Ultra-Fast Silicon Detector

The holy Grail of PPS and AFP is a unified detector with the following performance:
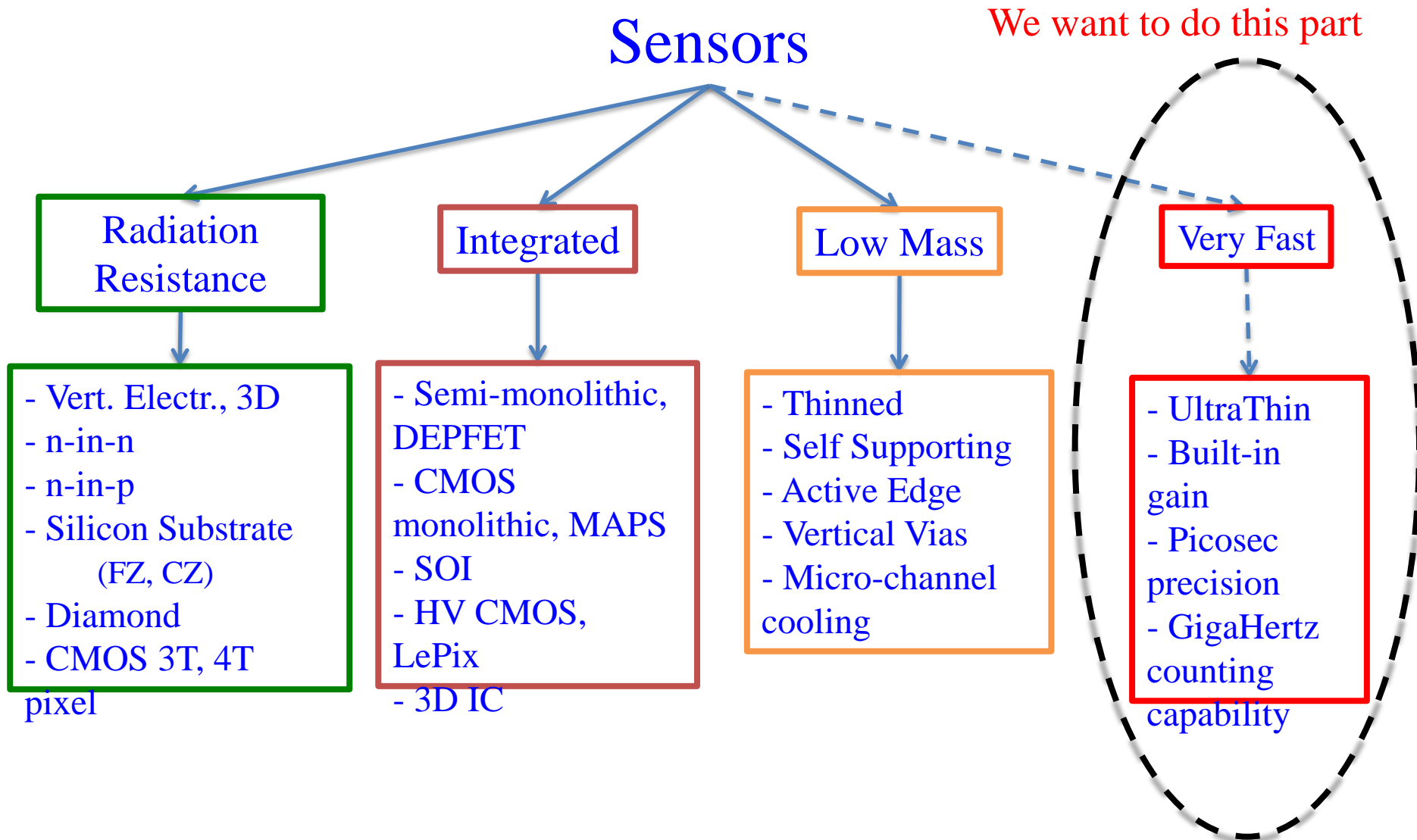
> » $\sigma_T \sim 20$ ps
>
> » $\sigma_x \sim 20$ μm

