Advanced Solid State Detector Technologies for Particle Detection

Danielle Moraes

on behalf of SIAM Collaboration

http://asi-hdet-project.web.cern.ch/asi-hdet-project/

CERN, Geneva, Switzerland
IMT, Neuchatel, Switzerland
ETH, Zurich, Switzerland
University of Minnesota, USA

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Motivation & Outline

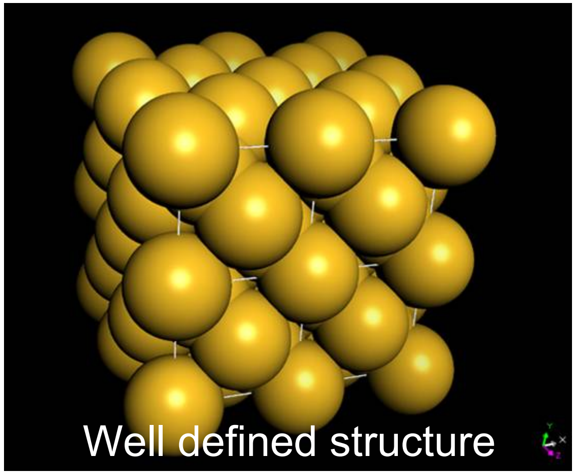
<u>To investigate an alternative solid state detector technology based on the deposition of a thin film sensor on top of an ASIC.</u>

<u>a-Si:H and HgI_2</u>

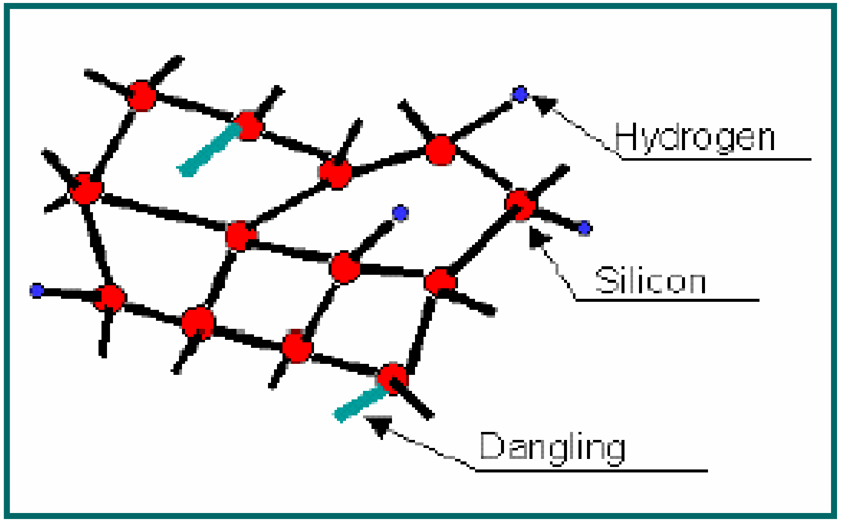
- What is hydrogenated amorphous silicon (a-Si:H) material ?
- Characteristics and Properties of the a-Si:H
- Why use a-Si:H?
- TFA technology
- Deposition technique
  - VHF-PECVD
- a-Si:H Sensors Developed at CERN
  - AFP, Macropad, Mibedo and ASiScope
- Leakage current study
- Charged particle detection and Noise Measurements
- Radiation Hardness of a-Si:H
- HgI_2 test structure
- Conclusion

What is hydrogenated amorphous silicon (a-Si:H) ?

c-Si



a-Si:H



- Silicon atoms not arranged in an ordered structure
  - Defects such as dangling bonds and distorted Si-Si bonds (in both lengths and angles)
- Defects yield energy levels in the energy gap where e-h recombine
  - Reduce mobility and limited current flow
  - Band edges of the Si are replaced by a broadened tail of states
- Hydrogen atoms saturate dangling and weak bonds reducing traps
  - Increases the tolerance to impurities

a-Si:H Properties

Property		Si	a-Si:H
Hydrogen Content	C_H	0	~10-20%
Band Gap at 300 K	E_g	1.12 eV	1.7–1.8 eV
Density		2.33 g/cm^3	2.1 g/cm^3
Pair creation energy	$E_{e\text{-}h}$	3.6 eV	~4–6 eV
Electron Mobility	μ_e	1450 cm^{2}s^{-1}V^{-1}	>10 cm^{2}s^{-1}V^{-1}
Hole Mobility	μ_h	450 cm^{2}s^{-1}V^{-1}	>1 cm^{2}s^{-1}V^{-1}
Full Depletion Field	F_D	< 1V/μm	~10V/μm
Typical Leakage Current	I_{leak}	few nA/cm^2	few nA/cm^2

Much worst properties! So why using it?

Why use a-Si:H ?

a-Si:H is widely used in various types of large-area electronics devices !

DEVICE	PRODUCTS
Photovoltaic cell	Photovoltaic modules, Calculators, watches, battery chargers, etc.
Photoreceptor	Electrophotography, LED printers.
Photoconductor	Colour sensors, light sensors, etc.
Image sensor	Contact-type image sensors, electronic white boards.
Solar control layer	Heat-reflecting float glass.
Thin-film field-effect transistor	Displays, television, logic circuits for image sensors.
High-voltage thin-film transistor	Printers.

⇨⇨ ⇨ It can be deposited on areas up to 1m^2 in a cost effective way.

- Encapsulated solar panels are produced by < 200U$/m^2 (large volume).
- Thin diodes + top contact ~ 50U$/m^2. For thicker diodes price is a bit higher.
- 300µm single sided Si detectors ~10^{5}U$/m^2.

Why use a-Si:H ?

- By using TFA technology, large area pixel detectors with minimal dead area between pixels can be produced.
  ➯ ➯ ➯ Attractive for both high energy physics and medical applications.

- a-Si:H operates at room temperature.

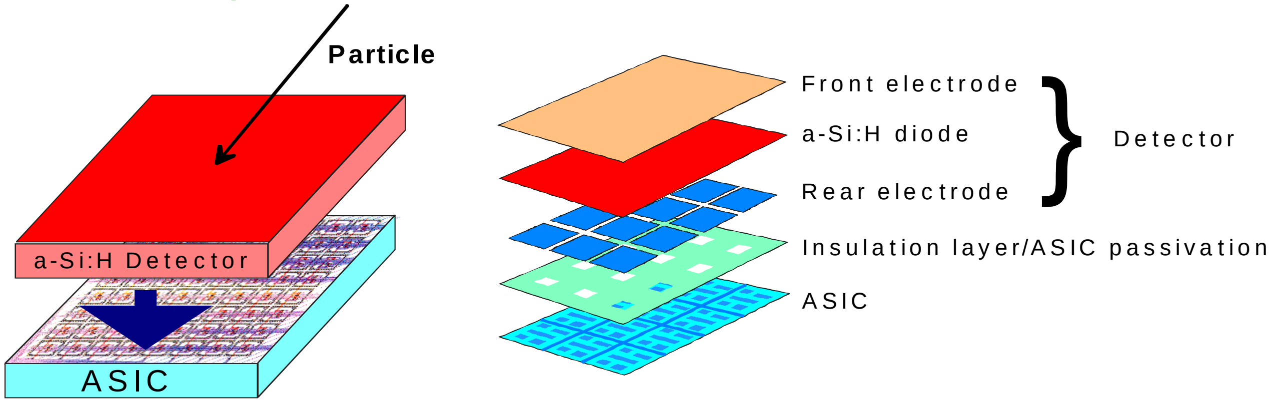
- a-Si:H is known to be a radiation hard material
  ➯ ➯ ➯ Attractive for HEP !

- Particle detection can be realized with thick a-Si:H diodes.
  - Minimum Ionizing Particle (MIP) detection needs to be study and optimized.
    ☹ Difficult to deposit thick a-Si:H layers (>10μm)

- Thick diodes are necessary to generate enough electron-hole pairs
  - Fabrication of thick diodes able to sustain high enough electrical field over the entire device thickness is a technological challenge.

Thin-Film on ASIC (TFA) Technology

- Vertical integration technique comprises the deposition of a detecting layer on top of a readout chip.



