Silicon Detectors

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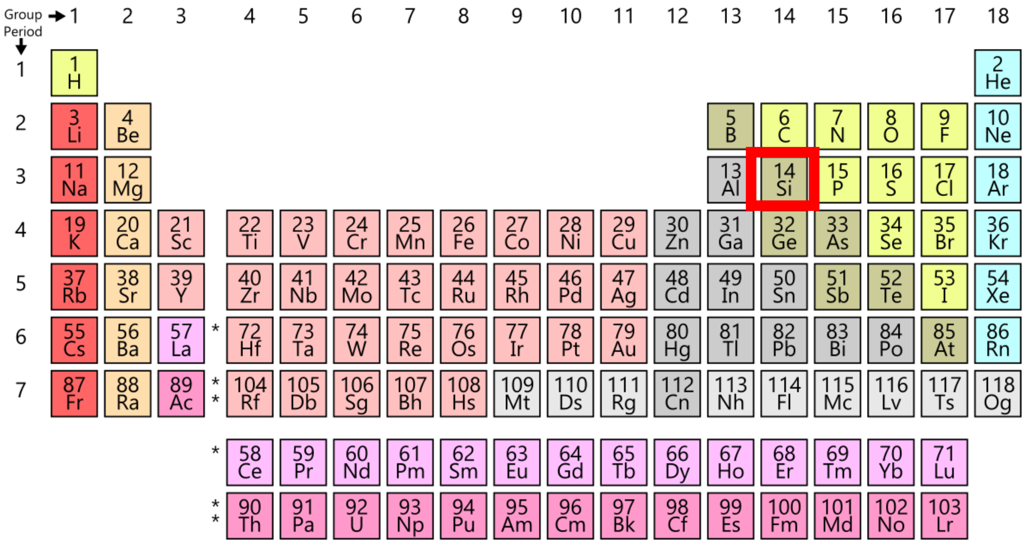
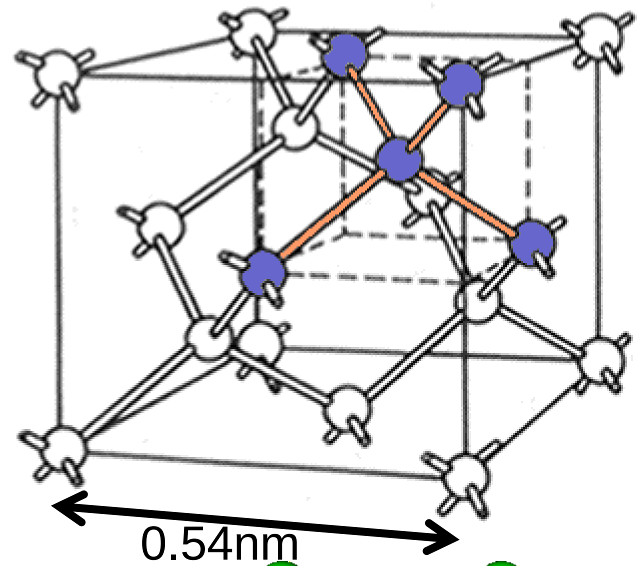
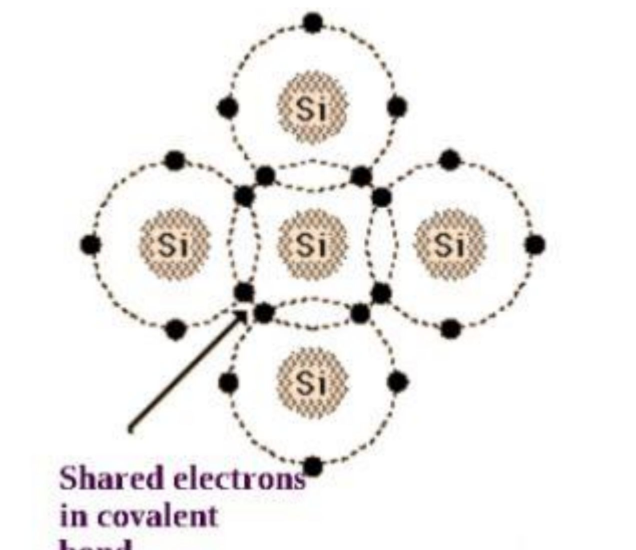
U.S. DEPARTMENT OF ENERGY

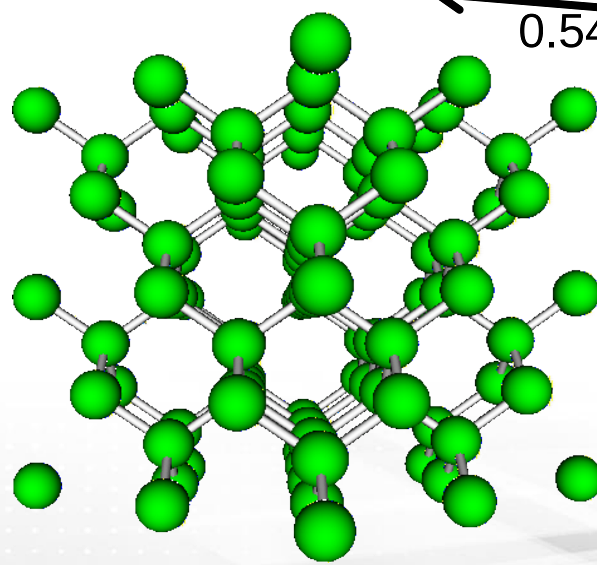
The silicon crystal

Diamond structure (tetrahedron)
Unit cell has 8 atoms









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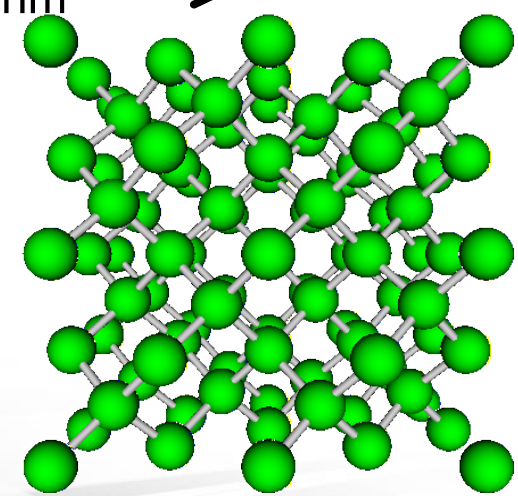

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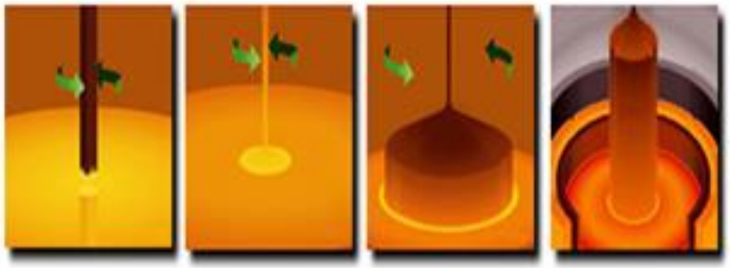
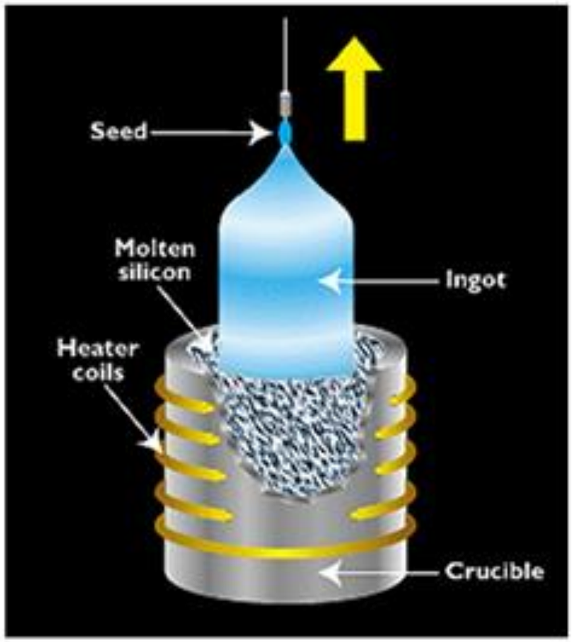
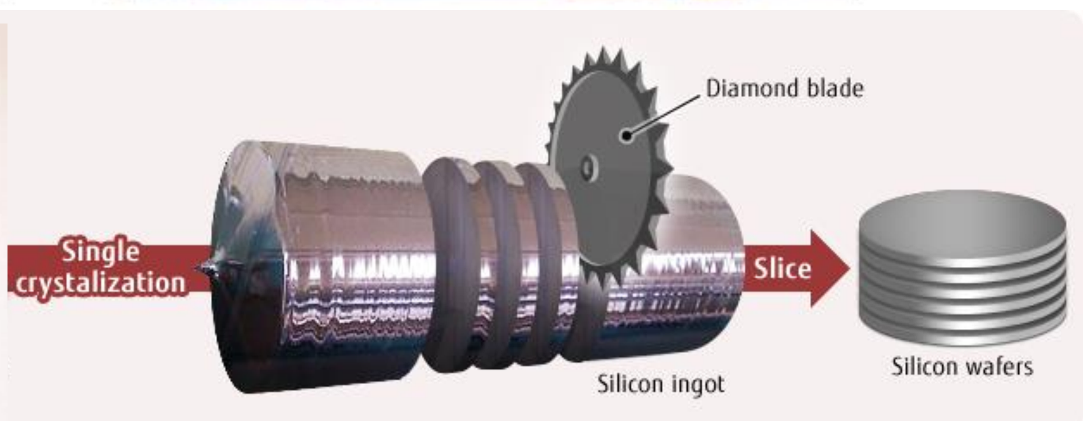
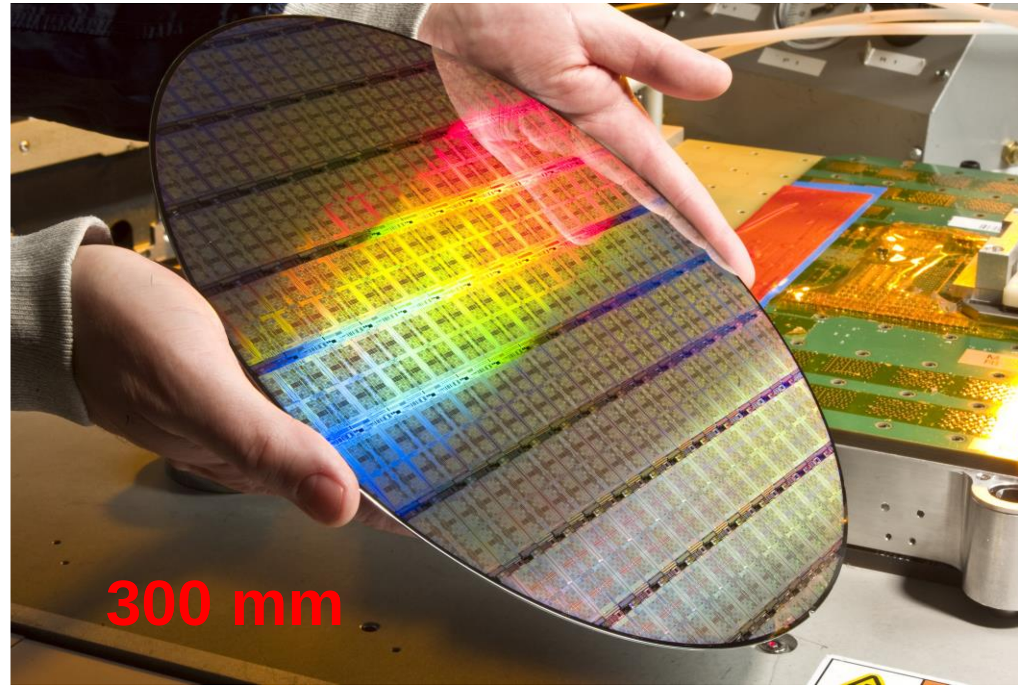



Seed
Molten silicon
Ingot
Heater coils
Crucible

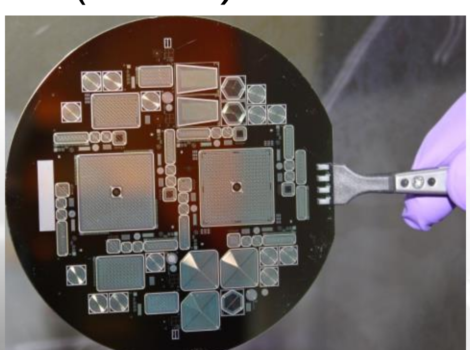

Diamond blade
Single crystalization
Slice
Silicon wafers
Silicon ingot

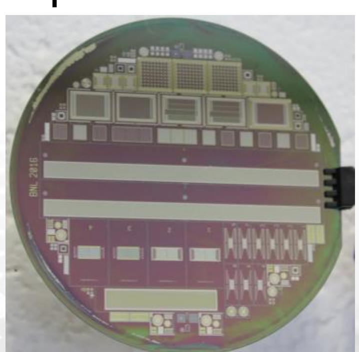
Silicon wafers as you can buy

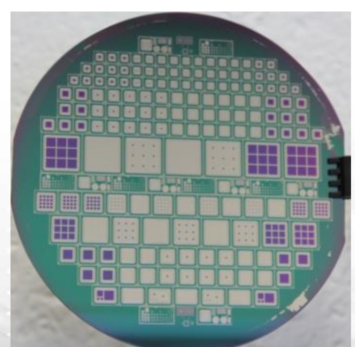
Integrated Circuits (IC) on a Silicon wafer

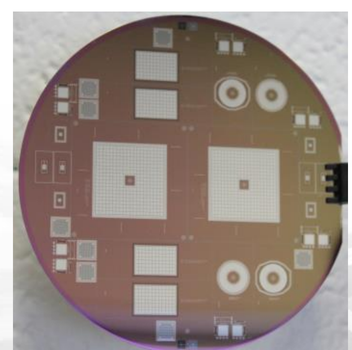


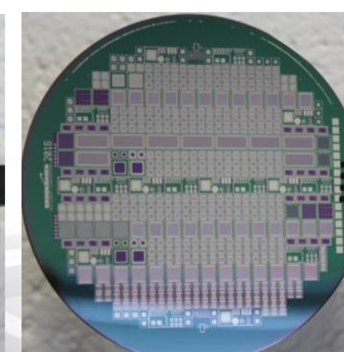
4” (10-cm) silicon wafer processed at BNL