We have therefore decided to try building it [ufsd]
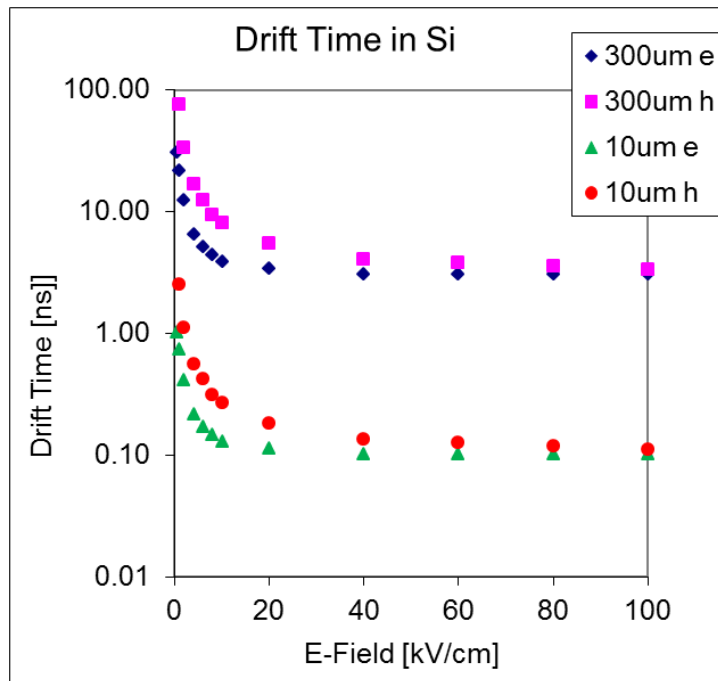
A planar pixel detector with excellent time resolution
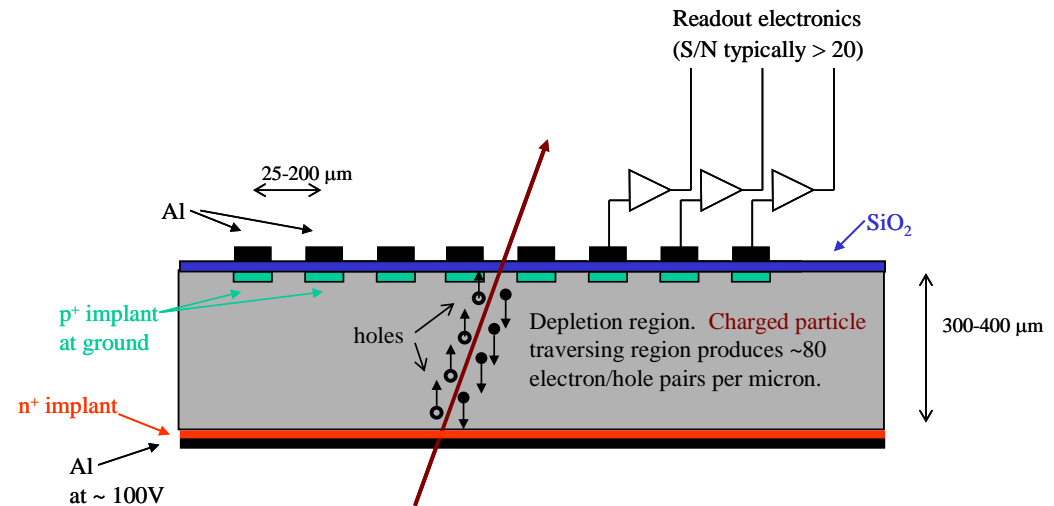
[ufsd] Ultra-fast Silicon Detector: H.-W. Sadrozinski, M. Bruzzi, N. Cartiglia., Nuclear Instruments & Methods in Physics Research A (2013), http://dx.doi.org/10.1016/j.nima.2013.06.033i

Lot's of silicon development

Sensors

We want to do this part

Radiation Resistance

Integrated

Low Mass

Very Fast

- Vert. Electr., 3D
- n-in-n
- n-in-p
- Silicon Substrate
    (FZ, CZ)
- Diamond
- CMOS 3T, 4T
pixel

- Semi-monolithic, DEPFET
- CMOS monolithic, MAPS
- SOI
- HV CMOS, LePix
- 3D IC

- Thinned
- Self Supporting
- Active Edge
- Vertical Vias
- Micro-channel cooling

- UltraThin
- Built-in gain
- Picosec precision
- GigaHertz counting capability

Signal in Silicon detector

Collection time is close to minimum when E-Field ≥ 20 kV/cm

Readout electronics (S/N typically > 20)

25-200 µm

Al

SiO_2

p^+ implant at ground

holes

Depletion region. Charged particle traversing region produces ~80 electron/hole pairs per micron.

