Introduction to Pixel Detectors

J. Beyer – ATLAS-SCT

Max Planck Institut für Physik

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Particle Physics School Colloquium - PPSMC

MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Physik
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Overview

1. What is a pixel detector
2. How does a pixel detector work
3. How to make the sensor of a pixel detector
4. Applications of pixel detectors

pixel

Also found in: Thesaurus, Medical, Acronyms, Idioms, Encyclopedia, Wikipedia.
Related to pixel: megapixel, pixel peeper

pix·el (pĭk′səl, -sĕl′)

n.

The basic unit of a digital image, representing a single color or level of brightness.

[pix + el(ement).]

"CITE"

pixel (ˈpɪksəl)

n

(Computer Science) any of a number of very small picture elements that make up a picture, as on a visual display unit

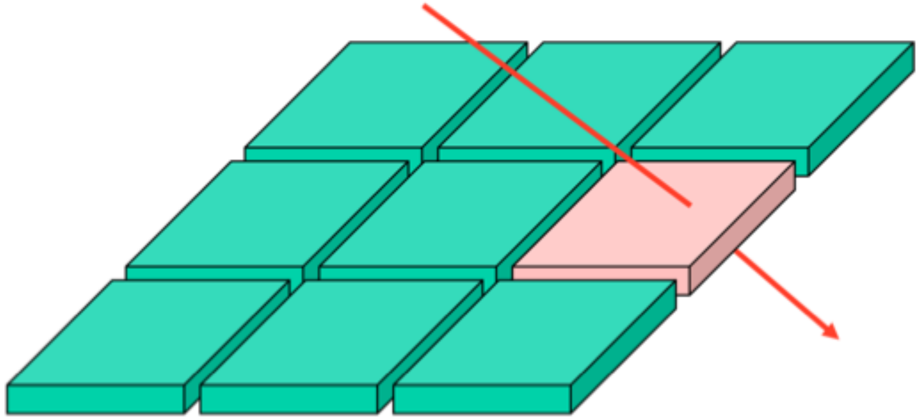
[C20: from *pix* pictures + *el*(*ement*)]

"CITE"

Part 2: Specific application: Development of pixel detectors for ATLAS (Natascha)

What is a Pixel Detector

Introduction



- a (solid state) detector which is segmented into 2-dimensional sensing elements
  - a charged particle or a gamma ray produces a signal by ionisation
  - pulse processing electronics amplify the signals and distinguish signals from noise
  - signal leads to true 2-dimensional spatial information (no ambiguities)

What is a Pixel Detector

Types of pixel detectors

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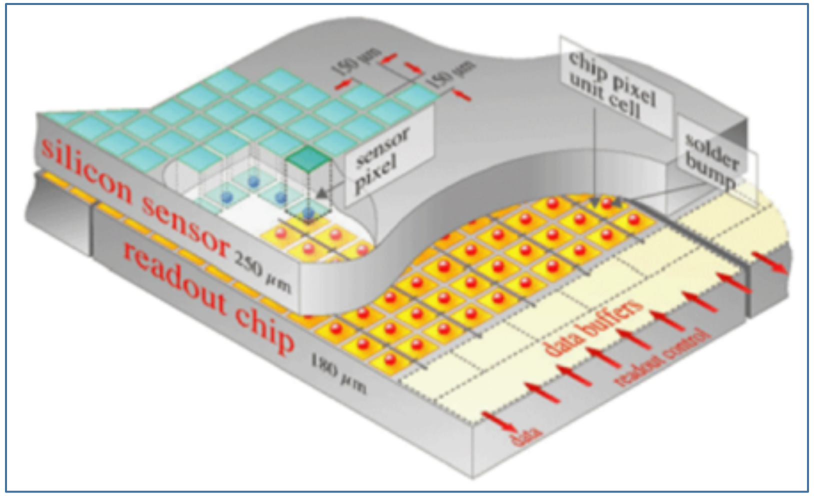
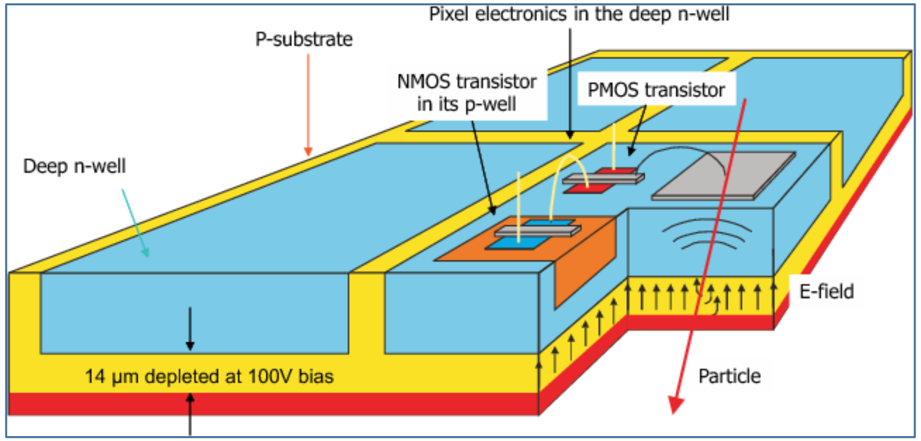
- pixel detectors differ by
  - construction type
    - **hybrid pixel detector**: sensor volume and signal processing unit in two separate chips with 1:1 cell correspondence
    - **monolithic detectors**: signal processing electronics in the same device as the sensor volume
  - signal processing
    - single event readout (HEP), counting (x-ray), integrating (imaging)
  - sensor type
    - silicon, germanium, high-Z material, ..





What is a Pixel Detector

Motivation and development in HEP

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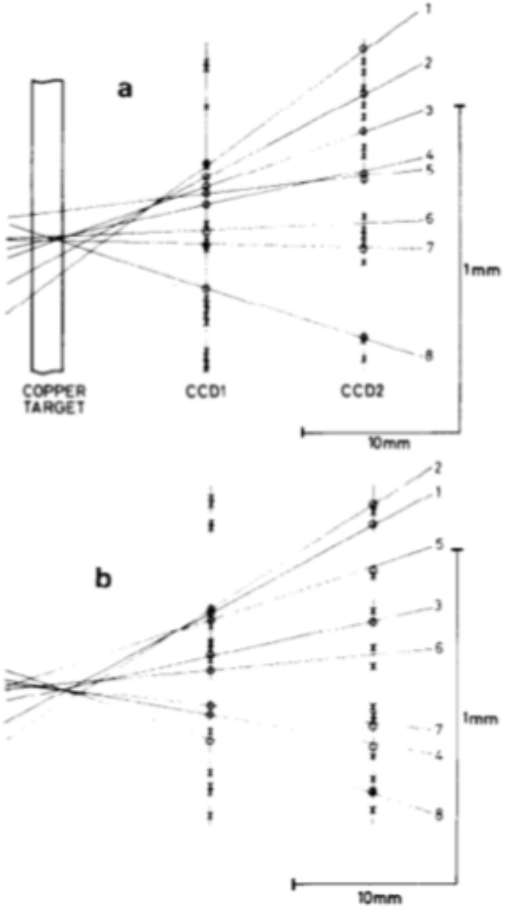
- pixel detectors are necessary to resolve the ambiguity in high multiplicity environments
  - typical task: tracking/vertexing close to the interaction point

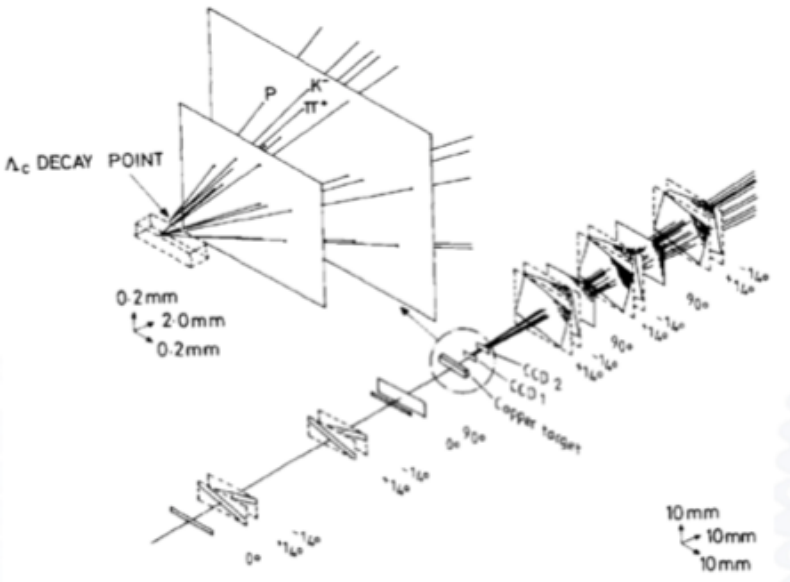
- first application: reconstruct charm decays in NA32 (1982-1986)

- first hybrid pixel detector in 1990: WA97

- technology became available through huge success of semiconductor industry



C.J.S. Damerell et al., *CCDs for vertex detection in high energy physics*, Nucl. Instr. and Meth. A253 (1987) 478-481

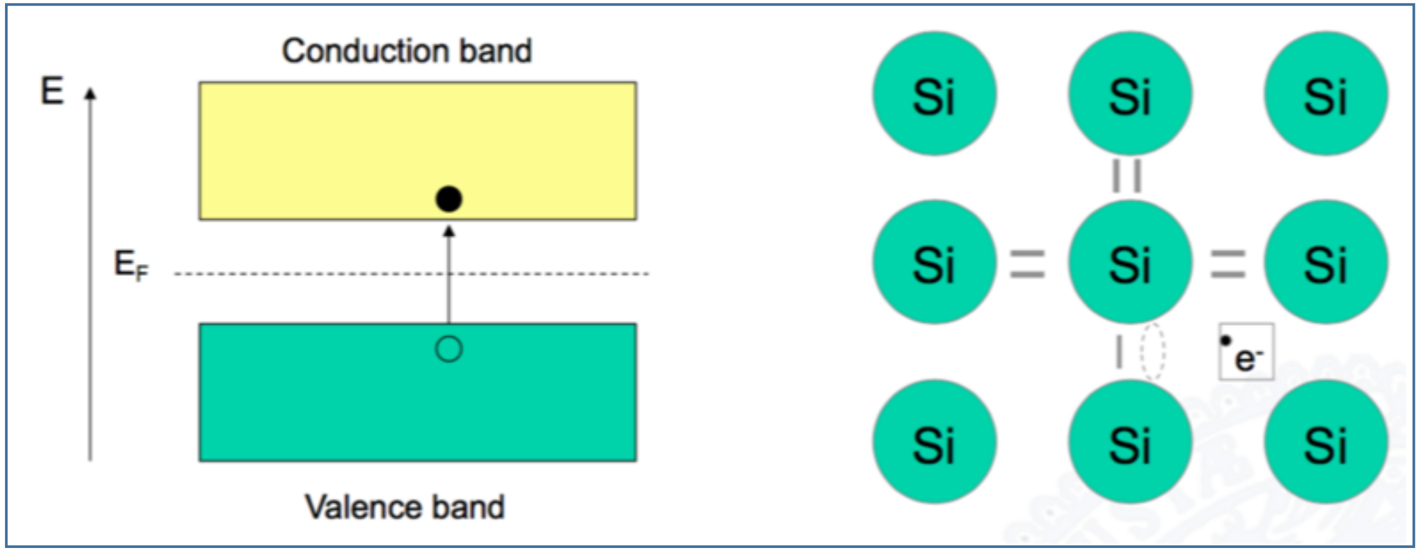


S.J. Watts, *CCD Vertex Detectors*, Nucl. Instr. and Meth. A265 (1988) 99-104

How Does a Pixel Detector Work

Semiconductor physics

- intrinsic silicon (at T=0K) has no free charge carriers
  - higher temperatures can lift charge carriers over the band-gap



