Hybrid Pixel Detectors

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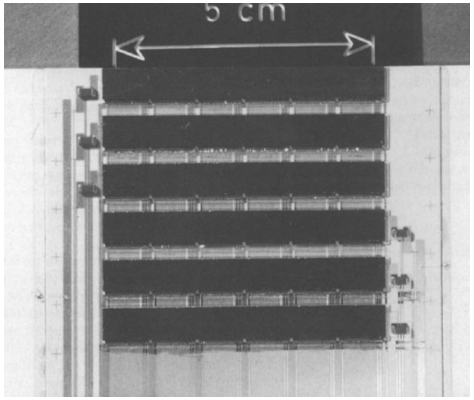
EDIT 2011 Excellence in Detectors and Instrumentation Technologies

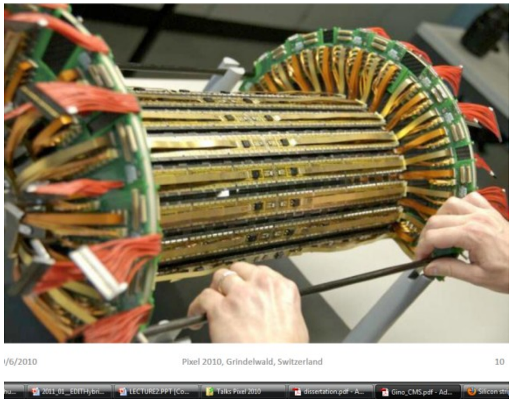
CERN, Geneva, Switzerland - 31 January - 10 February 2011

Silicon Strips and Pixel Technologies

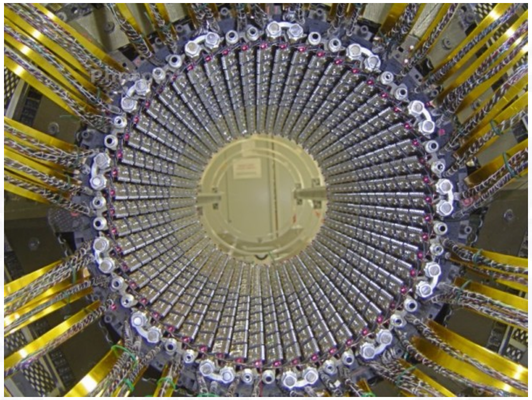
Introduction: Hybrid Pixel Detectors

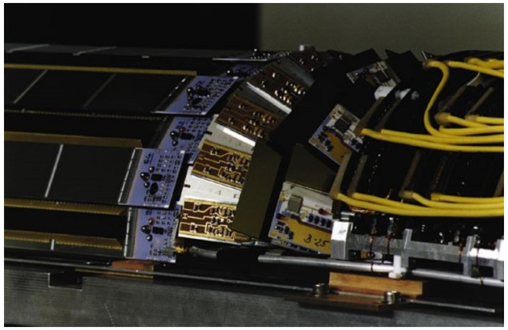


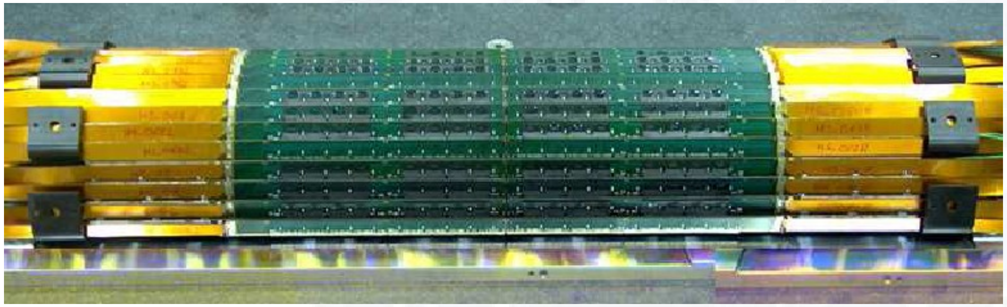
WA97 (1995)



CMS Barrel

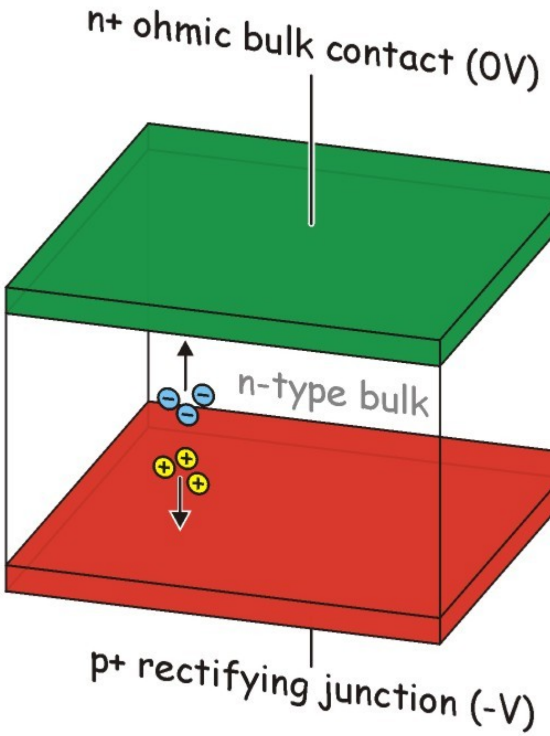

ATLAS Barrel Layer


DELPHI VFT (1996)


ALICE SPD Half Barrel

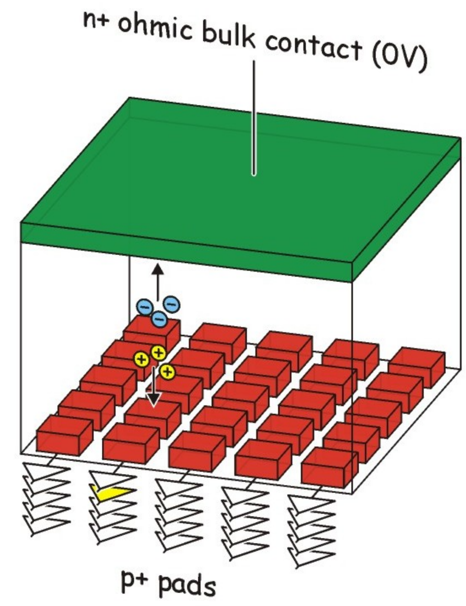
Semiconductor Detectors

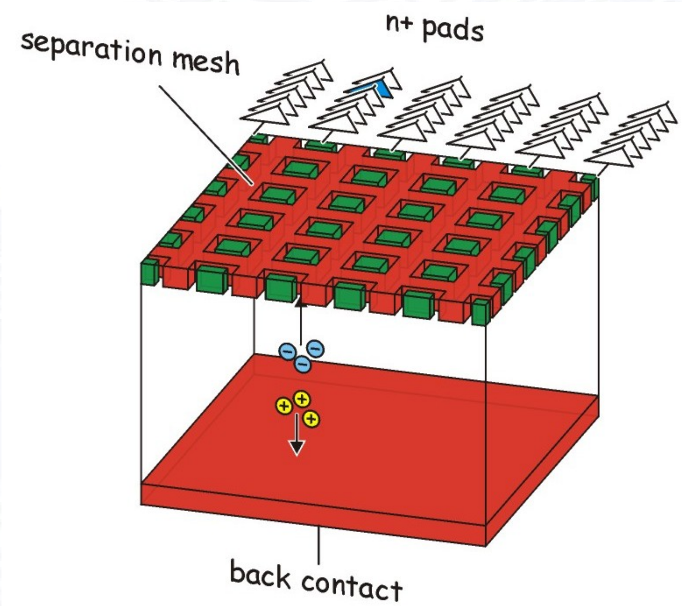
- Reverse-biased p-n-junction (cf. lecture of M. Krammer)
  - Zone with electrical field, free of movable charge carriers
  - Minimum ionising particle generates approximately 10^4 eh-pairs / % X_0
  - Ideal as a particle detector, but no spatial information yet
- Help came from IC industry:
  - Planar process allows “cheap” large scale production of segmented Si detectors



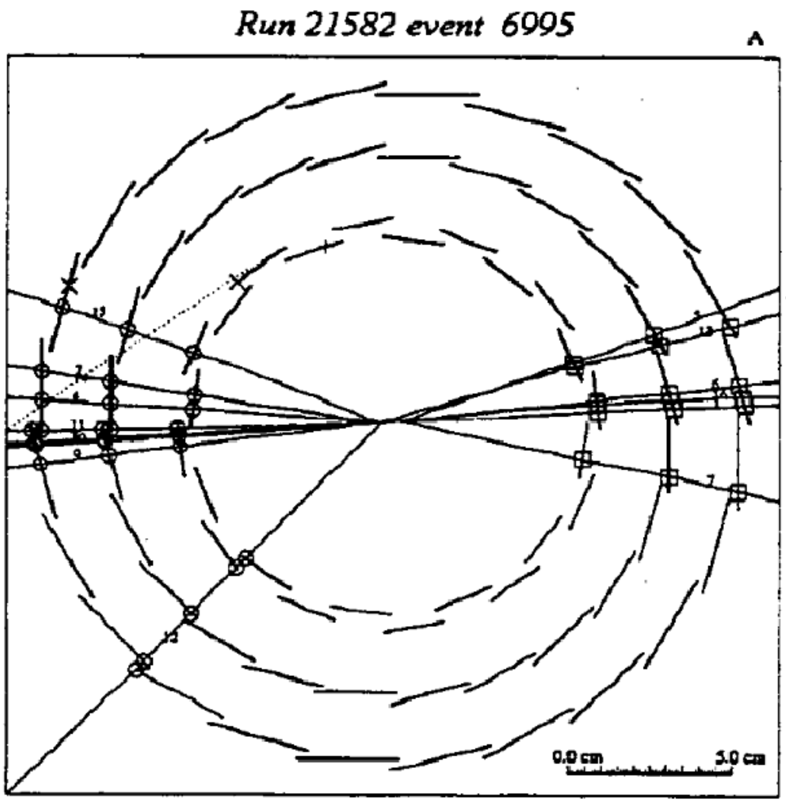
Pixel Detectors

- Segment one electrode into pixels
  - True 2D-information, no problem of ambiguities at high track densities
- Smaller electrode size brings other benefits
  - Lower leakage current → lower noise, better radiation tolerance
  - Lower capacitance → lower noise
- … but also complications
  - Large number of channels, proportional to sensor area
  - Signals of each channel needs to be processed

