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U.S. DEPARTMENT OF ENERGY

Silicon Detectors
part 2

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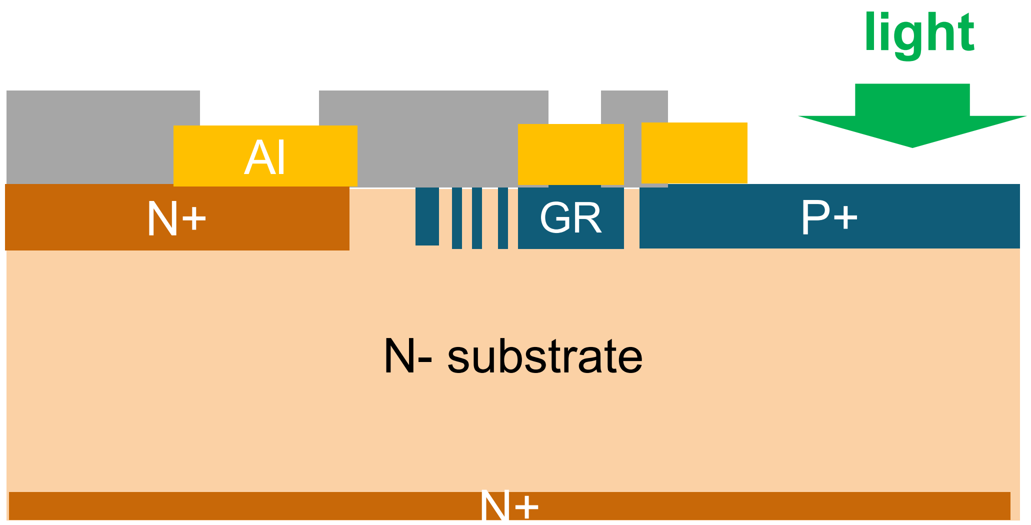
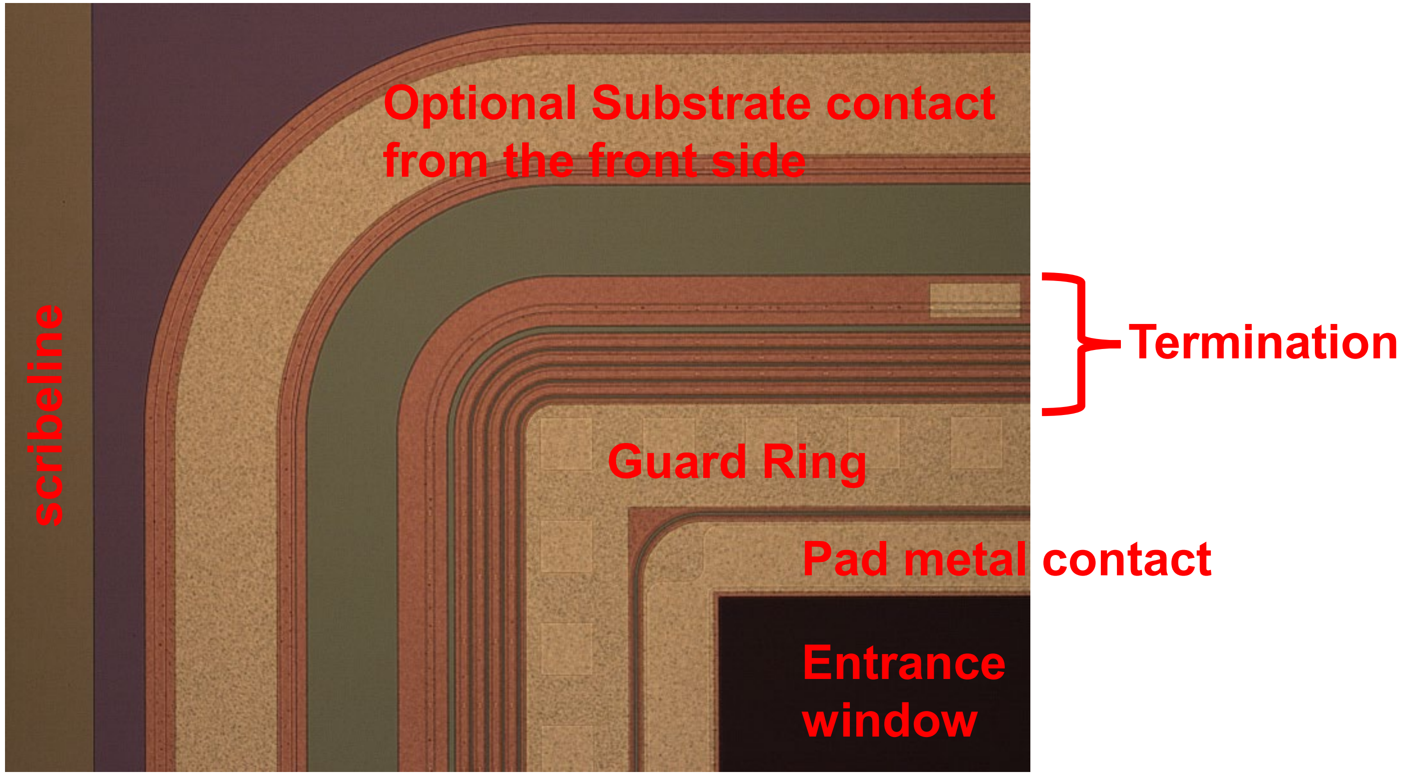
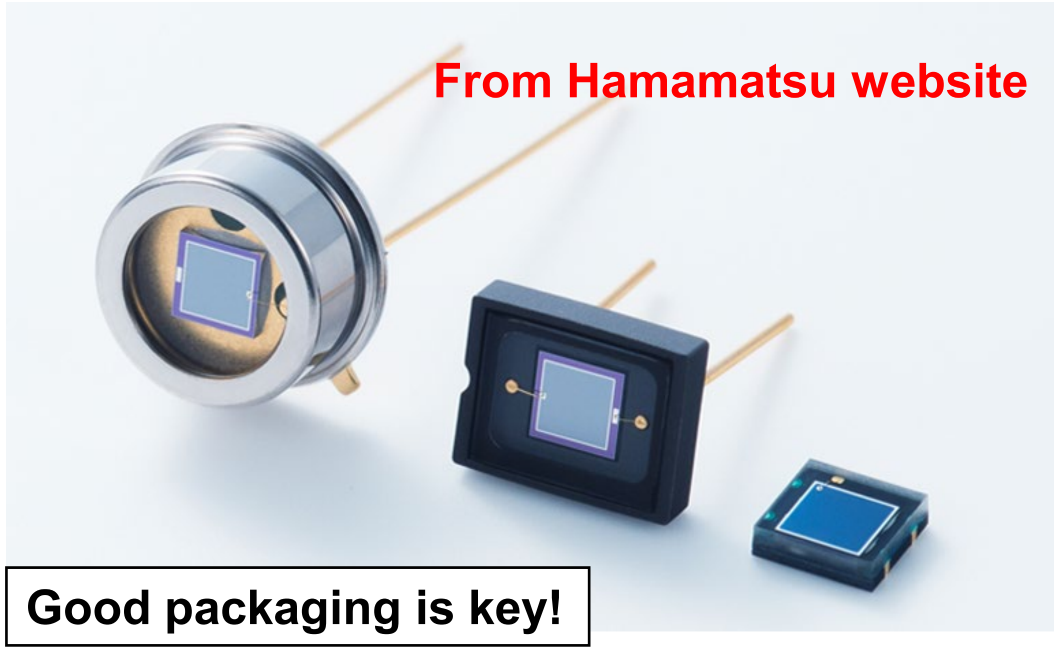
PIN diode



- PIN = p+ -- intrinsic – n+ silicon
- Single channel sensors
- If central pad is open from metallization sensitive to light
  → Photodiodes
- If central pad fully metalized, they are opaque to light, but still sensitive to X-rays and charged particles

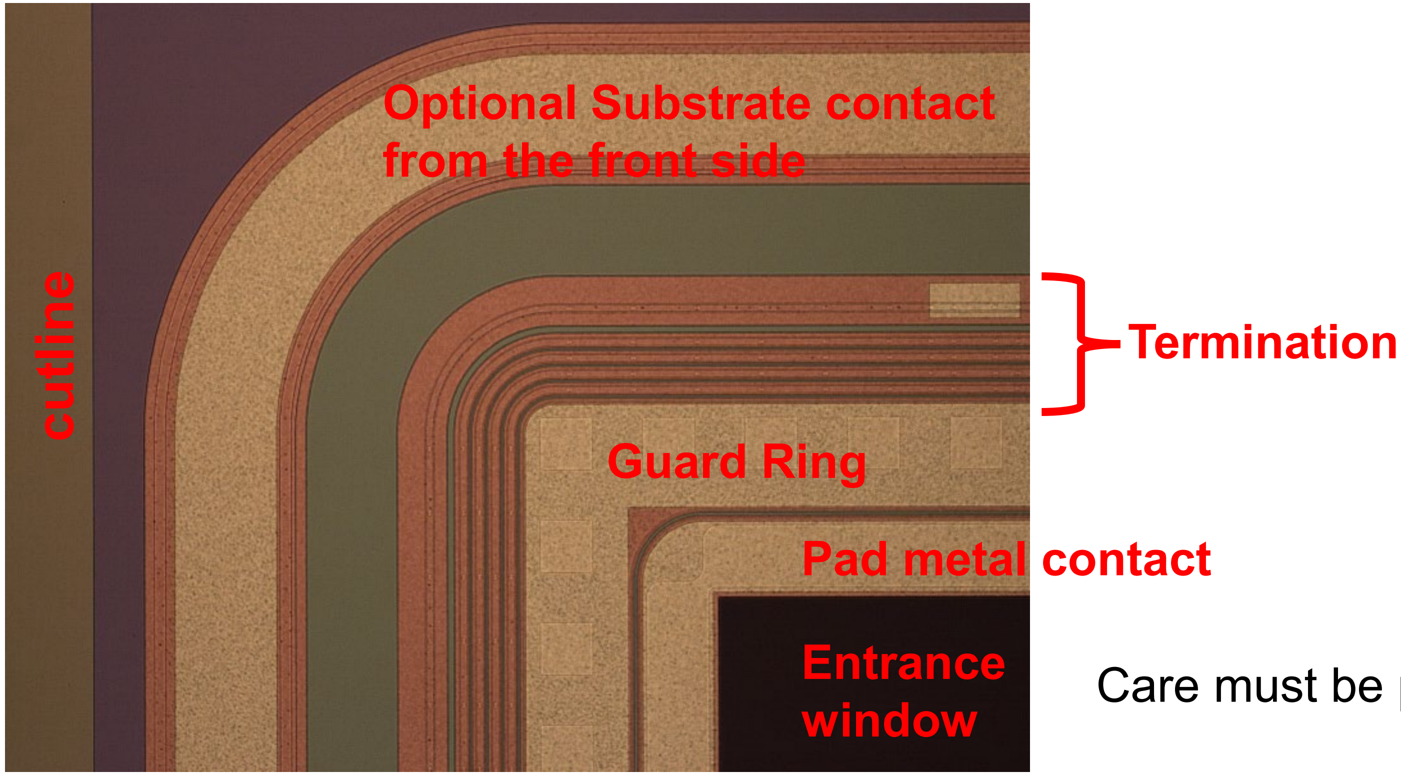




Termination

Devices need to be separated from the wafer by dicing though a scribeline: the vertical wall of cutline is full of defects and the depletion region extending from the active area must not reach it, lest a high dark current is injected into the active area

→ keep the distance of the scribeline 3x active thickness of the substrate



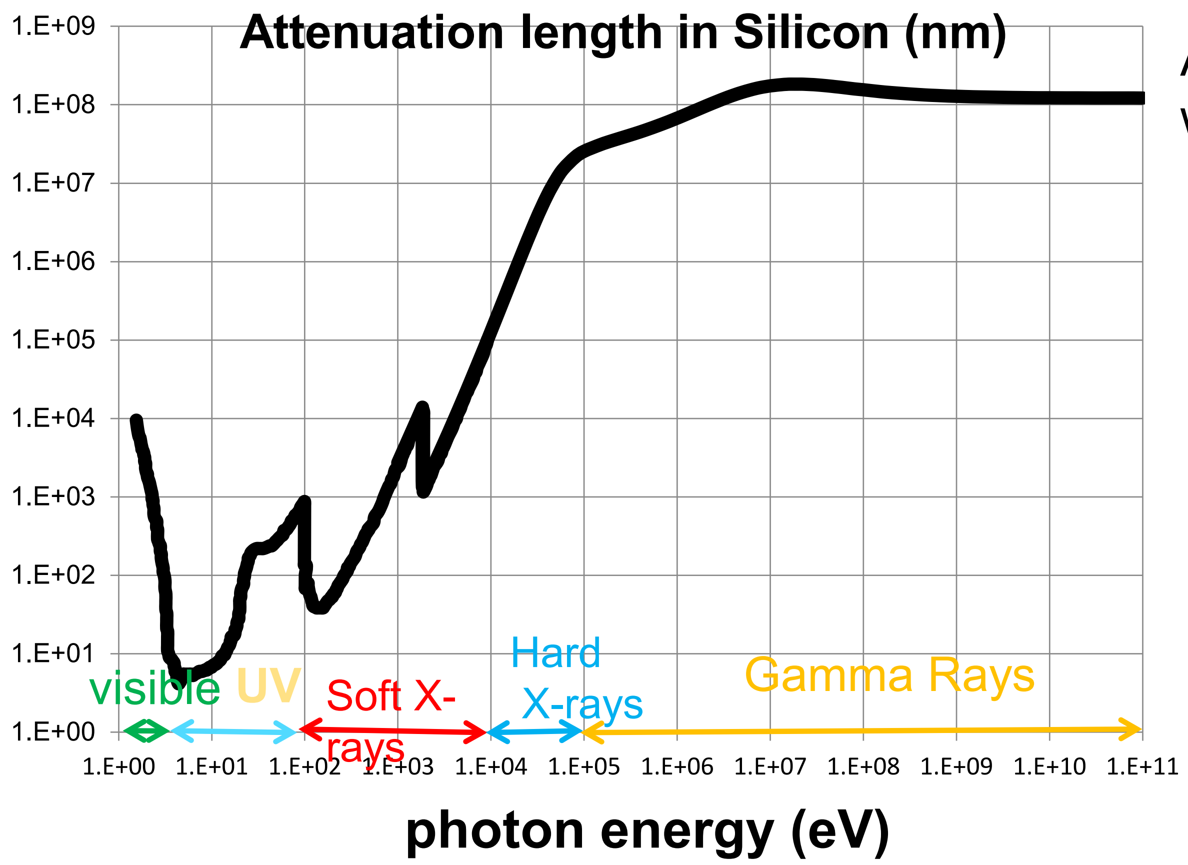
To control the edge, an implant of the same sign as the back is placed.
This can also act as an optional substrate contact

A PIN diode is a power device and HV is applied to the back. This is present also at the surface and Multi Guard Ring termination is needed for a smooth transition from 0V to HV.

Care must be placed in the control of the silicon/oxide interface.

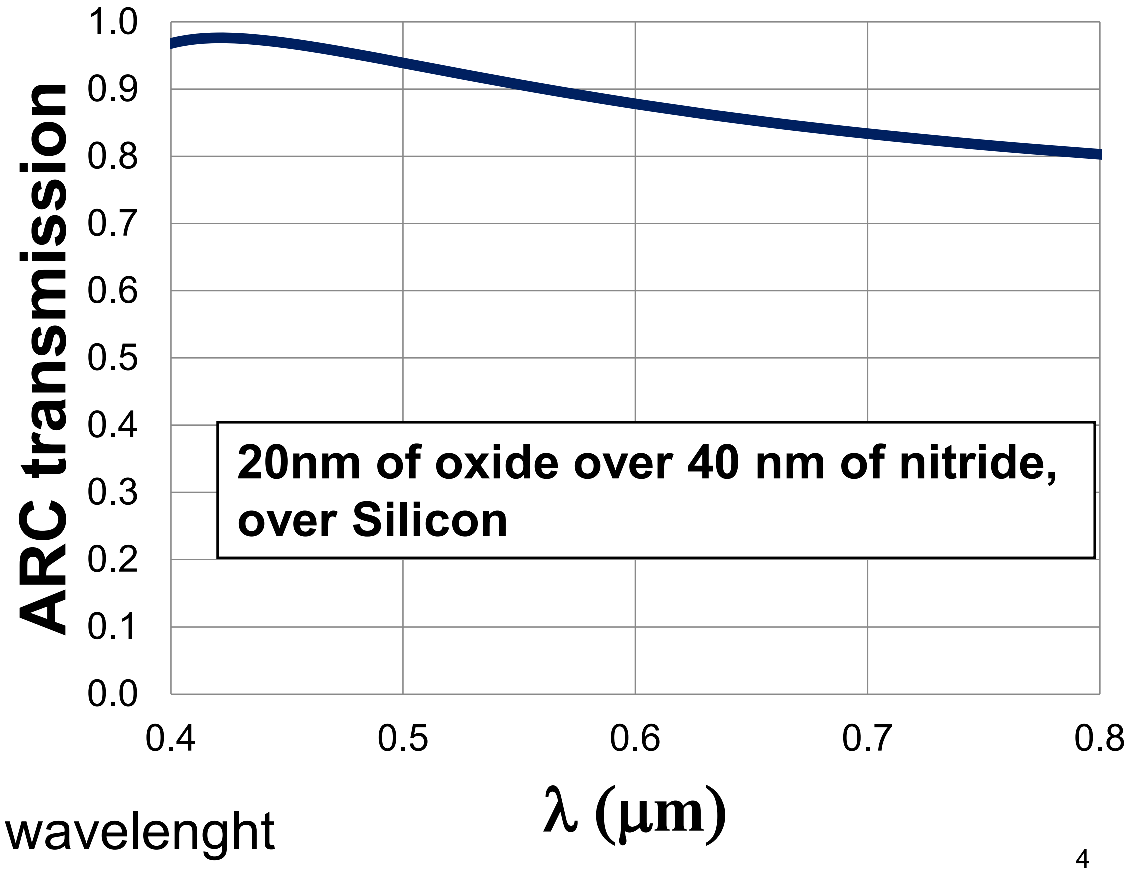
A PIN diode is a "bulk" device but the interface can mess things up if not properly treated.