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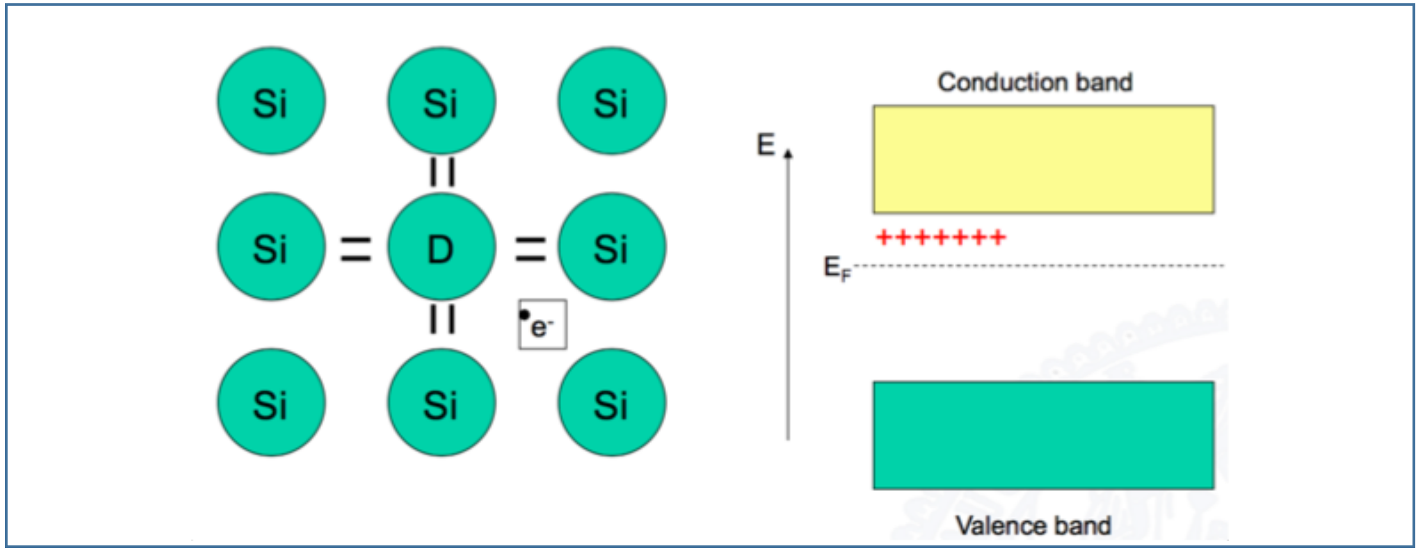
  - donors provide one weakly bound extra electron -> energy levels close to the conduction band



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Semiconductor physics

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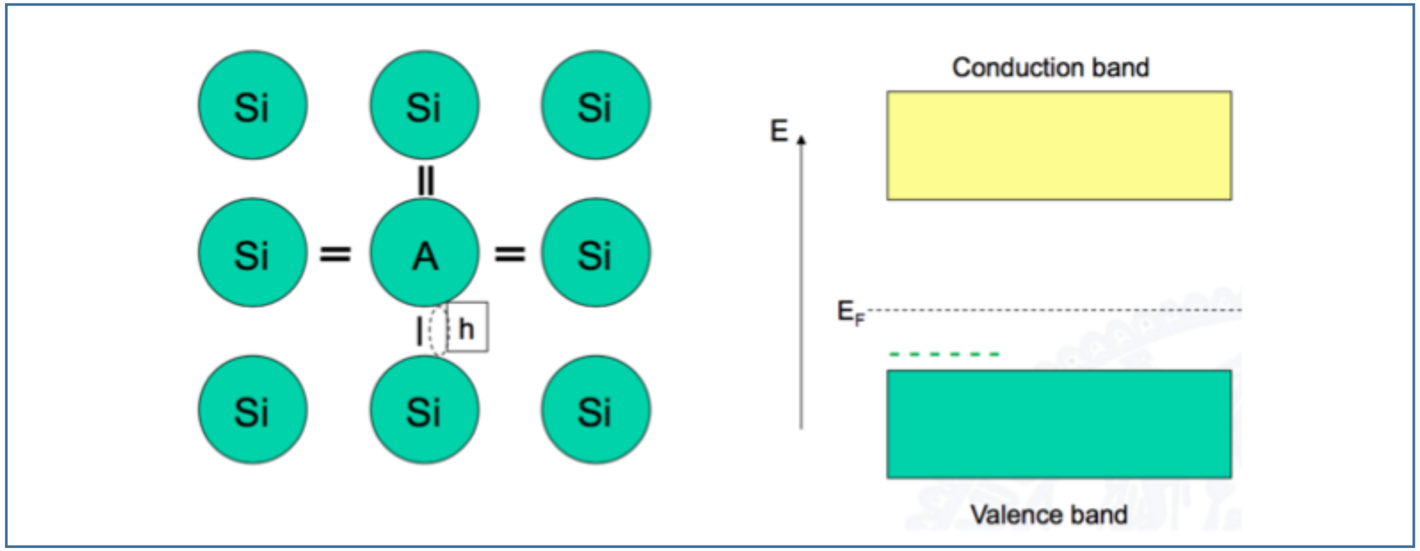
  - donors provide one weakly bound extra electron -> energy levels close to the conduction band
  - acceptors provide one more energy level which can be filled by neighbouring electrons -> holes

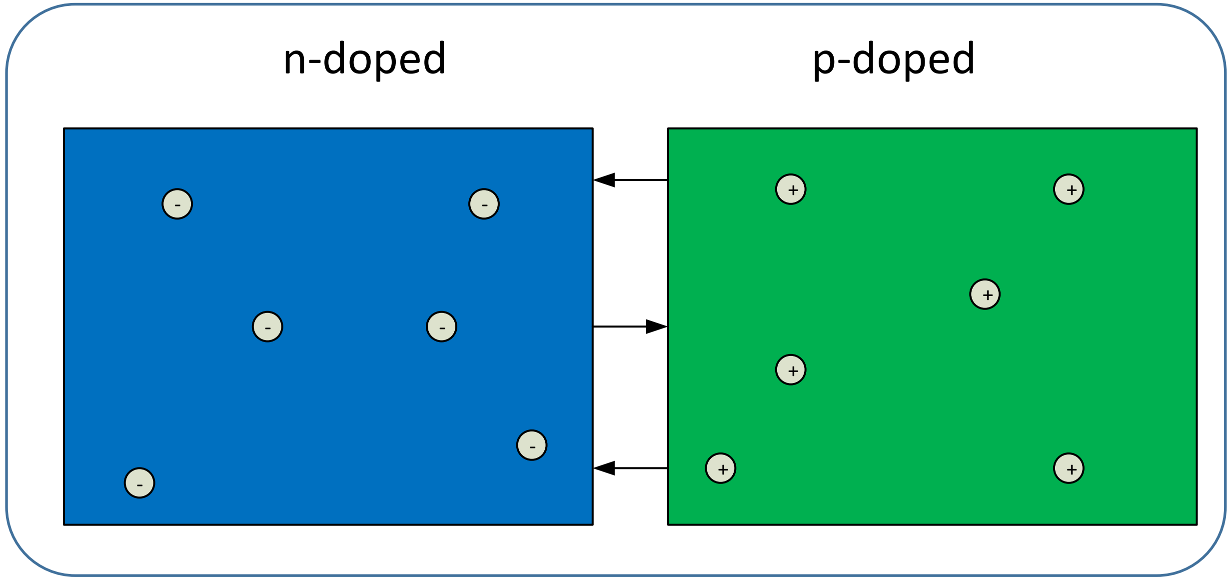
Attention:
despite doped silicon having free charge carriers, it of course stays electrically neutral.



How Does a Pixel Detector Work

Simple Detector

- create a junction between n-type and p-type material

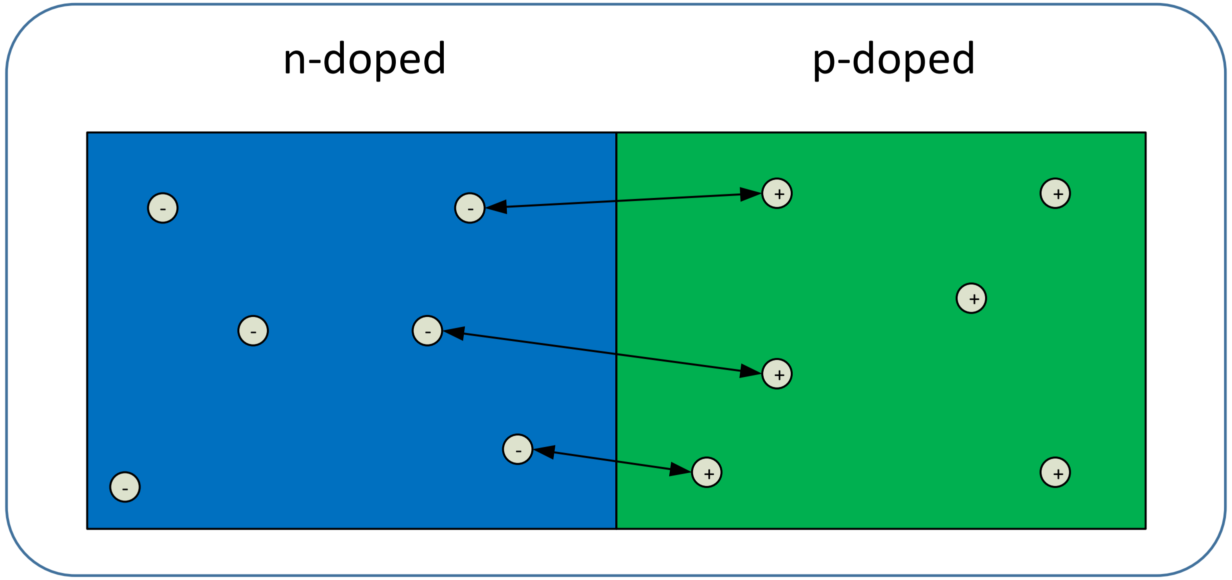


How Does a Pixel Detector Work

Simple Detector

- create a junction between n-type and p-type material

- electron/hole pairs recombine in the border region
  - driving force: concentration gradient -> diffusion



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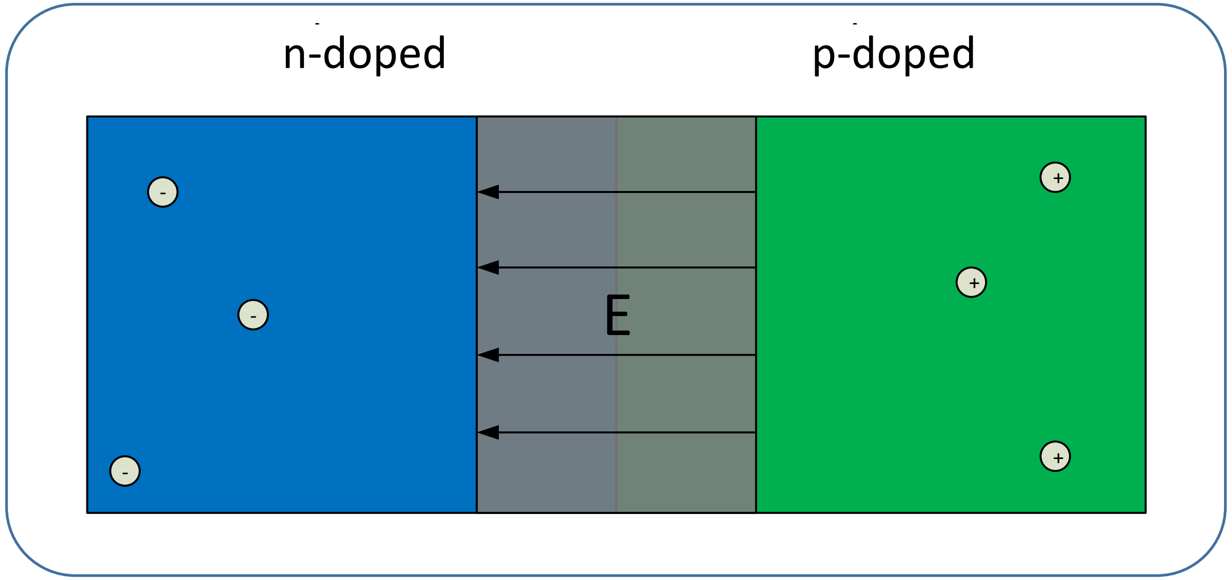
- an electrical field builds up because the material is no longer electrical neutral
  - driving force: electrical field -> drift