- TFA is an emerging technology that has first been used for the development of CMOS APS.

- Advantages of TFA using a-Si:H:

☑ High degree of system integration,

☑ Simple detector construction, compared to hybrid detector schemes.

☑ Large potential for system cost reduction.

☑ No need of bump bonding

a-Si:H Deposition Technique

- Plasma enhanced chemical vapour deposition (PECVD) technique.
  - Compatible with post processing on finished electronic wafers

- IMT Neuchatel - A. Shah, N. Wyrsch
  - Based on amorphous Photovoltaic solar panel technology
    - Currently industrialized by UNAXIS for low cost fabrication of 1.5m^2 panels
    - Low deposition rate of about 3-5Å/s
  - New high rate deposition technique with PECVD (VHF-PECVD)
    - Reactor specially developed for high deposition rate
      - ➢ mandatory for thick films (~30µm)
    - Thick layer leads to a lack of adherence and peeling problems
      - ➢ appropriate deposition parameters are needed. Specially temperature and plasma frequencies

New Plasma Reactor Deposition System

Very High Frequency Plasma Enhanced Chemical Vapour Deposition (VHF - PECVD)

imt

System

- Single chamber with load-lock
- Substrate size up to 6''
- Operates at VHF frequencies (50 – 150 MHz)

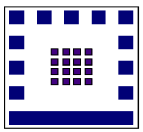
Deposition conditions

- PE-CVD at 70 MHz
- 180 to 220ºC
- Hydrogen dilution of silane

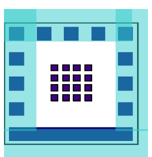
$$R = \frac{[H_2]}{[SiH_4]} = 3.5$$

- Deposition rate: Ca. 15 Å/s (2 hours for 10 μm)

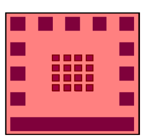
Sample Patterning



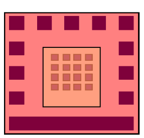
- Chip or chip-like test structure
- Dry etching to remove the polyimide on top of the pixels



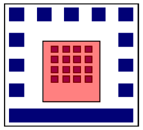
- Masking of the bonding pads



- a-Si:H and TCO deposition

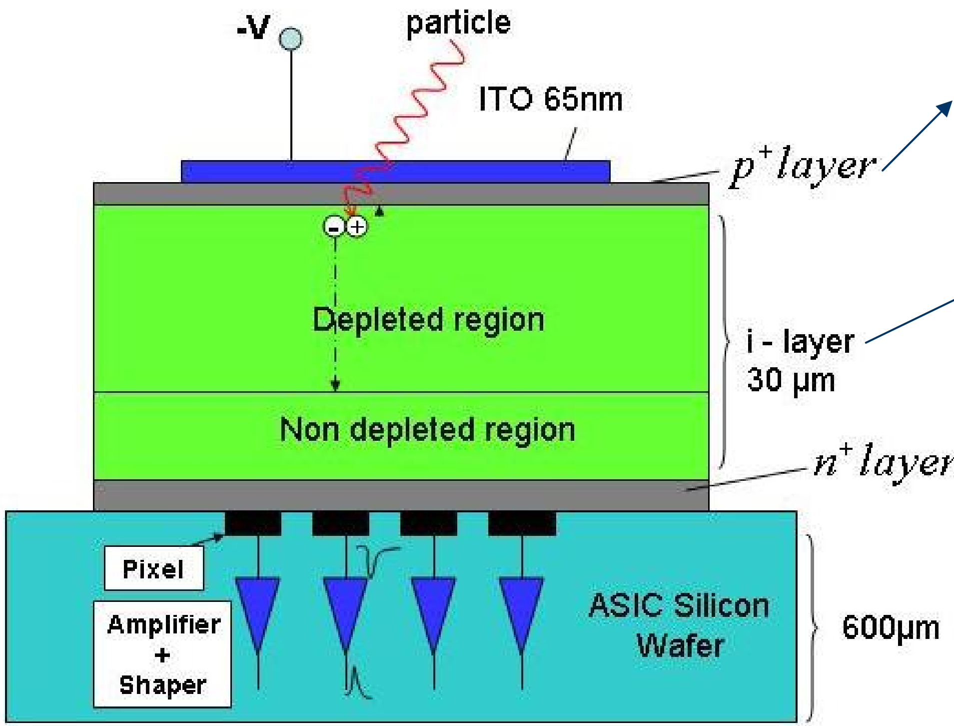


- Masking of TCO and Lift-off or wet etching



- Dry etching and lift-off of a-Si:H

a-Si:H Sensor



p-doped layer ~30nm

Thick intrinsic layer
5-30µm

High resistivity
n-doped layer ~30nm
provides pixel isolation

- Depletion layer from p-layer down to the n-layer

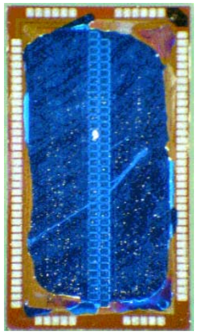
Thick diode where full depleted-state conditions should be achieved, with low dark current

a-Si:H Sensors Developed at CERN

- Characterization of a-Si:H Test Structures
  - n-i-p diodes deposited on glass substrate.
- Pixel sensors:

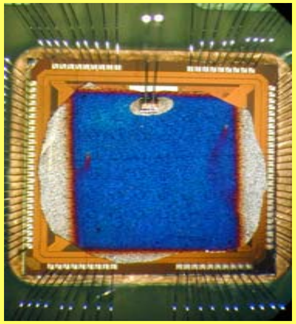
AFP

- $4x2mm^2$ ASIC
- 32 pixels of $68x94\mu m^2$
- t_{peak} = 5ns
- σ_{noise} < 300e- @ 1pF



MACROPAD

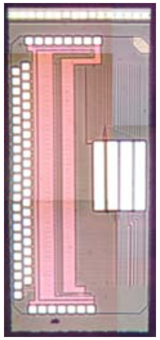
- $4x4mm^2$ ASIC
- 48 pixels with 380μm pitch
- t_{peak} = 160ns
- σ_{noise} < 30e- @ 0.4pF



- Strip detectors:

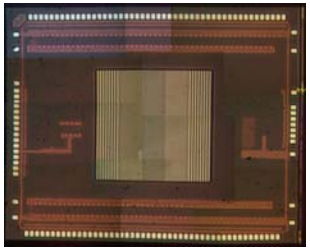
Mibedo

- beam dosimetry for ESRF Grenoble
- 1mmx740mm ASIC
- 1mm strips with 2-10μm pitch



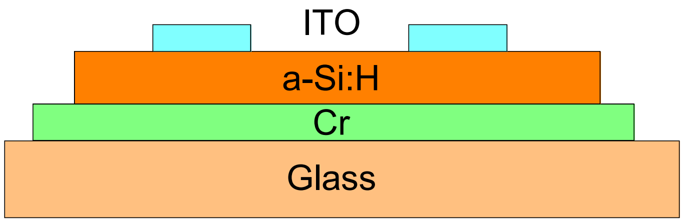
ASisCope

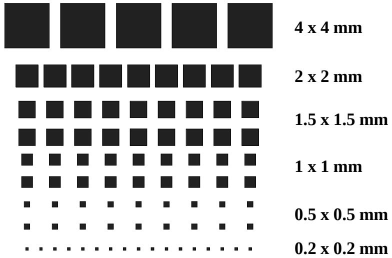
- beam tracker for NA60
- $2x2mm^2$ ASIC
- 96 strips



a-Si:H Test Structures

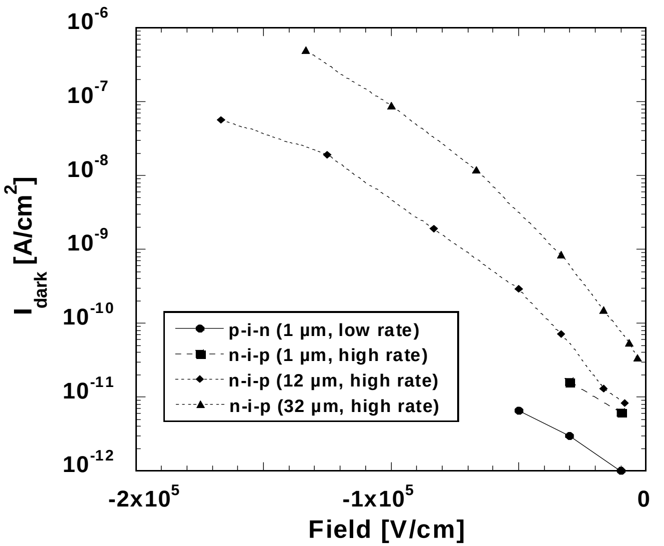
Test structures for material properties study

