Charge Multiplication in Si Sensors

with
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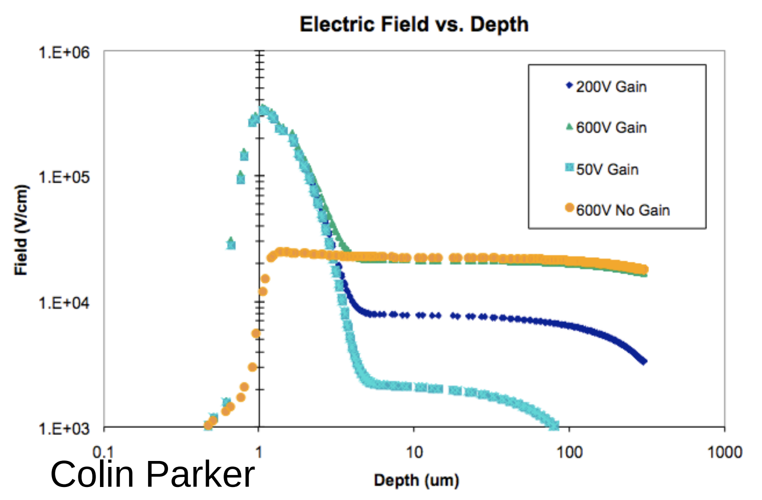
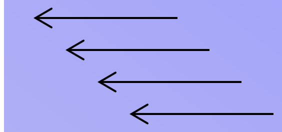
Charge Multiplication has been observed in silicon sensors in the past mainly after irradiations to high fluences
Pre-rad multiplication in traditional sensors has been hard to observe.
But sensors with a dedicated doping profile, Low-Gain Avalanche Detectors (LGAD) have been fabricated by CNM and show gain of 10-15.

LGAD in FZ and epi: Correlate αTCT and i-V and C-V,
investigate time resolution of thin sensors

Charge Collection with α's from Am(241)



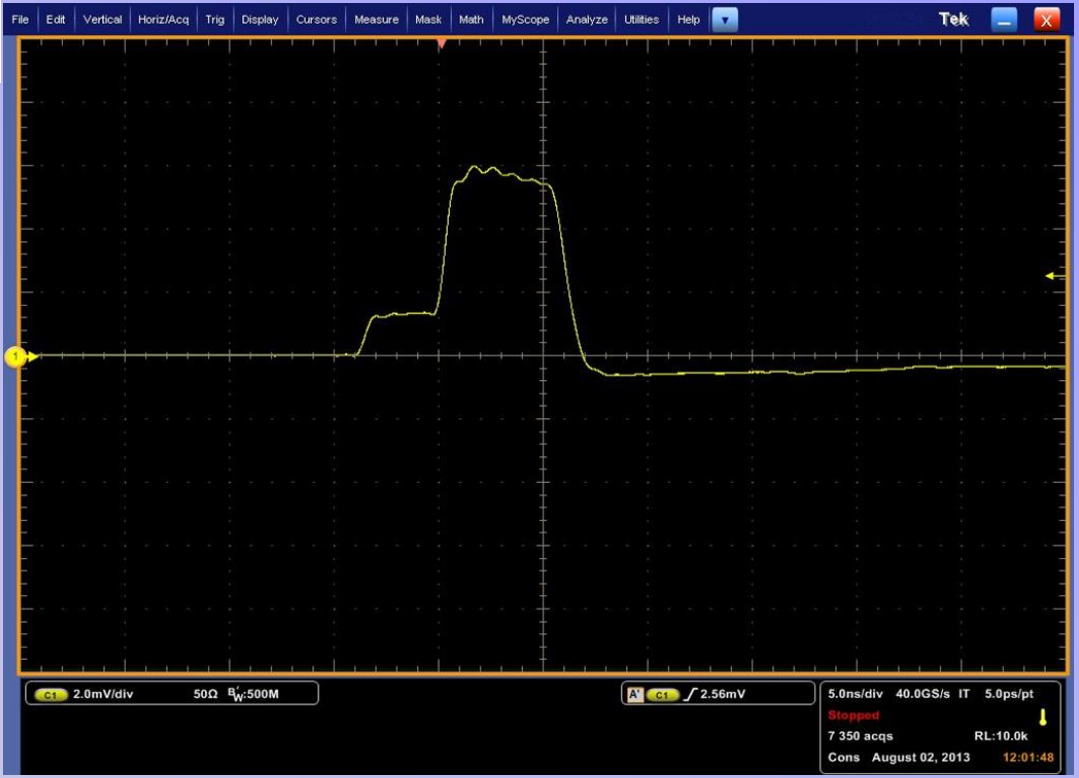
Colin Parker



α's

Am(241)

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



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

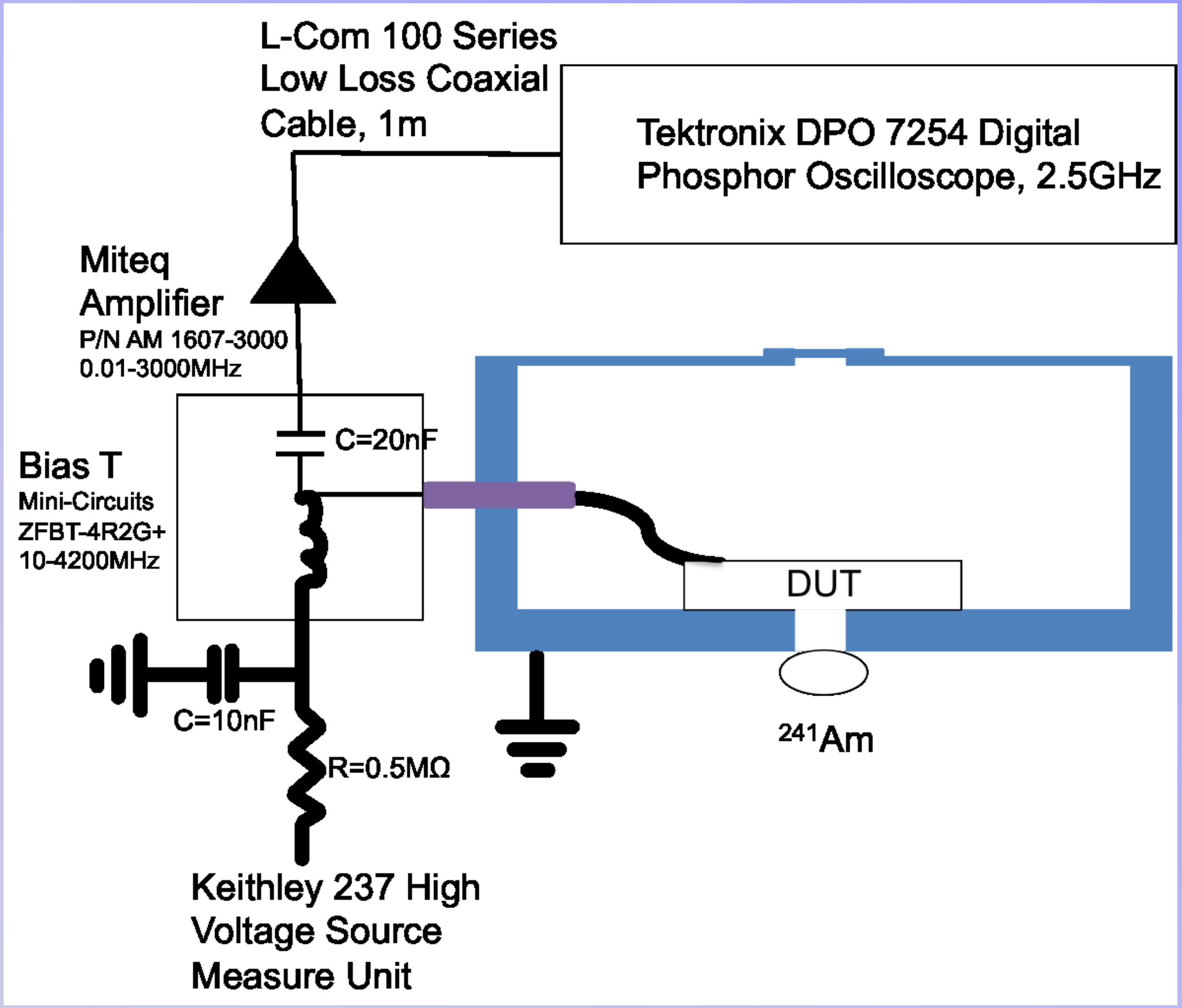
Fast signals!

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

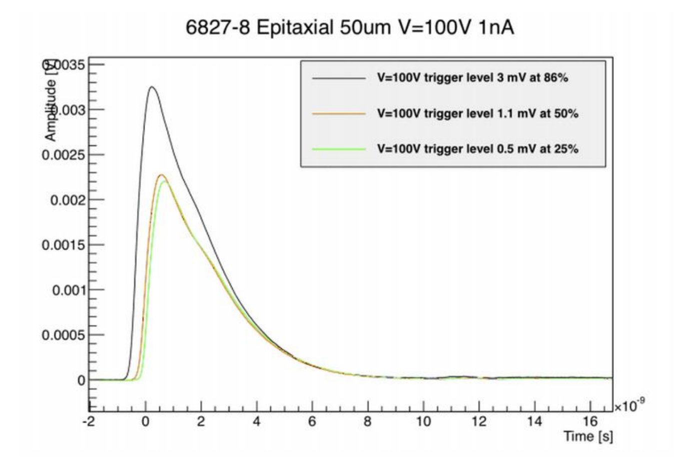
To understand fast signals need high BW set-up (ex Gregor)

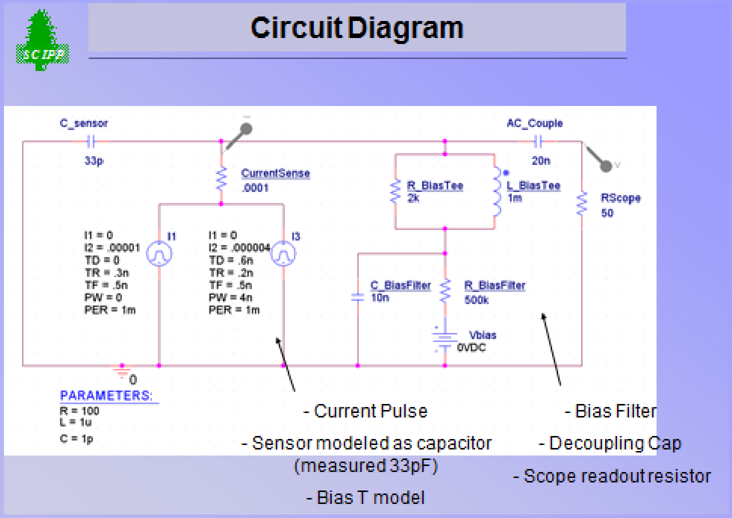


Hartmut F.-W. Sadrozinski, LGAD RD50 Nov 2013

Influence of RC Circuit on Pulse Tail
Coilin Parker (in Appendix)

- Some current transients from alphas on front of new epi sensors look dominated by an RC discharge, let’s investigate what could be the source.




Circuit Diagram

- Current Pulse

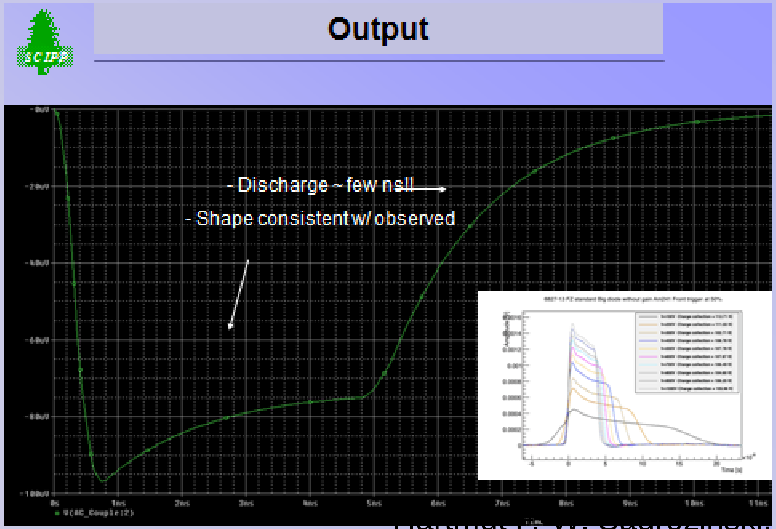
- Sensor modeled as capacitor (measured 33pF)

- Bias T model

- Bias Filter

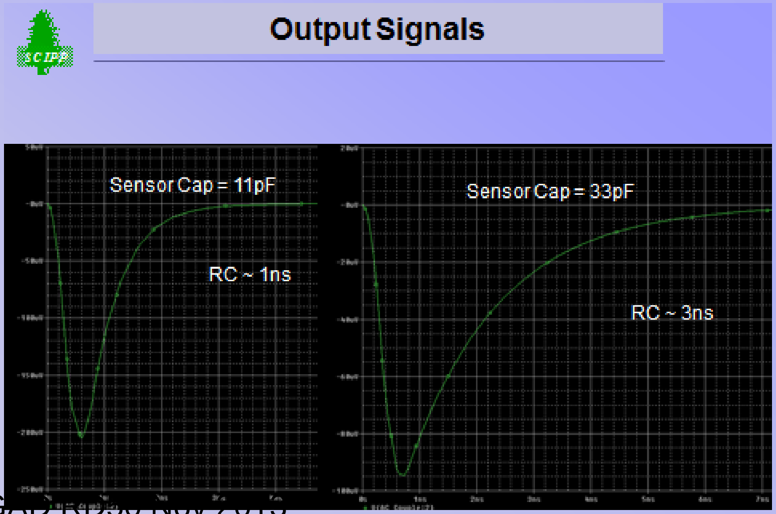
- Decoupling Cap

- Scope readout resistor


Output

- Discharge ~ few ns!!