300-400 µm

n^+ implant

Al at ~ 100V

Drift Time in Si

- ◆ 300um e
- ■ 300um h
- ▲ 10um e
- ● 10um h

For 300 µm Si
Collection time ~ 5 ns (h), ~ 3 ns (e)

Why is it difficult?

Good timing can be achieved with long signals only if the signals are extremely stable.
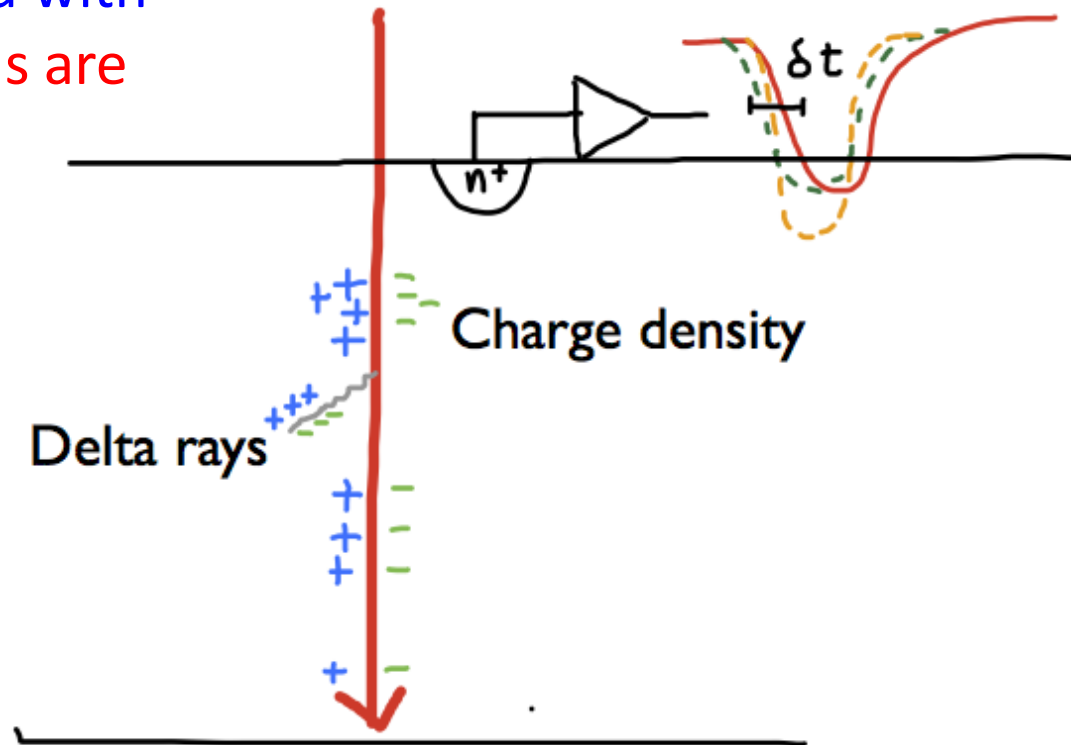
This is not the case in silicon detectors: local fluctuations of charge density cause signal distortions such that is difficult to time the arrival time better than ~ 1-200 ps

Solution: very thin detectors

If the drift time is really short (~100-200 ps), then the fluctuation will not spoil much the time resolution:

➔ make the active area very small

Following problem: thin area generate small signal, which is bad for timing.

➔ introduce gain to compensate for loss of signal

Gain in silicon: it turns out that if the drift velocity is high enough, there is multiplication of carriers.

Charge Multiplication

Charge multiplication in path length ℓ :