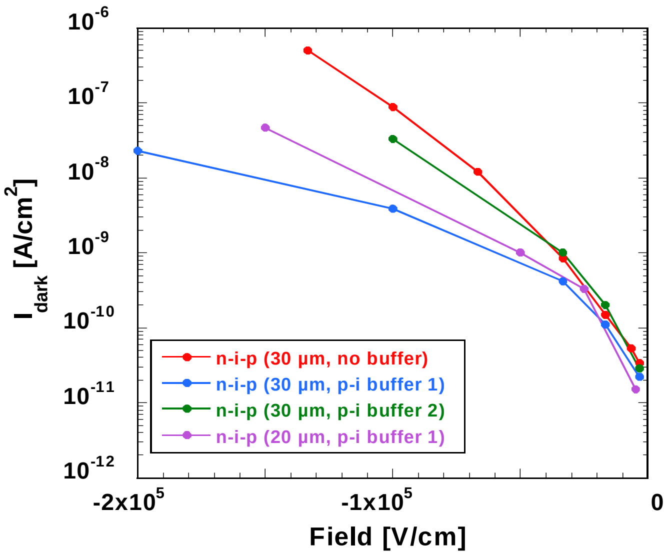




- Test n-i-p photodiodes evaporated on glass
  - ☑ Good compatibility with plasma process
  - ☑ Good chemical stability
  - ☑ Similar in the thermal expansion coefficient
- Diode patterning done by rubber stamping process
- Various pad configurations and detectors thickness were studied
  - dark current measurement
  - pixel to pixel uniformity
  - charge collection
  - voltage breakdown
- It provides low dark current

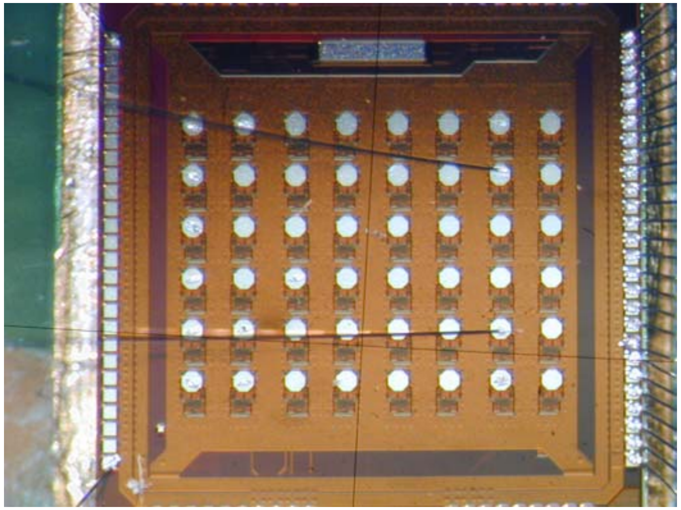
I-V Characteristics





- Dark current density as a function of reverse bias field increases with both the reverse bias field and the diode thickness.
- I_{Dark} also increases with the deposition rate.
  - Increase in deep defect density, leading to rising thermal generation carriers
  - I_{Dark} does not scale with the thickness
    - For a-Si:H > 15µm, the increase can be attributed to field-enhanced injection into the i-layer.
- Buffer layer deposited under much higher hydrogen dilution of silane resulted in a reduction of $I_{Dark.}$.
  - Thickness optimized for the lowest I_{dark} value.
- Several options are still being considered for further minimization.

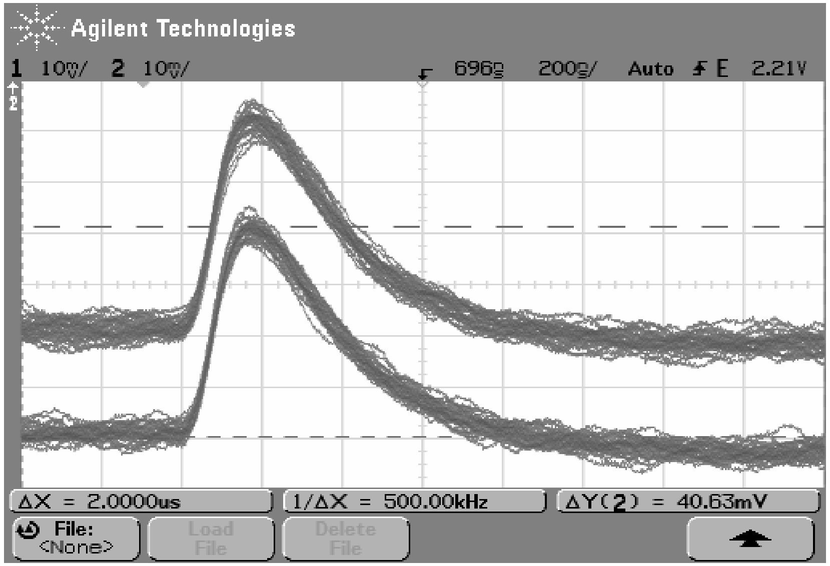
Macropad ASIC



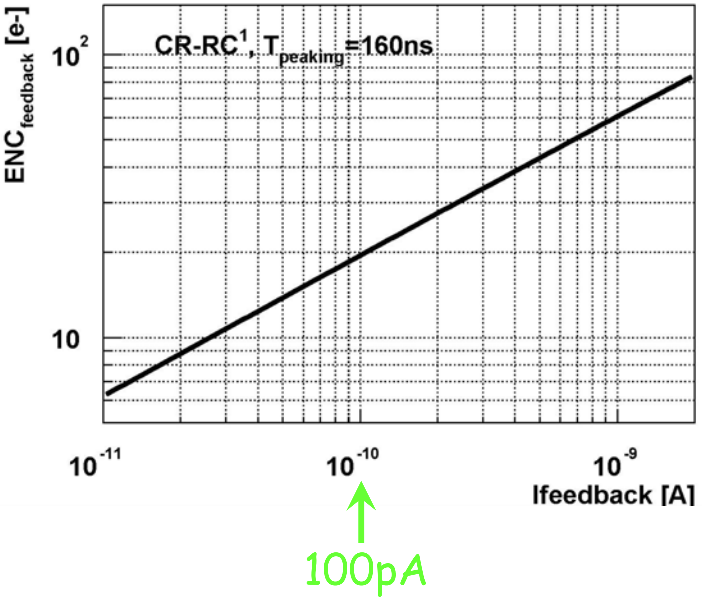
- $4x4mm^2$ ASIC with an array of 8x6 octagonal pixels with 380μm pitch.
- Implemented in 0.25μm CMOS technology.
- One channel consists of a charge amplifier with active feedback* and a shaper stage providing CR-RC shaping.
  - P. Jarron *et al.*, NIM A377 (1996) 435.
- Optimized to detect **0.1fC (625e$^-$)** signal with **30e$^-$** noise.