- Shape consistent w/ observed


Output Signals

Sensor Cap = 11pF

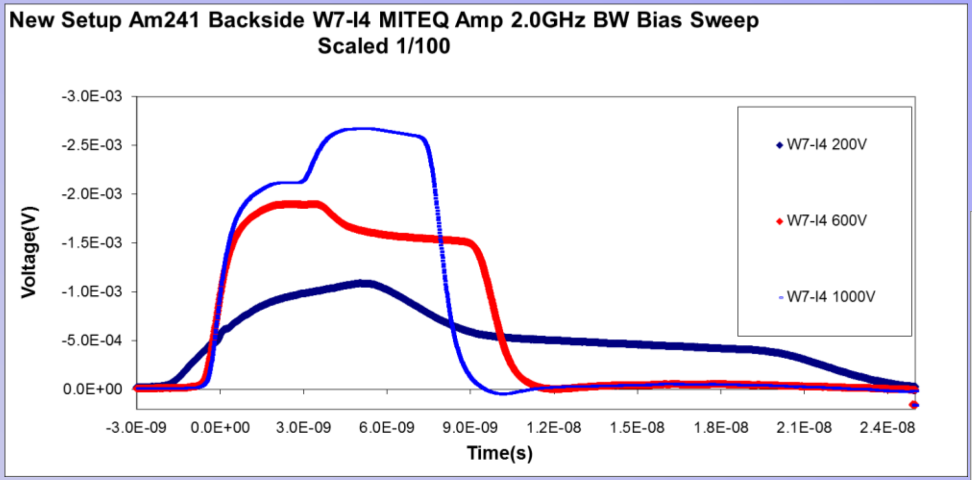
RC ~ 1ns

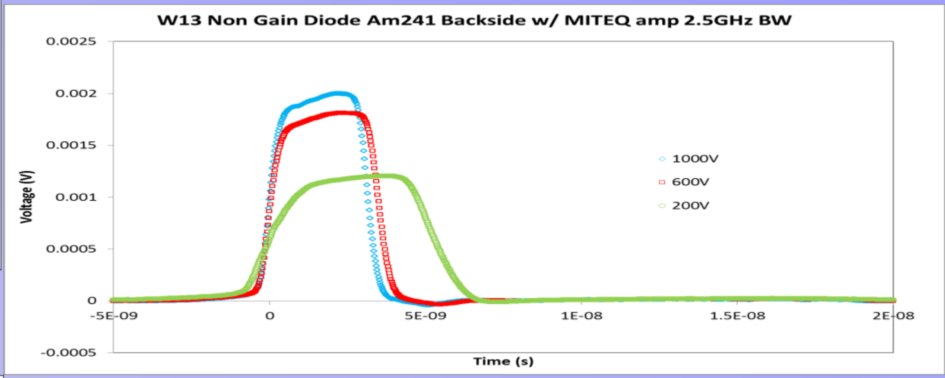
Sensor Cap = 33pF

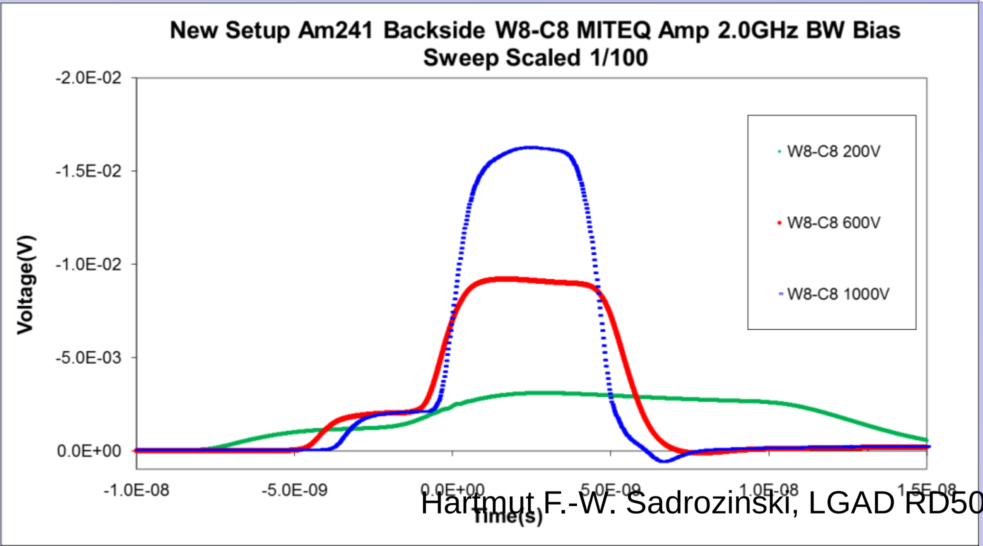
RC ~ 3ns

Pulse – shape analysis with α TCT

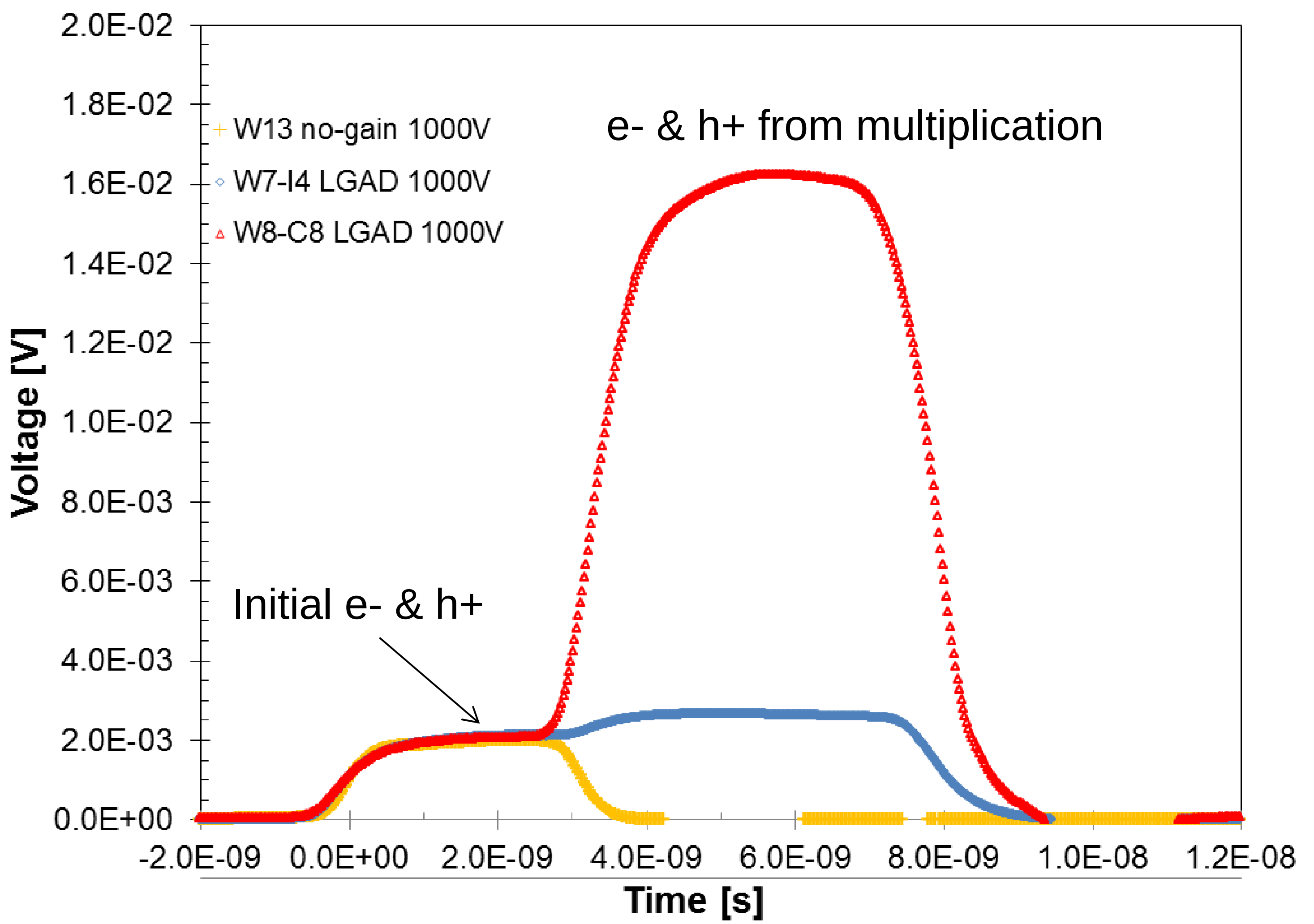
Two LGAD from Pablo’s fabrication run W8-C8 and W7I4 are compared as a function of bias with a diode without gain


