Large-area sensors

PV-lab
IEM NEUCHATEL

Content

- Applications
- Position sensors (a-Si:H)
- Particle detection
- Interaction of particle with matter
- Direct/indirect detection
- Photodiodes, depletion conditions
- Flat panel imager technologies (a-Si:H, a-Se)
- Other particle sensors

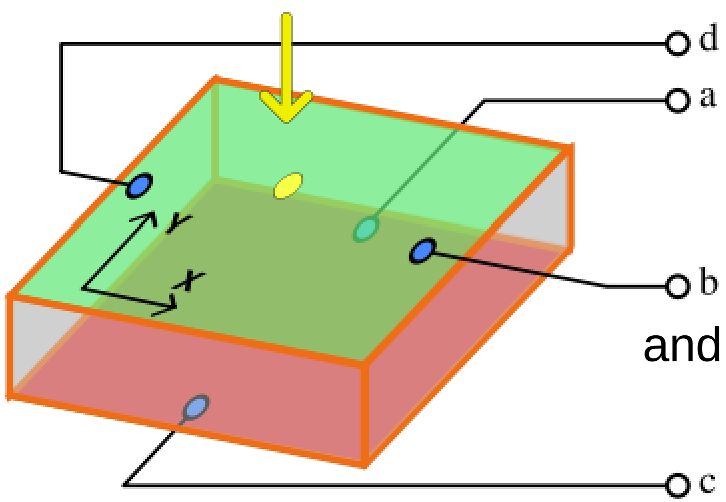
Devices and Applications

- Flat panel imagers (a-Si:H, a-Se)
  - X-ray imaging
    - Medical imaging
      - Radiography
      - Fluoroscopy
      - X-ray tomography,
    - Security
    - Non destructive testing
- Other particle detectors
  - Particle tracking
    - Medical imaging
      - Positron emission tomography
    - Nuclear physics
  - Non destructive testing
  - Dosimetry
- Position detectors

Position sensitive device (PSD)

Position detectors

Position sensitive device (PSD)



and

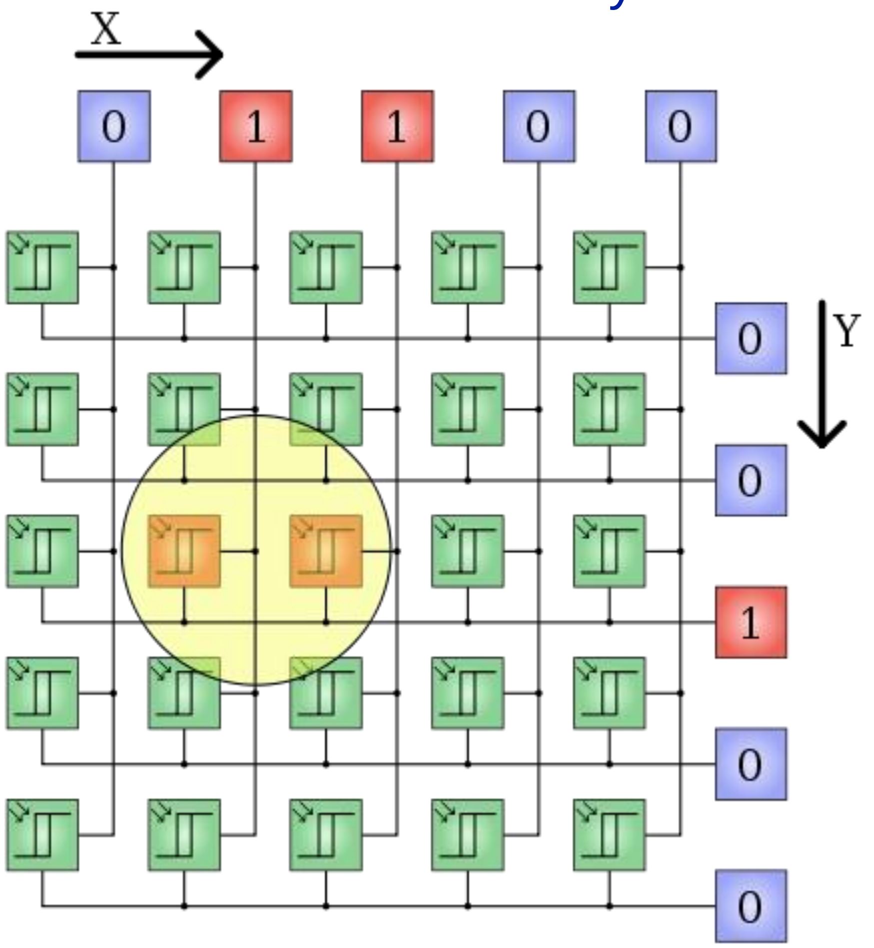
p-n, p-i-n or Schottky diode

Lateral photovoltaic effect

$$x = k_x \cdot \frac{I_b - I_d}{I_b + I_d}$$

$$y = k_y \cdot \frac{I_a - I_c}{I_a + I_c}$$

1D/2D diode arrays



PSD devices

- Semiconductor device with at least one high conductivity layer (equipotential) and one resistive layer
- Principle using lateral photoconductivity
- Lateral vs transversal measurement
- Photovoltaic vs photodiode (reverse bias) measurements

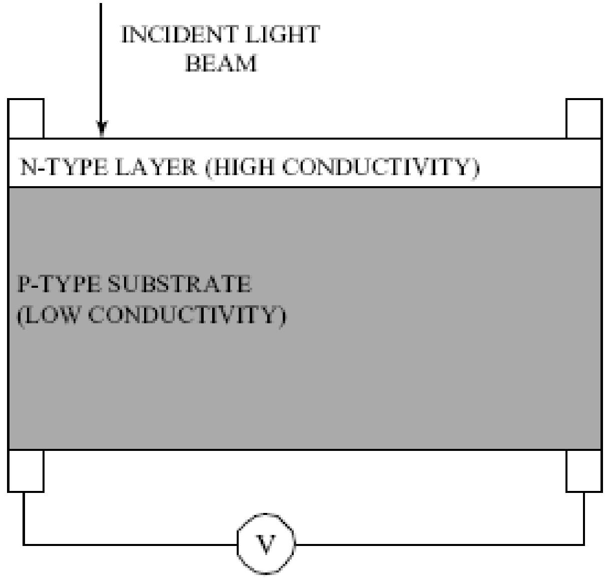


Figure 1. Photovoltaic mode.

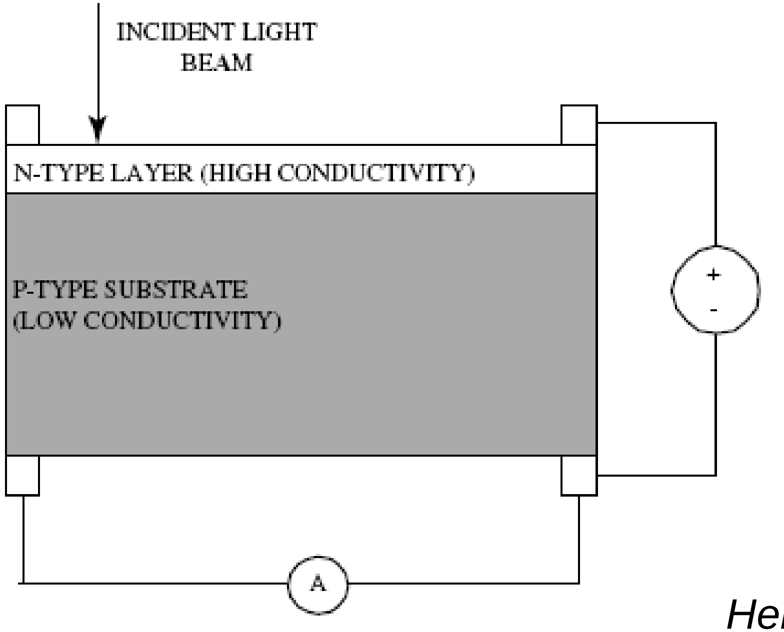
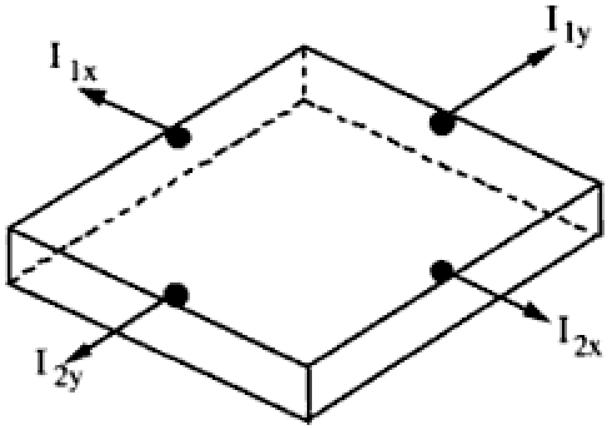


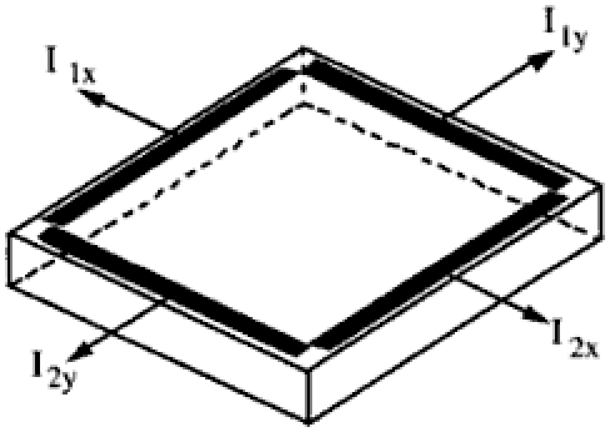
Figure 2. Photodiode mode.

Henry, 2002

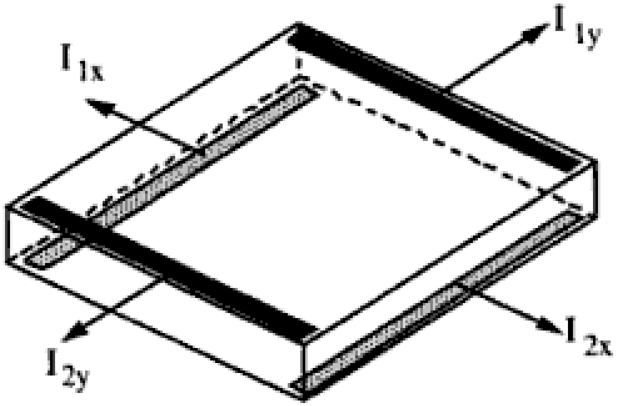
PSD types



(a) Dual-axis square Wallmark type.

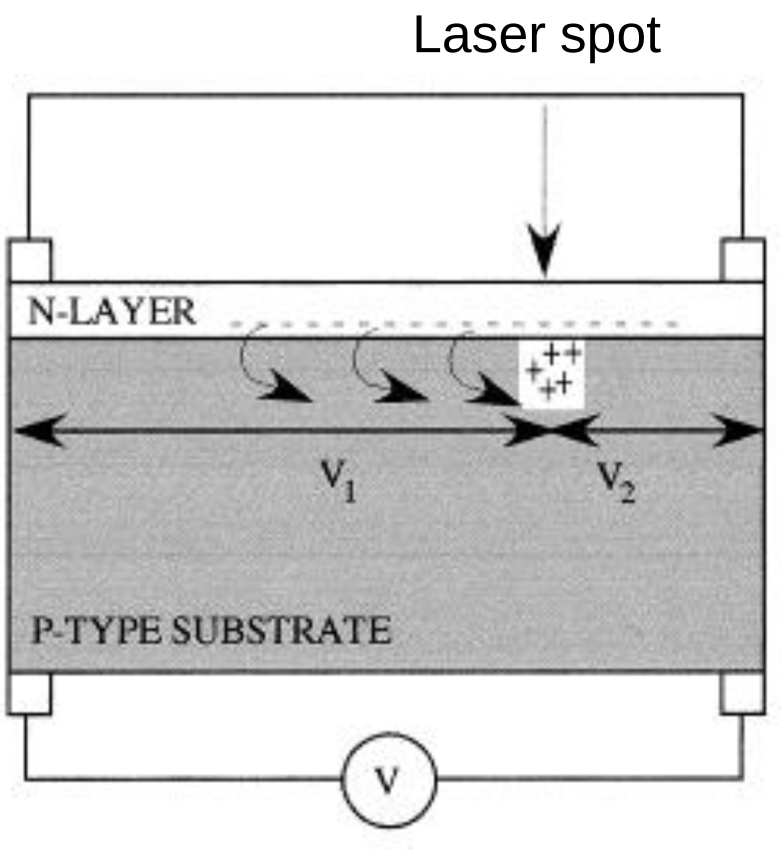


(b) Dual-axis tetralateral type.



(c) Dual-axis duolateral type.

c-Si PSD principle

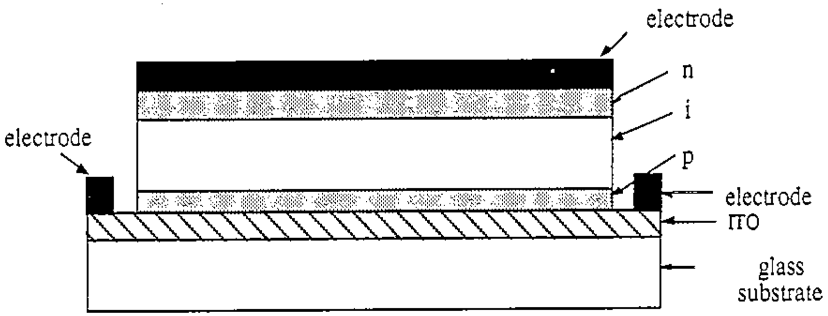


V_1-V_2= Lateral photovoltage

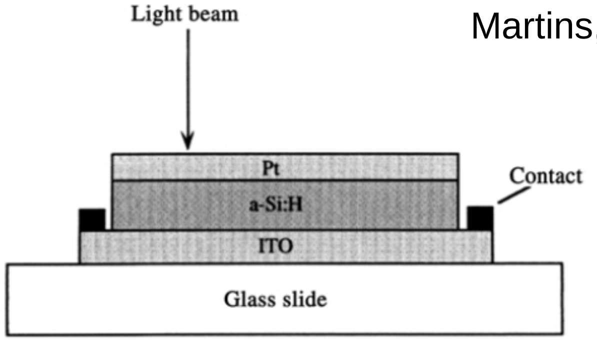
- Originally based on p-n junction solar cell
- Non uniform illumination (laser spot)
- Creation of e-h pairs at the illuminated spot
- Injection of e in n-layer and spead-out
- Re-injection of e into p-layer and recombination
- Build-up of a lateral space-charge region (potential)
- Lateral diffusion of h in p-layer and recombination

Henry, 2002

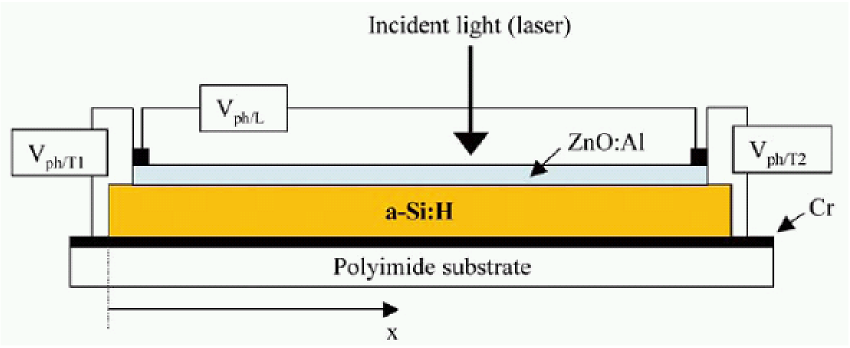
Large area thin-film PSD



Martins, 1996

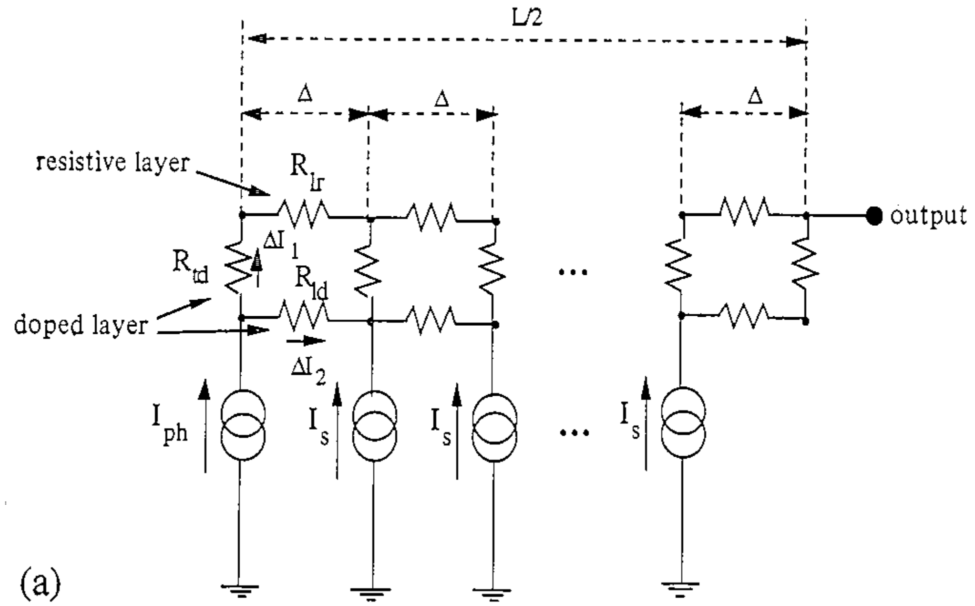


Henry, 2002

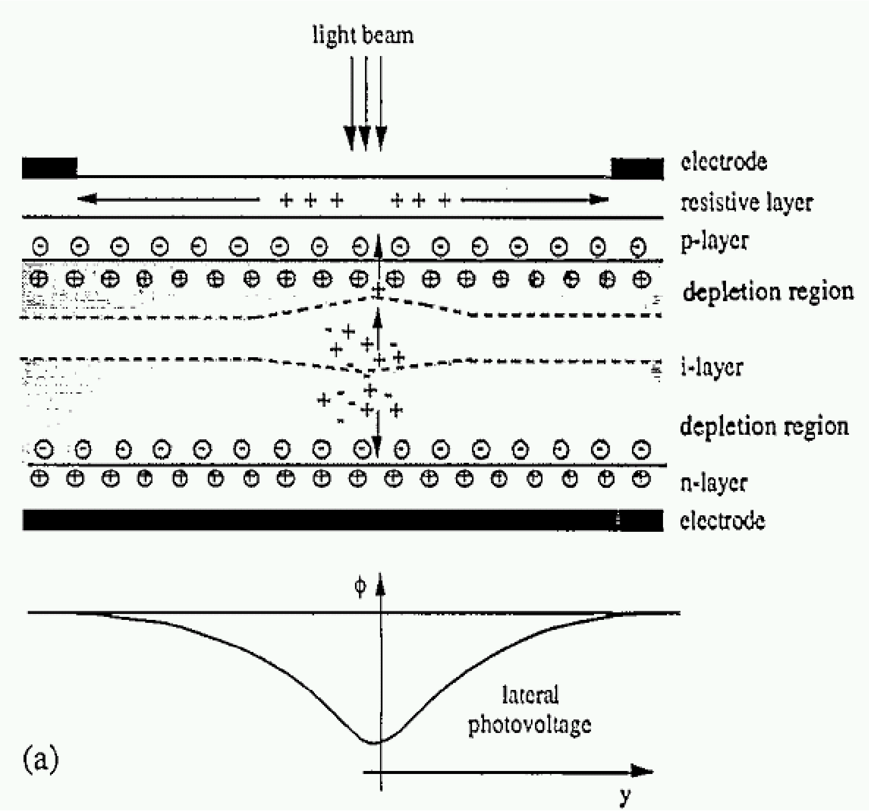


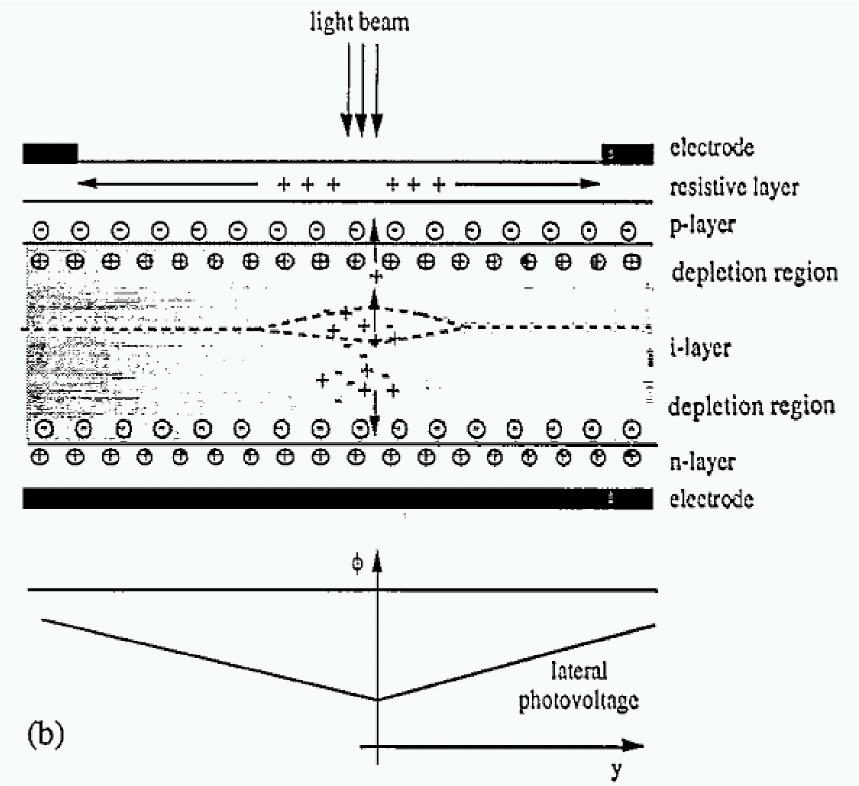
Fortunato, 2005

- Linearity and size of c-Si PSD limited (< 1cm)
- Better solution: Using a-Si:H as semiconductor and TCO for the resistive layer