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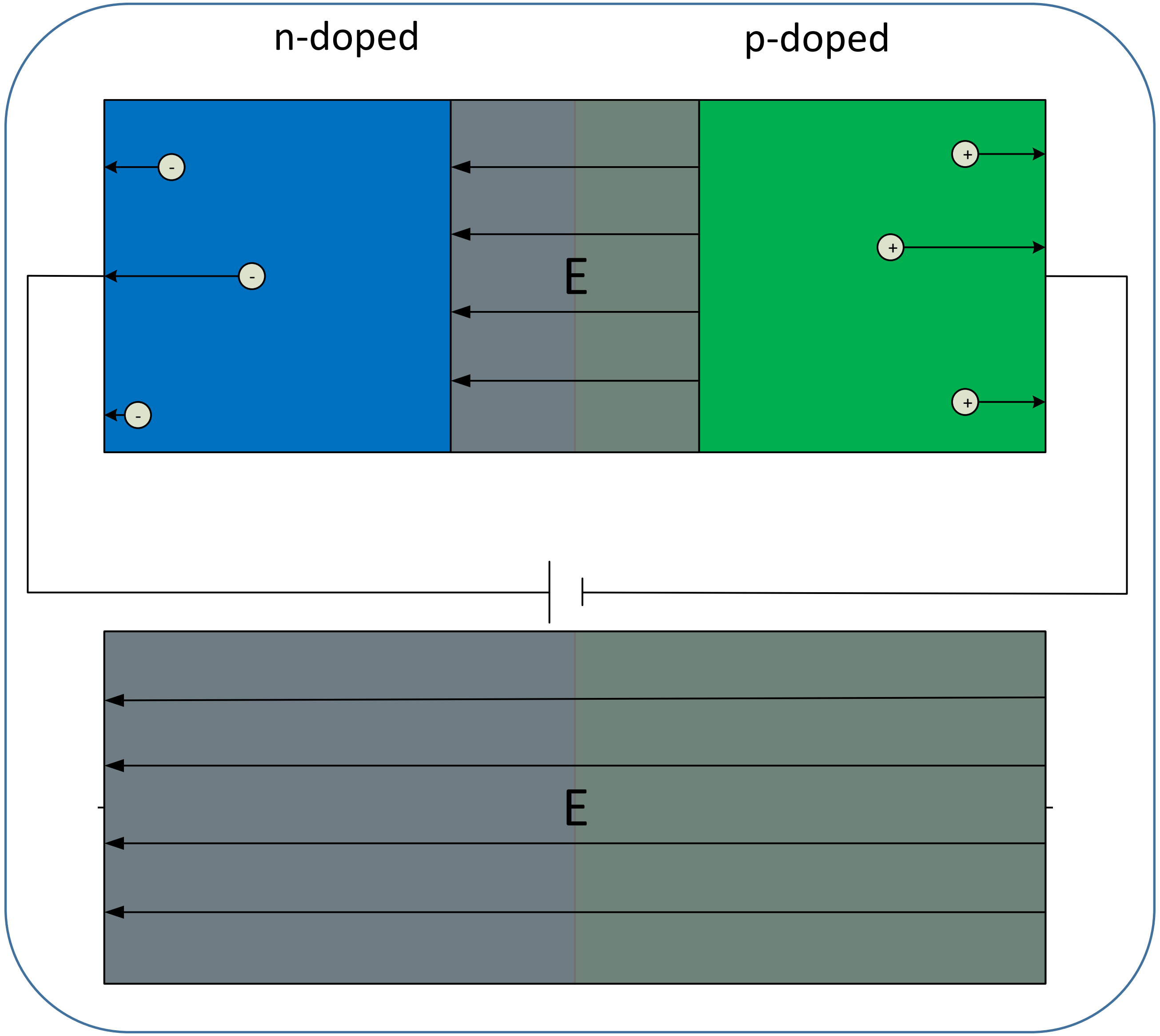
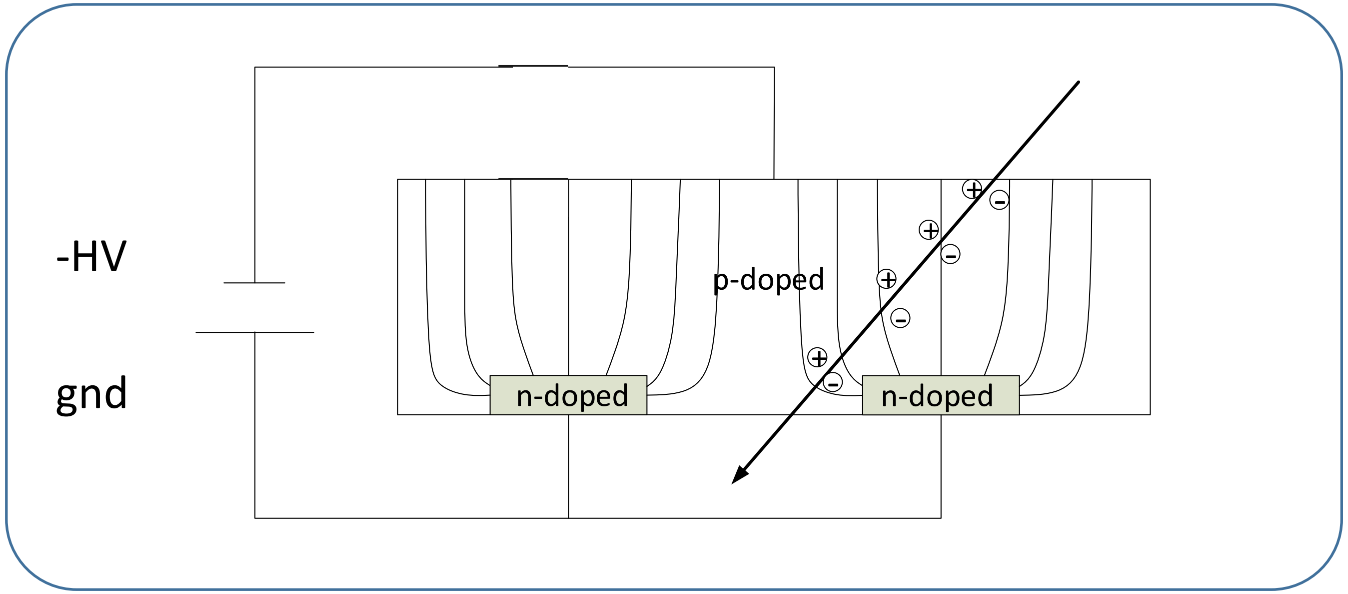
    - driving force: electrical field -> drift
- an external voltage applied in reverse direction increases the electrical field, newly generated charge carriers will be removed from the device now



How Does a Pixel Detector Work

Translate this to a real sensor

- junction is created between p-doped bulk material and n-doped pixel implant
- the electrical field created by the applied bias voltage is used to separate electron/hole pairs created by through passing ionising particles



How Does a Pixel Detector Work

Translate this to a real sensor

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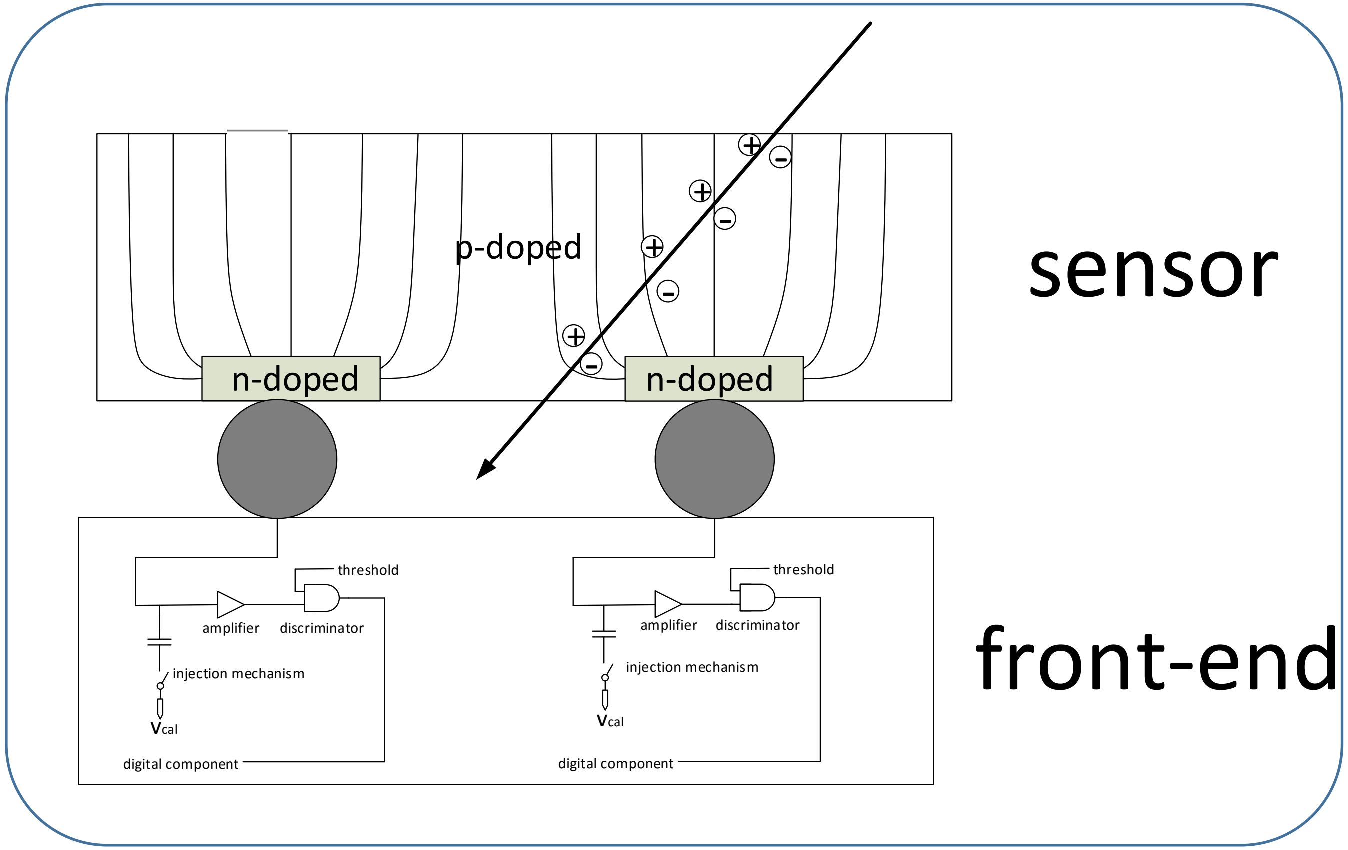
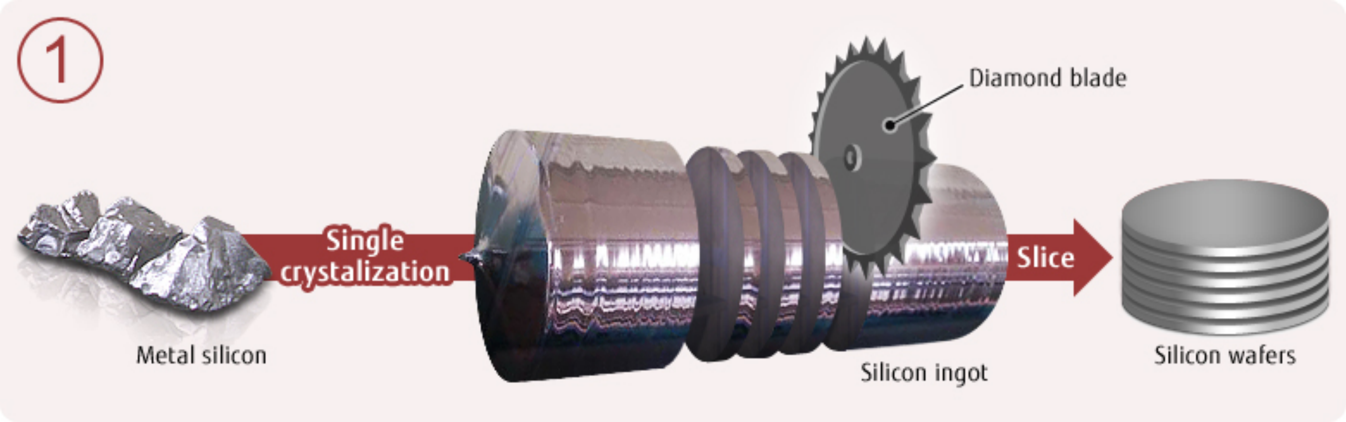
- junction is created between p-doped bulk material and n-doped pixel implant
- the electrical field created by the applied bias voltage is used to separate electron/hole pairs created by through passing ionising particles
- the signal is then read-out by the front-end chip: amplification, discrimination, digitalization, storage