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

$$\alpha_{e,h}(E) = \alpha_{e,h}(\infty) * \exp\left(-\frac{b_{e,h}}{|E|}\right)$$
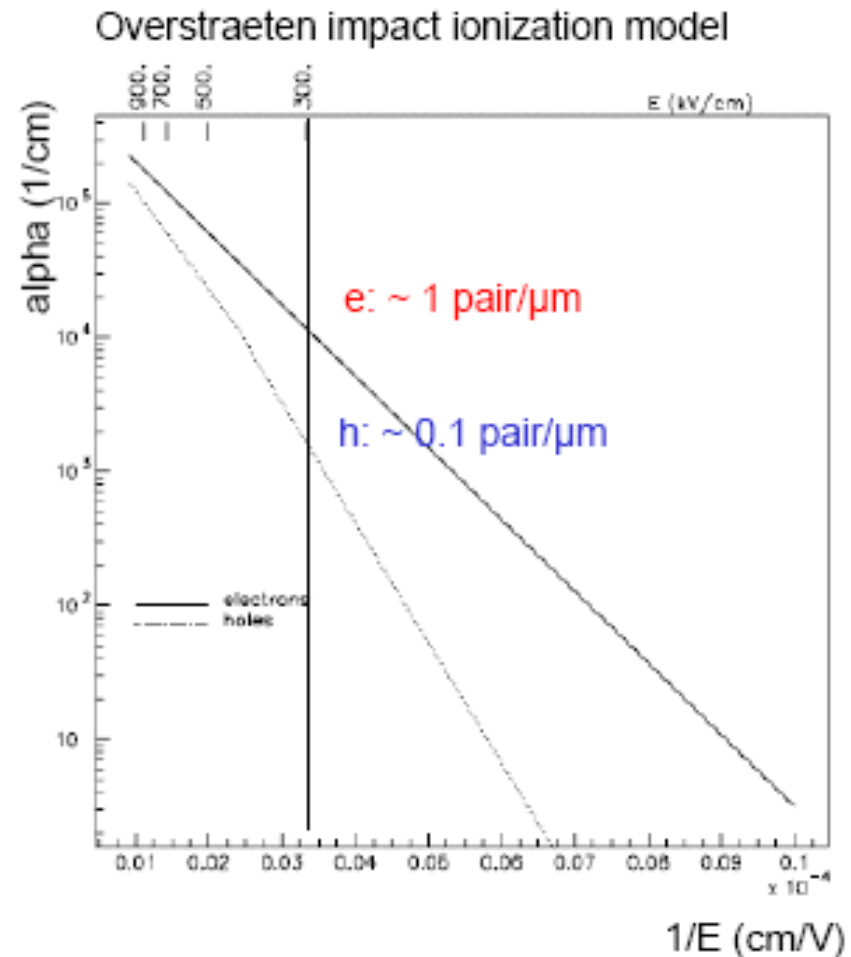
At the breakdown field in Si of 270kV/cm:

$\alpha_e \approx 0.7$ 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

Overstraeten impact ionization model
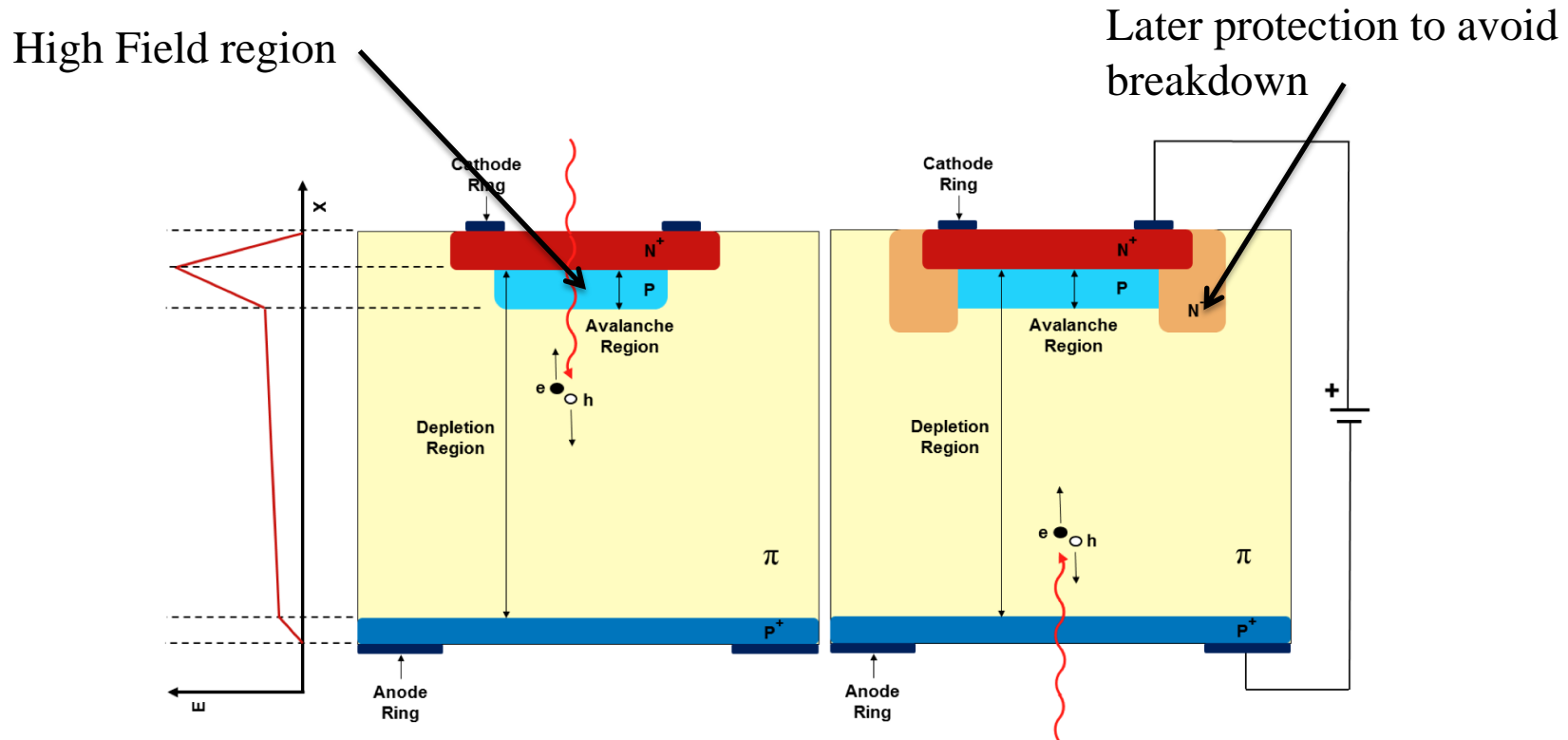
e: ~ 1 pair/μm