Macropad ASIC

Response of two randomly selected channels (not loaded) to 0.1fC charge as injected through a test capacitor
Bias condition: 300µA input transistor, 100pA feedback



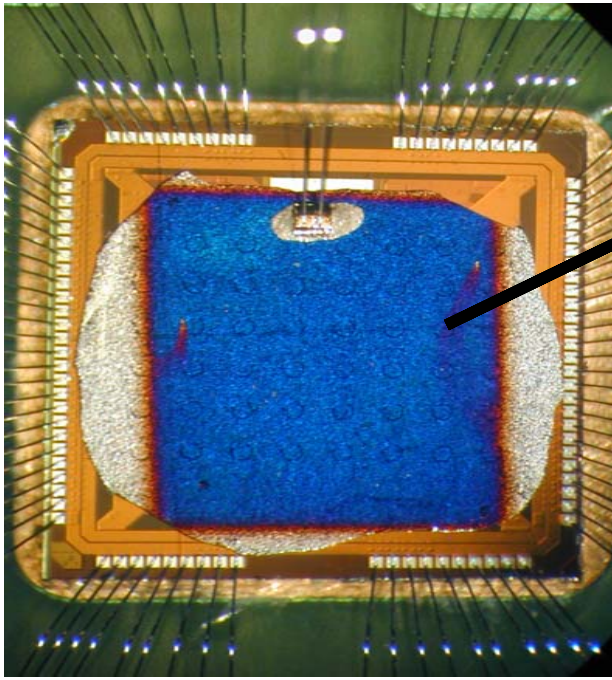
Parallel noise from feedback

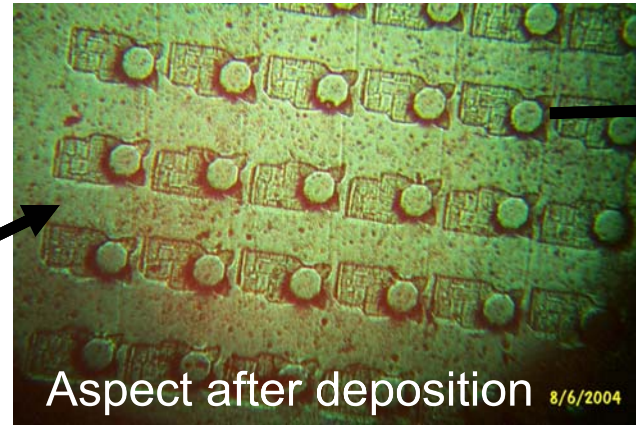


Measurement

Bare chip → Cinput ~0.2pF
Peaking time = 160ns
Amplifier gain ~ 430mV/fC
ENC: 20 – 27e- for I_{feed} 30 – 220pA
Good agreement with the noise model (Δ<1e- ENC)

