4D Sensors: Unifying the Space and Time Domain with Ultra-Fast Silicon Detectors

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with
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“4D”

Ultra-Fast Silicon Detectors (UFSD) incorporate the time-domain into the excellent position resolution of semiconductor sensors

they provide in the same detector and readout chain

- ultra-fast timing resolution [10’s of ps]
- precision location information [10’s of μm]

A crucial element for UFSD is the **charge multiplication** in silicon sensors investigated by RD50, which permits the use of **very thin** detectors without loss of signal-to-noise.

Hartmut Sadrozinski, “Exploring charge multiplication for fast timing with silicon sensors”, 20th RD50 Workshop, May 30 to June 2, 2012, Bari, Italy

https://indico.cern.ch/getFile.py/access?contribId=18&sessionId=8&resId=1&materialId=slides&confId=175330

2 questions need to be addressed for UFSD:

- can they work: signal, capacitance, collection time vs. thickness
- will they work: required gain and E-field, fast readout

Revisit in this talk:

- **Energy loss in thin sensors**
- **Charge multiplication data**
- **Collection time**

Energy Loss in thin Silicon sensors

Can 4D-UFSD work? Collected Charge & Capacitance

~~Signal = thickness*EPM (EPM = 73 $e^-/\mu m$)~~

~~Collection time = thickness/v_{sat} (v_{sat} (e) = 100 $\mu m/ns$)~~

WRONG

Details of Collected Charge in Thin Sensors

Energy loss measurement for charged particles in very thin silicon layers

S. Meroli, D. Passeri and L. Servoli

11 JINST 6 P06013

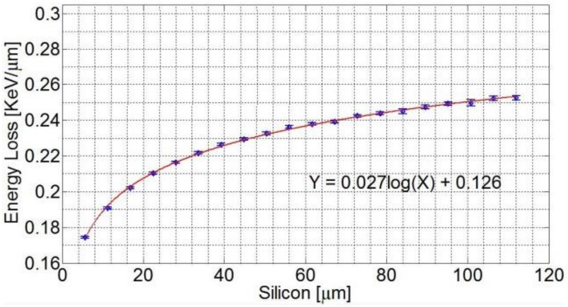


Figure 11. Energy loss for 12GeV protons passing through several silicon thickness.

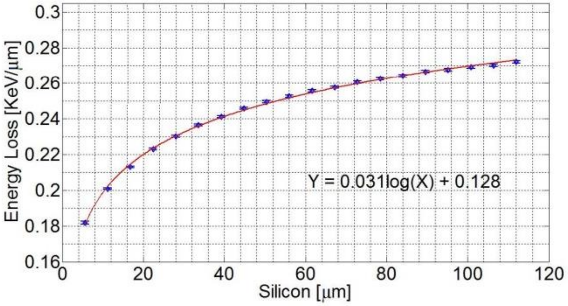
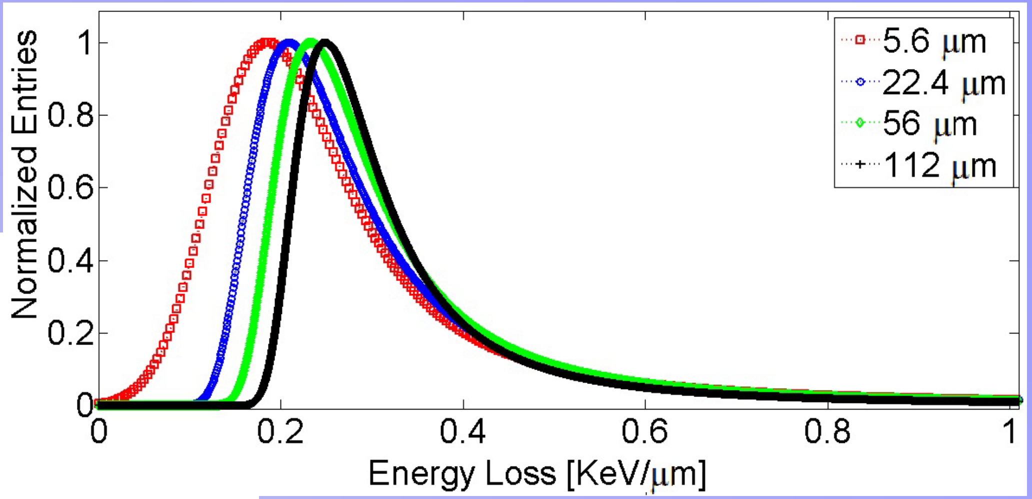


Figure 12. Energy loss for 100MeV electrons passing through several silicon thickness.



Reduced measured energy loss
in very thin silicon layers

Can 4D-UFSD work? Correct Collected Charge

Collection time = thickness/v_{sat} (v_{sat} = 80 μm/ns) (holes)

Thickness	BackPlane Capacitance		Signal	Coll. Time	Gain required	
[um]	Pixels [fF]	Strips [pF/mm]	[# of e-]	[ps]	for 2000 e	for 12000 e
1	**250**	5.0	35	13	57	343
2	125	2.5	80	25	25	149
5	50	1.0	235	63	8.5	51
10	25	0.50	523	125	3.8	23
20	13	0.25	1149	250	1.7	10.4
100	3	0.05	6954	1250	0.29	1.7
300	1	0.02	23334	3750	0.09	0.5

Realistic gain & cap

Good time resolution

For pixel thickness > 5 um, Capacitance to the backplane Cb < Cint (200 fF)

For pixel thickness = 2 um, Cb ~ ½ of Cint, and we might need bipolar (SiGe)?

Viable sensor thickness 2 µm – 10 µm (i.e. 20-100ps)

Needed Gain: Pixels 4 – 25, Strips (1 mm) 20- 150

(much less than APD's or SiPM)

Note: CNM (Barcelona) is routinely producing 10 µm thick sensors.