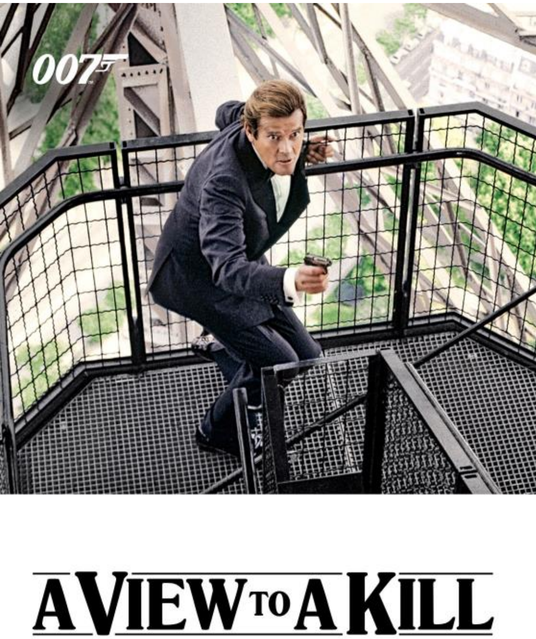




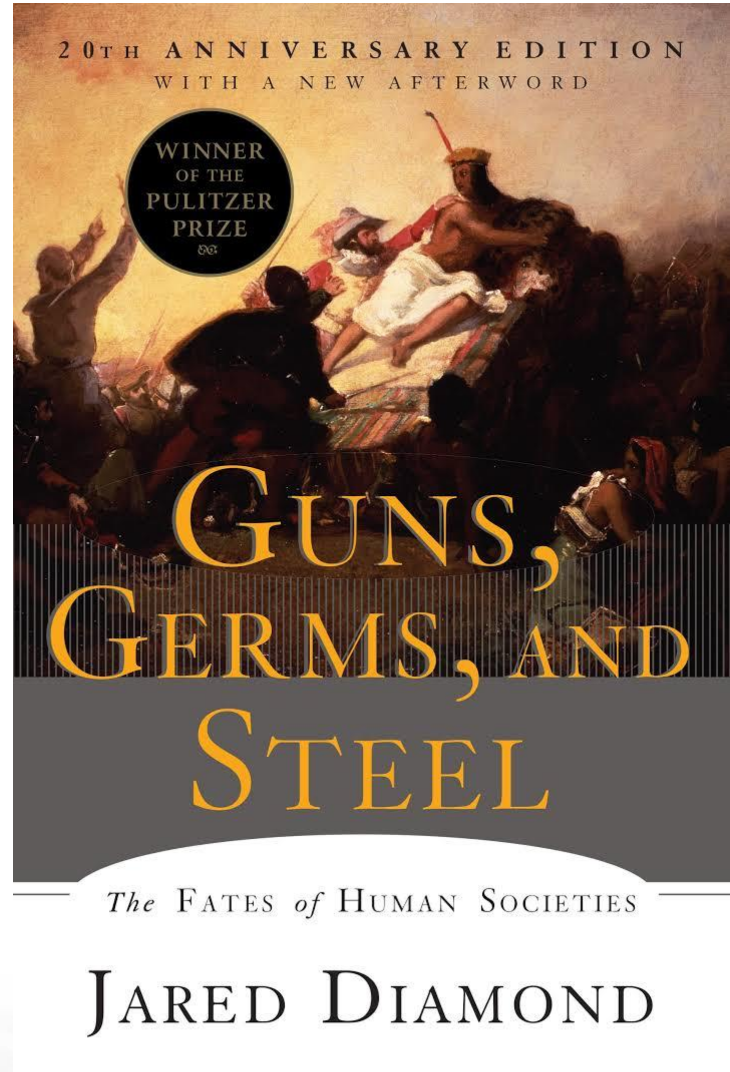




Two great materials: Silicon vs Steel



Max Zorin: "For centuries alchemists tried to make gold from base metals. Today, we make microchips from silicon, which is common sand, but far better than gold"



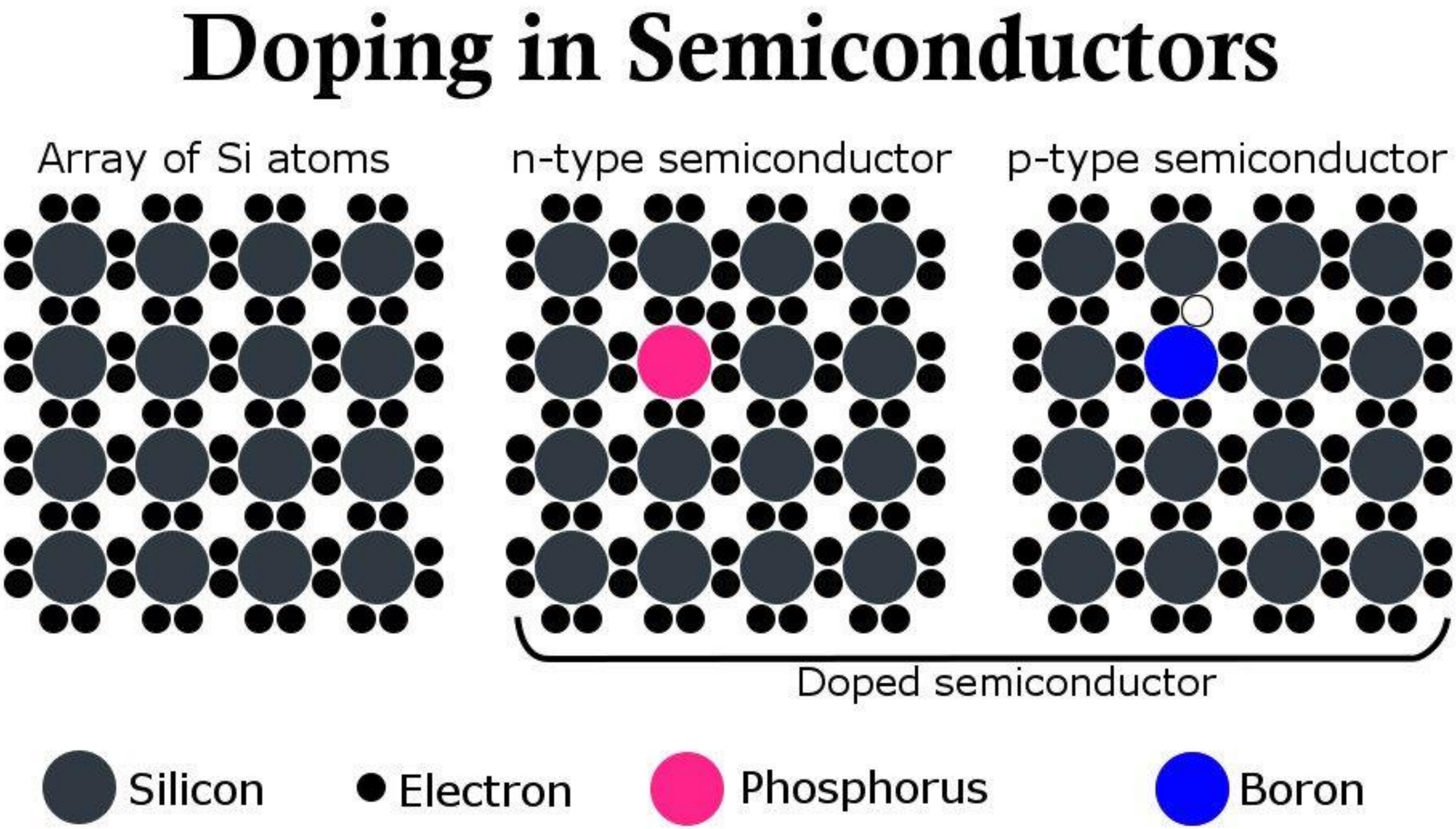
Two great materials: Silicon vs Steel

Shockley, Bardeen, Brattain 1950

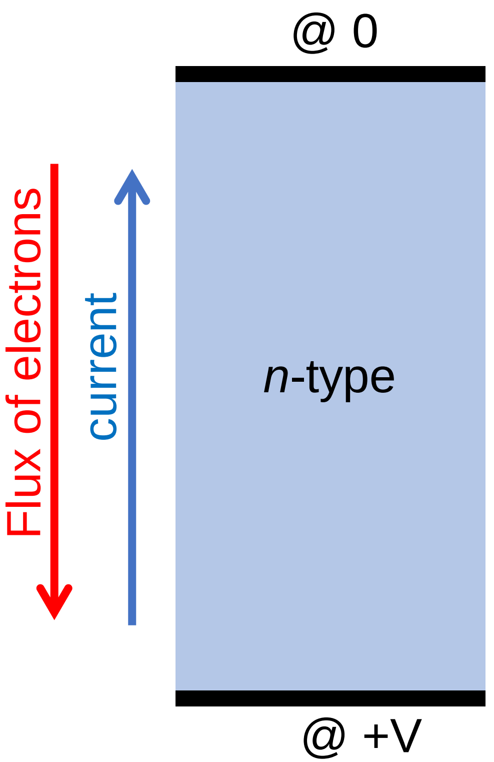
Moore, Noyce , Grove at Intel 1978

Falcata (4th century BC)

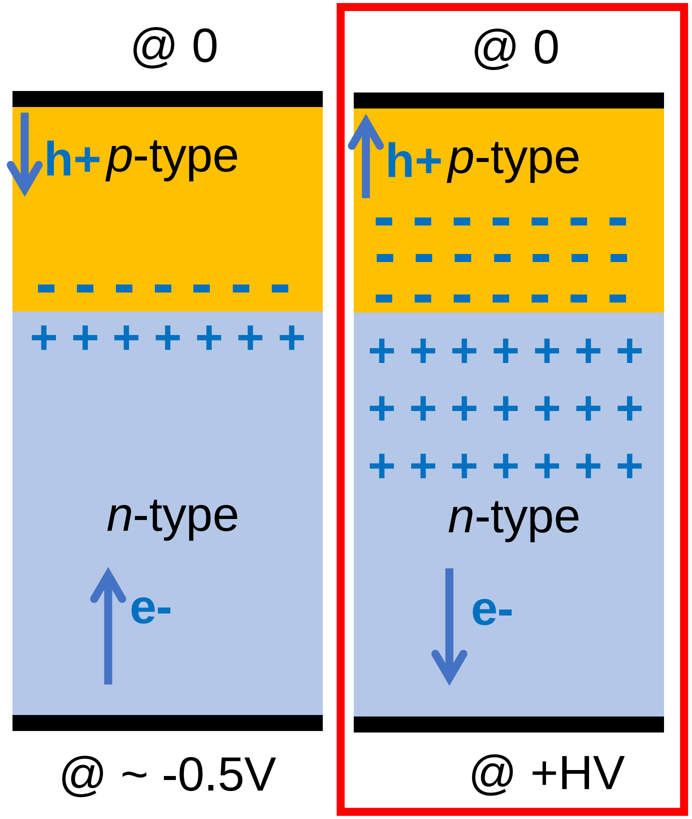
Electrons and holes

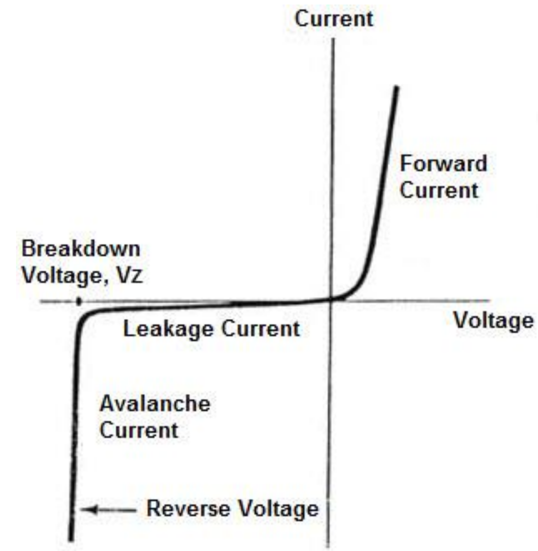


n-type silicon slab:
essentially a resistor



n-type slab + *p*-type slab = Rectifying junction (diode)



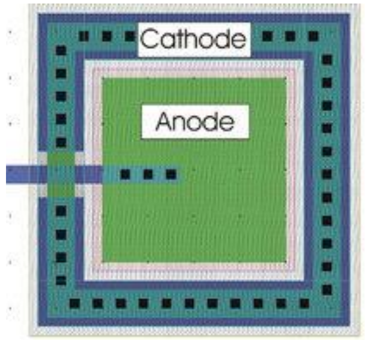


d**E**/dx = - ρ/ε
Since charge neutrality holds ($\rho=0$),
E = constant= V/thickness

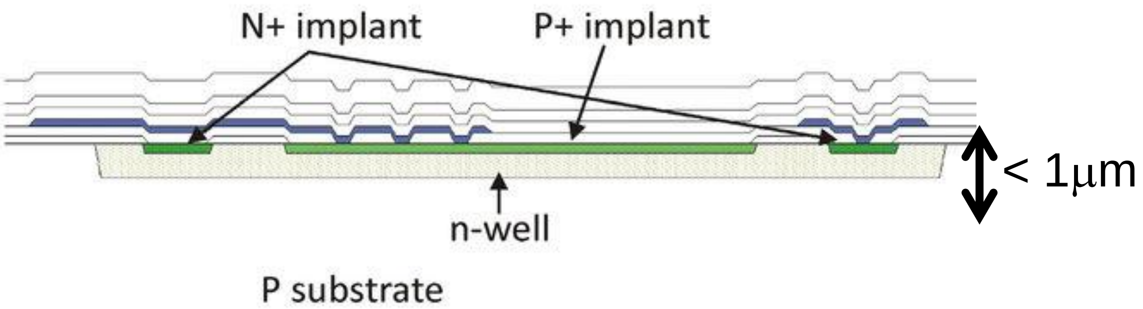
In forward bias, hgh currents flow.
In reverse bias, the current is blocked, so the Voltage must fall in a region with $\rho \neq 0$:
Electrons (holes) are swept away from n- (p-) type silicon leaving a net positive (negative) charge,