New Setup Am241 Backside W7-I4 MITEQ Amp 2.0GHz BW Bias Sweep Scaled 1/100

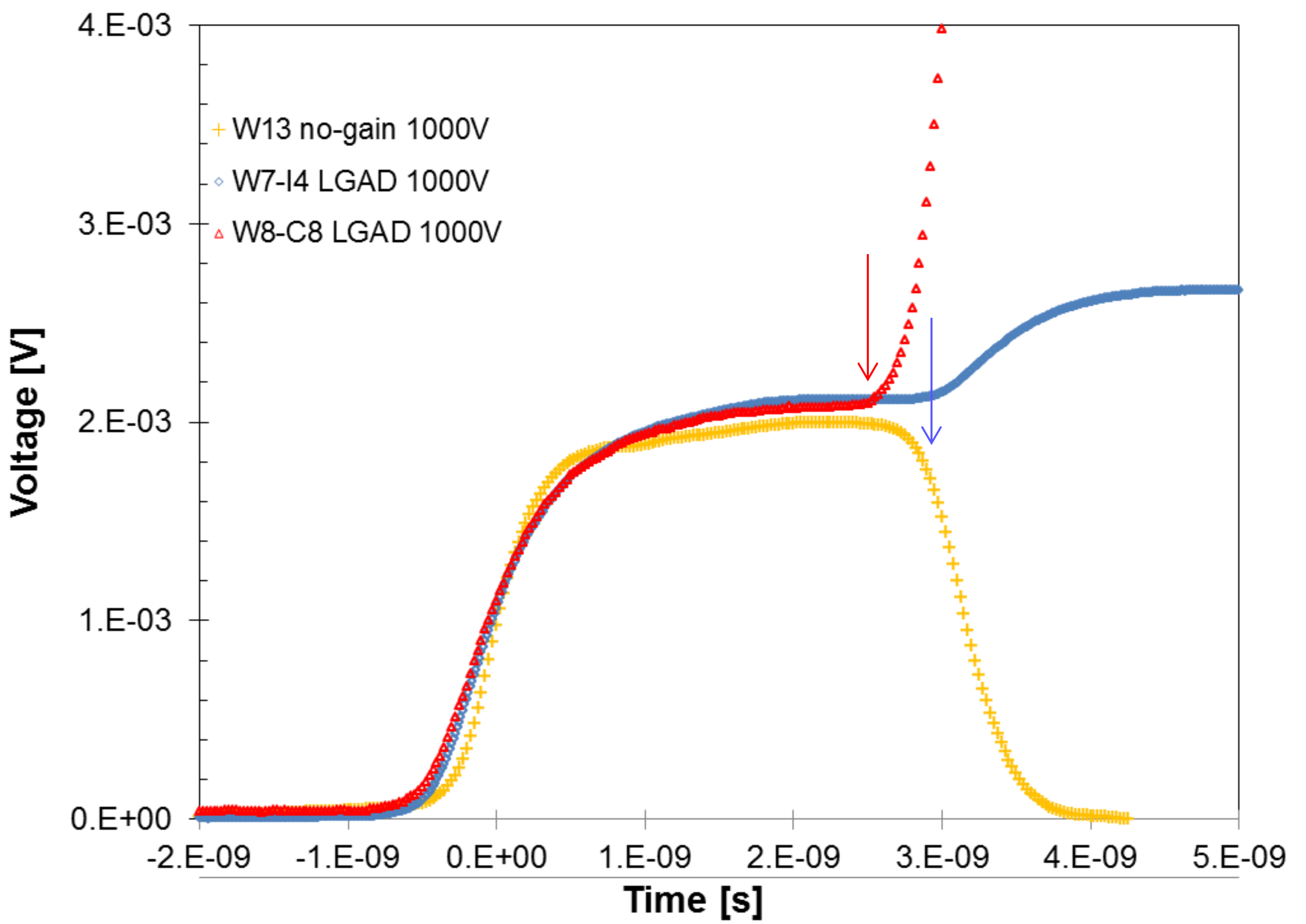

W13 Non Gain Diode Am241 Backside w/ MITEQ amp 2.5GHz BW


New Setup Am241 Backside W8-C8 MITEQ Amp 2.0GHz BW Bias Sweep Scaled 1/100

Pulse – shape analysis with α TCT



Initial Pulse charge

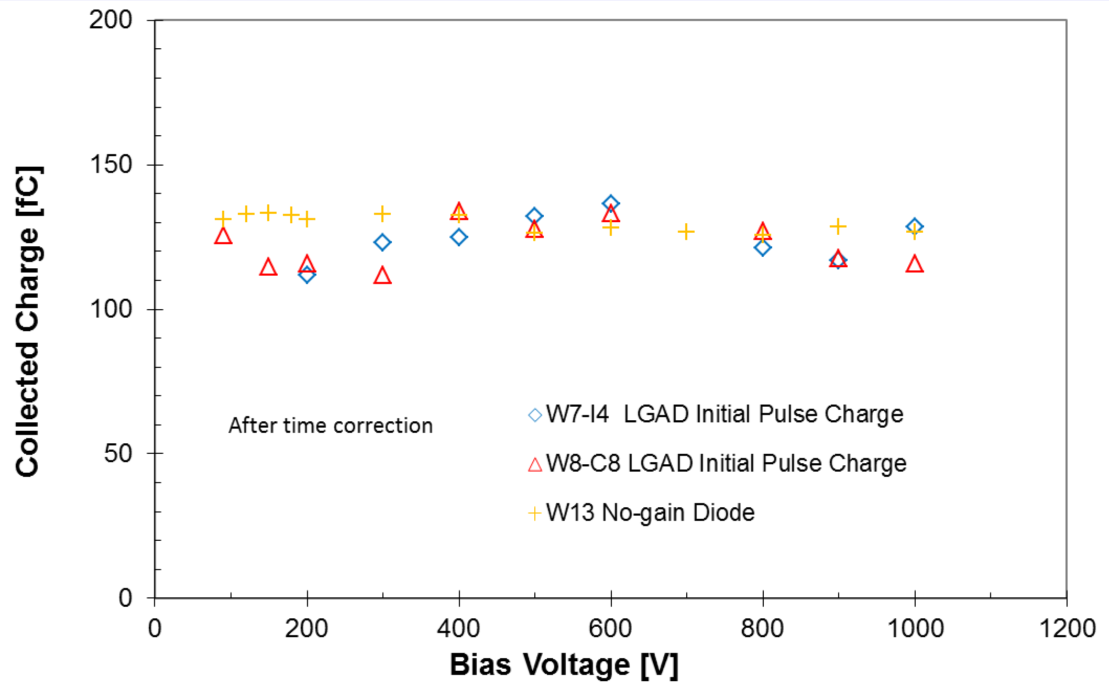


Correction : from fraction of no-gain pulse beyond time cut:

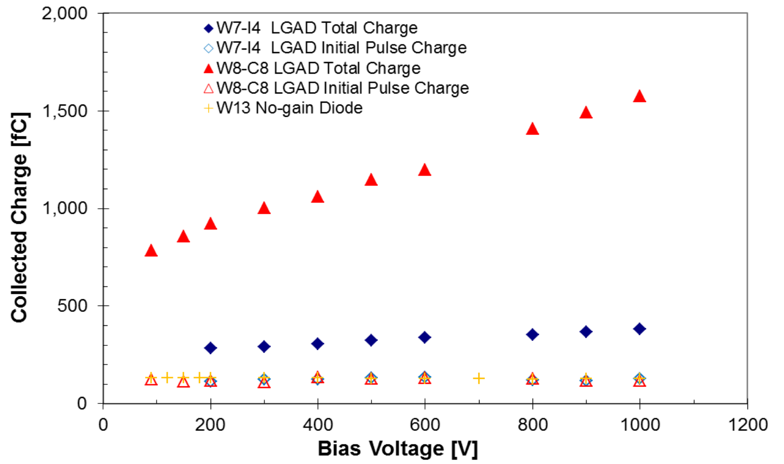
W8-C8 = 1.13

W7-I4 = 1.06

Total charge & initial Pulse charge

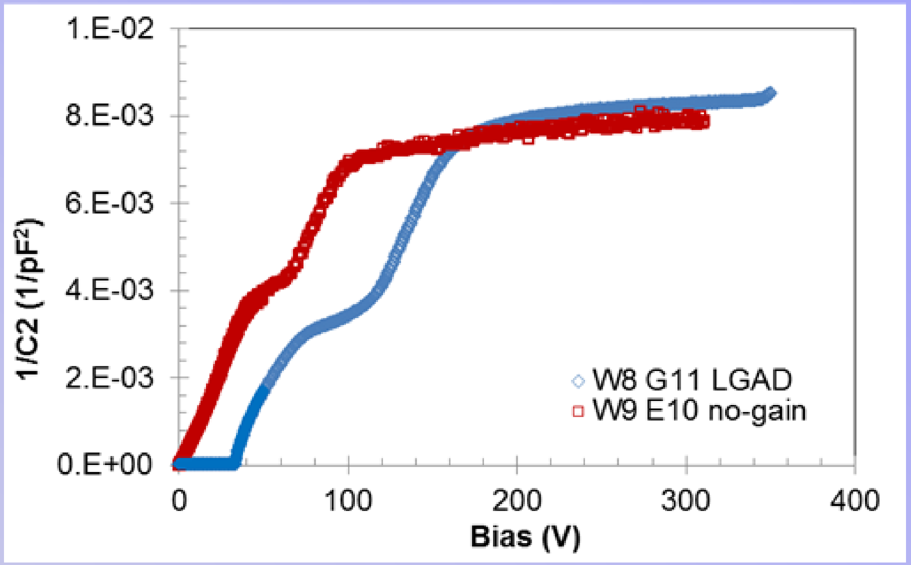


The initial pulse charge is identical for two different LGAD's (after correction) and a no-gain diode:
Reflects the initial electron drift.

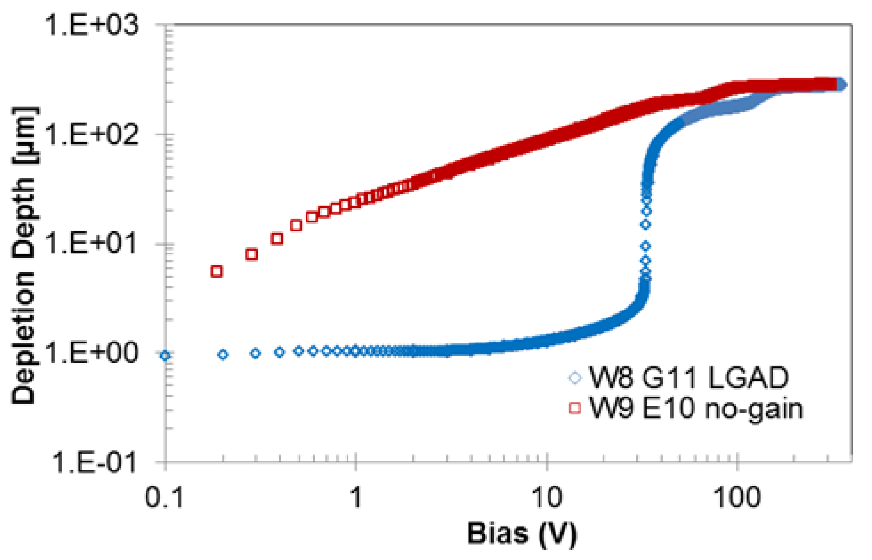


Initial pulse charge and total charge for the 3 devices.:
G(W8-C8)/G(W7-I4) ≈ 4 at 1000V bias.

Doping Concentration from C-V



1/C² shows a voltage "lag" ("foot") for the depletion of the p+ layer responsible for multiplication.
Use this data to extract an estimate of the doping concentration.

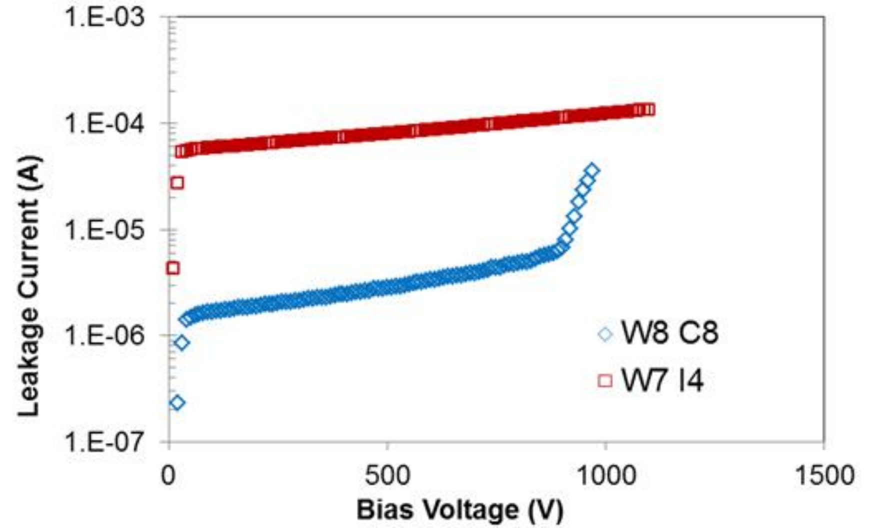


Depletion depth

x = A/C

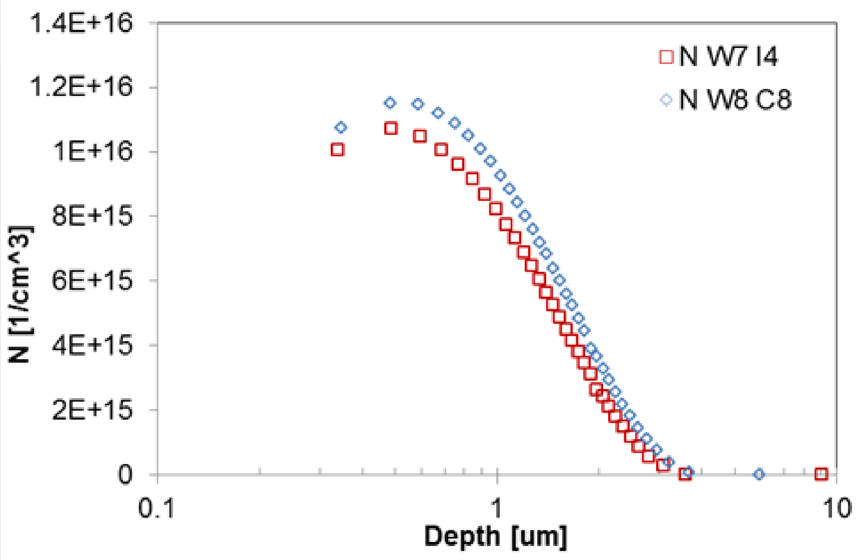
shows the voltage "lag" for the gain diode