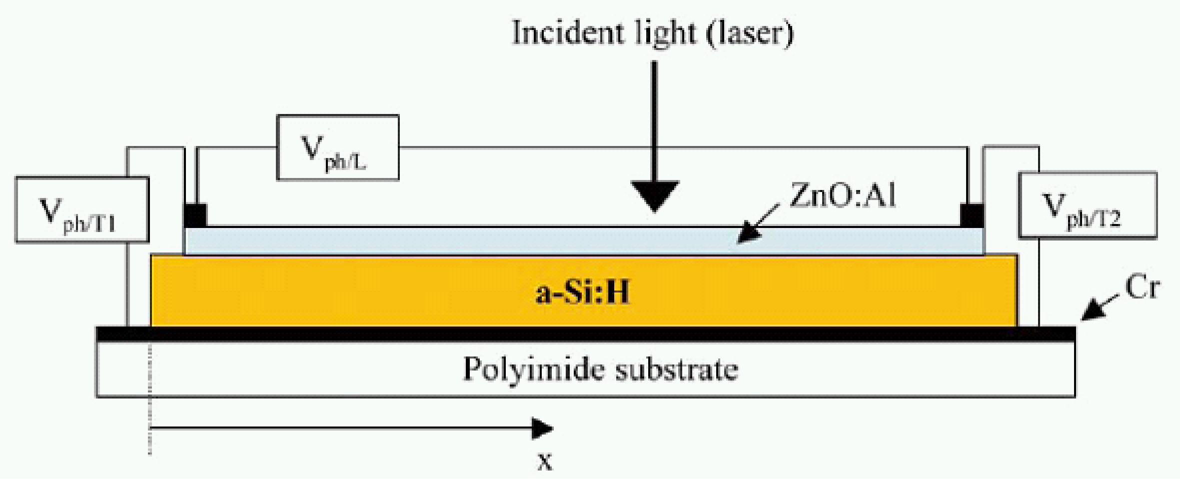
Thin-film PSD operation

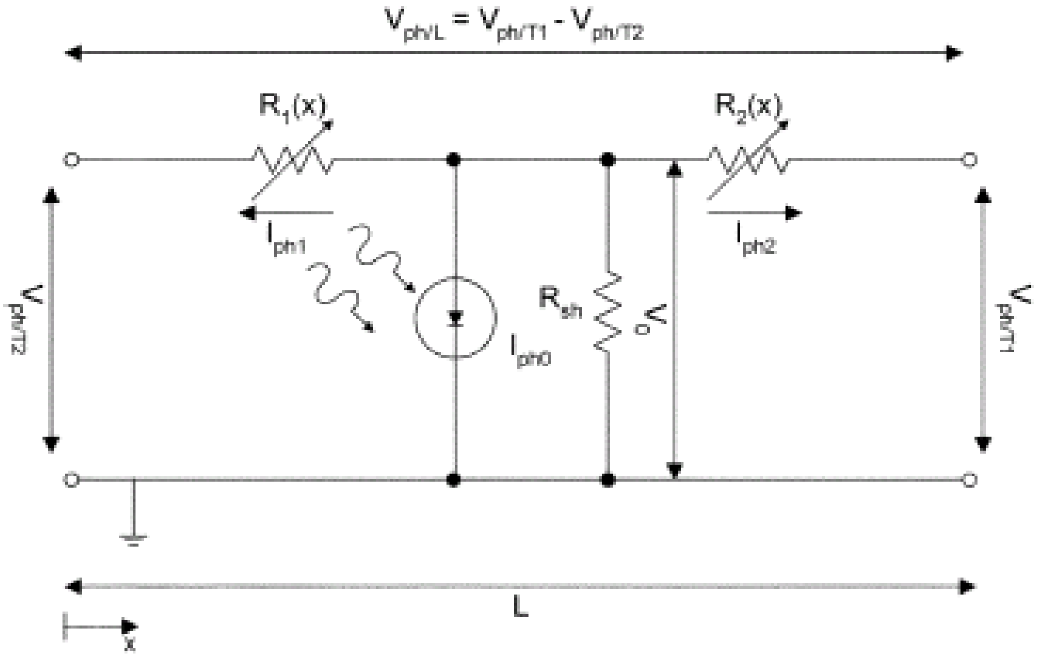




Flexible thin-film PSD

N. Wyrsch





Transversal photovoltages:

$$V_{ph/T1} = V_0 - R(L-x) I_{ph2} e^{-\alpha(L-x)}$$

$$V_{ph/T2} = V_0 - R(x) I_{ph1} e^{\alpha x}$$

α falloff parameter, depends on semiconductor and resistive layer

Fortunato, 2005

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Flexible thin-film PSD

- Transversal photovoltages:

$$V_{ph/T1} = V_0 - R(L-x) I_{ph2} e^{-\alpha(L-x)}$$

$$V_{ph/T2} = V_0 - R(x) I_{ph1} e^{\alpha x}$$

With V_0 given by $I_{ph0} = I_{ph1} + I_{ph2}$

- Lateral photovoltage:

$$V_{ph/L} \equiv V_{ph/T1} - V_{ph/T1} = V_0 \frac{e^{\alpha(L-x)} - e^{-\alpha(L-x)}}{e^{\alpha L}}$$

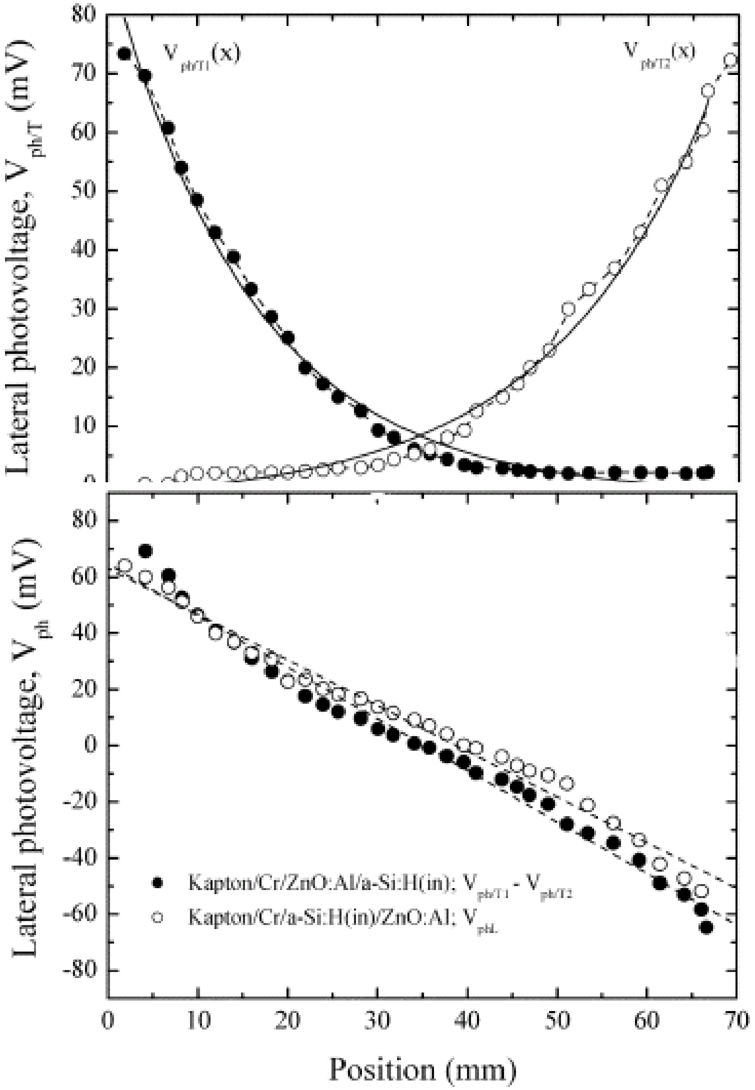
$$V_{ph/L} = V_0 \frac{\sinh \alpha(L-x)}{\sinh \alpha L}$$

- With α «1, we have

$$V_{ph/L} \approx V_0 \frac{L-x}{L}$$

- Position

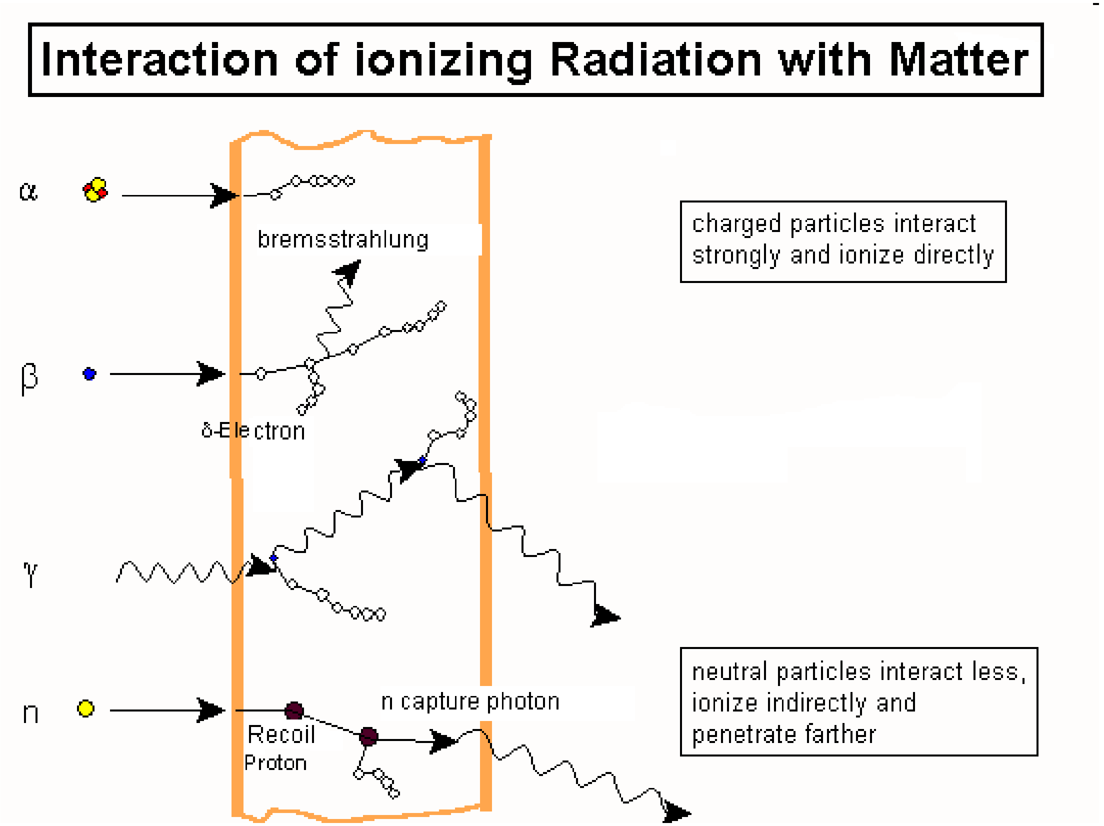
$$\frac{x}{L} \approx \frac{V_0 - V_{ph/L}}{V_0}$$



Fortunato, 2005

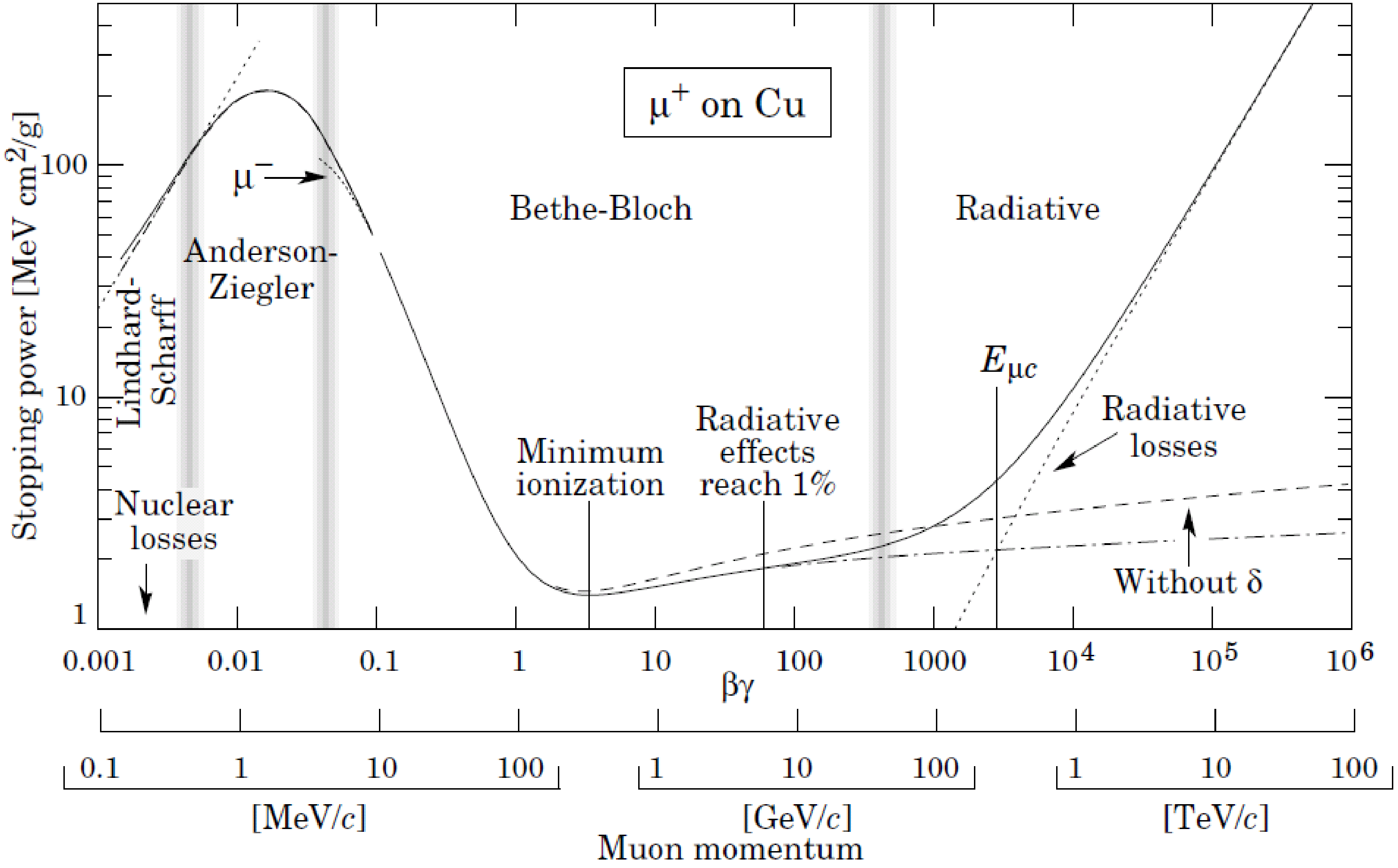
Particle detection

Interaction of particles with matter



- Main energy loss through ionization, interaction with electronic shells
- Stronger interaction for charge particles (small penetration depth)
- Electron-hole pairs created by ionization can be collected for detection (e.g. in a semiconductor diodes)

Stopping power



Stopping power for positive muons in copper as a function of βγ≈0.1. Solid curves indicate the total stopping power.