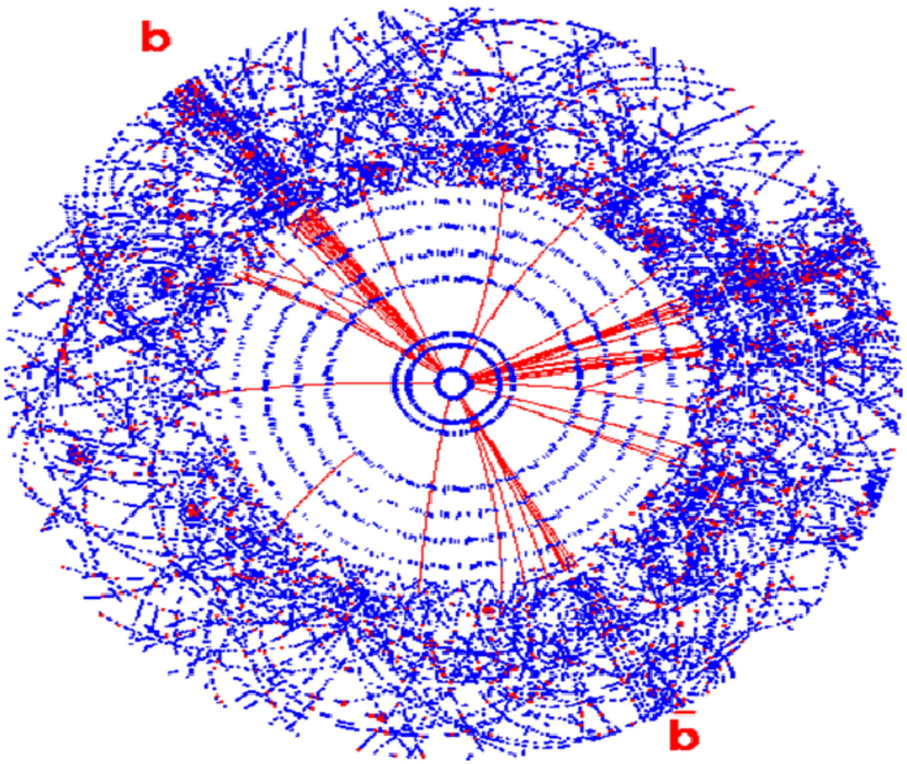




Why Pixels?



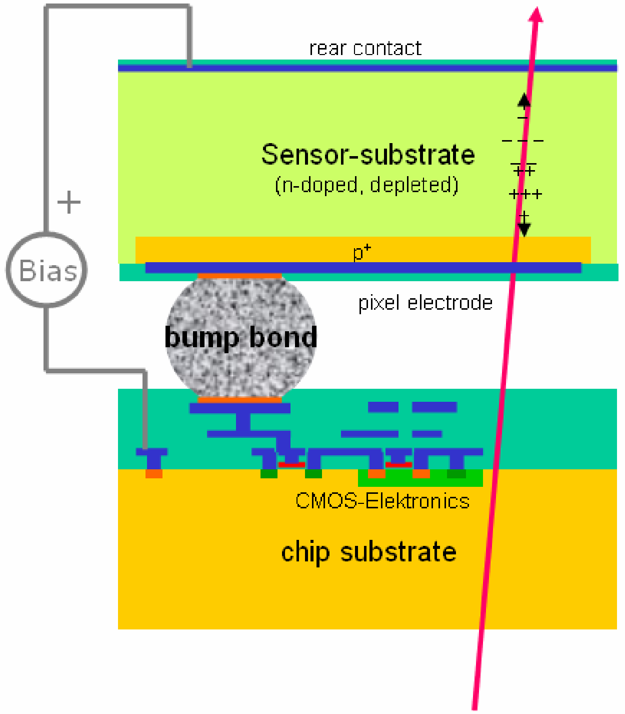
P. Weilhammer, NIM A 342 (1994) 1

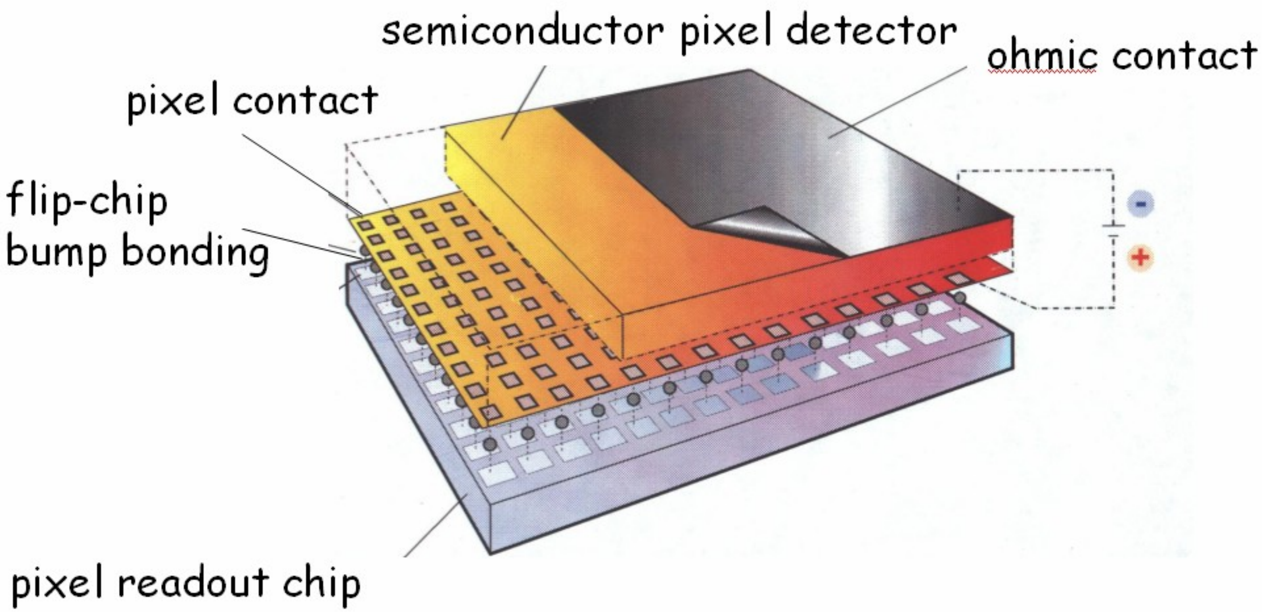


- $Z^0 \rightarrow b\bar{b}$ candidate at LEP (DELPHI Experiment)

- Simulated $H \rightarrow b\bar{b}$ event at LHC in the ATLAS tracker
- Including 22 pile-up collisions
- No chance without 2D-information

Hybrid Pixel Detectors





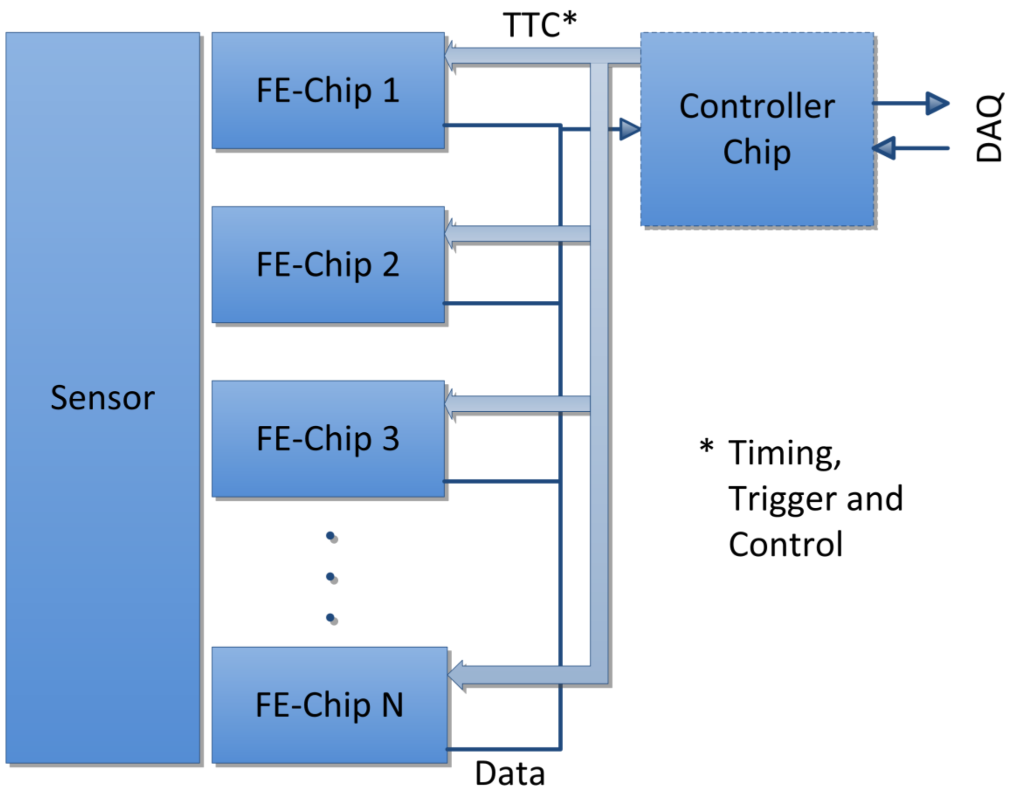
- A hybrid pixel detector is made from two separate chips
  - Signal is generated in the sensor chip, 200 – 300 µm thick
  - Amplification and signal processing in a dedicated readout chip
- 1:1 cell-correspondence between sensor and readout chip
- Connections between sensor and electronics pixels are established with bump bonds