Correlation Gain – p-dose



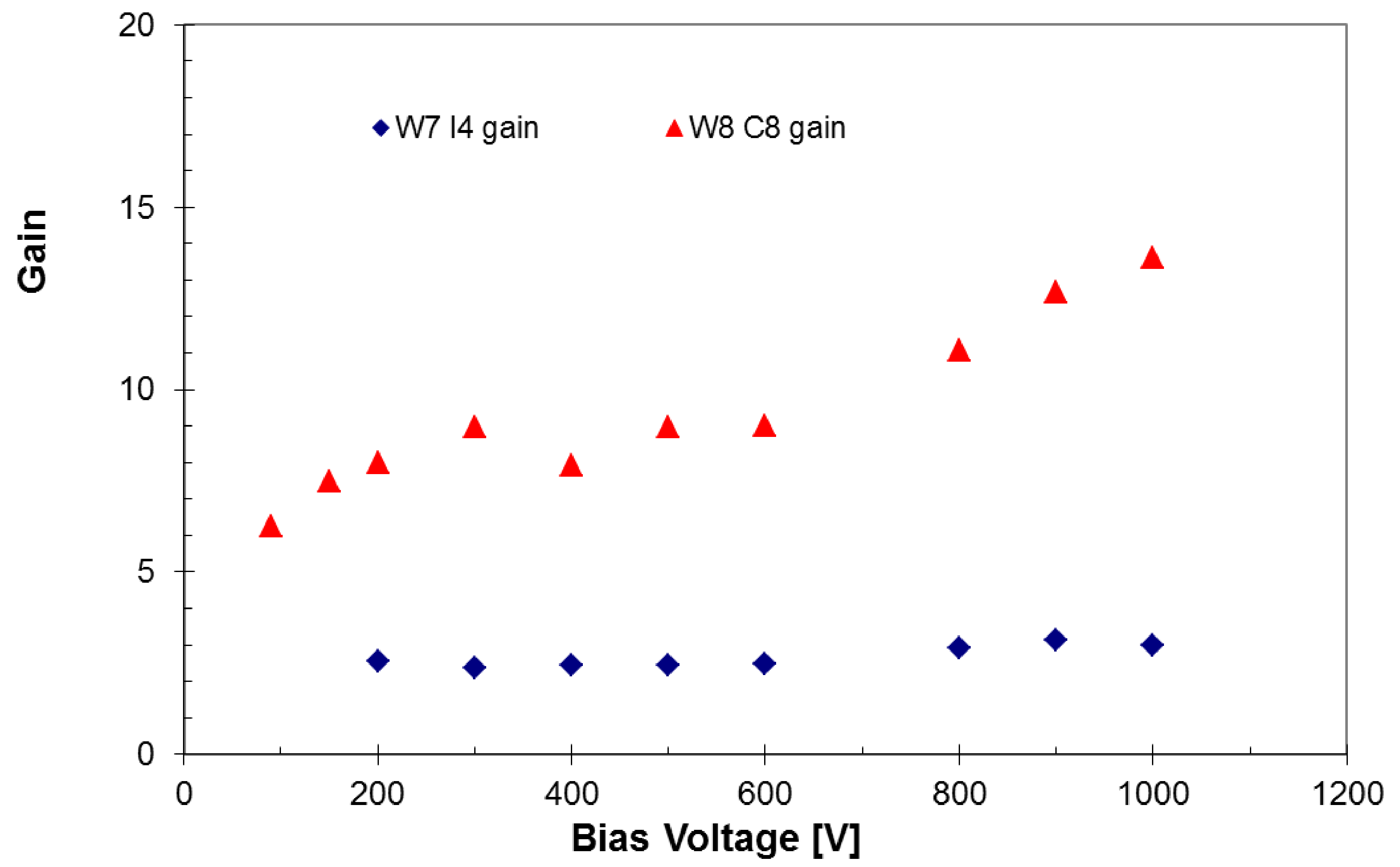
G(W8-C8)/G(W7-I4) ≈ 4 at 1000V bias. Given that W8-C8 has much lower current than W7-I4, the data do not support the notion that the leakage current scales with the gain.

This means that other effects have much larger effects on the leakage current besides the gain.



The gain is influenced by the p-dose in the multiplication layer, where higher gain is correlated with higher p-dose, as expected from simulations.

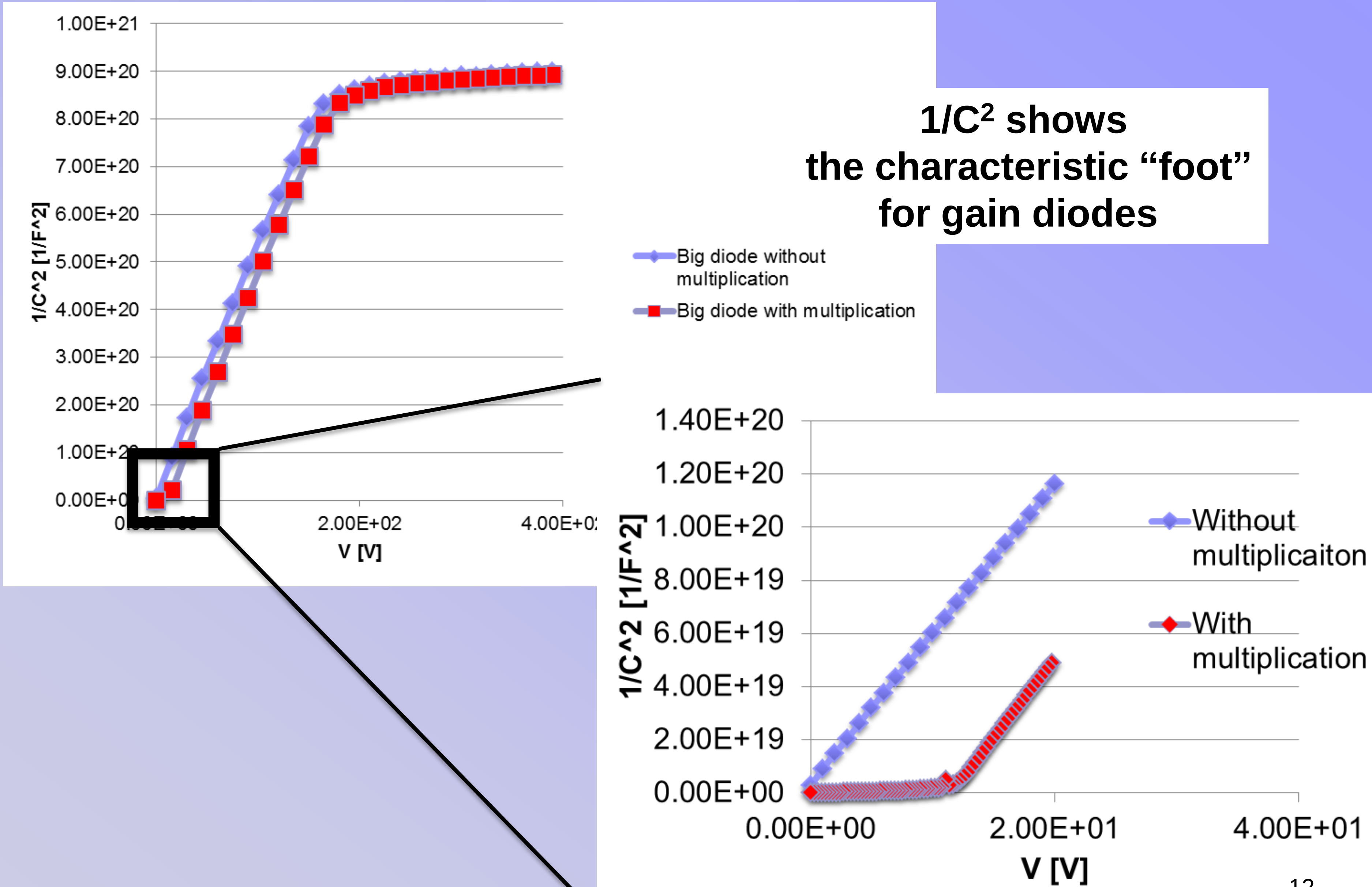
Gain = (total collected charge)/(corr. Initial charge



Difference in P+ dose: 20%

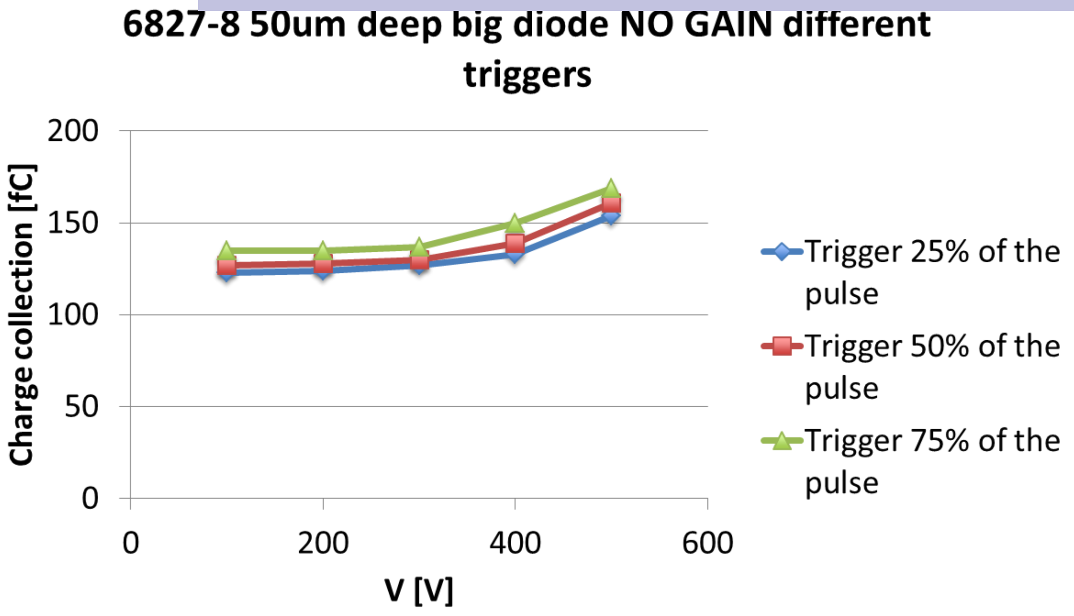
Even at the low bias voltage of 90V, we observe a gain G=6 for W8-C8.

50um epi 4mm Diode

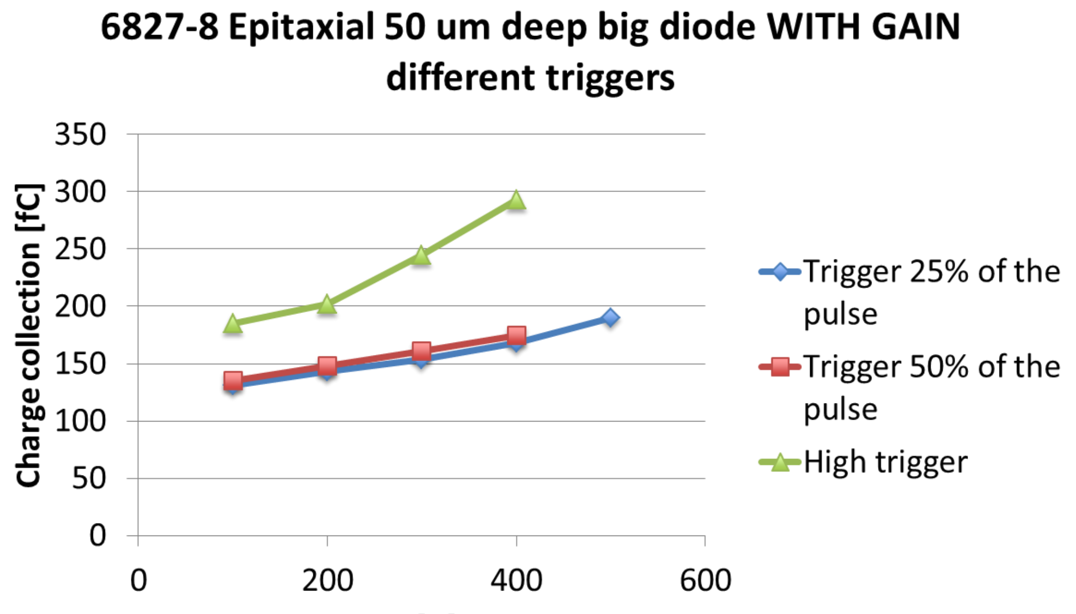


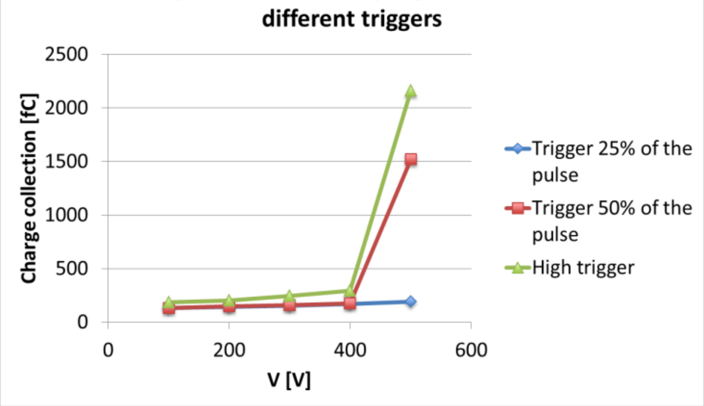
$1/C^2$ shows the characteristic “foot” for gain diodes

