Introduction to X-ray and gamma-ray detectors for physics
Principles and Technologies

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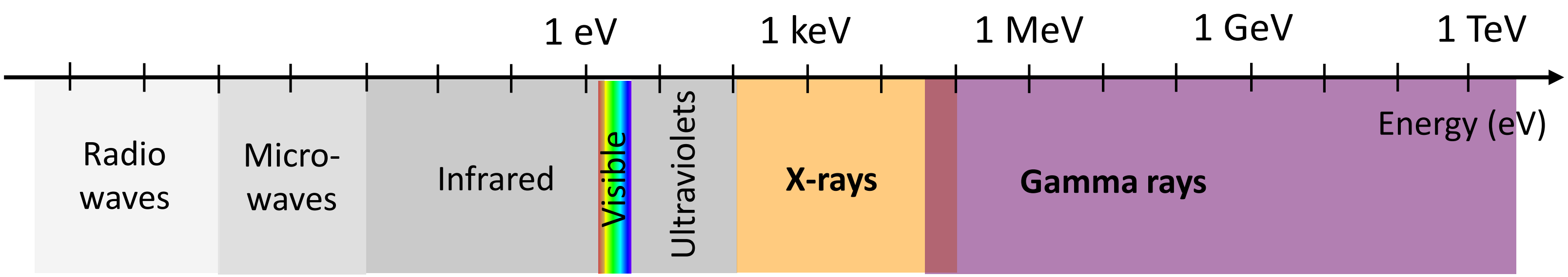
Tutorial Outline

1. Introduction to X-rays and gamma-rays
2. Light-matter interaction
3. Types of detectors and performance criteria
4. Semiconductor diodes
5. Semiconductor detectors with integrated electronics

1. Introduction to X-rays and gamma rays

DEFINITION

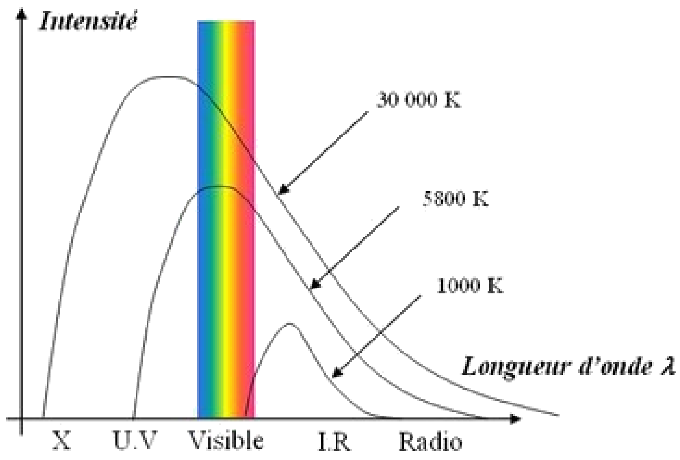
- **Electromagnetic spectrum**
  - Corpuscular theory: Light as quanta of energy **$E = h.\nu = h.c / \lambda$**
  - Unit: electron-volt $E = q.V = 1{,}6.10^{-19}$ J = 1 eV

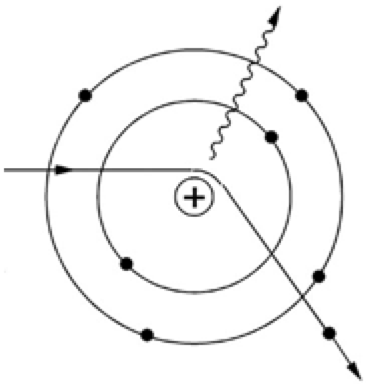


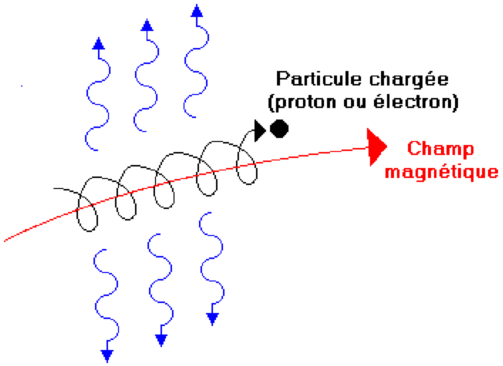
- **Blurred border between X-rays and gamma-rays around 100 keV**
  - X-rays: light from electronic transitions
  - Gamma rays: light from nuclear transitions

CONTINUOUS EMISSION PROCESSES

- **Thermal emission**: Planck's law and Wien's law
- **Bremsstrahlung emission**: electron deceleration in Coulombian collision with other electrons, ions, nuclei.
- **Synchrotron emission**: electron acceleration in magnetic field