Passage of particles through matter, D. E. Groom and S. R. Klein, 2000

Energy loss for charged particle

N. Wyrsch

Bethe-Bloch formula corrected for density and shell effect :

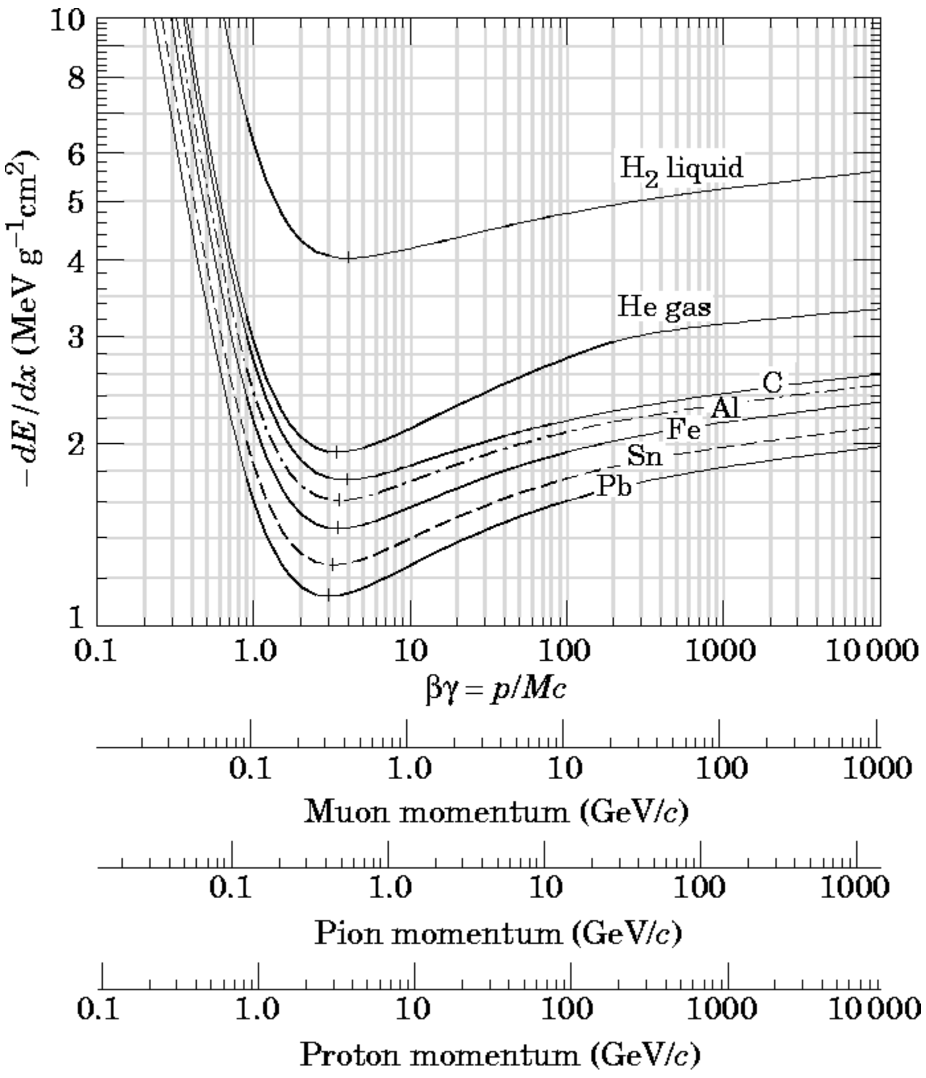
$$-\frac{dE}{dx} = 2\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e\gamma^2 v^2 W_{\max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right]$$

where

- x : path length
- m_e : electron mass
- c : the speed of light
- N_A : Avogadro number
- I : excitation potential
- Z : atomic number material
- ρ : density material
- z : particle charge
- $\beta = v/c$ with the particle velocity v
- δ : density correction
- C : shell correction
- W_{max} : maximum energy transfer in a single collision

W.R. Leo, 1994

Energy loss and MIPS

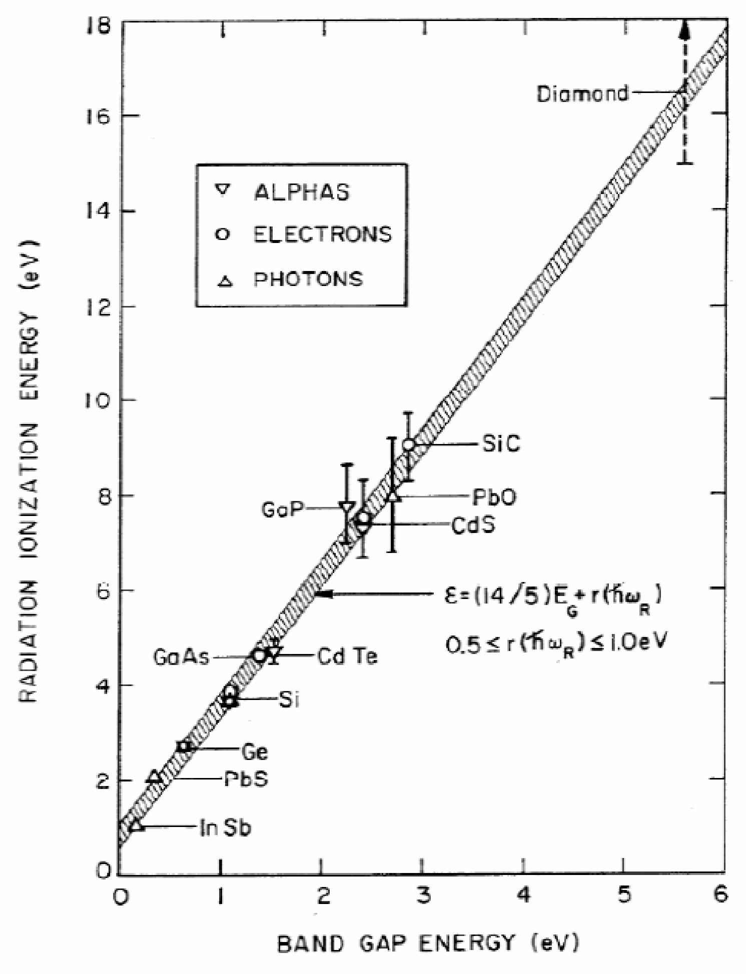


http://pamela.physik.uni-siegen.de/pamela/glossary.html

- MIPS : Minimum ionizing particles
- Beth-Bloch formula valid for heavy (with respect to the electron's mass) charged particle
- "universal behavior" for all materials and charge particles

- Loss $\propto z^2$ (particle charge)
- Loss $\propto Z$ (atomic number)
- Loss $\propto \rho$ (material density)

Electron-hole pair creation



C.A. Klein, J. Applied Physics **39** (1968) 2029

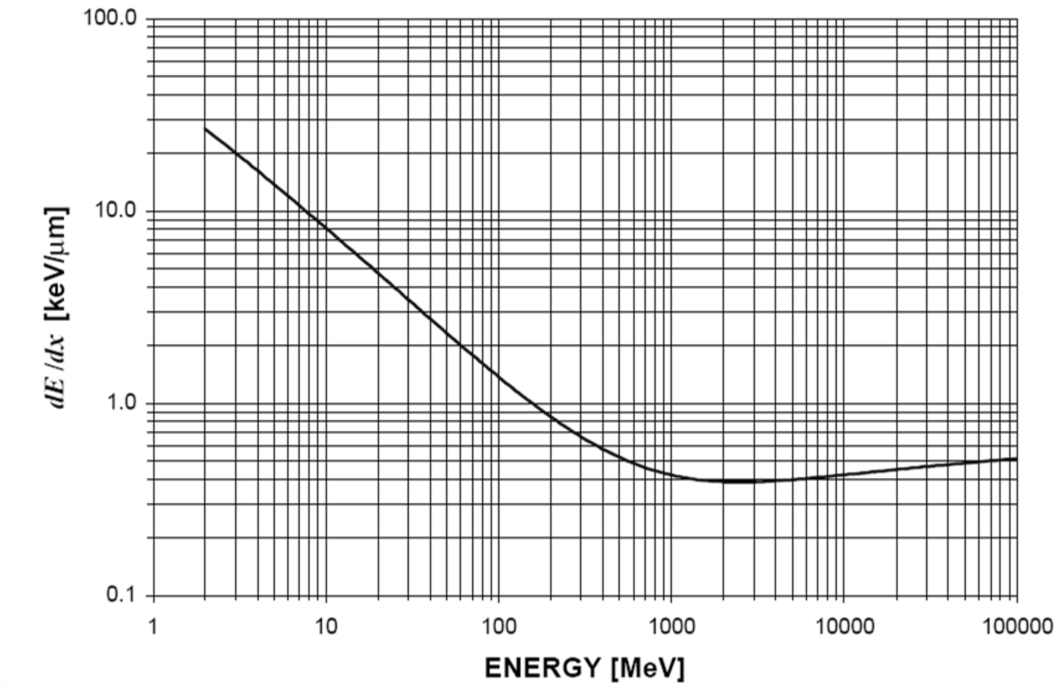
- Mean ionization energy exceeds band gap due to phonon excitation to conserve energy and momentum

- Value for a-Si:H not exactly known (3.4-6 eV/pair)
  - Reason ?
  - No single value for a-Se (field dependant) !

MIPS

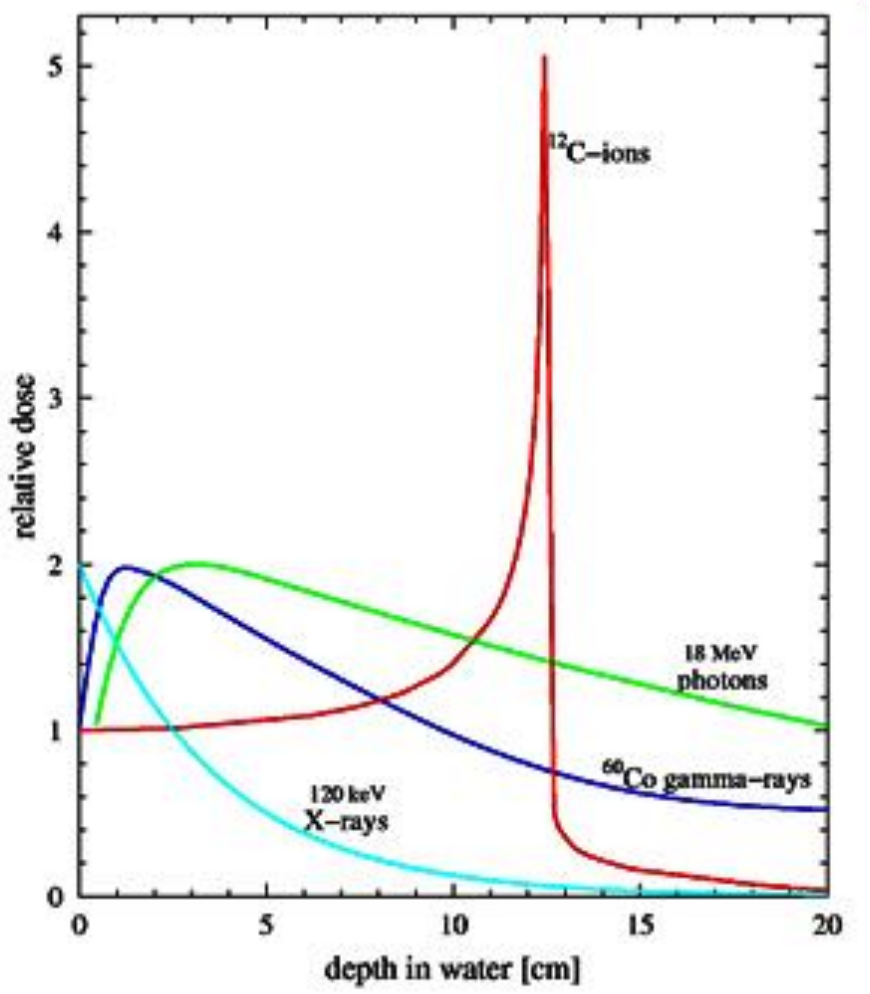
N. Wyrsch

p^+ in Si



- For minimum ionizing, a particle deposited ≈1.5 Mev/(g cm^2)
- Electron-hole pair creation energy W:
  - c-Si : 3.6 eV
  - a-Si:H : 3.4 - 4.8 (– 6 eV)
- Proton in Si
  - At the minimum of dE/dx a creation of 110 electron holes pairs/micron is predicted
  - Actual figure is measured to be about 80 e-h pairs per micron
  - The difference between the two being accounted for by energy lost by the incident particle to the lattice via phonon interactions

Bragg curve

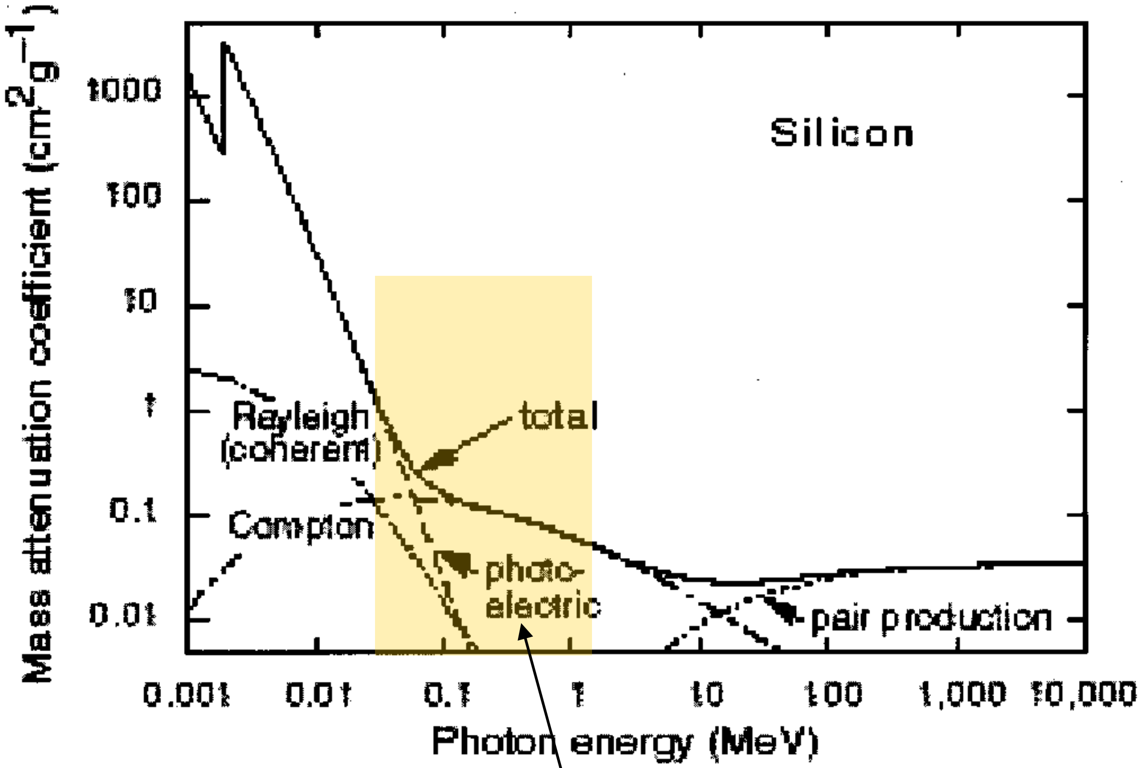


- For charge particle most of the energy deposited just before coming to a rest (Bragg peak)
- Peak can be enlarged by having an energy distribution of the particles

GSI Helmholtzzentrum

Photon interaction with matter

N. Wyrsch



Energy range of interest for radiography (medical and industrial)

- Energy transfer process depends on photon energy and material
- Attenuation given by

$$I(x)=I_0 \, e^{-\mu x}$$

With

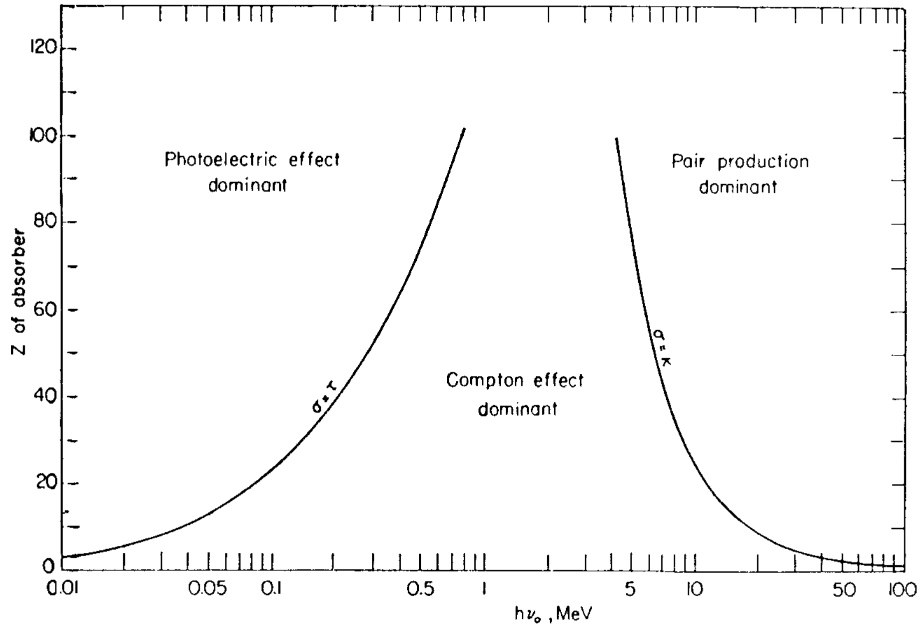
I_0: initial beam intensity

$\mu=n\sigma$, n the number of atoms /cm^3 and σ the cross-section

- High energy photon much more penetrating

Hartmut & Sadrozinski, IEEE 2001

X-ray interaction with matter



- Interaction of X-ray with matter
  - Photo effect (photoemission)
  - Compton scattering
  - Pair creation
- Major effect depends on energy and atomic number

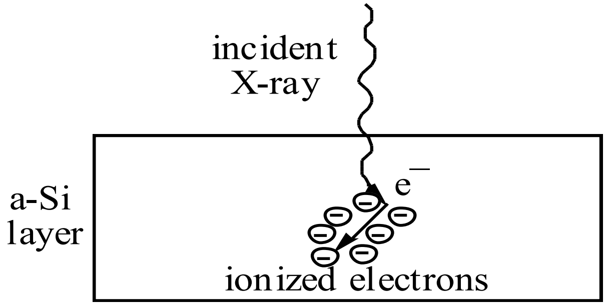
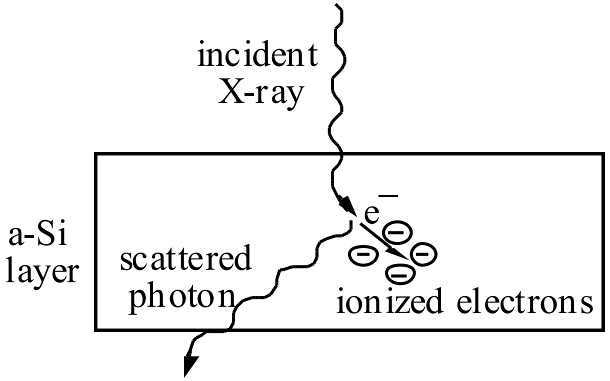
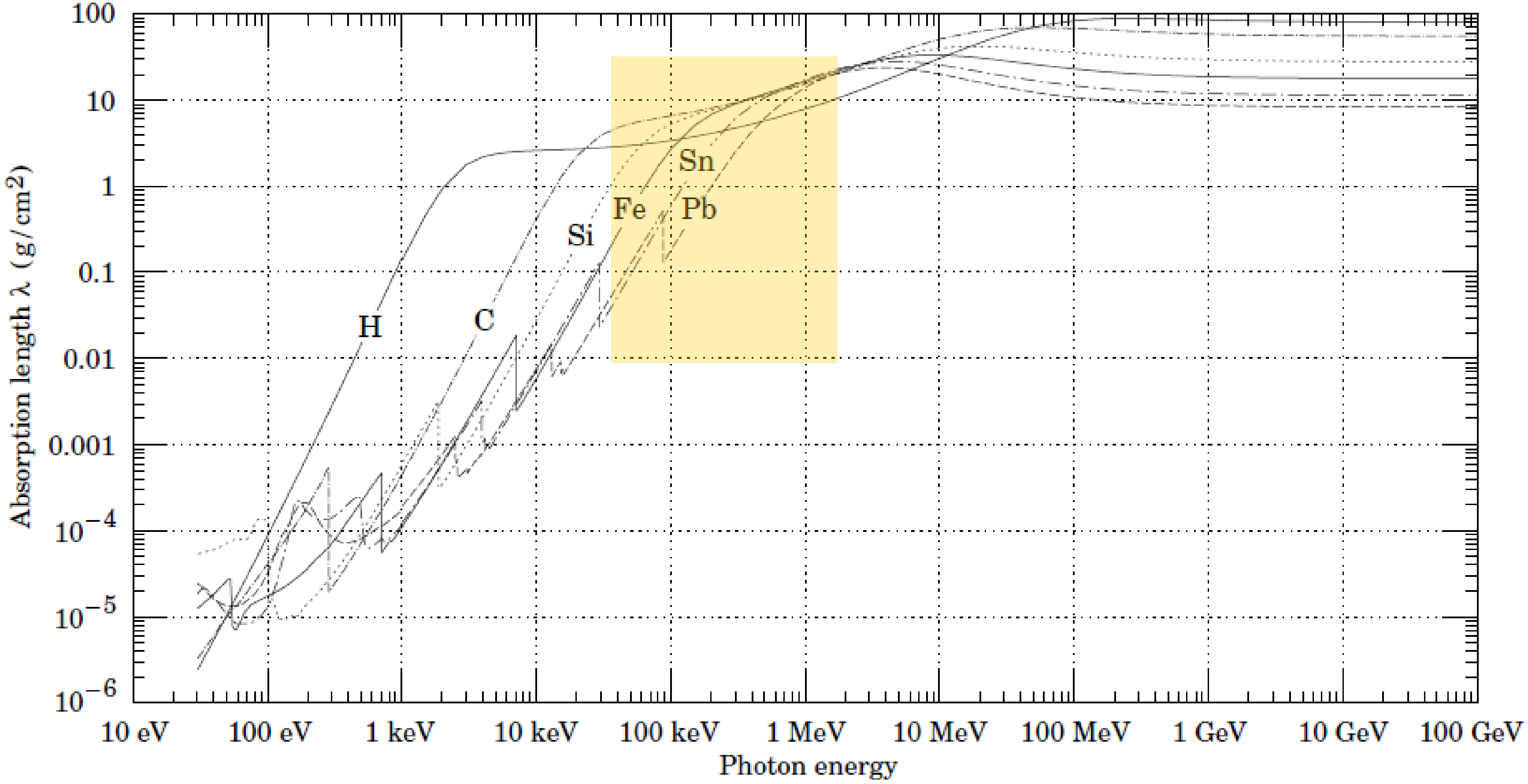