TCT from Front 50um epi 4mm Diode

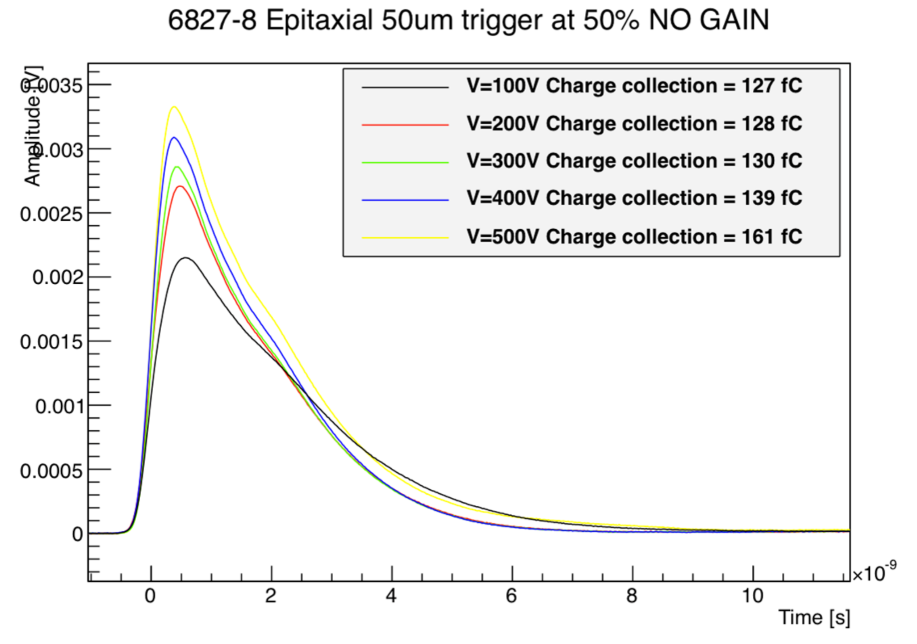


N.B.
α TCT from Back in FZ
Initial Pulse Char.
~120fC

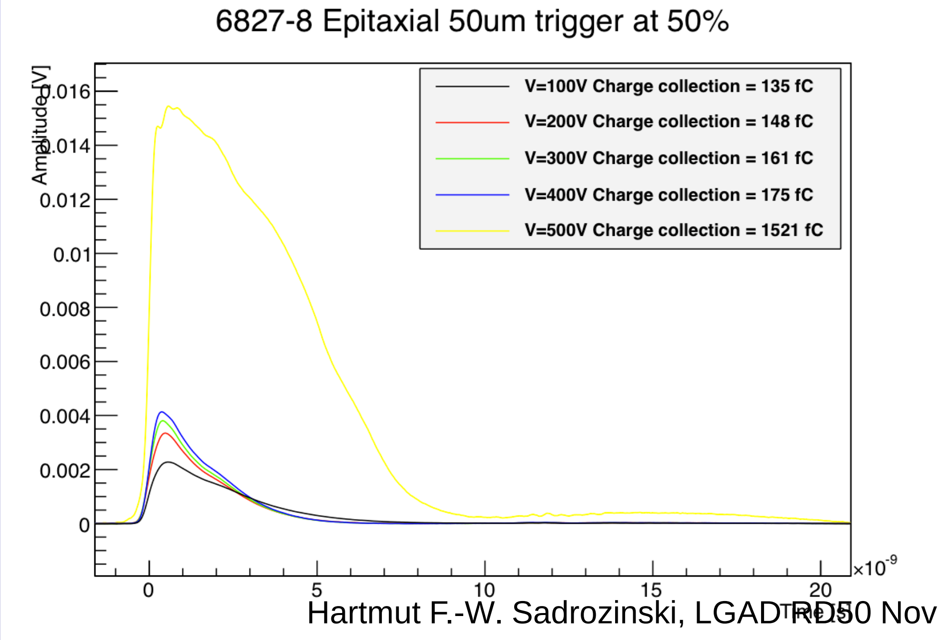




α TCT from Front 50um epi 4mm Diode


6827-8 Epitaxial 50um trigger at 50% NO GAIN

No-gain
Pulse distribution
~independent of bias


6827-8 Epitaxial 50um trigger at 50%

Gain:
Very large pulses at
500V bias: gain or breakdown?

Issues with 50um epi Strips

1. **Low breakdown voltages**
    Diode needed 500V (?), strips break down at <200V
2. **No comparison with non-gain parts (coming)**
3. **Only partial coverage with p+ implant (select AC7-AC9)**
    Scan with x-rays at Diamond (Glasgow)

Conclusions on LGAD

1. α TCT on FZ LGAD from the back-side shows gain up to 14.
2. α TCT on FZ LGAD from the back-side shows gain at a bias as low as 90V
3. Gain in FZ LGAD is associated with p+ dose, not with excessive current.
4. Epi 50um diodes might exhibit gain at 500V (Front data)
5. Epi 50um strips have low breakdown.
6. Epi 50um strips have only limited coverage by p+ implant.
7. Thin sensors have high rate capability
   and reduce dependence of noise on excess leakage current.

Fast Rise Time Sensors for Timing

Why thin sensors for fast timing? Thin sensors allow fast rise time because of the fast collection time. But their S/N is reduced.
Why not use thick sensors, and collect only the early part of the electrons or integrate the charge over longer time, reduce noise and trigger low on the rising pulse, like in LHC pixel sensors?

In general: induced pulse development is fairly complicated (i.e. bipolar pulses in neighboring strips, possibility of increased “cross-talk”) so shaping at the collection time seems to be a safe thing to do.

Time resolution due to noise and time walk (amplitude dispersion of Landau):
Assume pulse of amplitude S with dispersion **ΔS/S**, electronic noise RMS N and rise time $\boldsymbol{\tau_R}$:

$$\boldsymbol{\sigma_t = \left[\left({}^{N}\!\Big/\!\frac{dS}{dt}\right)^2 + \left(\Delta S \cdot \frac{dt}{dS}\right)^2\right]^{1/2} = \left[\left(\frac{N}{S}\tau_R\right)^2 + \left(\frac{\Delta S}{S}\frac{S_{thr}}{S}\tau_R\right)^2\right]^{1/2}}$$

$\boldsymbol{\frac{\Delta S}{S}}$ **= 0.16 – 0.4** S. Meroli, D. Passeri and L. Servoli, “Energy loss measurement for charged particles in very thin silicon layers”, 11 JINST 6 P06013, 2011.

Timing Resolution

In the following, the rise time = shaping time will be set equal to the collection time to get optimal performance.

This correlates the rise time and the sensor thickness.

(i.e. τ_R=6.5 ns for 300 µm, . τ_R= 1 ns for 50 µm, τ_R= 200 ps for 9 µm)

For ATLAS type pixels

(i) a noise N=1000e$^-$ at a shaping time of 500 ps, and

(ii) the noise scaling like $1/\sqrt{\tau_R}$ with the shaping time.

These assumptions are consistent with the measured noise on the ATLAS pixels

(iii) the threshold be set at 10 times noise RMS to suppress noise counts

$$S_{thr}=10*N$$

(iv) **a reduction of time walk by a factor CFD due to the use of a constant fraction discriminator ,**

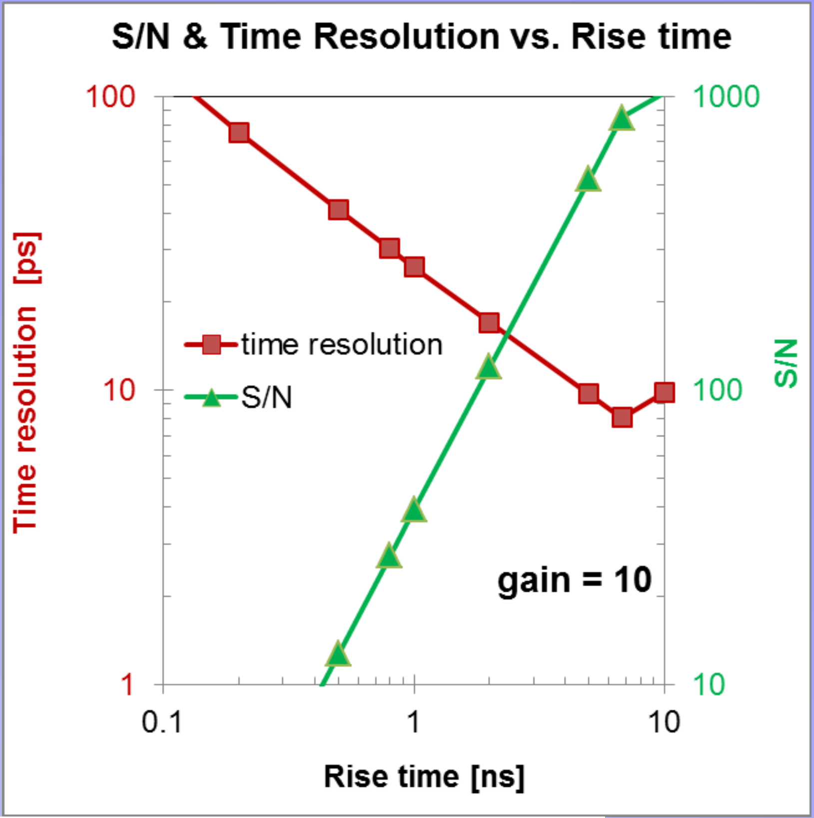
$$\sigma_t(CFD) = \tau_R \frac{1}{(S/N)} \left[1 + \left(CFD \cdot 10 \frac{\Delta S}{S}\right)^2\right]^{1/2} .$$

For high-rate sensors, we look for the fastest rise time with a realistic S/N >30. Then the time resolution depends on the gain as shown in Table 1, with a marked improvement with the use of a constant fraction discriminator even with a modest CFD = 1/3.

For a gain G=10, a rise time of τ_R=800ps and a sensor thickness of 36µm the time resolution will be 30 - 40ps.

Rise Time, Thickness, S/N, Time Resolution

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



Need S/N > 30

CDF = 1/10

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

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:

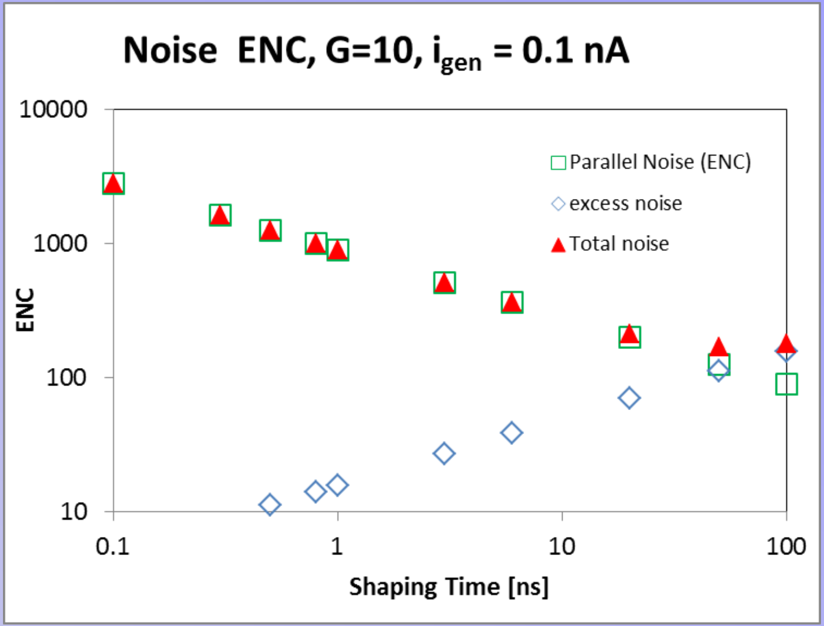
Current i_{gen} = 10 µA/cm^2

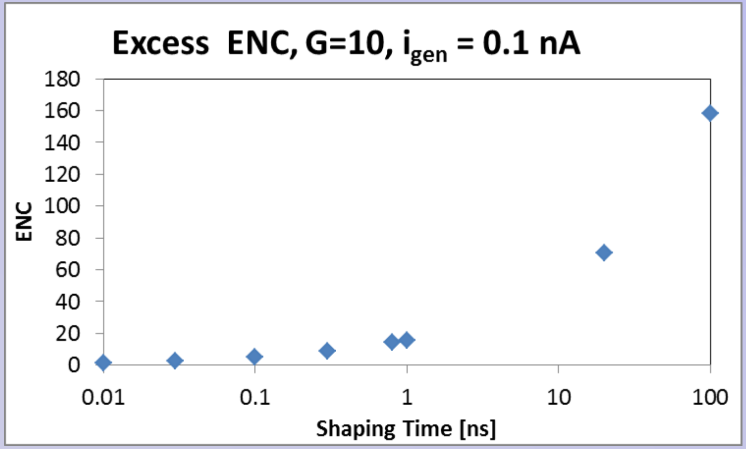
-> current per pixel i=1nA , i_{gen}=0.1nA

Gain = 10, F=2

-> excess Noise at τ=800 ps: 14 e$^-$

-> extcess Noise at τ= 20 ns : 70 e$^-$





Conclusions on Timing

Shaping at the collection time correlates sensor thickness.
Decisive parameter is S/N.

Thin sensors = fast shaping time:
Motivator is high rate and low excess noise!