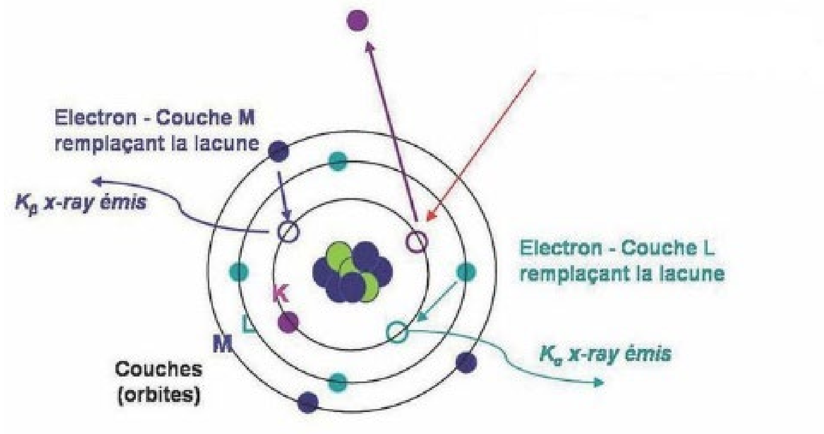




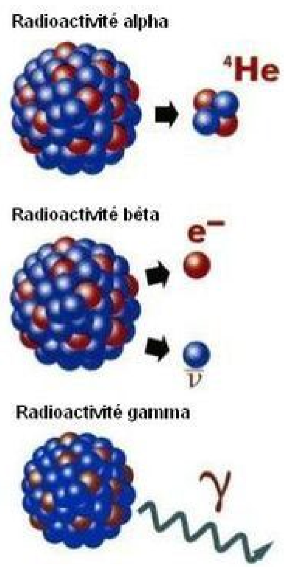


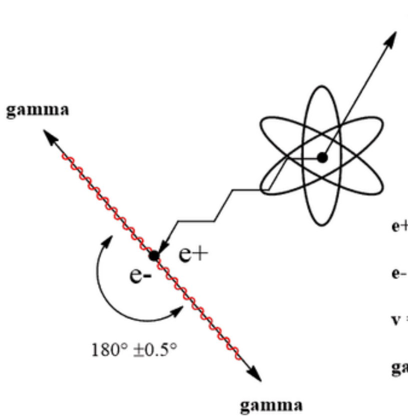
DISCRETE EMISSION PROCESSES

- X-ray fluorescence



- Gamma and beta+ radioactivity





Light-matter interaction

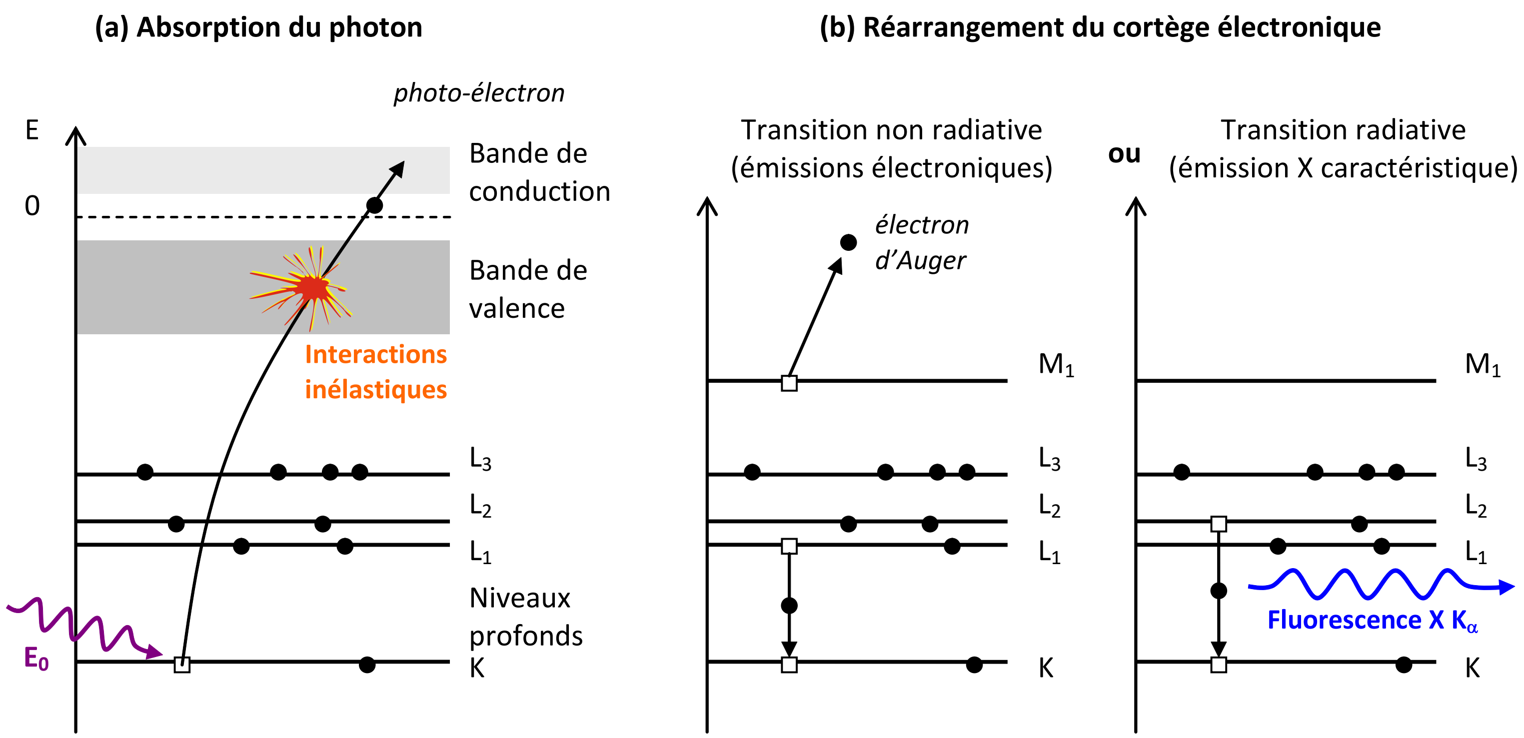
Photoelectric effect

Compton scattering

Pair effect

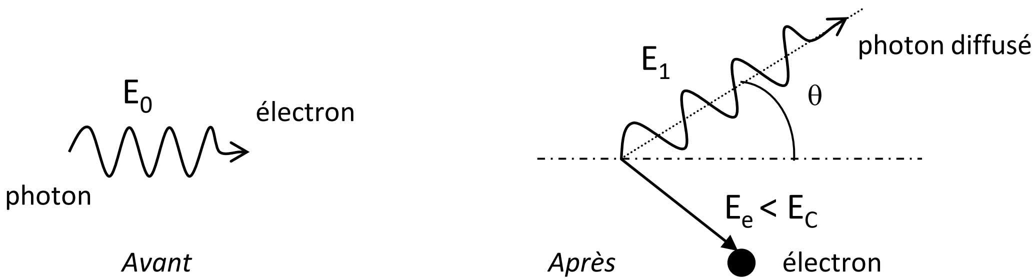
PHOTOELECTRIC EFFECT

- **Total absorption** of the photon and release of a photoelectron of kinetic energy $E_C = E_0 - E_B$
- The energy E_C is transfered to other atoms which are ionized in turn → creation of a free charge cloud.
- The atom de-excitates and releases the left energy E_B.



COMPTON SCATTERING

- **Partial absorption** of the photon energy



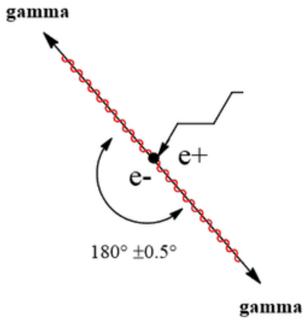
- The scattered photon has an energy: $$E_1 = \frac{E_0}{1 + \frac{E_0}{mc^2}(1 - \cos\theta)}$$

- All scattering directions are not equiprobable (**Klein-Nishina formula**)

- The recoil electron can have an energy between 0 and E_C (Compton front energy): $$E_C = \frac{E_0}{1 + \frac{mc^2}{2E_0}}$$

PAIR EFFECT

- Conversion of the photon energy in **mass energy** and kinetic energy:
  - Creation of the **electron-position pair** if $E_0 > 2.mc^2$ (1.022 MeV)
- The electron and the positron step by step lose their energy in the medium.
- The positron will annihilate with a electron by emitting **2 photons of 511 keV** in opposite directions.
  - These photons will escape and interact by photoelectric effect or Compton scattering.