Diode in integrated circuits

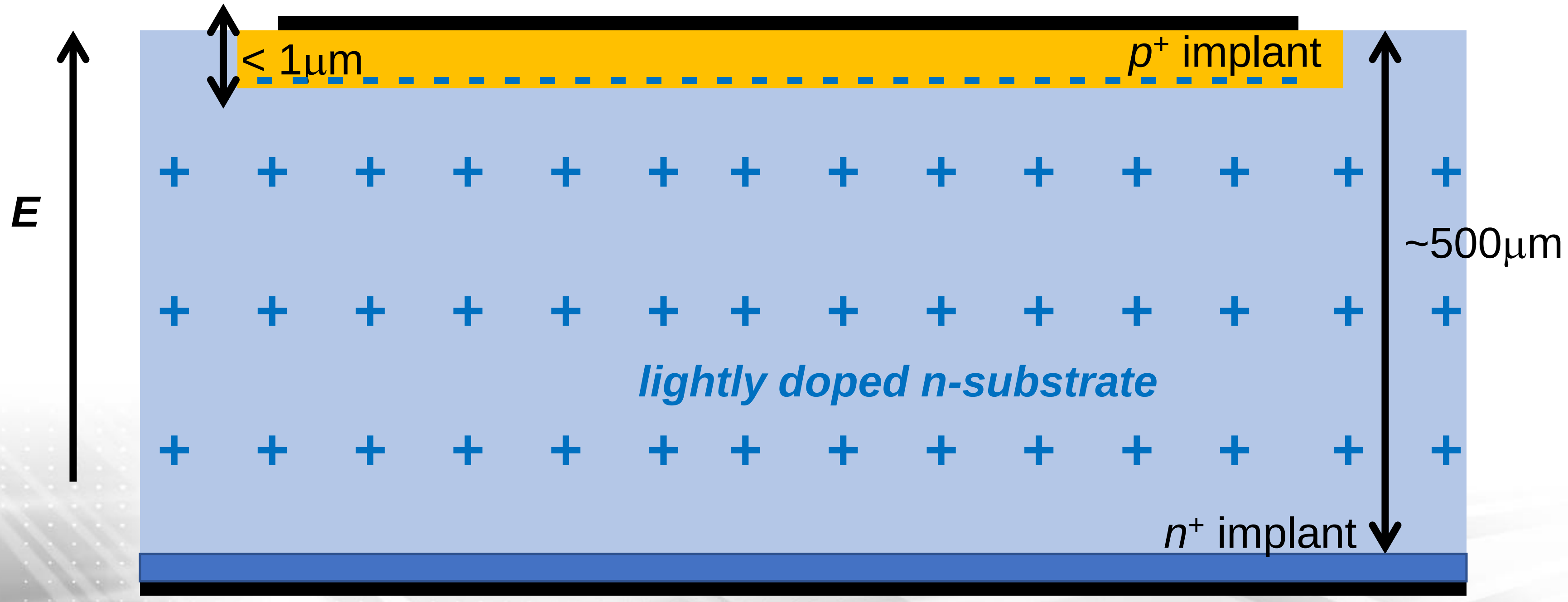
From the top



Section

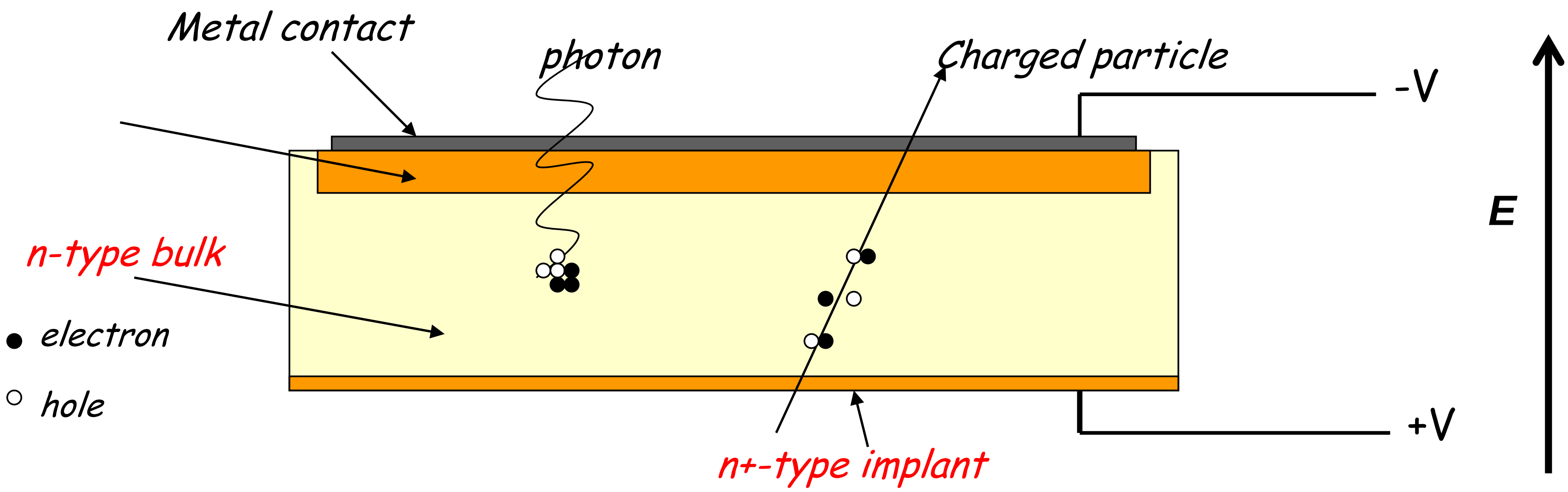


Diode as a sensor unit



Mechanism of radiation detection

Ionizing radiation (photons or charged particles) creates free charges in the bulk. Electrons and holes drift in opposite directions, following the electric field lines, creating current pulses at the electrodes

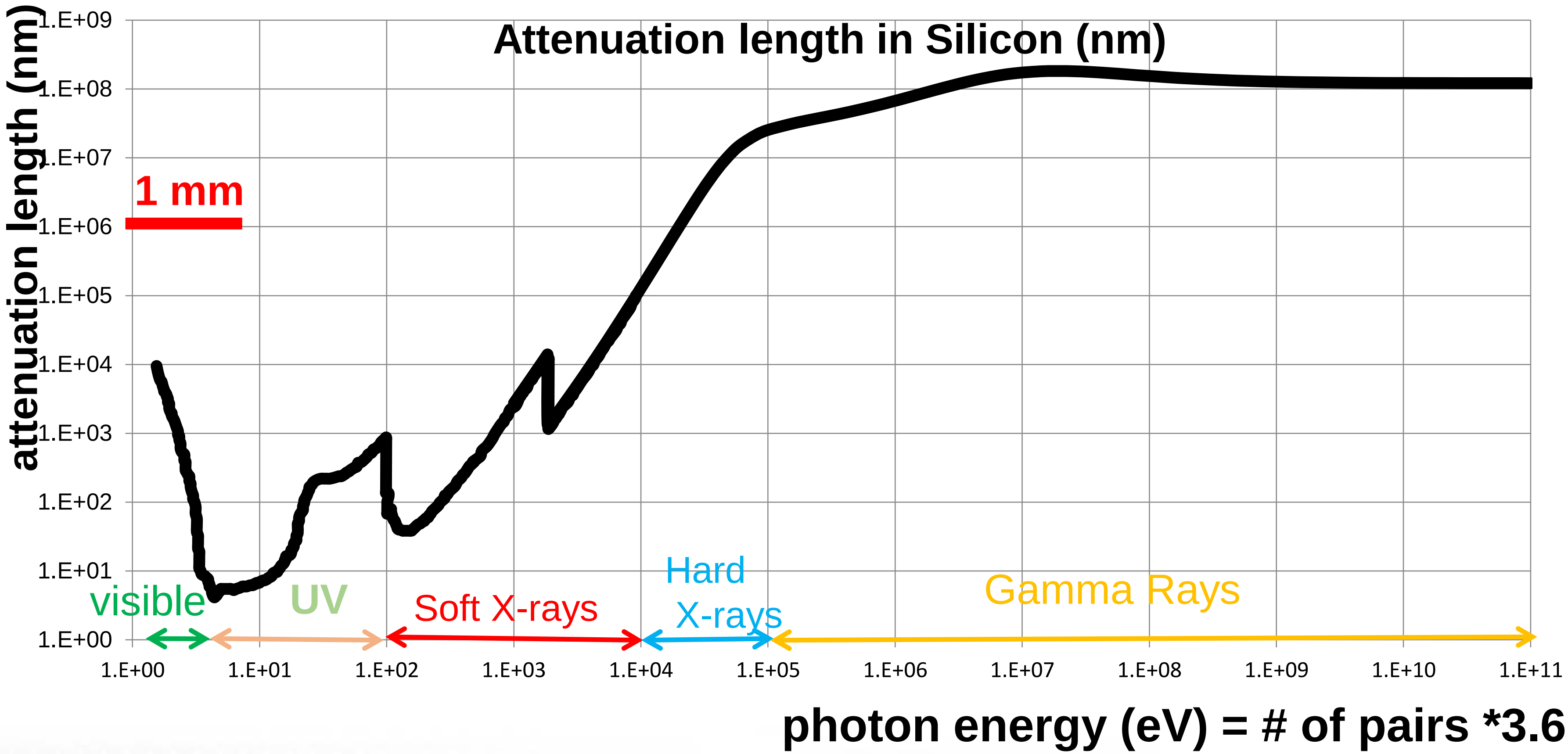


Why sensors made of silicon?

- Very well developed technology (simplified version of IC's)
- Fair signals created, "easily" detected (3.6 eV for the creation of an electron/hole pair)
- Operation close to Room Temperature (RT)
- Possibility to finely segment the electrodes down to few tens of μm

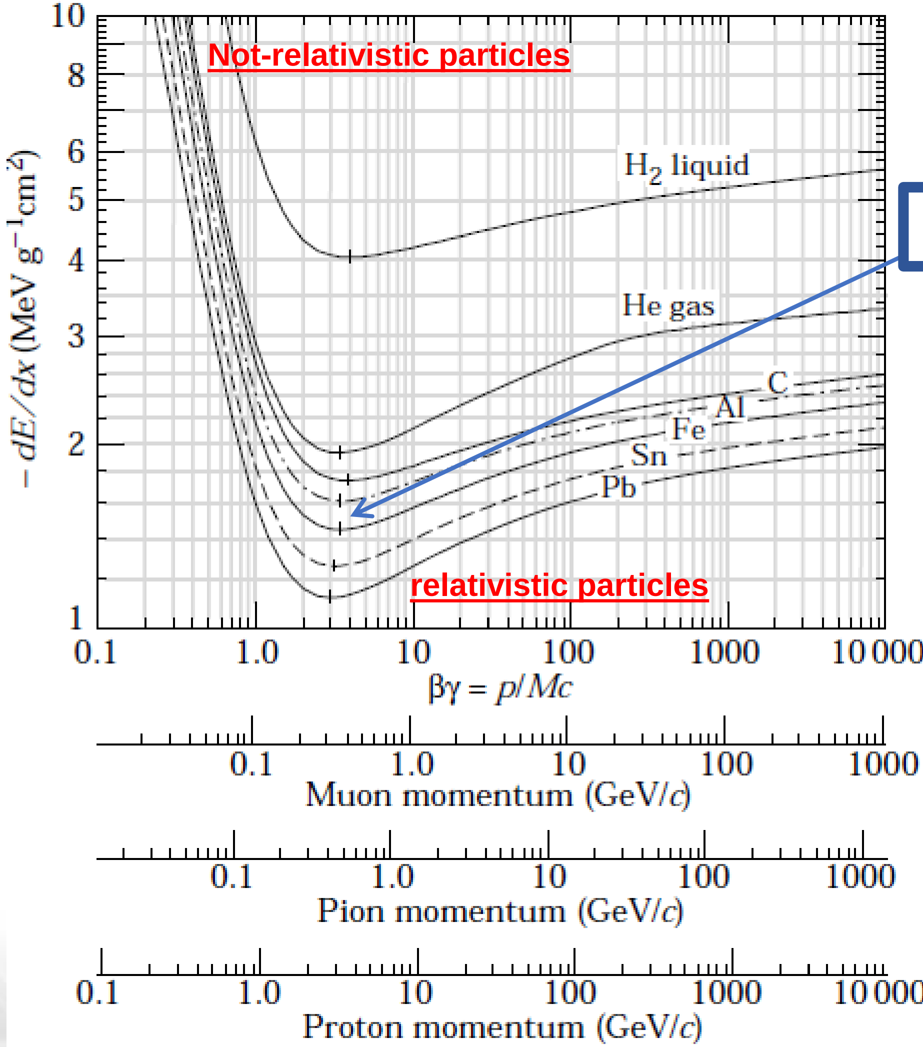
Absorption of photons in Silicon

If N_0 photons enter the silicon, after a distance L, the number of photons which have not been absorbed by silicon is: $N = N_0 \exp(-L/l)$, where l is the attenuation length



- Silicon detects with good efficiency above 20 eV and below 20 keV
- Visible photons create just one couple e^-/h^+