Charge Multiplication

Charge Multiplication

A. Macchiolo,16th RD50 Workshop Barcelona, Spain, May 2010

Charge multiplication in path length *ℓ* :

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

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

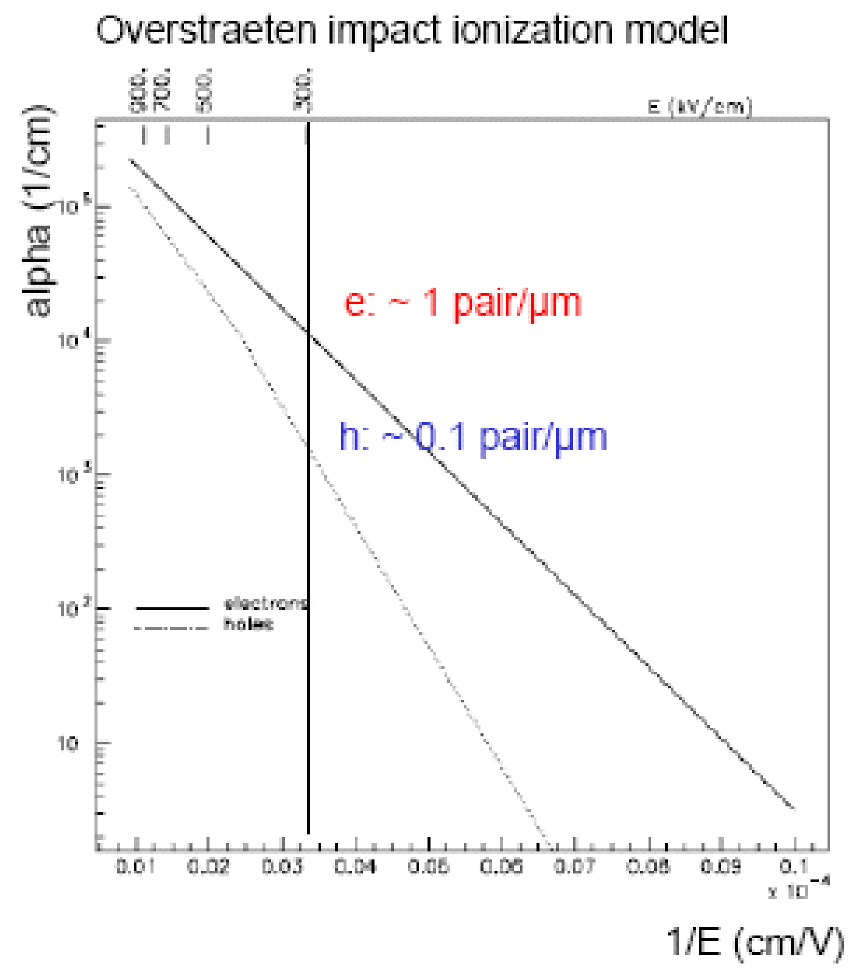
At the breakdown field in Si of 270kV/cm:

$\alpha_e \approx 0.7$ pair/µm

$\alpha_h \approx 0.1$ pair/µm

→ gain g = 33 possible in *l* = 5 µm.

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



Need to raise E-field as close to breakdown field as possible for high gain but not too much to prevent breakdown!

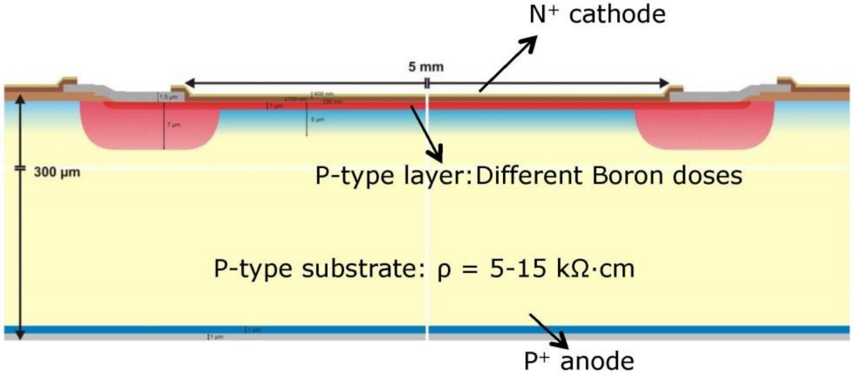
Gain in Silicon Diodes w/o Radiation

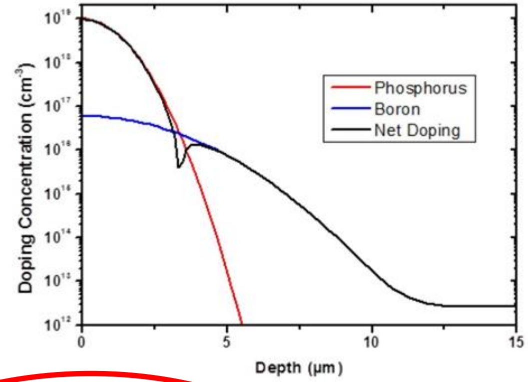
Breakthrough 2013:
Gain on un-irradiated diodes from CNM
Design, manufacturing, measurements
Marta Baselga
Giulio Pellegrini
P. Fernandez, et al, NIM A658(2011) 98–102.

Measurements
MIPs: Gregor Kramberger,
Red TCT: Marcos Fernandez Garcia,
α's: Marta Baselga, Scott Ely

Pads detectors with multiplication

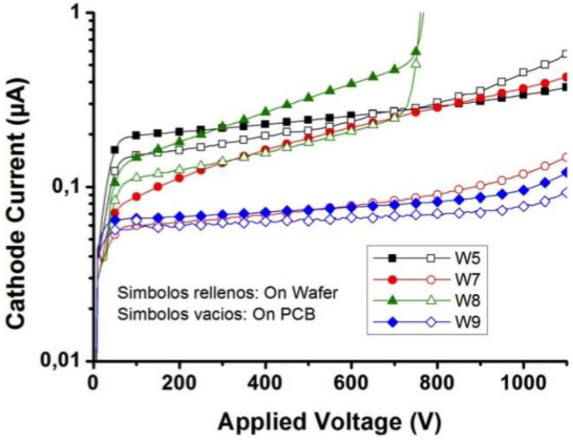
300 µm thick n-on-p diode

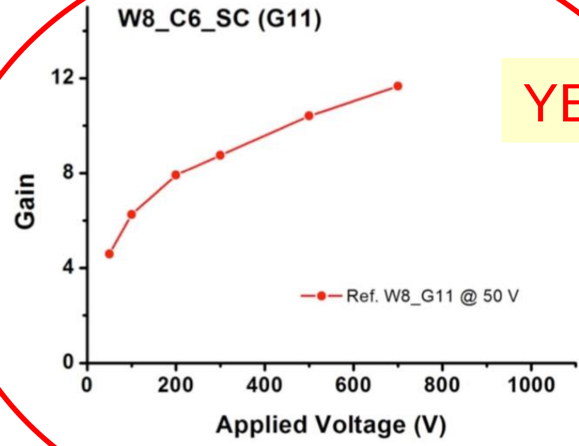




see
Salvatore Hidalgo's talk

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





YESSS!