Hybrid Pixel Detectors

- Advantages:
  - Chip and sensor can be optimised separately for the requirements of the experiment, in particular in terms of radiation hardness
  - Fast parallel readout
  - Relatively large signal, low noise (S/N ~ 100)
  - Mature technology
- Challenges:
  - Complex interconnection necessary
  - Readout chip heats sensor → Good cooling necessary
  - High material budget in the sensitive volume (Sensor + Readout chip + Support + Cooling)

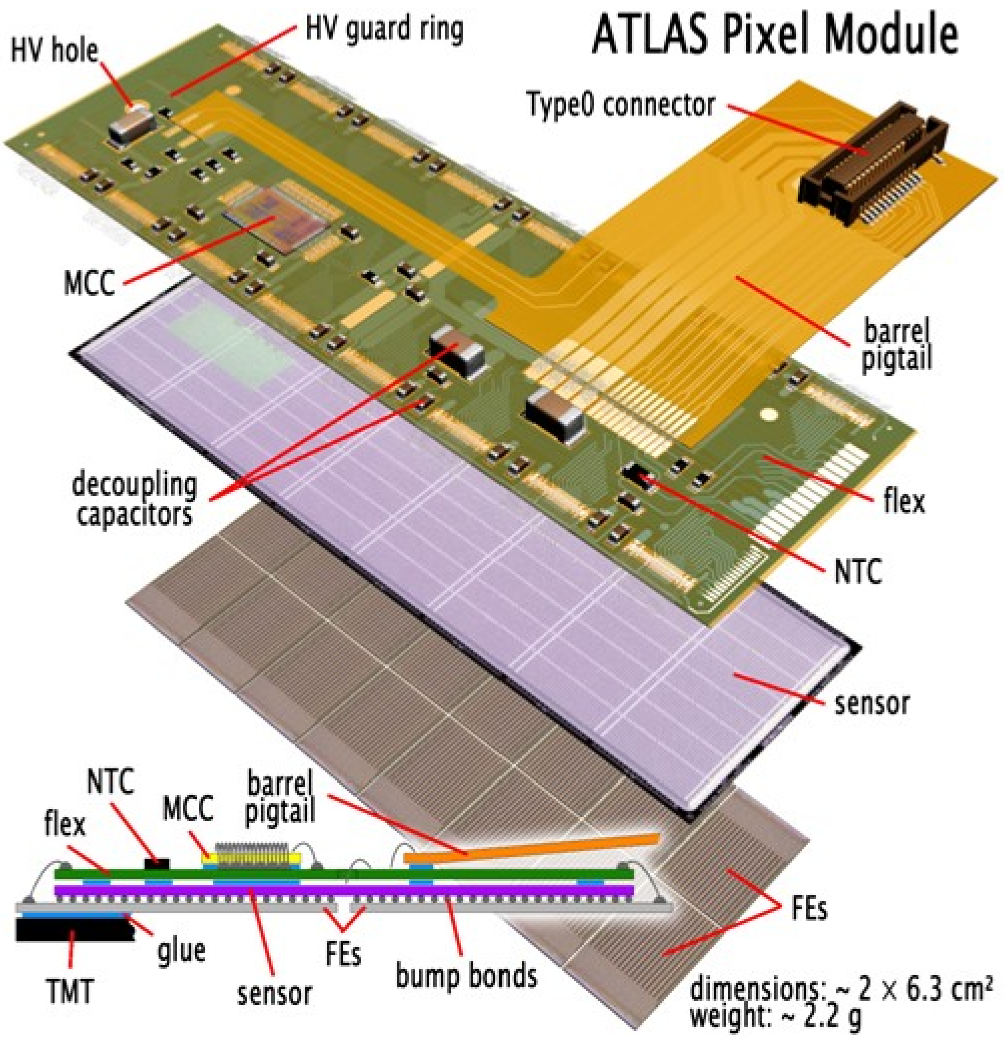
The generic readout chain

- Sensor signals are processed by several readout (front-end) chips
- FE-chips are controlled by on-detector controller chip
  - Controller chip can be on the module or on the ladder or similar
- Controller chip communicates with off-detector data acquisition
  - Typically via optical links (Additional interface-chips for electro-optical conversion on detector- and DAQ-side

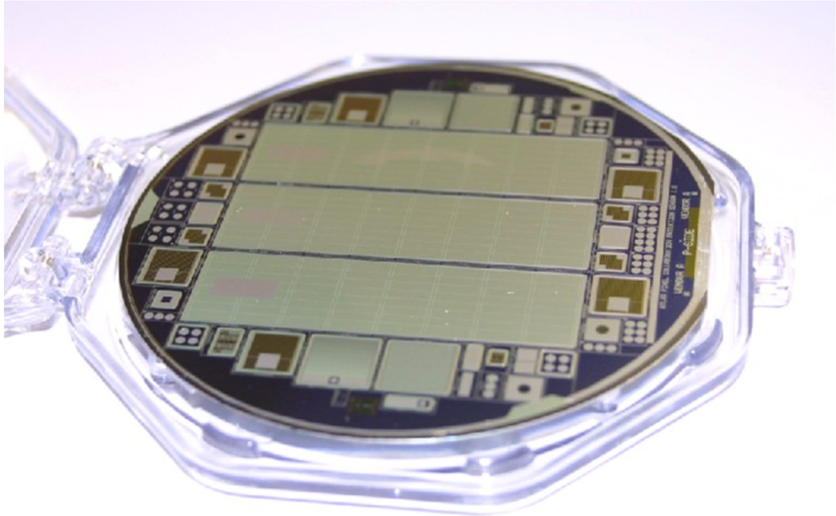


Components of a pixel detector module

- Sensor is connected to FE-chips with bump bonds
  - Here: 1 sensor tile, 16 FE chips in 2 rows
- FE periphery with contact pads sticking out from underneath sensor
- Connected to flexible PCB with wire bonds
- Flexible PCB carries controller chip, passive components and connection to off-module electronics



The Sensor



The Pixel Sensor

- The production of silicon sensor has profited from the developments in microelectronics; but there are also differences:
  - Sensor needs much purer, high-resistivity silicon (→ floatzone process)
  - In microelectronics everything happens in the upper few µm of the wafer – for the sensor the complete volume and in particular also the backplane is important
- Different possible choices for pixel and substrate material type

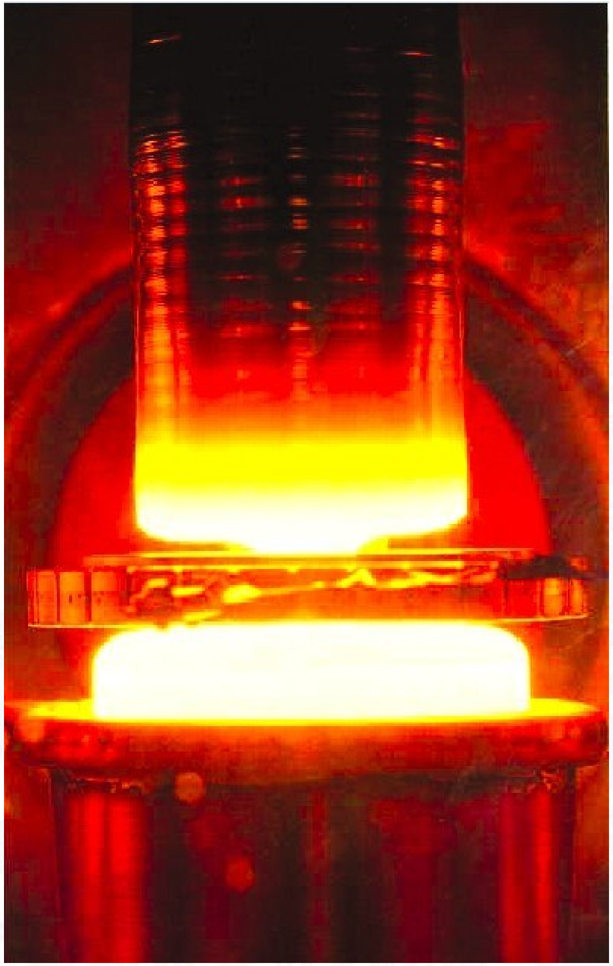
	N-type substrate	P-type substrate
N-type pixel	High radiation tolerance Double sided process → expensive	Single sided process No type inversion Less developed approach
P-type pixel	Single sided process Low radiation tolerance	Double sided process No advantage with respect to n-on-p

