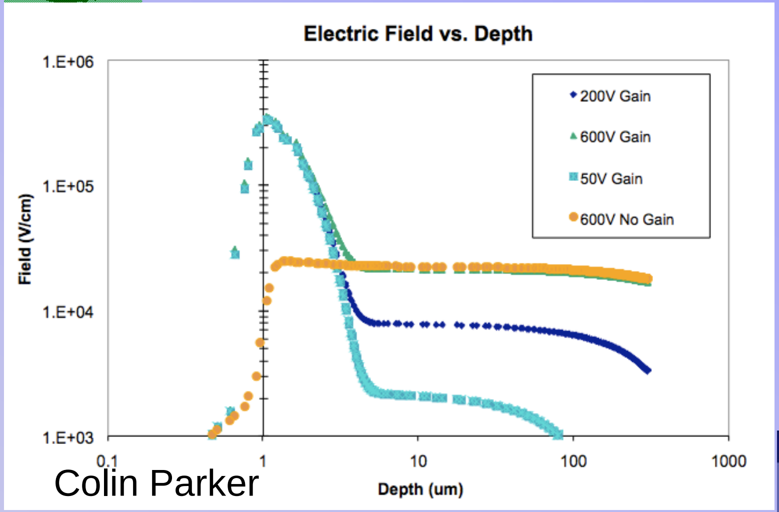
CNM Barcelona

α's : 5.5 MeV Am(241) (we detect about ½ of that)

"ps" Laser 850 and 1064

Both front and back illumination

Charge Collection with α's from Am(241)



Colin Parker

α's

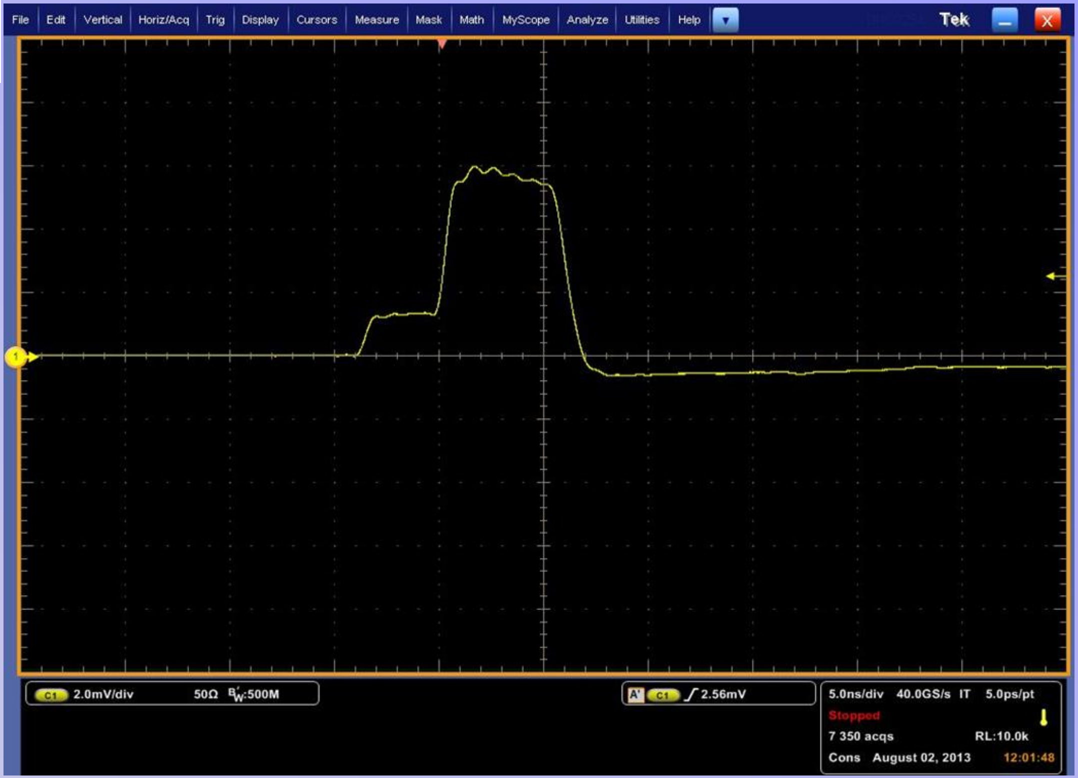
Am(241)

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.