Macropad Sensors

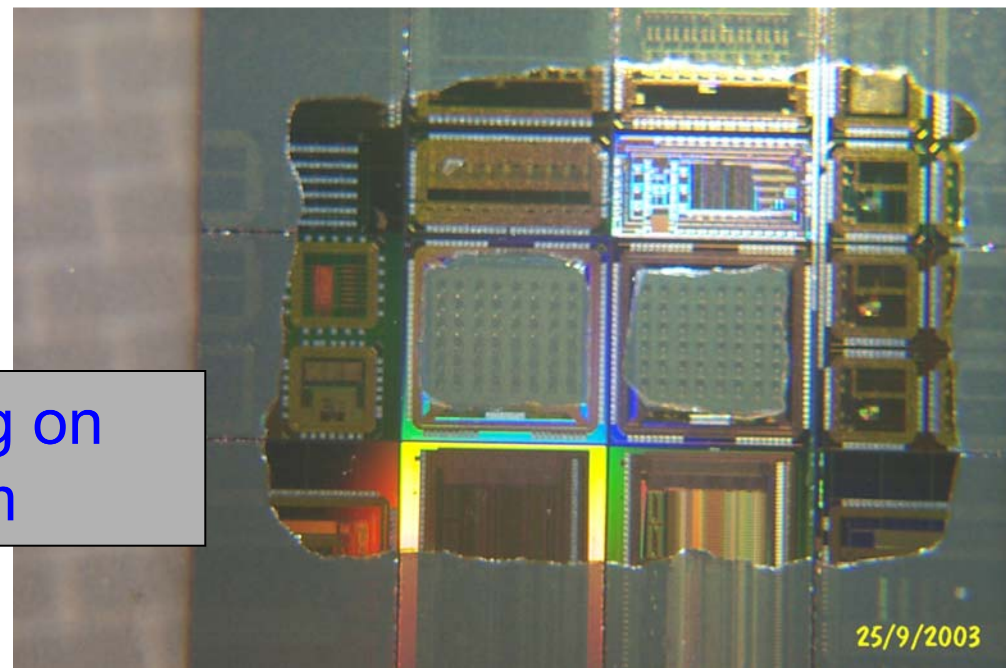




~140 µm

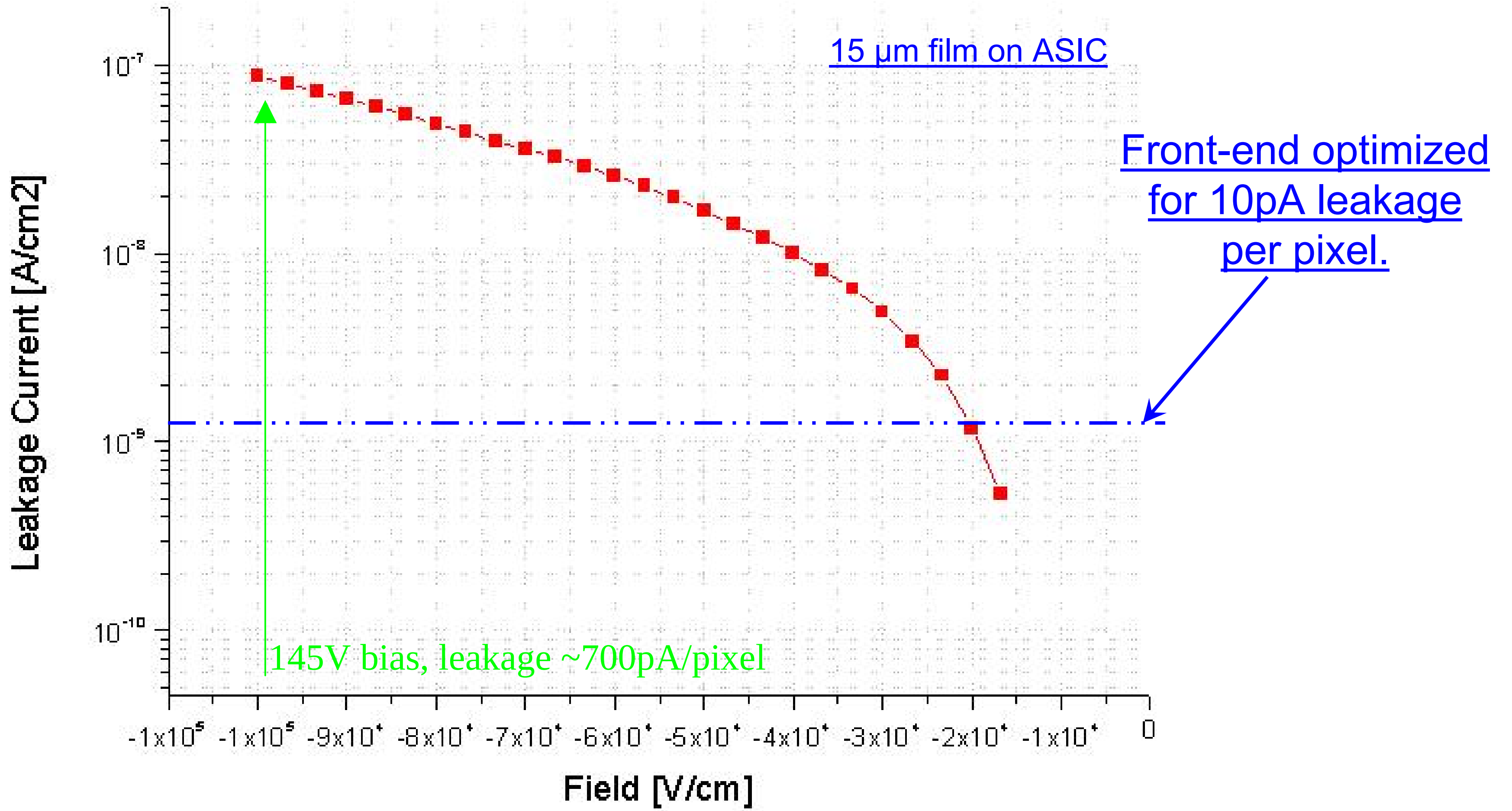
$C_{pad} \sim 0.2pF$

$C_{15\mu m} \sim 0.1pF$



Deposition and etching on reticules of 1.5cmx2cm

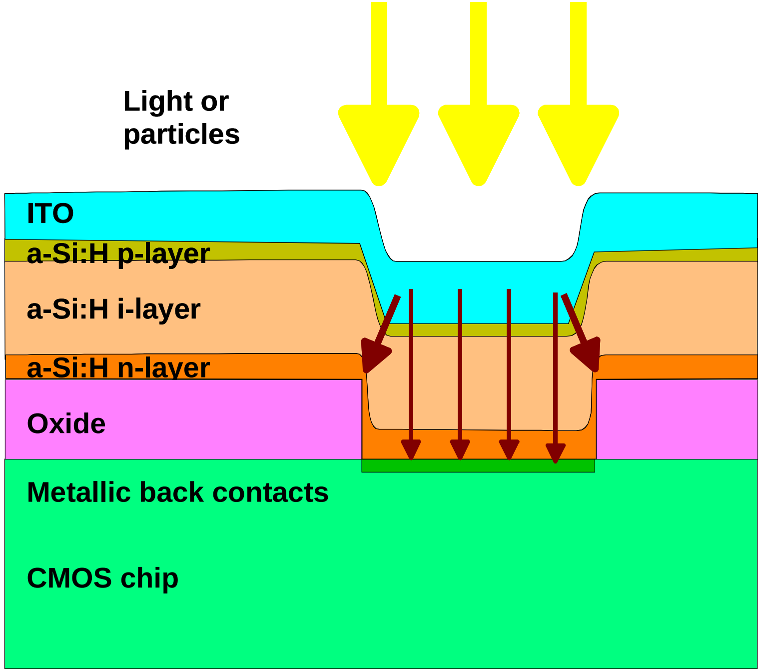
15µm Macropad Sensor Leakage Current

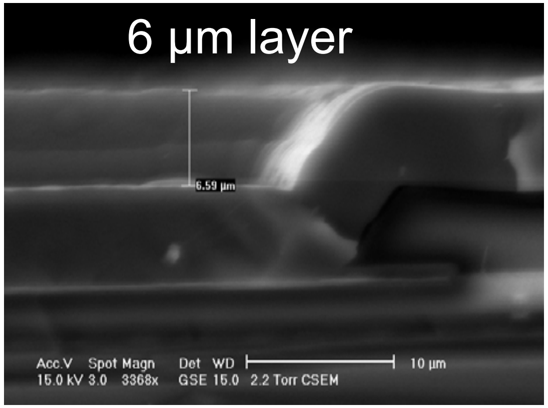


☺ Great improvement with the new design of Macropad !!!

⇨ Bigger opening window on the passivation.

Leakage Current Study

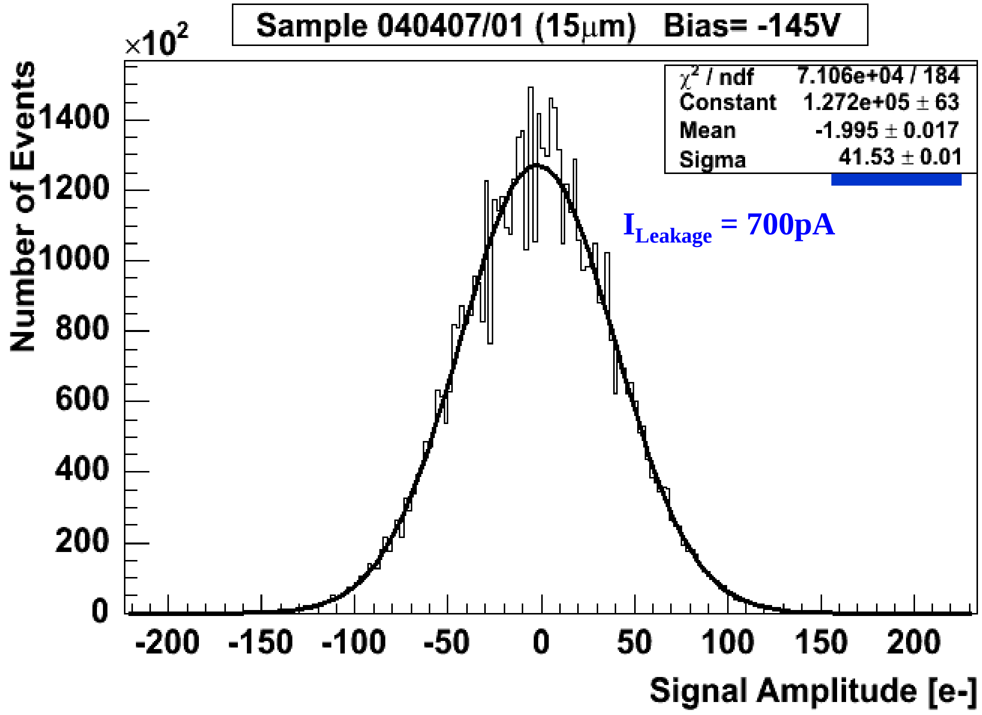


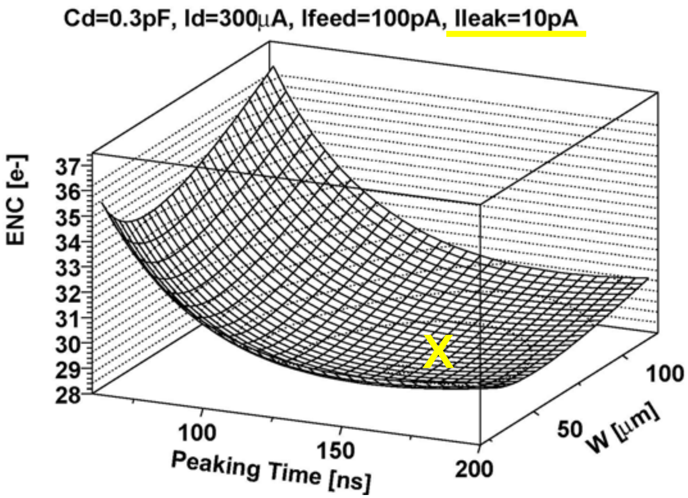


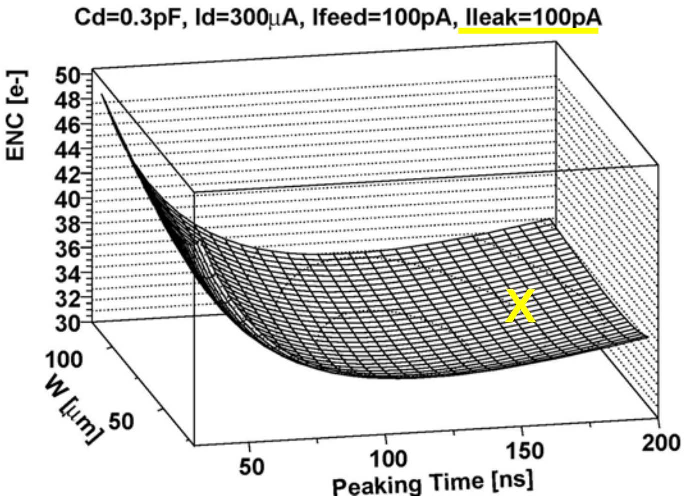
- a-Si:H diodes deposited on non-planar substrates may exhibit increased leakage currents.
  - field concentration at substrate steps, spikes or other sharp surface features
- Thick polyimide passivation

✓ Bigger opening on the passivation reduces the total leakage current !