How to Make a Pixel Detector Sensor

Example: Silicon



- silicon dioxide (quarz -> sand) is the origin of all silicon sensors (and CPUs, GPUs, ASICs, FPGAs, …)
- reducing the SiO_2 to pure silicon results in a polycrystalline structure
- following the path to a planar pixel sensor…

Technics to produce ingots:

- Czochalski: pull the monocrystalline silicon ingot out of molten silicon
- Float-Zone: melt a polycrystalline cylinder stepwise to get a monocrystalline ingot

Slicing the ingot with a diamond saw results in silicon wafers

How to Make a Pixel Detector Sensor

Processing silicon wafers - oxidation

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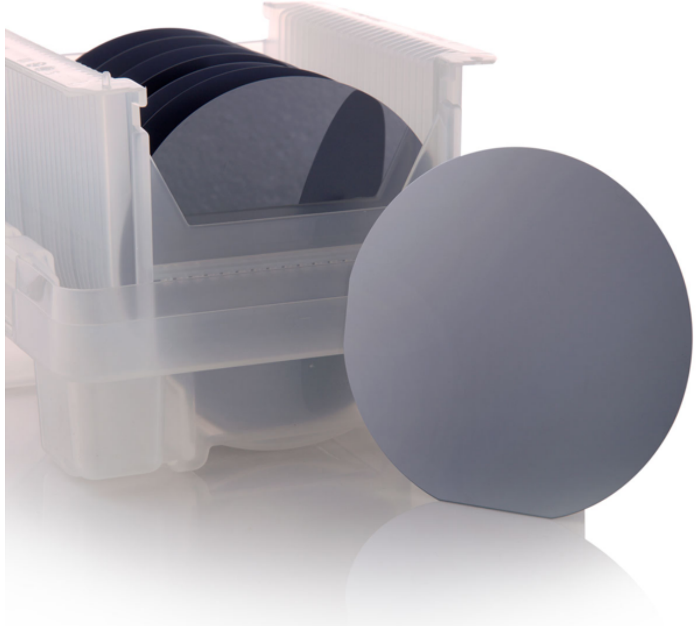
Step 1: Oxidation

- the wafer is put in an oven at a high temperature (~1000°C)
- the surface atoms react with the oxygen and build an oxide layer on top
- longer exposure times lead to thicker oxide layers



How to Make a Pixel Detector Sensor

Processing silicon wafers - photoresist

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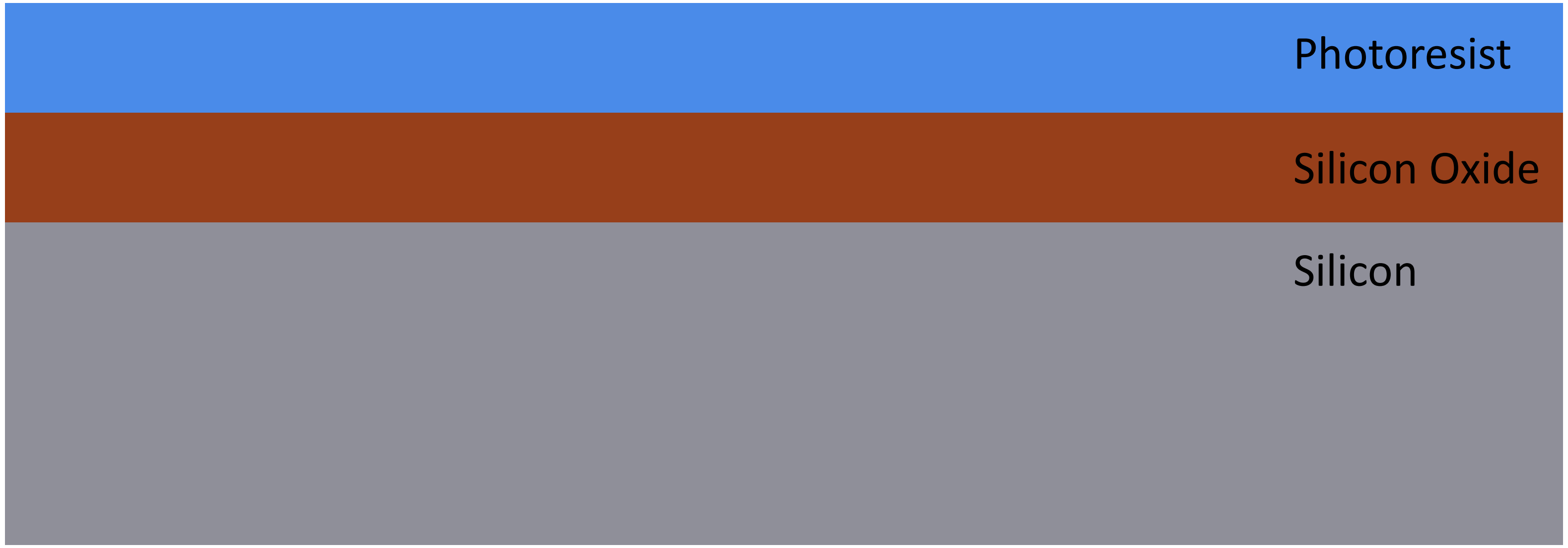
Step 2: Photo resist

- a liquid photo resist is put in the center of the wafer
- the wafer is rotated at a precise speed such that a homogeneous layer of defined thickness of photo resist stays on top of the wafer



How to Make a Pixel Detector Sensor

Processing silicon wafers - photolithography

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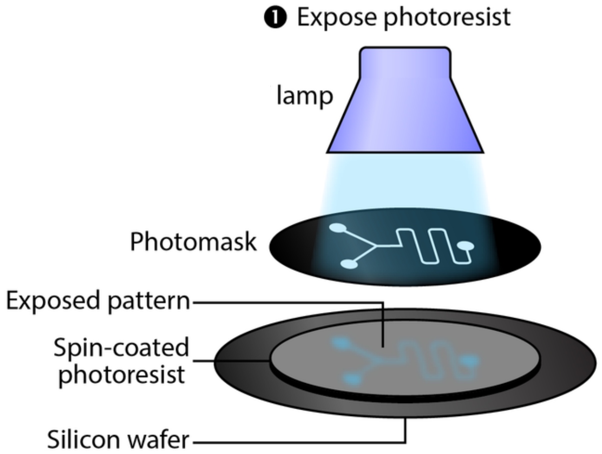
Step 3: Photolithography

- expose the photoresist through a mask to a lamp
- not-exposed parts can be removed afterwards



How to Make a Pixel Detector Sensor
Processing silicon wafers - etching

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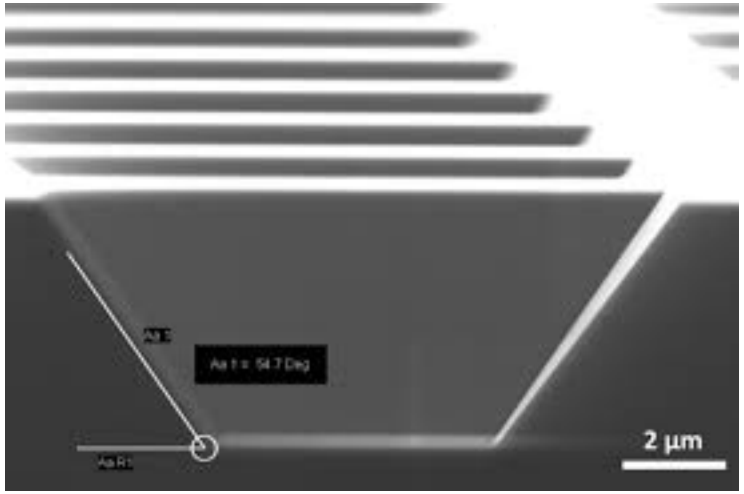
Step 4: Etching