Photo effect followed by ionization processes



Compton effect followed by ionization processes

Photon absorption length

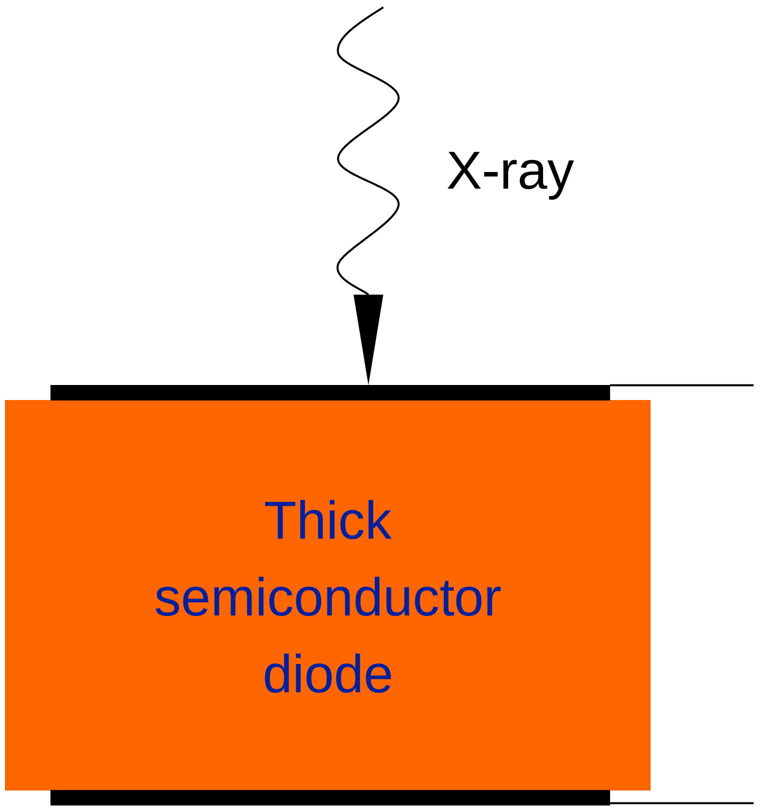


Passage of particles through matter, D. E. Groom and S. R. Klein, 2000

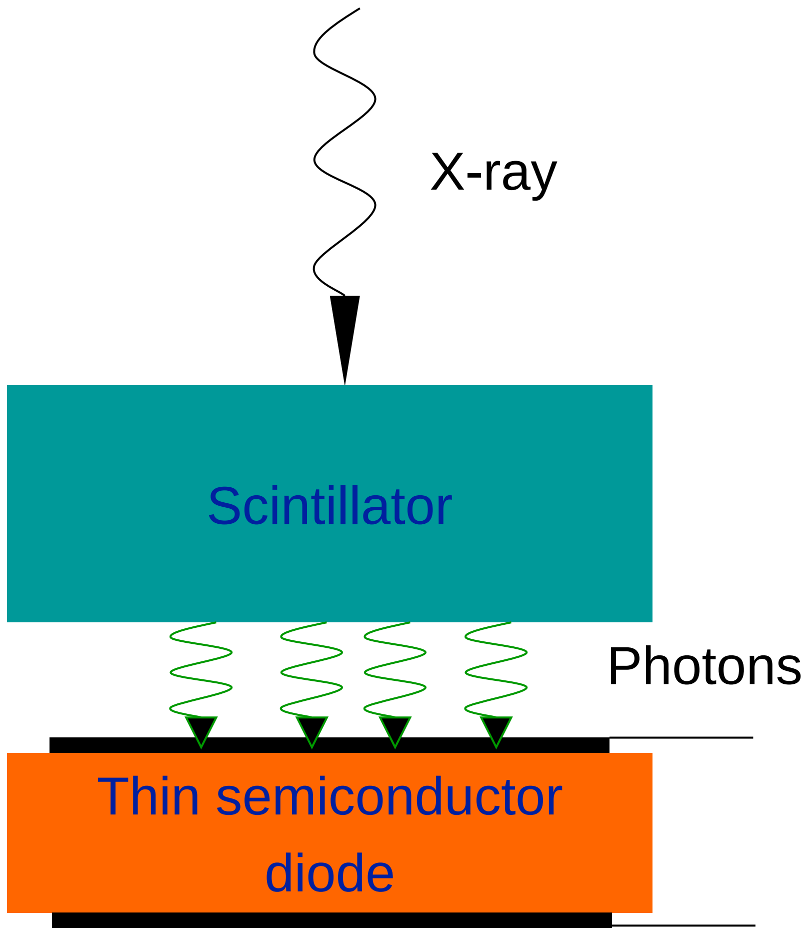
Direct / indirect detection

N. Wyrsch

- Direct



- Indirect



X-ray detectors

N. Wyrsch

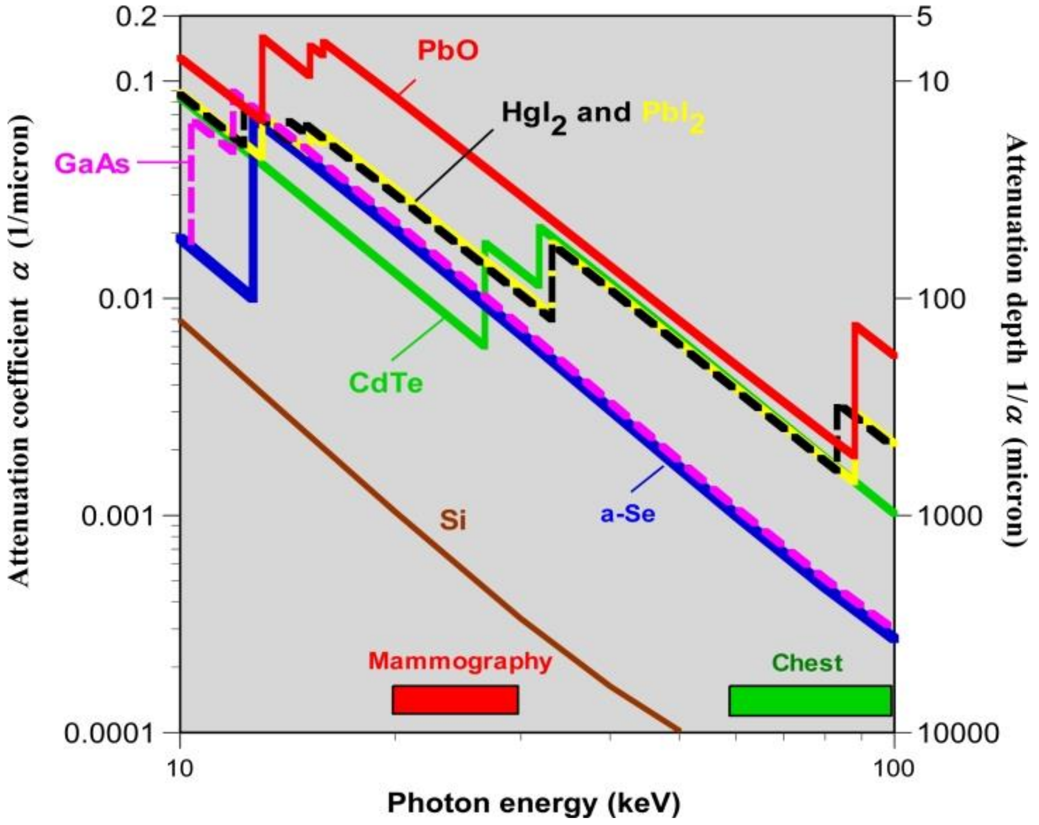
Detector performances: x-ray detectors

	CR	Indirect	Direct Conversion	new detectors	
	Gd_2O_2S:Tb	CsI:Tl	a-Se amorphous	CdTe Sing. cryst.	PbI_2 polycryst.
Atomic number	64	55,53	34	48,52	82,53
Density	7.5	4.5	4.3	6	6.2
K edges (keV)	50.2	33.1, 36	12.7	26.7, 31.8	88, 33.1
Average abs. coeff. (cm^{-1}) RQA5 (70 kVp, 21 mm Al)	52	48	16	48	57
Bandgap (eV)			1.7-1.9	1.5	2.4
$\mu\tau$ electrons (cm^2/V)			3×10^{-7}	2×10^{-3}	10^{-5}
$\mu\tau$ holes (cm^2/V)			4×10^{-6}	4×10^{-4}	2.10^{-6}
Conversion efficiency	~ 60 $h\nu$/keV	~ 60 $h\nu$/keV	20 el/keV	~ 220 el/keV	~ 240 el/keV
Refractive index	> 2	1.78			2.7
Emission spectrum (nm)	540	500-600			

CR: computed radiography

R. Padovani, 2006

a-Se

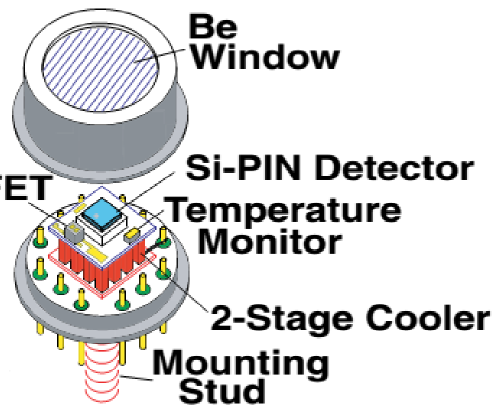


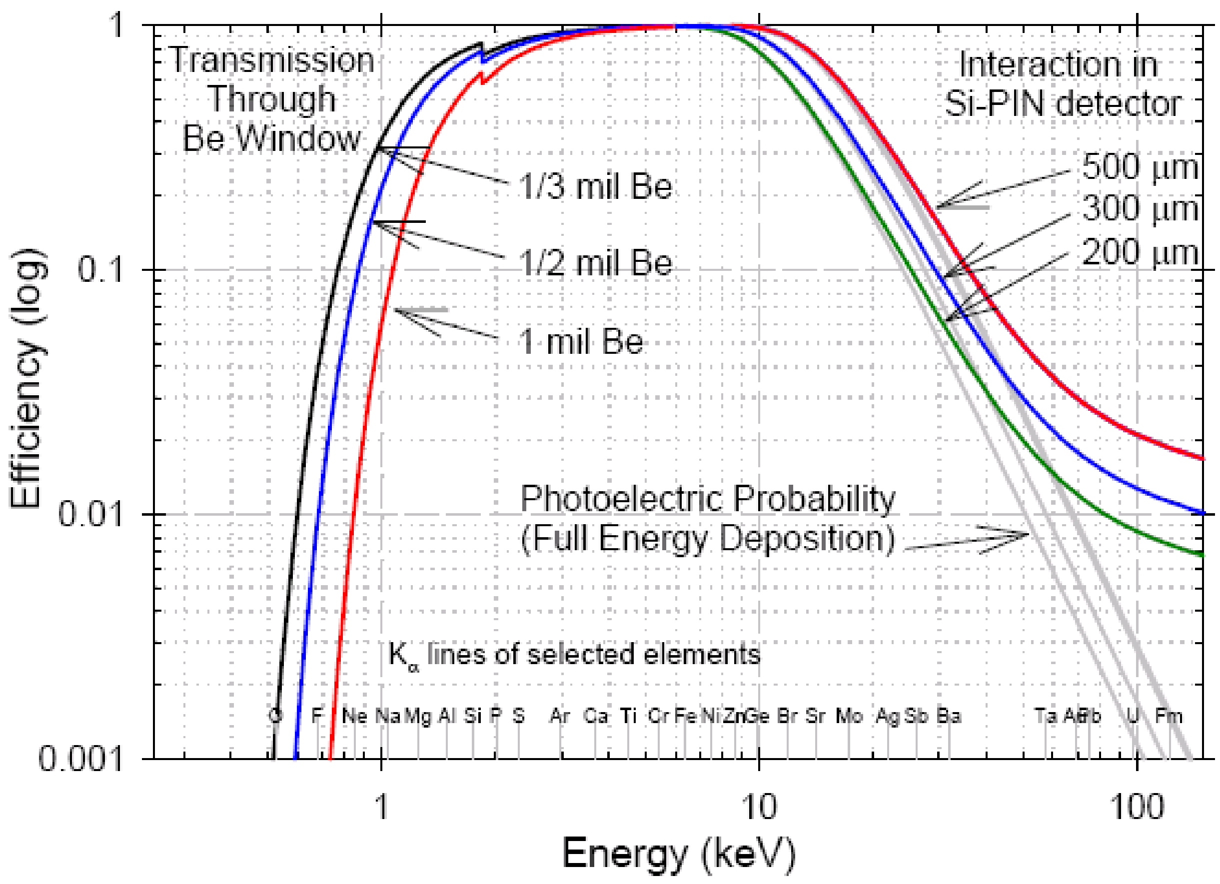
S. Kasap et al., Sensors 11 (2011)

- Amorphous semiconductor
- Two fold coordinated chains and rings
- Bandgap : 2.3 eV
- No doped a-Se
- As and/or Cl doping/alloying for material stabilization (to hinder crystallization)
- High absorption of X-rays
- e-h pair creation energy: 6-10 eV (field dependent)
- Deposition by evaporation

- Typical detector thickness: 200 µm

X-ray detection using Si diodes





- Si detector efficiency as a function of X-ray energy and Si detector thickness

http://www.amptek.com

Scintillators

Scintillator	Type	Density (g/cm^3)	Light Yield Ph/MeV	% (NaI) conversion efficiency	Peak emission λ (nm)	Decay time τ (μs)	Hygroscopic	Application
NaI(Tl)	Single crystal	3.67	38 000	100	415	0.23	Yes	SPECT
CsI(Tl)	Single crystal	4.51	54 000	45	550	1.0	Slightly	SPECT PET, XCT
BGO	Single crystal	7.13	9 000	10	480	0.3	No	PET
CWO	Single crystal	7.90	28 000	35	470/540	20/5	No	XCT
$(Y,Gd)_2O_3$:Eu	Ceramic	5.9	-	34	610	1000	No	XCT
Gd_2O_2S :Pr,Ce,F	Ceramic	7.34	-	51	520	2.4	No	XCT

Crystalclear, CERN

Commonly used scintillators in Nuclear Medecine

- Efficient but slow
- Emission mostly in visible range

Scintillators (2)

Scintillator	Type	Density (g/cm^3)	Light Yield Ph/MeV	% (NaI) conversion efficiency	Peak emission λ (nm)	Decay time τ (ns)	ref
$PbWO_4$	Single crystal	8.28	100		420	5 + 15	
Lu_2O_2S:Ce	Single crystal	8.9					
$Bi_3Ge_4O_{12}$	Single crystal	7.13	8200	10	505	300	43
LuF_3:Ce	Single crystal	8.3	8000		310	23+slow	62
$LuAlO_3$:Ce	Single crystal	8.34	11400		365	17	45
Lu_2SiO_5:Ce	Single crystal	7.4	27000		420	40	59
$LuBO_3$:Ce	Single crystal	7.4	26000		410	39	62
$ZnWO_4$	Single crystal	7.87	21500		480	22000	53
$CdWO_4$	Single crystal	7.9	19700		495	2000	43
Lu_2S_3:Ce	Single crystal	6.2	28000		592	32	62
$CaWO_4$	Single crystal	6.1	6000		430	6000	54
$BaLu_2F_8$	Single crystal	6.94	870		313	1+slow	34,68
$BaLu_2F_8$:Ce	Single crystal	6.94	400			35+slow	34,68
Gd_2O_2S: Pr,Ce,F	ceramic	7.34	40000	51	580	2100	42
$Lu_2Si_2O_7$:Ce	Single crystal	6.23	30000		380	30	67
$Lu_3Al_5O_{12}$:Sc	Single crystal	6.7	22500		270	610	44

Crystalclear, CERN

New scintillators for Nuclear Medecine

- Interesting scintillators emit in UV (low diode quantum efficiency)

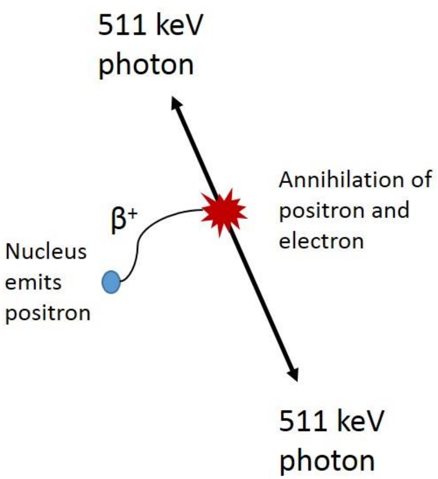
PET scanner

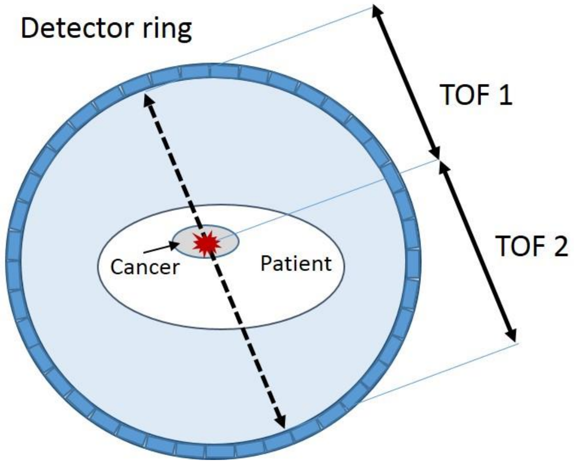
- Positron emission tomography used for imaging of cancer cells

  Radiotracer ^{18}F-Fluorodeoxyglucose

  Cancerous cells 'light up'

- Need coincidance detection of the 2 γ's
  - Fast detection
  - Based on indirect detection using **scintillators**
- Reconstruction of image
- Time-of-flight (TOF) detection would offer
  - Easier reconstruction
  - Better images
  - Lower dose for the patient
  - Need really fast detectors (10 ps $\leftrightarrow$ 3 mm) (not achievable with scintillators)





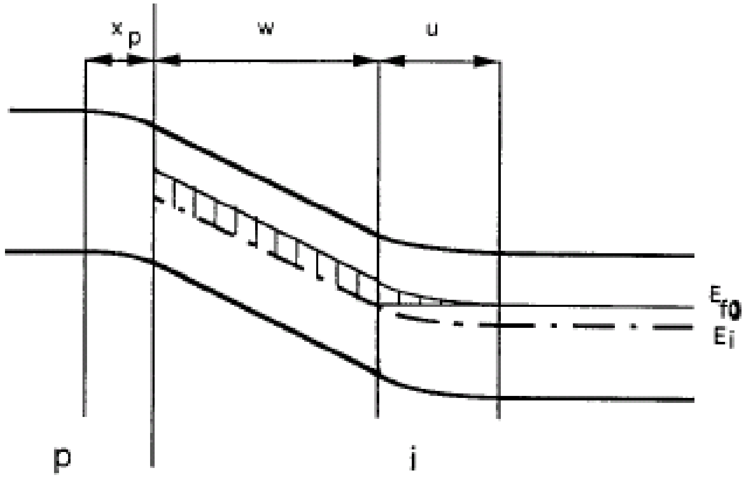
EPFL

Depletion condition (p-i-n diode)

- Electric field must be present throughout the diode
  - Electron-hole pair generated anywhere in the diode must be collected.
  - No field screening
  - Depletion region should extend to the entire thickness of the diode
- Depletion condition
  (from Poisson equation)