15μm Macropad Sensor Noise Measurement

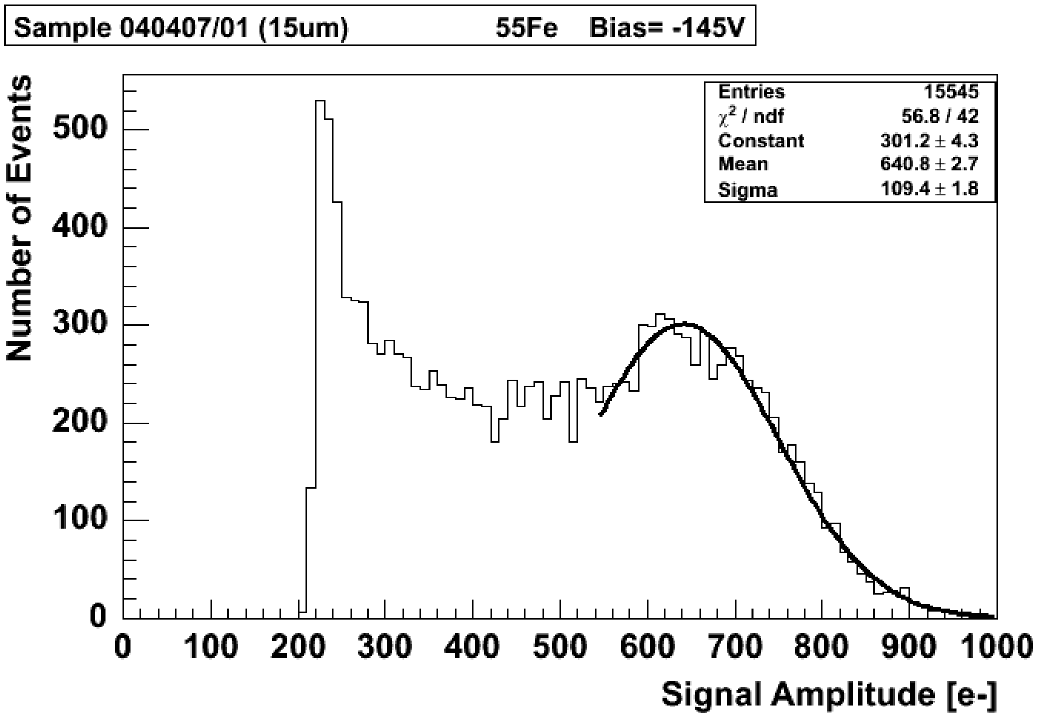


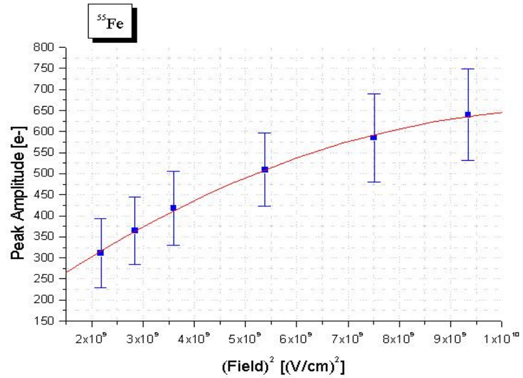




J. Kaplon is working on the optimisation!

15μm Macropad Sensor
^{55}Fe Spectrum





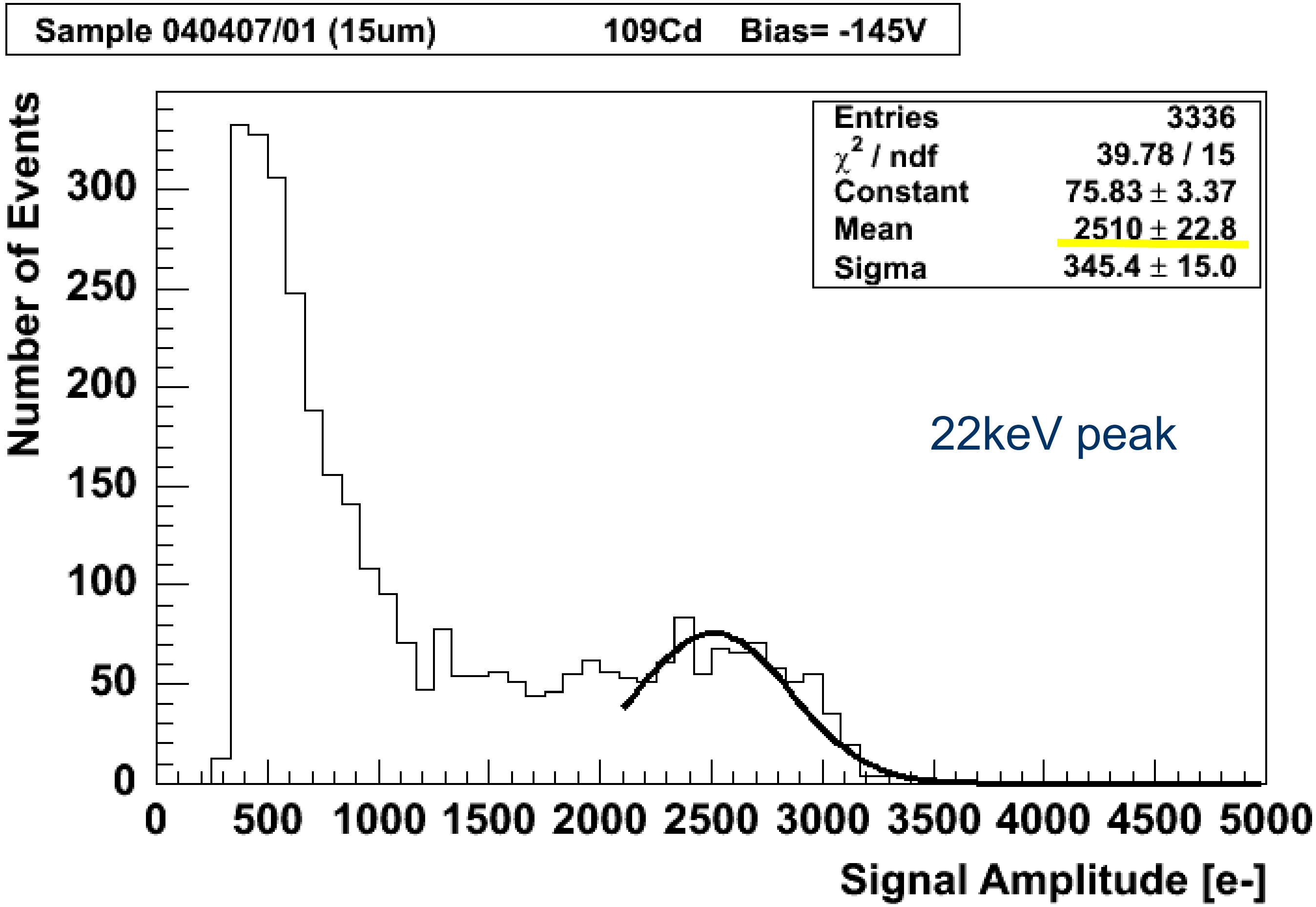
Self trigger

- Pedestal 5 σ = 200 e^-
- σ = 41 e^- r.m.s

5.9keV peak

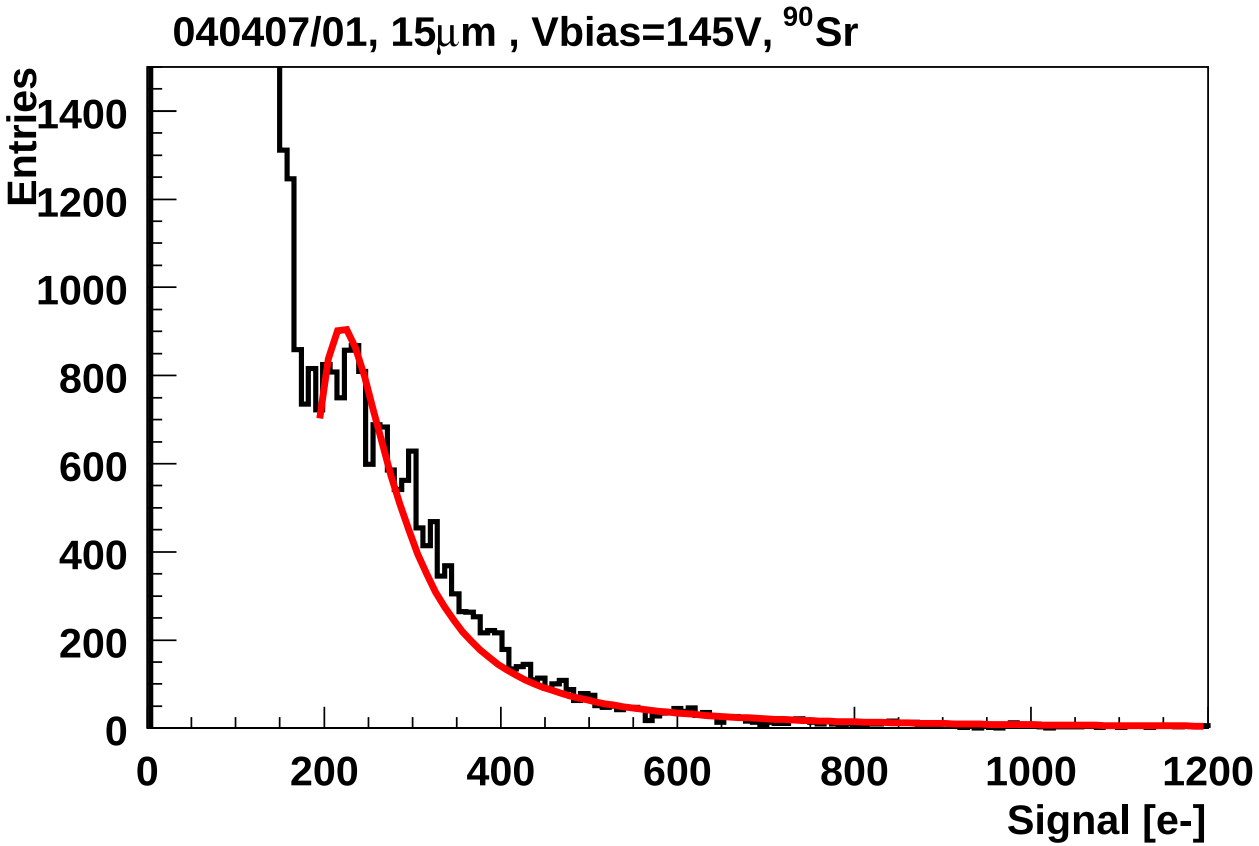
- 640 e^-
- σ = 109 e^- r.m.s
- Collected charge seems not complete
  - Ionization not fully contained in a 15μm film
  - Unclear CCE in between electrodes
  - Possible loss of signal due to charge recombination

15μm Macropad Sensor
^{109}Cd Spectrum



- 2400e$^-$ expected from the comparison to ^{55}Fe
- Good agreement!

15μm Macropad Sensor
MIP from ^{90}Sr



Geometrical efficiency of scintillator trigger ~0.002%
MIP ~ 220e-
S/N ~ 5

Radiation Hardness of a-Si:H