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!**
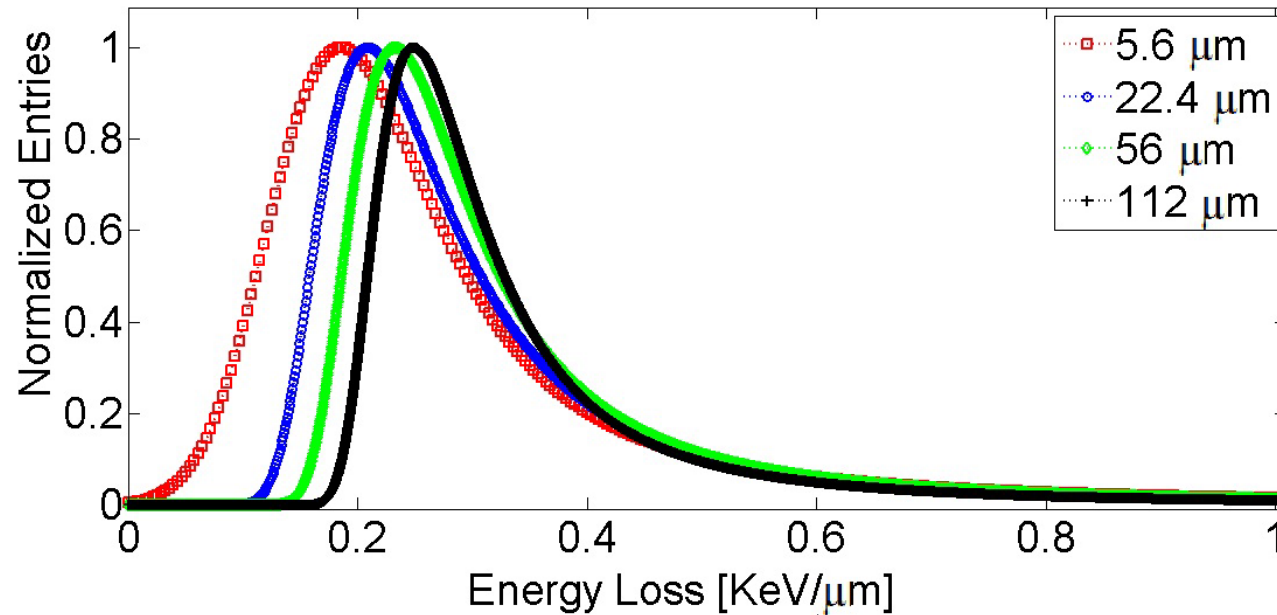
How to do it

Thin silicon sensor with built in gain:

- Add   "deep p+" diffusion layer to achieve charge multiplication (see SiPM).
- Change the sensor shape to avoid break-down