Gain/No-Gain Diodes: Top/Back with Am(241) α's

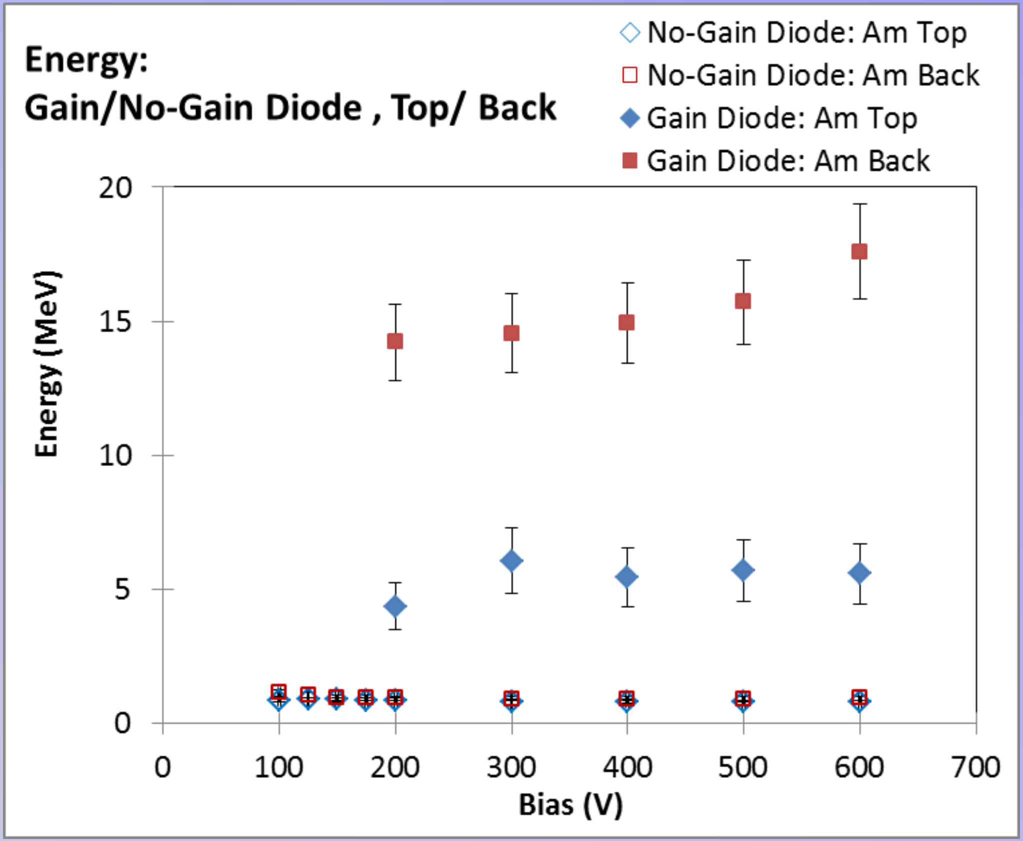
Charge collection with α's from Am(241) at UC Santa Cruz

2 CNM 300um thick diodes
One with gain ("Gain"),
one without gain ("No-gain")
α's from junction side ("Top") and back ("Back")