Anti-Reflective Coating (ARC)



A stack of dielectrics (nitride and oxide) over the entrance window enhances the Quantum efficiency of the device

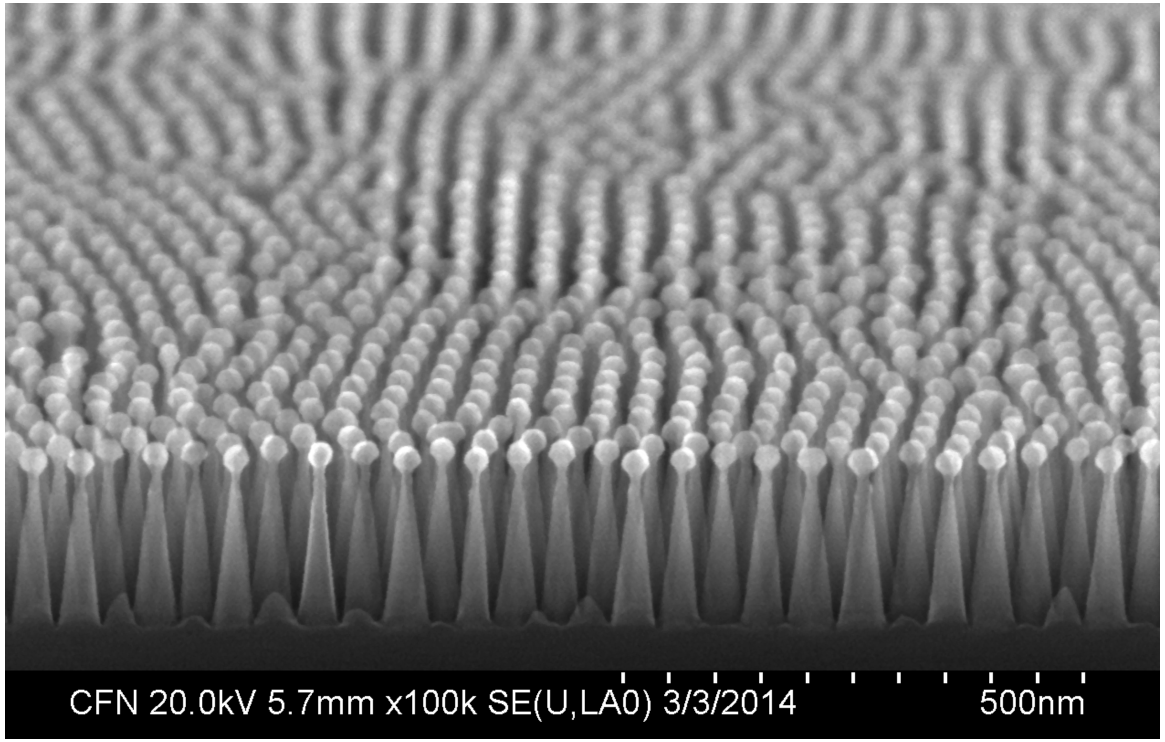
QE = # electron/hole pairs produces/ # of photons in

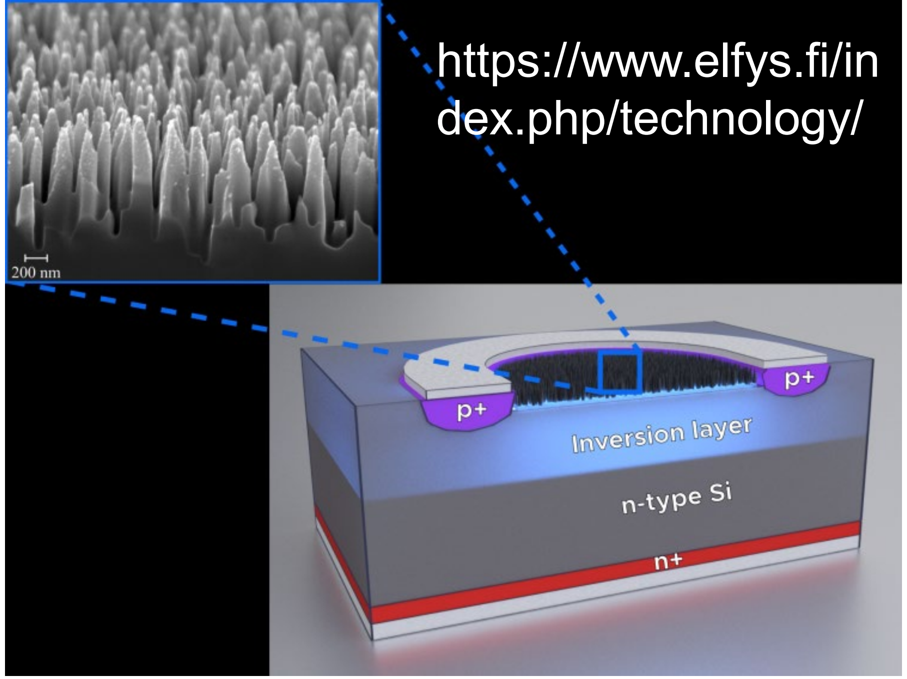


Usually, QE optimized on a specific wavelenght

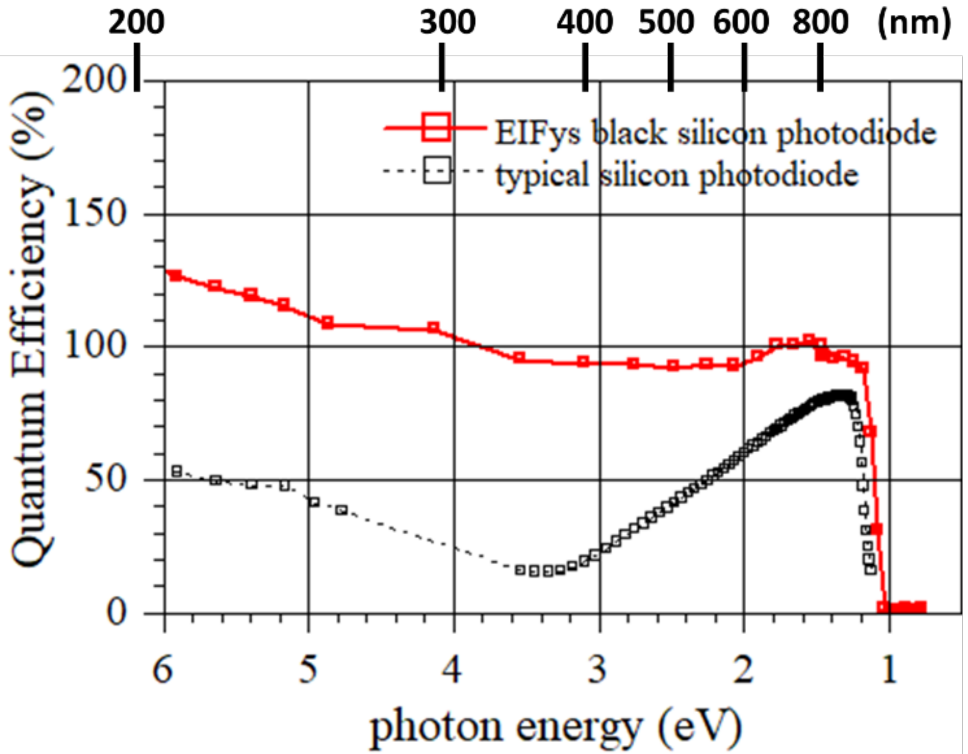
Black Silicon Concept

100% QE over a wide wavelength range, for every angle
by nanopatterning the silicon surface





https://www.elfys.fi/index.php/technology/



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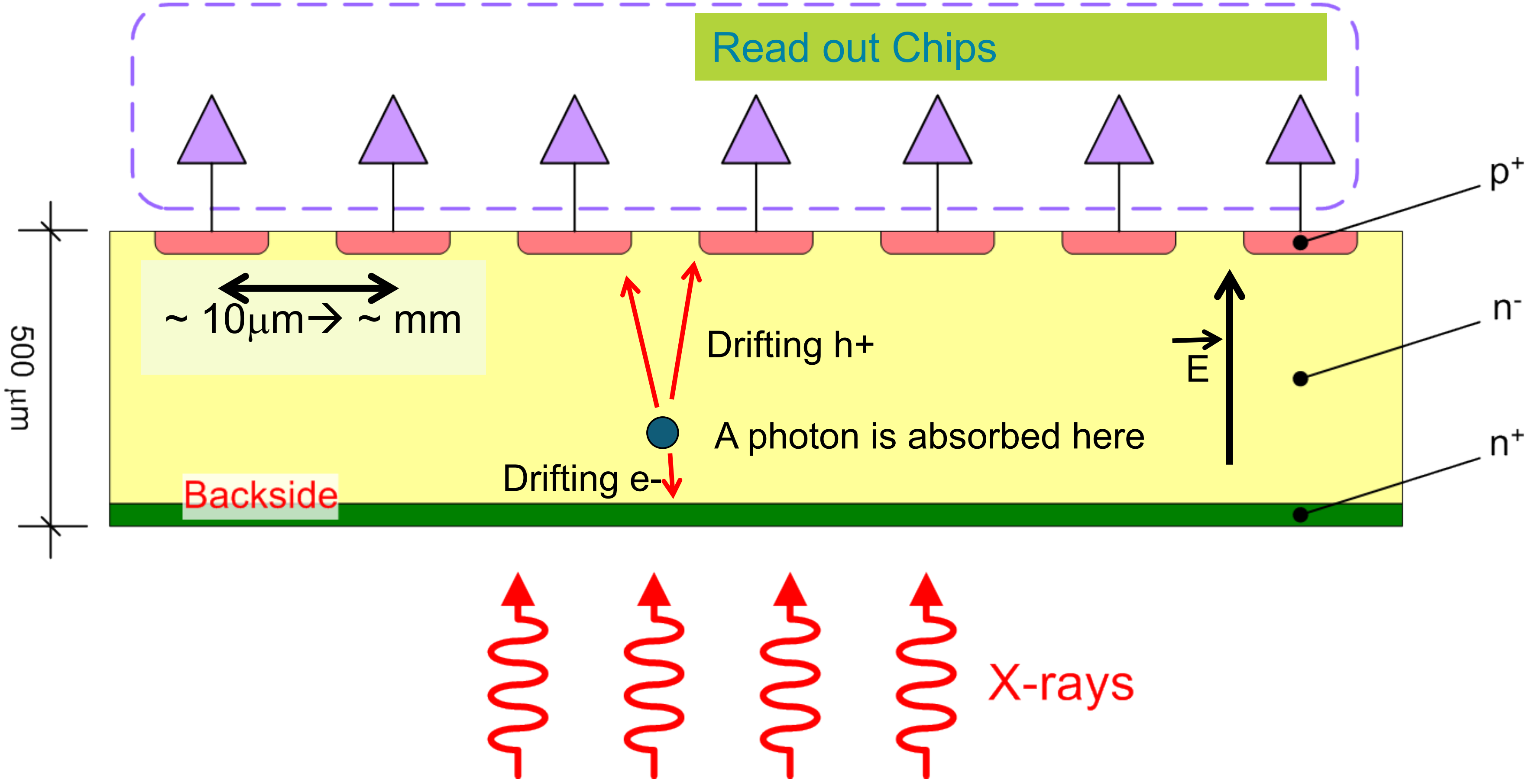
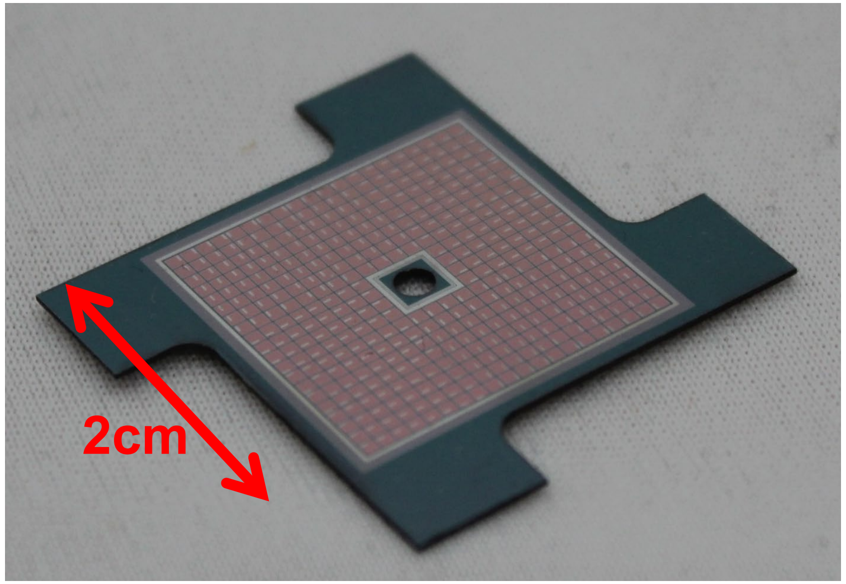
Patterning the electrodes

It gives information about the position of the incident radiation

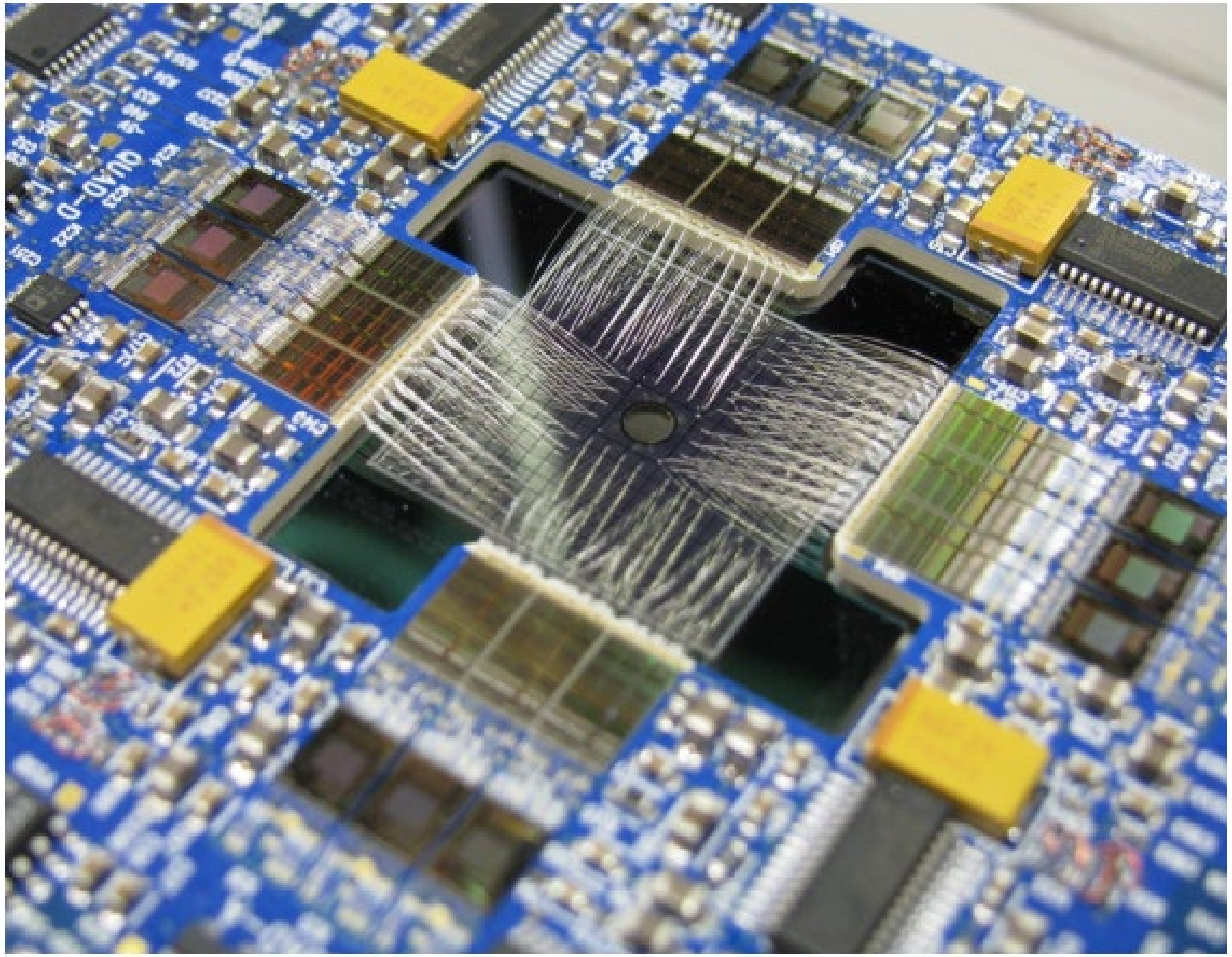


Pixels, pads, strip are possible, in a large variety of dimensions, ranging from few μm to mm, depending on the application

Pad sensor



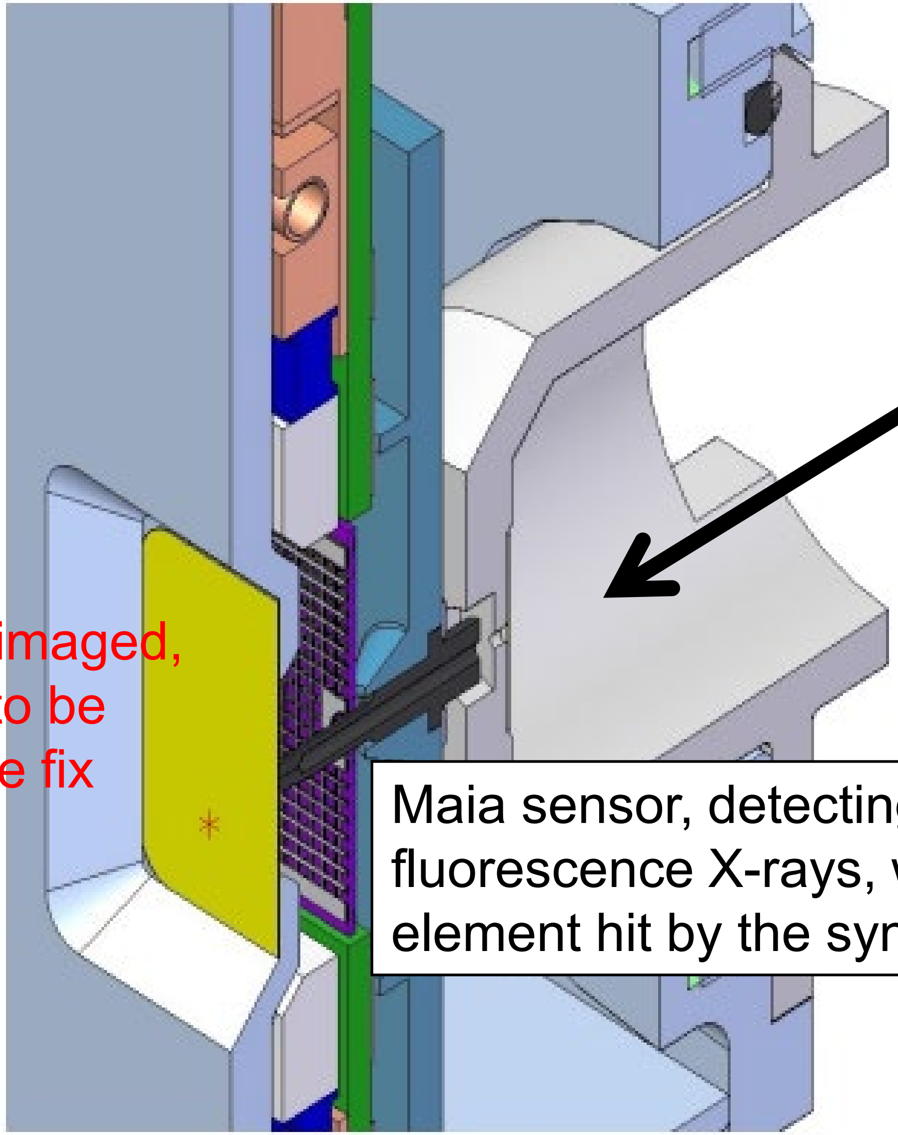
MAIA microprobe detector for elemental analysis in synchrotrons



Siddons et al., Journal of Physics:Conference series 499 (2014) 012001

- Array of 20x20 pixels (1mm x 1mm) – minus the 4x4 at the center to leave space for a capillary inserted through a hole
- Read-out in parallel for high-rate event detection