C1 2.0mV/div 50Ω BW:500M

A' C1 ∫ 2.56mV

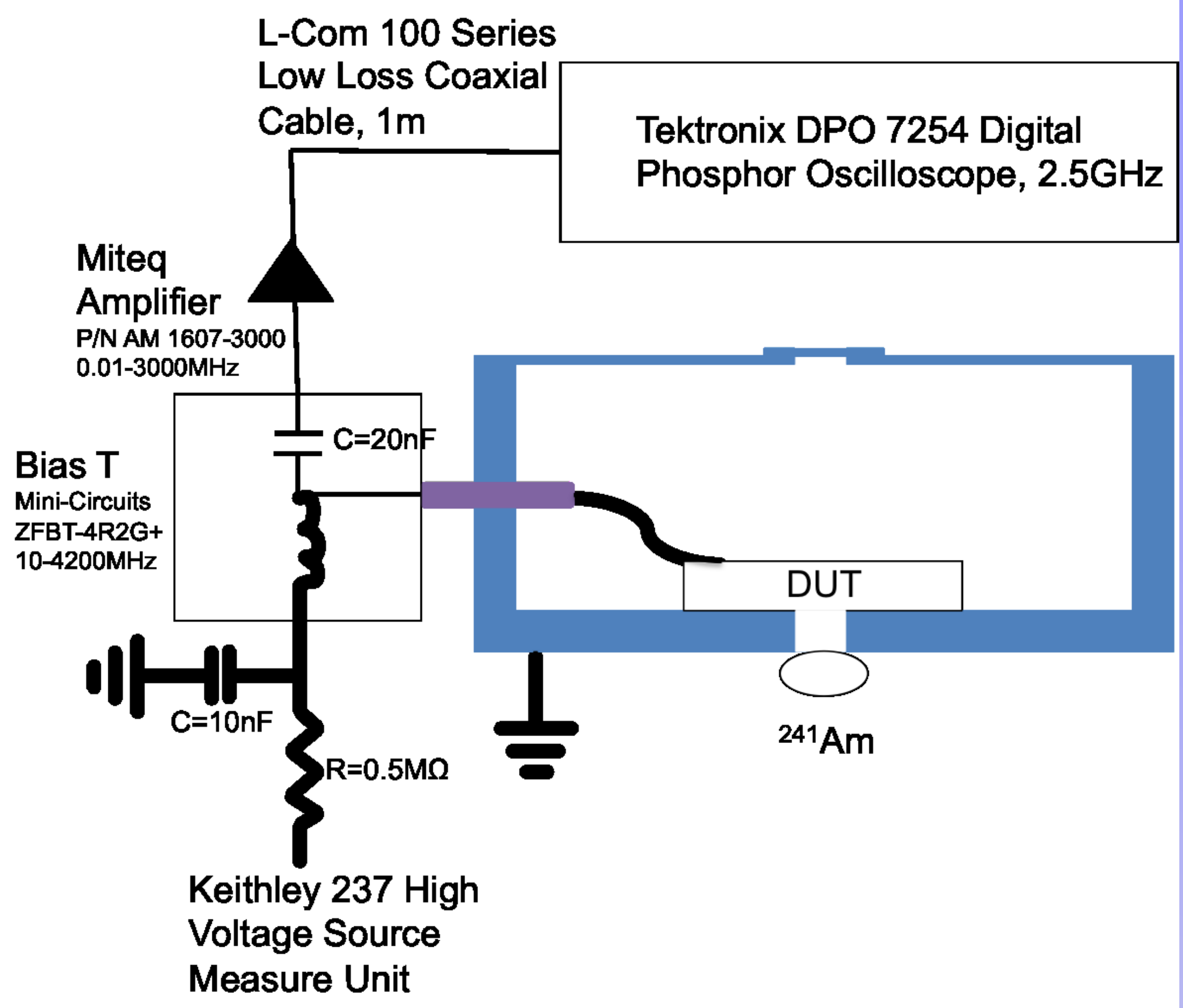
5.0ns/div 40.0GS/s IT 5.0ps/pt

Stopped