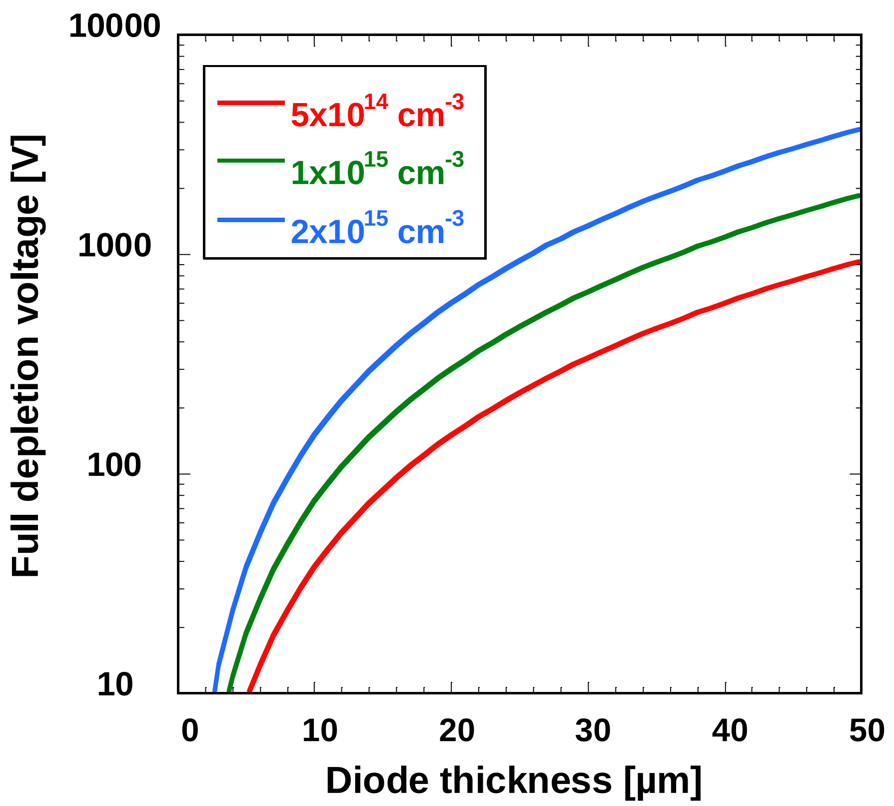
$$W = \sqrt{\frac{2\varepsilon\varepsilon_0}{qN_{DB}^*}}\sqrt{V_{bi} - V} > d$$

$$V_{FD} \approx \frac{q}{2\varepsilon\varepsilon_0} N_{DB}^* d^2$$



With W the depletion region width, N_{DB}^* the density of ionized *DB*, V_{bi} the built-in voltage and d the thickness of the intrinsic layer of the diode

Depletion condition in a-Si:H

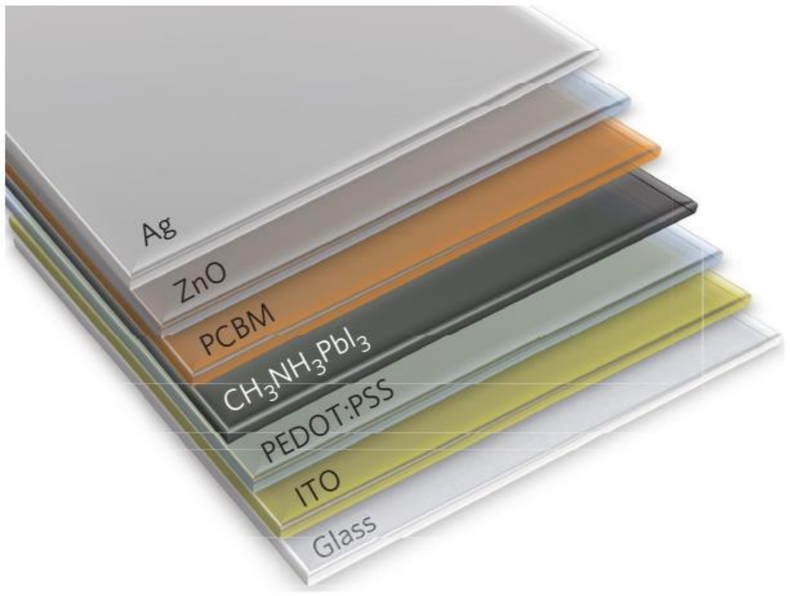


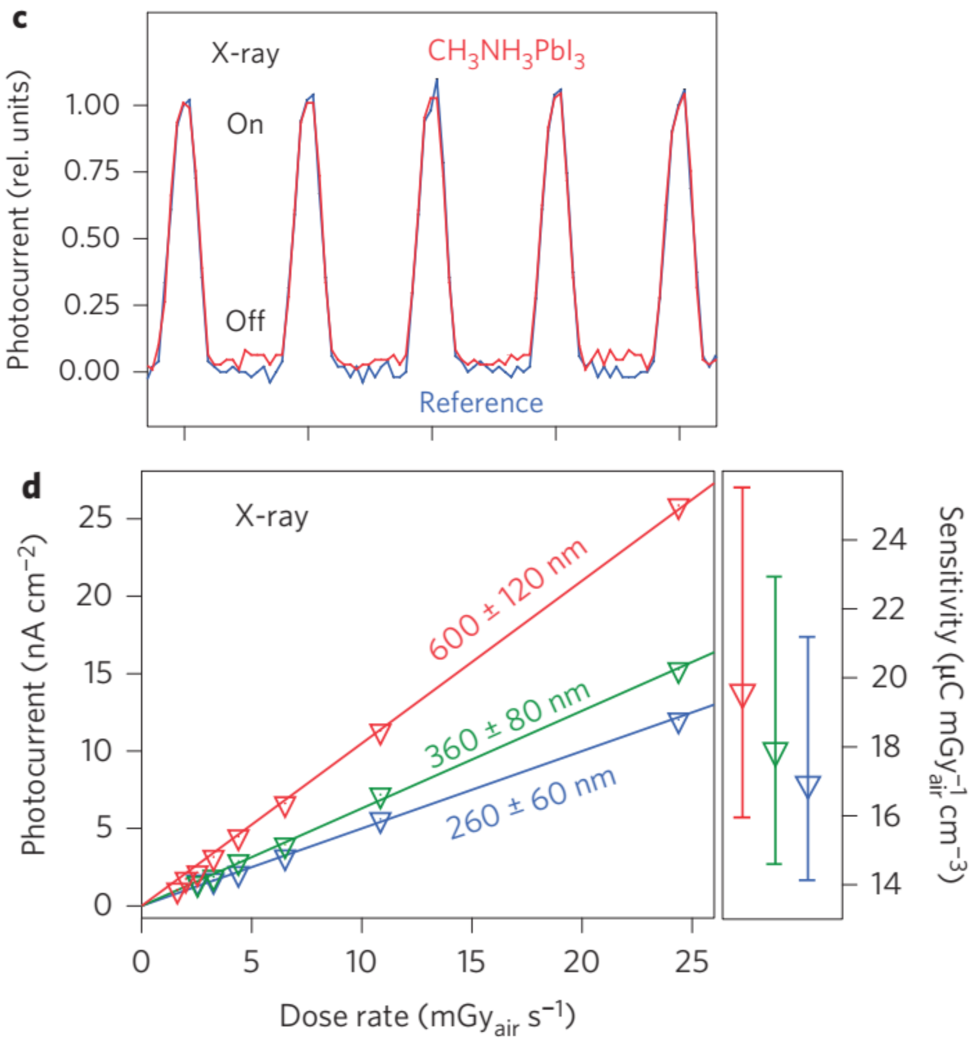
Full depletion voltage V_{FD} as a function of ionized defects density

- Full depletion voltage $V_{FD} \propto d^2$
- **≈ 600 V for 30 µm** (undegraded diode, assuming 30% of ionized DB)
- In a-Si:H diodes, dark (leakage) current depends
  - Thickness due to carrier thermal generation, bulk (volume) effect
  - Electrical field, carrier injection, Pool-Frenkel effect
- Supra-linear dependence on thickness !
- Dark current limits the diode thickness rather than depletion condition

Perovskites for X-ray detection

- Lead halide PK : $CH_3NH_3\mathbf{PbI_3}$, heavy materials for enhanced sensitivity



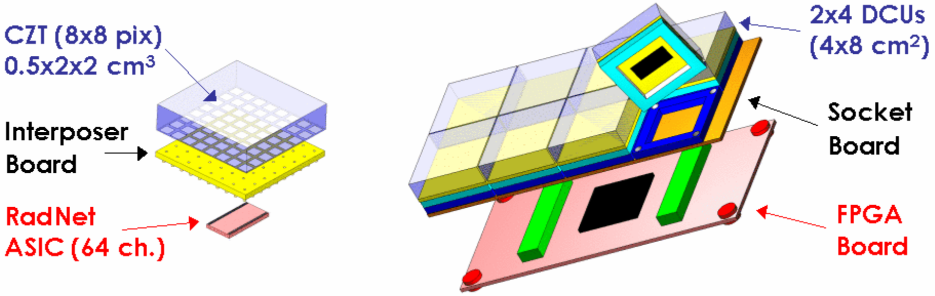


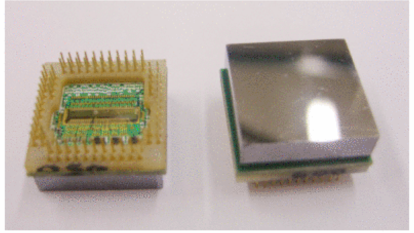
S. Yakunin et al., Nature Photonics 9 (2015)

Alternative materials for direct particle detection

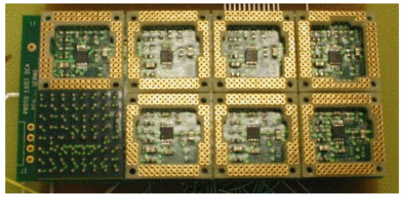
Radiation hard materials

- Cadmium zinc telluride (CZT)
  - Direct bandgap, 1.4-2.2 eV
  - high sensitivity for X-rays and gamma rays (high atomic number)
  - Use as photoconductor
- CdTe
  - Direct bandgap, 1.45 eV
  - high sensitivity for X-rays and gamma rays (high atomic number)
  - Use as photoconductor or diode with CdS p-layer
  - Main applications for hard x-ray detection (cooled)
- HgI_2, PbI_2
  - Relatively high bandgap: HgI_2 : 2.13 eV, PbI_2 : 2.38 eV
  - High sensitivity for for X-rays and gamma rays (high atomic number)
  - No practical application yet





Detector Crystal Unit (DCU: 4 cm^2)



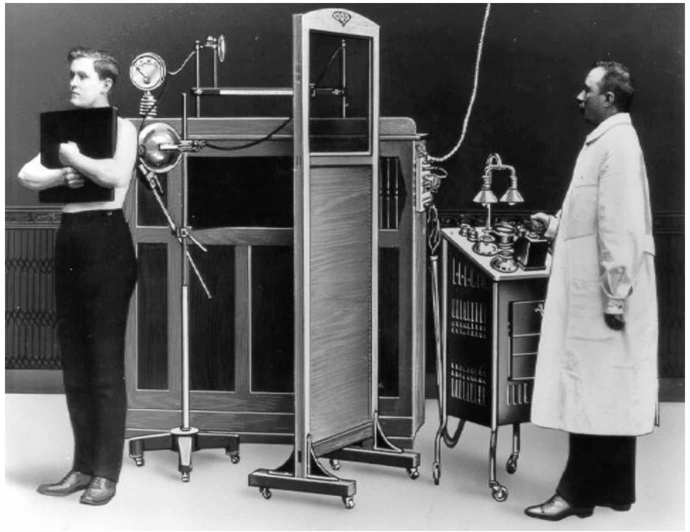
Detector Crystal Array (DCA: 32 cm^2)

Detector for Energetic X-ray Imaging Survey Telescope (NASA)

N. Wyrsch

Active Matrix Flat panel Imagers (AMFPI) for radiography

Radiography evolution



Si vs Se based AMFPI for direct radiography

N. Wyrsch

a-Si:H

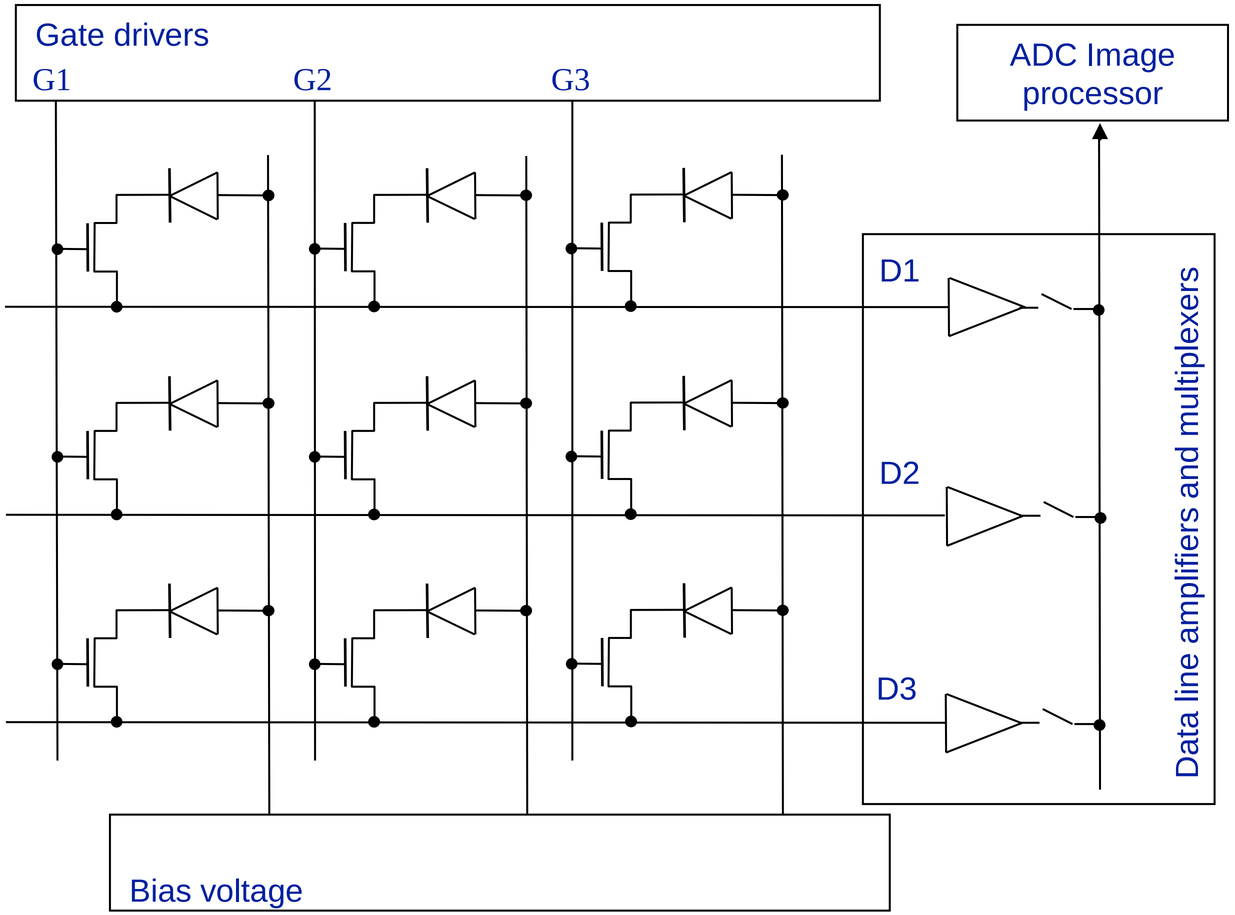
- Indirect detection (scintillator)
- Typical scintillator: Cs:I
- Dedicated active matrix
- High cost
- High sensitivity
- Low dose needed
- Lower spatial resolution (indirect detection, light spread out, > 70 µm pixels)
- Work horse for medical radiography

a-Se

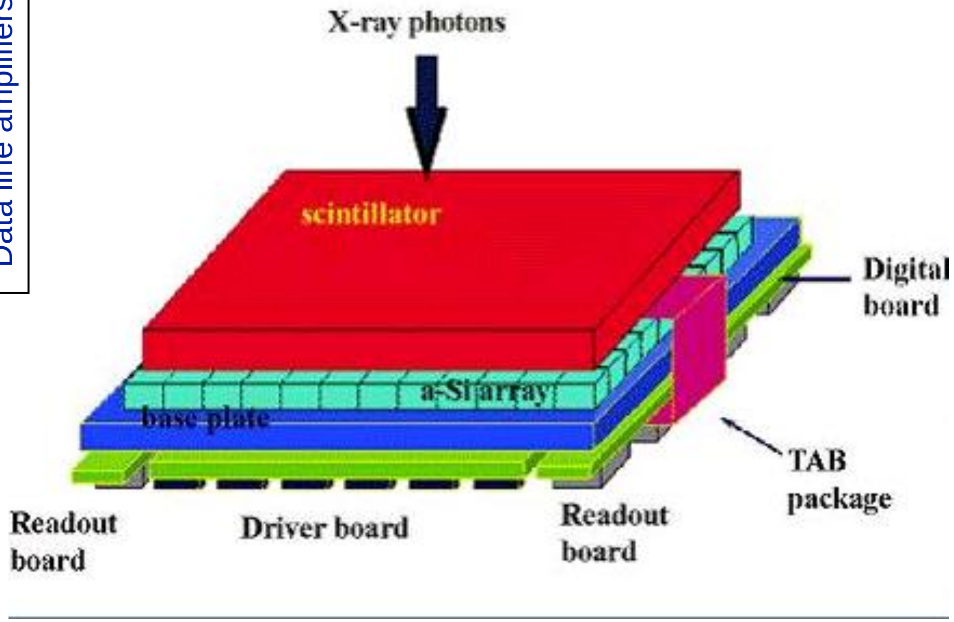
- Direct detection
- Used as photoconductor (cannot be doped)
- Can use FPD active matrix
- Lower cost
- Lower sensitivity (photoconductor)
- Higher dose
- Better spatial resolution (> 70 µm pixels)
- Best for mammography

Imagers (with scintillators)