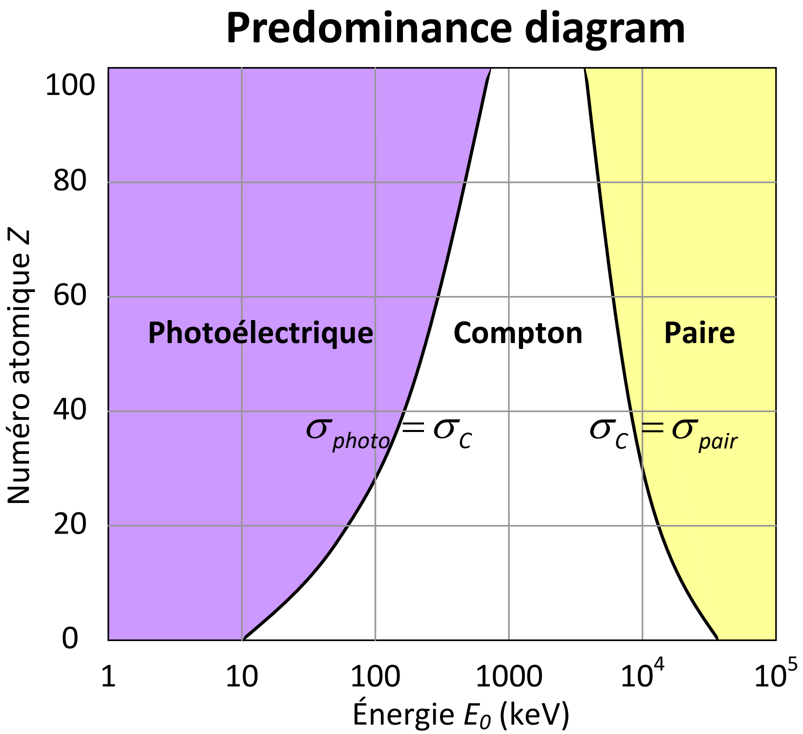
CROSS SECTIONS

- Apparent surface area of a target particle to explain its probability of interaction with the photon.
- The cross sections depend on the atomic number Z of the material.

  - $\sigma_{photo} \propto \frac{Z^{4,5}}{E_0^{\ 3}}$
  - $\sigma_C \propto \frac{Z}{E_0}$
  - $\sigma_{pair} \propto Z^2$

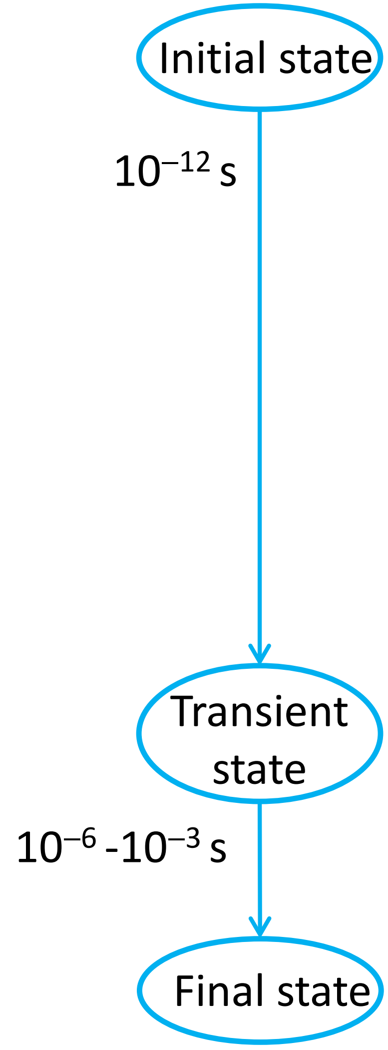
- Total cross section for an atom:

  - $\sigma_{tot} = \sigma_{photo} + Z.\sigma_C + \sigma_{pair}$



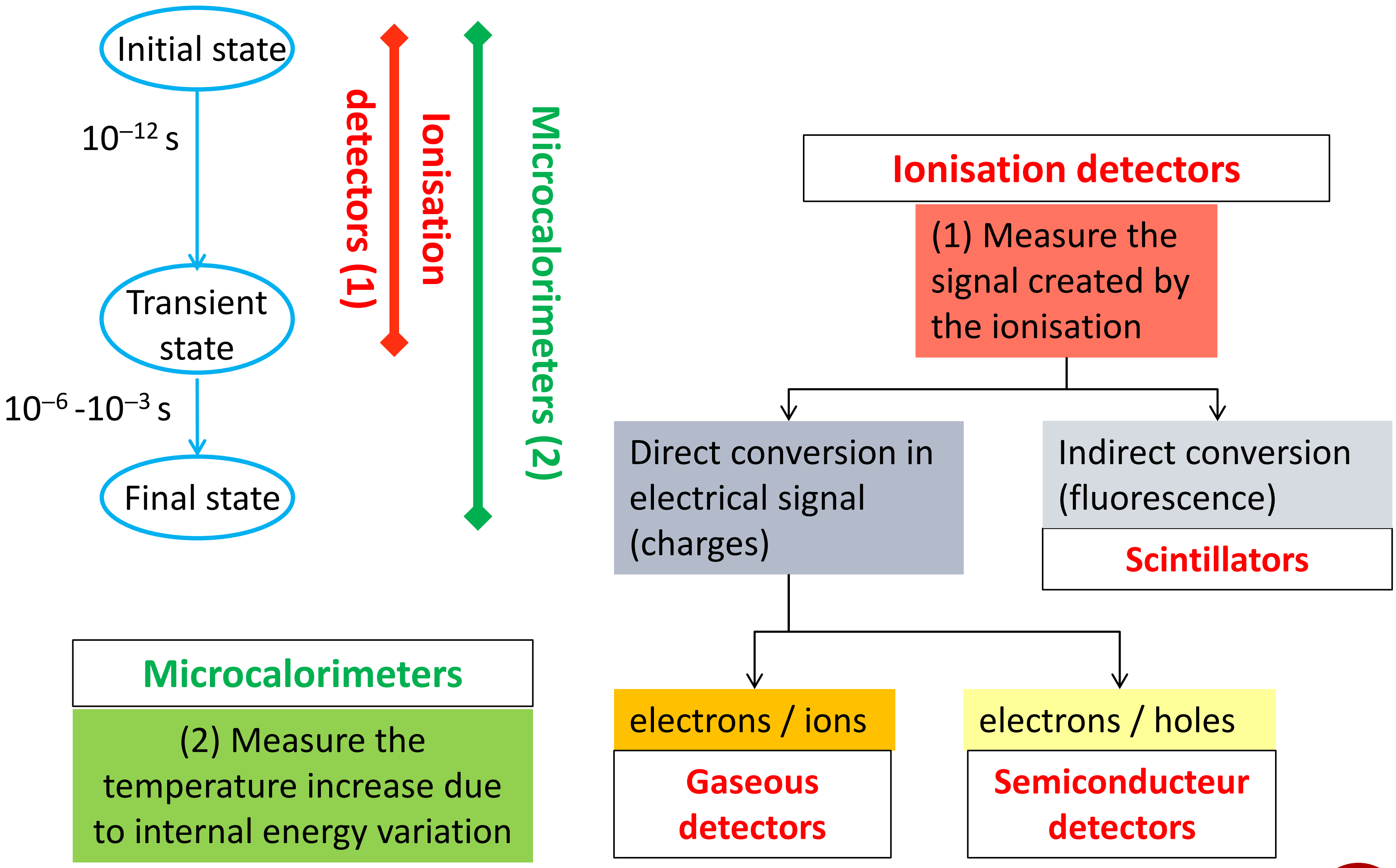
INTERACTION… AND WHAT NEXT?