- The design of the pixel sensors has to take into account the requirements in terms of efficiency, stability and radiation hardness

Floatzone Process

- A polysilicon rod is mounted with a seed crystal in an inert atmosphere
- A small zone of the rod is melted by a movable RF-heater
- This floatzone is slowly moved through the crystal, at the end of this zone the silicon freezes to a single crystal
- Most impurities remain in the molten phase
- Produces very pure silicon as needed for sensors

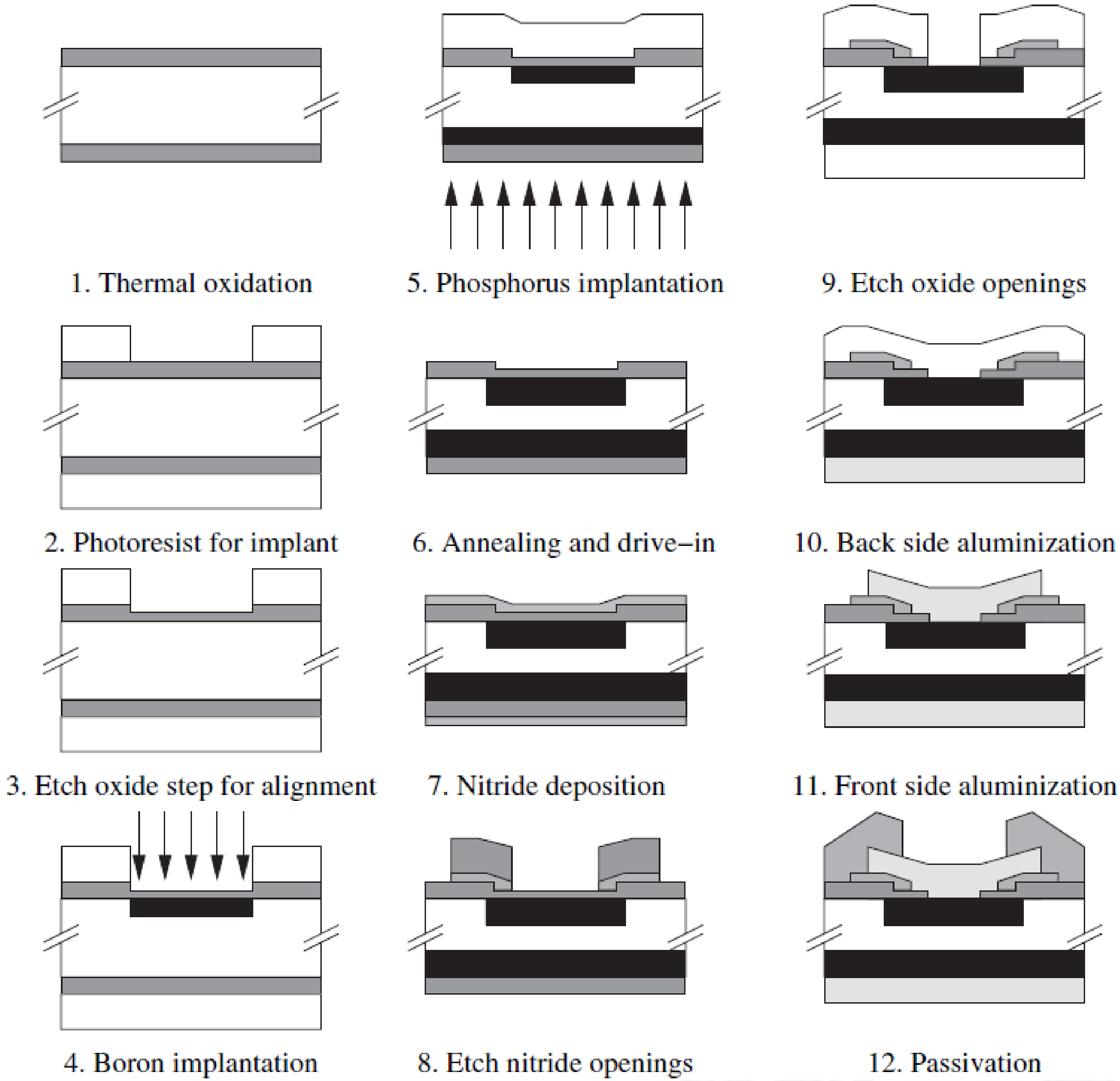
- Ingots are cut into wafers, which are then lapped and polished



Sensor Processing

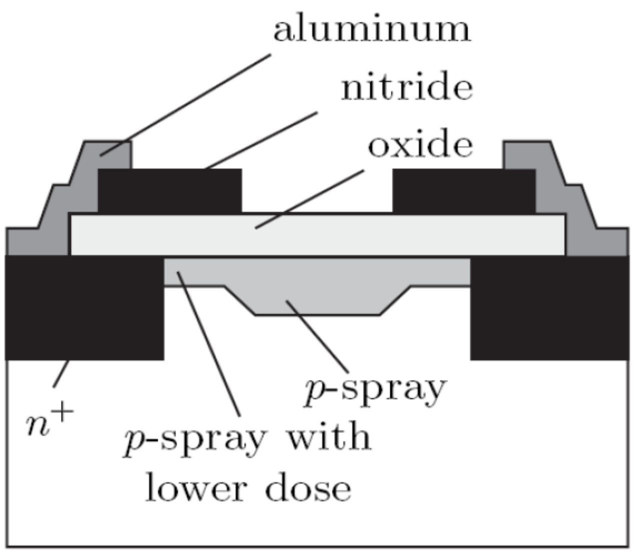
- Sensor processing is a sequence of
  - Thermal treatments (e.g. for thermal oxidation or annealing steps)
  - Photolithography
  - Etching
  - Doping (by diffusion or ion implantation)
  - Layer deposition of insulators (oxides, nitrides) or metals (Al)
- Spatial precision usually less critical than in microelectronics, but purity is much more important
- Double sided processing, cost depends on the number of structured masks

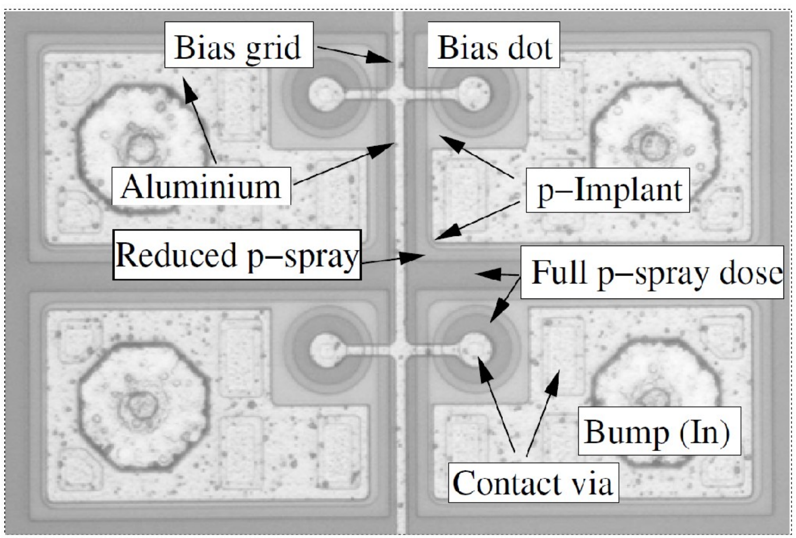
Sensor Process Flow (Example)



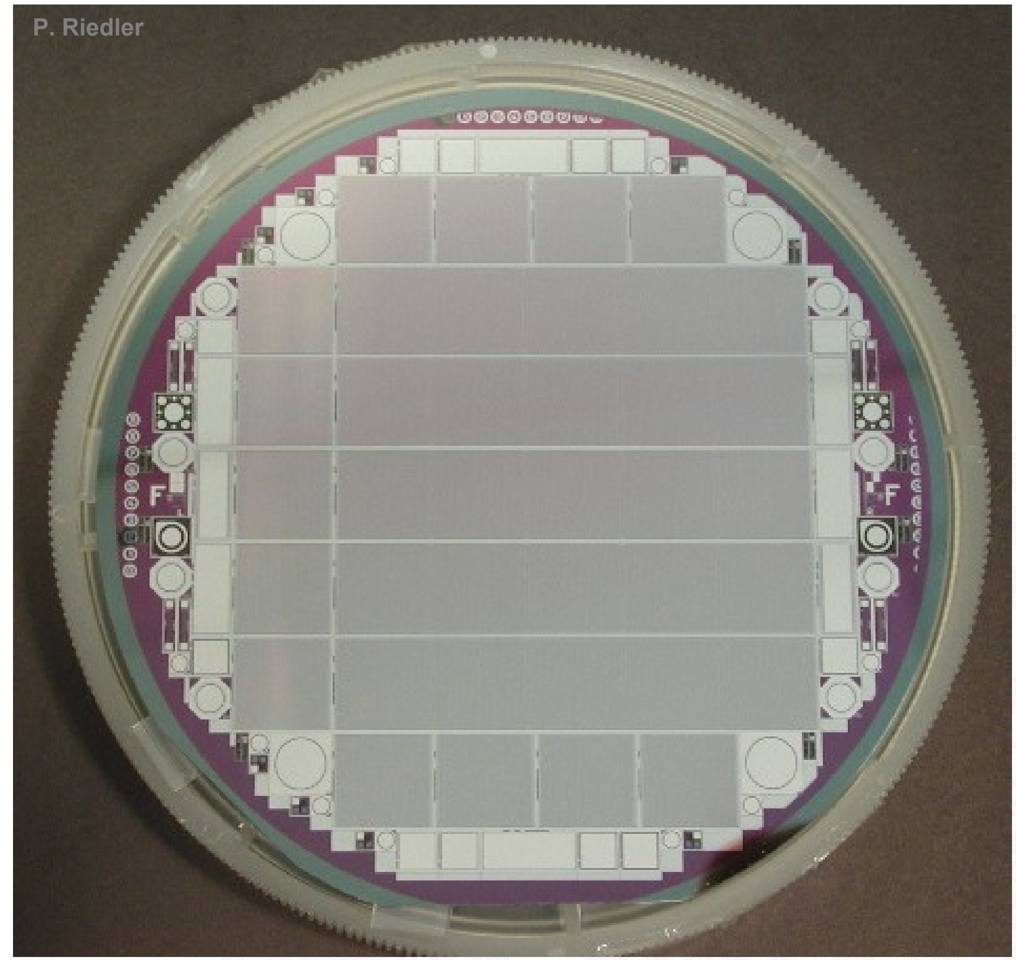
From: Fischer, Rohe, Rossi, Wermes: Pixel Detectors