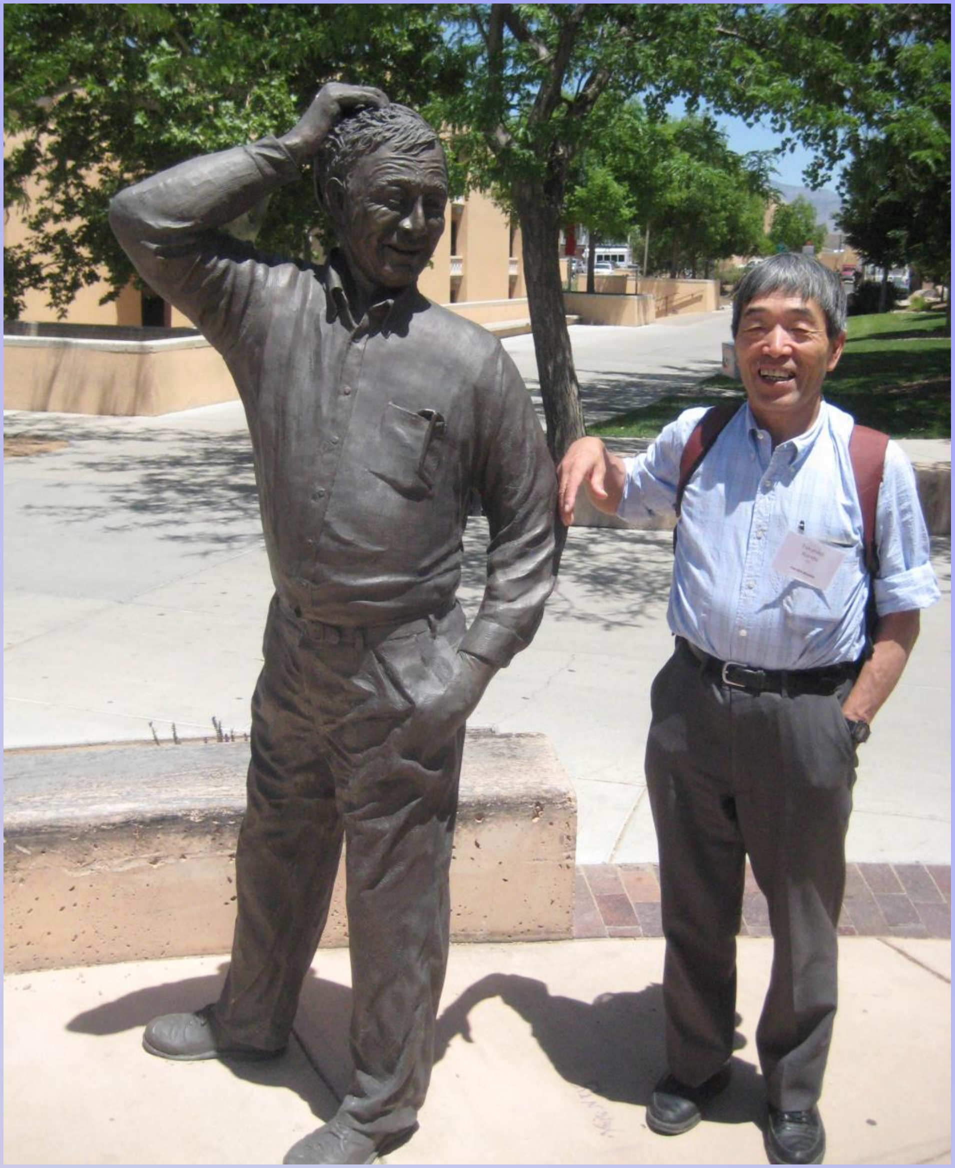
Details: Scott Ely's talk

Energy =
(# of collected e&h)*3.6eV

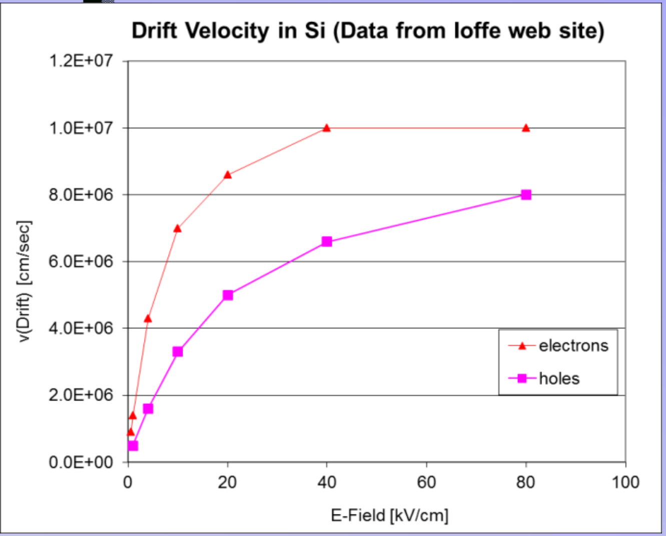
Collection time:
300ns



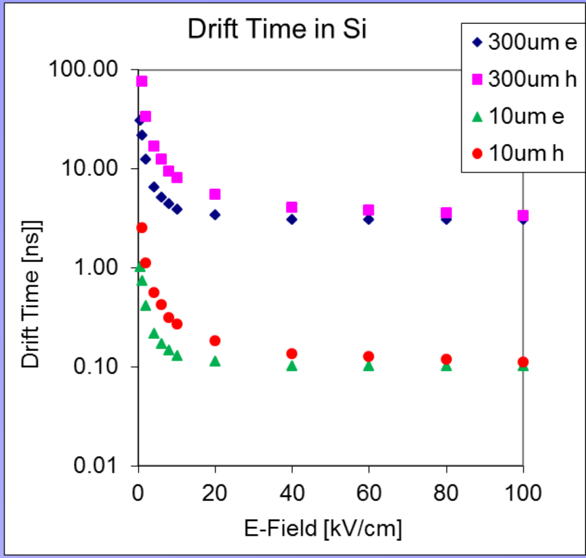
Charge Collection

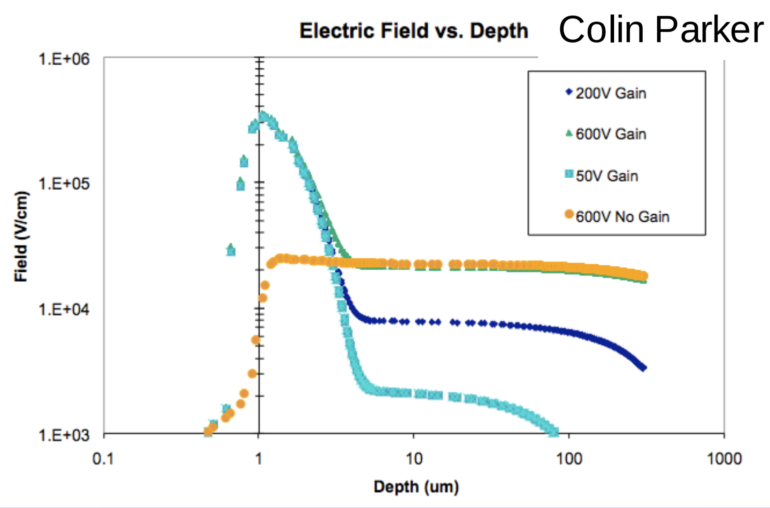


Collection of Charges in Diodes w-w/o Gain



Collection time
E-Field = 20 kV/cm
300um Si
~ 5 ns (h), ~ 3 ns (e)
10um Si
~ 0.3 ns (h), ~ 0.1 ns (e)





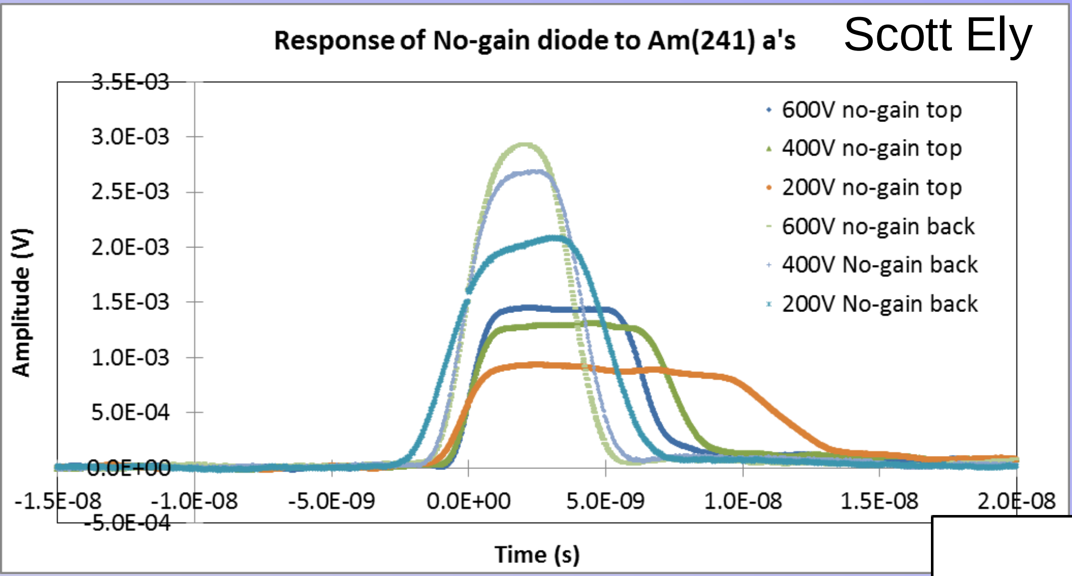
Colin Parker

Field Simulations: Colin Parker’s talk
-> charge collection should be fast <10 ns
-> bias dependence of the collection time for back