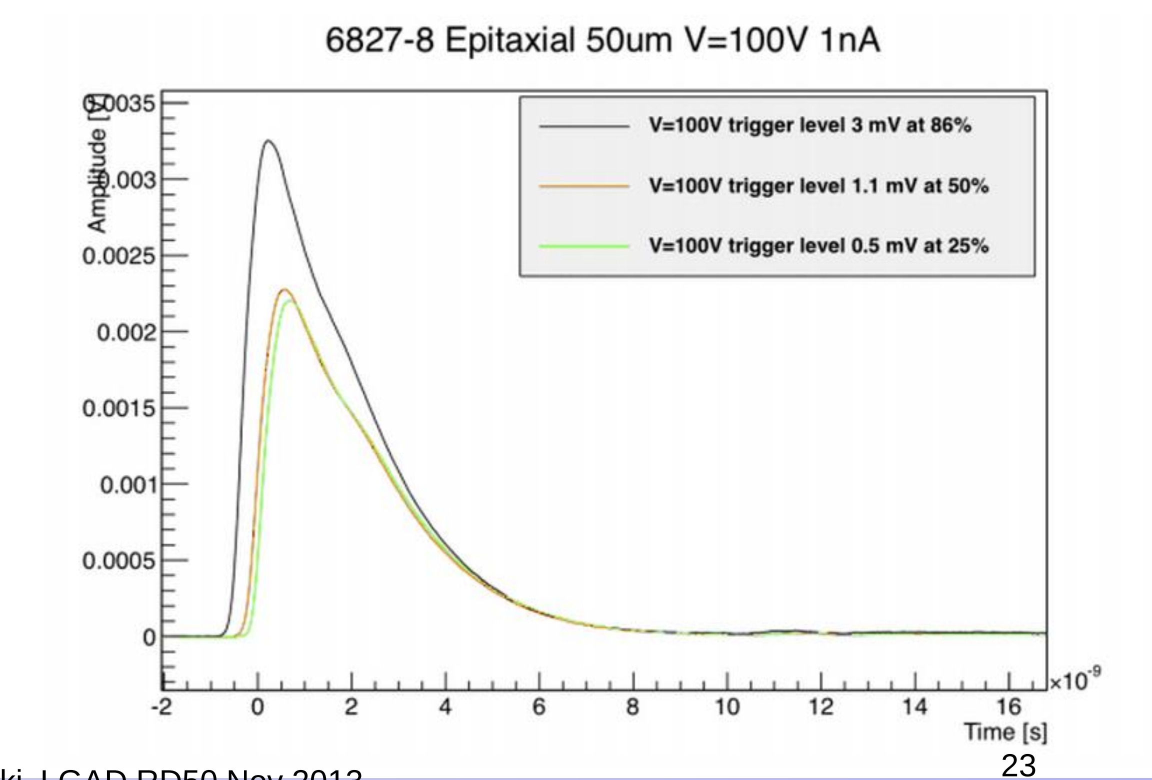
Investigating RC sources in the TCT experiment

Colin

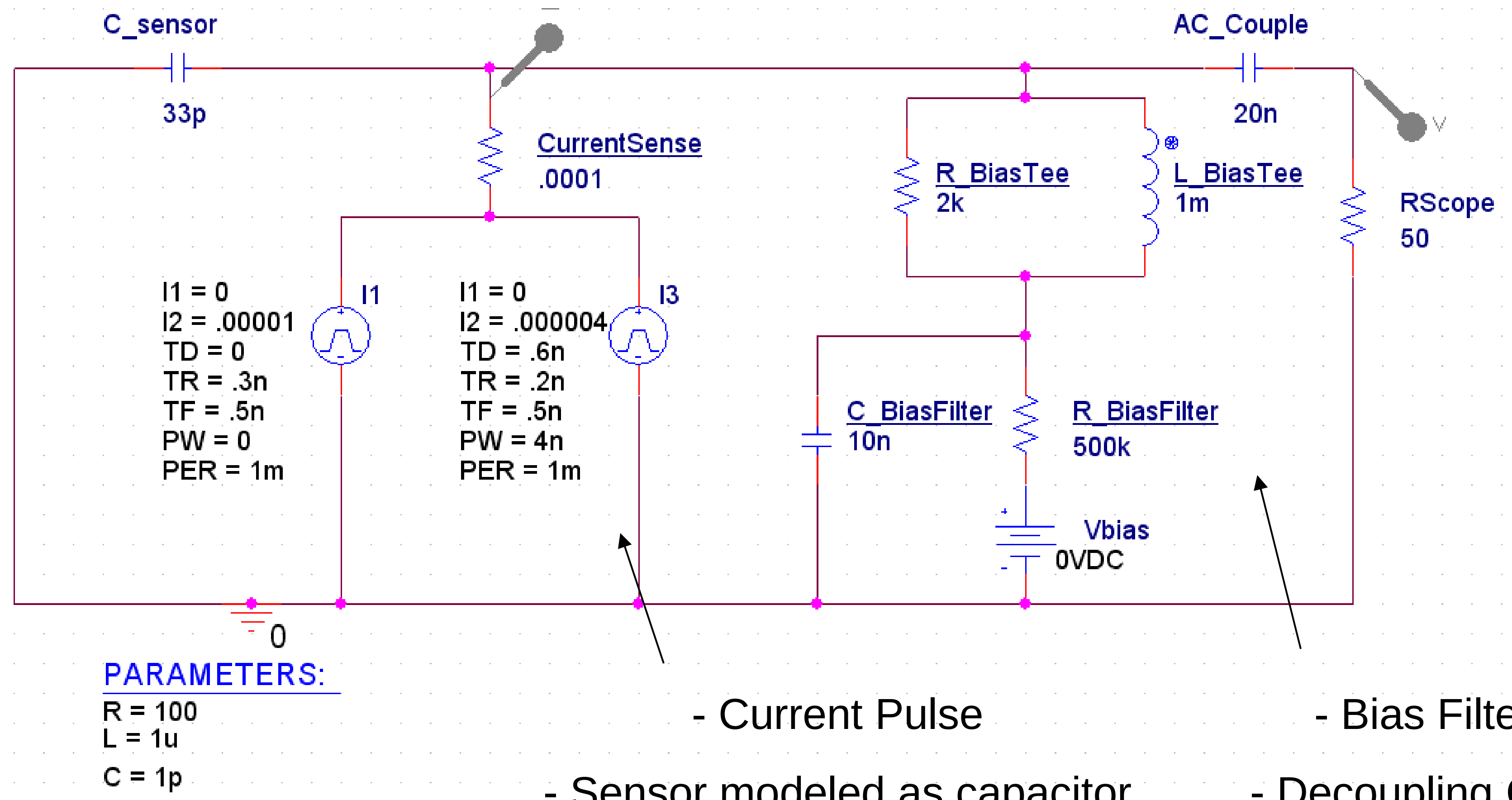
11/5/13

Intro

- Some current transients from alphas on front of new epi sensors look dominated by an RC discharge, let’s investigate what could be the source.



Circuit Diagram



- Current Pulse

- Sensor modeled as capacitor (measured 33pF)