Sensor – Schematic and Reality



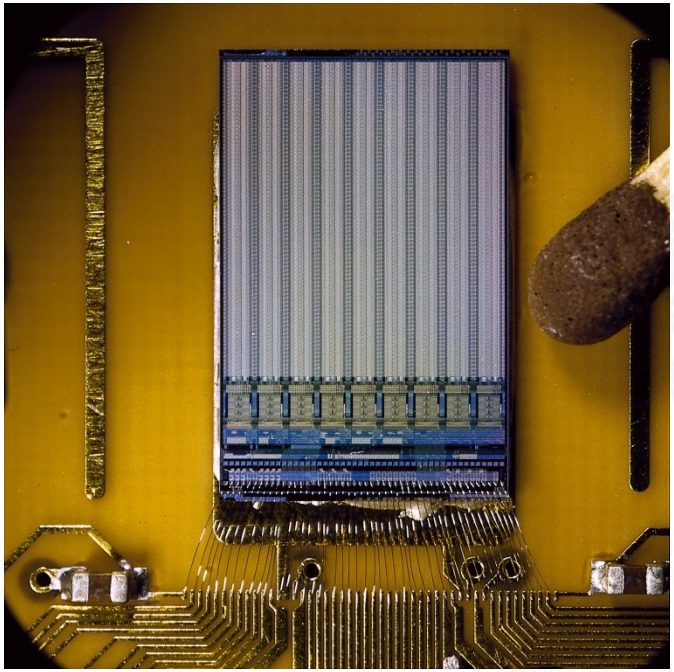


Four pixels of a CMS barrel pixel sensor



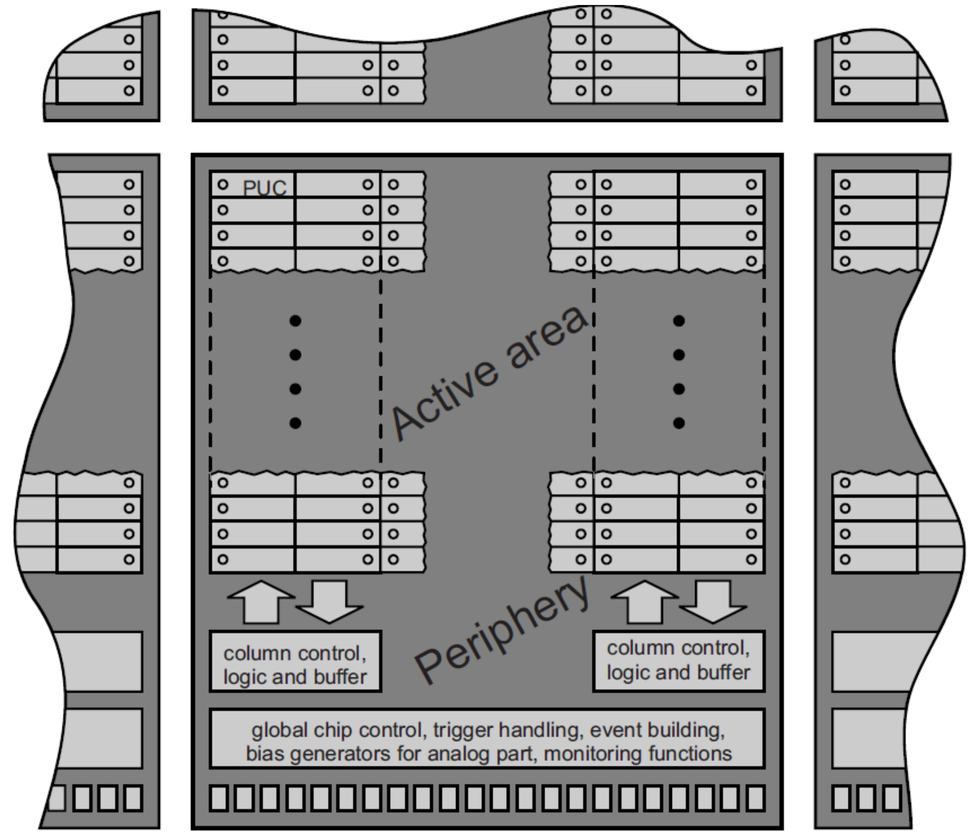
ALICE sensor wafer

The Frontend Chip



The FE-Chips

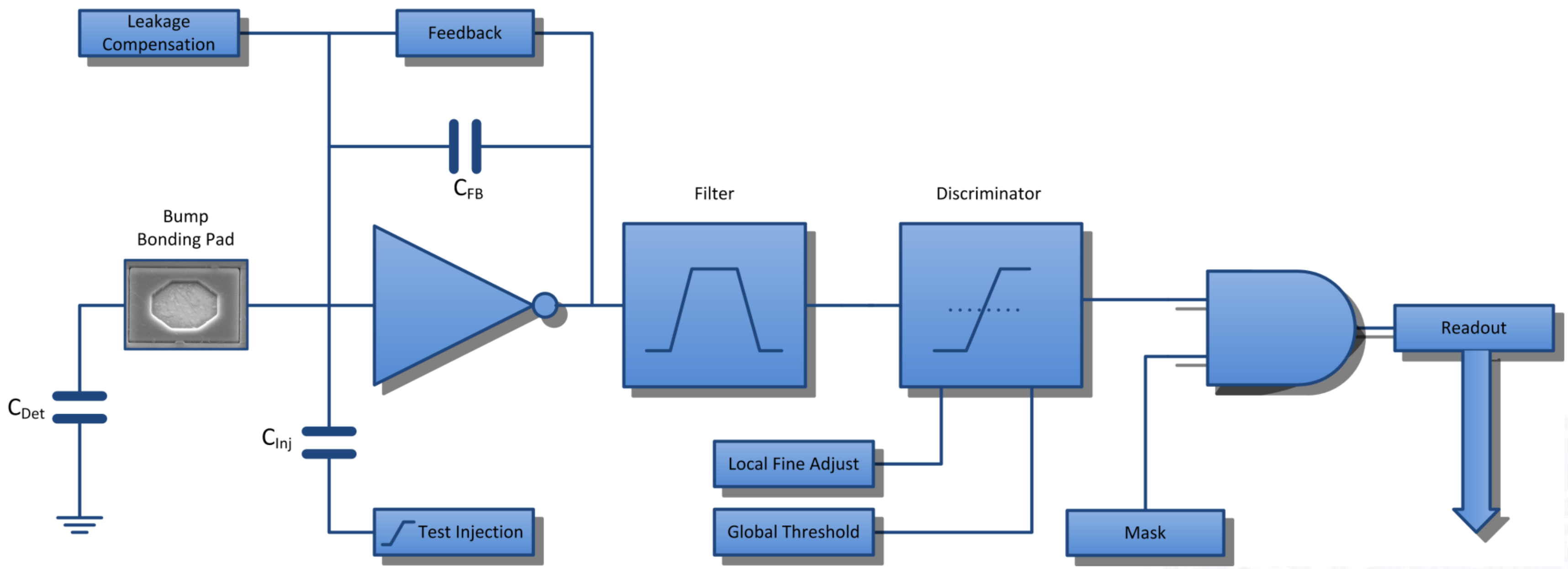
- Usually several smaller FE-chips read out one sensor tile
  - Sensor size is limited by wafer size and bump bonding requirements (flatness)
  - Electronics chip size limited by yield considerations (+process rules)
- Signal processing steps in the FE-chips:
  - Amplification of sensor signal
  - Hit decision
  - Hit storage
  - Trigger validation
  - Readout of triggered hits



From: Fischer, Rohe, Rossi, Wermes: Pixel Detectors

- First two steps are always done in the pixel cell, in some designs more
  - Readout architecture depends on hit rate, trigger rate, trigger latency and geometric constraints