Interaction of charged particles with silicon: the Bethe Block formula



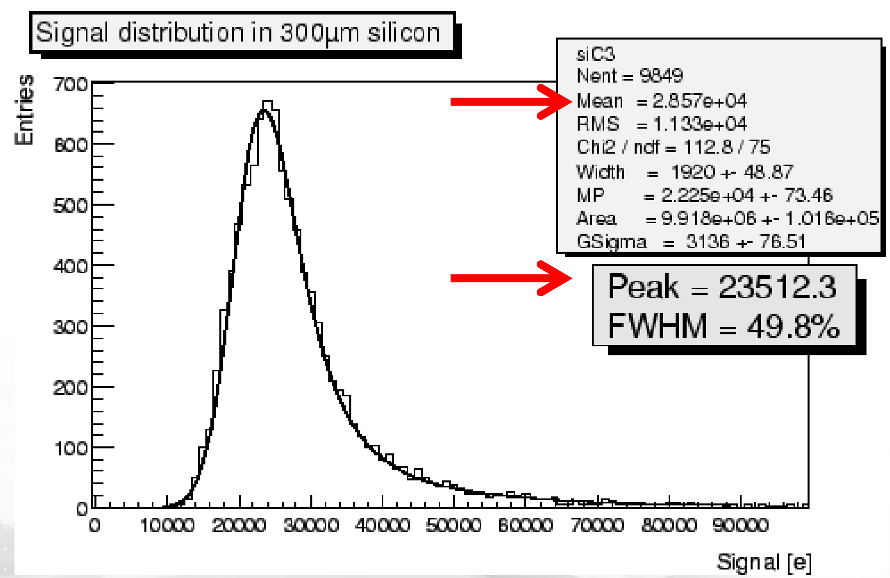
In most practical cases,

we are here

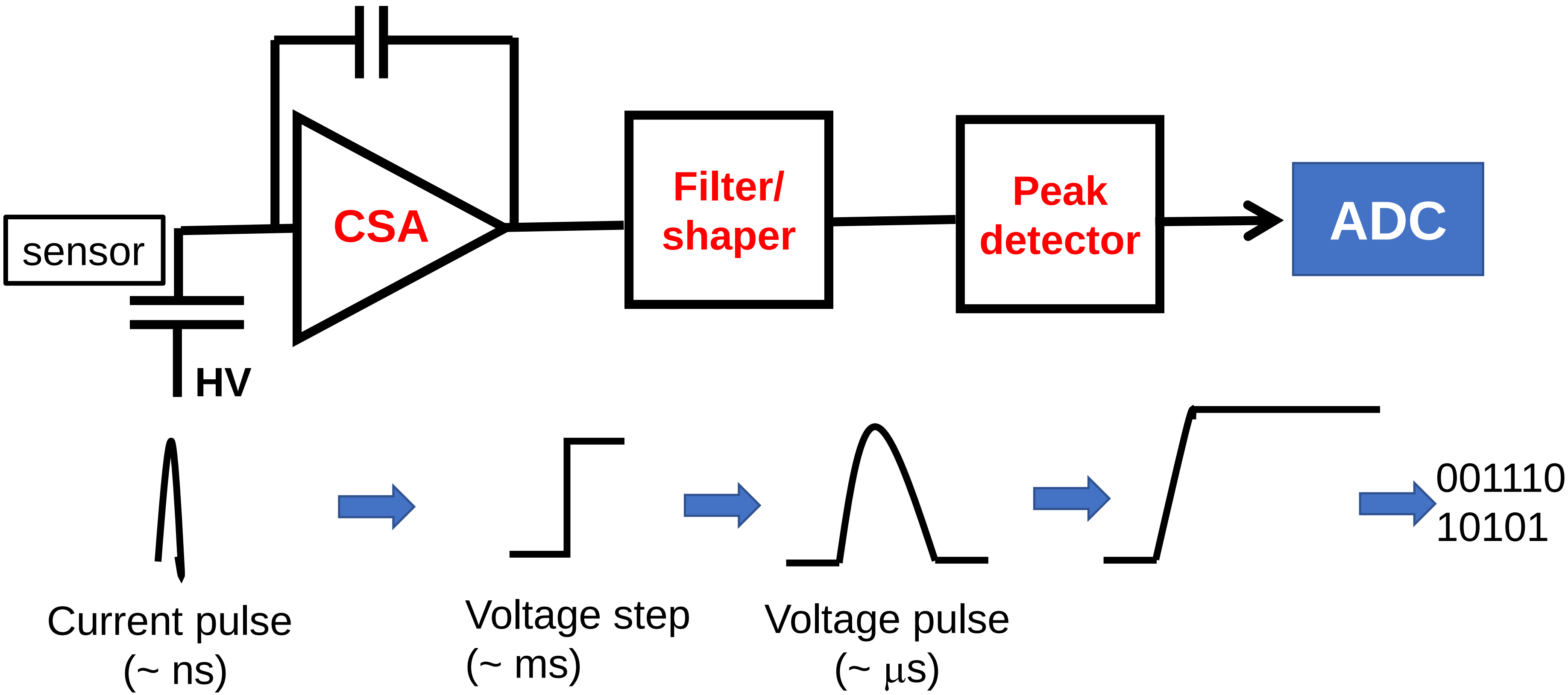
i.e. at the minimum of energy loss.

Still, a m.i.p. (minimum ionizing particle) produces 80 pairs/μm in Silicon (for 300 μm → 24k electrons)

Landau distribution

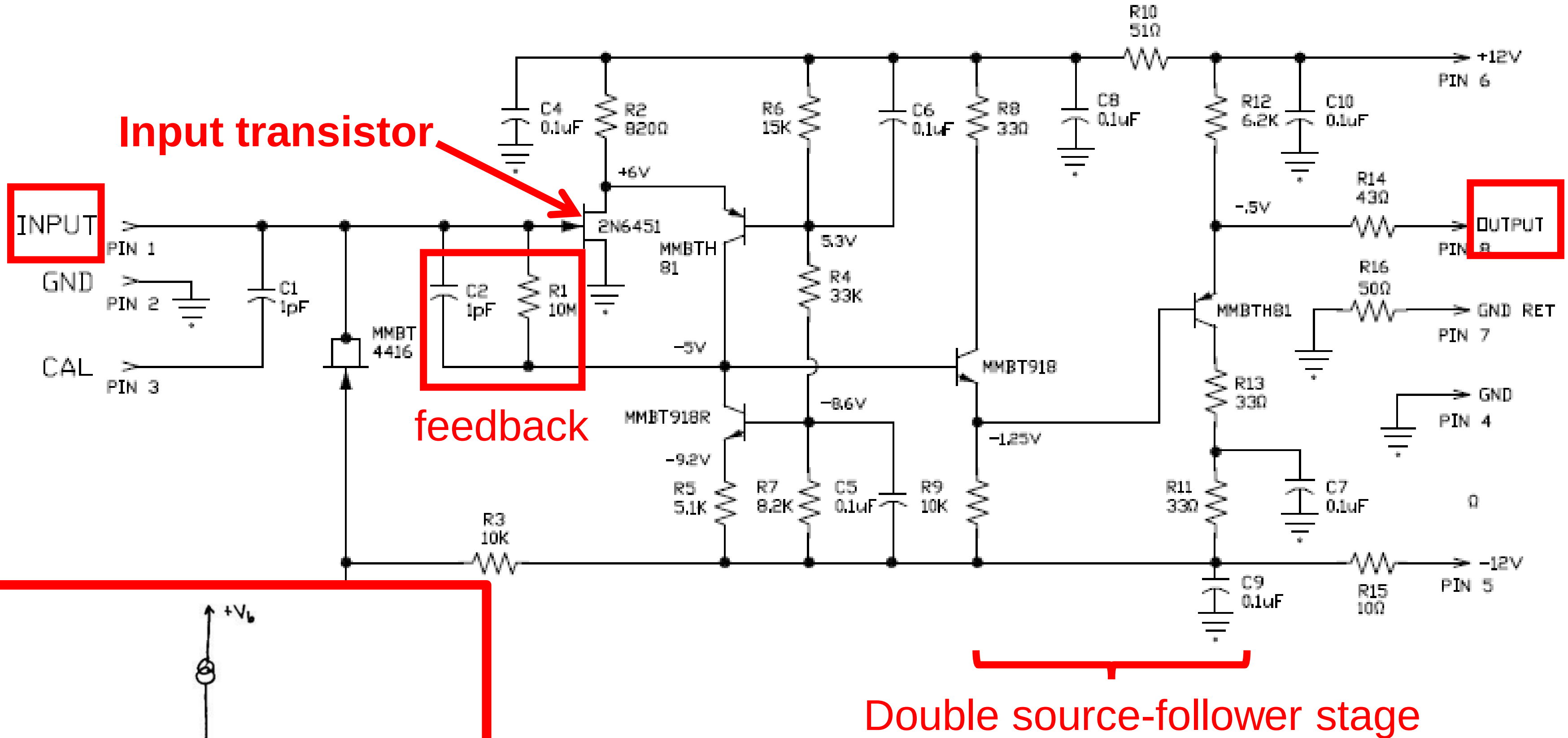


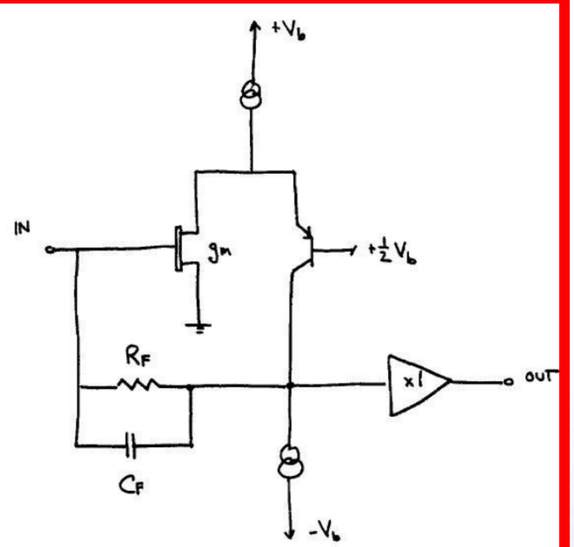
Read-out chain



- Can be made by separate blocks
- Modern trend: integrate everything in a IC
  ASIC: Application Specific Integrated Circuit, designed in house but fabricated in TSMC, IBM, AMS, ST, …

Charge Sensitive Pre-Amplifier

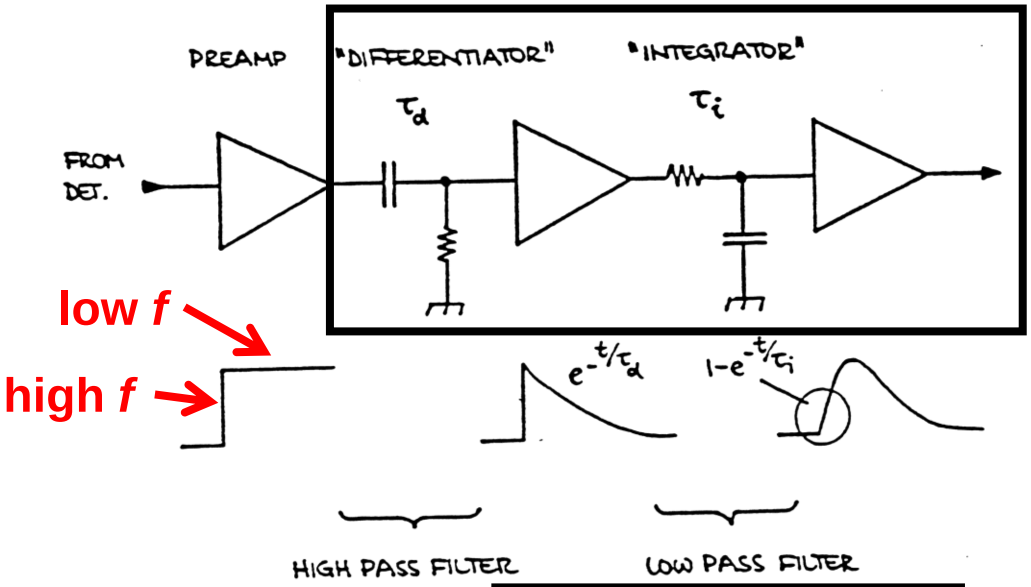


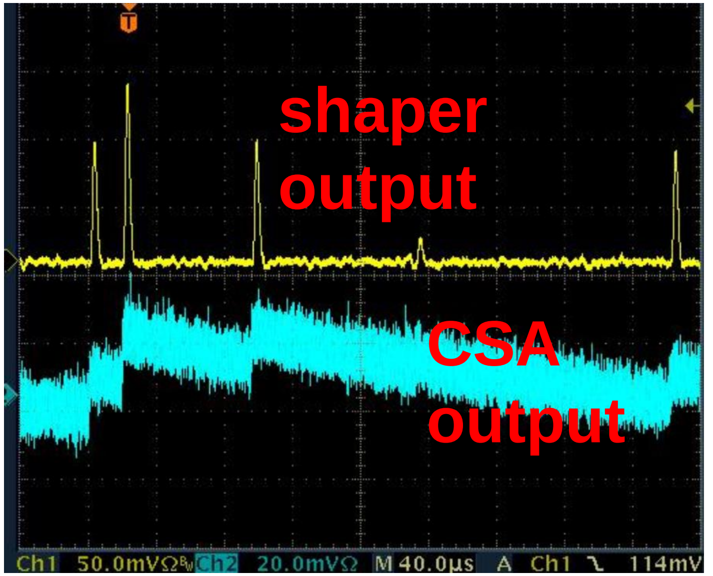


Charge preamp ©Radeka 68

The common trend is to fabricate the CSA in CMOS technology: smaller, good electrical properties, cheap. For example, state-of-the-art is CUBE ~1x1x1 mm^3

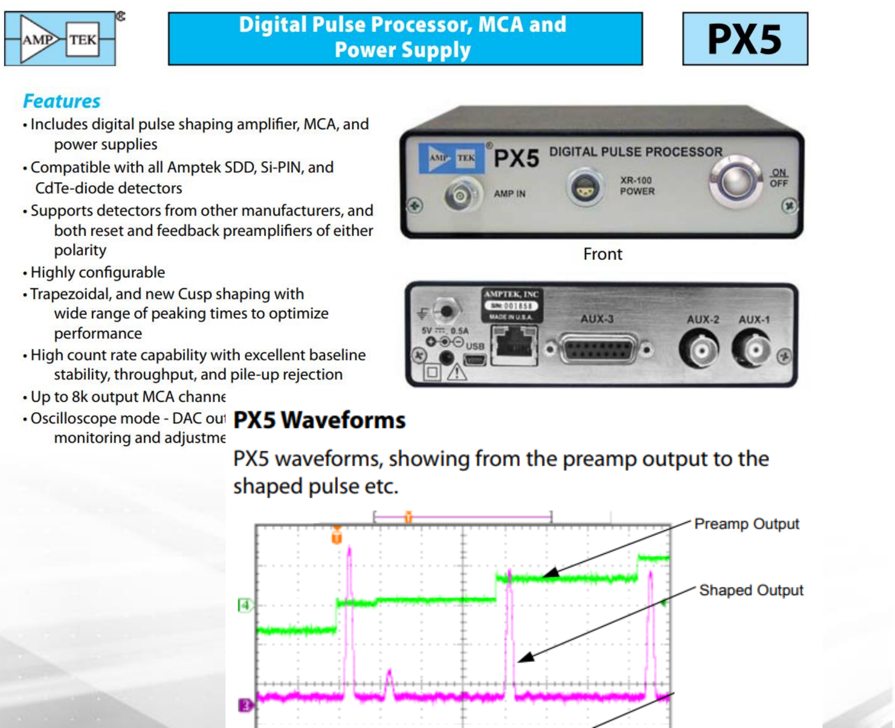
Filter/shaper





- Filtering in the frequency domain = Shaping in the time domain
- Limit the bandwidth to limit the noise
- Noise depends on shaping time
- Modern trend: to go from analog to digital shaping

NIM analog shaper


AMPTEK

Digital Pulse Processor, MCA and Power Supply

PX5

Features

- Includes digital pulse shaping amplifier, MCA, and power supplies
- Compatible with all Amptek SDD, Si-PIN, and CdTe-diode detectors
- Supports detectors from other manufacturers, and both reset and feedback preamplifiers of either polarity
- Highly configurable
- Trapezoidal, and new Cusp shaping with wide range of peaking times to optimize performance
- High count rate capability with excellent baseline stability, throughput, and pile-up rejection
- Up to 8k output MCA channe
- Oscilloscope mode - DAC ou monitoring and adjustme