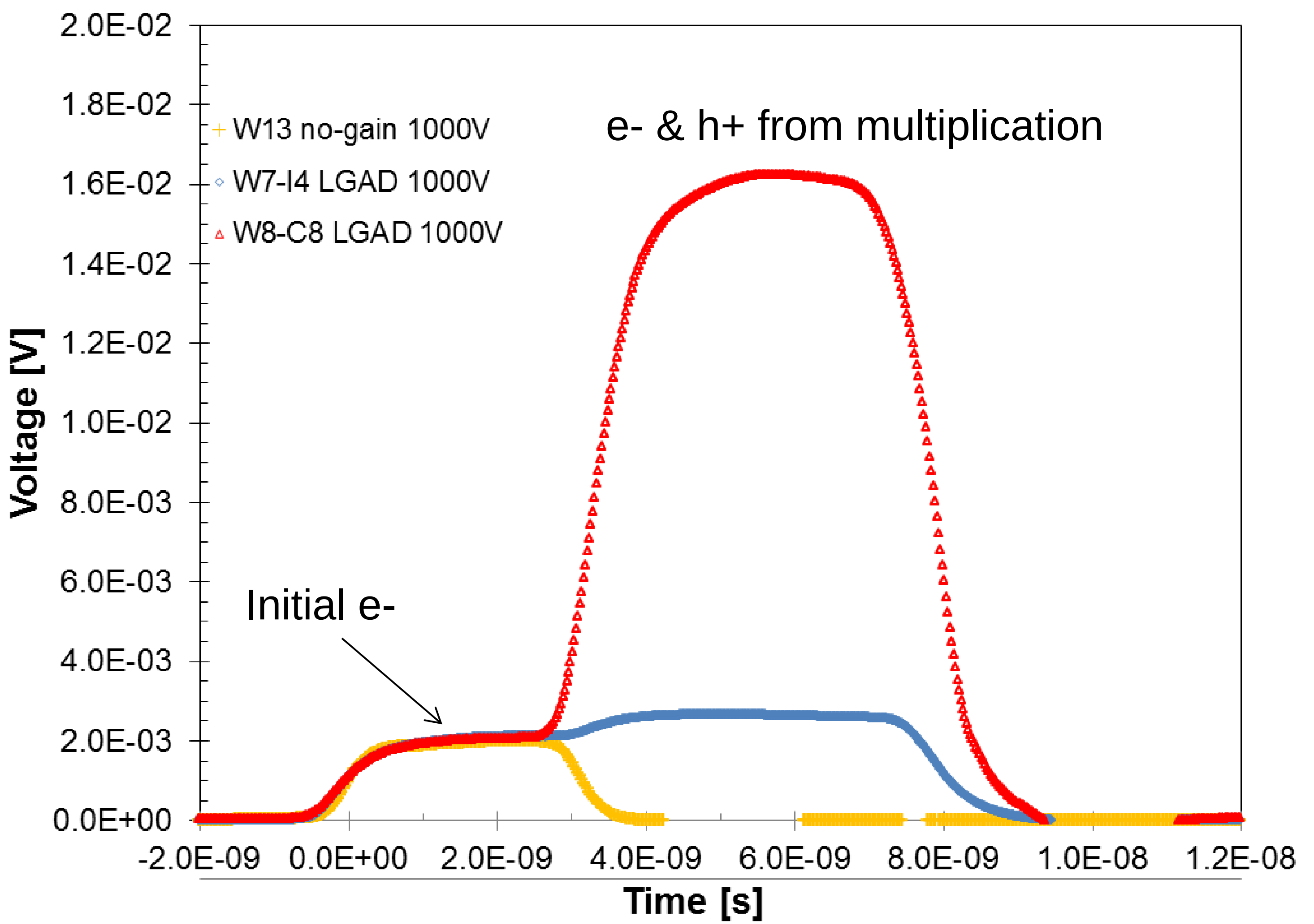
7 350 acqs RL:10.0k

Cons August 02, 2013 12:01:48

High BW α TCT Set-up

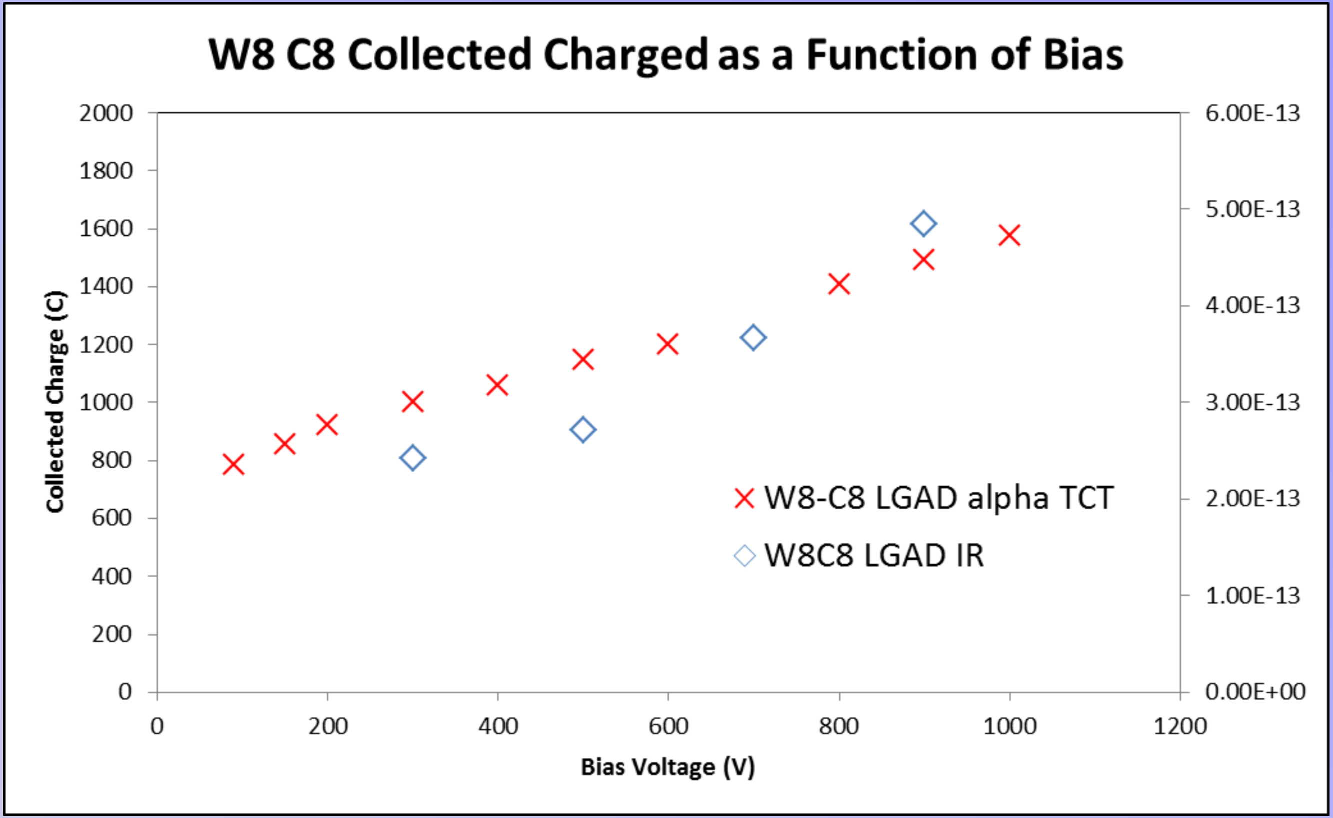