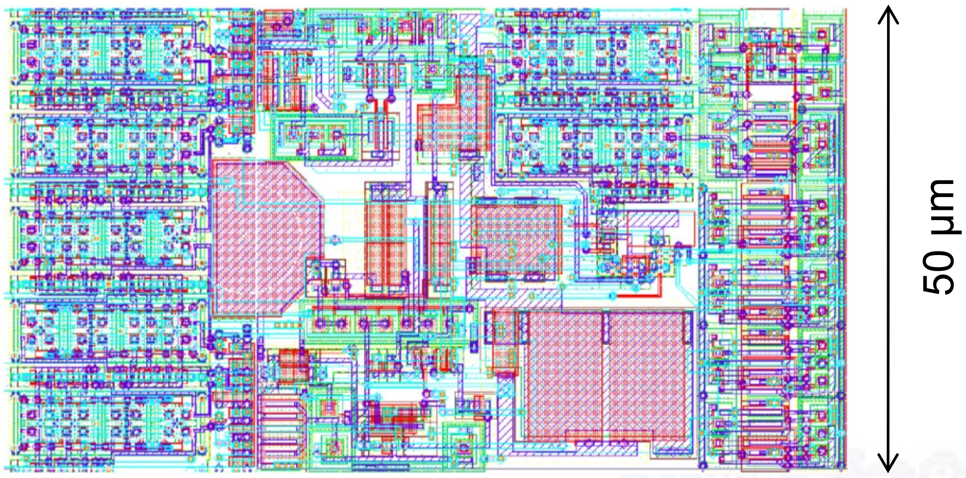
A Pixel Unit Cell



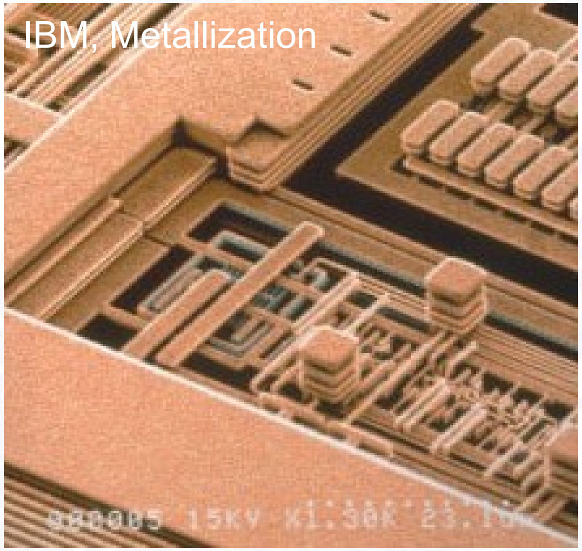
- Integration of signal charge
  - In 250 µm Si: Most probable value 19000 e, but consider charge sharing between pixels, smaller charge depositions, radiation damage
- Hit decision
- Transfer of hit data to periphery
- Swiss army knife: many (conflicting) requirements: fast, low noise, low power consumption

Electronics Design

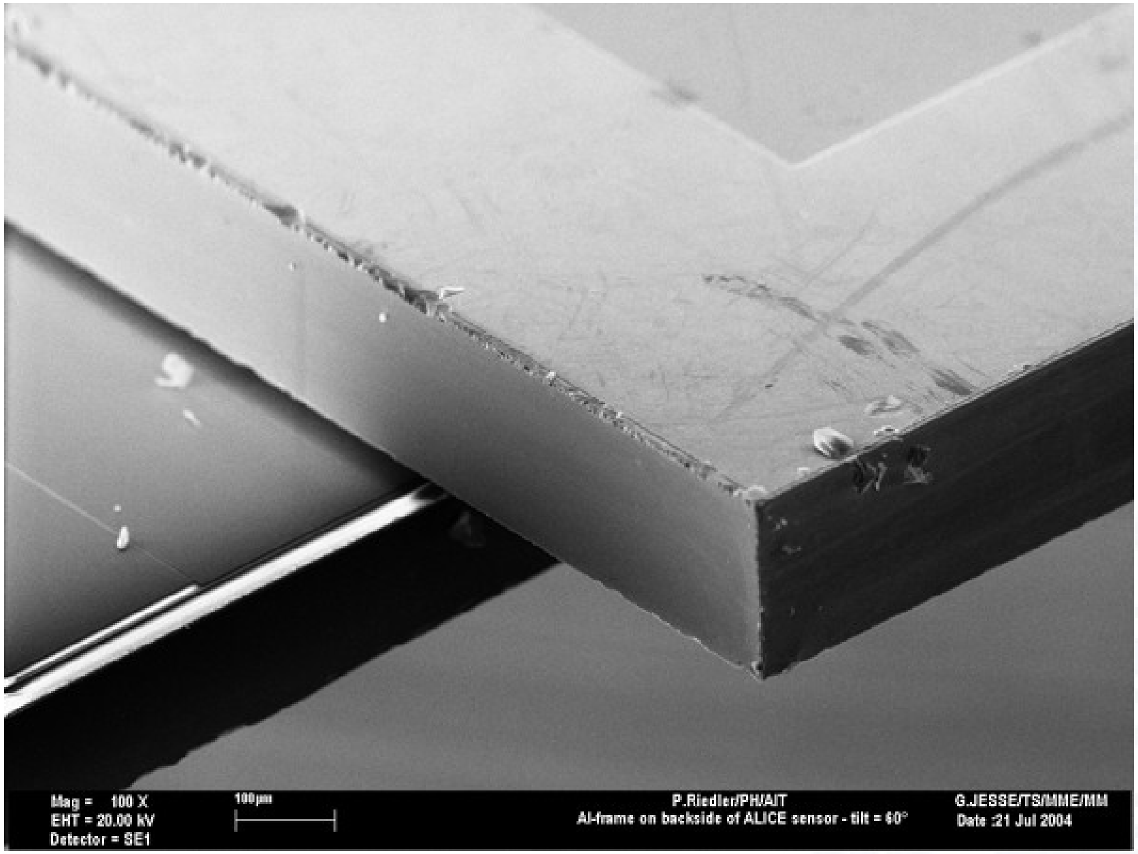
- Pixel chips use commercial microelectronics processes
- However the designs are “full-custom”
- Optimised for radiation hardness (non-standard design rules)
- Layout challenge: implement all necessary functionality in the area of a single pixel
  - LHC-type chips: 500 – 1000 transistors per pixel cell
- Mixed designs (analogue and digital)
  - Careful shielding necessary to avoid injection of noise



P. Fischer, CERN-2002-003, p.91



Bump Bonding



Bump Bonding

- Connection between chip and sensor is established with bump bonds
- Process used in industry, but pitches needed in HEP are typically smaller than industry standard
- Two main process parts:
  - Bump deposition
  - Flip-chip assembly
- Bump deposition usually done on wafer-level
- Electronics wafers are thinned after bump deposition (e.g. 750 µm → 150 µm)

- Two main techniques in HEP:
  - Electroplated solder bumps
  - Indium bumps

Solder Bumps

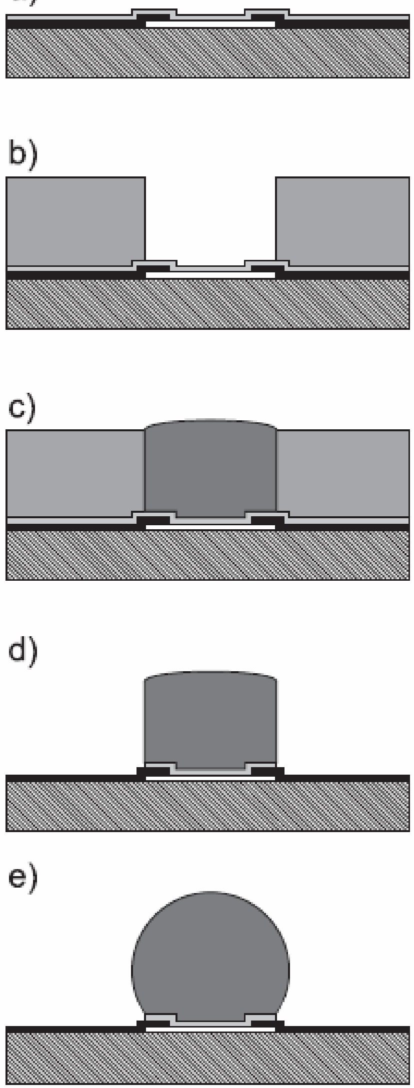
a) Sputter etching and sputtering of the plating base / UBM