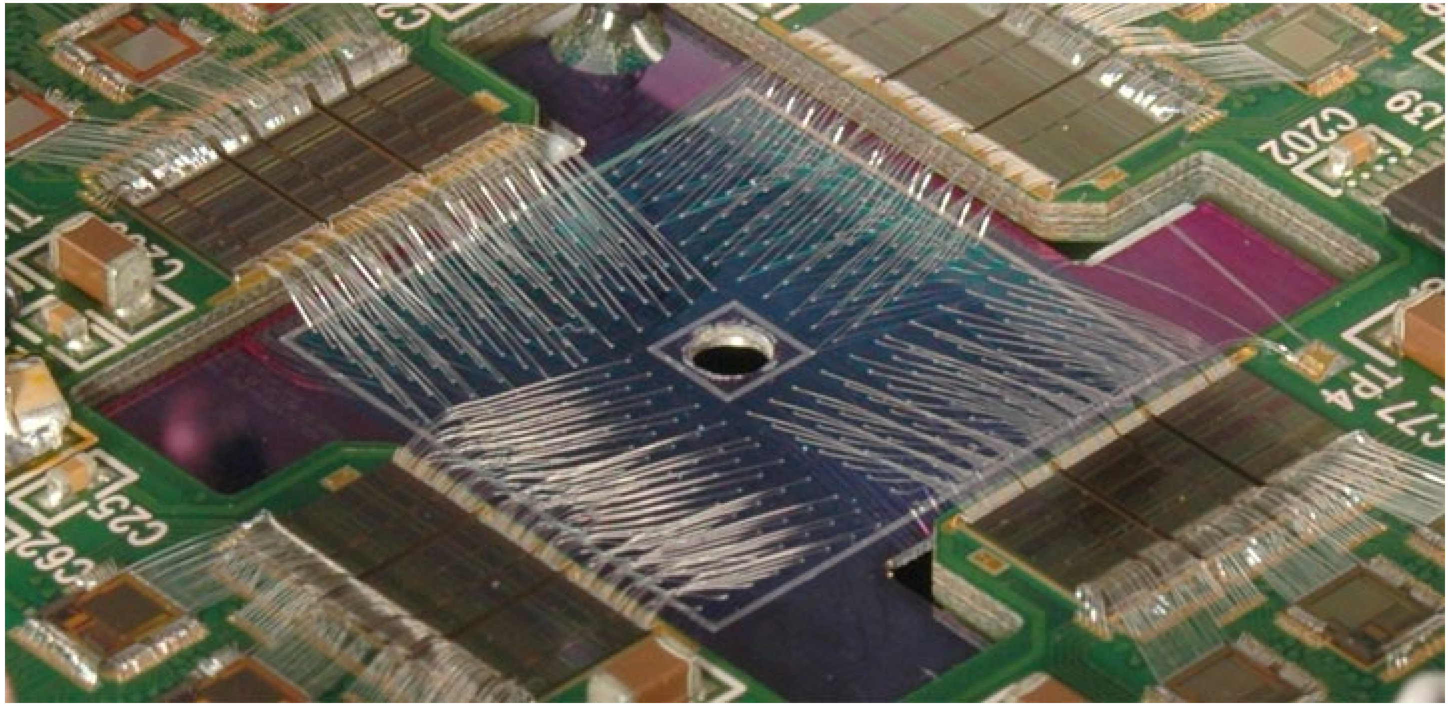
Maia at work

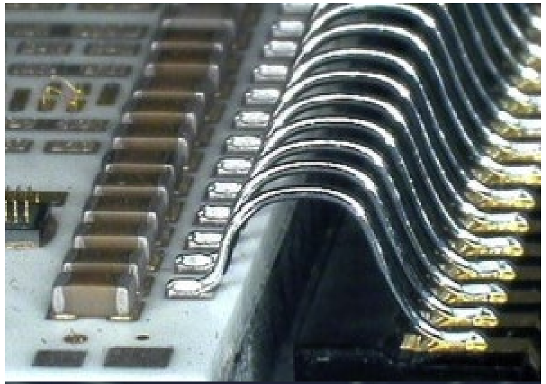


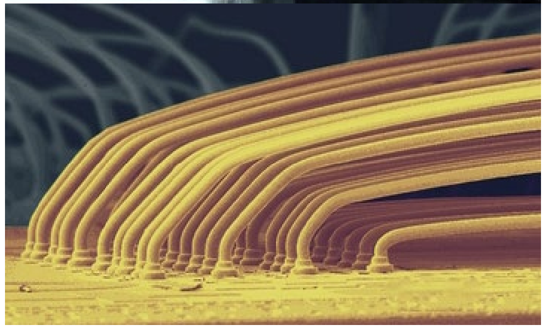
Primary X-rays from beamline
Sample to be imaged, which moves to be scanned by the fix beam
Maia sensor, detecting backscattered fluorescence X-rays, which are typical of the element hit by the synchrotron X-ray beam

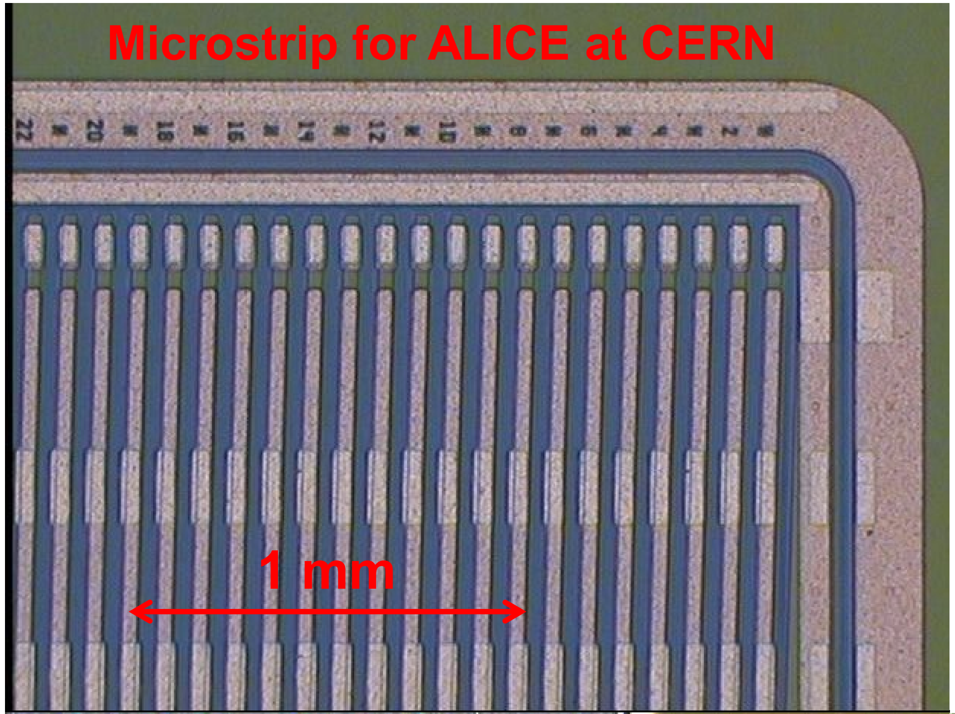
Interconnection is key

Aluminum (or gold) wire bonding, from sensor pads to chip pads.





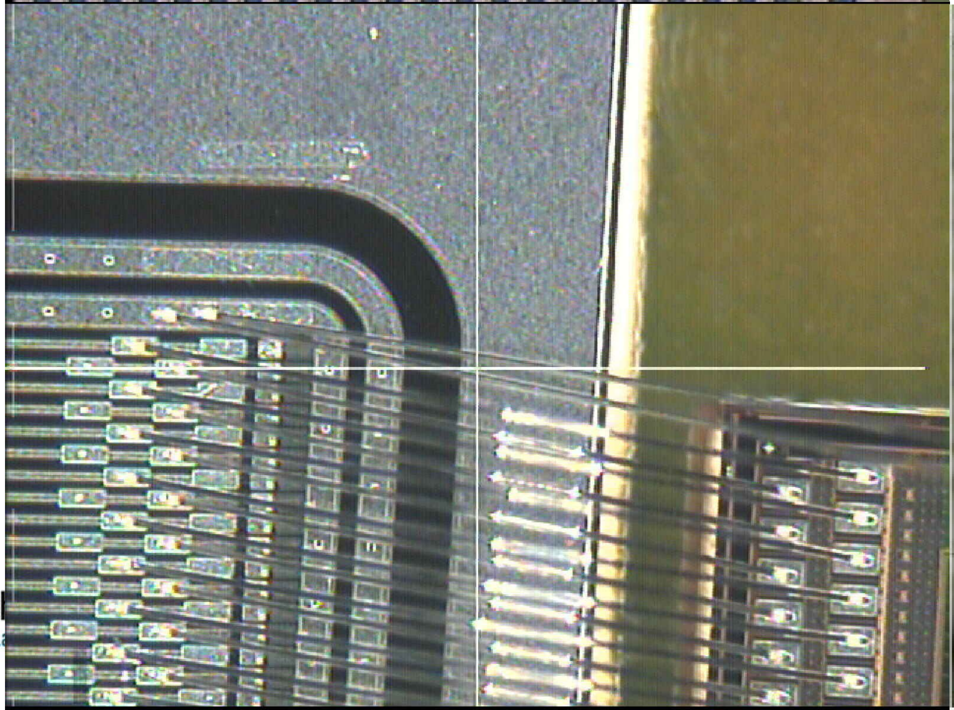


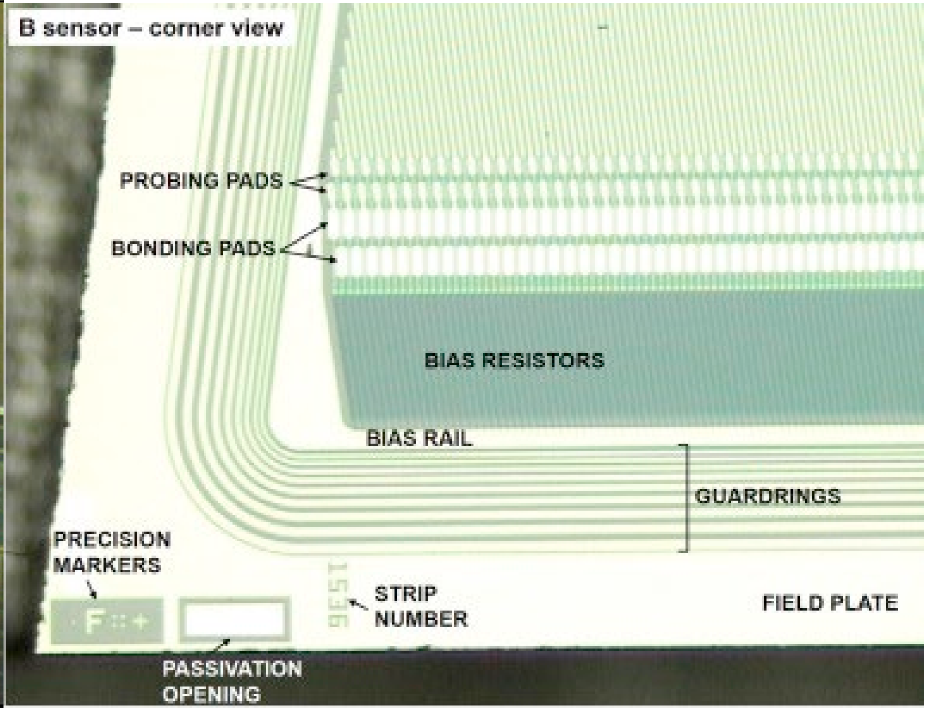


Microstrip sensors

Long narrow electrodes give position just in direction normal to the strips:
Two planes to reconstruct the 2D position

Used in trackers in physics experiments, and in few other applications that need just 1D

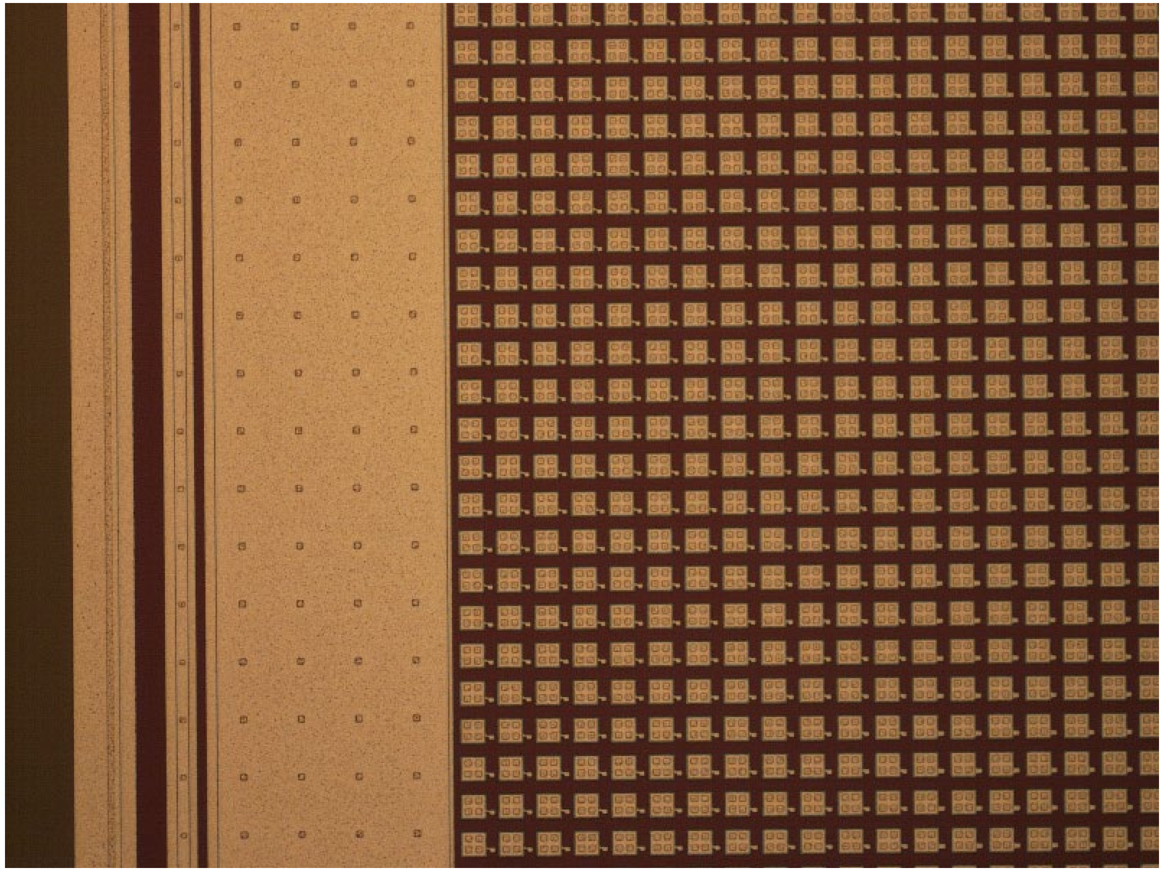




Pixel sensor

Pixel give 2-D spatial information: X and Y, with high spatial resolution, as they are at a pitch of a few tens of microns.
Thousands of channels/cm^2: how to wire-bond them to an external readout?

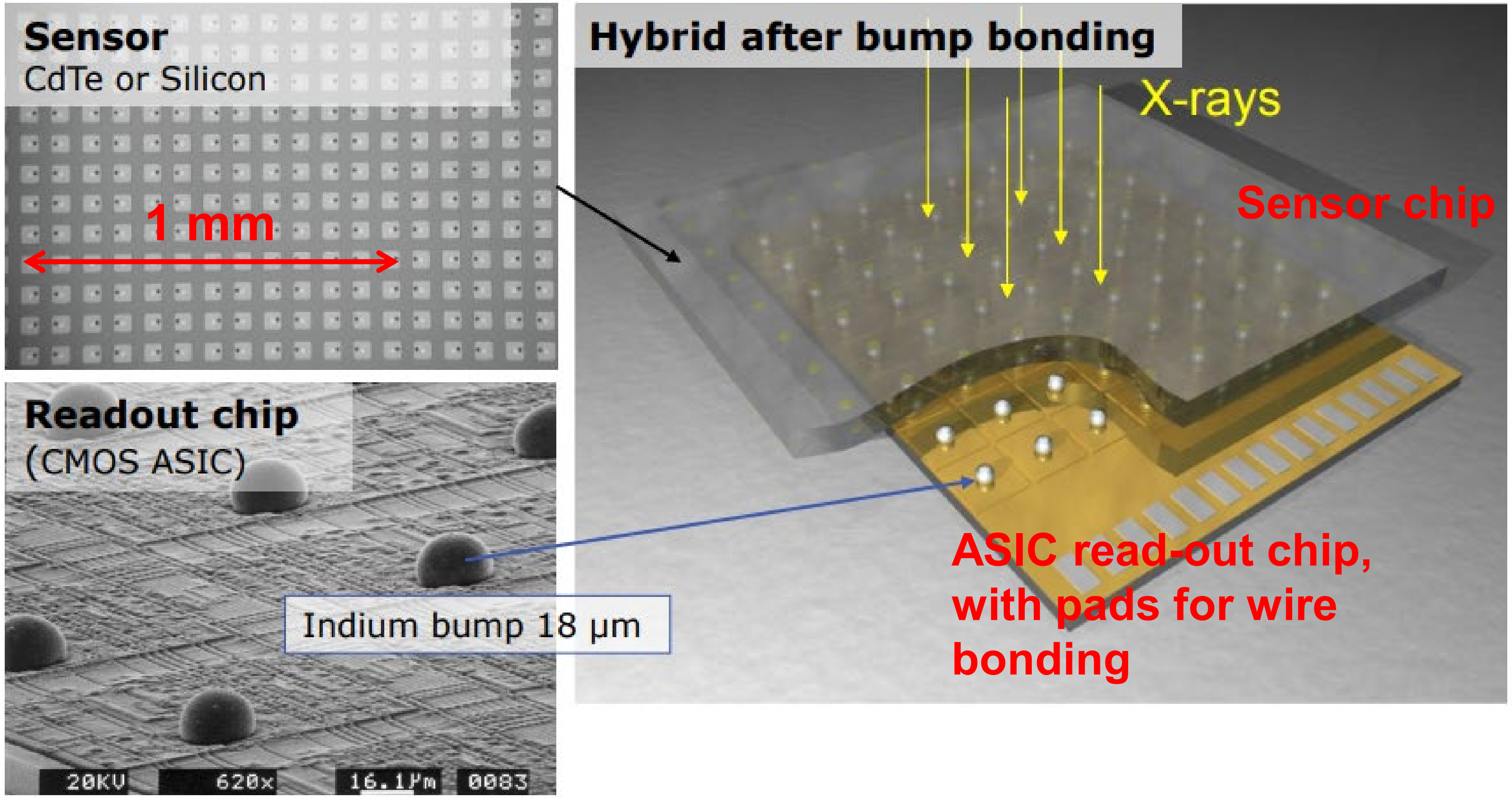
Pixels at 65 um pitch



Read-out is pixelated as well, to match the geometry.