- **Primary ionisation**: creation of a photoelectron by one of the 3 defined processes
  - Photoelectric, Compton, pair
- **Secondary ionisations**: the photoelectron transfers its energy to the medium.
  - Creation of a charge cloud
- **De-excitation of the electronic cortege** to a stable state
  - Radiative (fluorescence) or not transitions
- **De-excitation of the cristalline network** (for a solid-state detector) to a stable state
  - Back to thermodynamic equilibrium



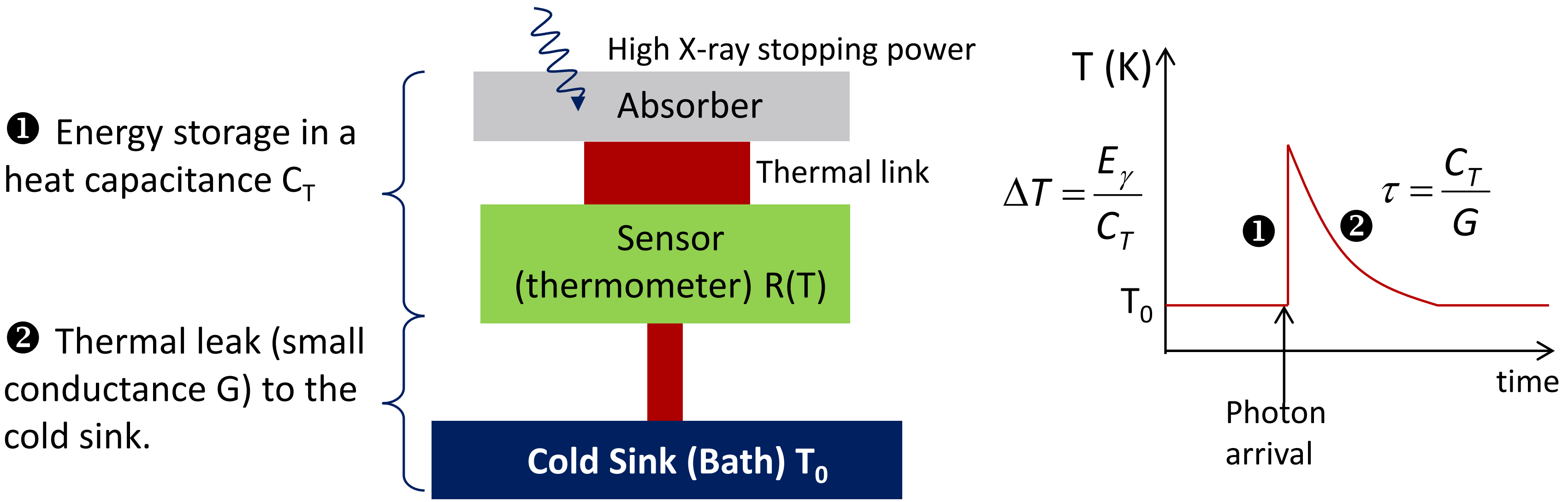
3. Type of detectors and performance criteria

TYPE OF DETECTORS

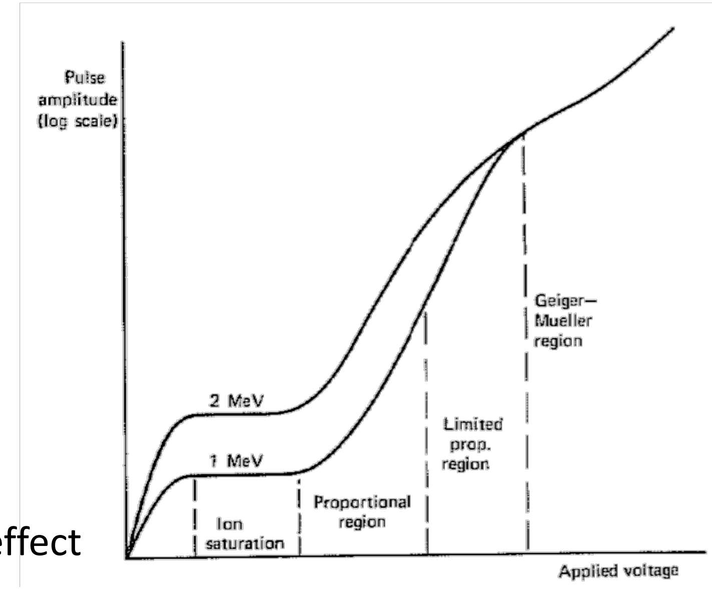


BOLOMETERS

- Definition: instrument showing a temperature excess caused by the absorption of incident particle (or photon flux) → requires a cooling < 1 K. They are called **cryogenic microcalorimeters.**
- **Detection chain**
  - Conversion of the photon energy in temperature pulse by an absorber.
  - Conversion by the thermistance in contact in detectable electrical pulse.
  - Limitation of the counting rate because of slow de-excitation (ms).