High Field region

Later protection to avoid breakdown

Details of Collected Charge in Thin Sensors

Energy loss measurement for charged particles in very thin silicon layers

Reduced measured energy loss in very thin silicon layers

S. Meroli, D. Passeri and L. Servoli
11 JINST 6 P06013

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

Thickness [um]	BackPlane Capacitance		Signal [# of e-]	Coll. Time [ps]	Gain required	
	Pixels [fF]	Strips [pF/mm]			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)?
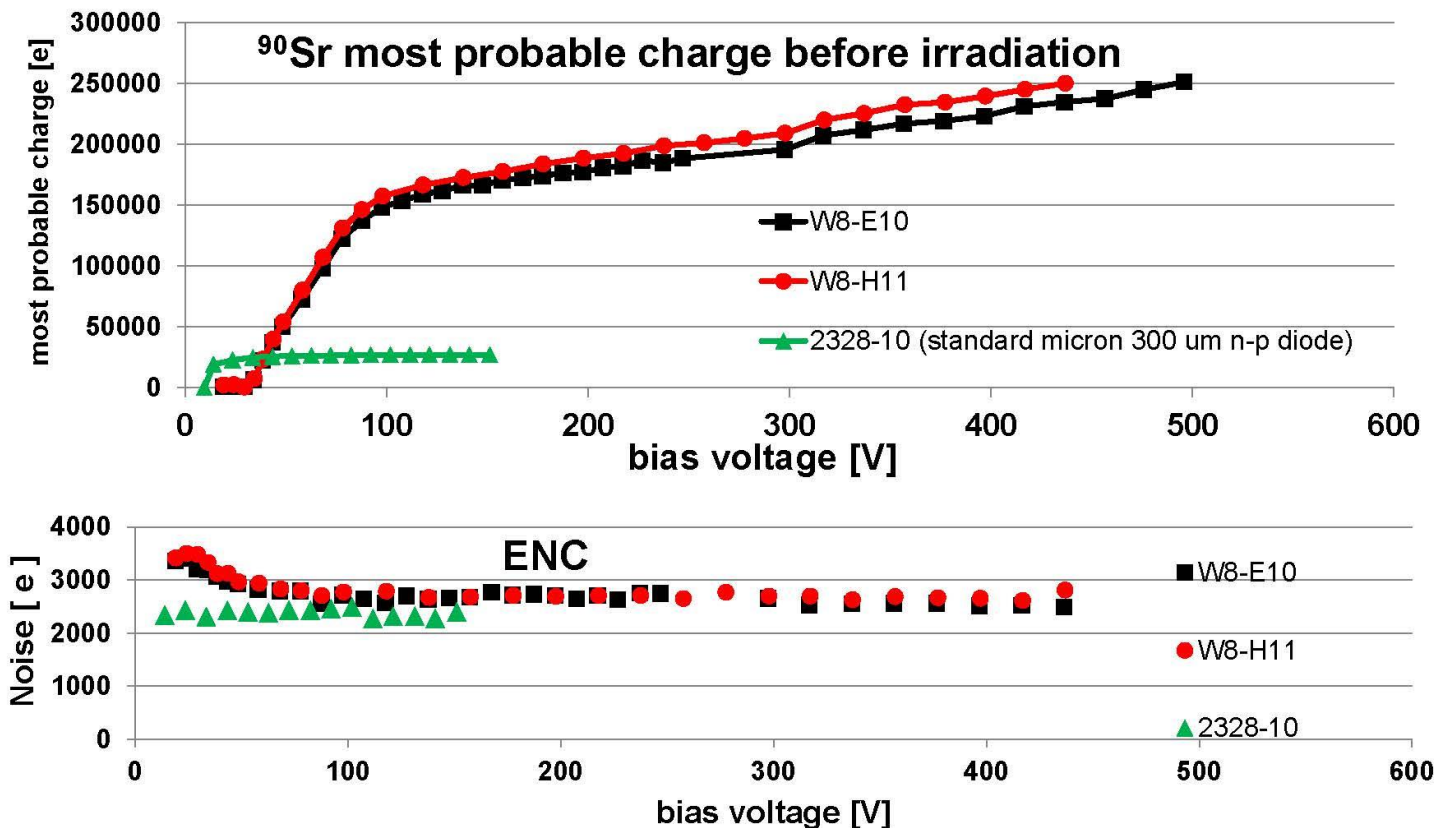
Viable sensor thickness 2 µm – 10 µm (i.e. 20-100ps)

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.