- etch part of the previously grown oxide away



How to Make a Pixel Detector Sensor

Processing silicon wafers – ion implantation

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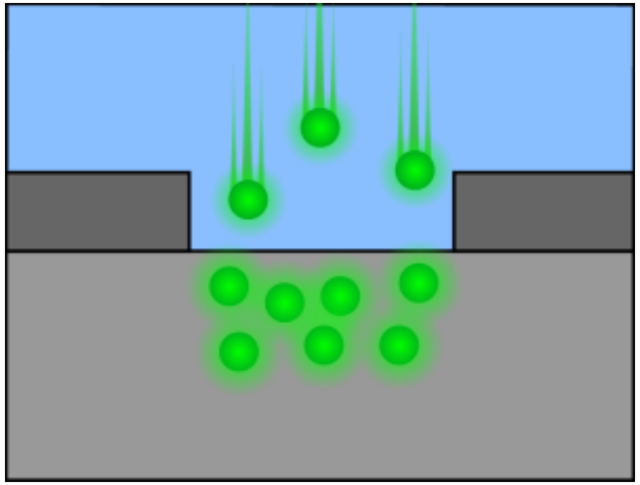
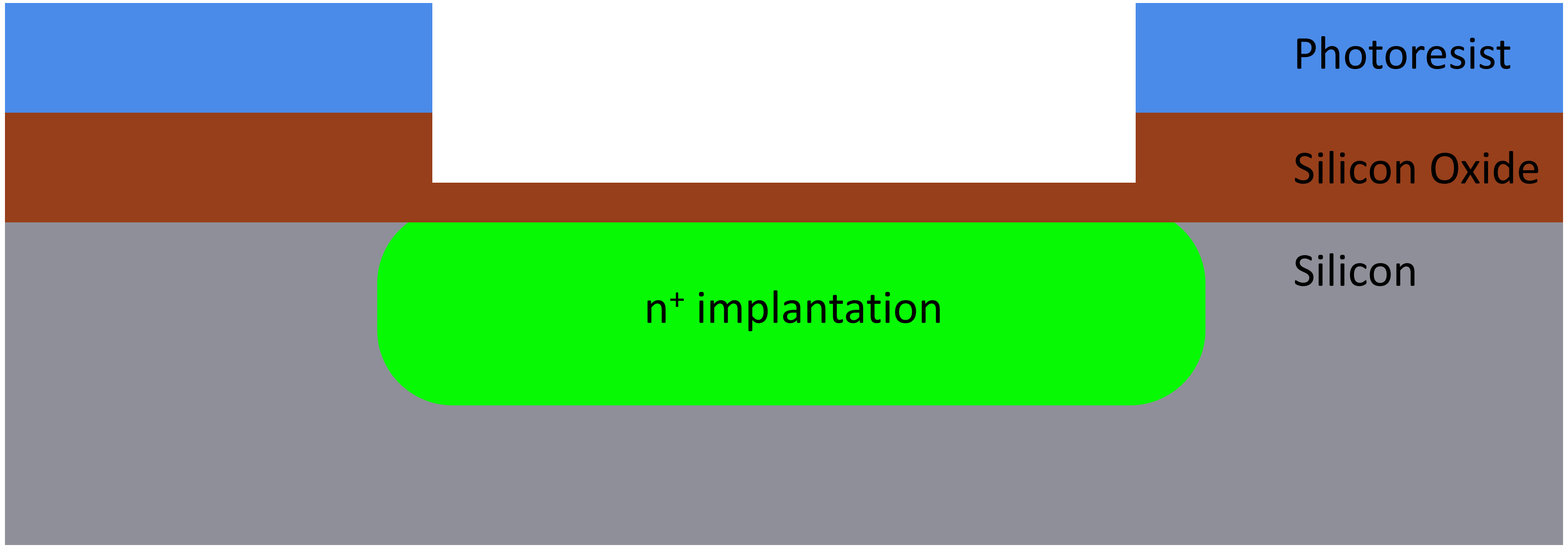


Step 5: Ion implantation

- doping atoms are ionized, accelerated and shot onto the wafer
- usually, another high-T step is applied to anneal the defects introduced into the silicon lattice by the high energetic ions



How to Make a Pixel Detector Sensor

Processing silicon wafers – aluminium

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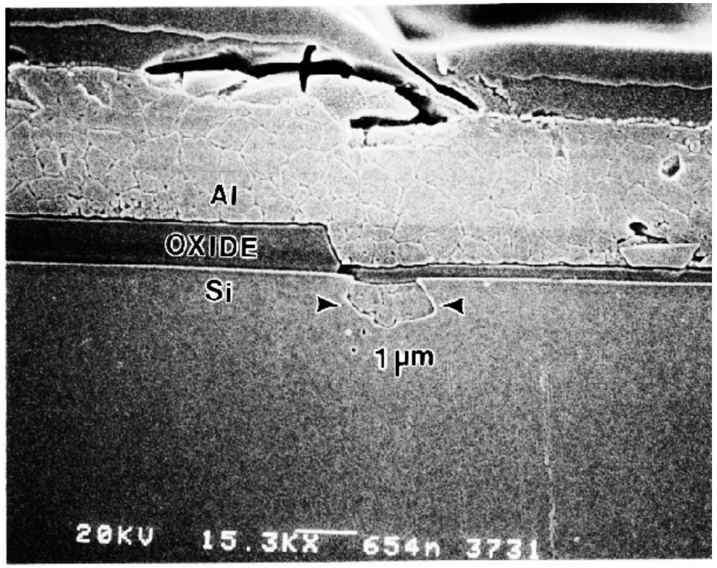
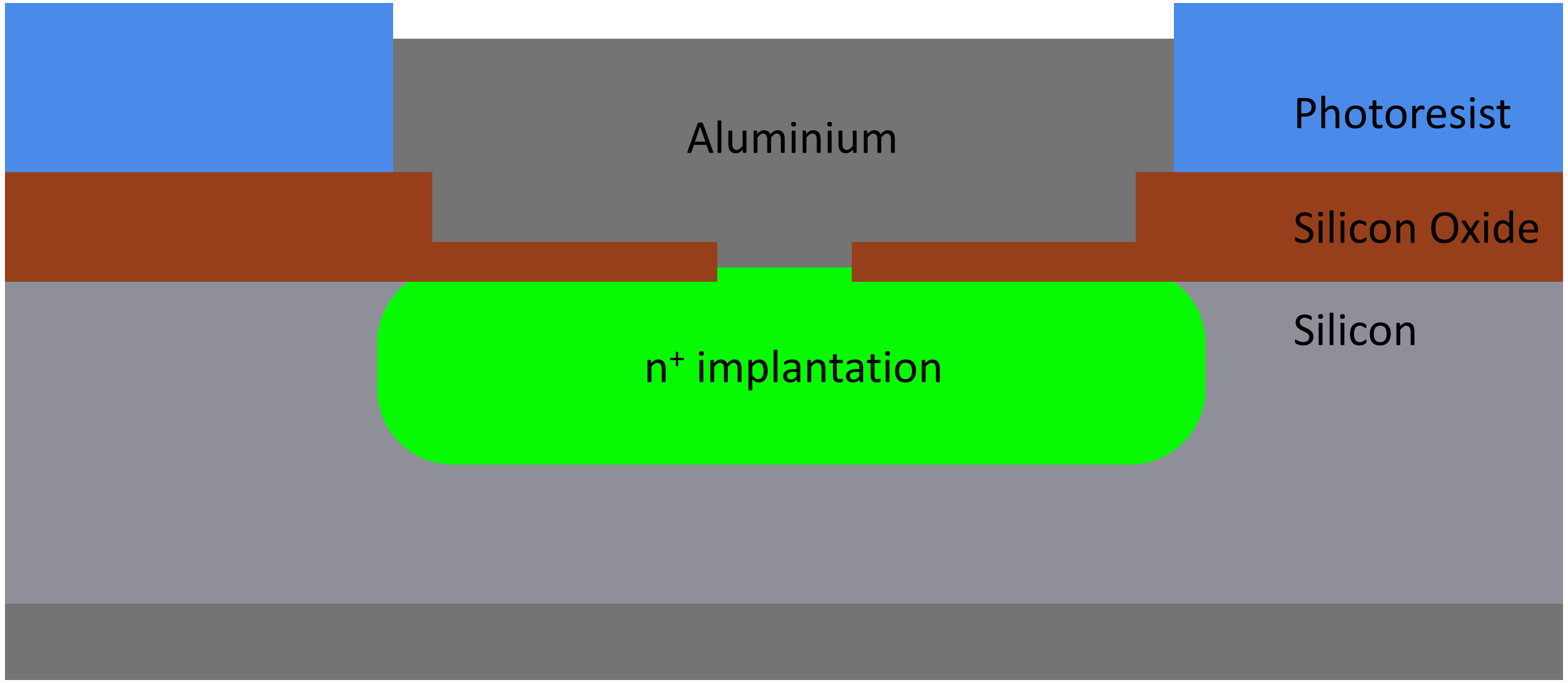


Step 6: Aluminium deposition

- after some more higher order processing steps, a contact to the pixel implant is etched
- aluminium is sputtered on the surface using another photo resist mask
- another layer on the backside provides electrical contact



How to Make a Pixel Detector Sensor

Processing silicon wafers – aluminium

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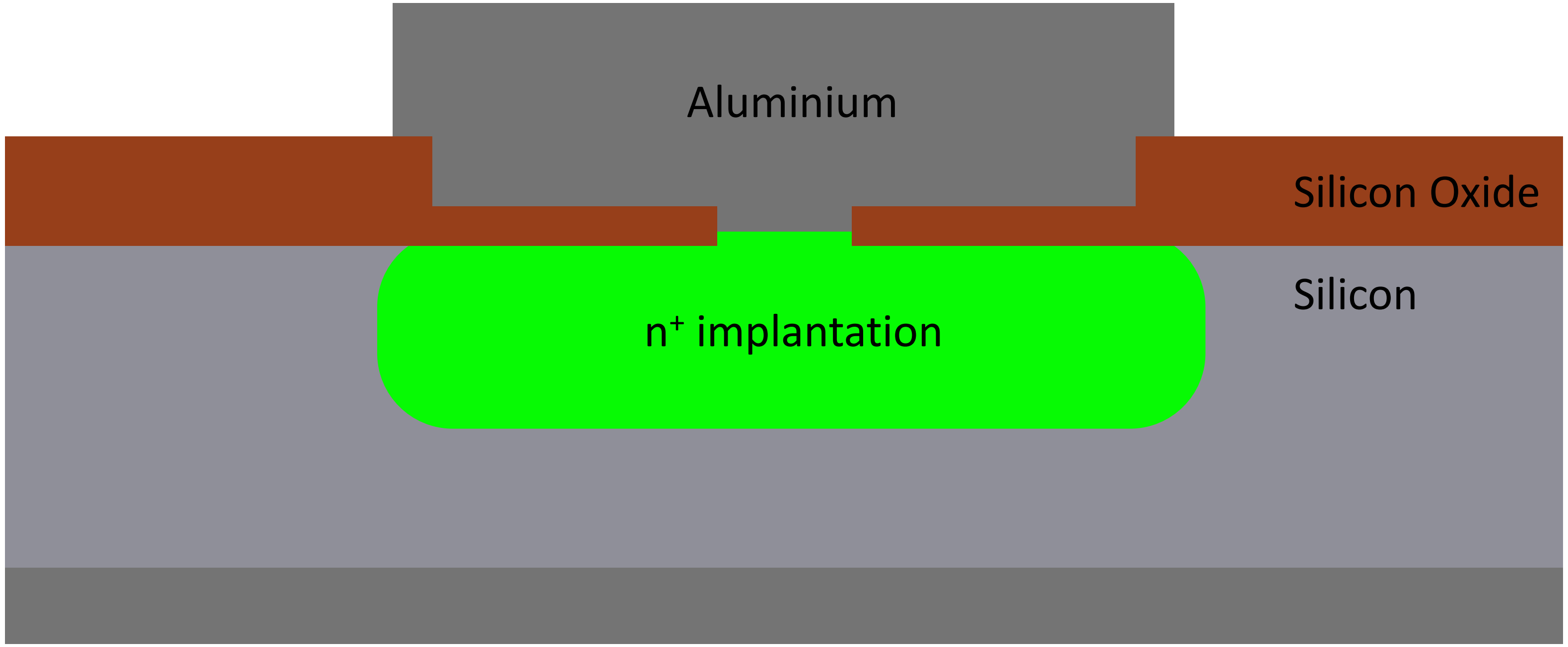
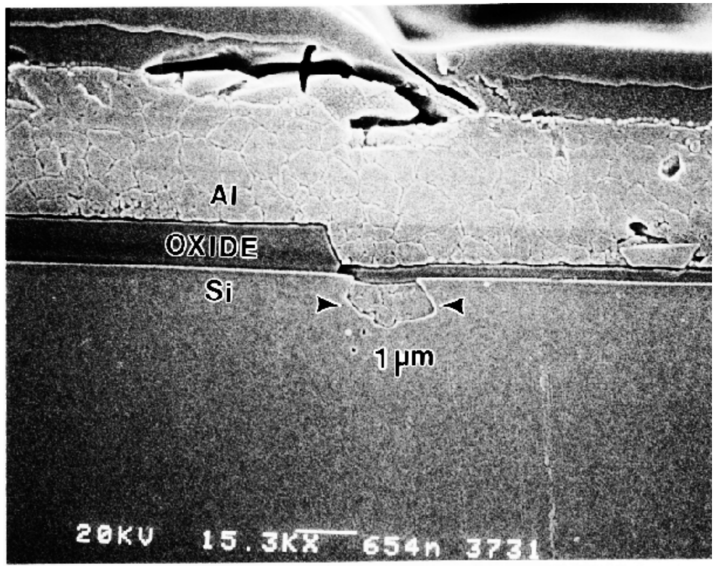
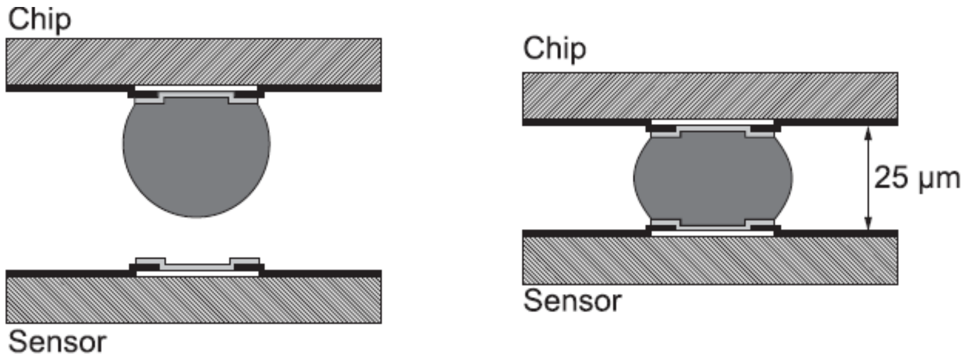
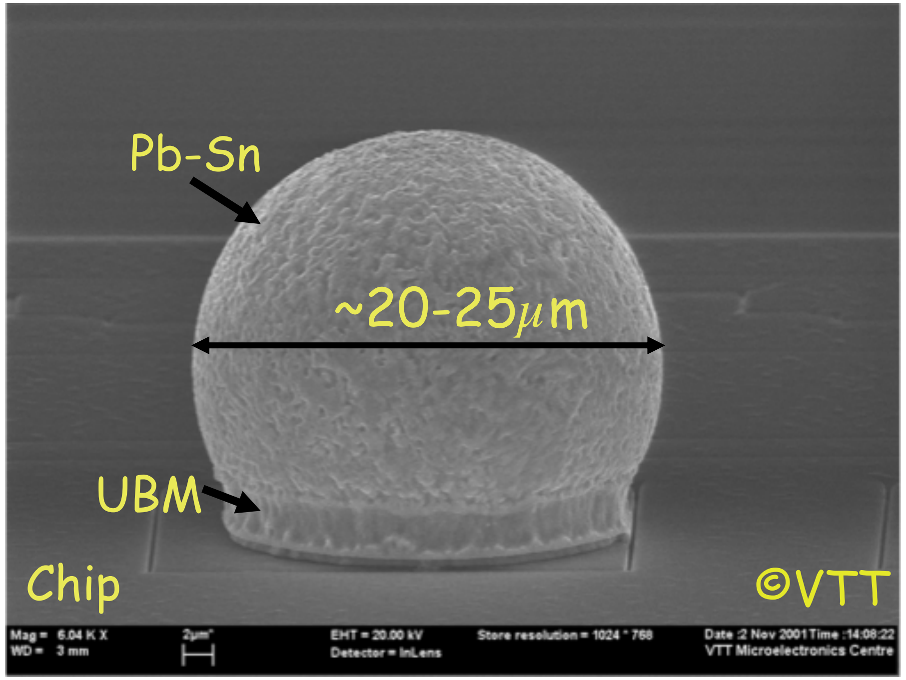