2D read-out: Pixel detector

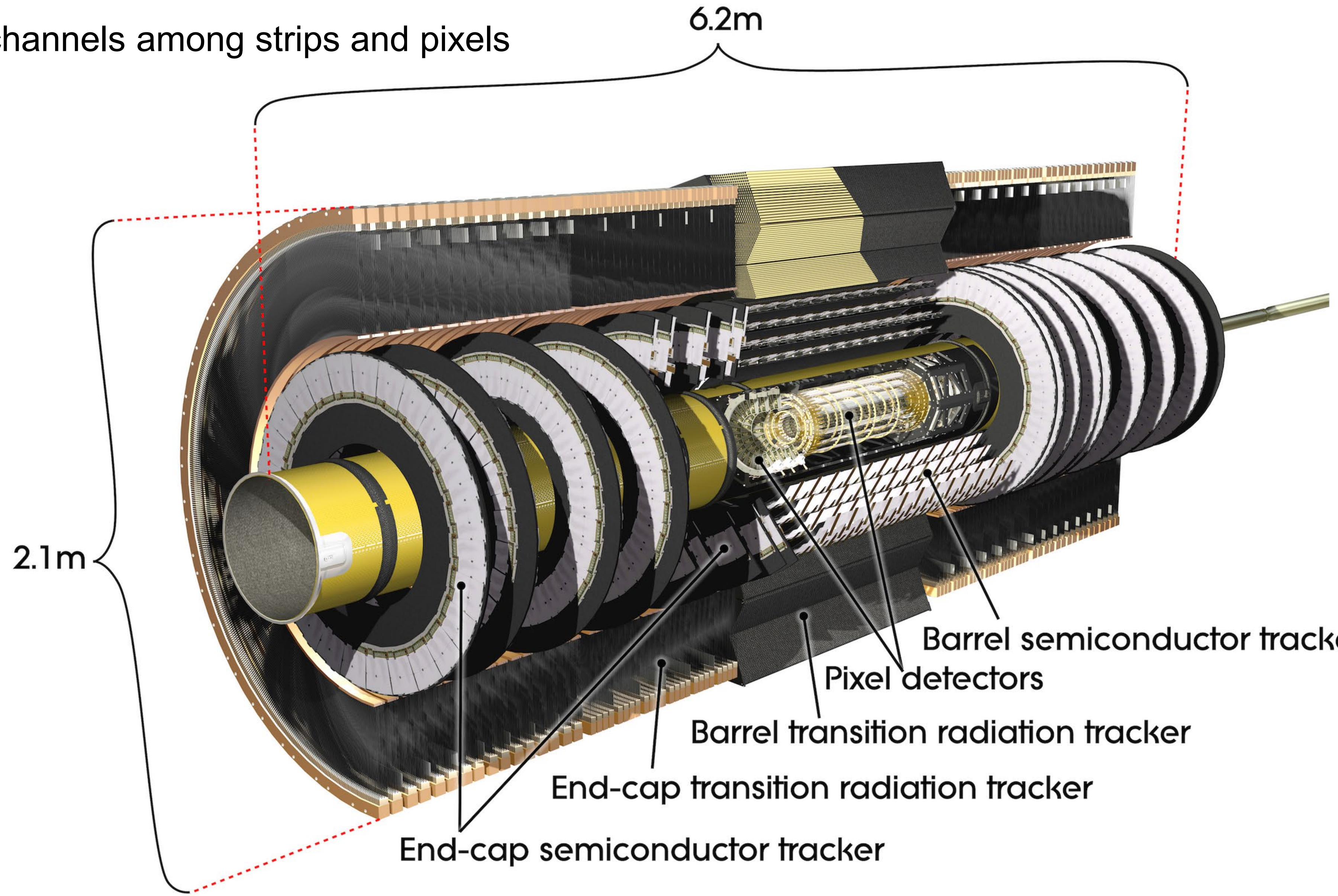
Hybrid pixel = sensor + readout



Price to pay? N^2 channel w.r.t. 2*N of strip sensor

ATLAS inner tracking system

Millions of channels among strips and pixels



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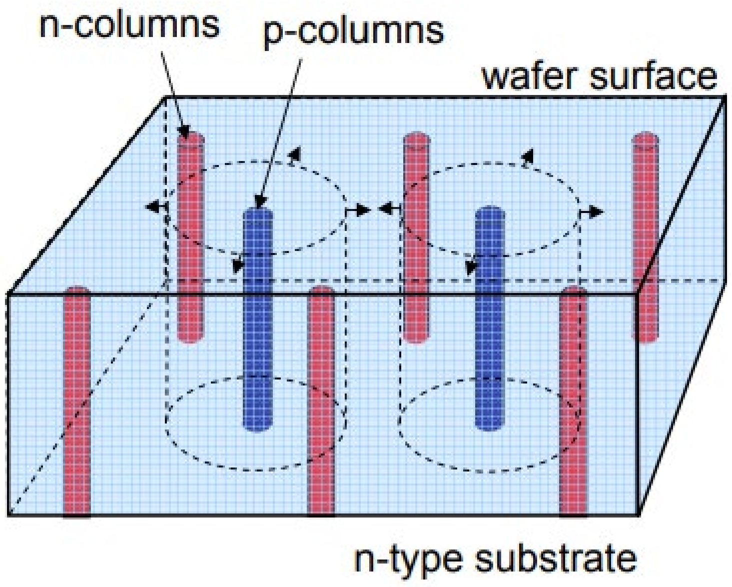
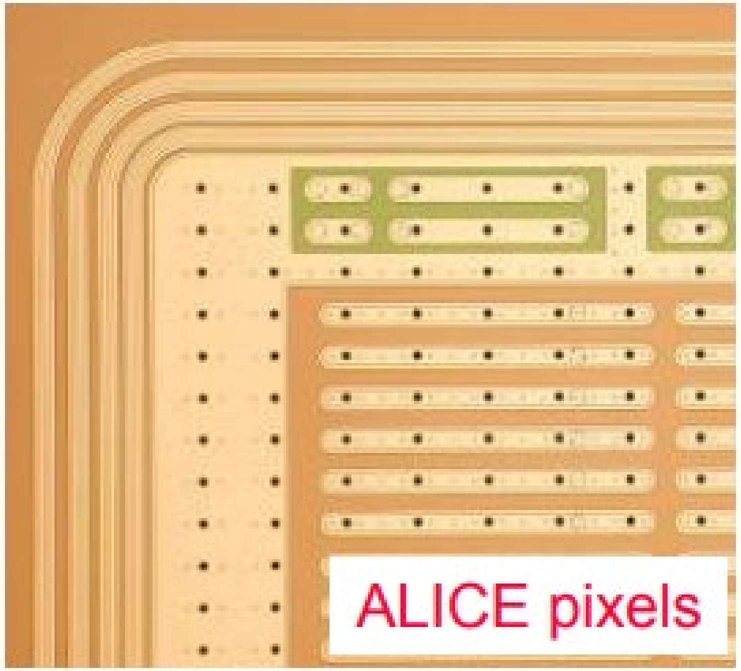
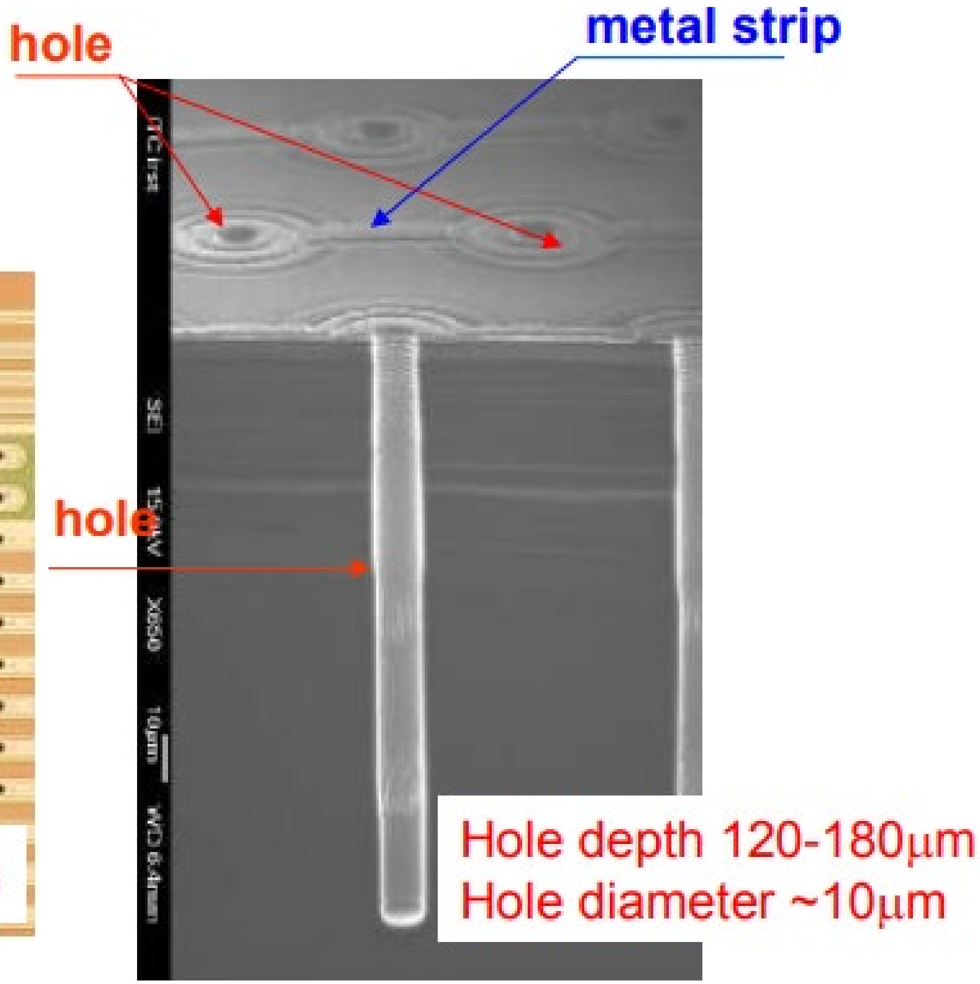
3D detectors

N,P electrodes can also be etched into silicon by DRIE process, in the shape of columns and trenches.
Very close together → very radiation hard, used and proposed for inner pixel layers in HEP colliders.



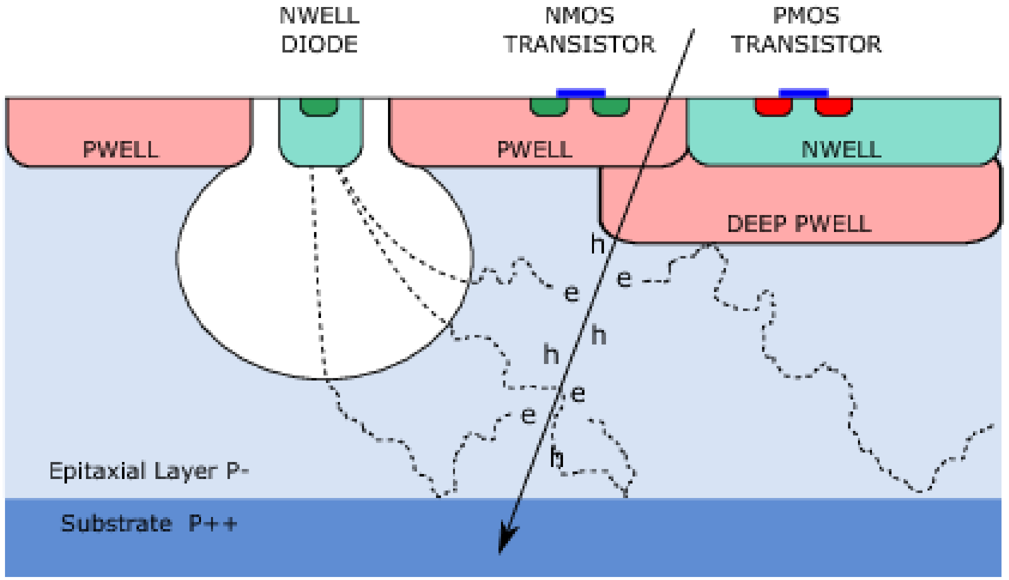




Made by FBK, CNM

G-F Dalla Betta, 6th SiLC meeting, 2007

Bump bonding is difficult and expensive → go for a pixel sensor on a chip!!



As both are made out of silicon, the sensor is integrated in the same substrate of the electronics.

Pro: relatively cheap, low power, reliable (state-of-the- art tech), fast turnaround, large volumes.
An ASIC designer does the design, an external foundry does the chips.

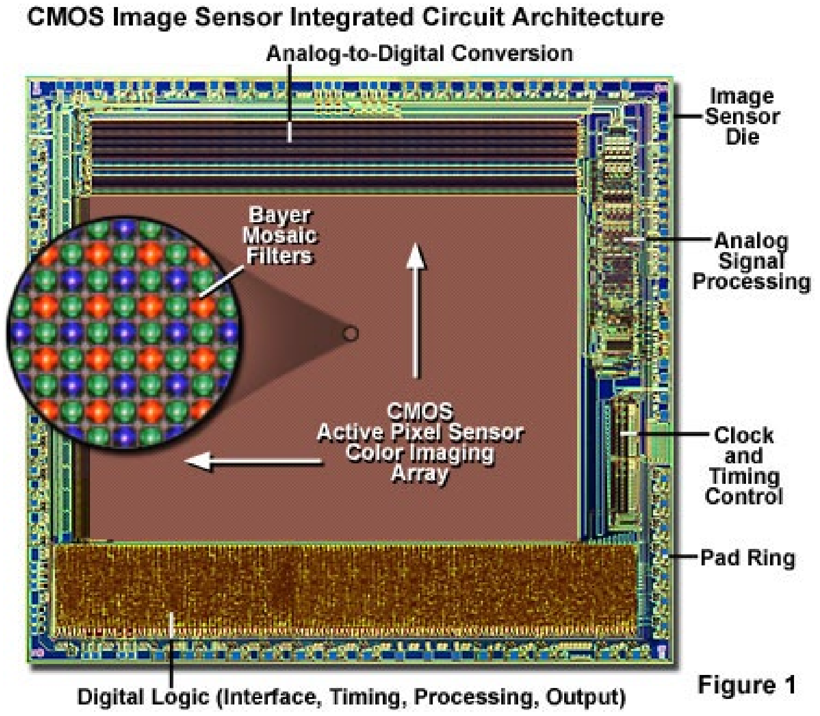
Drawback: large CMOS companies own the tech, which has to be adapted for sensor applications.
Usually, substrate is highly doped and the applied voltage low → small depleted region, leading to small and slow signals

Modern trend: Inner tracking system in physics experiment are made of Monolithic Active Pixel Sensors (MAPS).

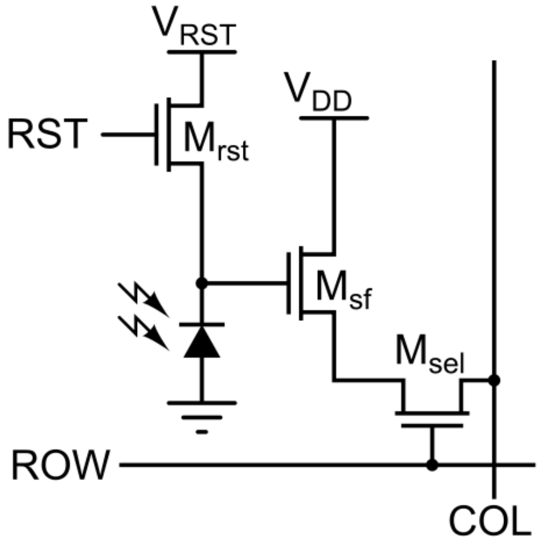
← STAR tracker, LBNL for BNL

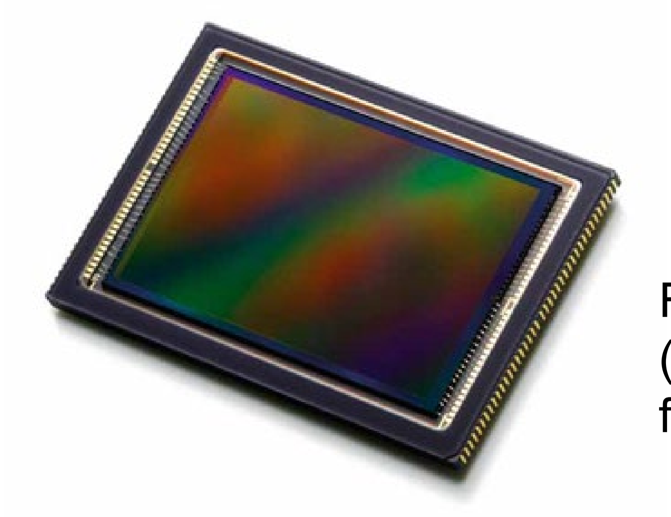
CMOS Cameras

- Array of many small pixels (~ M),
  for visible light detection
- Fabricated in CMOS technology
- Pushed by digital photography



"*three-transistor read-out*" in each pixel





From few mm^2 (smartphones) to full reticle (reflex)

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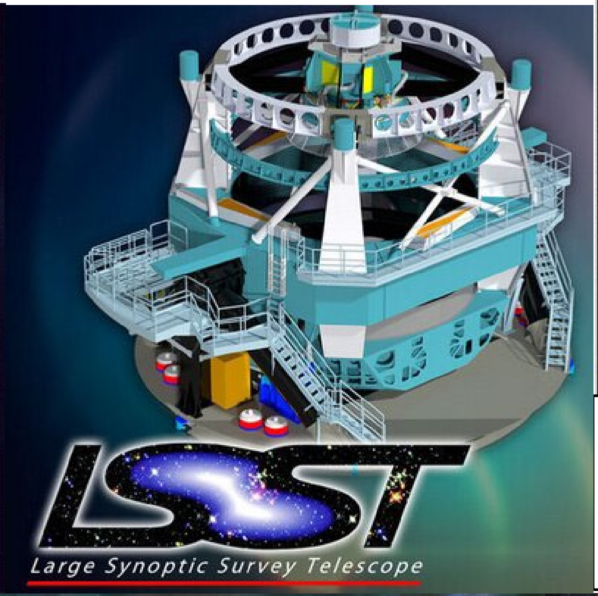
Surpassed by 4T architecture

Charge Coupled Devices (CCD)



Willard S. Boyle and George E. Smith developed the charge-coupled device in 1969 while working at Bell Laboratories

CCD concept

Bucket brigade

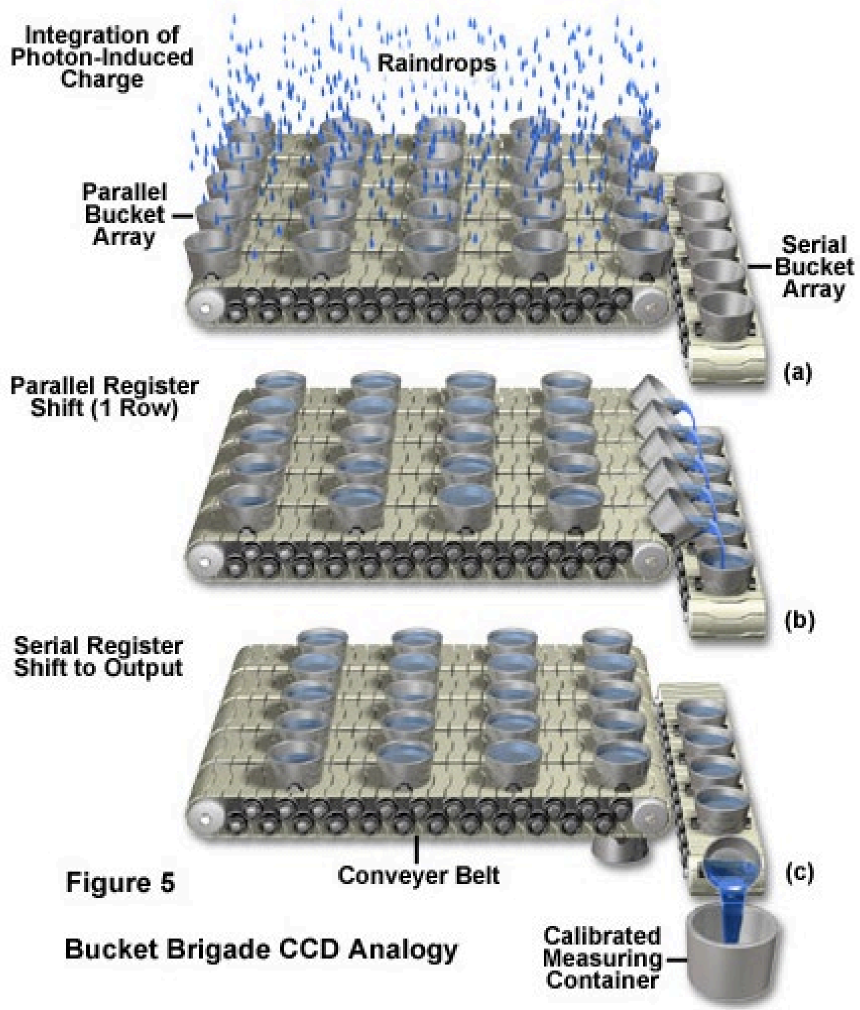
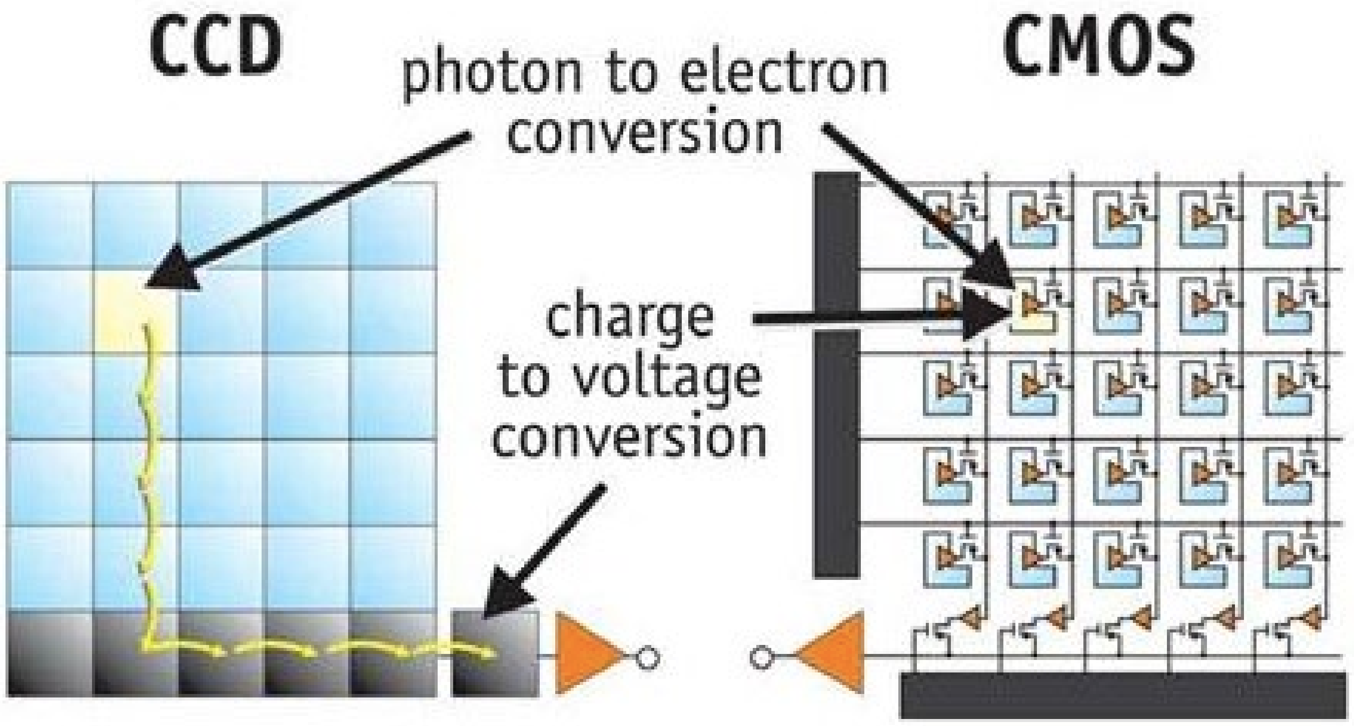