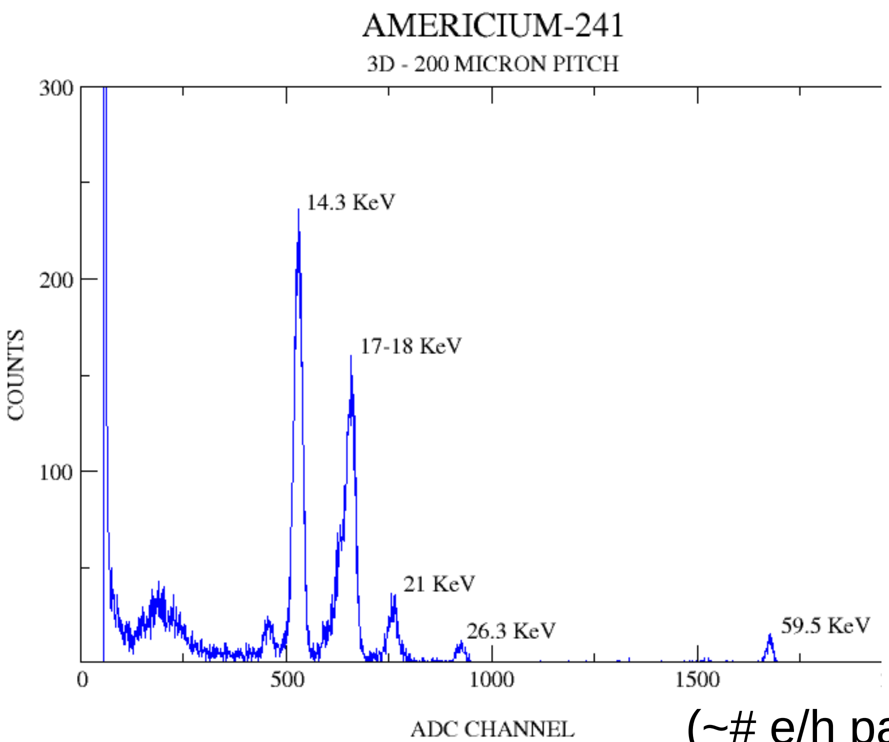
PX5 Waveforms

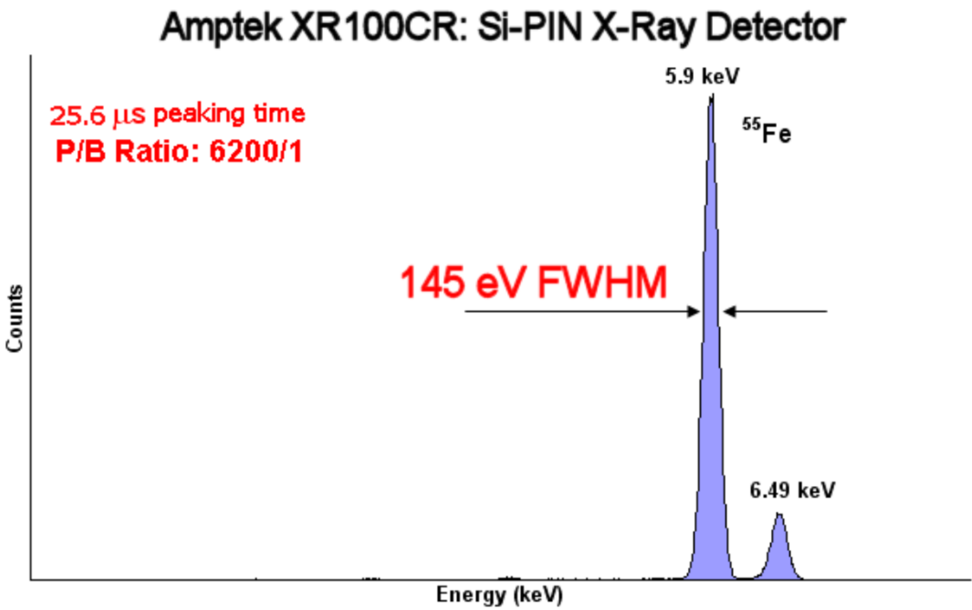
PX5 waveforms, showing from the preamp output to the shaped pulse etc.

Peak detection

electron/hole pairs ~ amplitude of CSA output ~ amplitude of shaper output.

Stored for a short period of time, then fed to Analog-to-Digital Converter.
Then sent out for processing

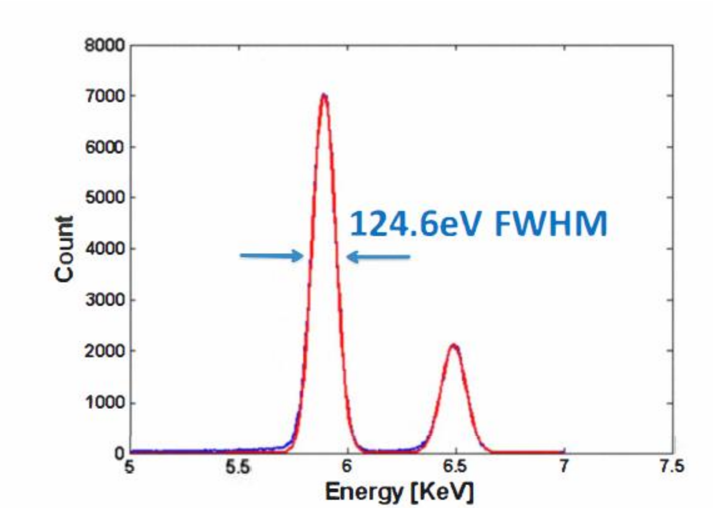


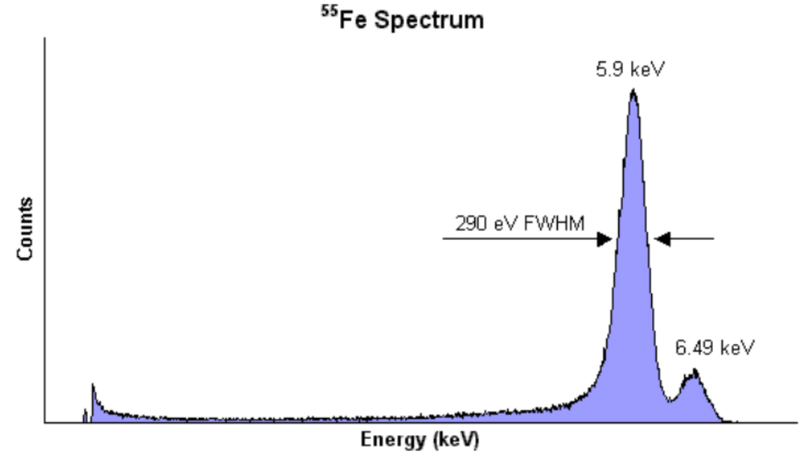


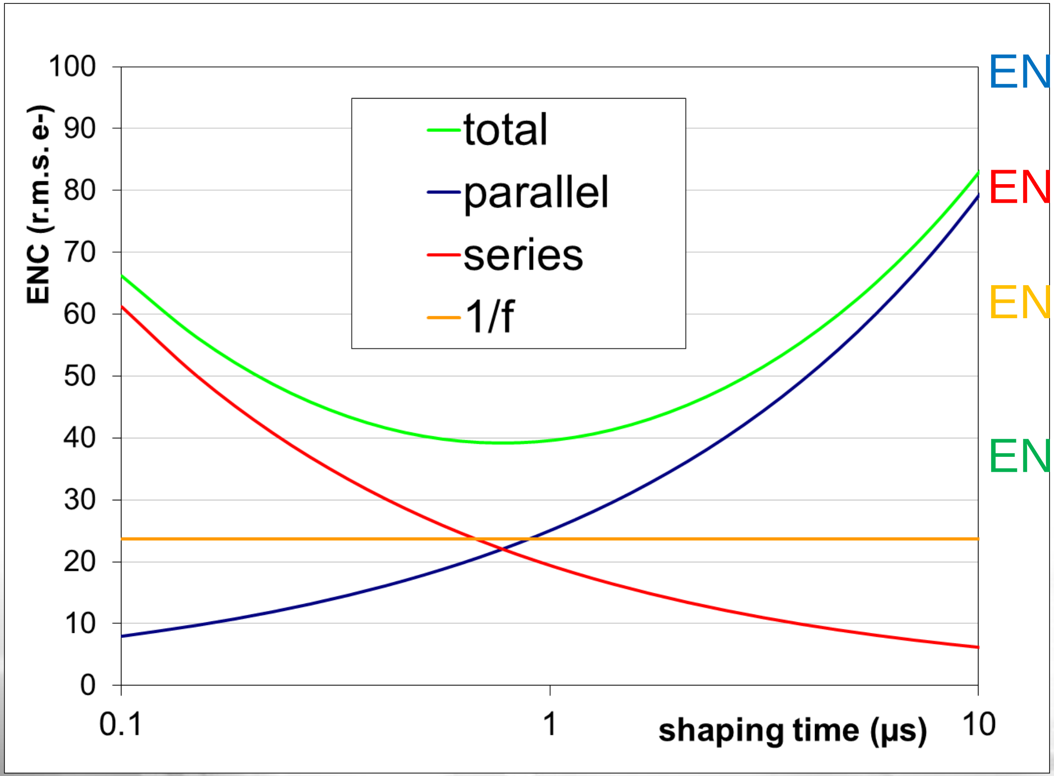
(~# e/h pairs, ~ energy)

Low-activity X-ray-emitting radioactive materials are used as calibration sources

Noise in a detection system







$ENC^2_{parallel} \sim I_{leakage}\,\tau$

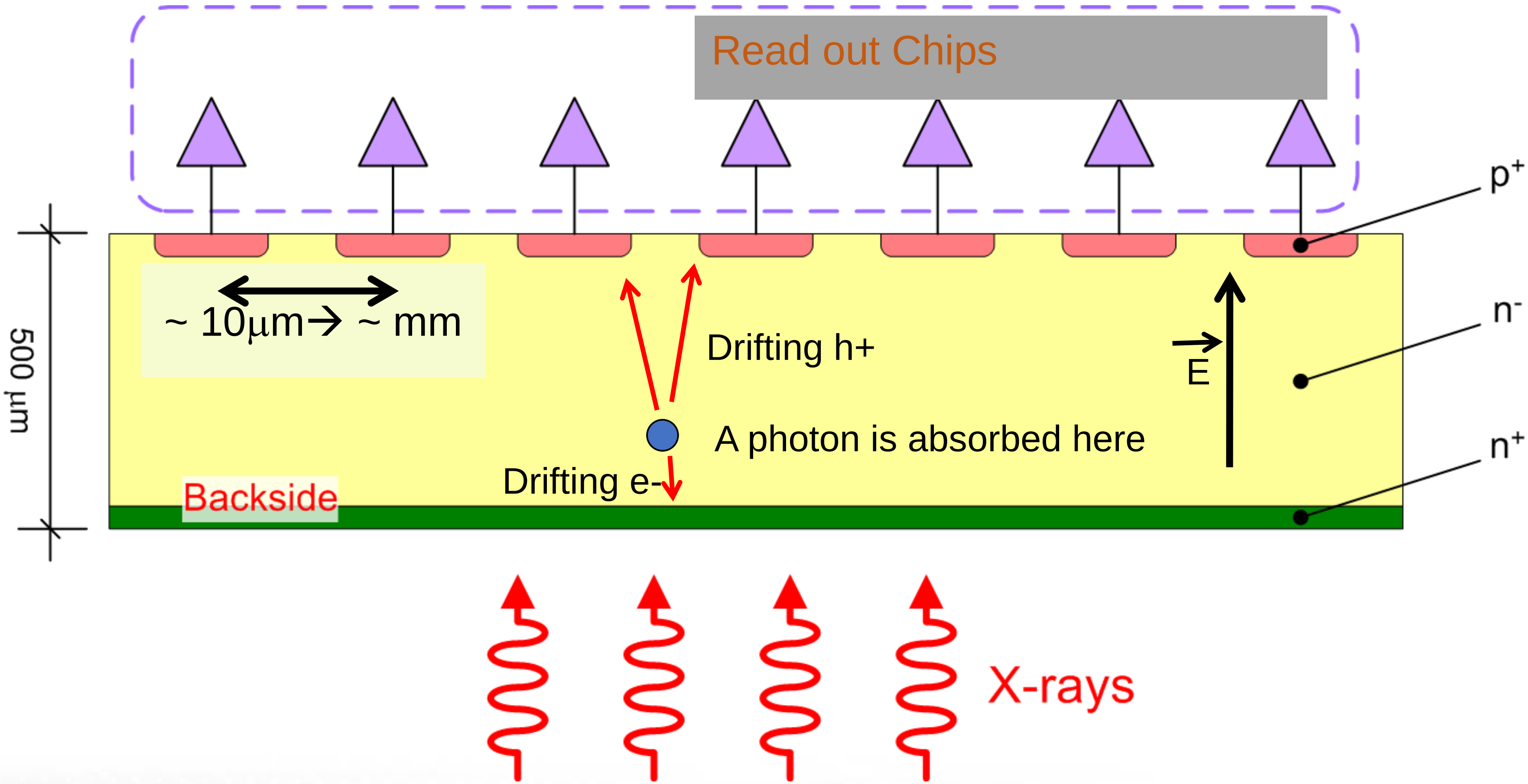
$ENC^2_{series} \sim C^2/\tau$

$ENC_{flicker} \sim$ constant

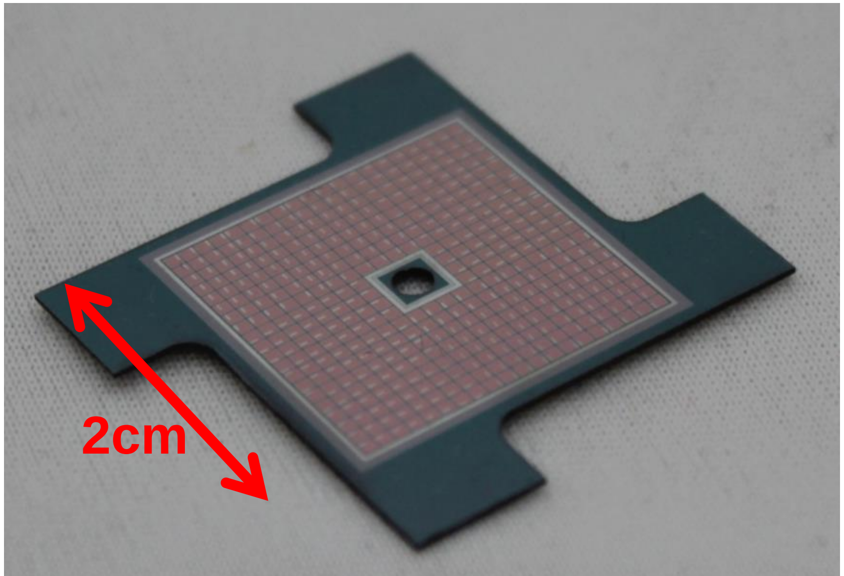
$ENC^2_{total} = ENC^2_{parallel} + ENC^2_{series} + ENC^2_{flicker}$