GASEOUS DETECTORS



- Ionising chambers filled with gas (He, Ar, CH_4).
- Direct detection of ionising electrons and ions.
- Used in the proportional regime: **proportional counters** (spectroscopy)

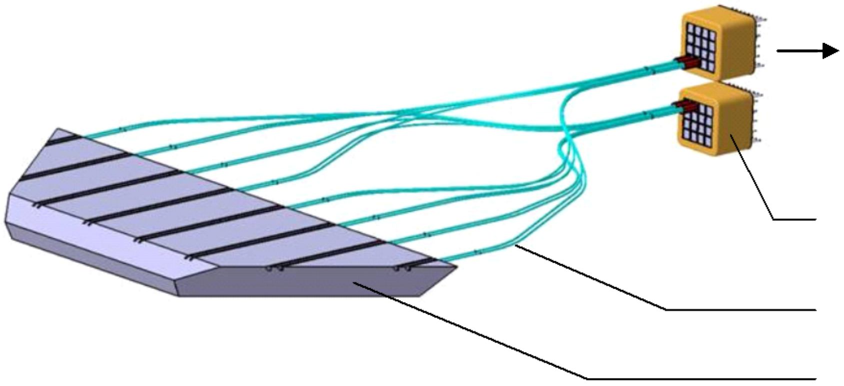
- **Detection chain**
  - Creation of electron-ion pairs by photoelectric effect
  - Charge drift towards collection electrode (due to electrical field)
  - Readout of the signal by front-end electronics

- Segmenting the anode and measuring the time of arrival allows determining the photoelectron trajectories (imaging, polarimetry)

- **Gas Electron Multiplier** (1997, Sauli): region of intense electric field to provoke an avalanche phenomenon and create a detectable current for the front-end electronics.

SCINTILLATORS

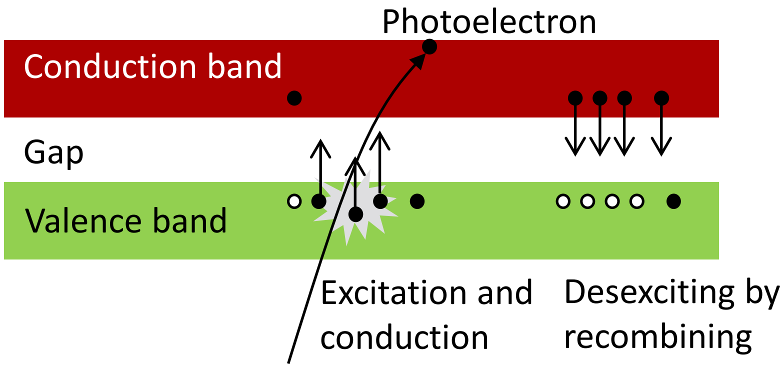
- **Detection chain**
  1. Conversion of the incoming energy in visible or UV light
     - The atom excited by the photon absorption will desexcite by emitting **fluorescence** photons (10 ps) or **phosphorescence** photons (> 1 µs).
  2. Conversion of the scintillations in electrical pulse by a photomultiplier, direct coupled or through waveguide.
  3. Detection and energy measurement by front-end electronics

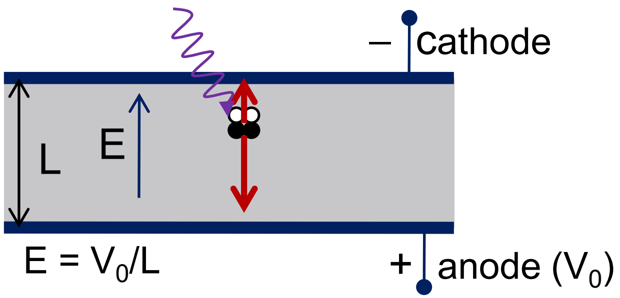


Anticoincidence detector for Simbol-X space mission

SEMICONDUCTOR DETECTORS

- Energy band structure
  - The voids left by electrons in the valence band can be considered as positive charges called holes.
  - The electrical conduction in this media type is insured by the movement of electrons in the conduction band and the movement of holes in the valence band.





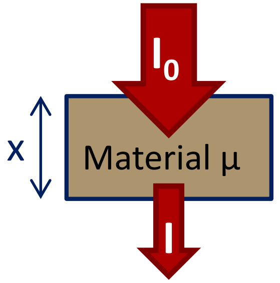
- **Detection chain** (similar to gaseous detectors)
  - Creation of electron-holes pairs by photoelectric effect
  - Drift of electrons towards anode and holes towards cathode
  - Signal readout by front-end electronics.

QUANTUM EFFICIENCY

- **Total efficiency** $\eta_{tot} = \dfrac{\text{Number of detected quanta}}{\text{Number of incoming quanta}}$

- For spectroscopy applications (energy measurement), the relevant parameter is the **peak efficiency**

$$\eta_P = \frac{\text{Number de fully absorbed quanta}}{\text{Number of incoming quanta}}$$



- The efficiency depends on the material choice (absorption coefficient µ) and the thickness choice (x).

$$\eta = \frac{I_0 - I}{I_0} = 1 - \exp(-\mu x)$$

@300 K	Gaseous	Scintillators	Semiconductors	
Detector	Ar	CsI	Si	CdTe
µ/ρ (cm²/g)	0,204	2,035	0,183	1,671
η @100 keV for e = 1 mm	0,15 %	60 %	4,2 %	62 %

SPECTRAL RESOLUTION

- Smallest measurable energy difference. Full width at half maximum of the spectral line.
- **Intrinsic spectral resolution (limit)**

Gas and semiconductors

- The ionisation statistics follows a Poisson law with a so-called Fano factor.

$$\Delta E_{stat} = 2{,}35 \cdot \sqrt{F \cdot \varepsilon \cdot E_\gamma}$$

ε: Pair creation energy

Bolometers

$$\Delta E = 2{,}35 \cdot \xi \sqrt{k_B T^2 C_T}$$

X-ray spectroscopy

- Energy Resolution at 5.9 keV (Mn-Kα)
  - Gas : 885 eV (**15 %**)
  - Si : **123 eV** (2%)
  - TES Bolometer : **3 eV** (0,05%)

Gamma-ray spectroscopy

- Energy resolution at 1.33 MeV (Co60-γ)
  - Ge : 2 keV (0.15 %)
  - NaI : > 5 %
  - BGO : 10 %

COUNTING RATE CAPABILITY

- Maximal number of detectable events per time unit.