Figure 5

Bucket Brigade CCD Analogy

One read-out channel vs many

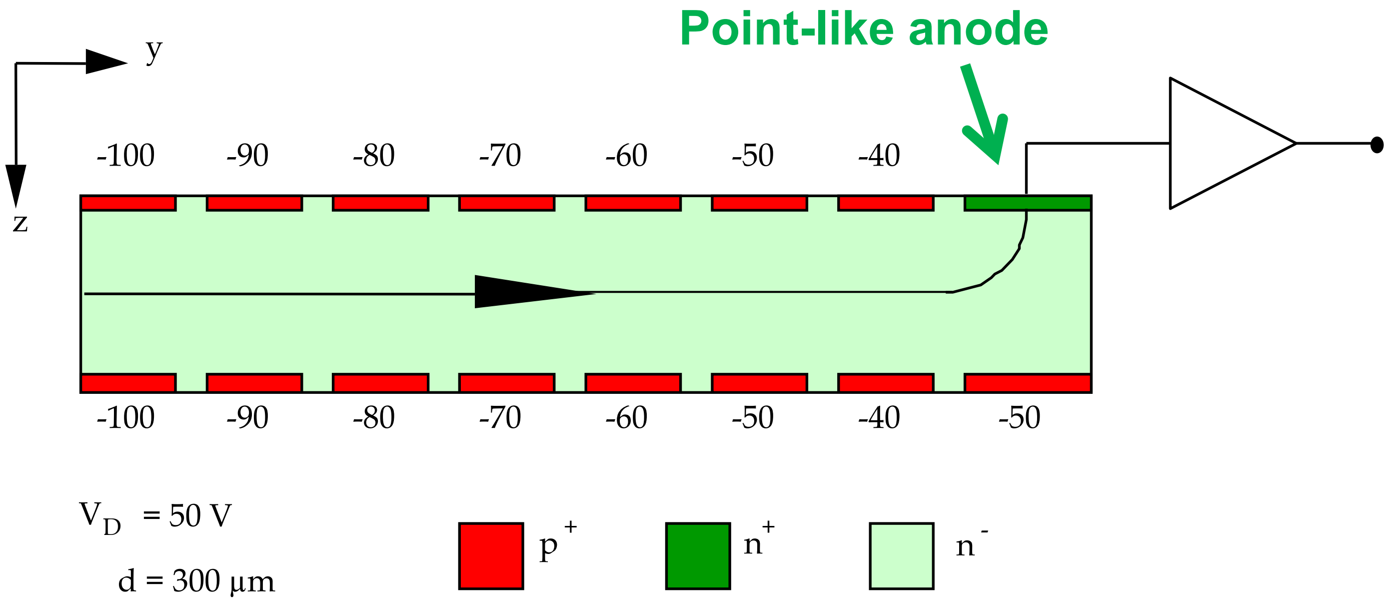


Slide from A. Nomerotski

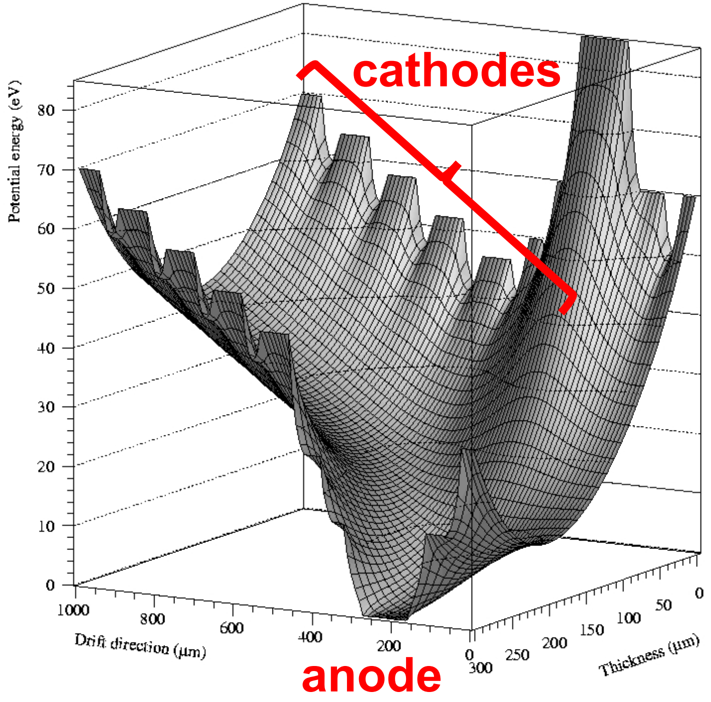
Silicon Drift Detectors

<u>Invented at BNL in 1984 (Gatti & Rehak)</u>

It is possible to deplete the substrate by means of a point-like anode.
Anode connected to ROIC, while voltages applied to the cathodes create an electric field following which the electrons drift to and are collected by the anode.
No matter how large the area is, the anode is small and so the capacitance and the noise.



Electrostatic potential



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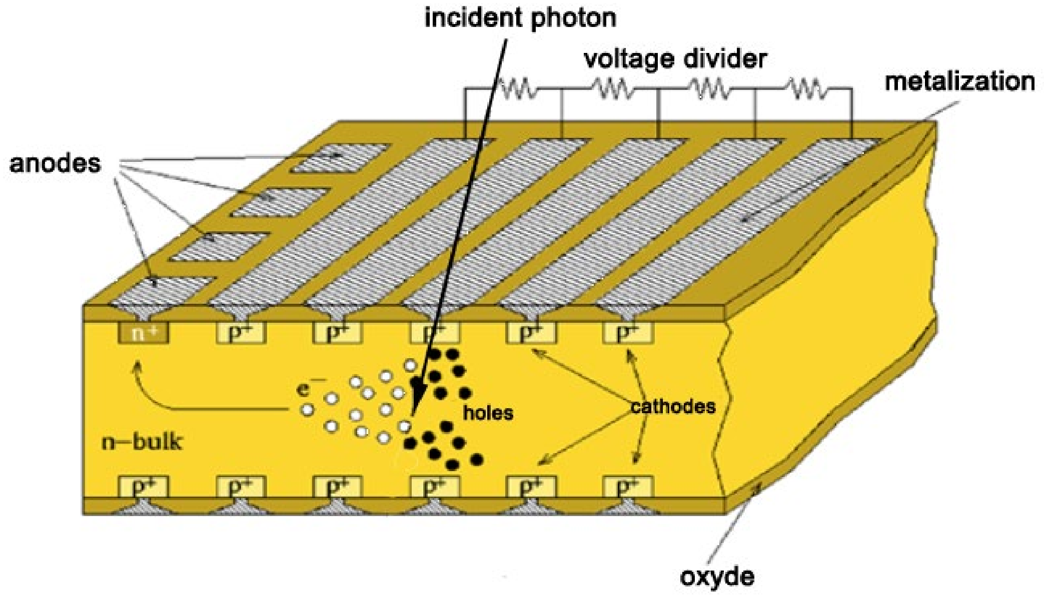
Linear Silicon Drift Detector

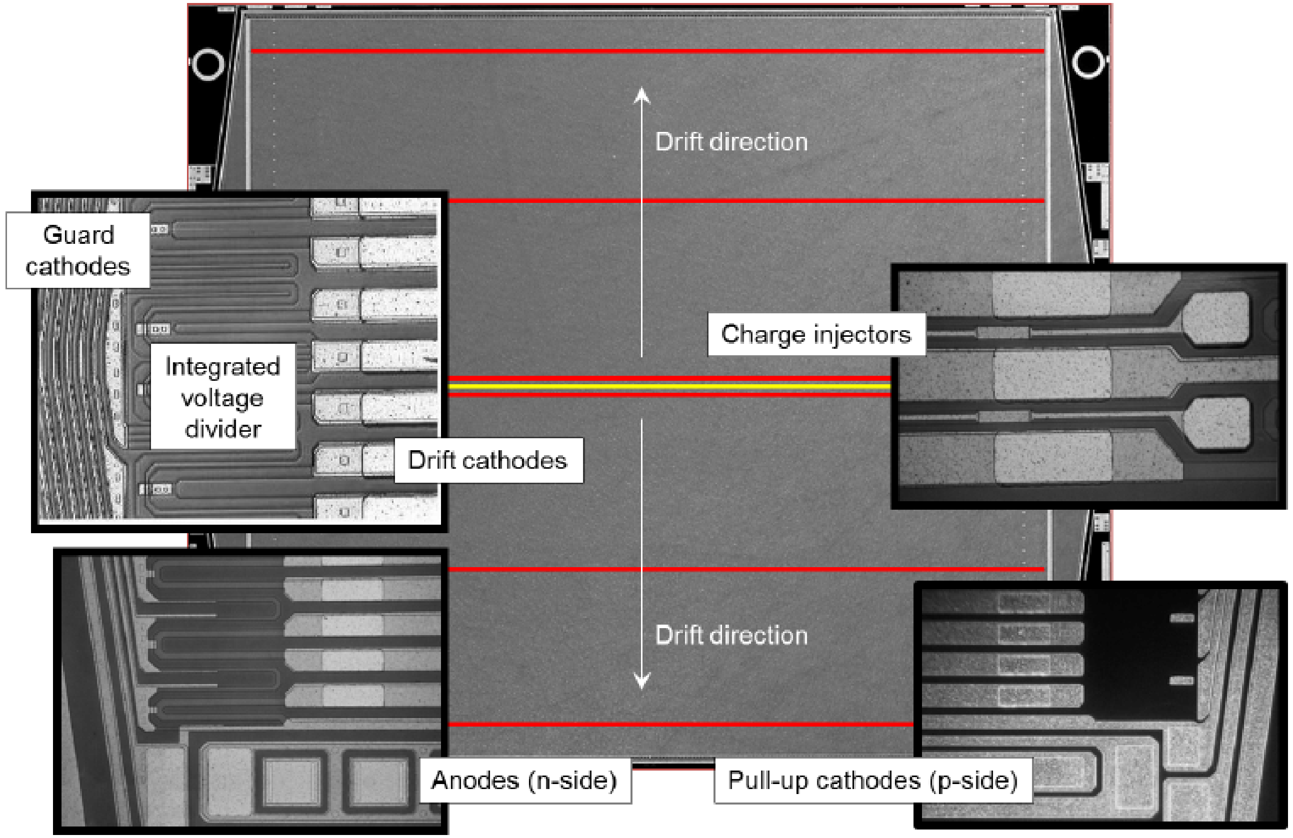
True 2-D:

- X by 1-D anode coordinate
- Y by drifting time (if trigger exists) → kind of time projection chamber

Used in STAR, ALICE



https://www.isdc.unige.ch/loft/technology.html



A Rachevski et al 2014 JINST 9 P07014

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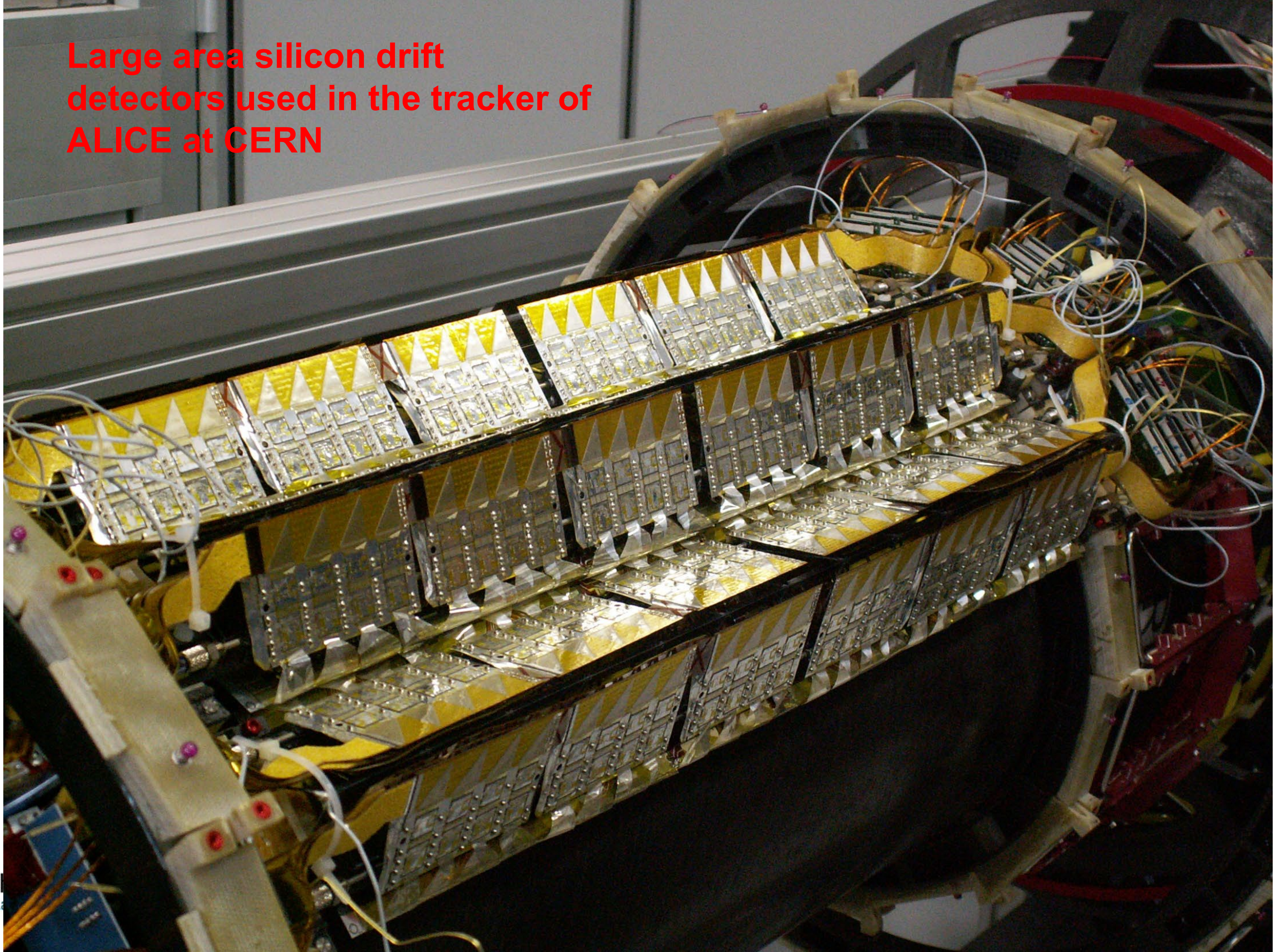
Large area silicon drift detectors used in the tracker of ALICE at CERN



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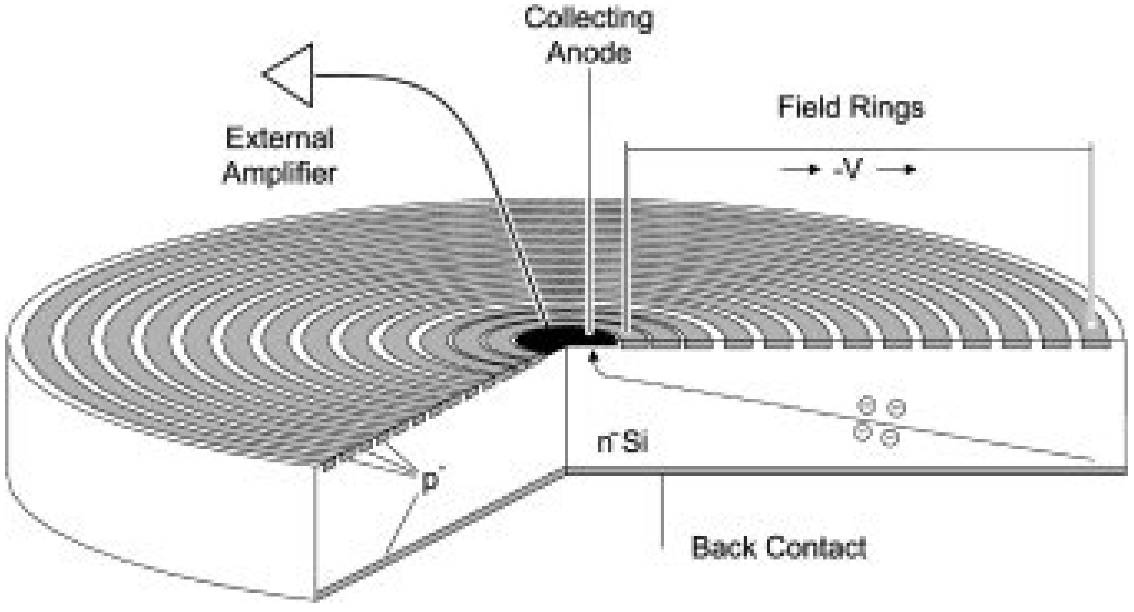
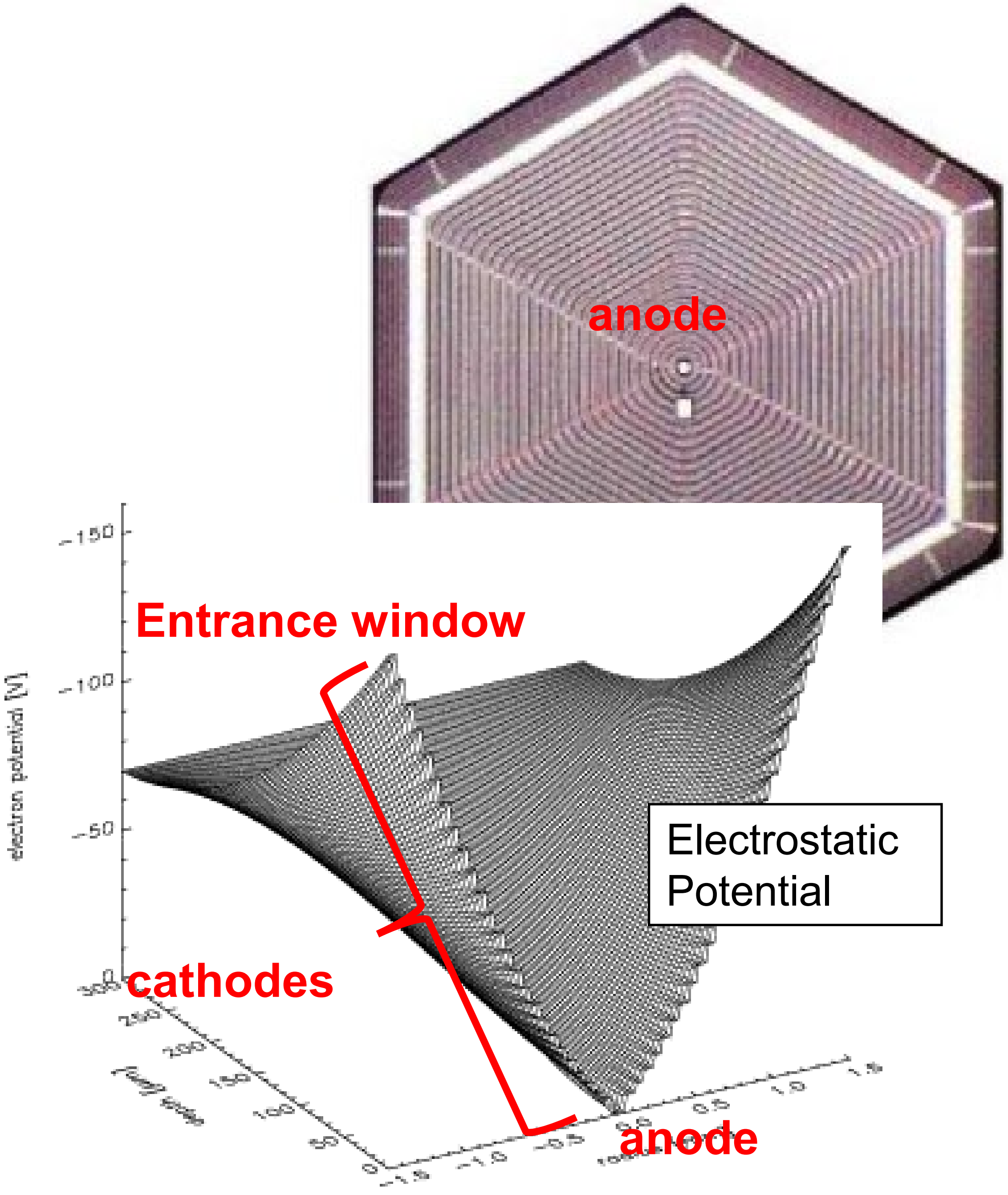
Silicon Drift Detectors for X-ray spectroscopy