Hartmut F.-W. Sadrozinski: UFSD RD50 ABQ 2013

No-gain Diode: Signal from Am(241) α’s

“ Top” = holes
“Back” = electrons



Scott Ely

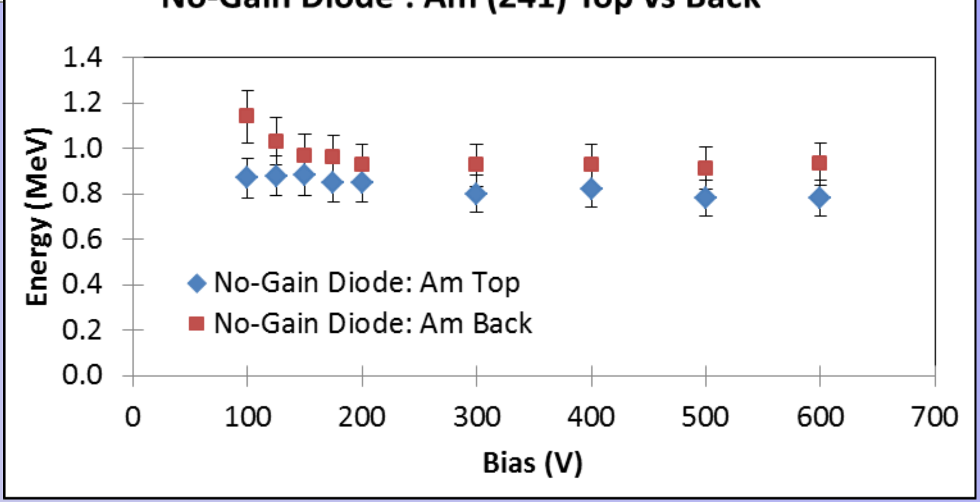
Collection time scales
with drift velocity.
Electron-hole difference
Bias voltage dependence

“slight” tail due to high charge concentration: “screening”?

Am(241) α’s :
“ Top” ≈ “Back”

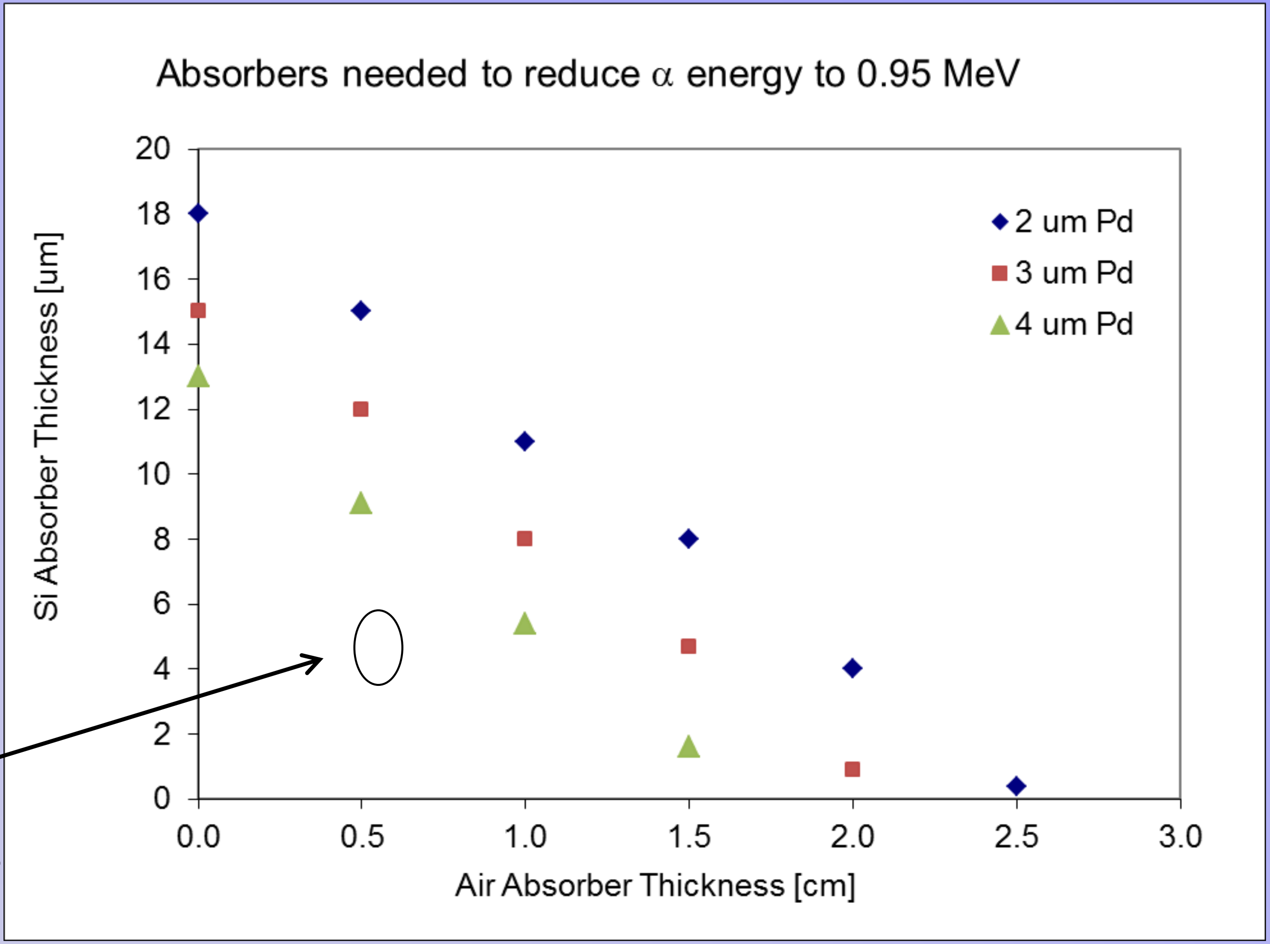
5.45 MeV -> 0.95 MeV

Absorption or recombination?