- Depends on the whole detection chain:
  - Relaxing time of the detector
  - Collecting time of the signal (charge drift)
  - Filtering time of front-end electronics (to minimise noise)
  - Readout / acquisition / processing time (system sizing)

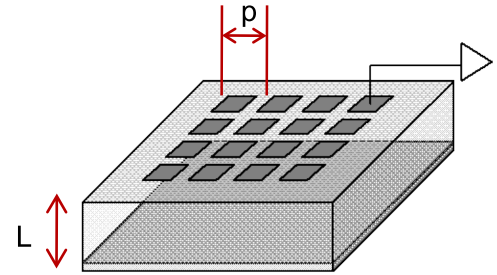
- Orders of magnitude
  - TES (transition edge sensor) bolometers: 10^3 cps/s
  - Gaseous: 10^4 cps/s
  - Semiconductor: 10^5 cps/s
  - Scintillator + PM: 10^7 cps/s

4. SEMICONDUCTOR DIODES

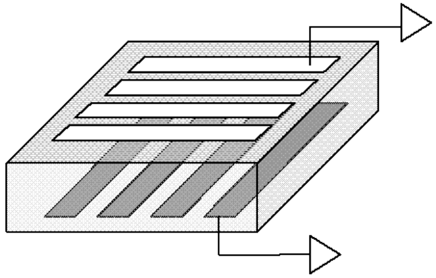
Position sensitive sensors

- **Segmented semiconductor detectors - working principle**:
  - The whole detector volume is sensitive to radiation.
  - The signal is mainly induced in the electrode which is the closest to the photon interaction and the charge drift. **Shockley-Ramo theorem for charge induction.**
  - Signal can be induced on several electrodes: **charge sharing, split events.**

- **Pixel detectors**
  - The signal induction is favored by the **small pixel effect.**
  - No ambiguity in the interaction position.



- **Double-sided strip detectors**
  - Highest segmentation (10-100 µm)
  - Connection to a large number of analog channels on the sides.

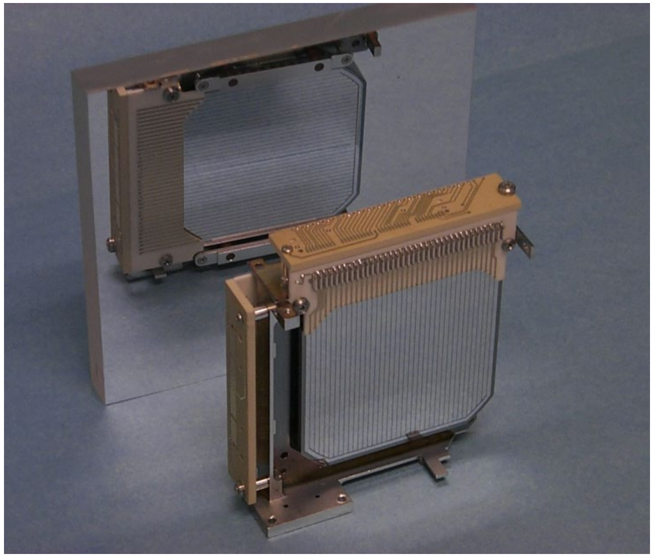


State-of-the-art technologies

- Segmentation processes: chimical, optical, mechanical (photolithography)

- **Si**
  - Thickness of 250 to 450 µm, surface up to 10 cm side (8 inch wafer)
  - Pixelisation down to 15 µm, typ. 50 µm for X-ray applications

- **Cd(Zn)Te**
  - Thickness of 0.5 to 2 mm with CdTe,
  - 2 to 10 mm with CZT, surface up to 3 cm side
  - Strips ~50 µm, pixels ~200 µm



- **Ge**
  - 10 to 15 mm thickness (efficacité gamma)
  - Conventional diodes (N-type Li, P-type B) : 2 mm pitch
  - Blocking contacts with metallic film (LBNL): 0.5 mm pitch

5. Semiconductors detectors with integrated electronics

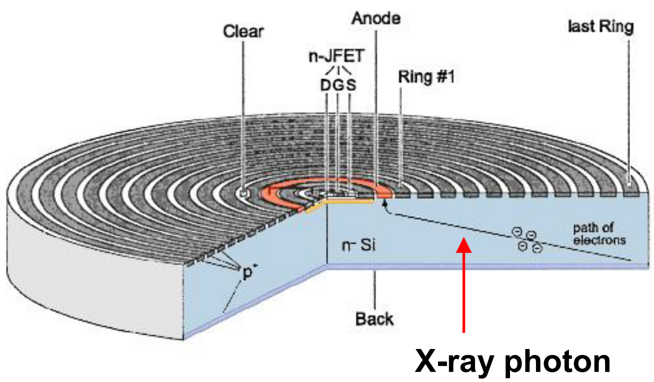
Silicon Drift Detectors (SDD)

Coupled Charge Device (CCD)

Active pixels sensors (APS)

SILICON DRIFT DETECTORS (SDD)

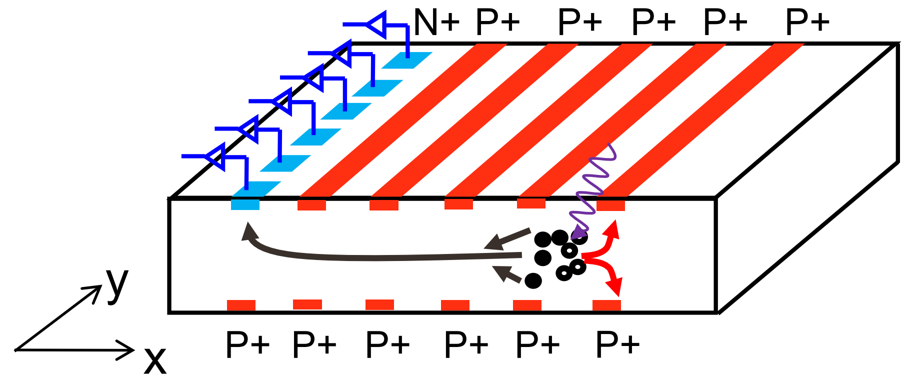
X-ray spectroscopy



Drift towards the structure centre

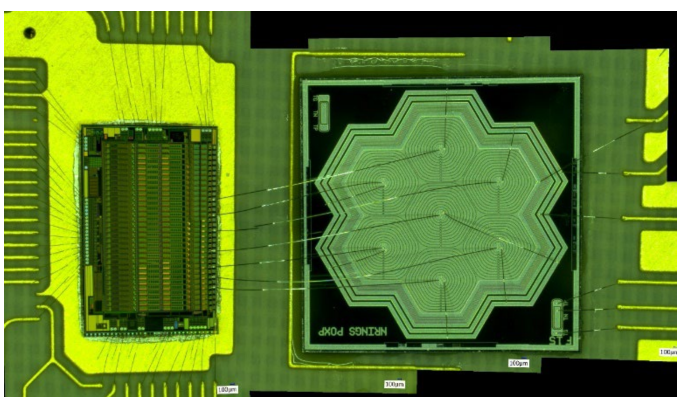
Low anode capacitance for low electronic noise.