Patterning the electrodes

It gives information about the position of the incident radiation



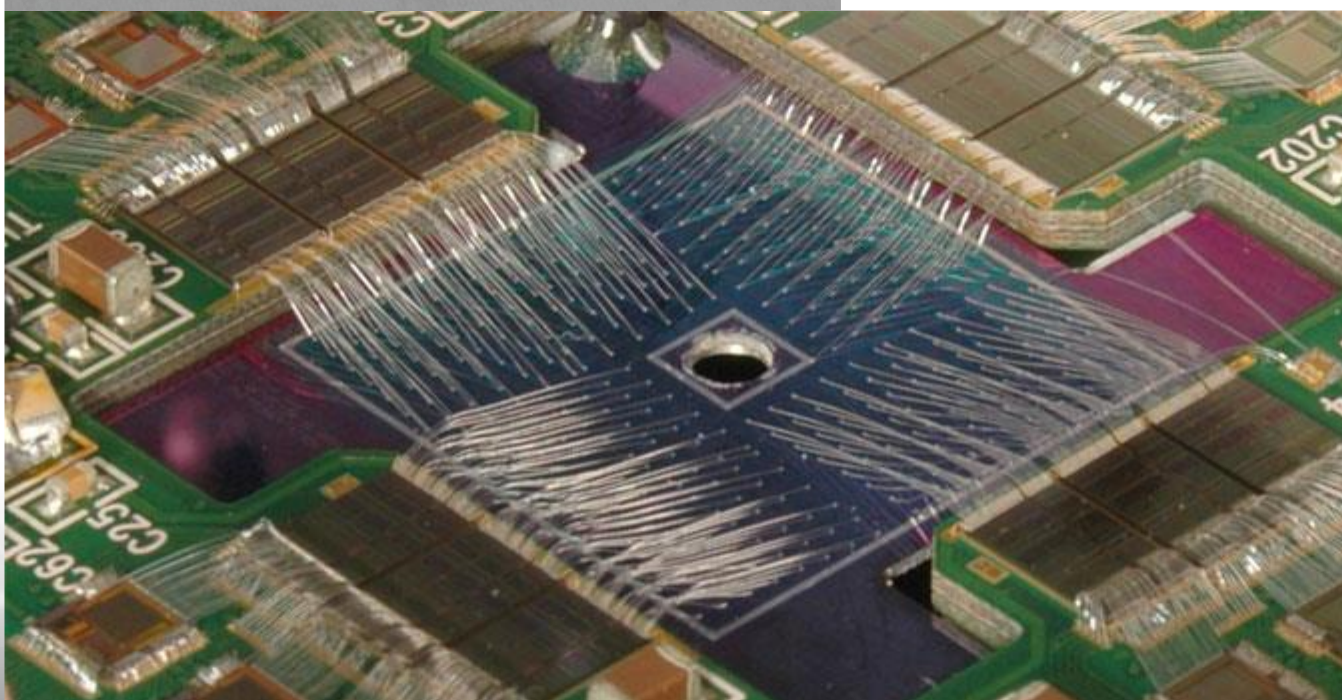
Pixels, pads, strip are possible, in a large variety of dimensions, ranging from few µm to mm, depending on the application

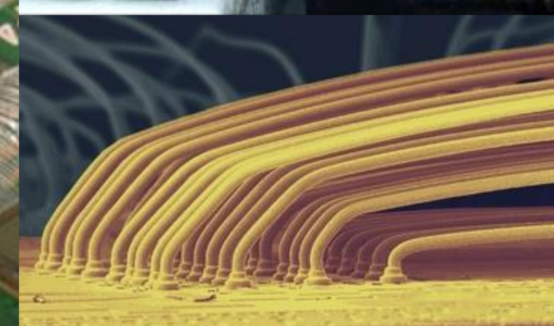


Pad sensor

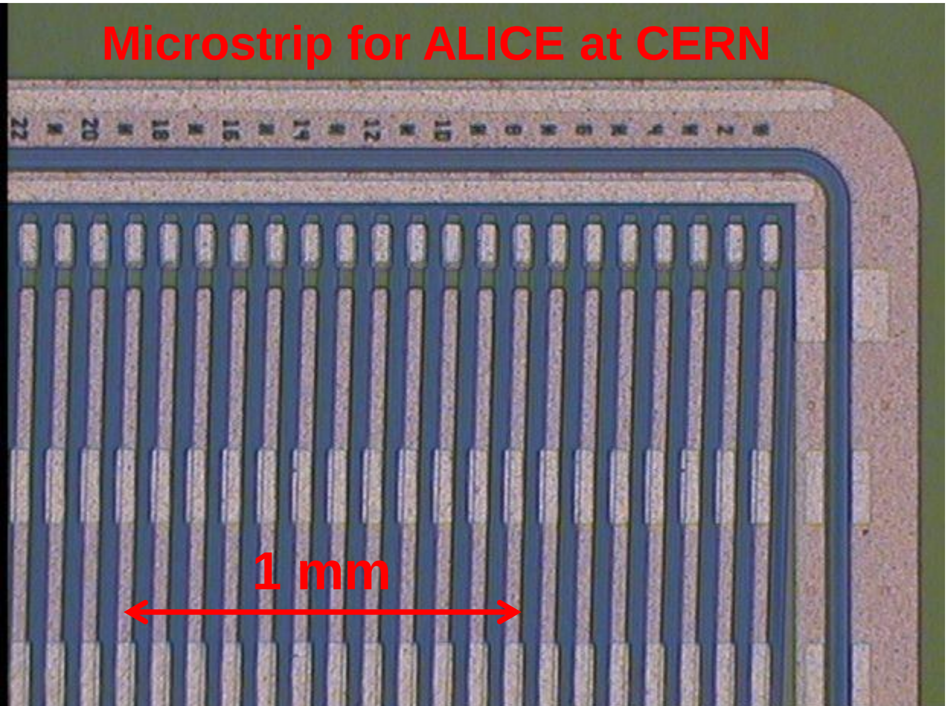
Array of ~ 400 square pads at a pitch of 1 mm

MAIA microprobe detector for elemental analysis in synchrotrons



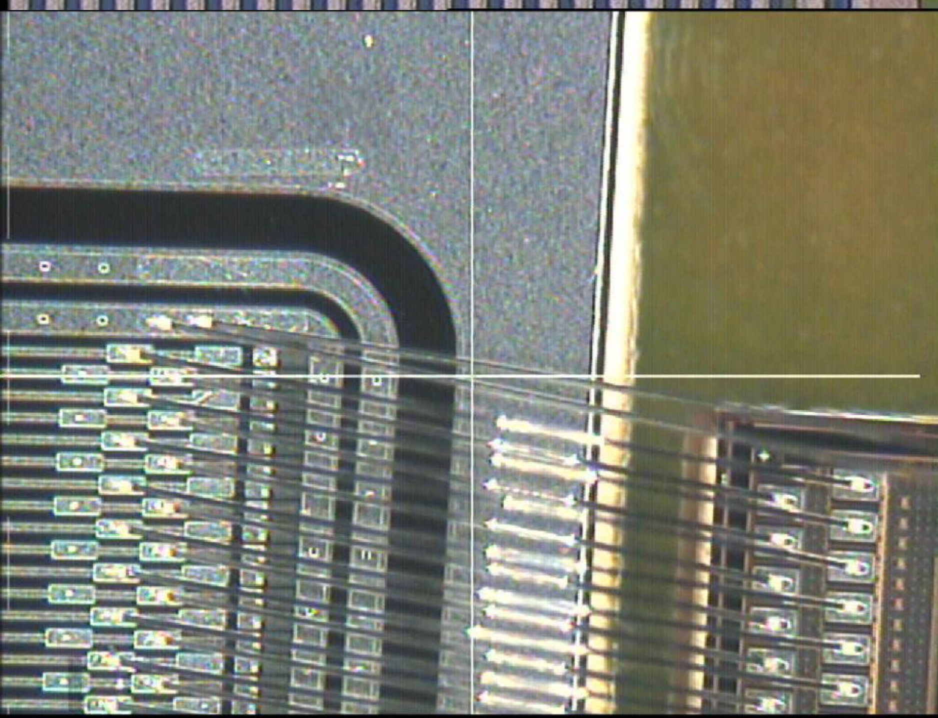


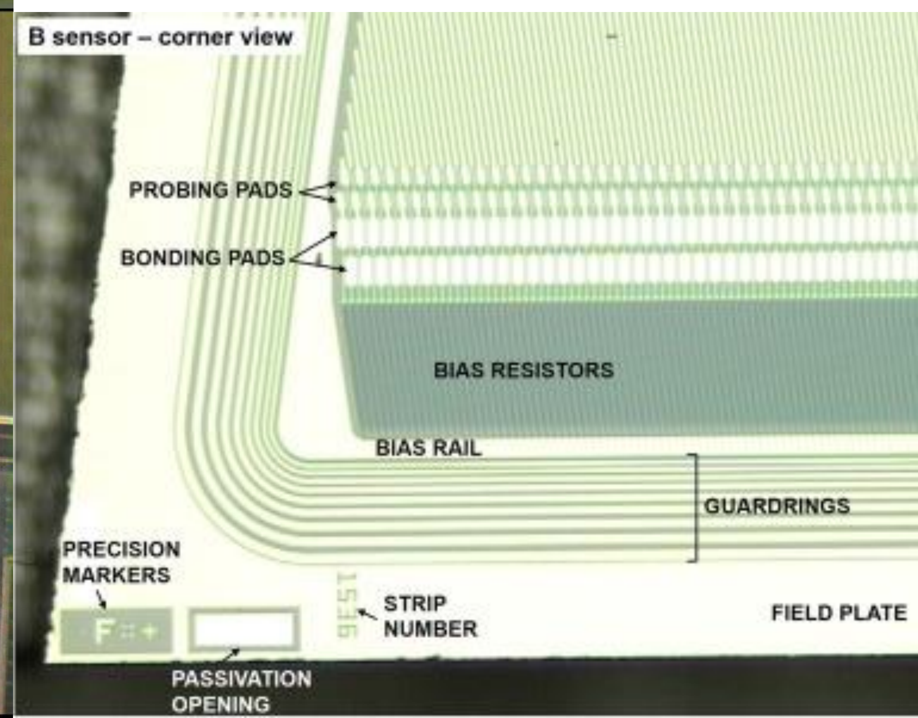
Microstrip sensors



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

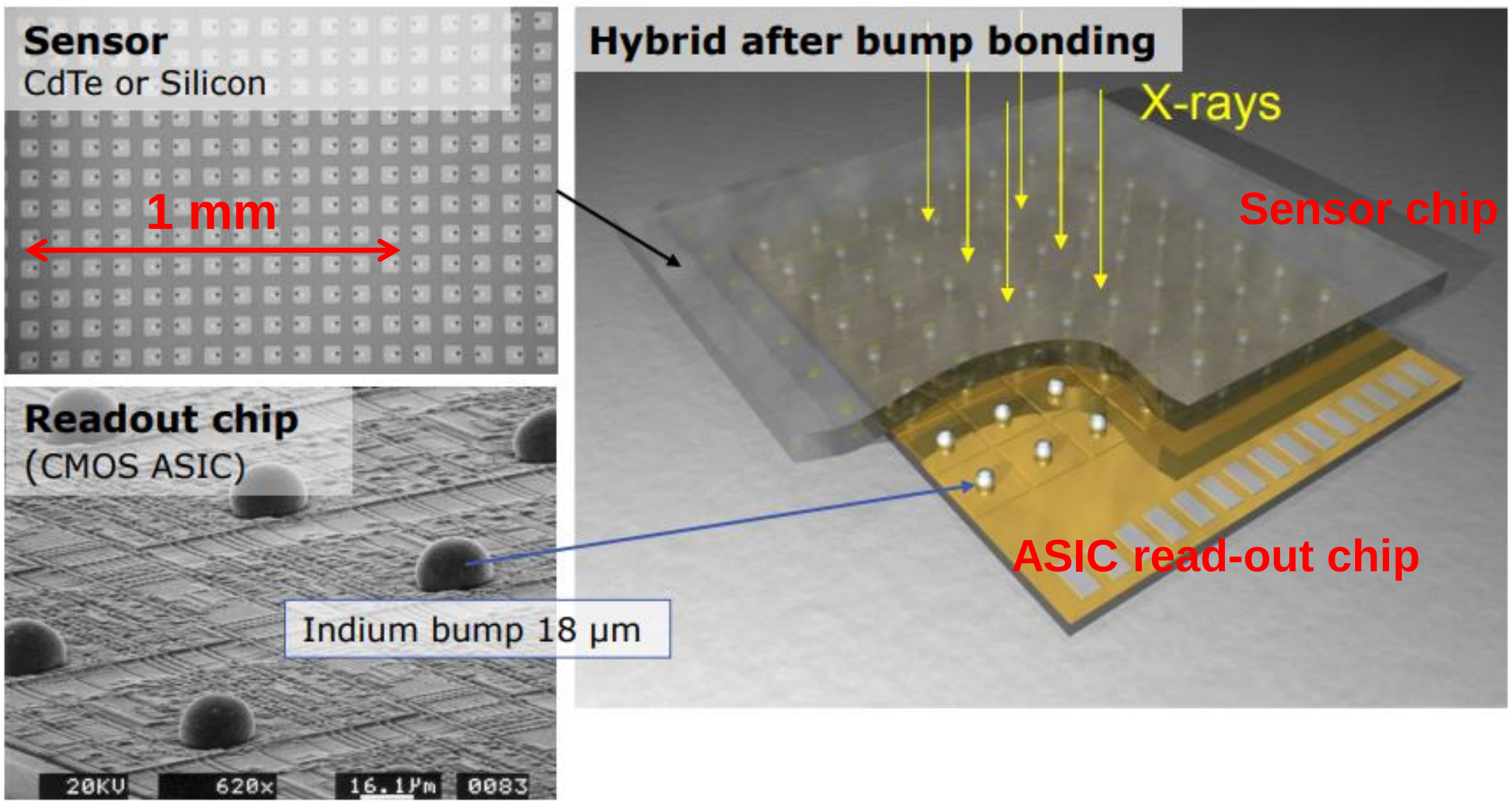
Used in trackers in physics experiments, and in few other applications that need just 1D