Signal from Am(241) α’s : 5.45 MeV -> 0.95 MeV

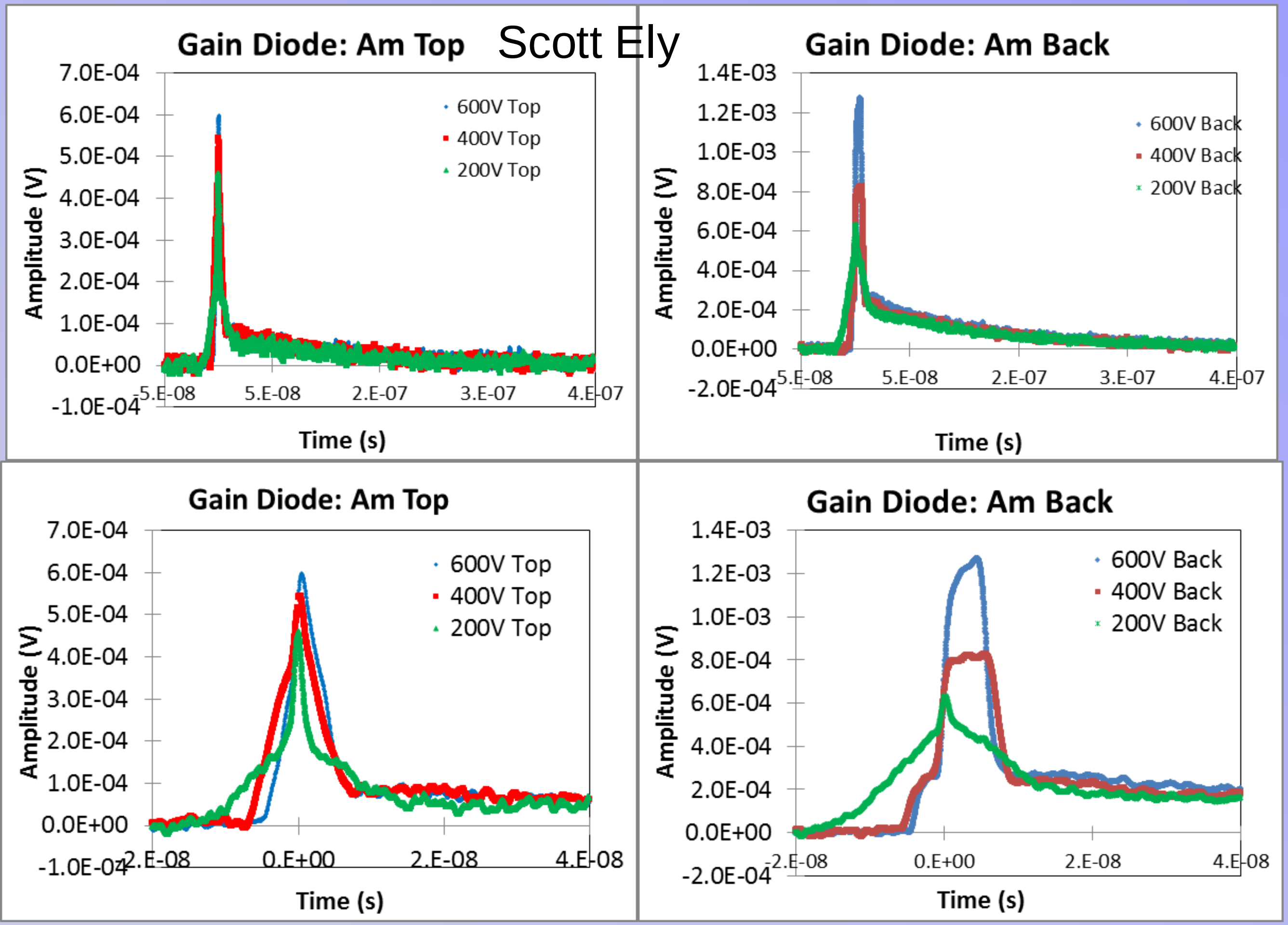
Absorption: ~2umPd window, 5 mm air, few um of inactive Si oxide and Si implants



Expectation from layout?

Evidence for recombination ?

Gain Diode: Signal from Am(241) α’s



Scott Ely

Back / Top = 2-3:1

Long tail: 300 ns,
typical of diffusion,
not drift (~10ns)

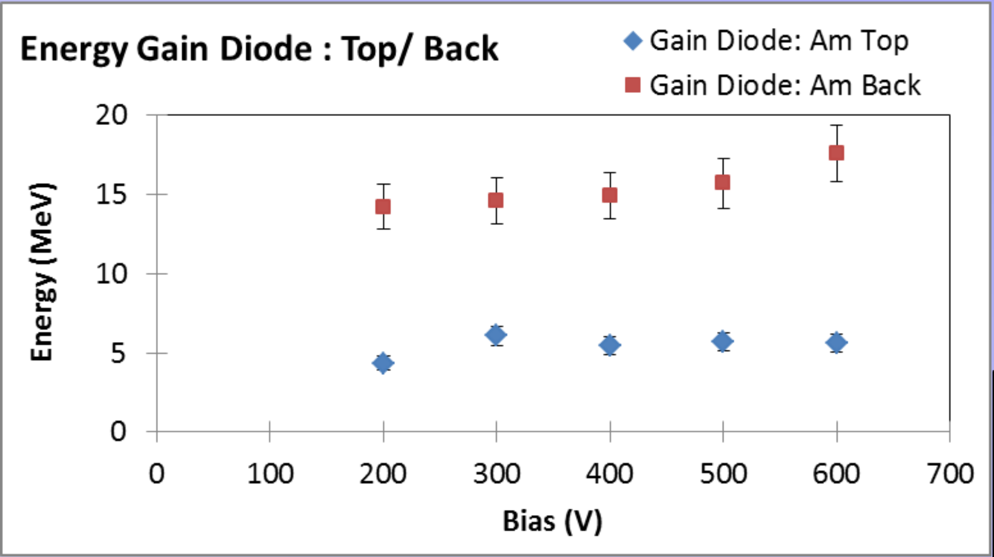
Bias dependence:
Back: yes
Top: no

Top: Fast collection of e’s
Long tail: 300 ns

Back:
Fast collection of direct e’s
Fast collection of multiplied e’s
Long tail: 300 ns