N. Wyrsch

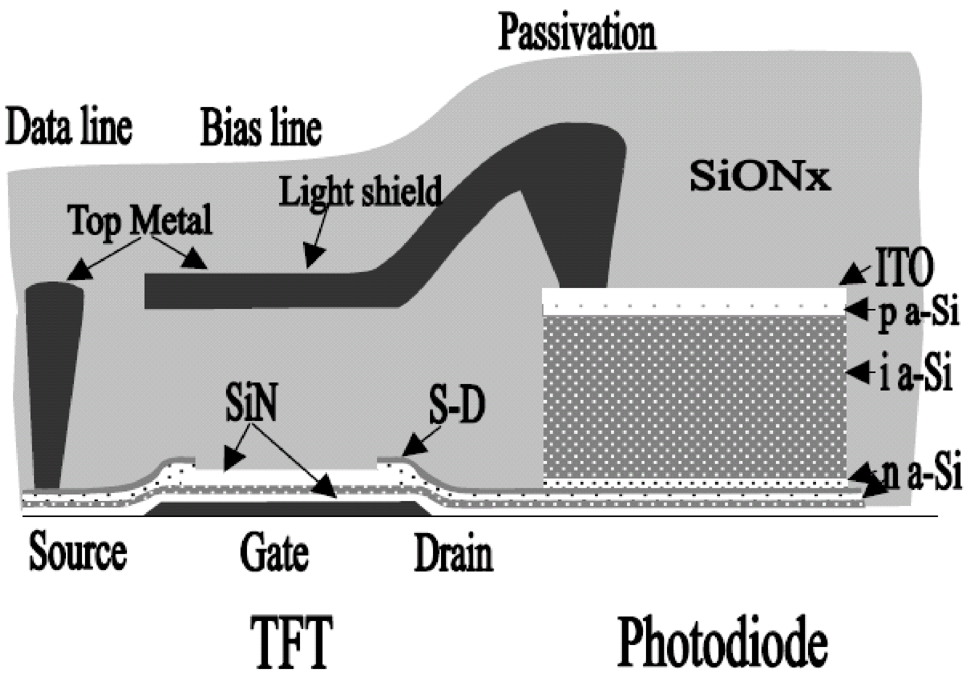


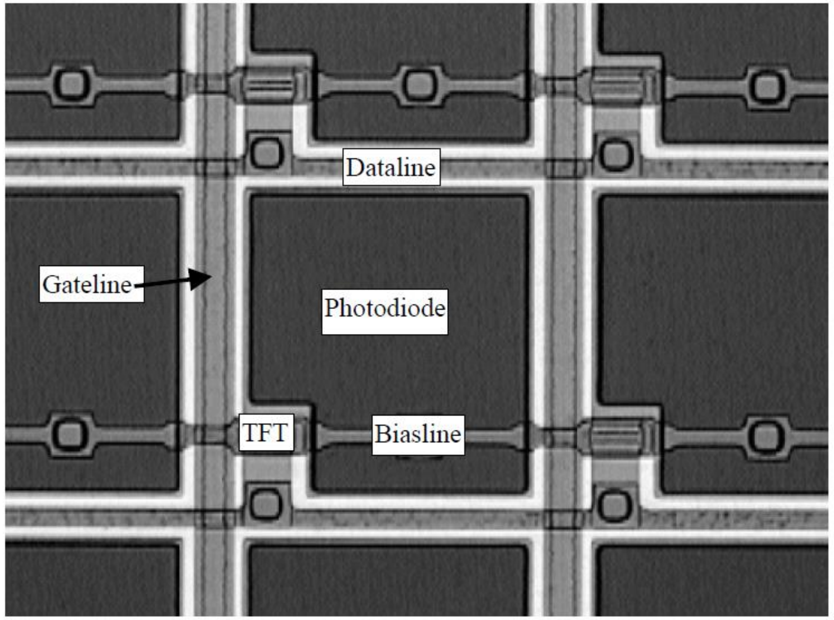
- 2D photodiodes arrays addressed by TFT
- Photodiodes coupled with a scintillator layer (Cs:I) for conversion of x-rays to visible photons



a-Si AMFIP

N. Wyrsch





Weissfield, DPix

PV-lab
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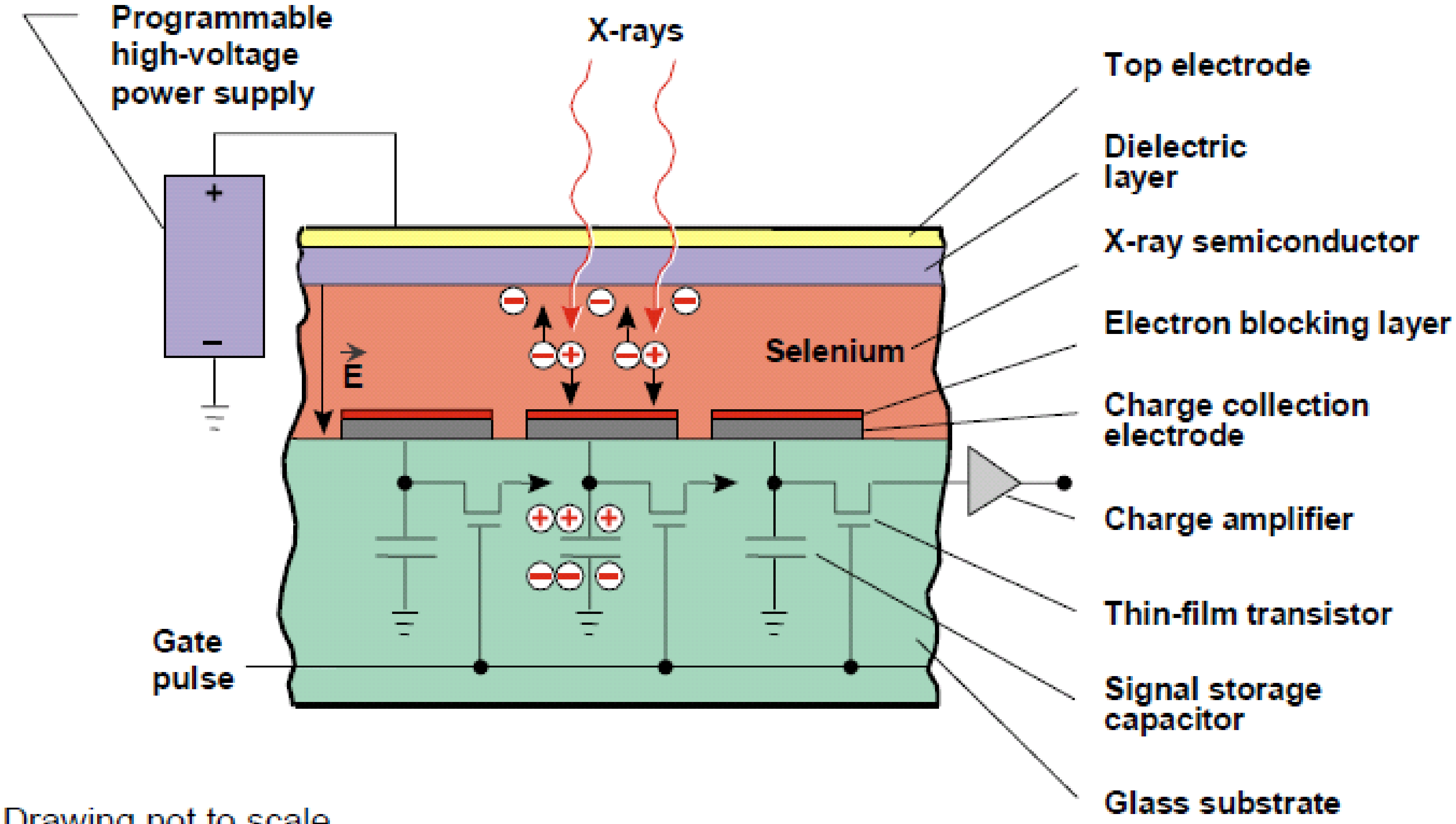
a-Se AMFPI

N. Wyrsch



Drawing not to scale

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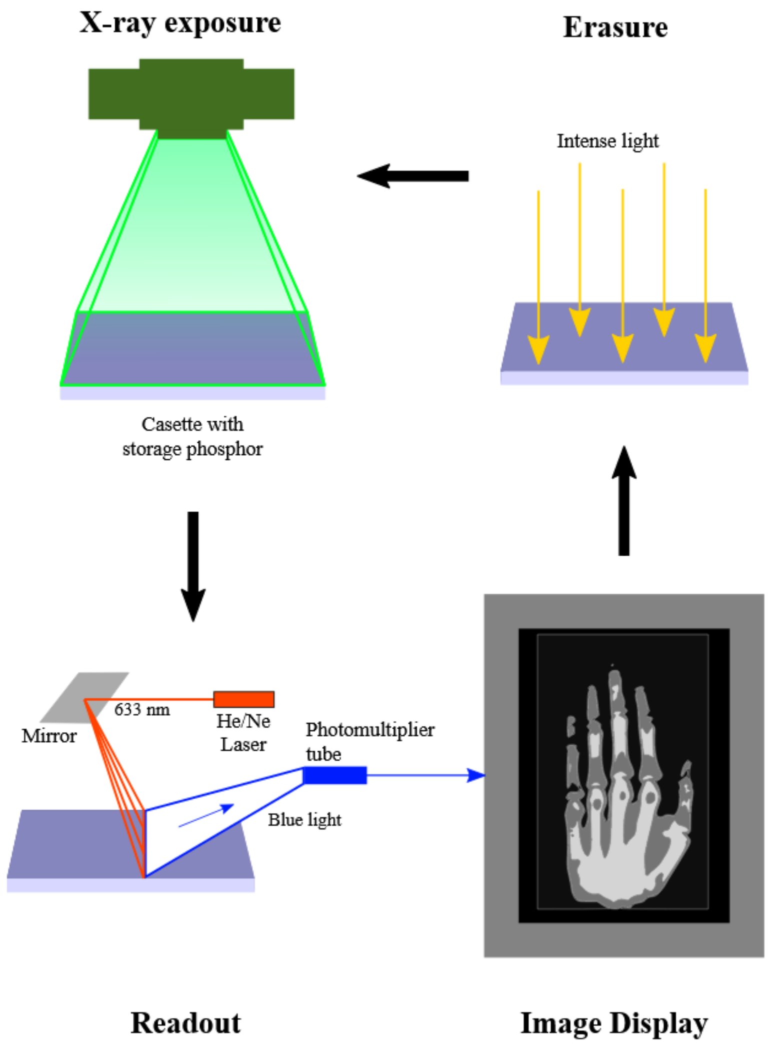
Alternative digital radiography technology

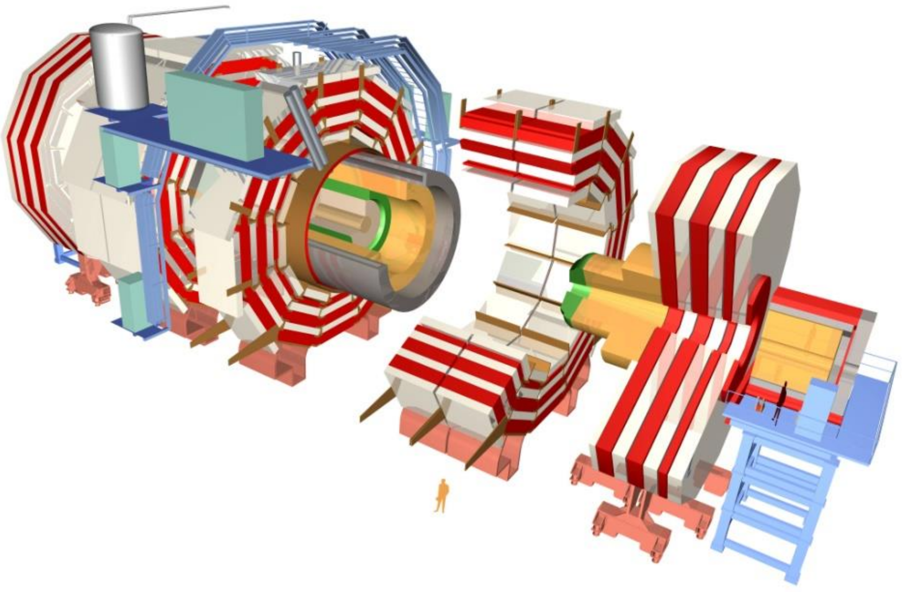
- Indirect radiography
- Computed radiography using photostimulated luminescence
- Enable the use of standard X-ray radiographic system with cassettes
- Films replaced by photostimulable phosphor plates
  - Exposure using short wavelength (X-ray), creation of metastable luminescent state
  - Reading using red light
  - Erasure using intense white light
  - Plate can be reused thousands of times



Wikipedia

Other particle detectors
a-Si:H for particle detection

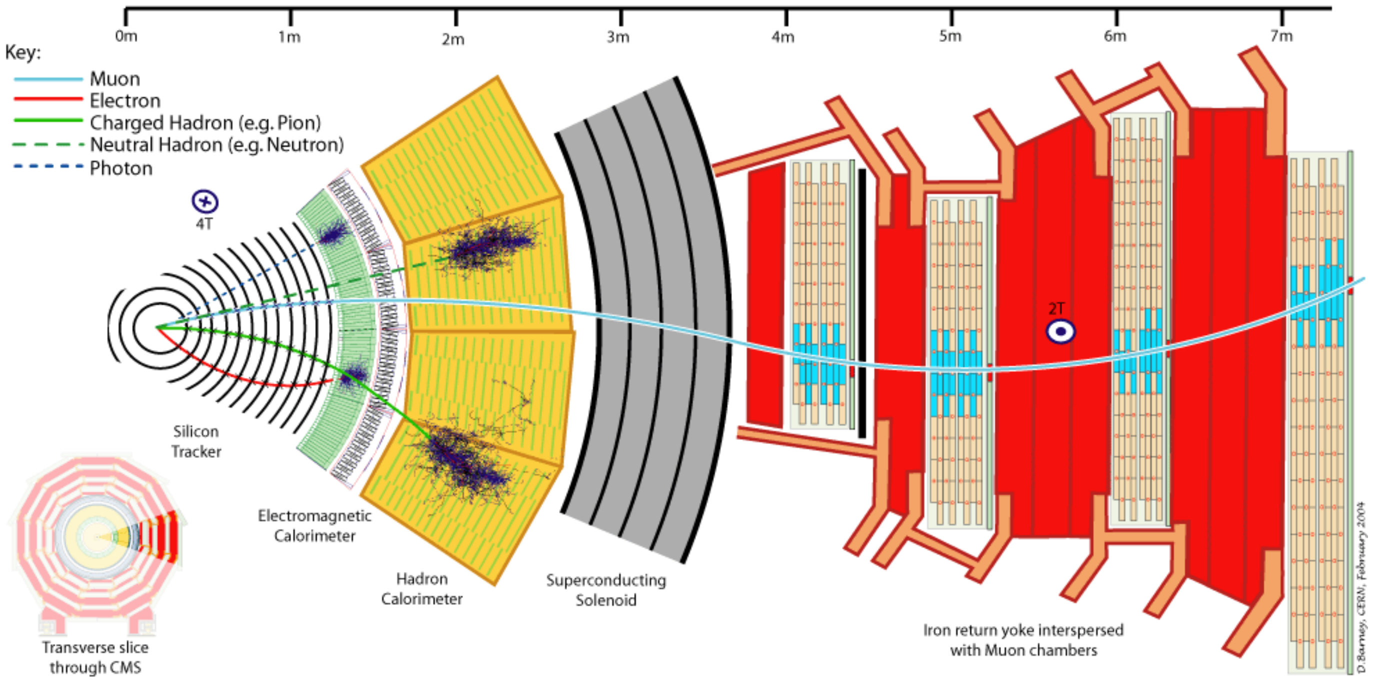
CMS detector for LHC



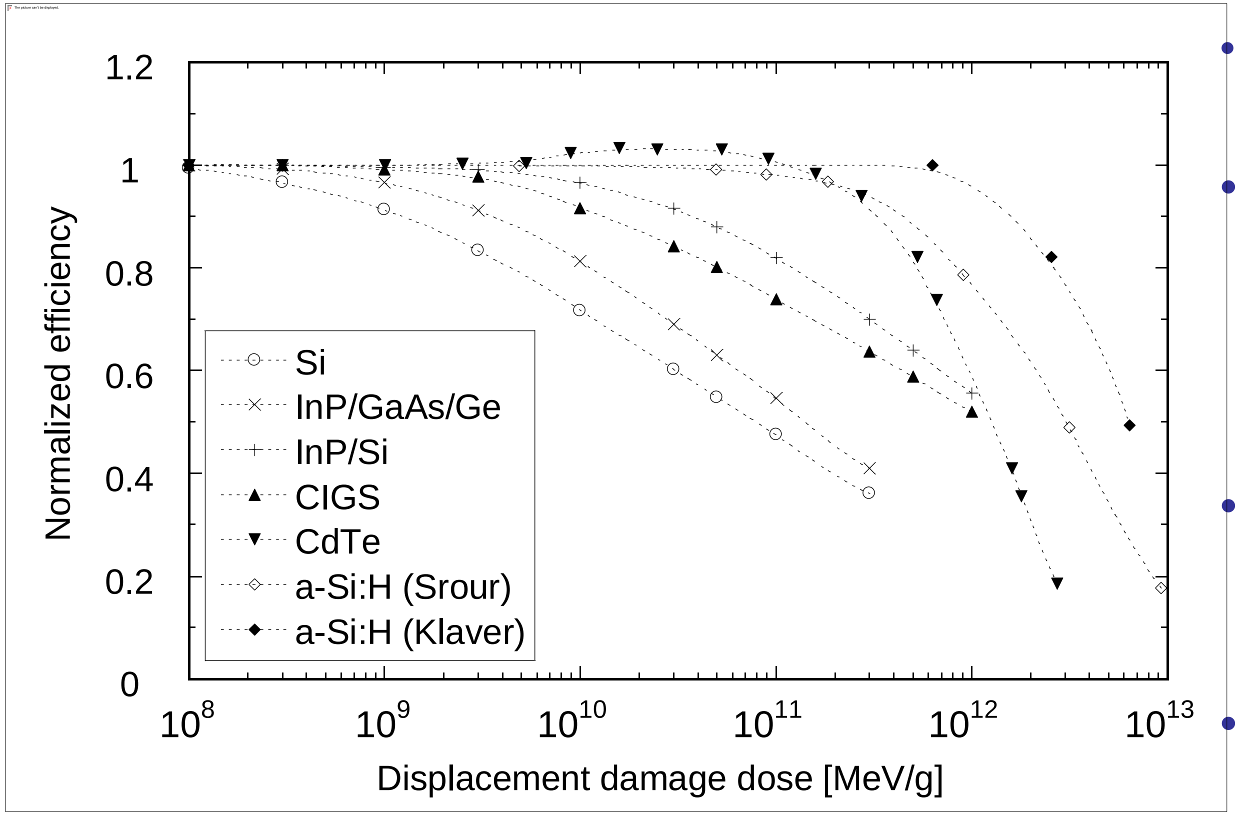
LHC: Large Hardron Collider
CMS: Compact Muon Solenoid

Silicon tracker

- Pixelized detectors
- Very large area (>100 m^2)
- High radiation hardness needed



a-Si:H particle detectors

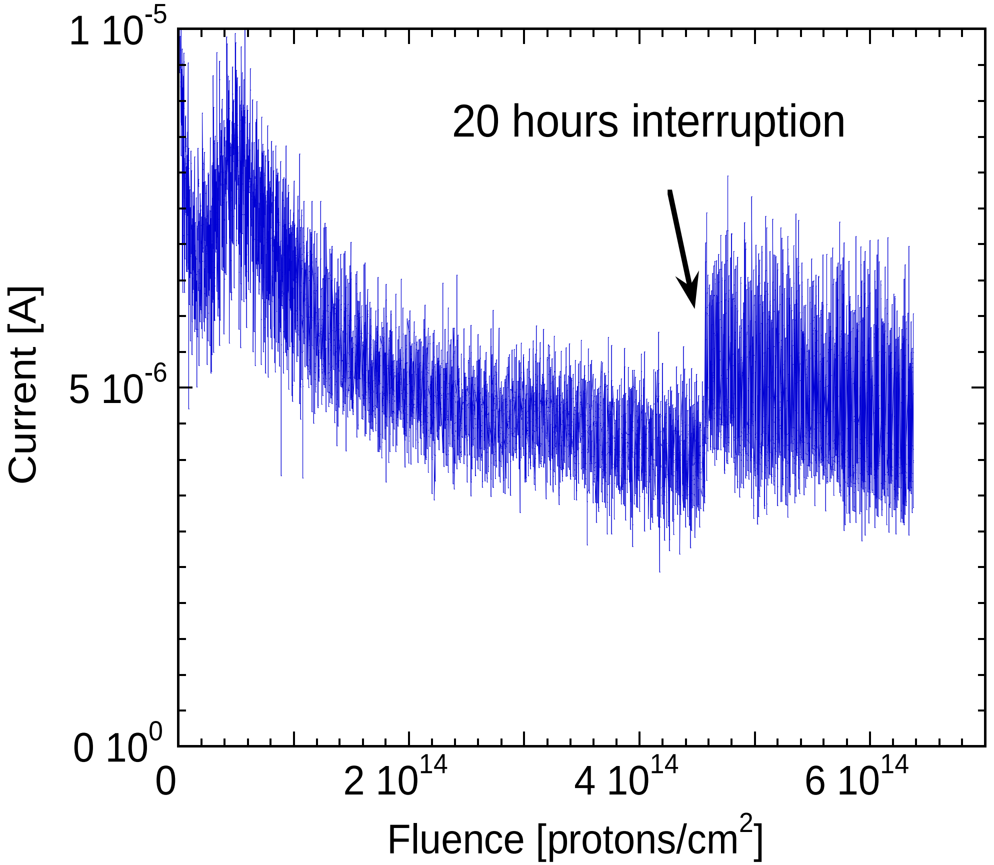


Effect of radiation on various solar cell technology (Bätzner, 2004, Srour,1998, Klaver,2007).