Pulse – shape analysis with α TCT

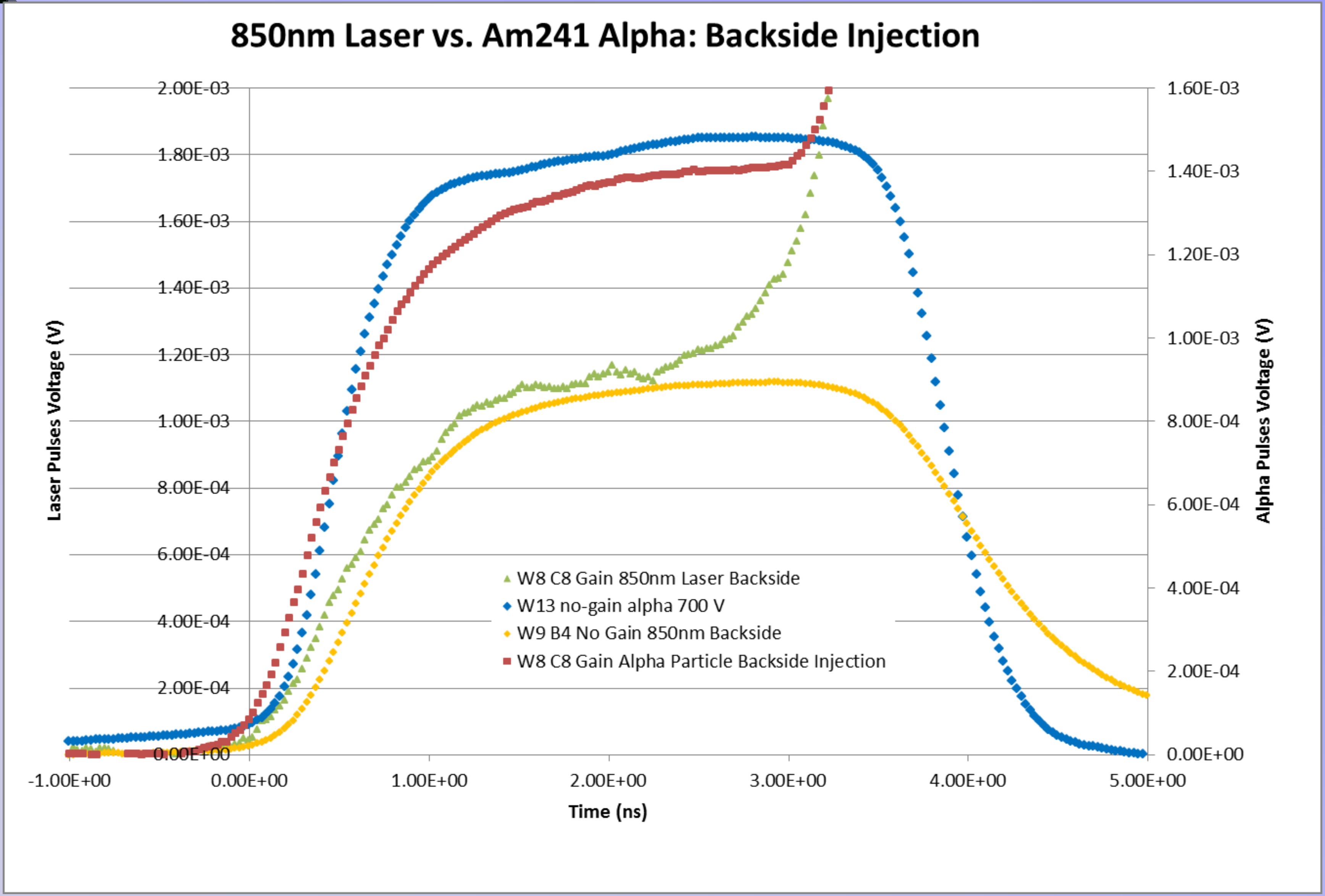


Gain = Total pulse area / Initial Pulse Area

TCT: more gain with IR laser than with α?



TCT: red laser ~ same speed as α



TCT: more gain with red laser than with α?