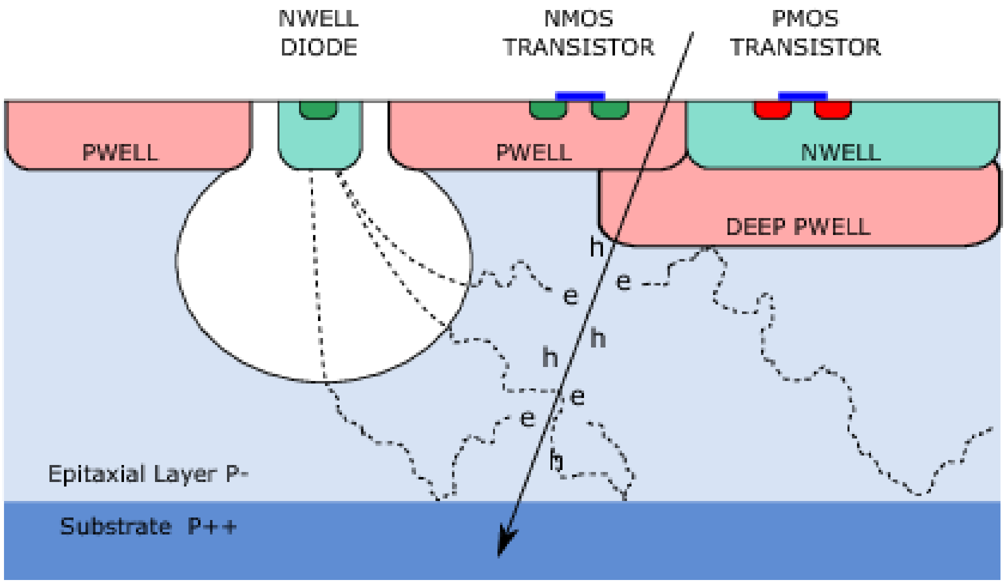
2D read-out: Pixel detector

Hybrid pixel = sensor + readout



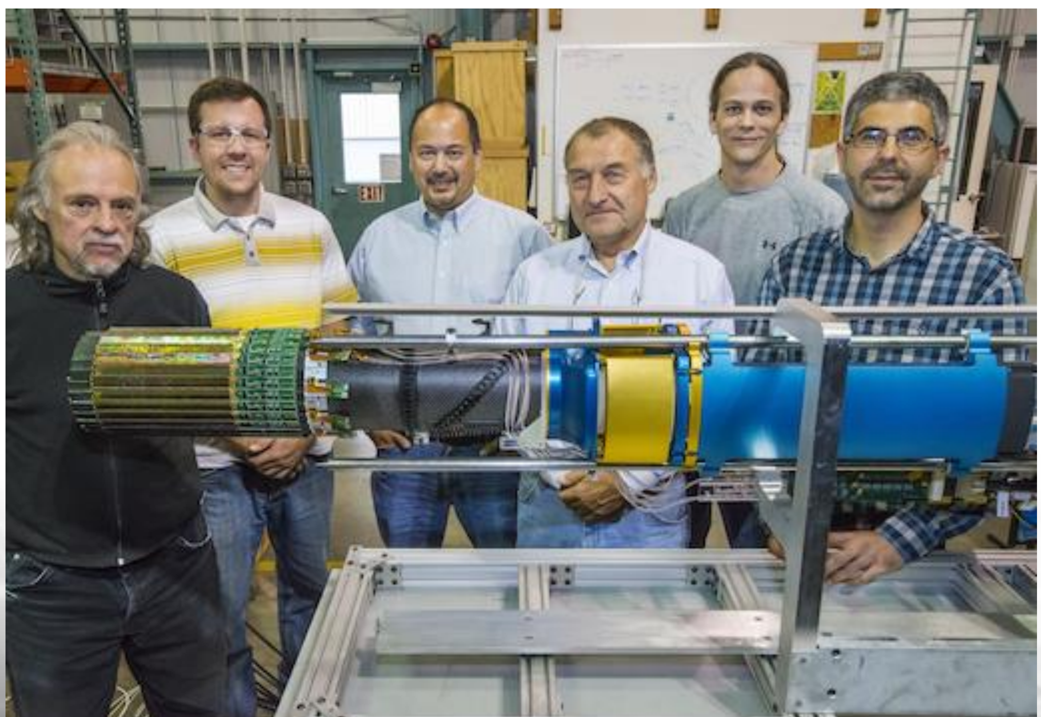
Price to pay? N^2 channel w.r.t. 2*N of strip sensor

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



The sensor is integrated in the same substrate of the electronics.

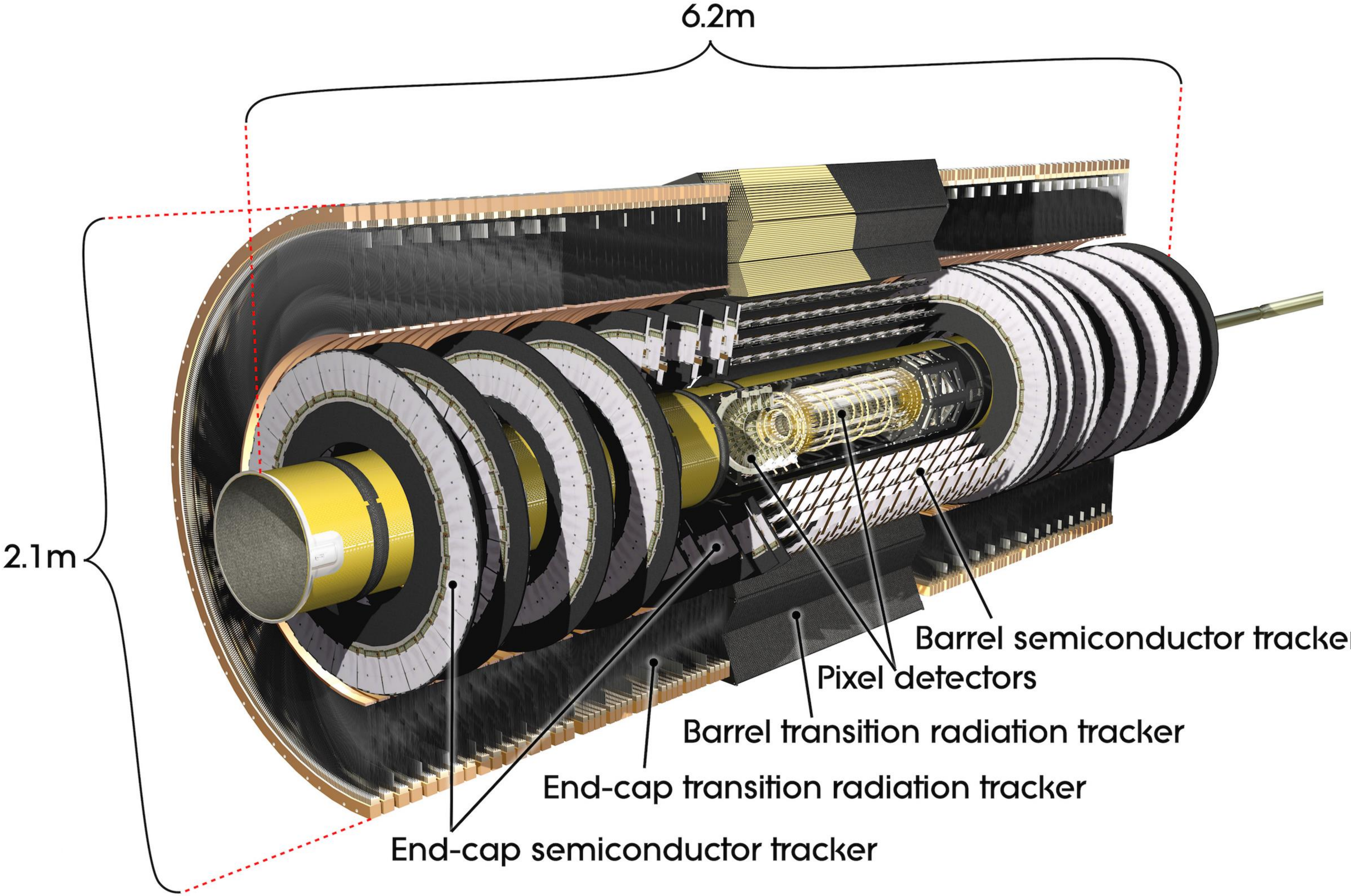
Drawback: the active region is thin (not a problem for mip, problem for X-rays)



Modern trend: Inner tracking system in physics experiment are made of MAPS

← STAR tracker

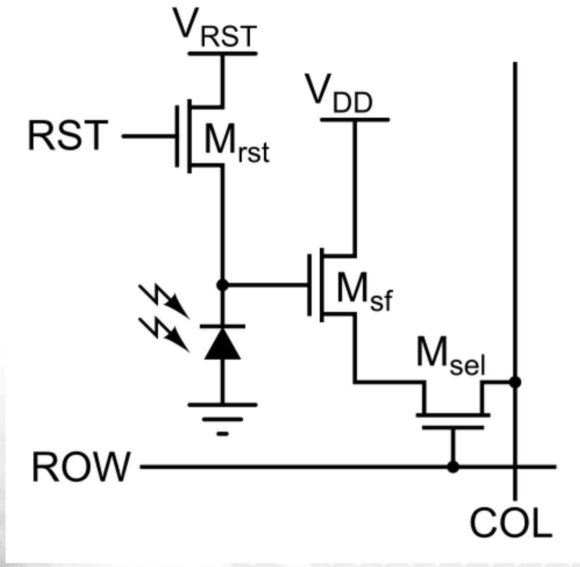
ATLAS inner tracking system



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



CMOS Image Sensor Integrated Circuit Architecture

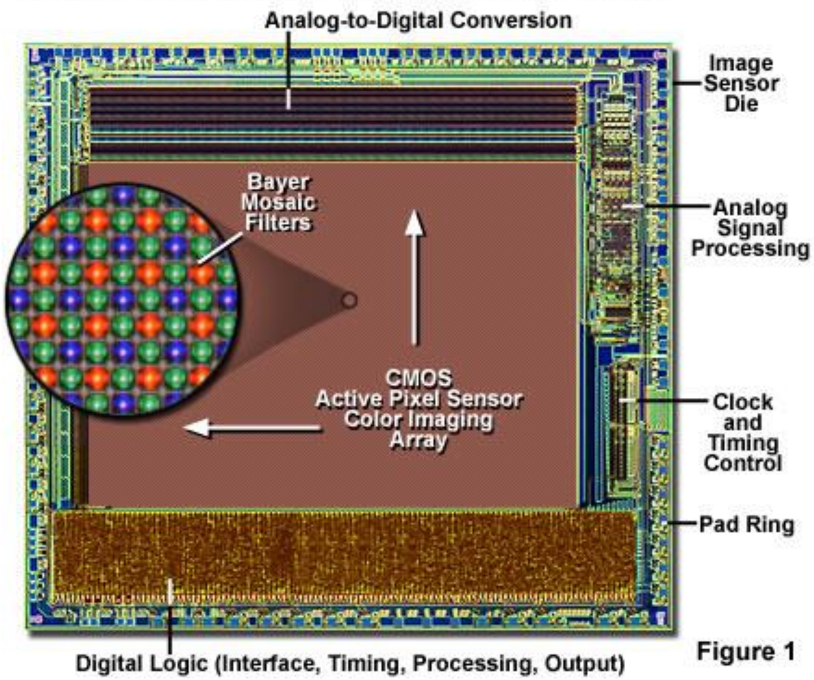
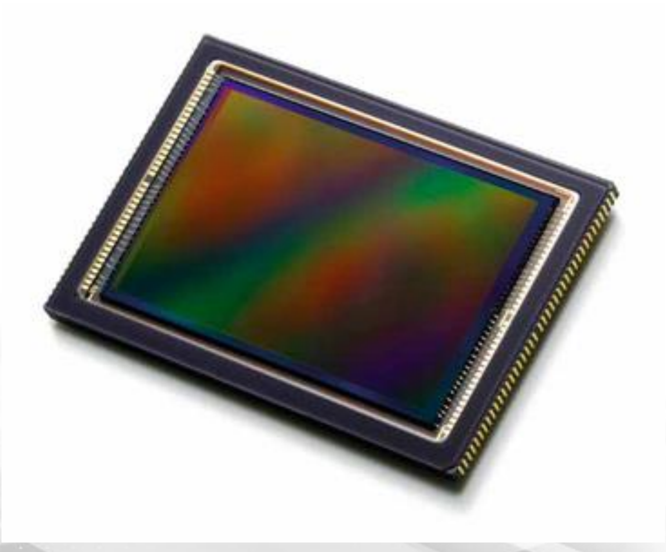