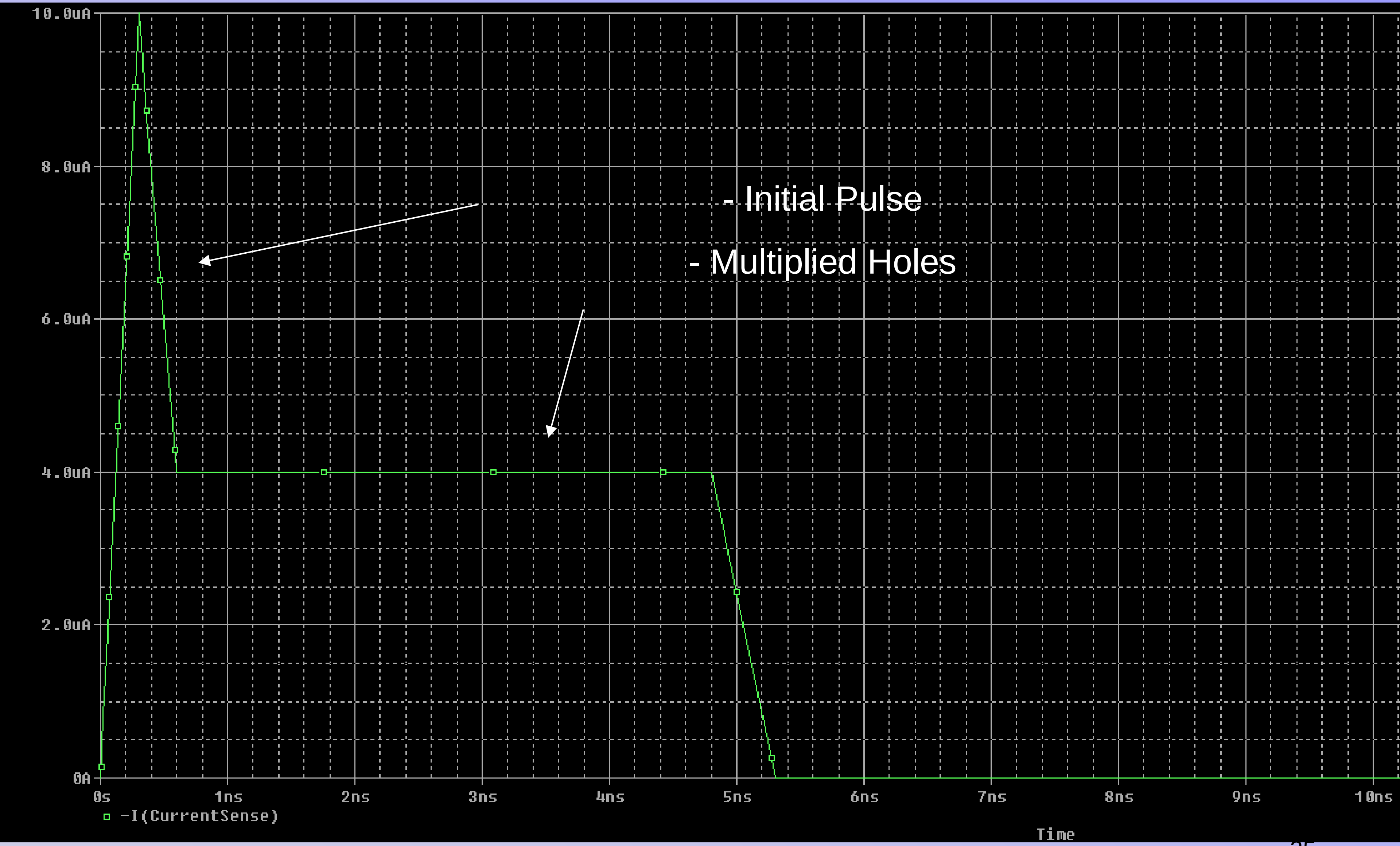
- Bias T model

- Bias Filter

- Decoupling Cap

- Scope readout resistor

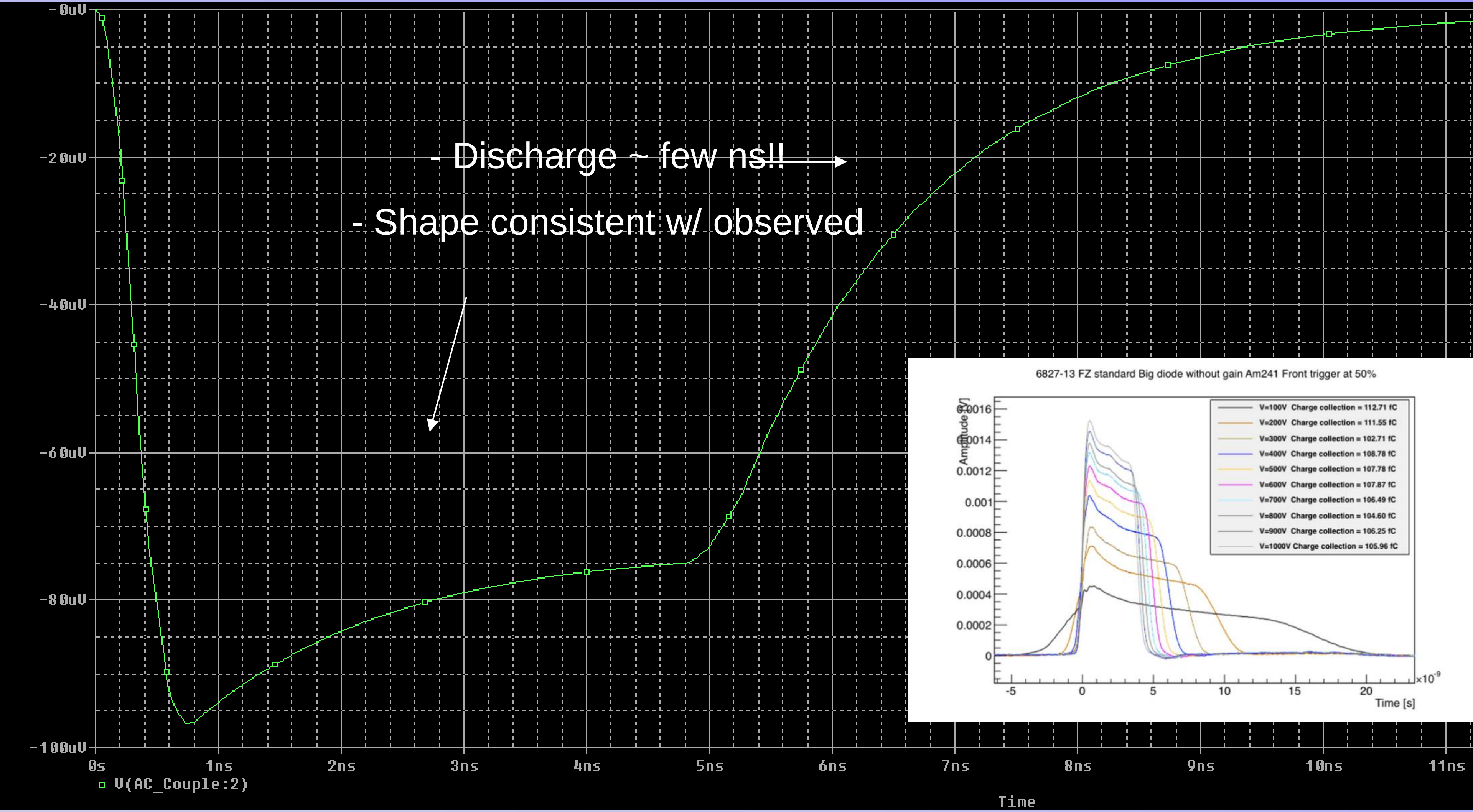
Shape of Current Pulse



- Initial Pulse

- Multiplied Holes

Output

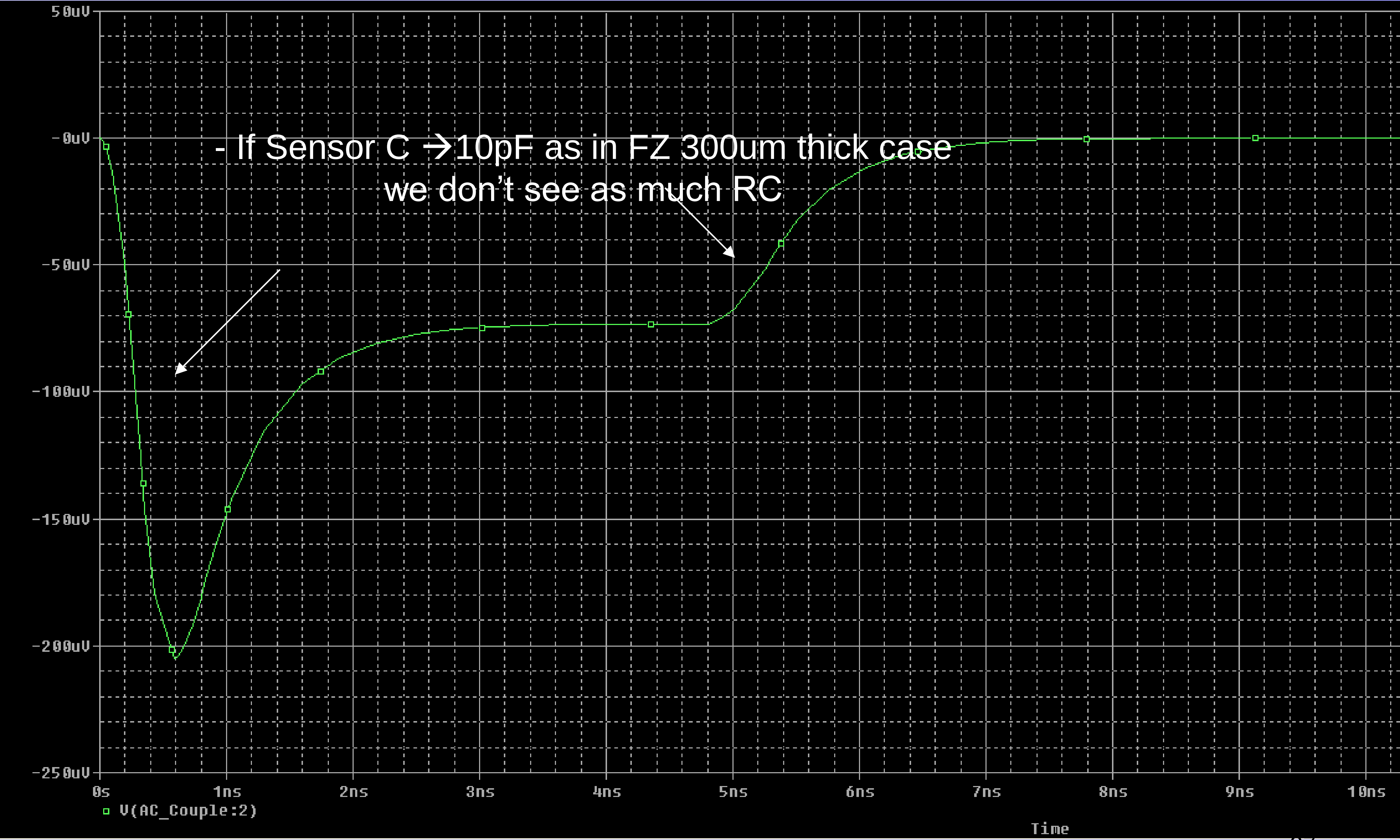


- Discharge ~ few ns!!

- Shape consistent w/ observed

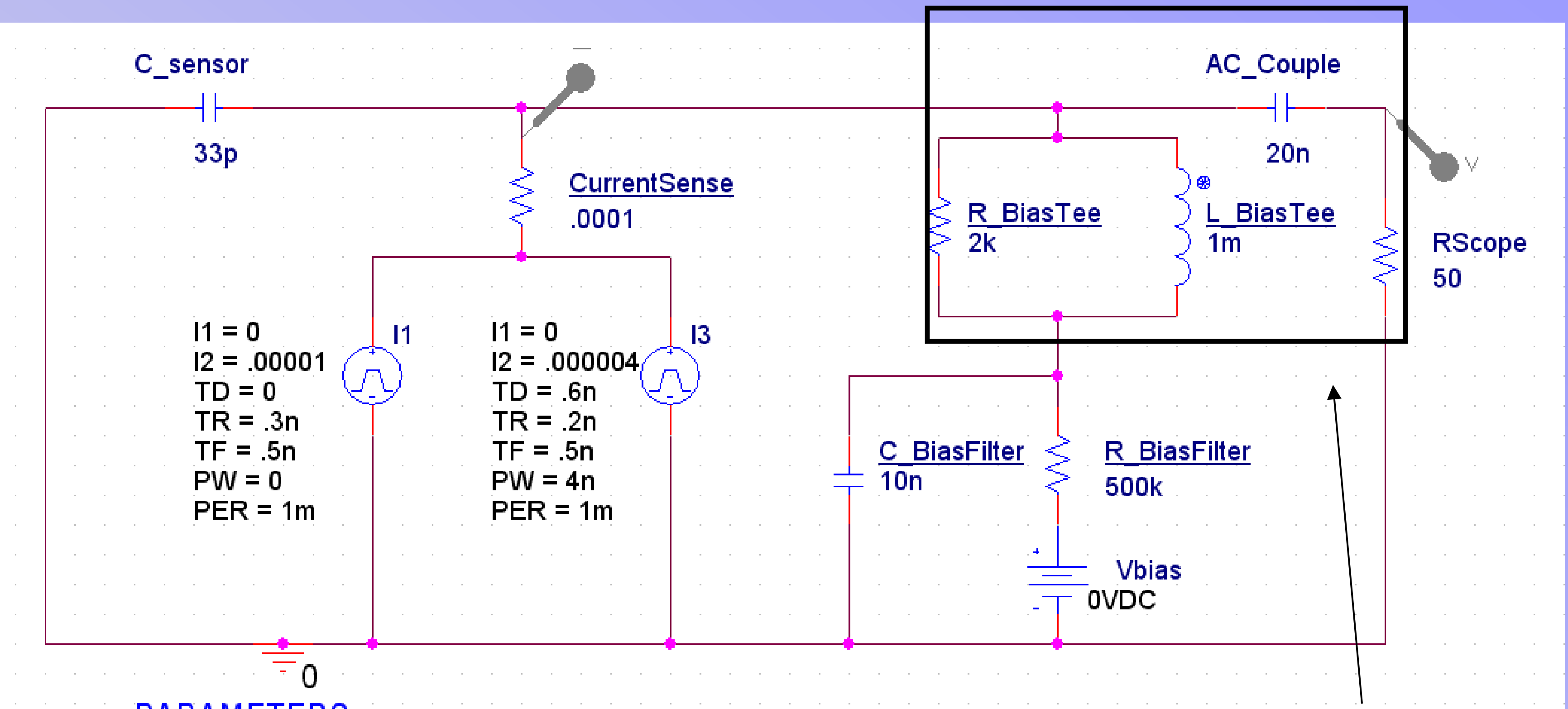
Hartmut F.-W. Sadrozinski, LGAD RD50 Nov 2013

Sensor C=11pF



- If Sensor C →10pF as in FZ 300um thick case we don't see as much RC

Other Important Parameters?



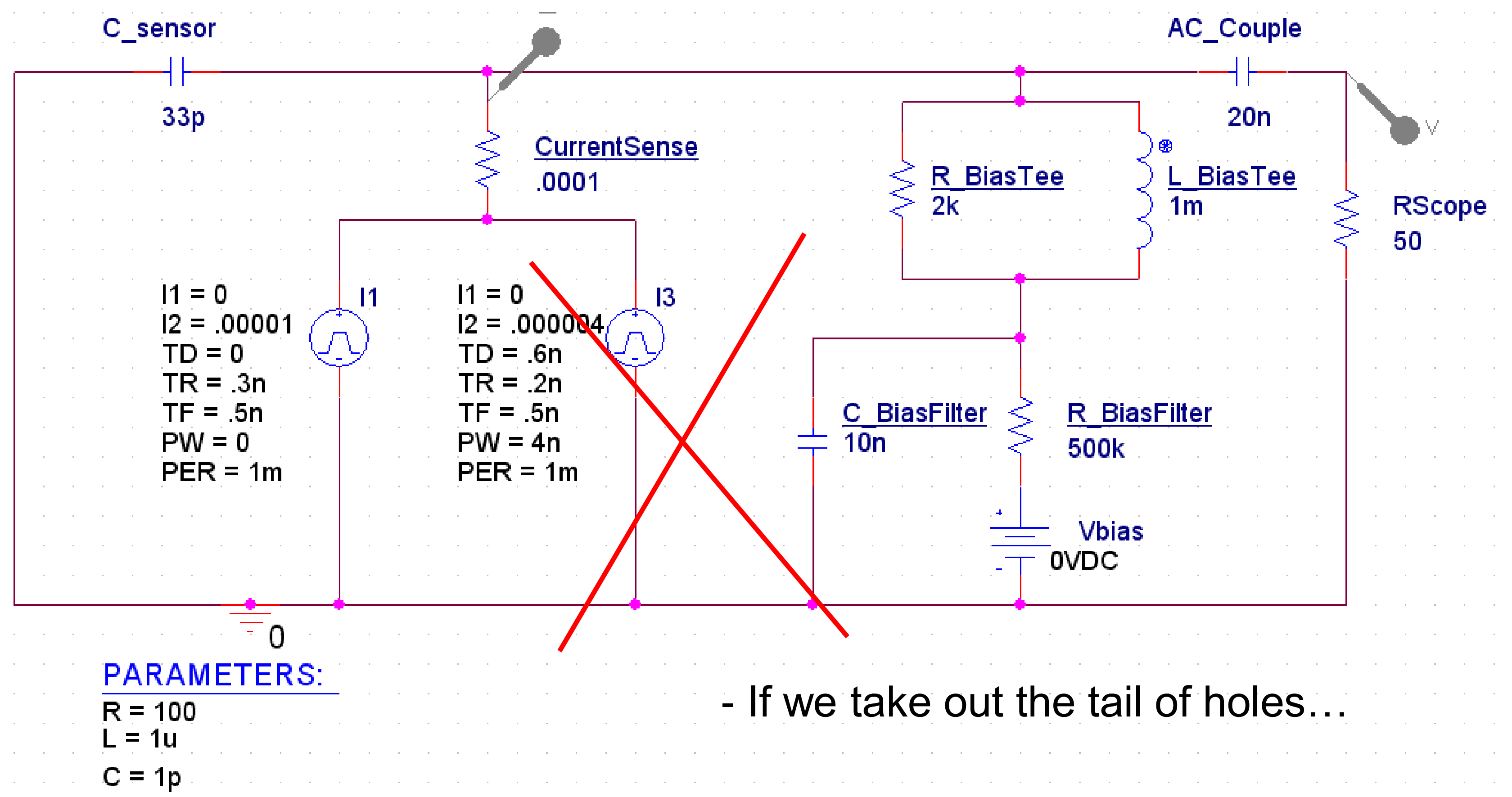
I1 = 0
I2 = .00001
TD = 0
TR = .3n
TF = .5n
PW = 0
PER = 1m