X-ray imaging

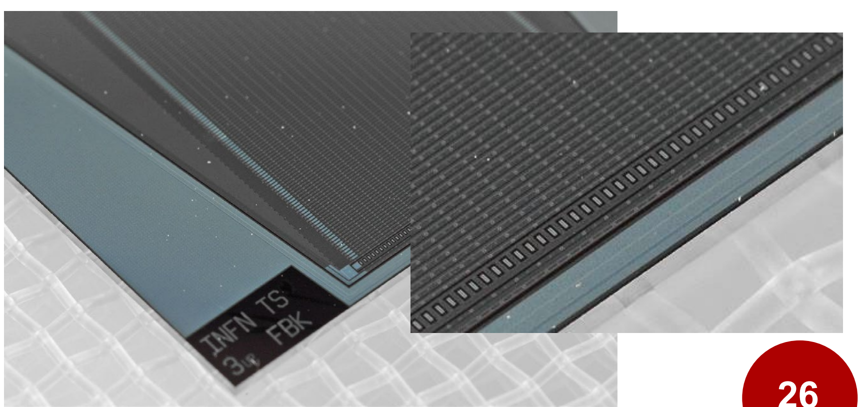


Drift towards a segmented anode

Use of the diffusion to determine the drift time and the position x_0



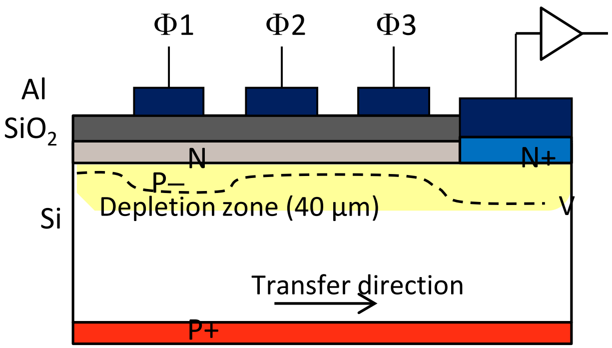
Credits:
MPG-HLL
INFN



COUPLED CHARGE DEVICE (CCD) : STRUCTURE

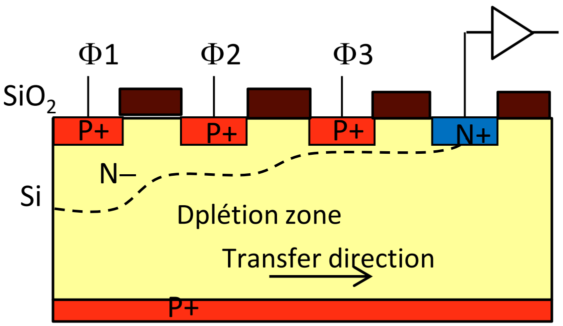
MOS CCD

- Structure derived from a classical MOS structure by dividing the metallic electrode into strips.



Pn-CCD

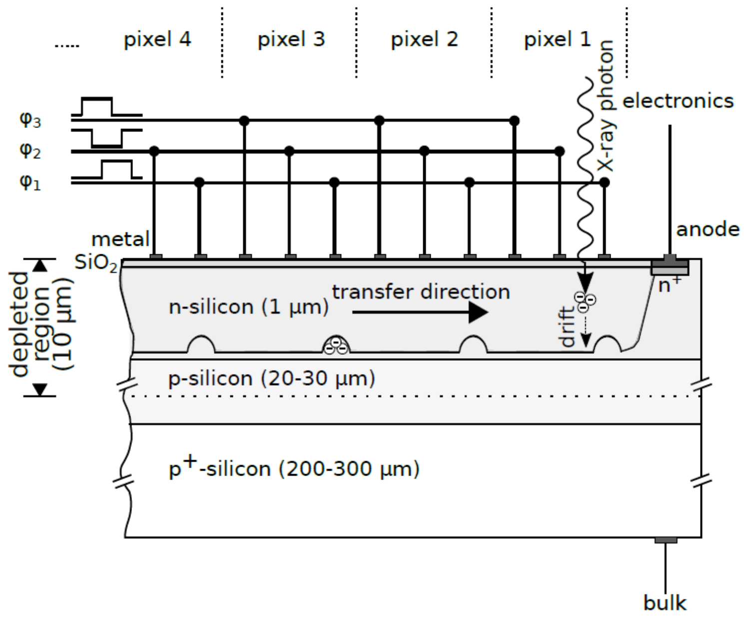
- Double pn diode structure
→ Full depletion over the total wafer thickness (up to 450 µm)
→ Quantum efficiency of 90 % at 10 keV



Coupled Charge Device (CCD) : readout

Readout principle (in 4 steps)

1. Detection of incoming photons by photoelectric effect.
2. Charge accumulation in the MOS capacitance (or underneath the pixel structures).
3. Charge transfer step by step towards the anode and the first stage of signal amplification (electronics placed on the substrate).
    1. For each pixel: one collecting electrode, two barrier electrodes
    2. Channel (P-)stops perpendicular to electrodes to avoid charge planar diffusion
4. Readout of the signal by external front-end electronics



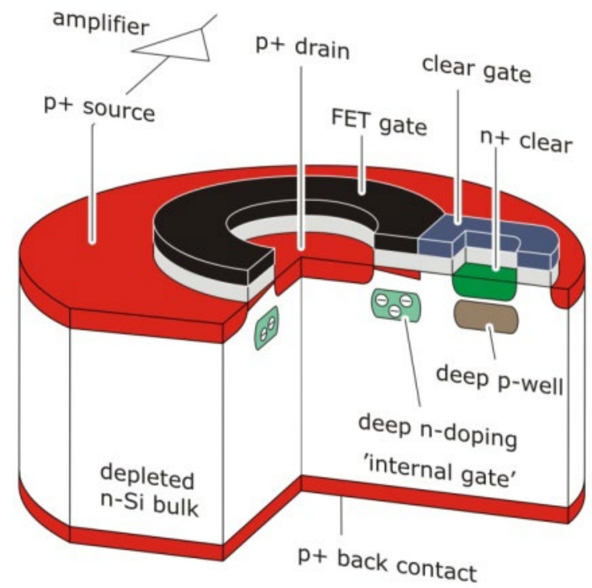
ACTIVE PIXEL SENSORS: STRUCTURE

- The detector integrates the sensitive part and the first stage of signal amplification. The signal is measured locally (no transfer).
  - Example: **Depleted p-channel field effect transistor (DePFET)**

- Technological challenges:
  - Substrates and fabrication standards a priori non compatible
  - Double side fabrication processes