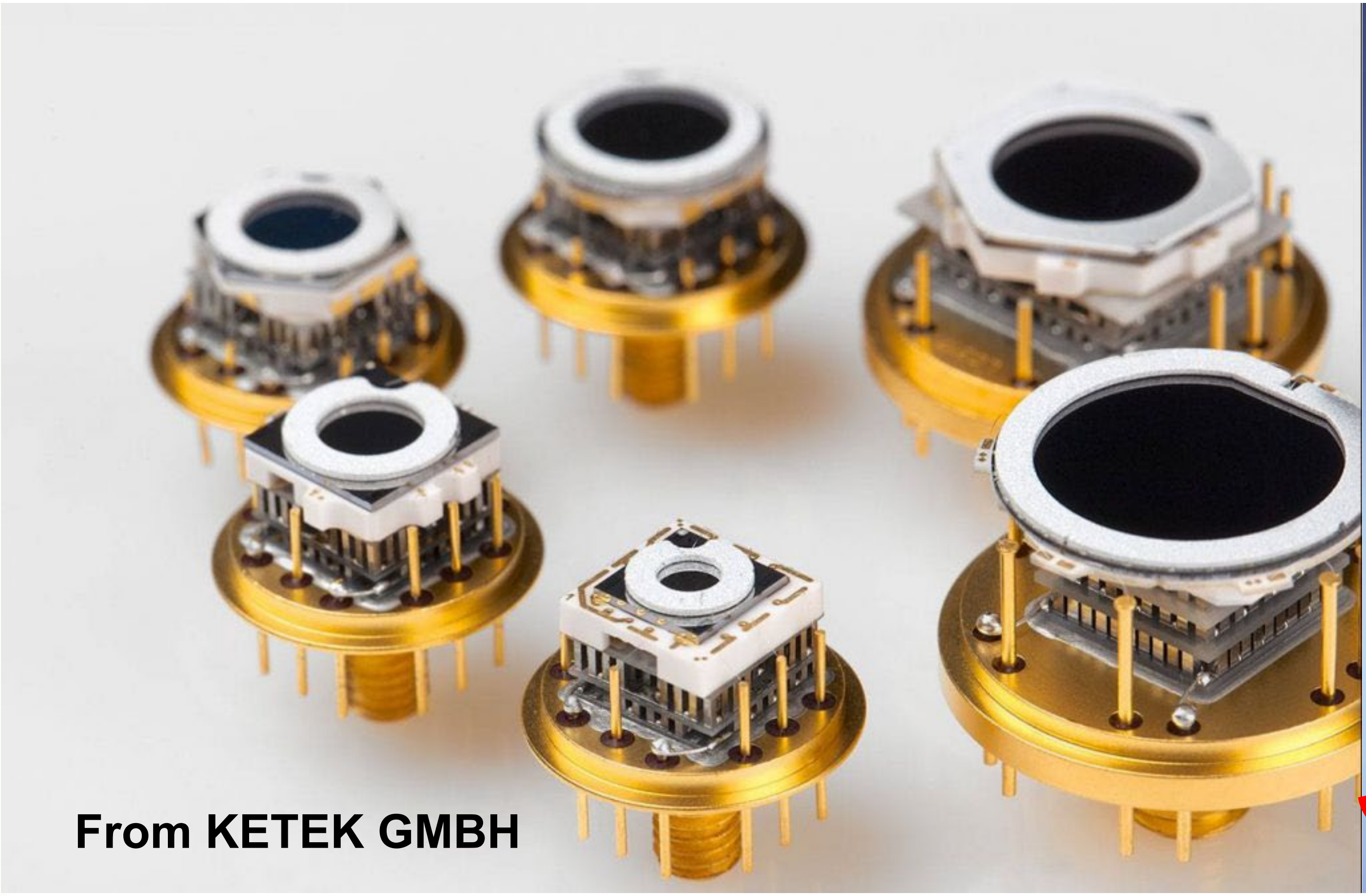
Due to the low capacitance of the point-like anode, they have the lowest noise: can detect lowest-energy X-rays, down to Boron line – mainly limited by Fano noise

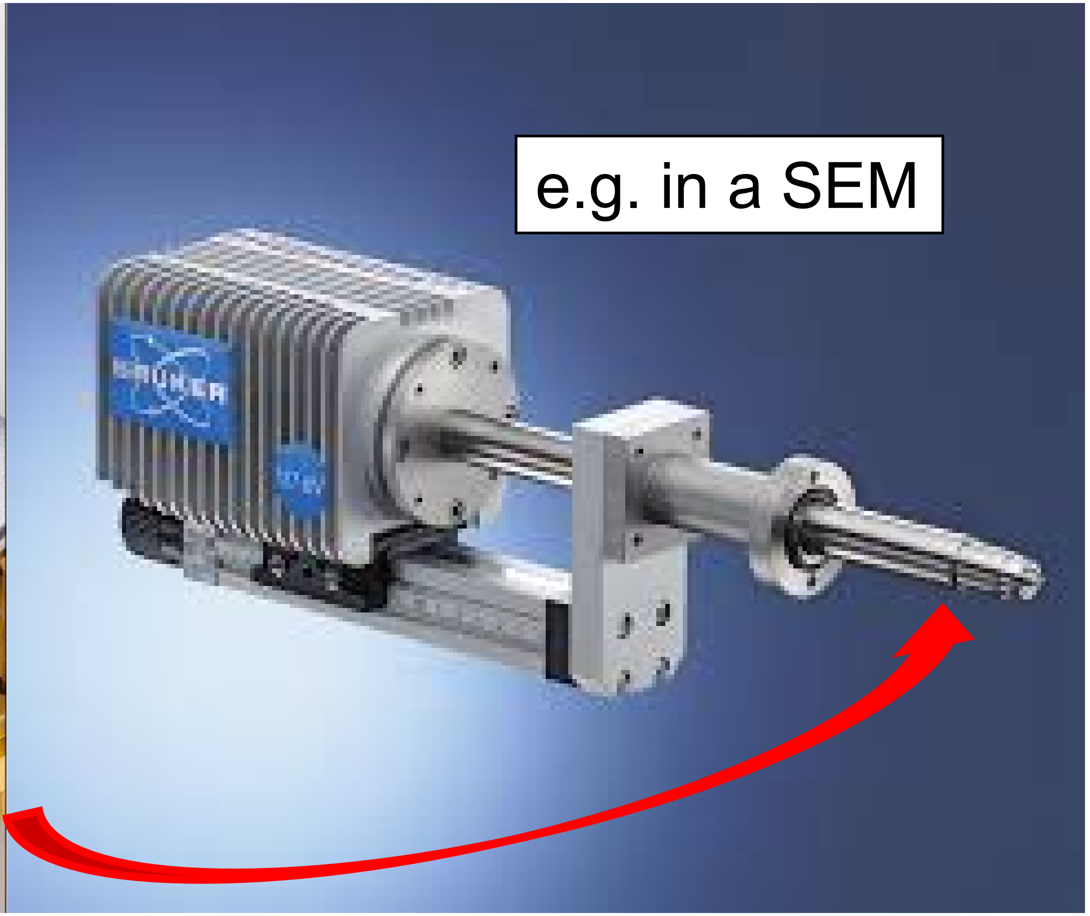


X-rays enter from the uniform entrance window



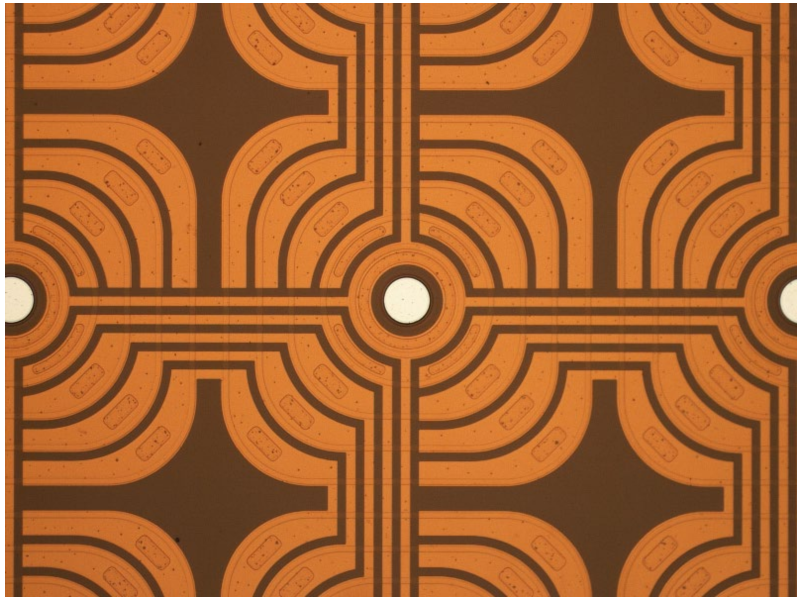
Silicon Drift Detectors as X-ray spectroscopy detectors

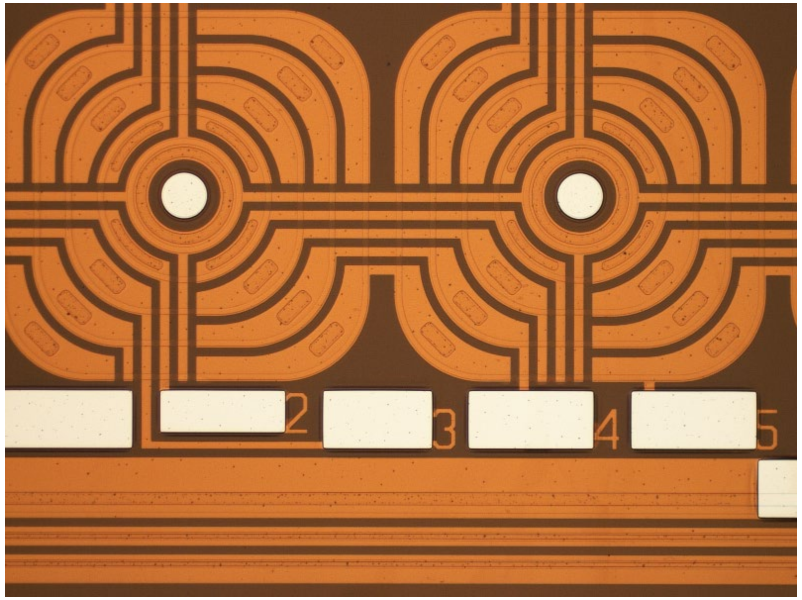


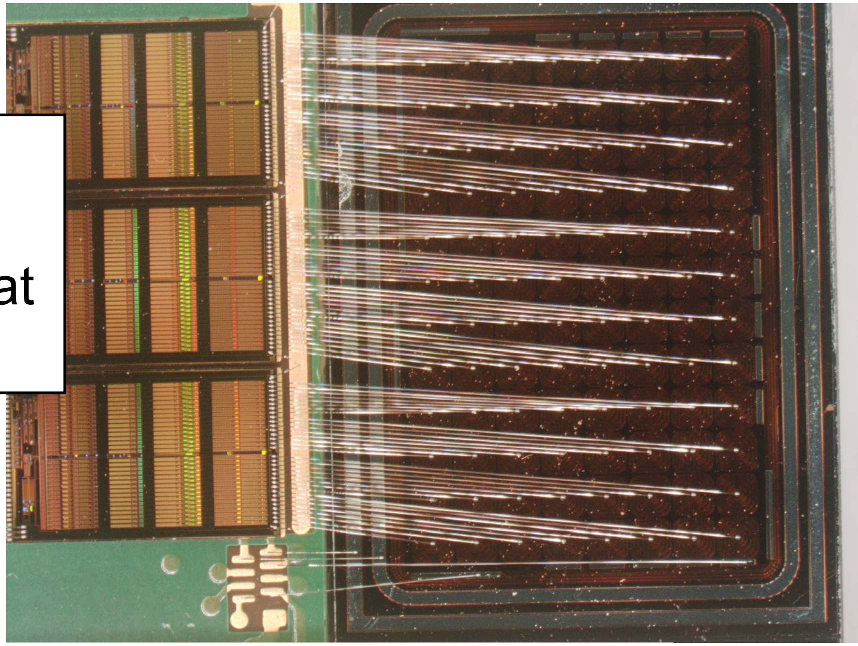


A new Maia Detector: Hera

1mm x 1mm mini SDD.
Only 6 drift rings (cathodes),
biased by external voltage divider

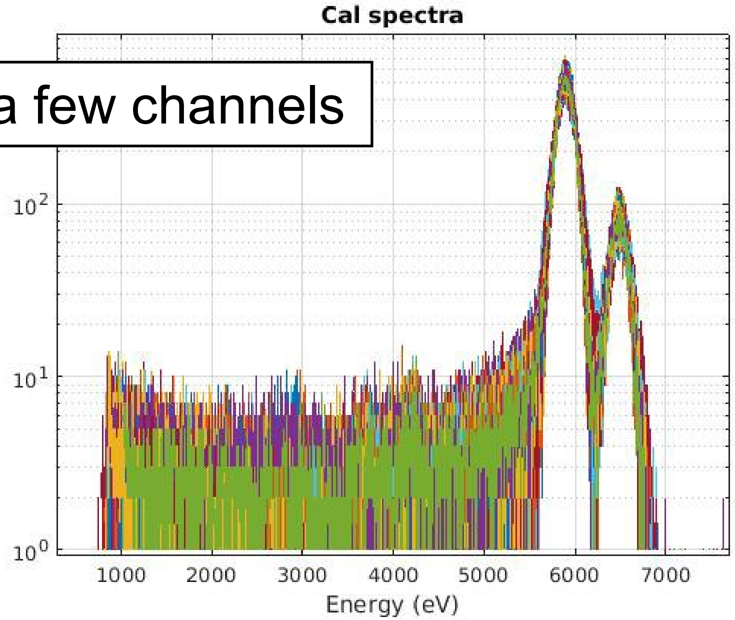






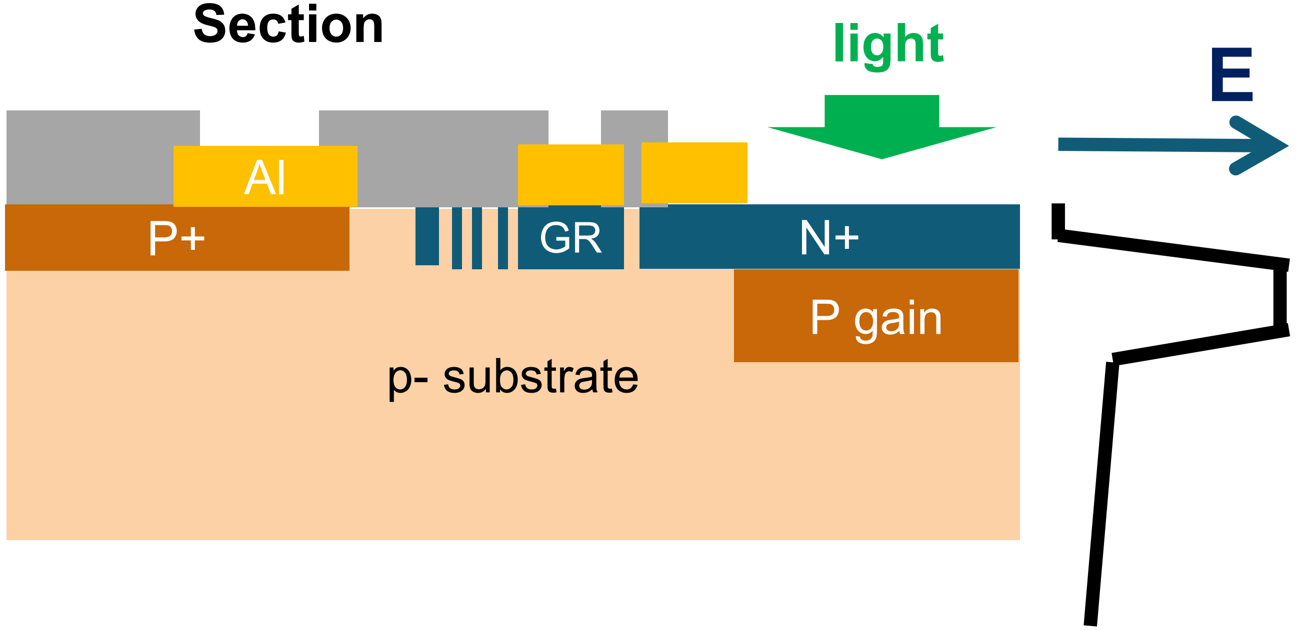
96-ch assembly.
Due to the low capacitance of the anode, **better noise** at even shorter shaping times.