Figure 1



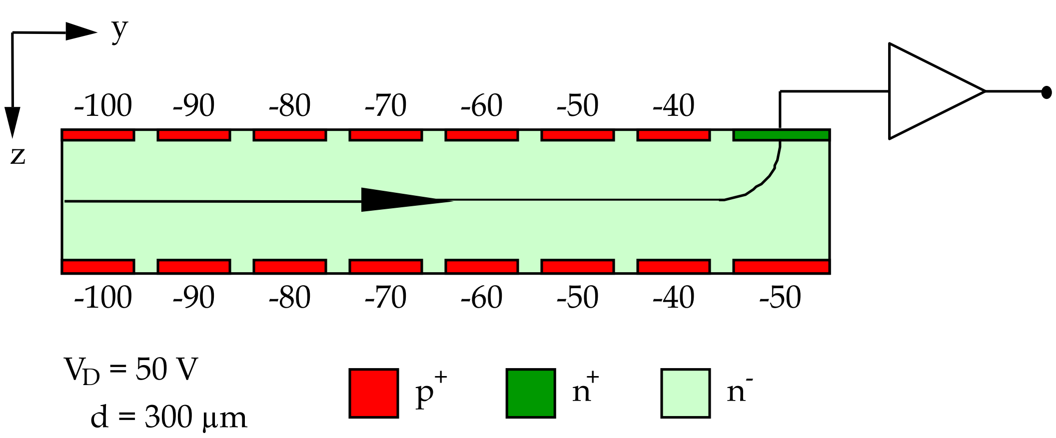
Charge Coupled Devices

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

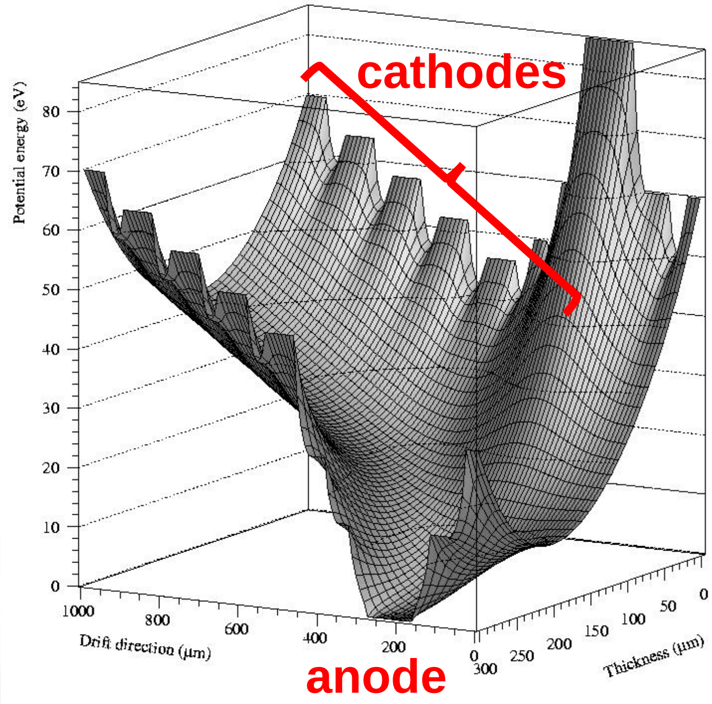
Silicon Drift Detectors

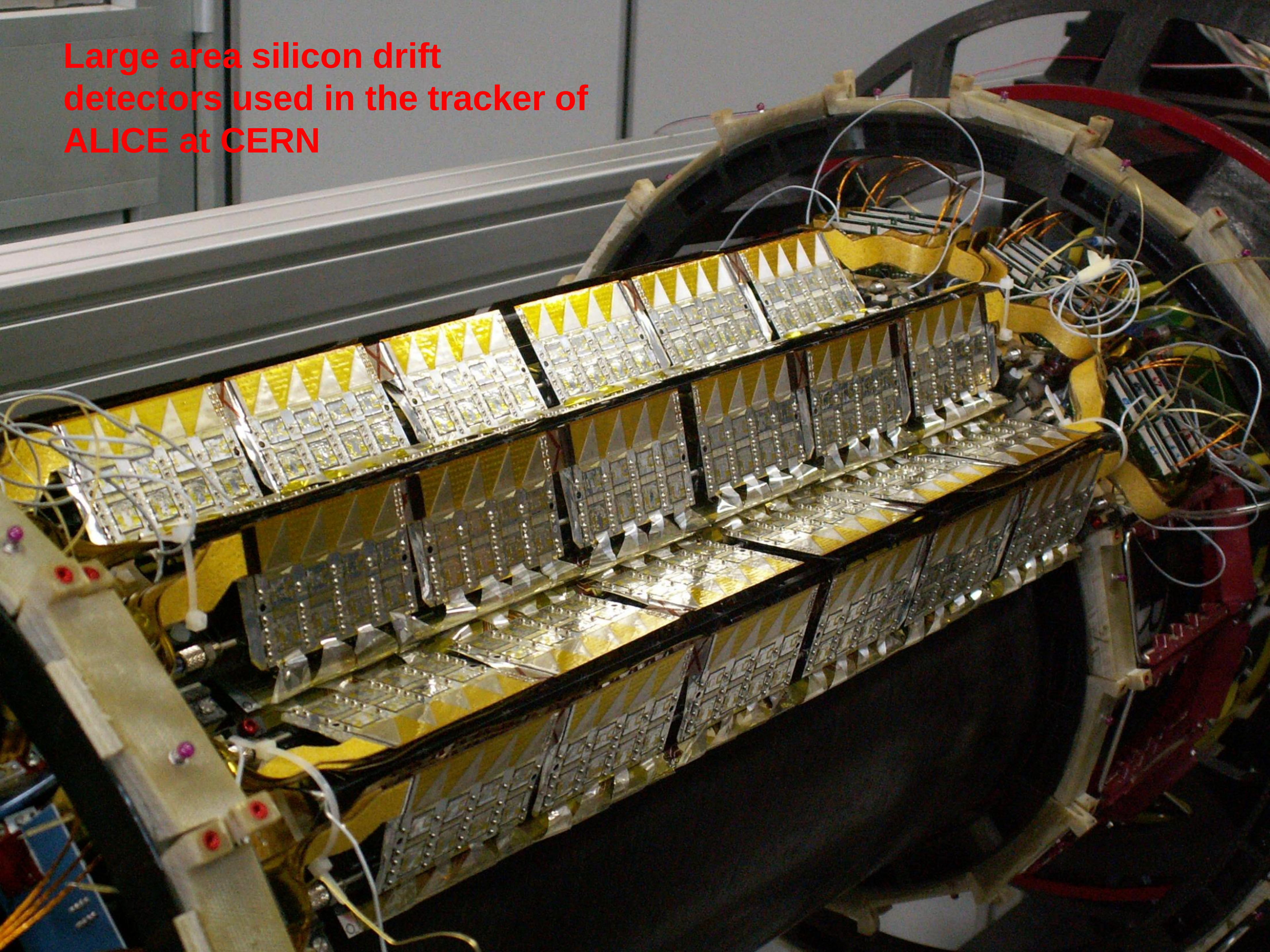
Invented at BNL in 1984

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.



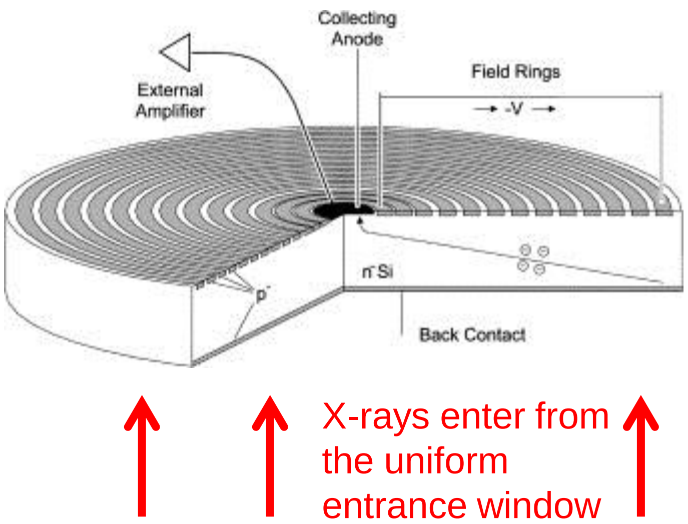
Electrostatic potential



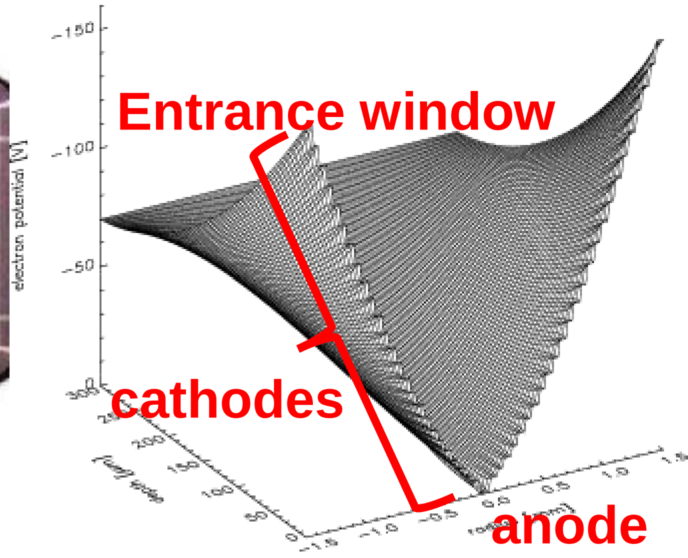

Large area silicon drift detectors used in the tracker of ALICE at CERN

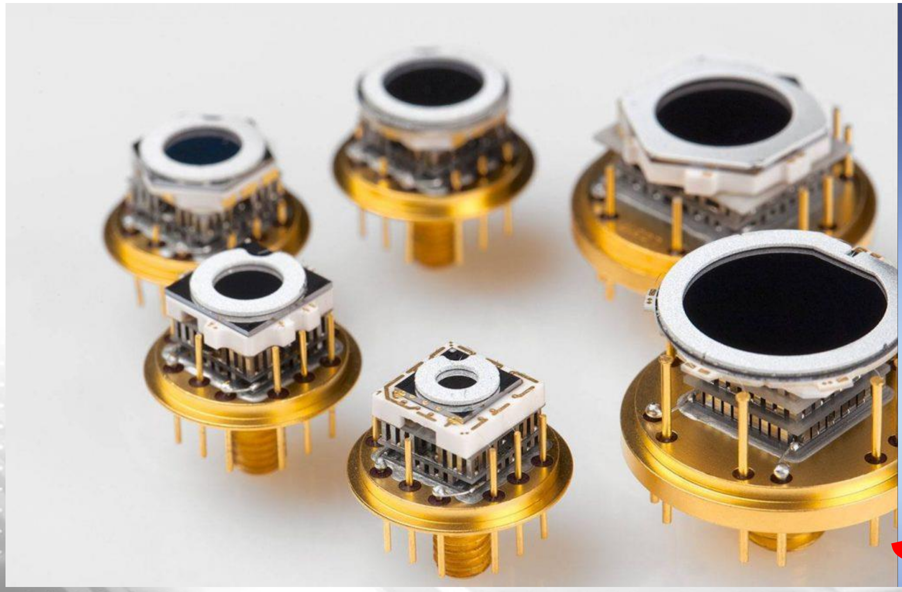
Silicon Drift Detectors as X-ray spectroscopy detectors

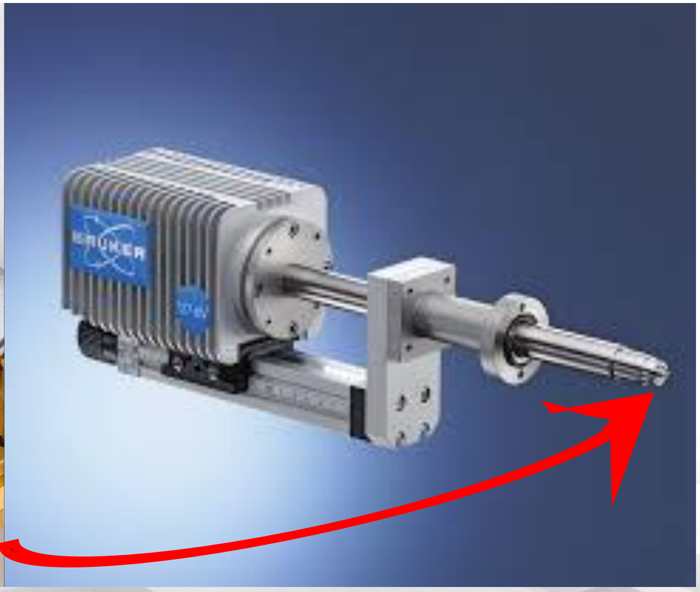
Due to the low capacitance, they have the lowest noise: can detect lowest-energy X-rays



Electrostatic Potential

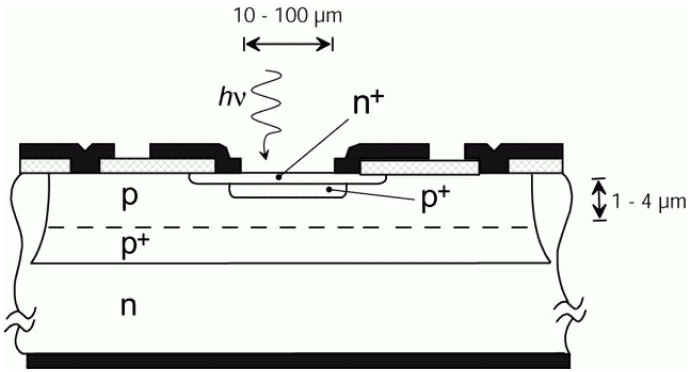




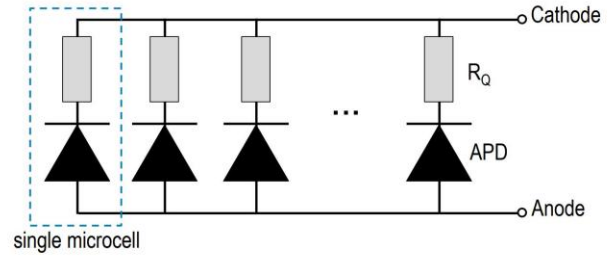


Silicon PhotoMultiplier (SiPM)

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.



SiPM structure: array of APDs

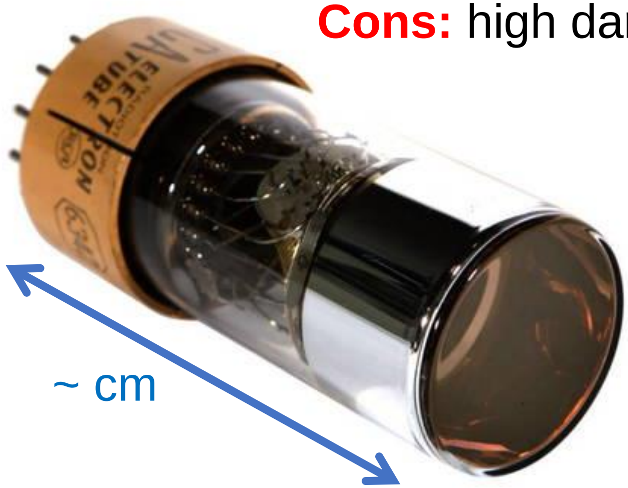


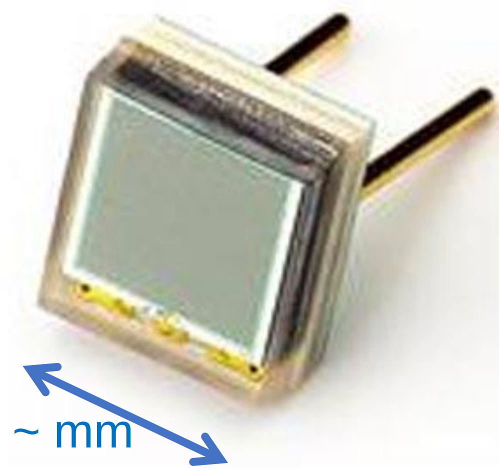
All of the microcells are connected in parallel

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





Single Photon Detection

A signal is induced by just one electron, but it is made by ~1M electrons (i.e. huge gain)