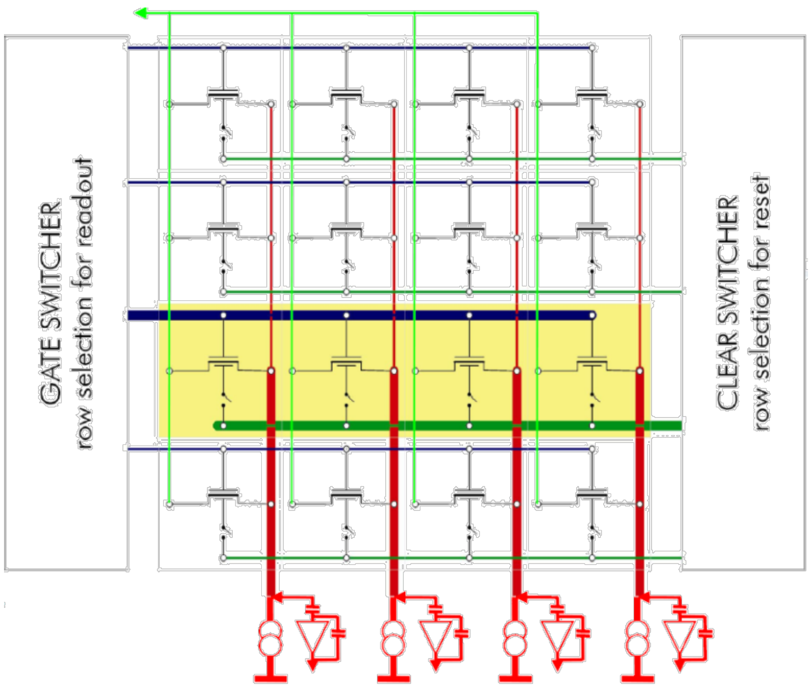
Charge sensitive amplifier (FET) with doped silicon

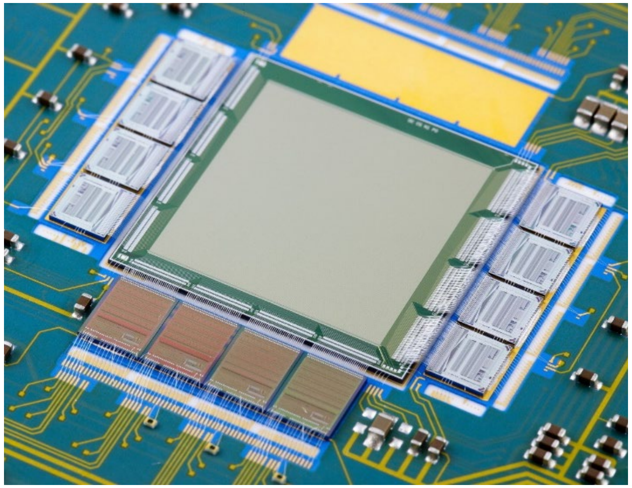
Sensitive area with fully depleted high resisitivity silicon (high charge carrier lifetime)



ACTIVE PIXEL SENSORS: READOUT

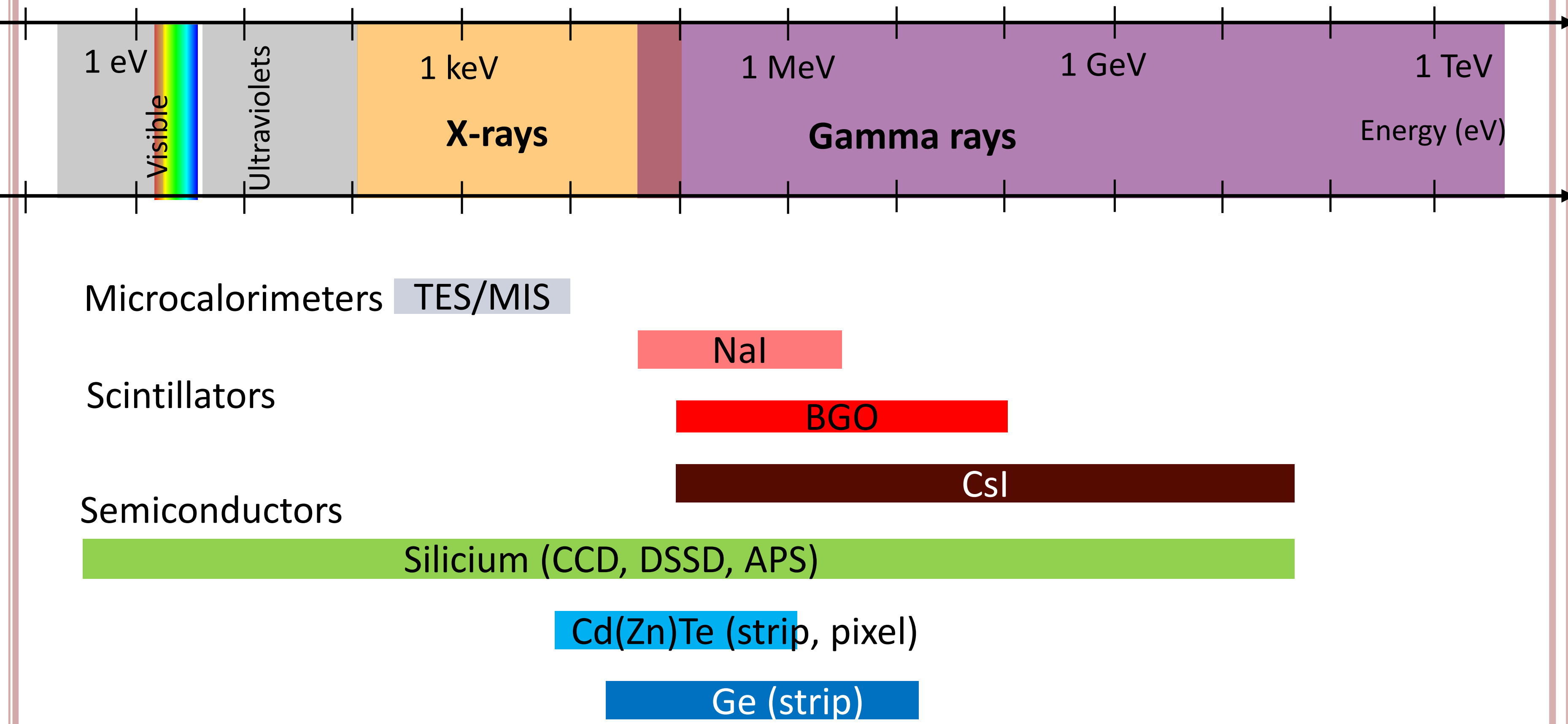
- Transistors are switched on row by row to read a current proportionnal to the charge stored in the pixel.
- Columns are read in parallel thanks to an external front-end electronics.





Credits: MPG-HLL

CONCLUSION



Semiconductor detectors allow for:

- Compact designs for high energy photons detection
- High modularity and versatility in the designs for time-resolved imaging spectroscopy