- J. Kuendig *et al*., Solar Energy Materials & Solar Cells 79 (2003) 425.
- Fluence = $1.5.10^{13}$ protons/cm^2
- Parameters reach their initial value after annealing.

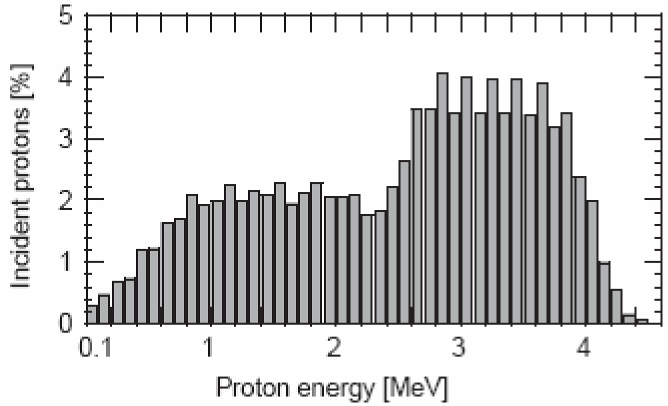


Fig. 2. Energy spectrum of the incident protons.

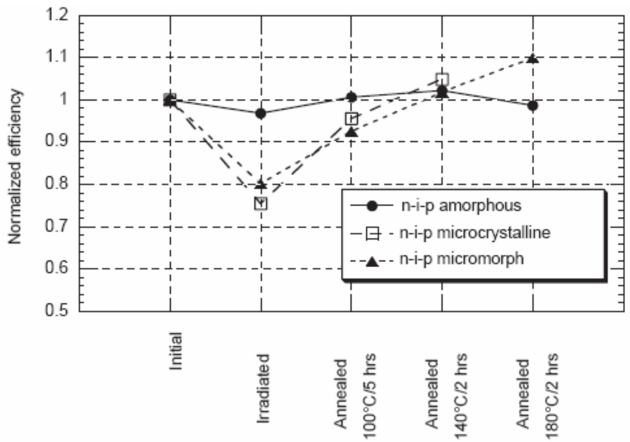


Fig. 3. Normalized efficiencies of n–i–p a-Si:H, n–i–p μc-Si:H and n–i–p micromorph solar cells on glass substrates. The datapoints are averaged curves, averaged over 4 cells, on the same substrate.

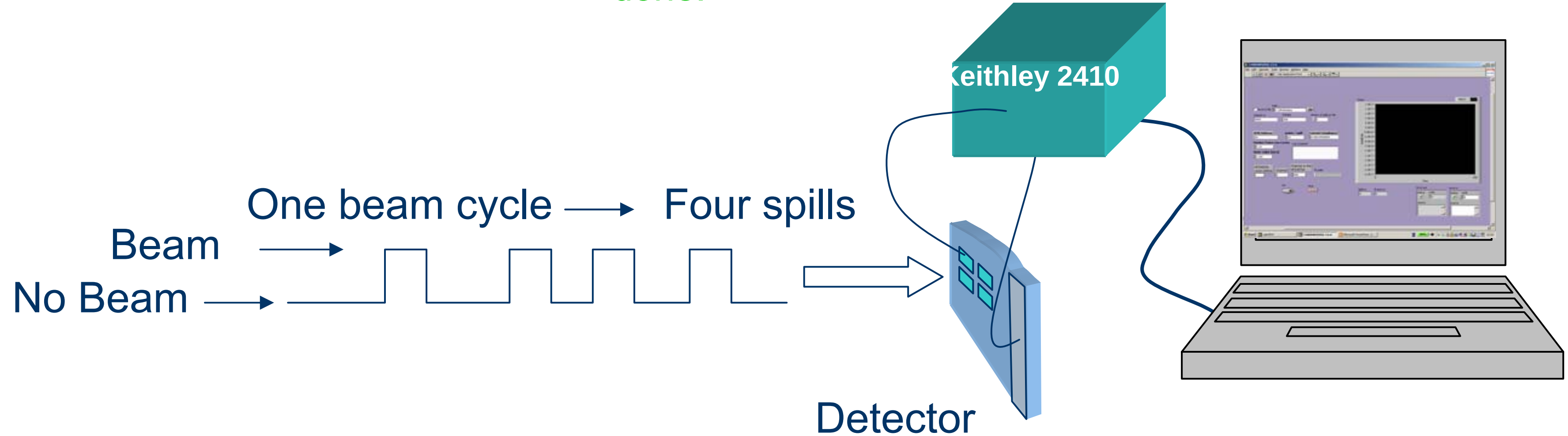
- Further experimental results have demonstrated that the a-Si:H film can survive irradiation with 1MeV protons up to a fluence of $1.6.10^{15}$ protons/cm^2
  - J.J. Hanak, J.R. Woodyard, "Radiation Hardness of Amorphous Silicon and Silicon-Germanium alloy solar cells to 1MeV protons".