- a-Si:H is very radiation hard light-weight material (and low Z)
- similar to c-Si ⇒ weak interaction
  (≈ 80 electron hole pairs per micron of silicon created)
  ⇒ thick DEPLETED diode needed
- a-Si:H diodes can be deposited directly on CMOS readout chips (TFA - technology)
- Can be deposited on flexible substrates
  - Detectors with cylindrical symmetry
  - Non-flat detection surfaces
  - Small/thin detector

Radiation hardness of a-Si:H

N. Wyrsch

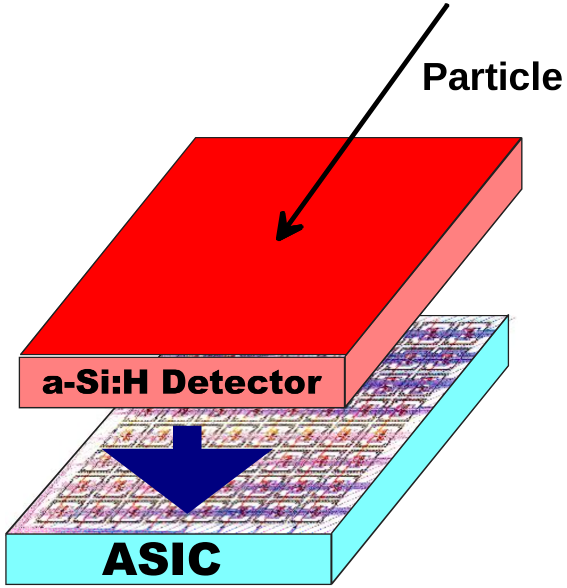


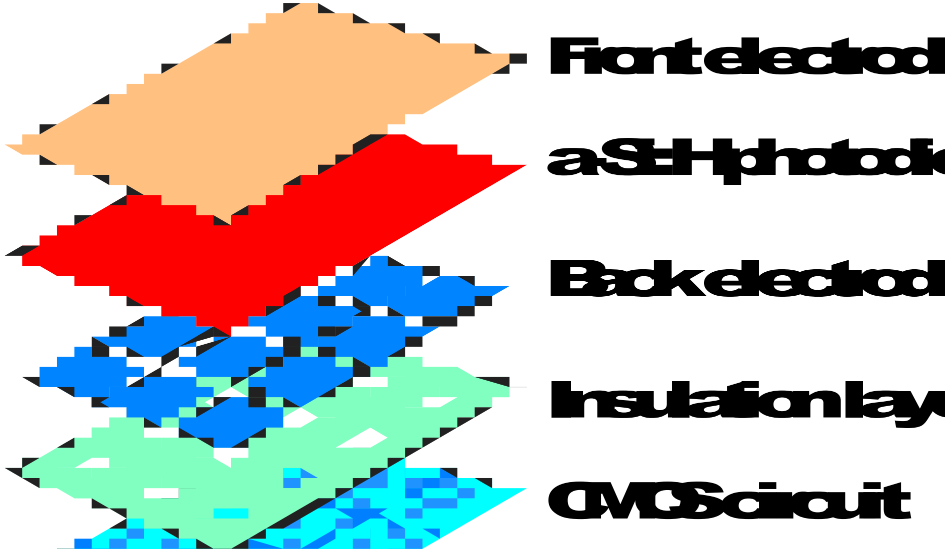
- Test of a-Si diodes under 24 GeV proton irradiation. Degradation of carrier collection by 50% for a fluence of 10^{16} p^+/cm^2

- Stabilization attained after ≈$4x10^{15}$ p/cm^2
- Relaxation process observed

- High and renewed interest for high fluence/high flux application

TFA detectors



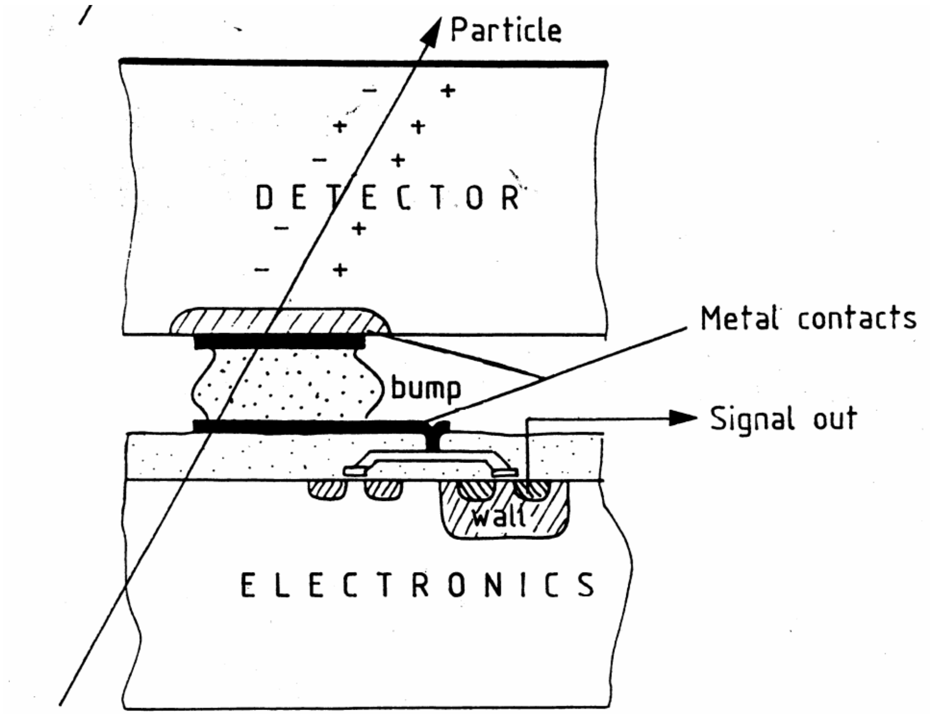


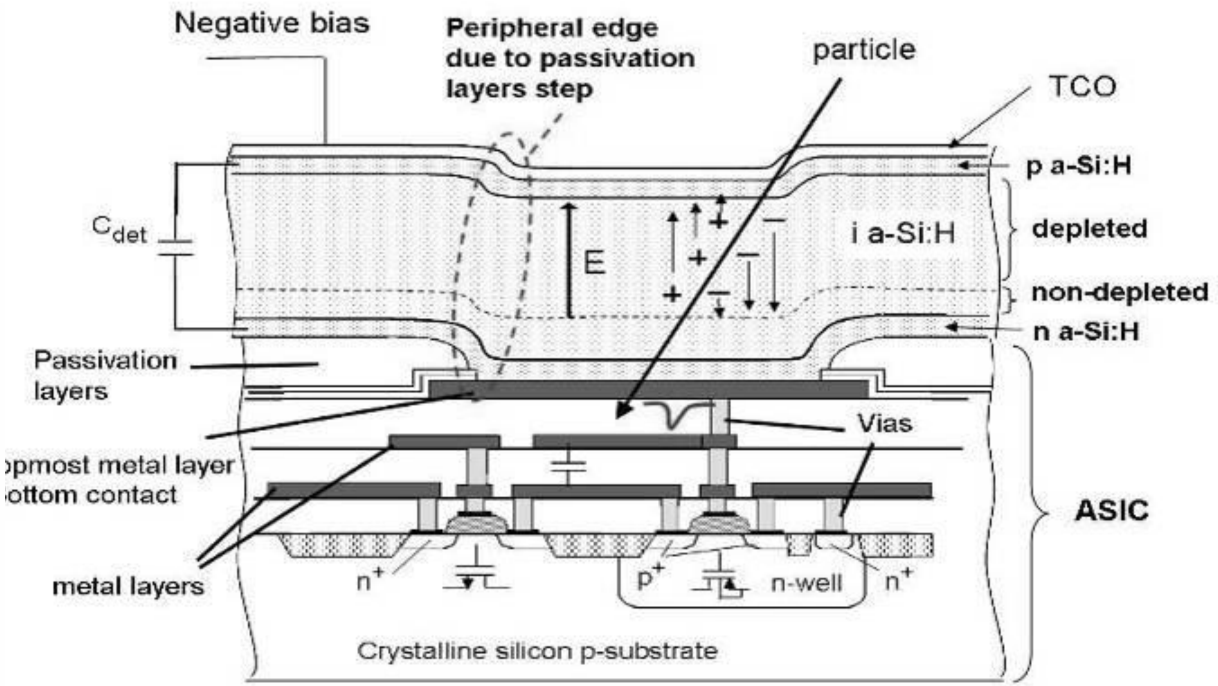
- Thin-Film on ASIC (TFA)
  - Thin-Film on CMOS (TFC)
  - Above IC technology
- Advantages
  - Entire chip space floor dedicated to detection
  - High geometrical fill-factor (ratio of sensitive to total area) ⇒ Higher sensitivity
  - Optimisation of detectors independent of CMOS design
  - **No dead area (for particle tracking)**

Sensor integration

- Si standard technology
  - c-Si sensor thickness : 300 µm
  - Low radiation hardness
  - Critical system integration

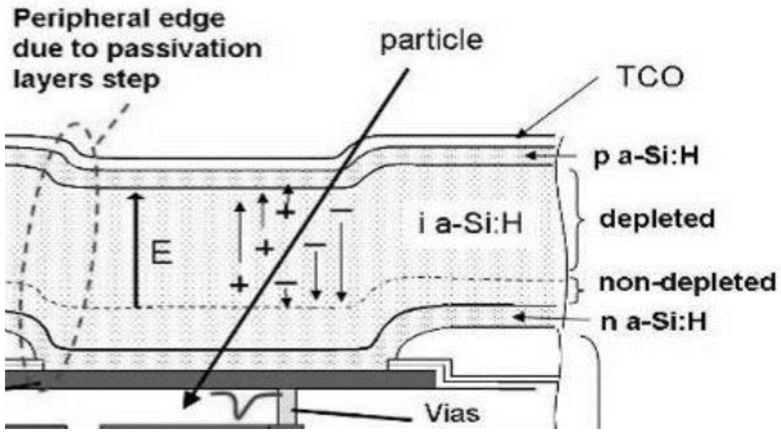
- TFA technology
  - a-Si:H sensor thickness: ≤ 20µm
  - High radiation hardness
  - High integration level

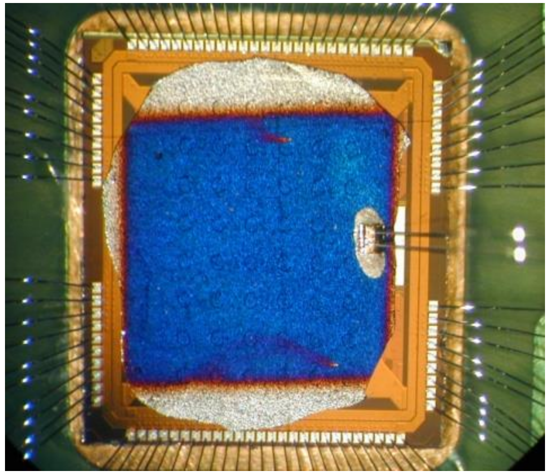




a-Si:H particle detectors

- a-Si:H is a very radiation hard material
- light-weight material (low Z) similar to c-Si
  ⇒ low interaction
  (≈ 80 electron hole pairs per micron of silicon created for MIPS) ⇒ thick diode needed
- Thick a-Si:H diodes (≈20 µm) can be deposited directly on CMOS readout chips (TFA - technology)
- **Diode must be depleted ! No charge collection outside the depleted region!**

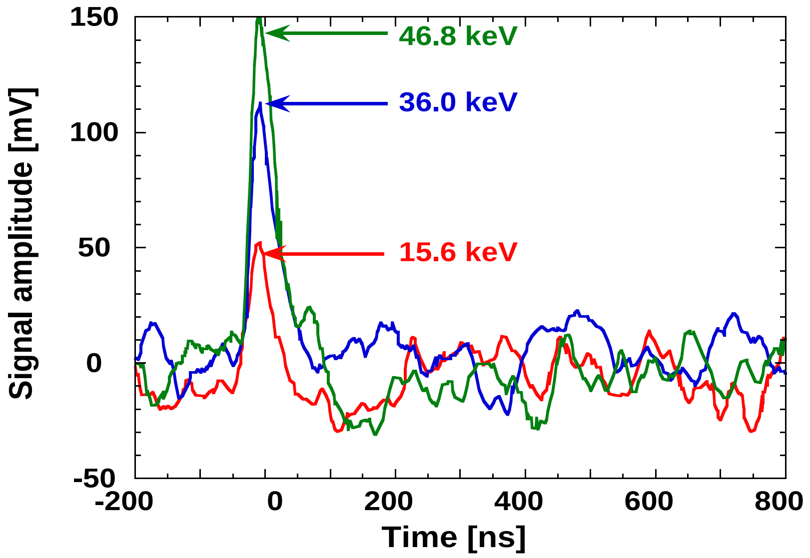




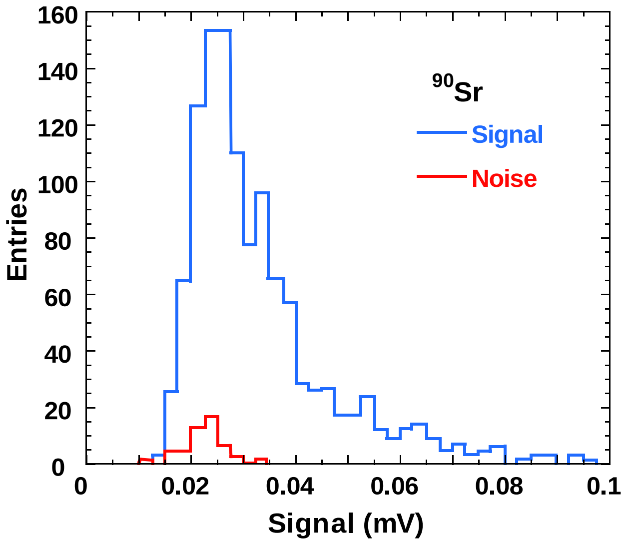
picture of a 8x6 pixel particles sensor in TFA technology with a 32 µm thick a-Si:H photodiode layer (CERN/EPFL-IMT).

β Particle Detector

IBM 0.25 µm technology (MPW)
- 4x2 mm^2 ASIC
- 32 pixels 38x94 μm^2, connected to active feedback amplifiers
- 32 µm thick a-Si:H diode (not fully depleted)

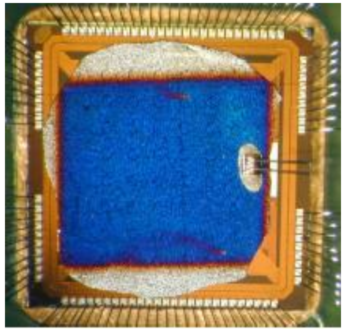


^{63}Ni source (low energy β)

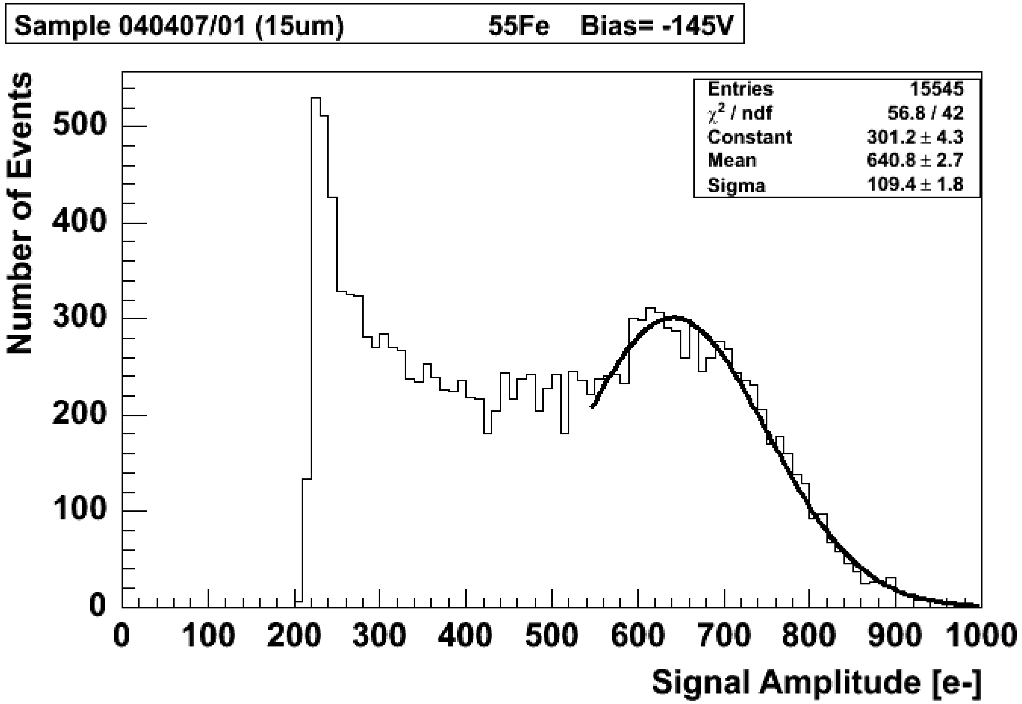


^{90}Sr (0.546 MeV β) : 1200 e^- collected per β

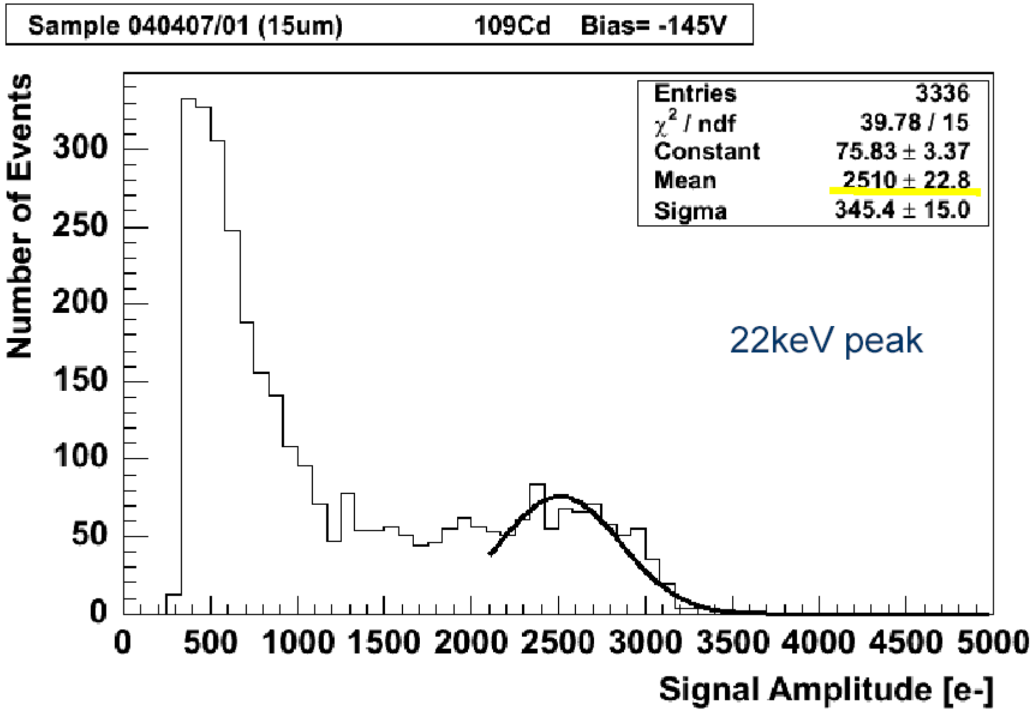
X-ray Detection



IBM 0.25 µm technology (MPW)
- 4x4 mm2 ASIC
- 48 pixels with 150 µm size and 380 µm pitch
  connected to active feedback amplifiers
- 15 µm thick a-Si:H diode