I1 = 0
I2 = .000004
TD = .6n
TR = .2n
TF = .5n
PW = 4n
PER = 1m

PARAMETERS:
R = 100
L = 1u
C = 1p

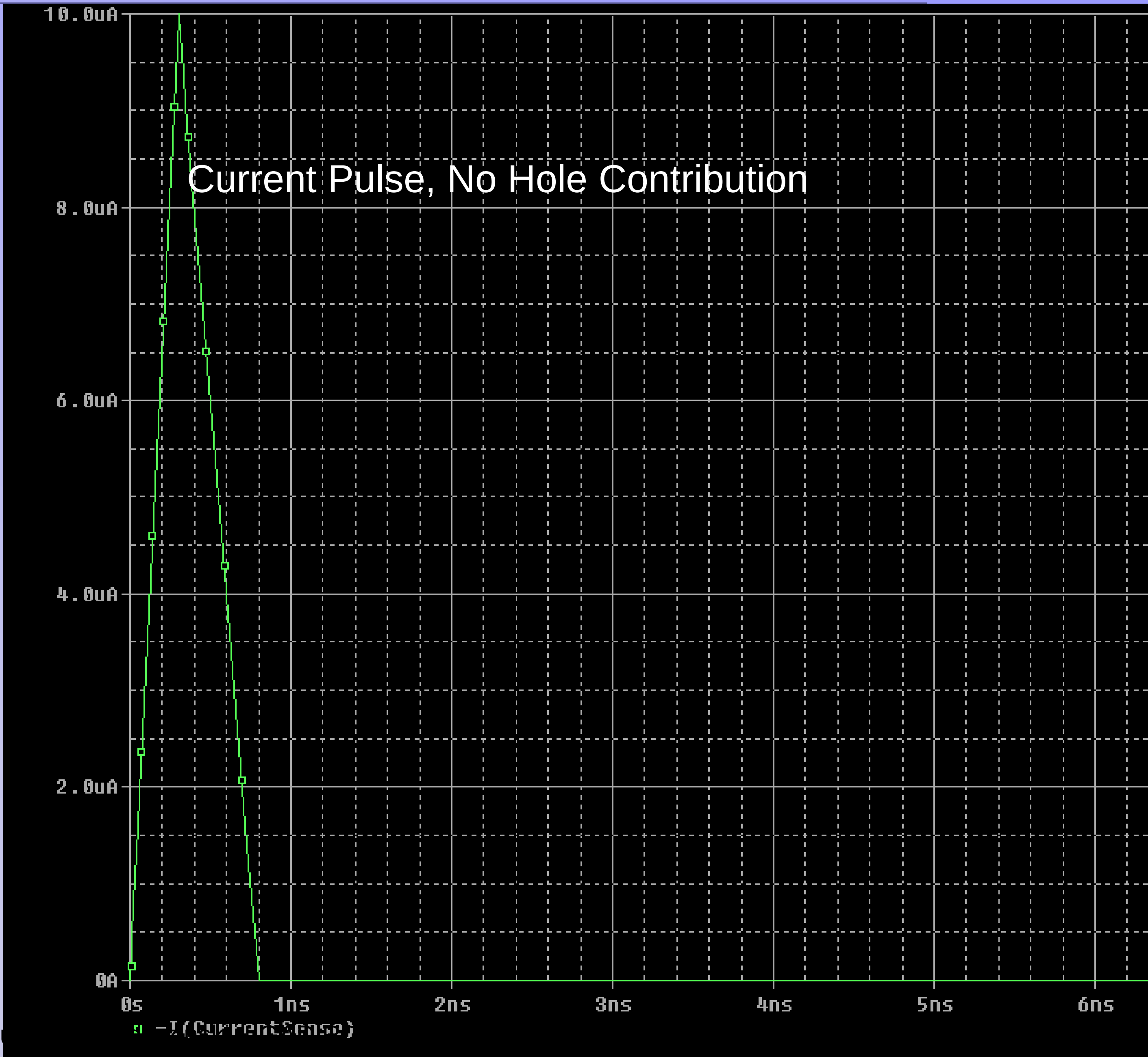
Varying L, R, and C parameters for Bias T doesn’t affect output much.

Current Pulse w/ No Hole Contribution



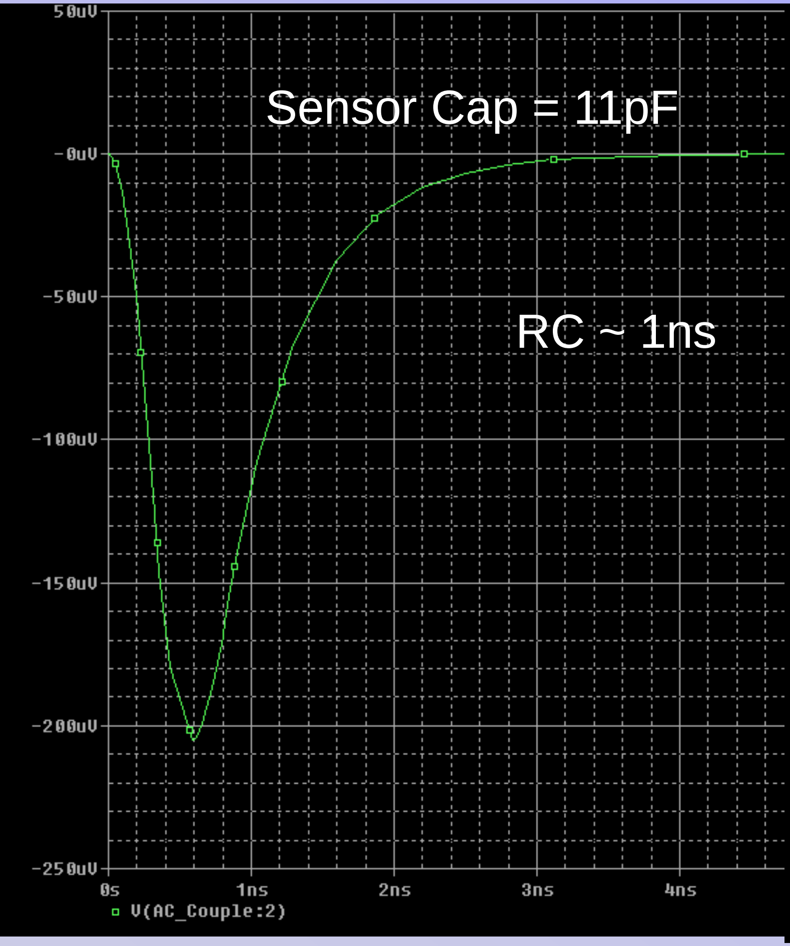
- If we take out the tail of holes…

Input: Electrons Only



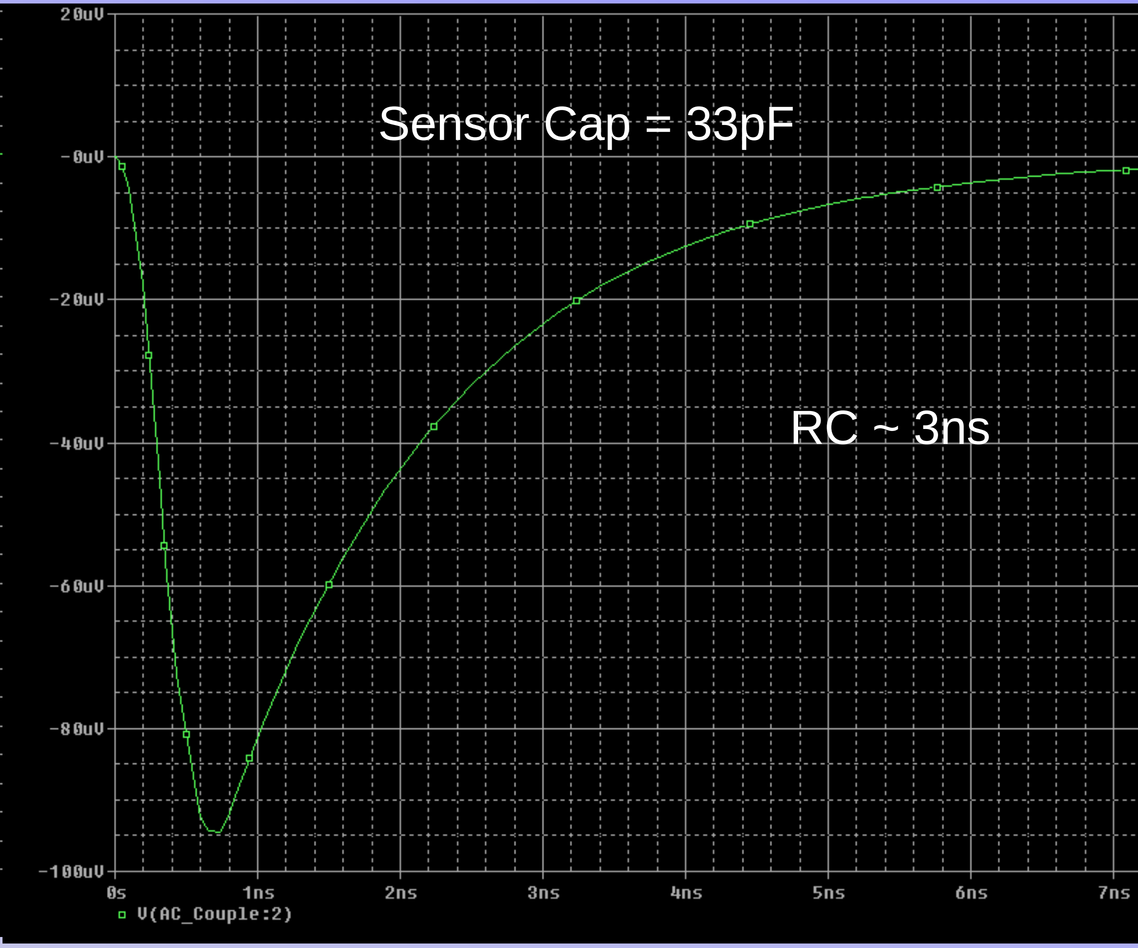
Current Pulse, No Hole Contribution

Output Signals



Sensor Cap = 11pF

RC ~ 1ns



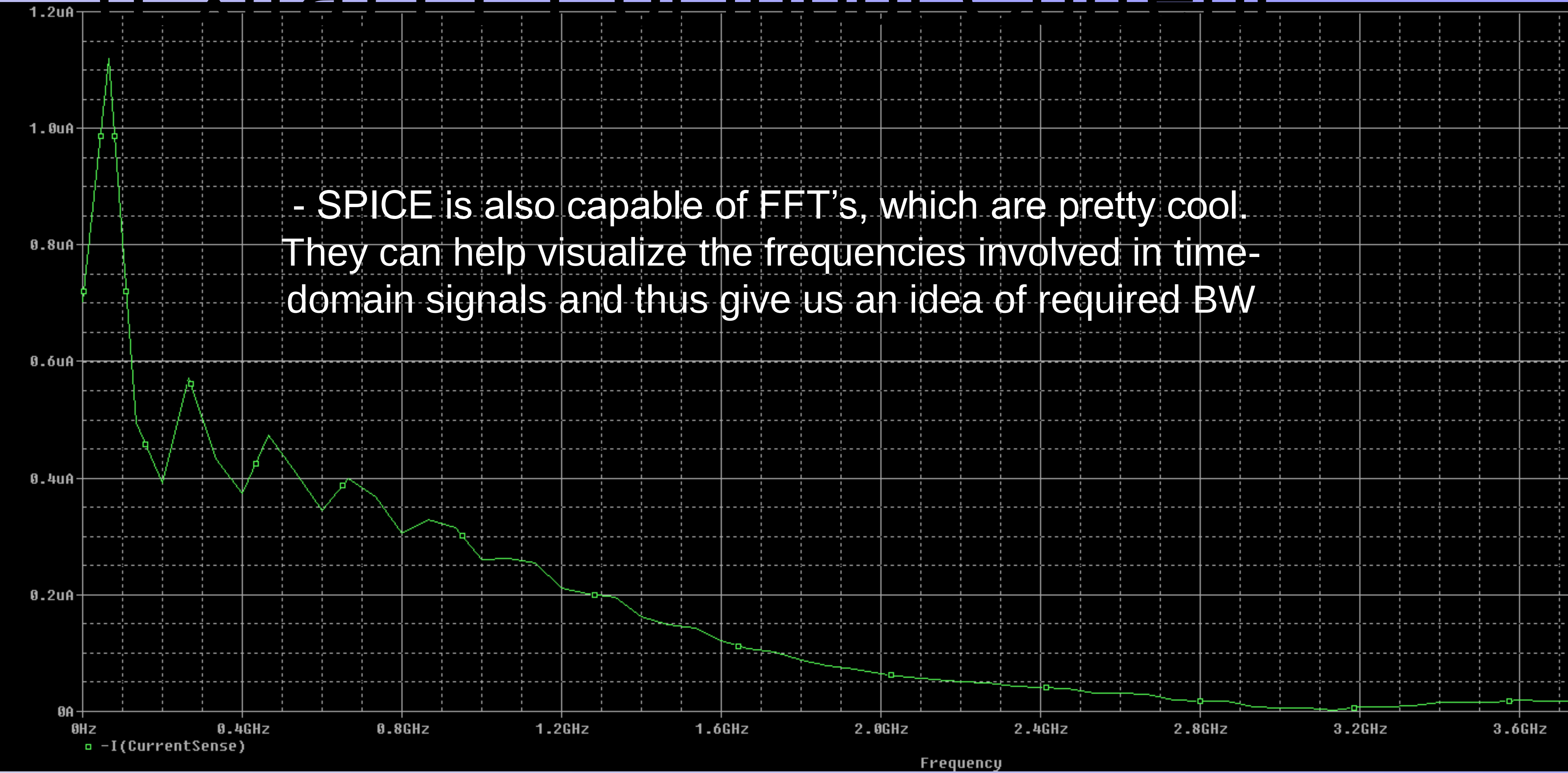
Sensor Cap = 33pF

RC ~ 3ns

Conclusions

- SPICE indicates that the sensor capacitance should be the dominant factor in discharge time.
- For our circuitry RC is of order ~ few ns
- Bias T seems not to play an important role, neither does bias filter

(Extra) FFT of Input Current



- SPICE is also capable of FFT's, which are pretty cool. They can help visualize the frequencies involved in time-domain signals and thus give us an idea of required BW