Gain Diode: Top/Back from Am(241) α's

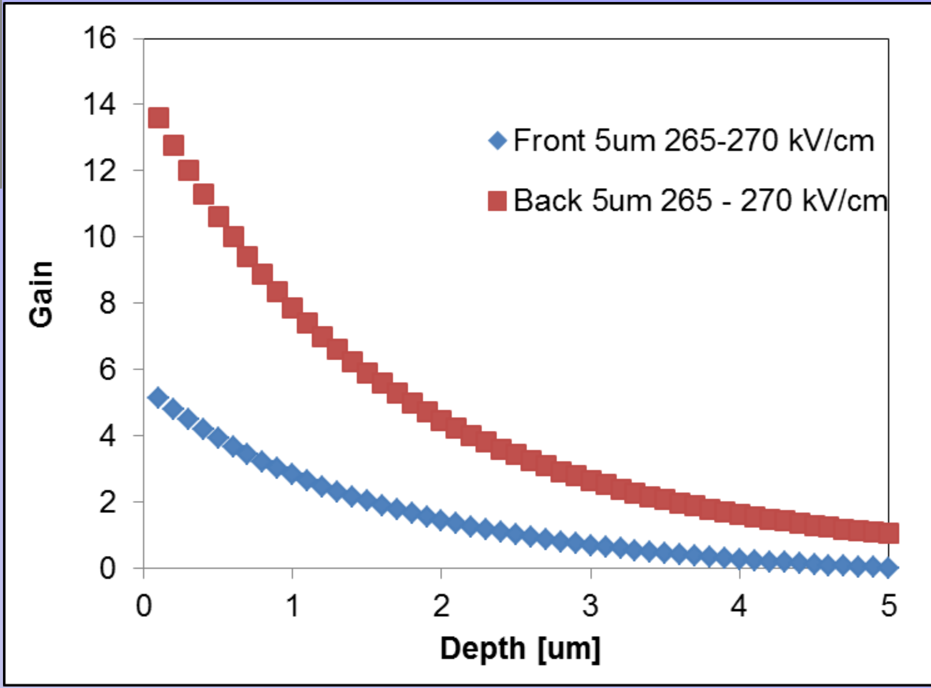
Gain = Charge collected from Gain Diode/ Charge collected from No-Gain Diode



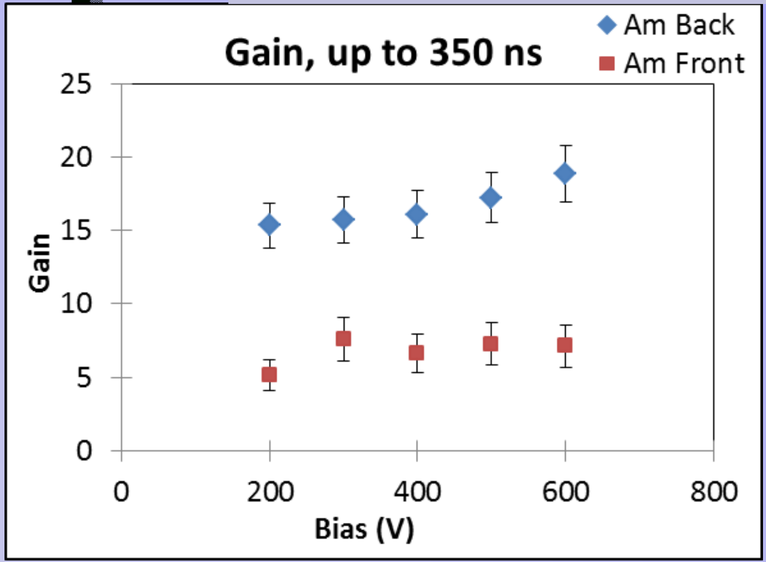
Ratio Gain(Top)/Gain(Back) ≈3

Toy simulation:
Assume 5um deep amplification field
Linear from 265 kV/cm to 270 kV/cm

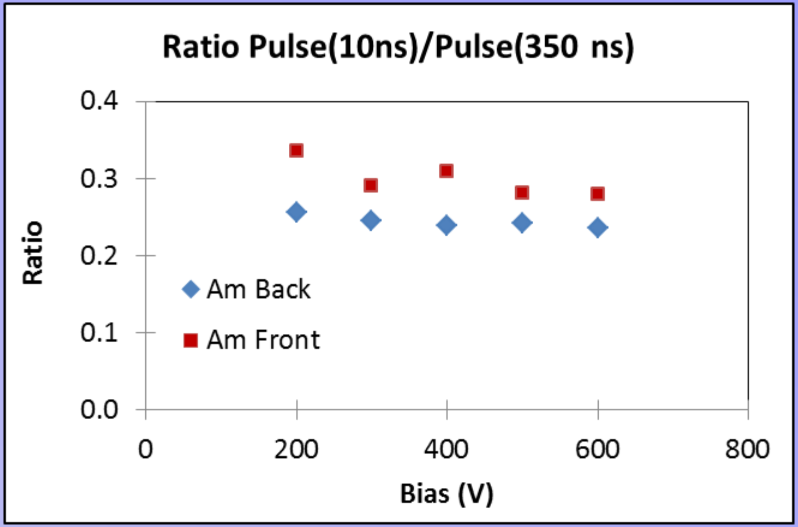
"Back": All e's get maximally amplified
"Top": Most e's get amplified less than max.