^{55}Fe spectra from a few channels

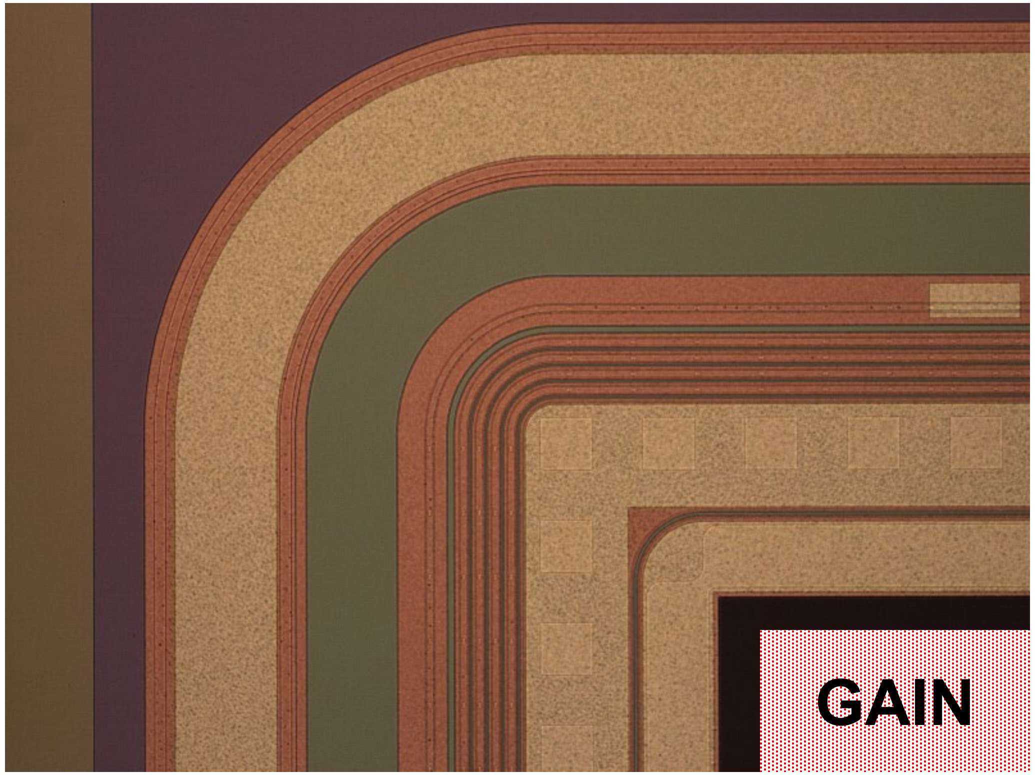


Avalanche Photo Diodes (APD)

Section



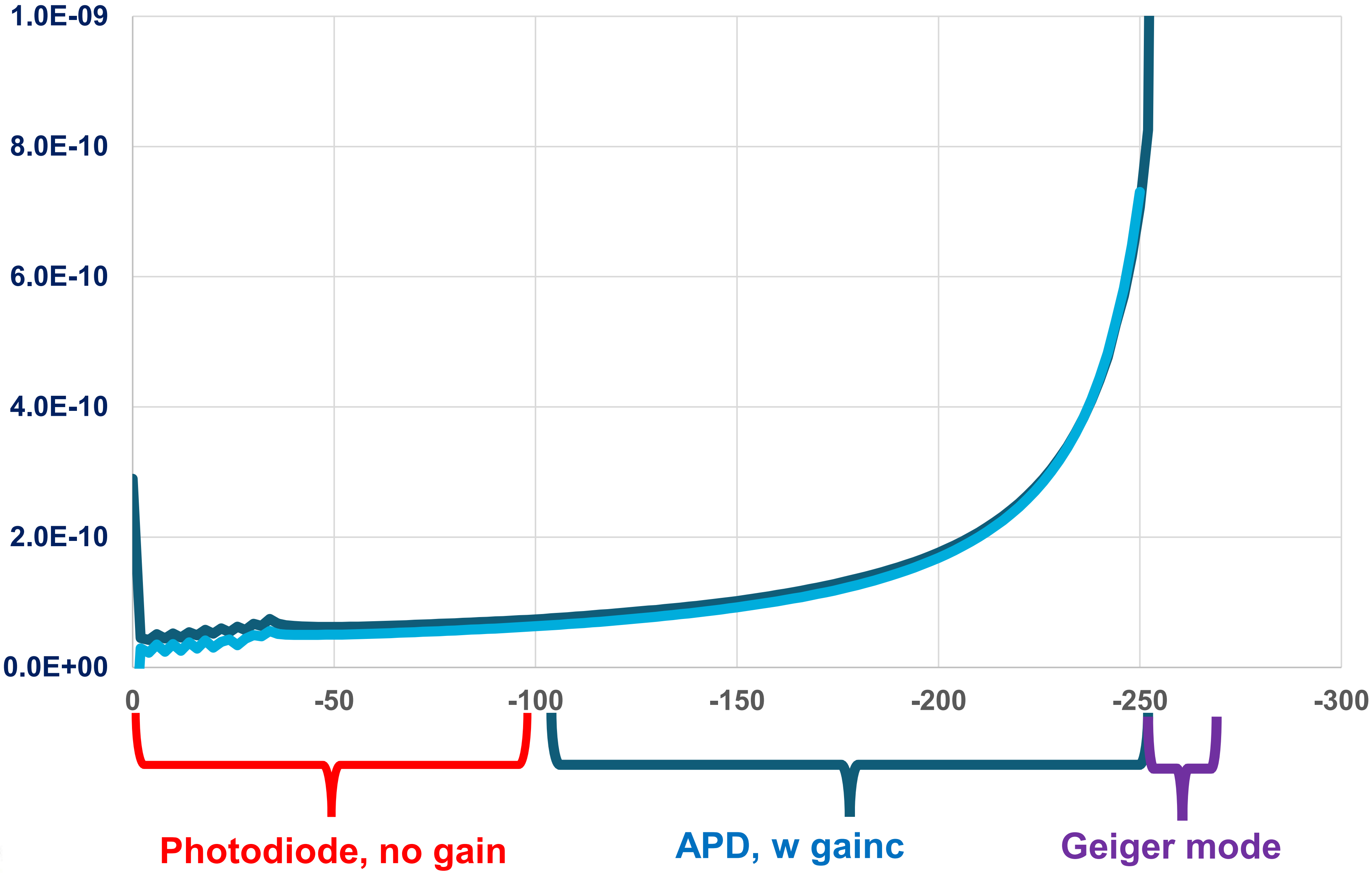
From the top



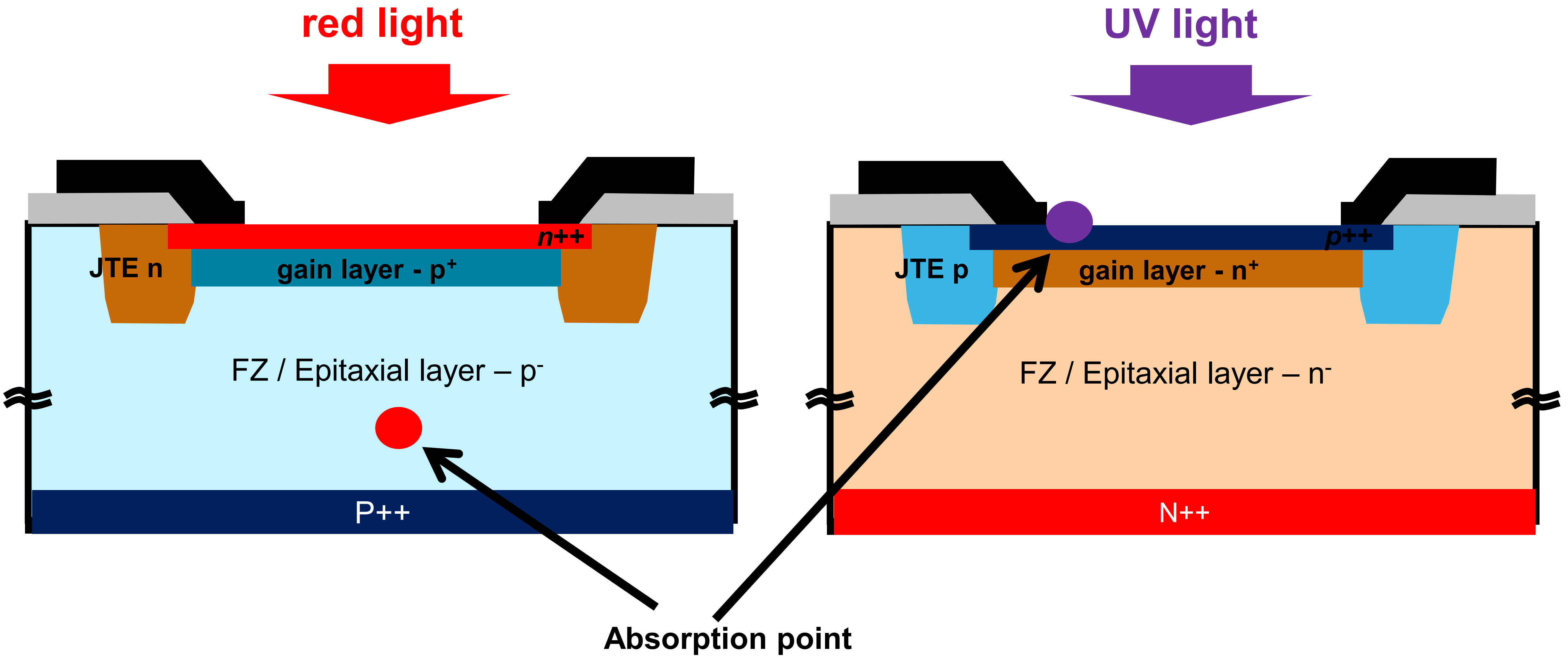
Electrons passing through a high electric fields (~3e5V/cm) undergo impact ionization and create electron/hole pairs
→ signal amplification

Holes experience less impact Ionization (their coefficient is less than for electrons).
When they get multiplied → Avalanche breakdown (Geiger mode)

Typical I-V of an APD

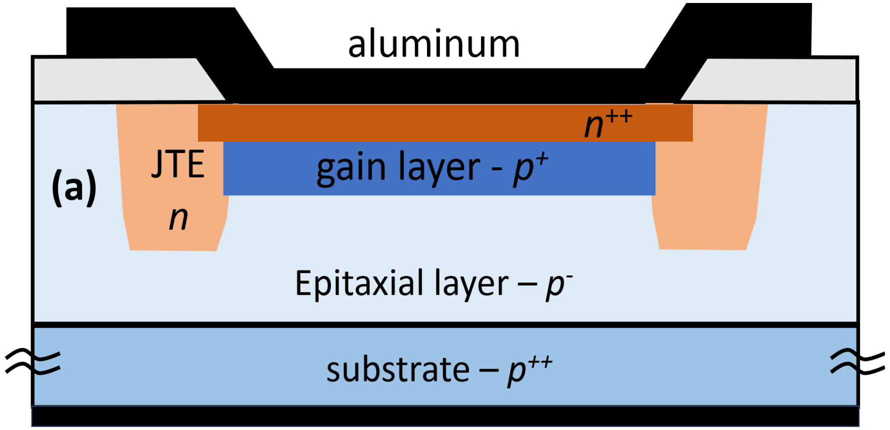


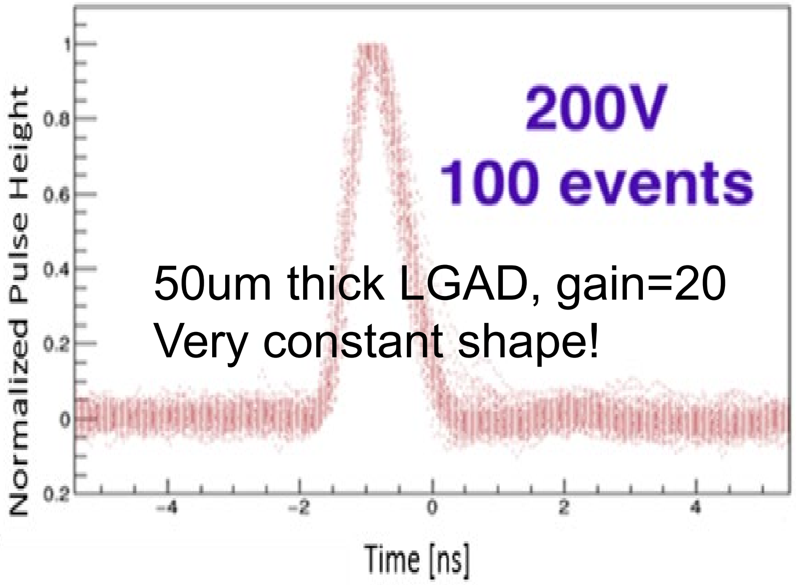
APD for deep and shallow penetrating particles



Once e/h pair is created by radiation, electrons must travel through high field region!

Low-Gain Avalanche (Photo) Diodes





LGADs and APD work before Geiger regime.
A highly doped, thin layer of *p*-implant near the *p-n* junction in silicon creates a high electric field that accelerates electrons enough to start multiplication (*gain*).

- **Low Gain Avalanche Detectors (LGADs)**:
  - **Gain 5-100**
  - **20-50 μm thickness**
  - **Large S/N ratio**
  - **Fast-timing: ~30-50 ps per hit, dominated by Landau fluctuations**

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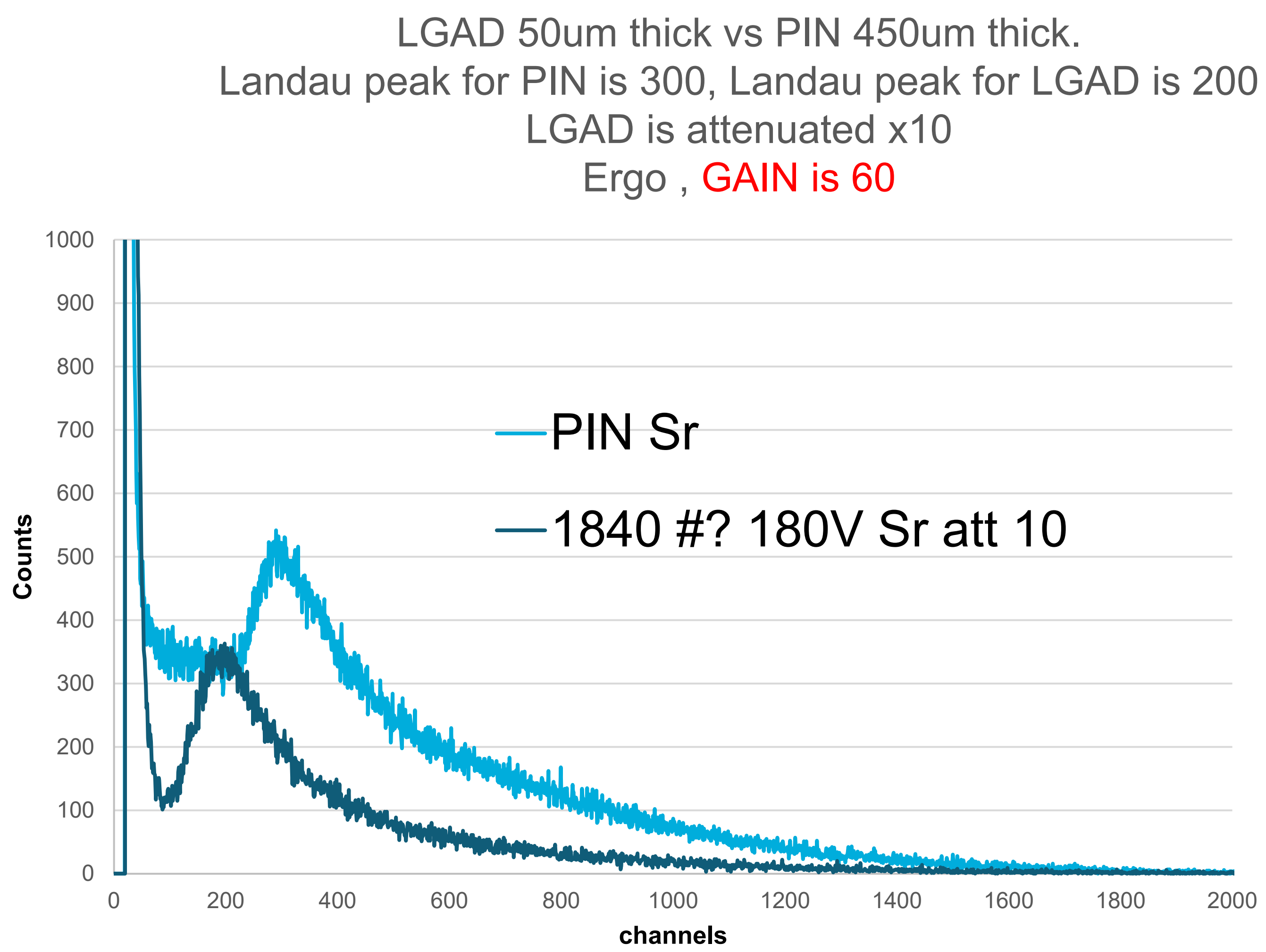
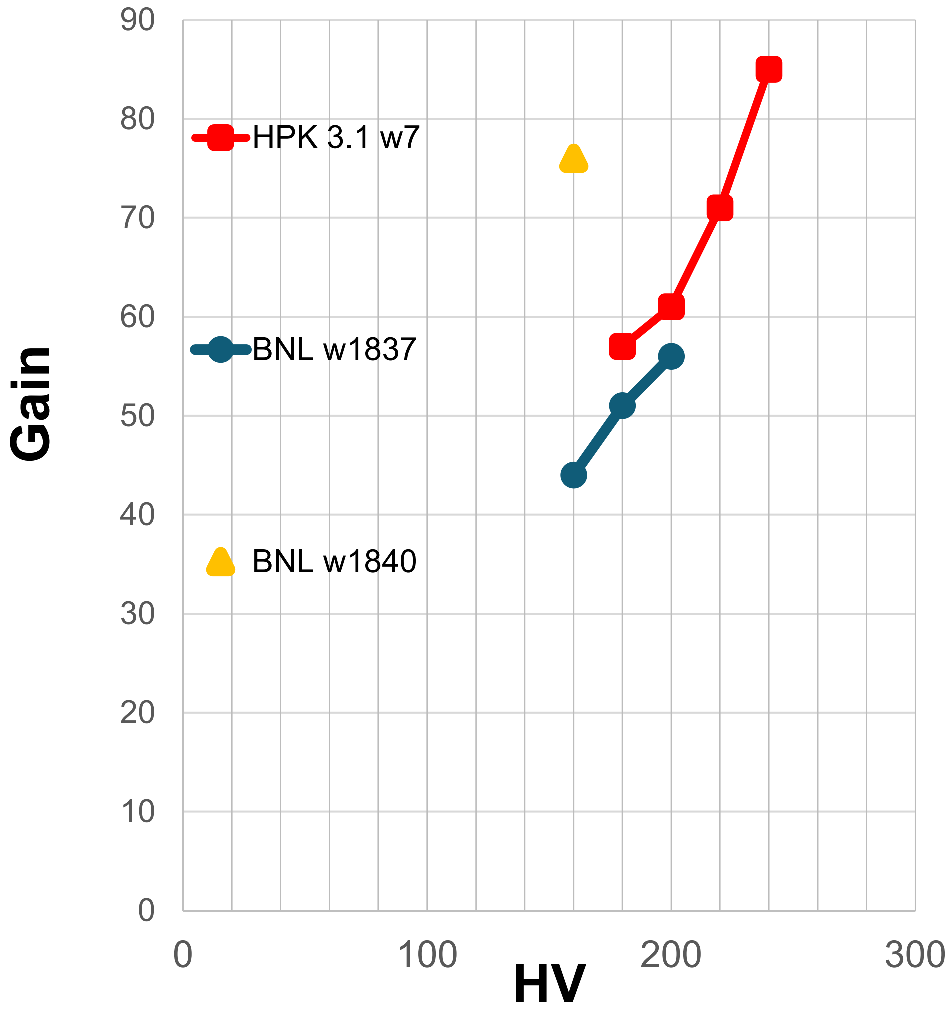
Gain in an LGAD - 1

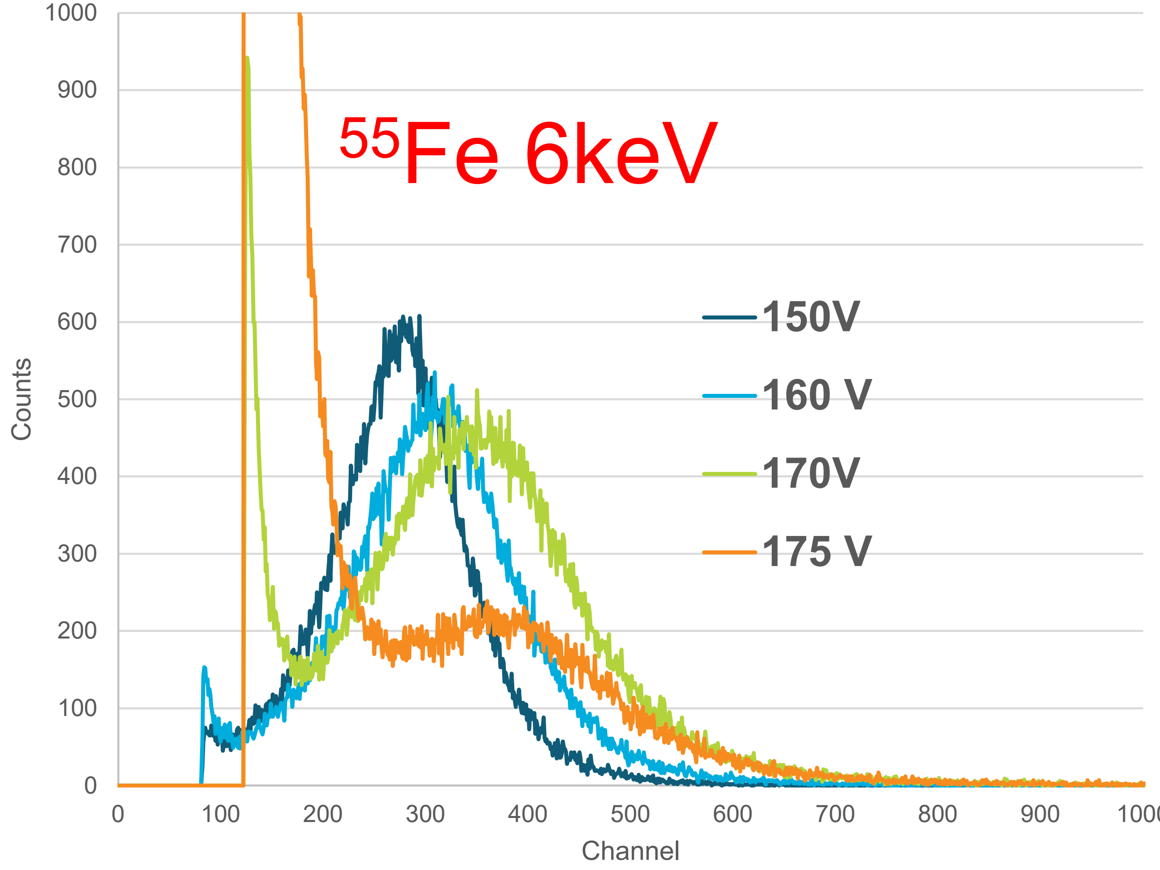
Response to a mip





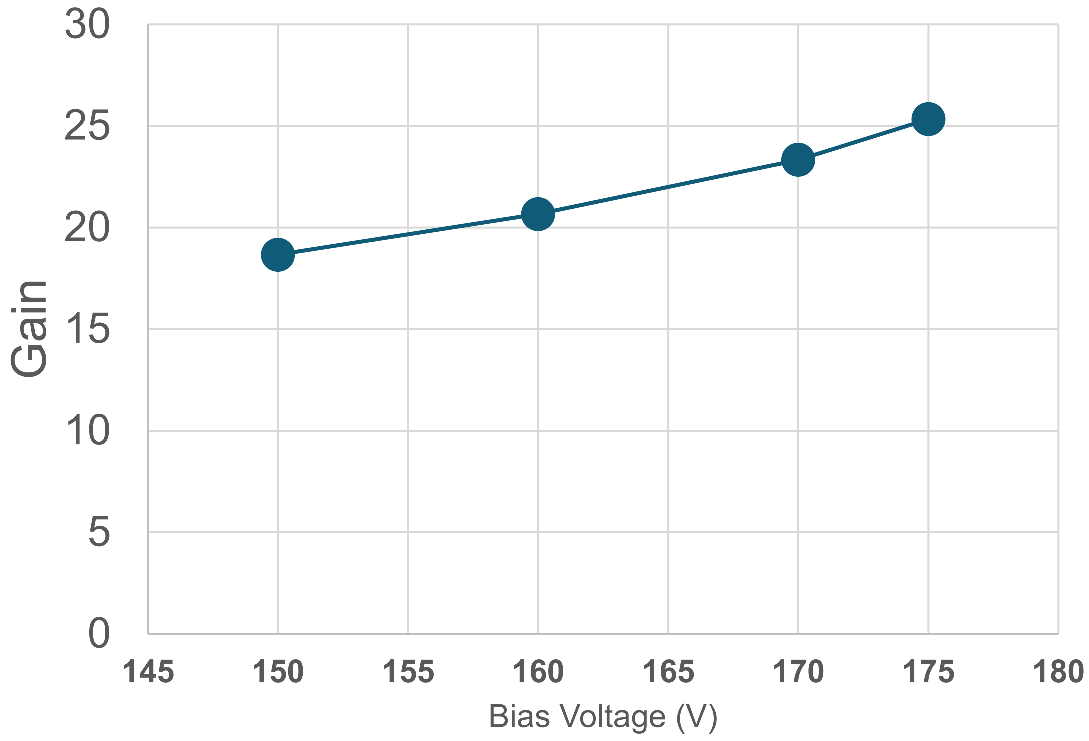
Gain in an LGAD - 2

signals from X-ray sources



Broad peaks are due to multiplication noise. Pulser peaks are very narrow in this scale, so noise is not due to leakage current