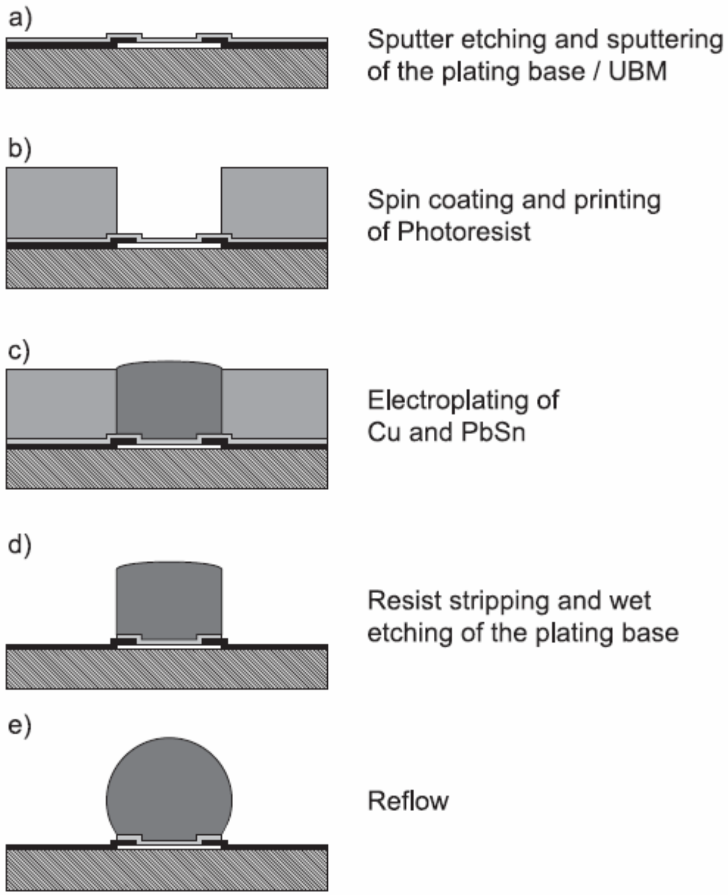
From a Sensor to a Detector

Solder bump-bonding



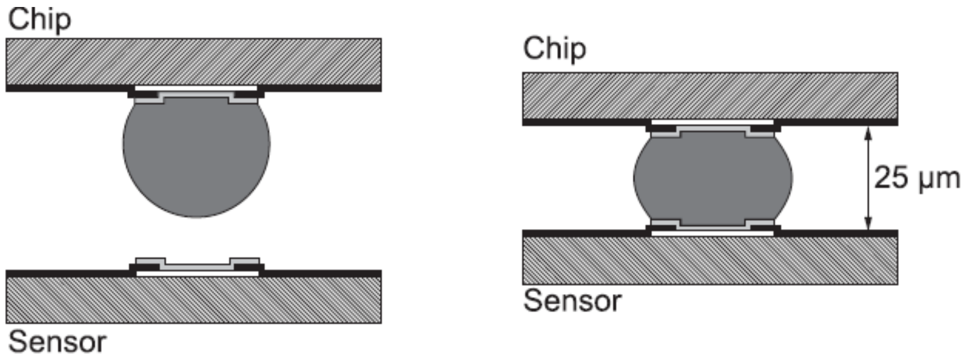


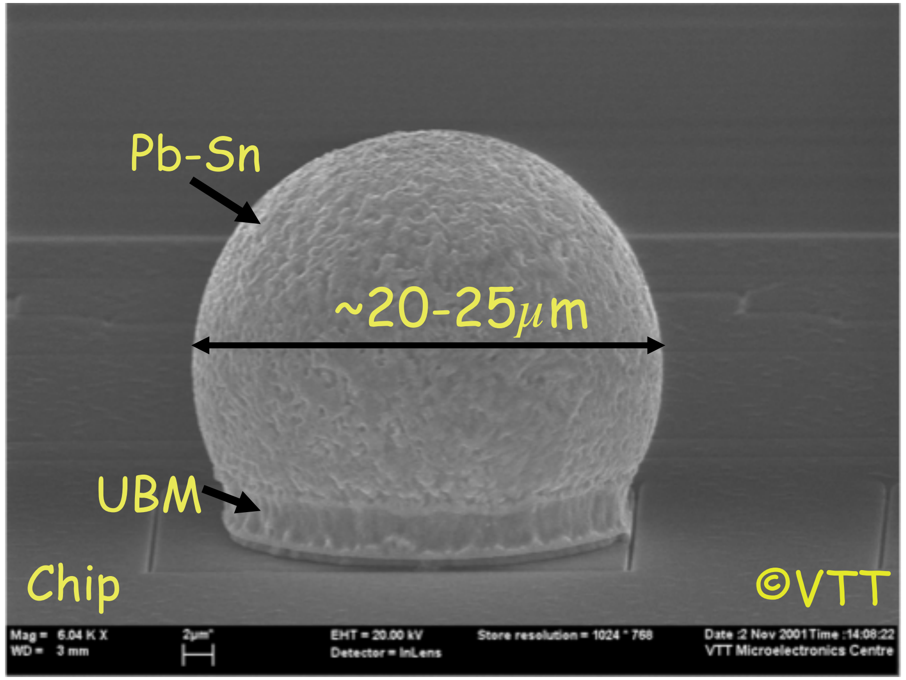
Step 7: Bump-bonding



From a Sensor to a Detector

Solder bump-bonding





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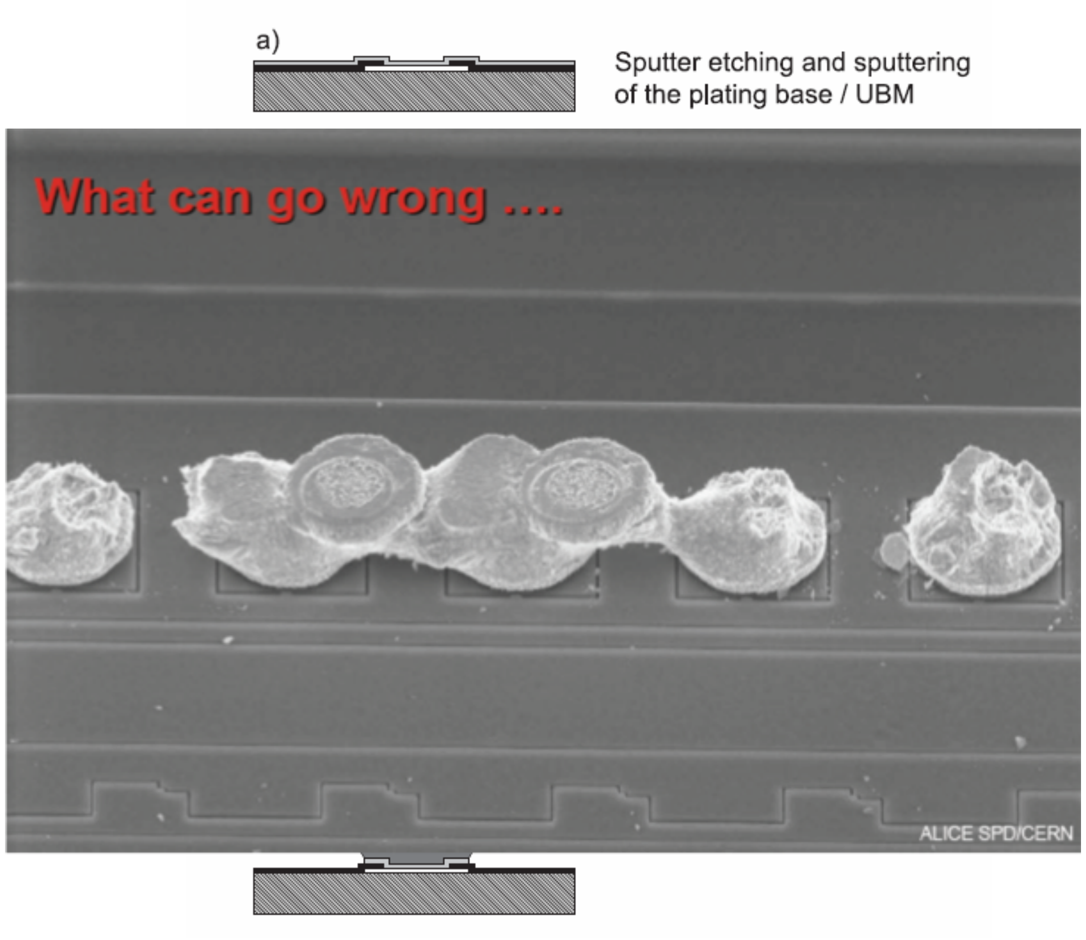
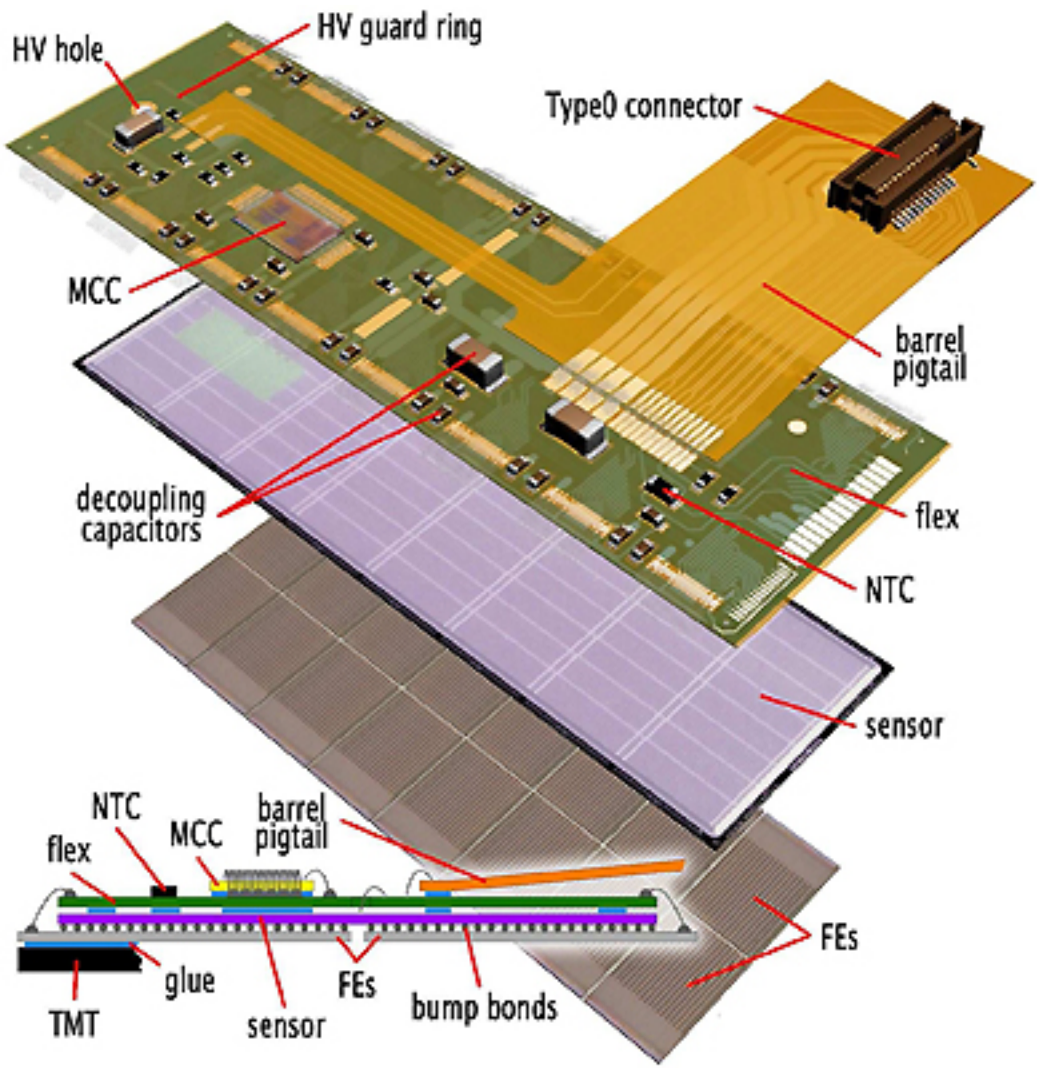


From a Sensor to a Detector

Putting the pieces together

Step 8: Module construction

- example: ATLAS pixel detector module
- 16 front-end chips flip-chipped to one sensor