Radiation Tests of a-Si:H films

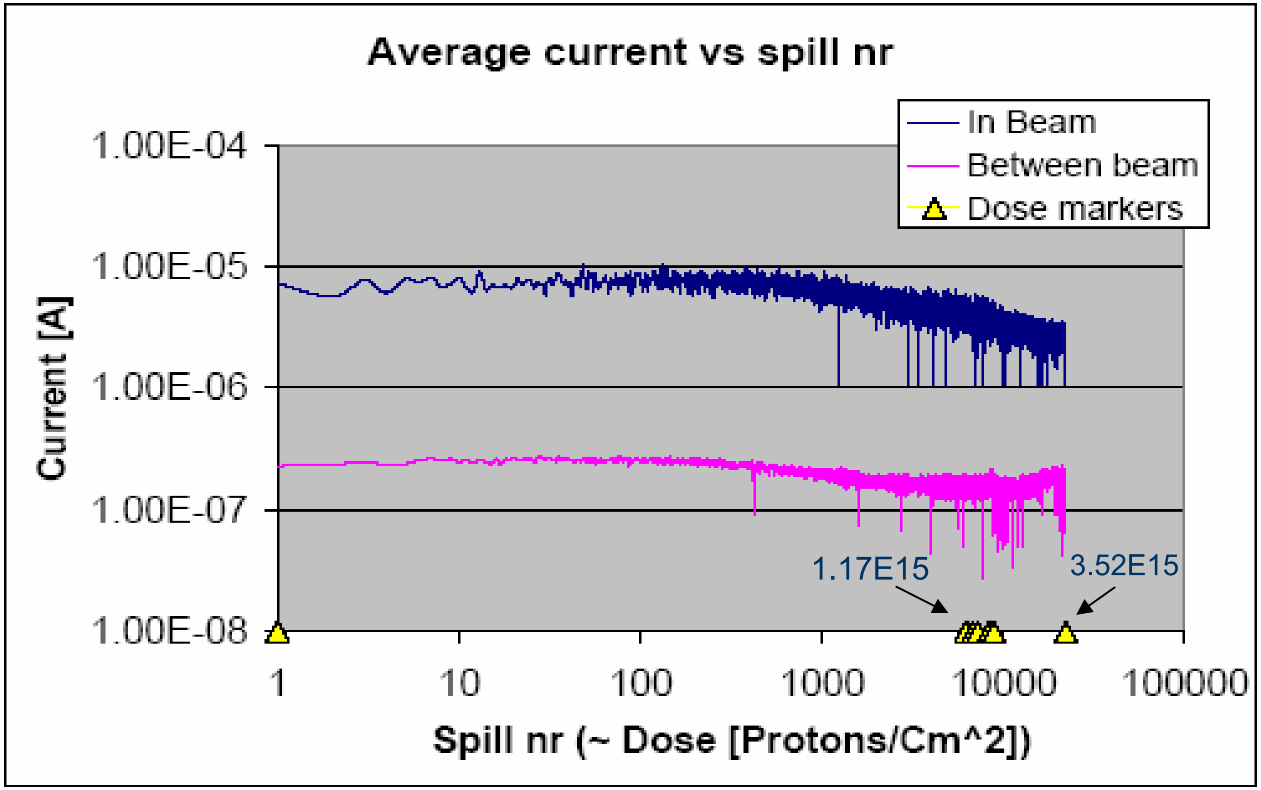
<u>IRAD1 Facility @ CERN</u>

24GeV Proton beam
~ 3.10^{13} protons /(cm^2 * hour)
Beam size is $2x2cm^2$

- Try test until film is dead
  - No success yet !
  - First test at $1.8\ 10^{16}$ p/cm^2
    - No increase of leakage current
    - Problems with the trigger system prevented proper data analysis.
  - Second detailed test up to $3.5\ 10^{15}$ p/cm2
    - Too high flux to measure single count
      - Average spill signal current
      - off beam dark current
    - Particle spectra measurement during irradiation still to be done.



Preliminary Results up to $3.5\ 10^{15}\ p/cm^2$



30µm n-i-p a-Si:H diode
$2x2mm^2$ pads

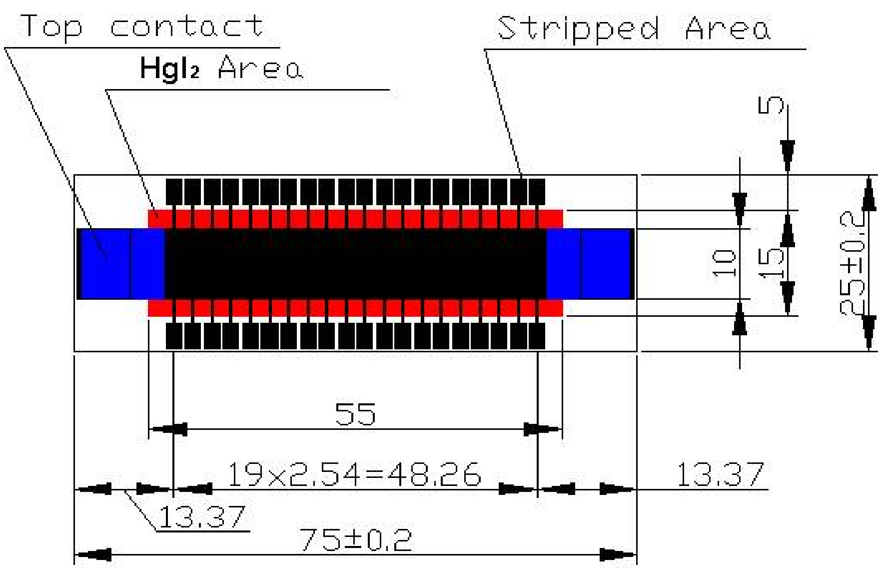
- ⇨ 3 days of irradiation
- ⇨ Total accumulated dose $= 3.5\ 10^{15}\ p/cm^2$

- ☞ Radiation induces dangling bonds that work as recombination centres for e-h pairs.
  - ☞ reduction of the radiation induced current on the detector.
- ☞ The behaviour at higher doses suggests a maximum number of dangling bonds.
  - ☞ equilibrium between radiation induced annealing and radiation induced creation of dangling bonds?

Polycrystalline HgI2

- HgI2 is a photoconductor
  - No depletion layer
    - High resistivity
    - No junction
  - TFA technique

Property		Si	HgI_2
Band Gap at 300 K	E_g	1.12 eV	2.15 eV
Density		2.33 g/cm^3	6.4 g/cm^3
Pair creation energy	$E_{e\text{-}h}$	3.6 eV	4.2 eV
Electron Mobility	μ_e	1450 cm^{2}s^{-1}V^{-1}	~100 cm^{2}s^{-1}V^{-1}
Hole Mobility	μ_h	450 cm^{2}s^{-1}V^{-1}	~4 cm^{2}s^{-1}V^{-1}



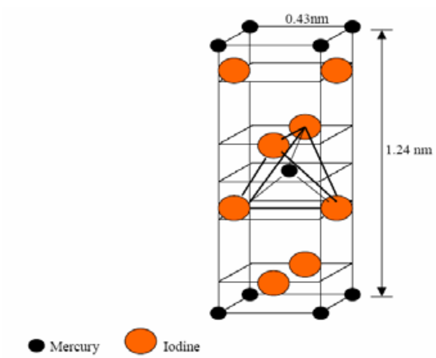


Figure 1.4 Elemental cell of tertragonal α-HgI_2

No results to be presented yet!

Summary

- ✓ A TFA technology has been successfully developed for the deposition of thick a-Si:H films
  - Deposition performed by VHF-PECVD
- ✓ Results of the Macropad chip are in good agreement with the model
  - $30e^-$ ENC is achievable (allows for the study of aSi:H)
- ✓ Pixel detectors based on 10 - 30μm thick n-i-p a-Si:H film were produced
  - Charged particles can be detected in thick a-Si:H diodes.
- ✓ Precise measurements on full depleted a-Si:H thick films and MIP detection to be done.
- ✓ a-Si:H looks to be very radiation hard.
  - Limit was not yet reached.

Conclusion

☺☺☺☺

Initial studies on a-Si:H Pixel Detector look very promising and may one day lead to an attractive alternative to crystal silicon in some detector systems !