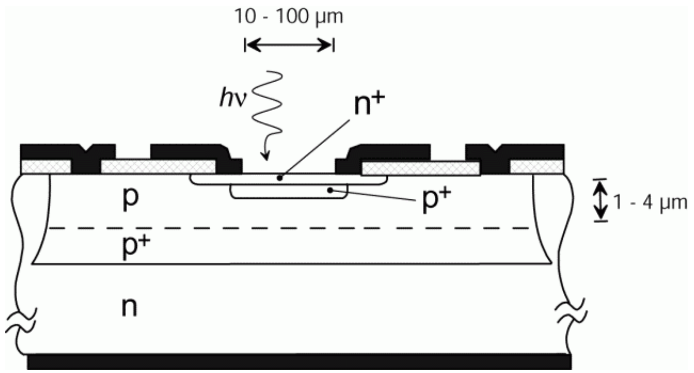
Gain of 70 with ^{90}Sr !! Only 20 with X-rays

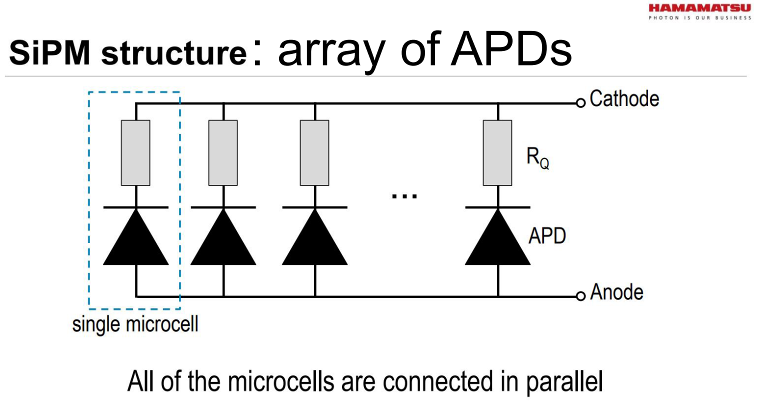


- Gain much less than Gain measured with ^{90}Sr: different shape of the charge cloud
- ^{55}Fe higher than gain with ^{251}Am: shielding effects

Silicon PhotoMultiplier (SiPM)

Visible photons create just one e-/h+ pair, beyond detection.
But, if one electron crosses a high-electric field region, it triggers an avalanche.
Microcells (single Avalanche Photo-Diodes) work above the breakdown voltage (**Geiger regime**).

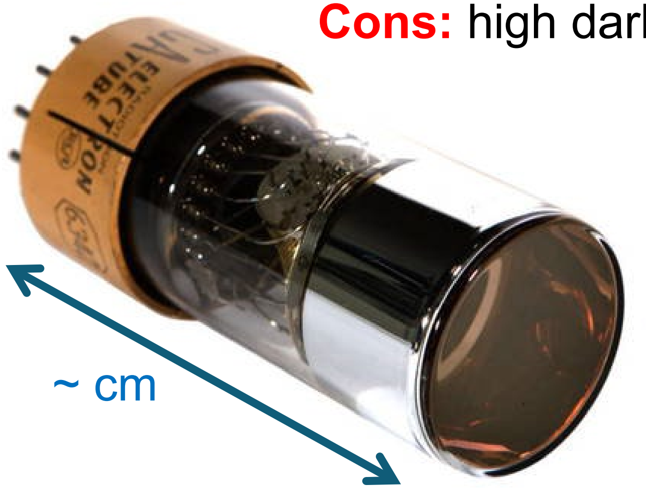


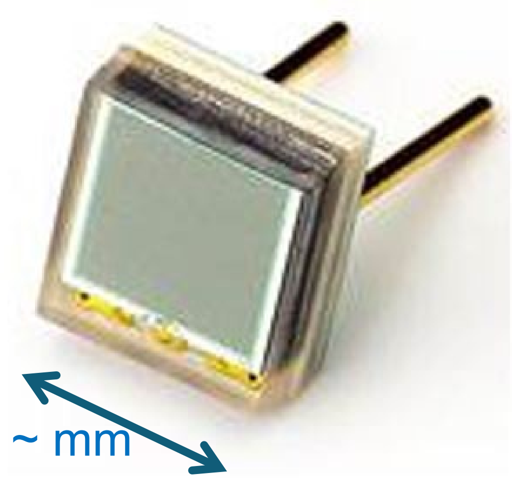


Alternative to vacuum photomultipliers tubes for the detection of single visible photons

Pros: smaller, insensitive to magnetic fields, low V, cheap

Cons: high dark count rate





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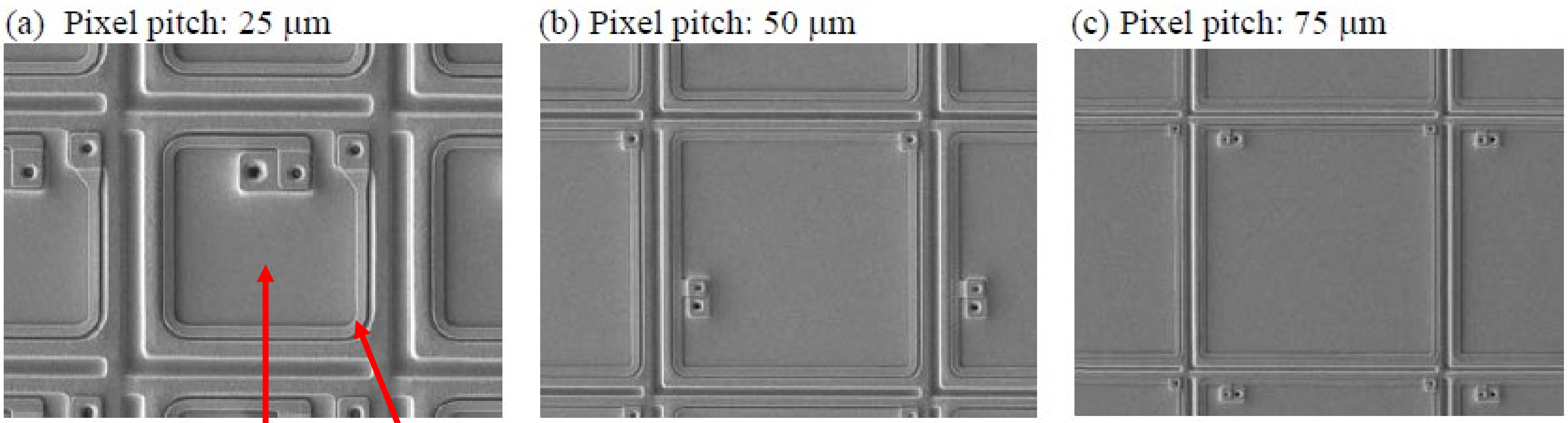
SiPM (or MPPC) structure

Large number of microcells in parallel, biased a few V over their breakdown voltage.
Quenching resistors between each cell and bias voltage prevent runaway current.



[Figure 1-17] Conceptual illustration of the MPPC as a matrix of GAPD pixels (microcells) connected in parallel

From: HPK, MPPC technical note

Entrance window for light

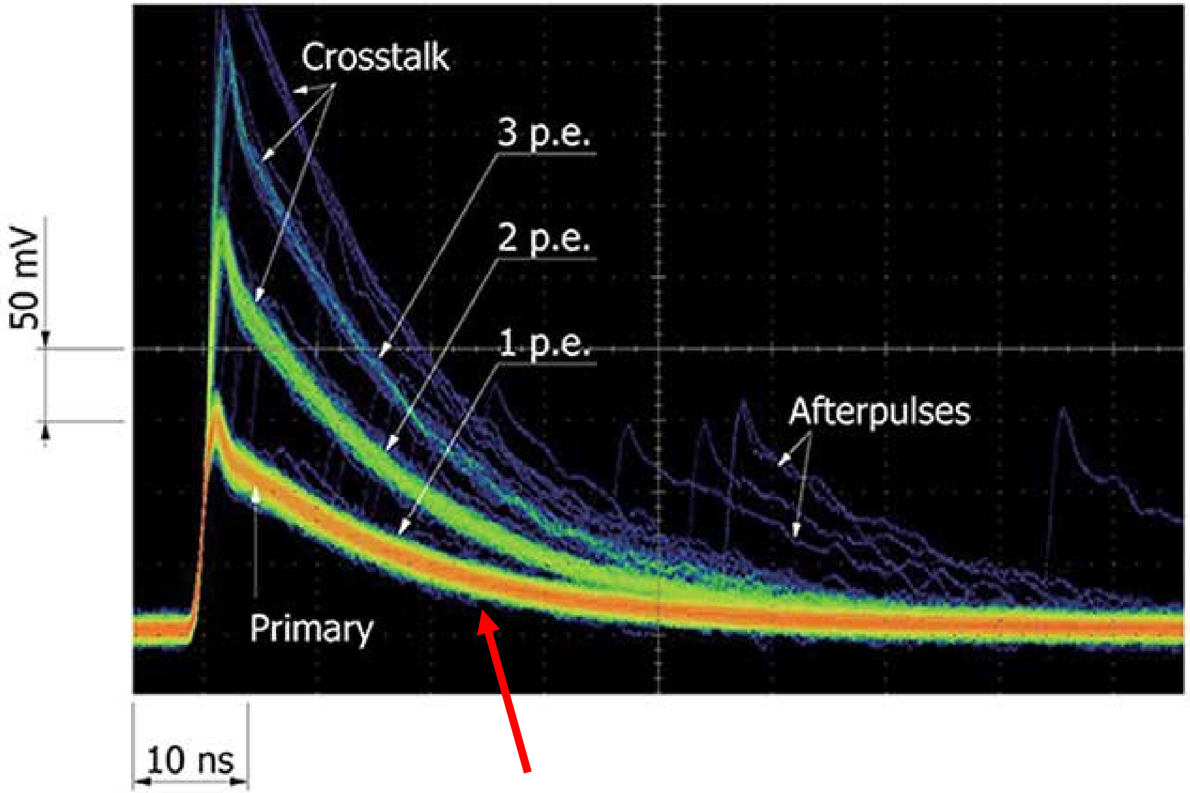
Quenching resistor

Brookhaven National Laboratory

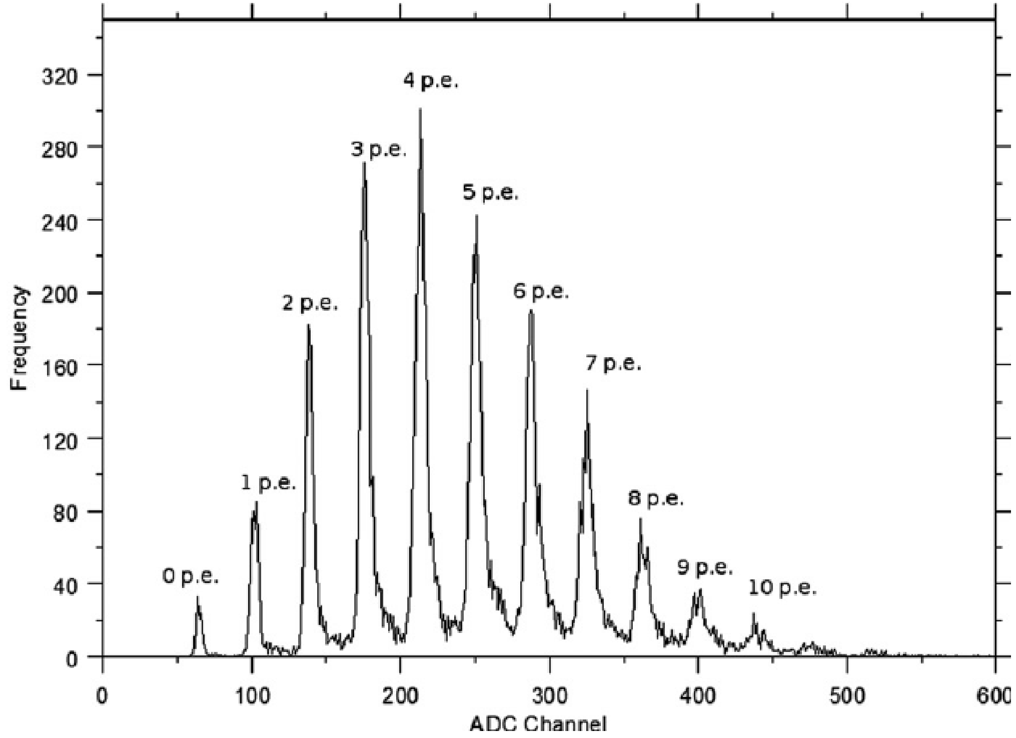
Single Photon Detection

A signal is induced by just one photon (that creates 1 electron/hole pair), but it is made by ~1M electrons (i.e. huge gain)

Signals as seen on the oscilloscope (no amplification stage needed)



We can count the # of photons hitting the SiPM!!!!

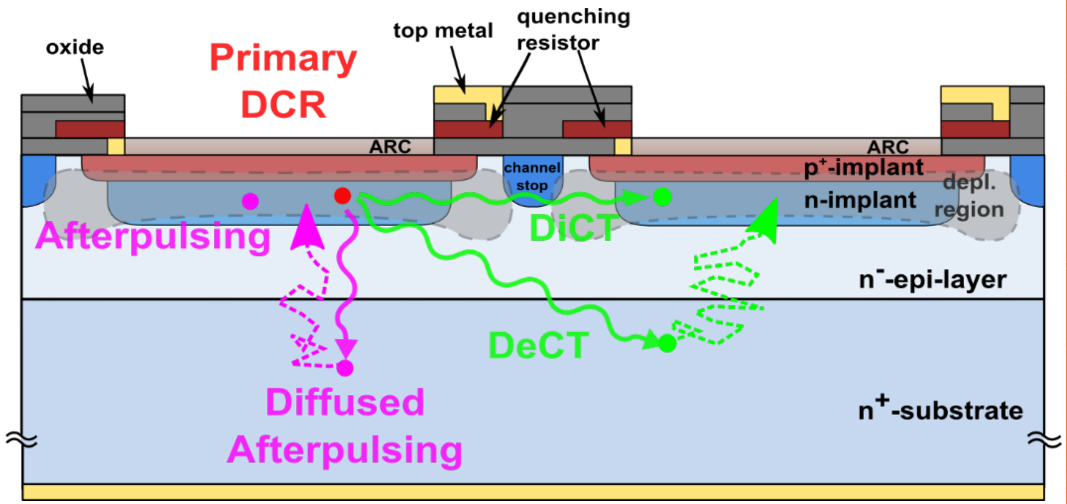


Decay time (~ μs) = quenching resistor * cell capacitance

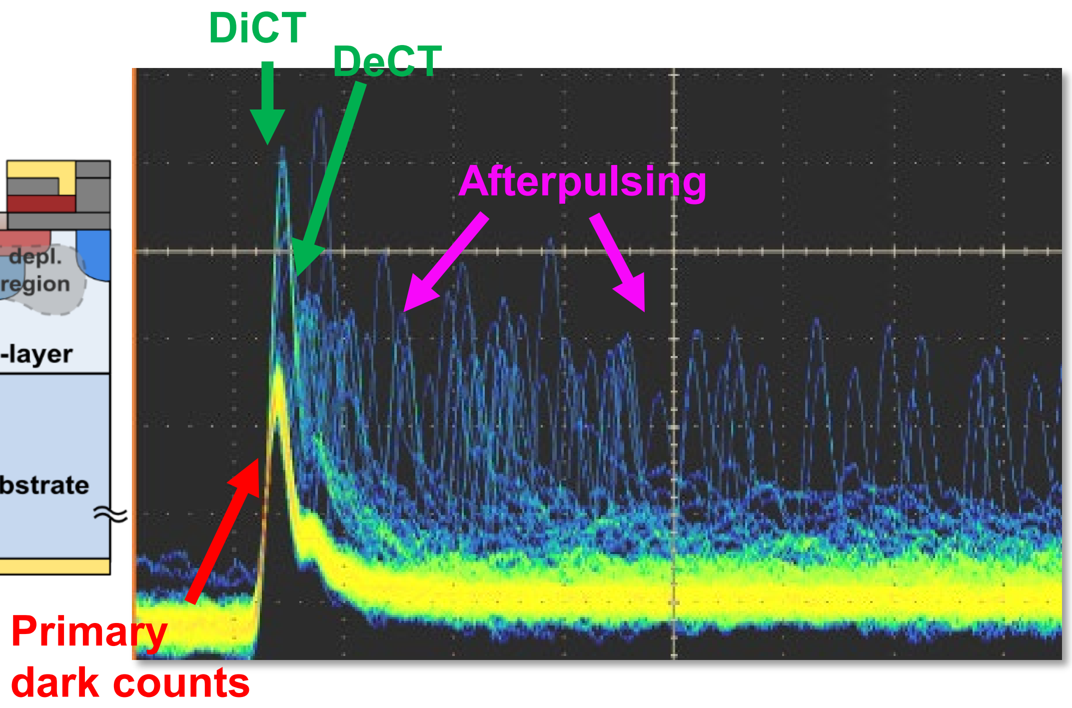
Noise in SiPMs

Different SiPM noise components are related to different physical phenomena.

- Every electrons of the leakage current crossing the high filed region generate a dark count
- Avalanche emits IR photons, which may be absorbed by nearby cells, create a e/h pair and trigger another avalanche (cross-talk)
- During the avalanche, electrons are trapped, and then released, creating an avalanche.



Cross-section of the SiPM microcells.



SiPM waveforms acquired with the oscilloscope, no external light

From A. Gola - FBK

Questions?