- flex circuit print to connect the module to the off-detector read-out electronics via a cable
- module controller chip (MCC) combines the data streams of all front-end chips



Application of Pixel Detectors

Tracking detectors

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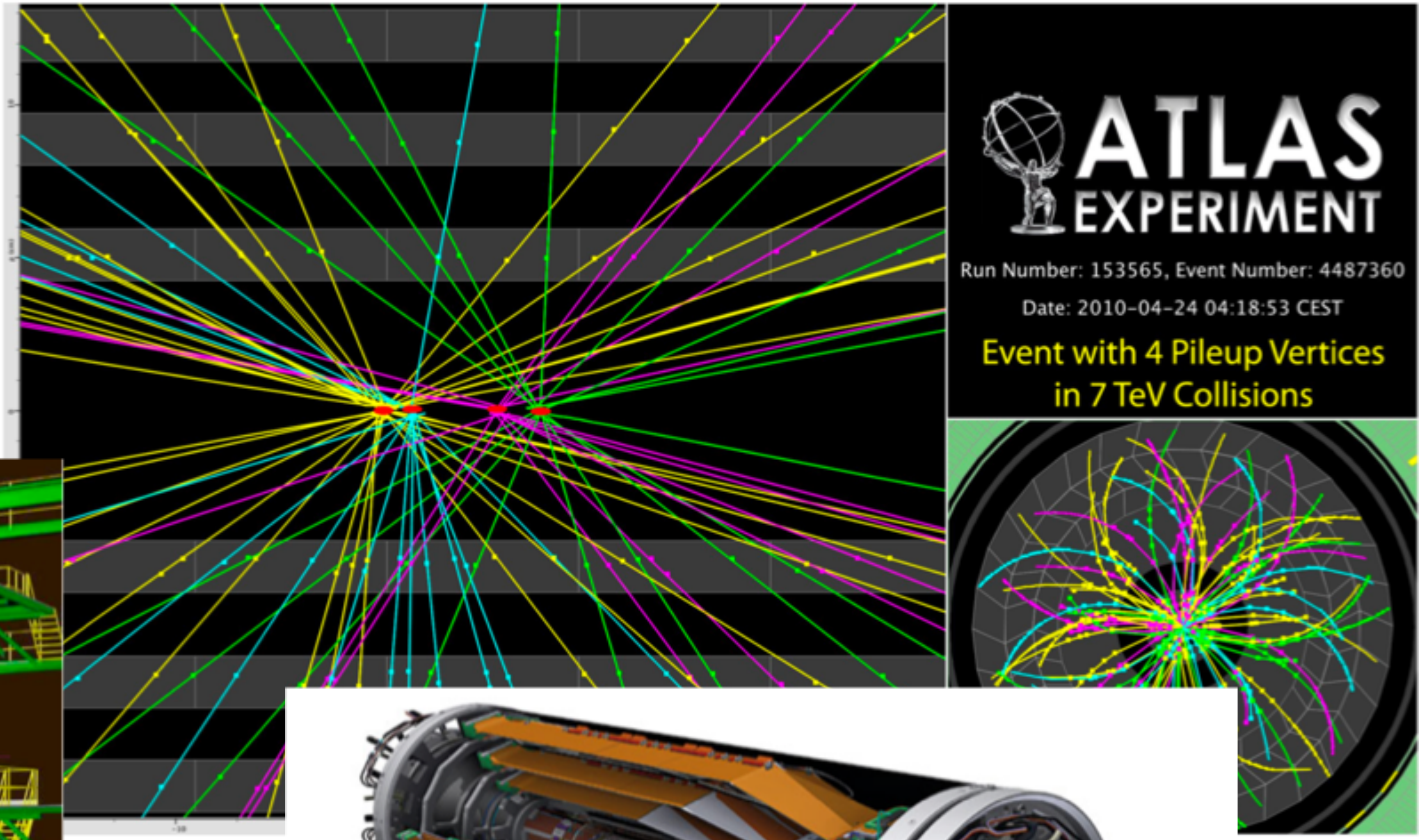
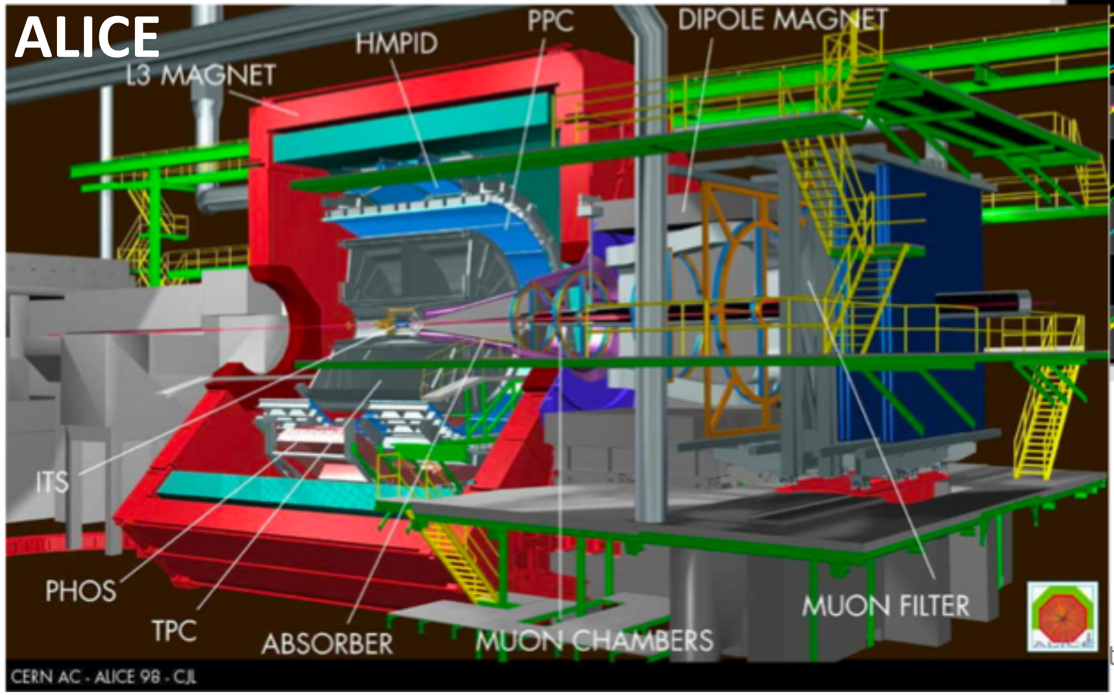
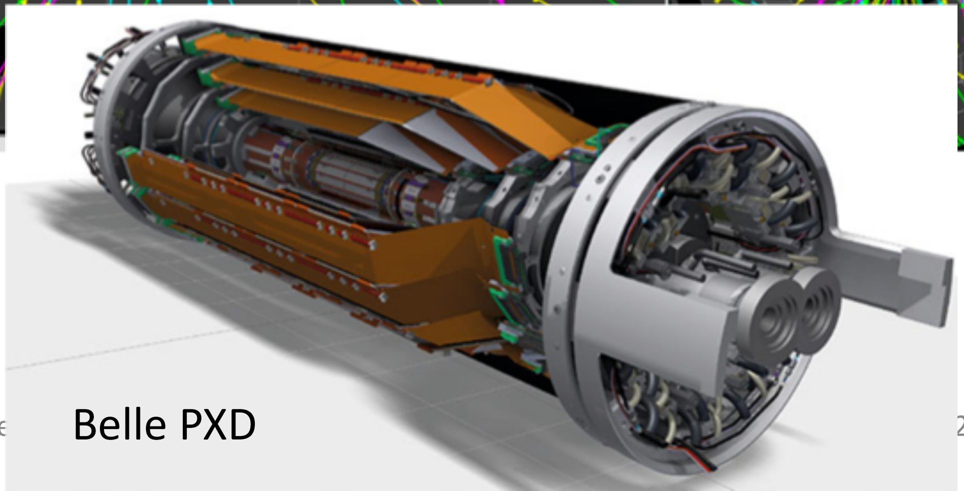
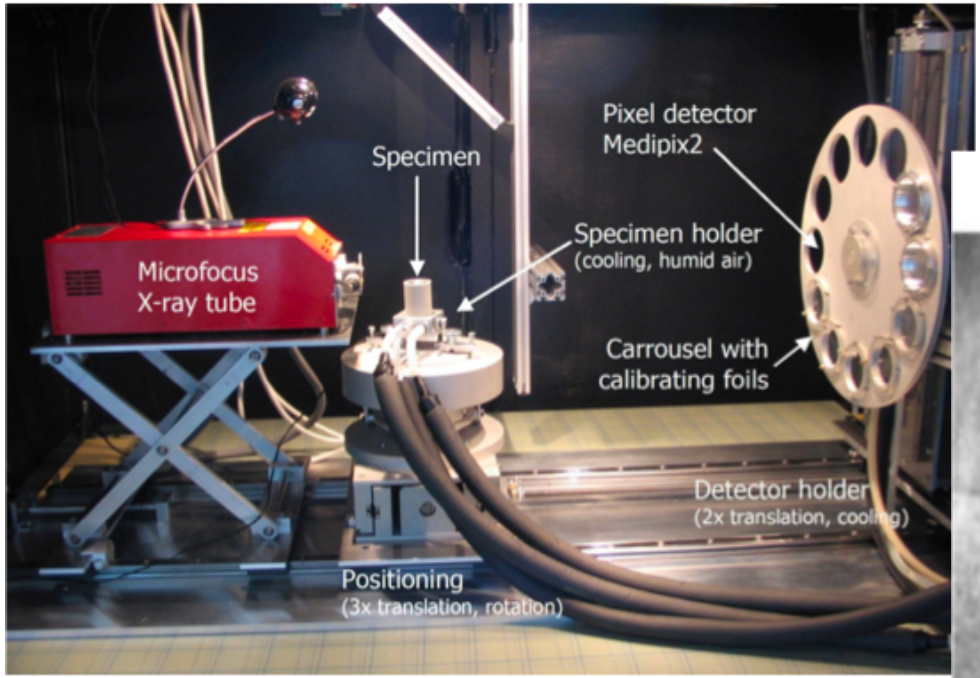
- pixel detectors are widely used as tracking detectors in HEP experiments
- detect charged particle tracks to locate vertices and measure momentum