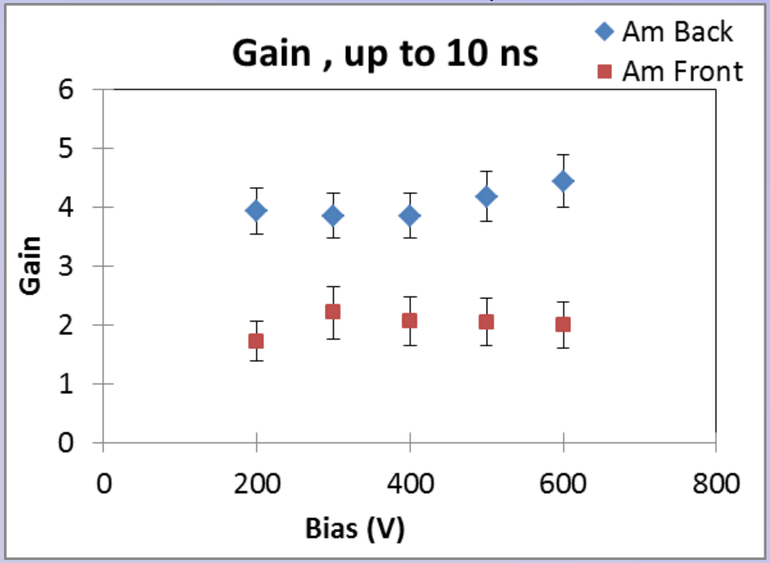


Integration Time Dependence of Gain with α's



Much of the charge from the impact ionization is delayed presumably due to screening.
Fast pulse (~10ns) has only ~30 % of total charge!





Important Question:
how much is this behavior specific to α's?
Energy density of α interaction: 50 keV/μm
i.e. 15,000 e/μm, in gain region 150,000 e/μm
Density of charges: α/MIP = 200.
Need to investigate MIP's or low-level red laser.
both with measurements and simulations.

Score Card for UFSD after one year

Improved understanding of collected charges in thin sensors: lost ~ factor 2
Gain in un-irradiated diodes: 10x observed!
Charge collection: MIPs, low-level laser needed to investigate screening ?
Readout electronics: SiPM readout for TOF-PET is on the right path

Important next step: measurements on sensors with pixels/strips which are in production at CNM.

What about fast readout?

- CERN fixed-target experiment (NA62) needs very fast pixel sensors: Gigatracker (GTK)
- Prototype CFD system (INFN Torino) has ~ 100 ps resolution, predicted to be 30 ps in next iteration.
- Optimized for 200µm sensors and hole collection (?), could it be re-designed for electron collection from 2 – 10µm sensors?

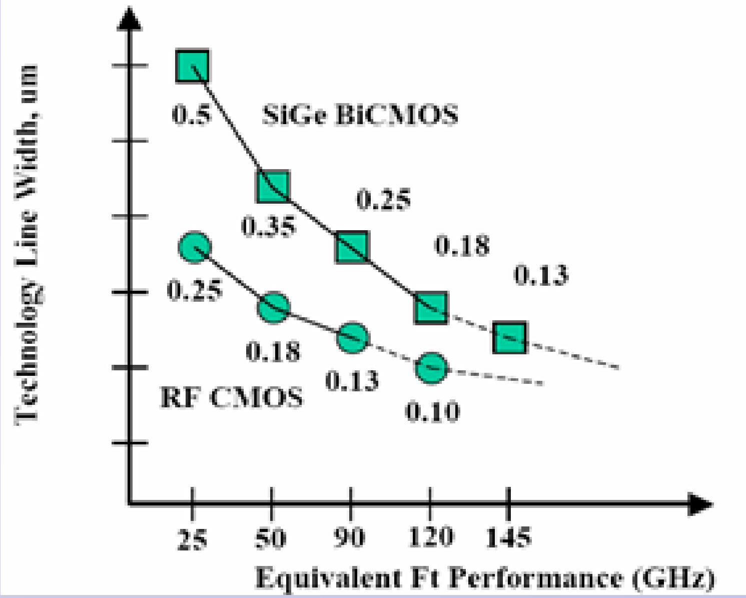


Figure 8 Comparison between CMOS and SIGe technologies

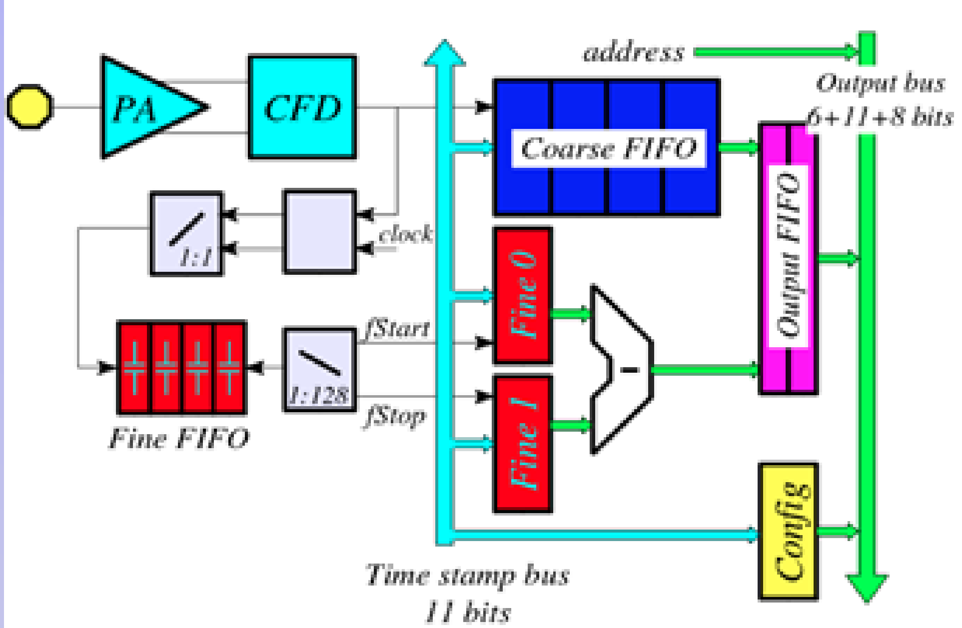


Figure 9 Example of the CFD-TAC approach proposed in [3]

Example of ASIC development for fast signal processing:

Here much larger dynamic range

Integrated Circuit Design for Time-of-Flight PET with Silicon Photomultipliers

Manuel Dionisio Rolo, Angelo Rivetti, Ricardo Bugalho,
Carlos Gastón, Gianni Mazza, Richard Wheadon,
Jose Carlos da Silva, Rui Silva, Joao Varela

LIP - Laboratorio de Instrumentaçao e Fisica Experimental de Particulas
INFN - Istituto Nazionale di Fisica Nucleare sez. Torino

"The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/ 2007-2013) under Grant Agreement n°256984."

8th "Trento" Workshop on Advanced Silicon Radiation Detectors (3D and p-type)
February 18-20 2013, FBK Trento, Italy