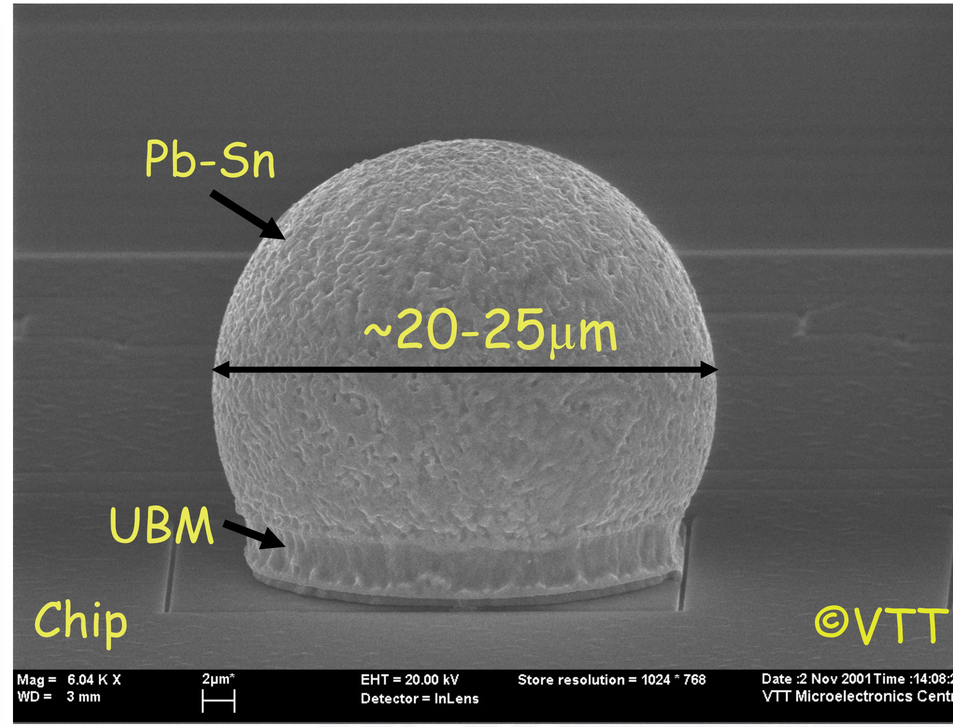
b) Spin coating and printing of Photoresist