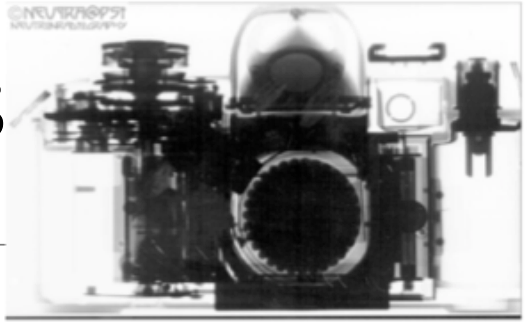


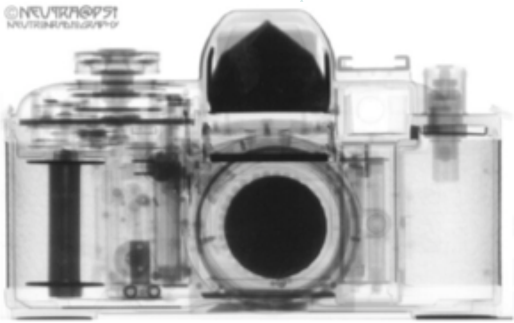


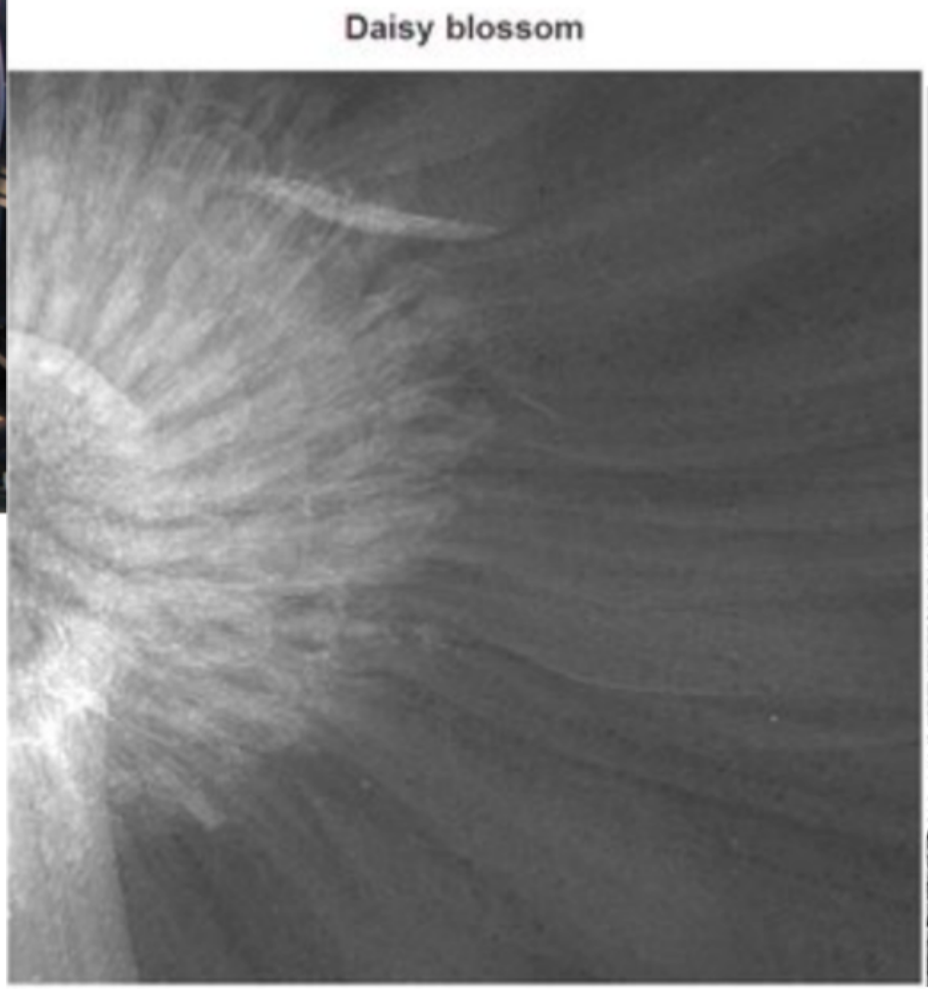


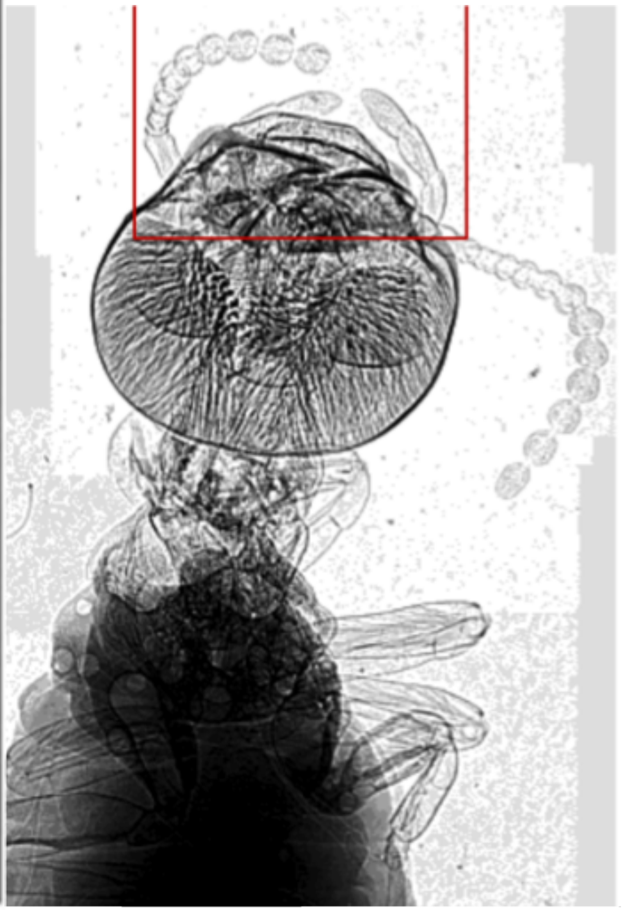
Application of Pixel Detectors
X-ray imaging




x-ray image


neutron image





- pixel detectors can be tailored to detect all kinds of radiation, e.g. x-rays or neutron
- example: Medipix-2 read-out chip (HEP origin)

Application of Pixel Detectors

Optical imaging

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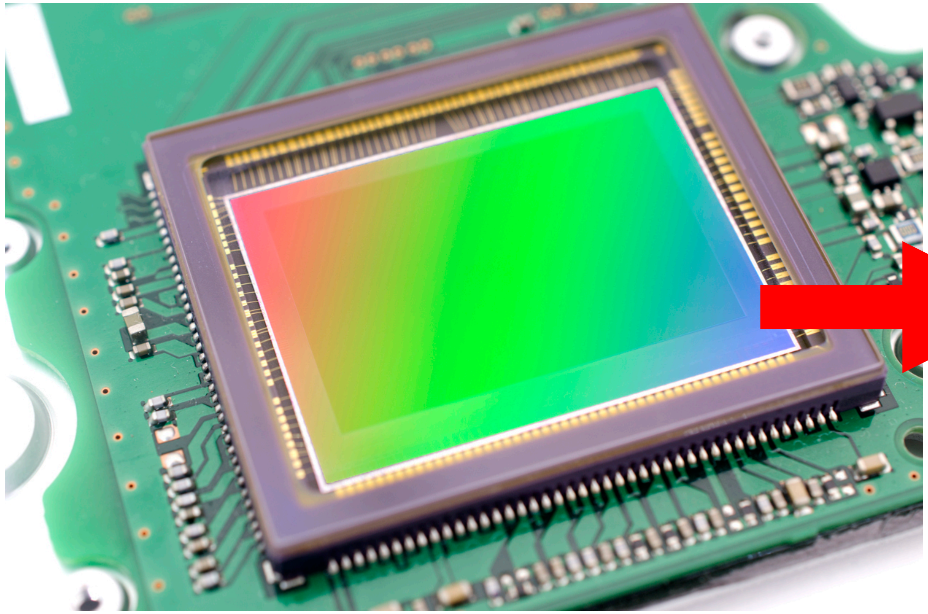

- pixel detectors are used every day in all optical cameras from DSLR to phones
- also: imagining in astronomy from satellites to telescopes

The End

Backup

Title

subtitle

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- text