Most probable signal and noise

^{90}Sr most probable charge before irradiation

(plot: most probable charge [e] vs bias voltage [V])
- W8-E10
- W8-H11
- 2328-10 (standard micron 300 um n-p diode)

ENC

(plot: Noise [e] vs bias voltage [V])
- W8-E10
- W8-H11
- 2328-10

➢ Improvement of signal **for a factor 8 at 300** V before irradiation
➢ No significant increase of noise – dominated by series noise

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?
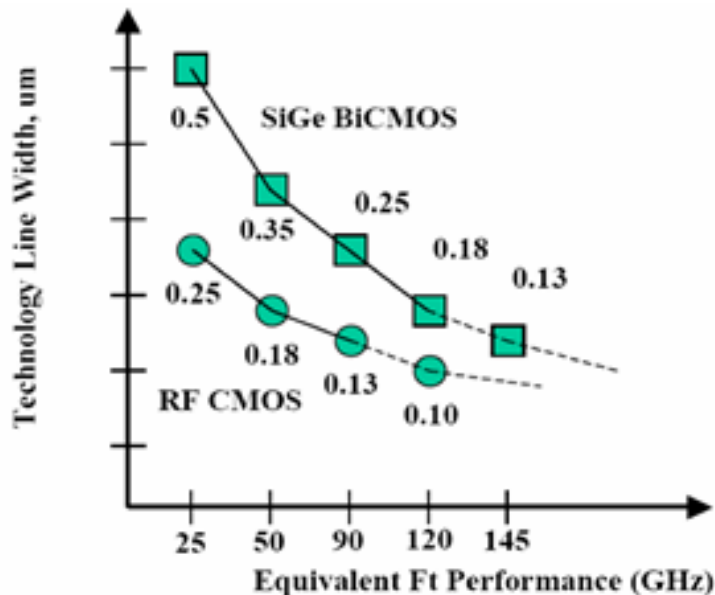

Figure 8 Comparison between CMOS and SiGe technologies
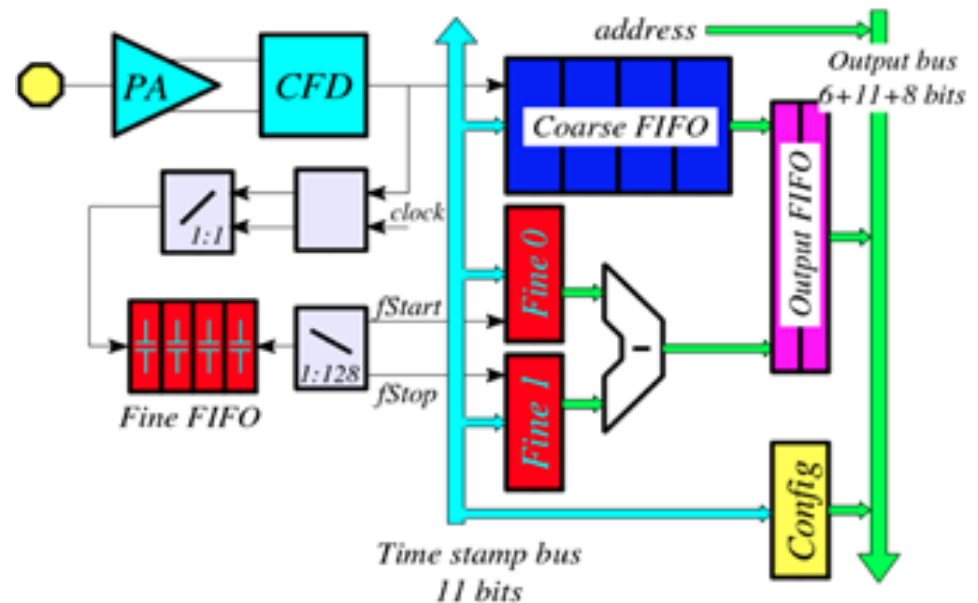

Figure 9 Example of the CFD-TAC approach proposed in [3]

Conclusions

Ultra Fast Silicon Detector can simplify the design of PPS and AFP by combining position and timing measurements

We have started to look at the sensor design, and the first prototypes have been manufactured by CNM, Barcellona.

We reached good gain, compatible with expectations.

UFSD can also be designed using 3D detector