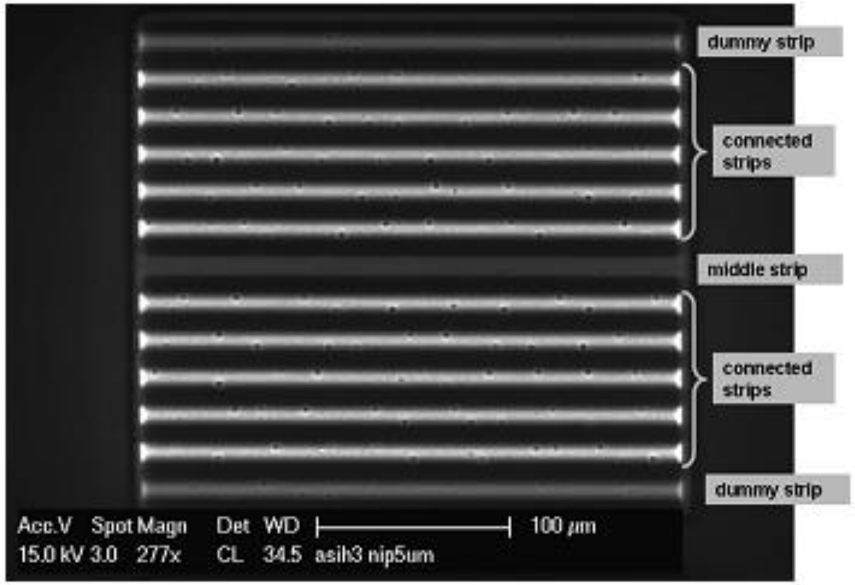
^{55}Fe source: peak at 5.9 keV

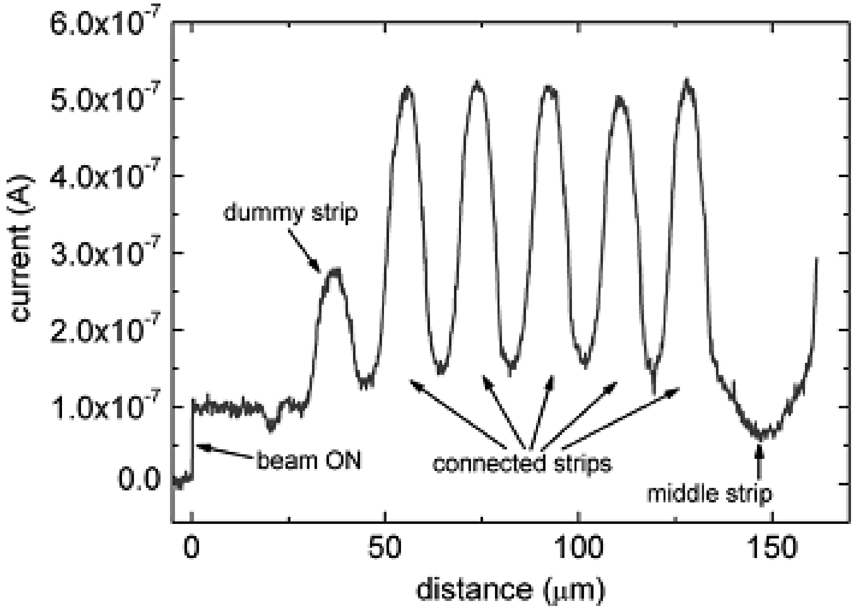


^{109}Cd source: peak at 22 keV

Spatial resolution

- Electron beam-induced current (EBIC) map and scan of TFA sensor





Microstrip spaced by 13.4 µm with 5 µm a-Si:H thick diode

A. Franco et al. , IEEE Trans. on Nucl. Sci. 59 (2012)

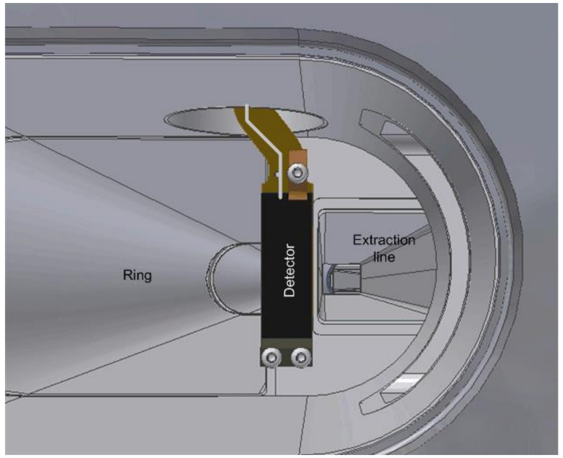
- Micrometer spatial resolution achievable
- Very small lateral collection → negligeable cross-talk between pixels/strips

Large a-Si:H particle detector

- Detector for beam extraction efficiency measurement in a synchrotron (at CNAO, Italy for hadron therapy – treatment of cancers using hardrons or heavy ions)
  - Need for a large radiation hard detector

40 mm

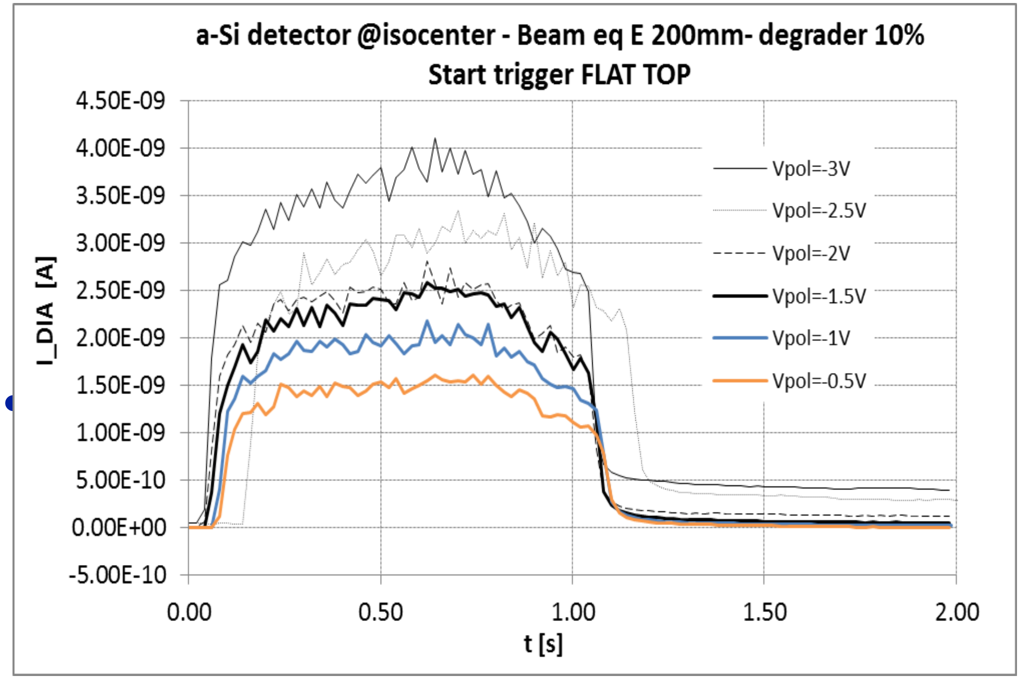
5 µm thick n-i-p a-Si:H diode on Cr coated glass substrate



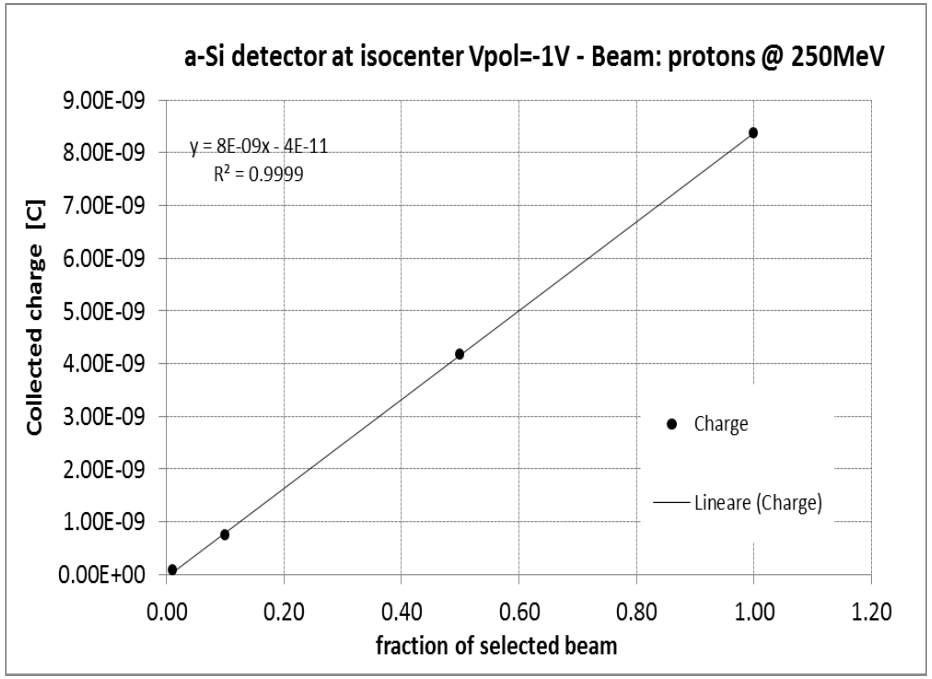
  - In development : ultra-thin large detectors to be placed in the beam without distortion of the beam parameters

Large a-Si:H particle detector

- Detector in proton beam (CNAO synchroton)



Average signal recorded during 3 proton spills (background subtracted)

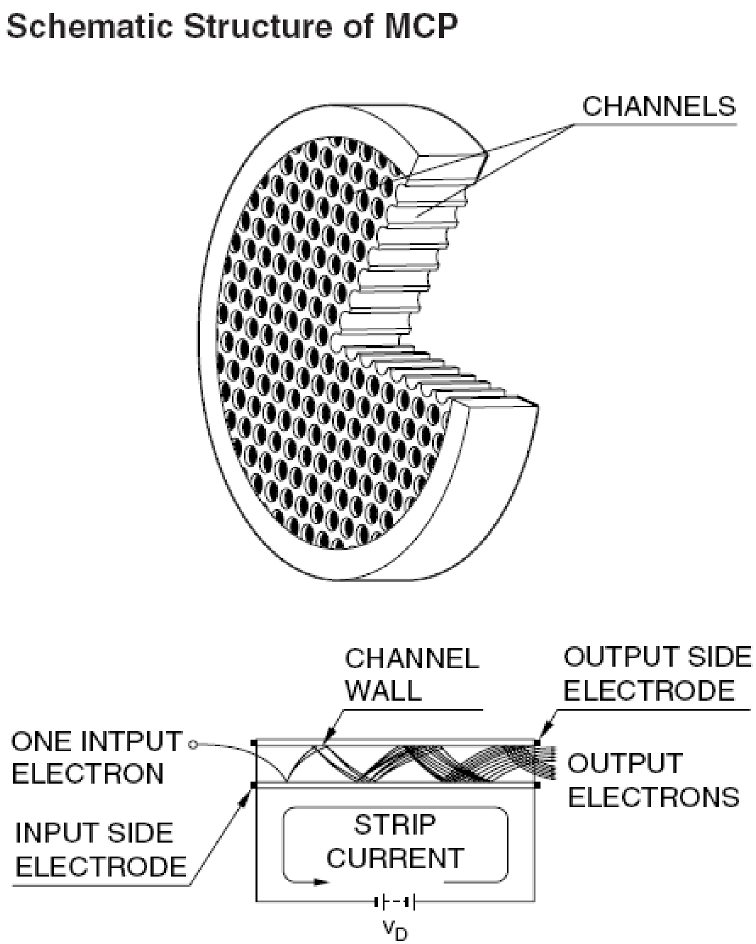


Collected charge as a function of beam fraction on detector (background subtracted)

- Successful operation for > 1 year (continuous operation)

Micro-Channel Plates (MCP)

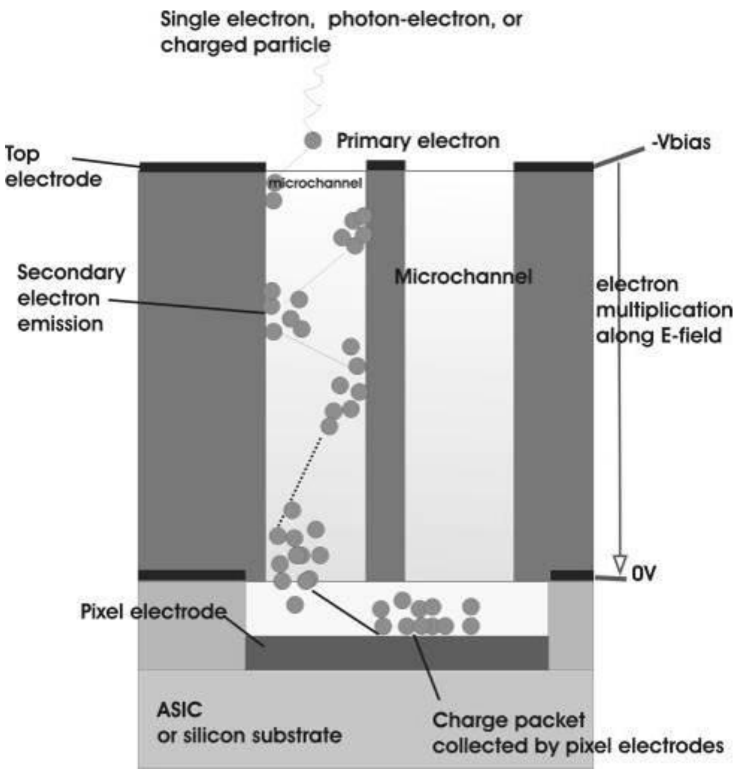
Conventional design (made of glass)



Hamamatsu

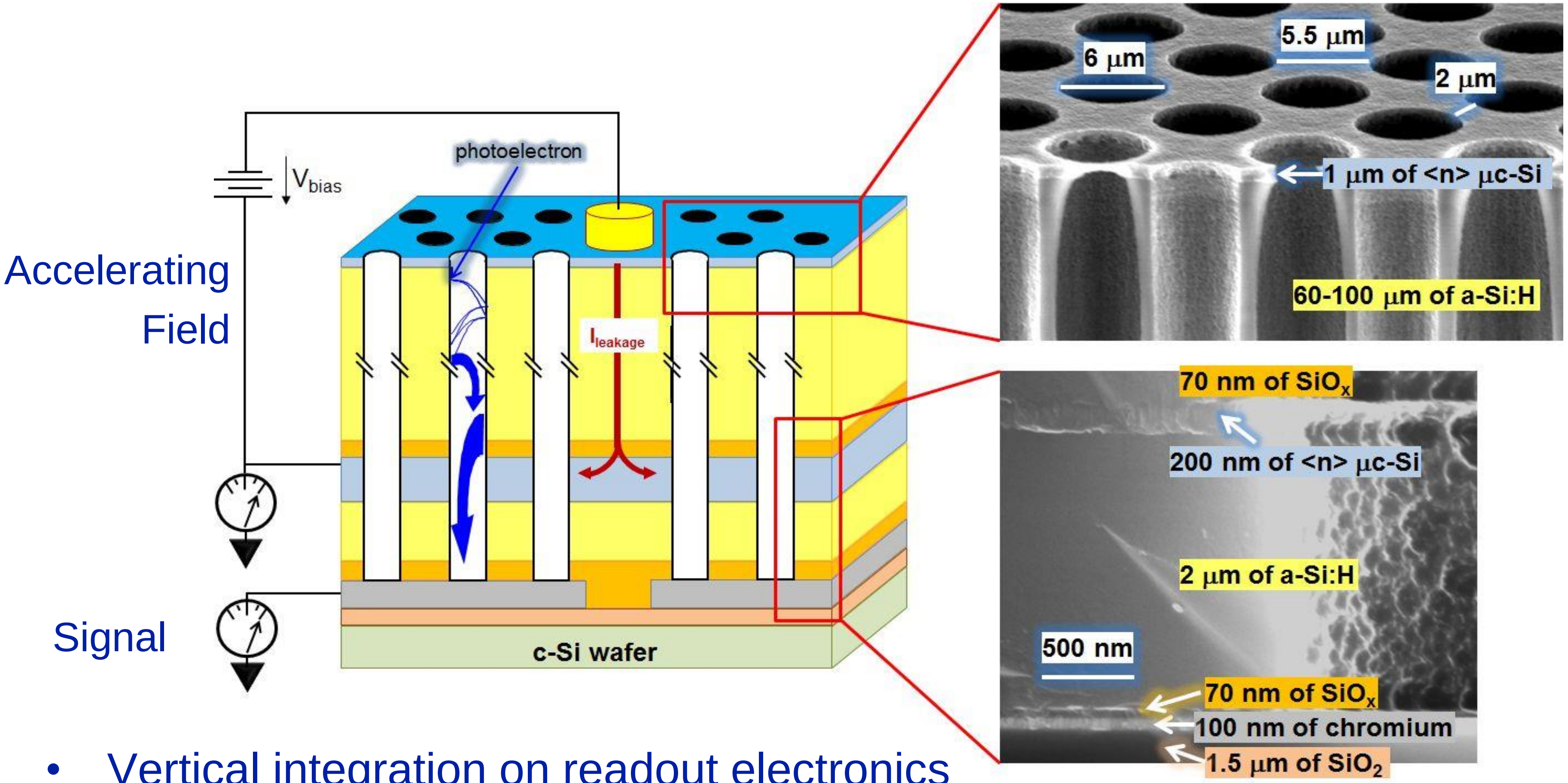
Proposed new design (based on a-Si:H) for

- vertical integration on readouts
- Flexibility in design
- Potential for better performances



P. Jarron, N. Wyrsch, Patent

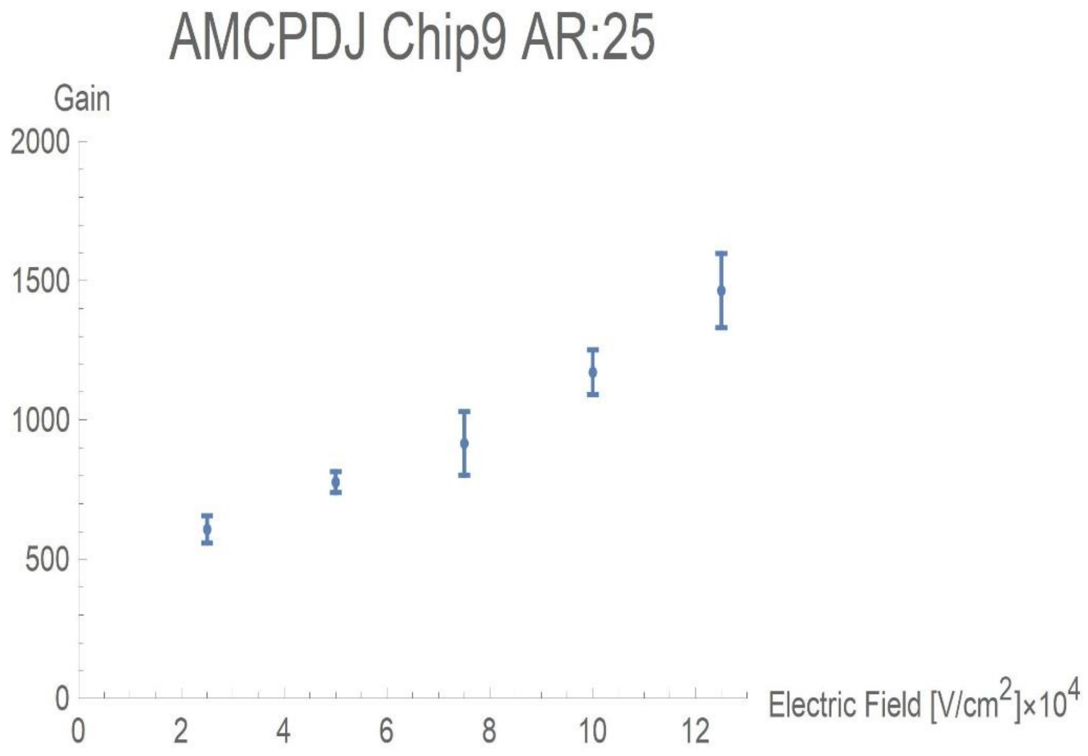
a-Si:H MCP (AMCP) design



- Vertical integration on readout electronics
- Gain depends on aspect ratio (gain ≈ δ^n for n collision)

A. Franco et al., Sci. Rep. 4 (2014) 4597
S. Frey et al., IEEE NSS/MIC 2019.

AMCP gain



- Gain is a function of aspect ratio (AR)
- Gain of up to 1500 with AR=25
- Gain can be increase with secondary electron emission layer
- Gain potential of up to 10000 (with AR of 35)
- Similar to conventional (glass based) MCP

- Potential for integration in readout chip
  - Monolithic integration (similar to TFA)

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