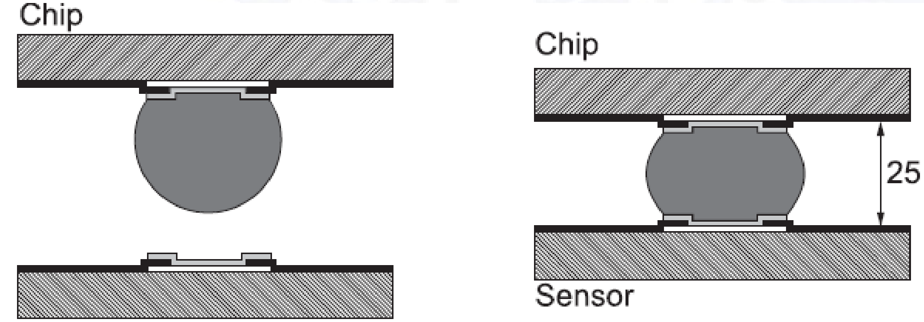
c) Electroplating of Cu and PbSn

d) Resist stripping and wet etching of the plating base

e) Reflow

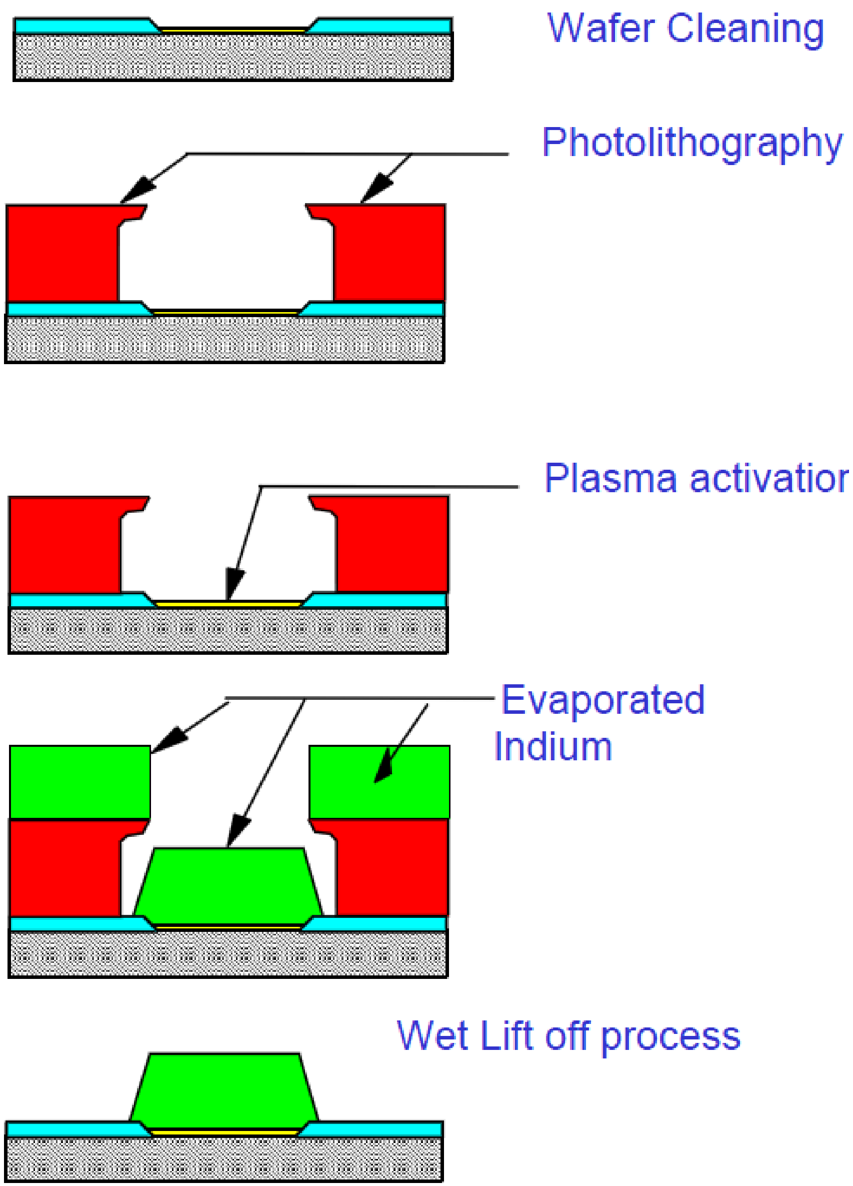




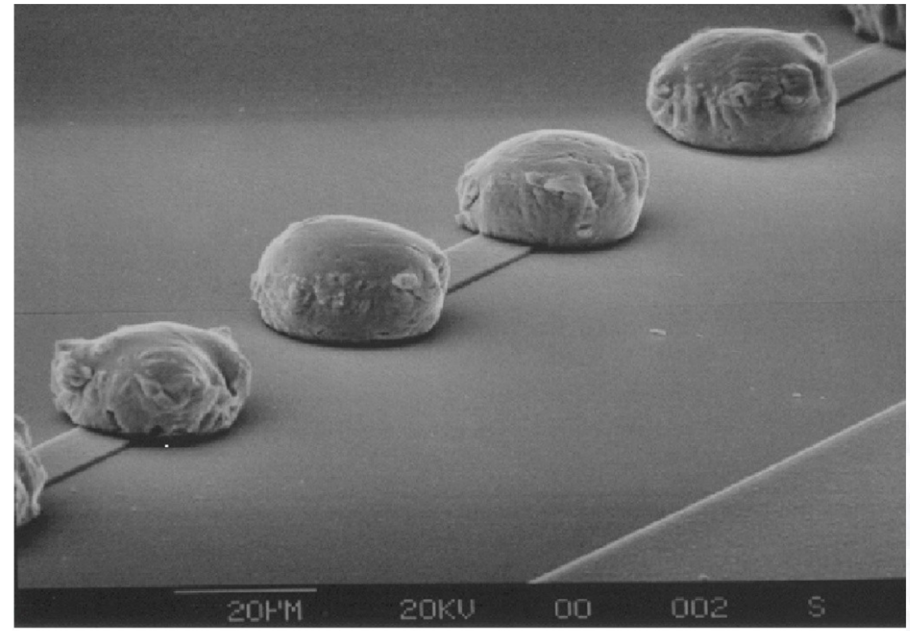


Fischer, Rohe, Rossi, Wermes: Pixel Detectors

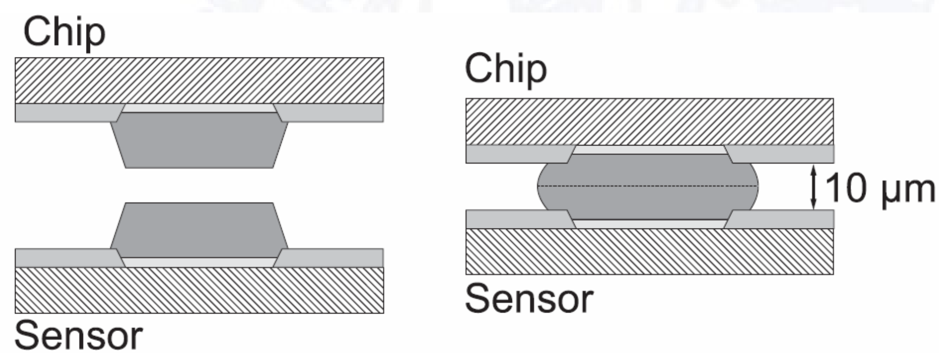
Indium Bumps



Alenia Marconi Systems

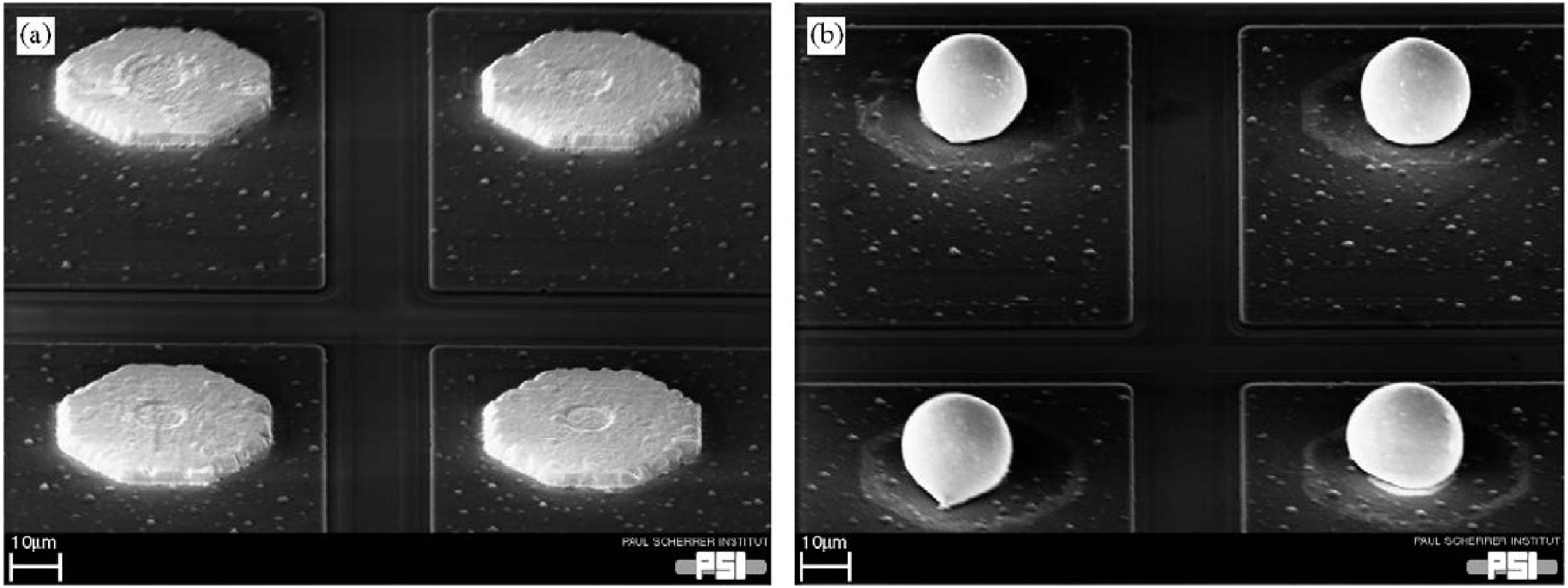


Alenia Marconi Systems, Rome



Indium with Reflow

- The standard In process does not include a reflow step
- One worry: small distance between readout chip and sensor could lead to noise injection
- Process used in CMS (pitch 100 μm): Indium bumps with reflow
  → distance sensor – readout chip approx. 15 μm

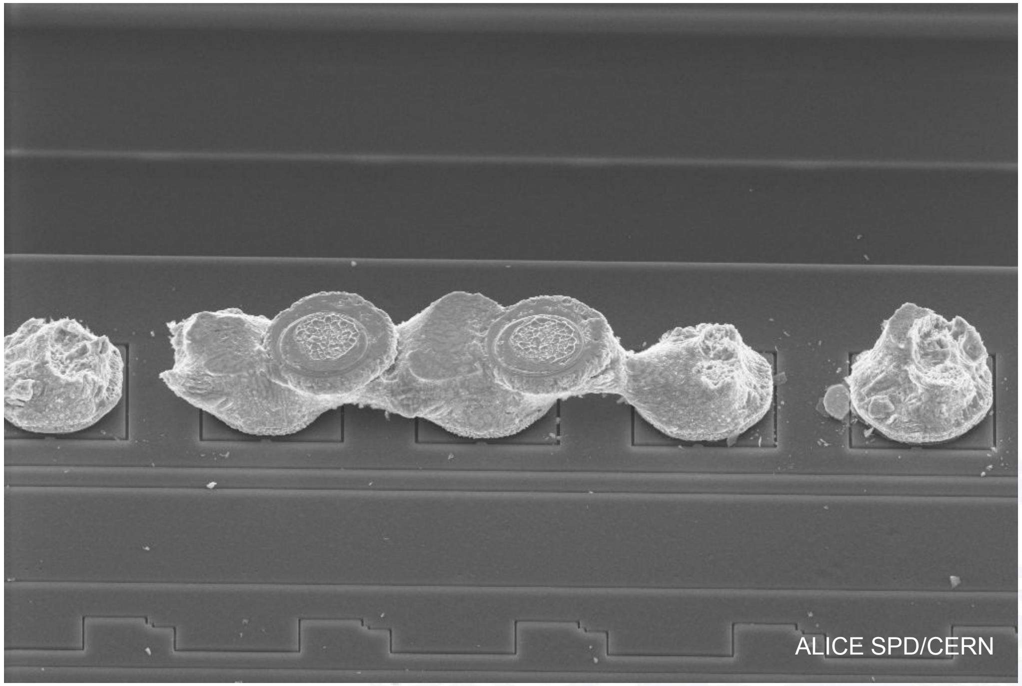


Ch. Broennimann et al., NIM A 565 (2006) 303 – 308

What can go wrong

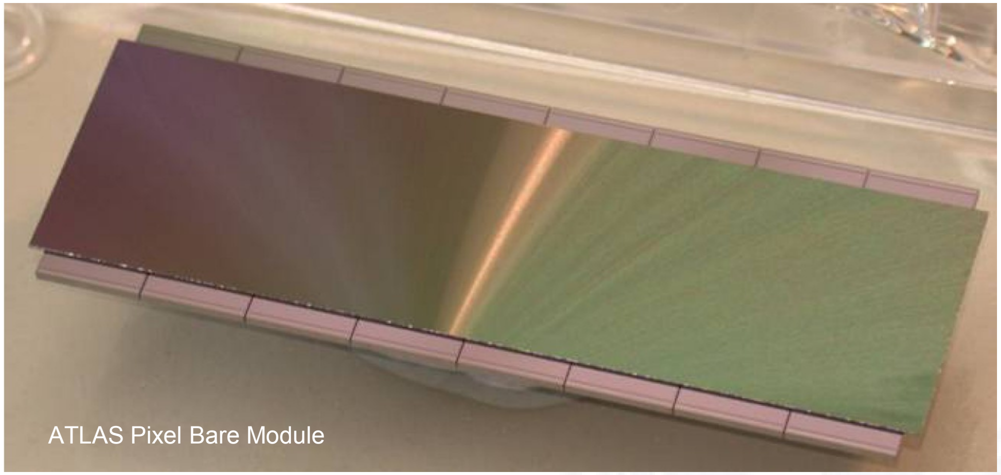
- Many possibilities for failures:
  - Missing or merged bumps (single dead pixels)
  - Mechanical defects, from chipped edges to broken wafers ("best" case: increase of currents, worst case: complete chips lost)
  - Incomplete removal of photo resist (if on wire bond pads, no bonding possible)
  - …

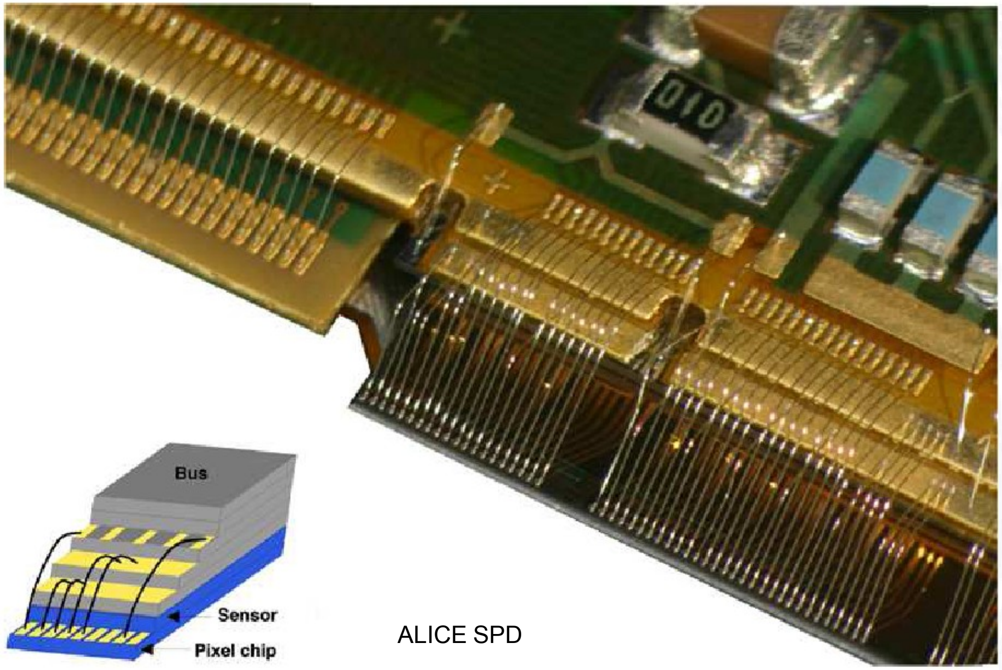
→ Careful inspection and testing after all process steps



Module “Dressing”

- In most cases signals and power are routed to the FE chip in a flexible PCB on top of the sensor
  - Problem: fast signals, low voltage drop with low material budget
- FE chips have contact pads at their periphery; these are connected with wire bonds to the PCB
  - Thin Al wires, contact is established by ultrasound welding

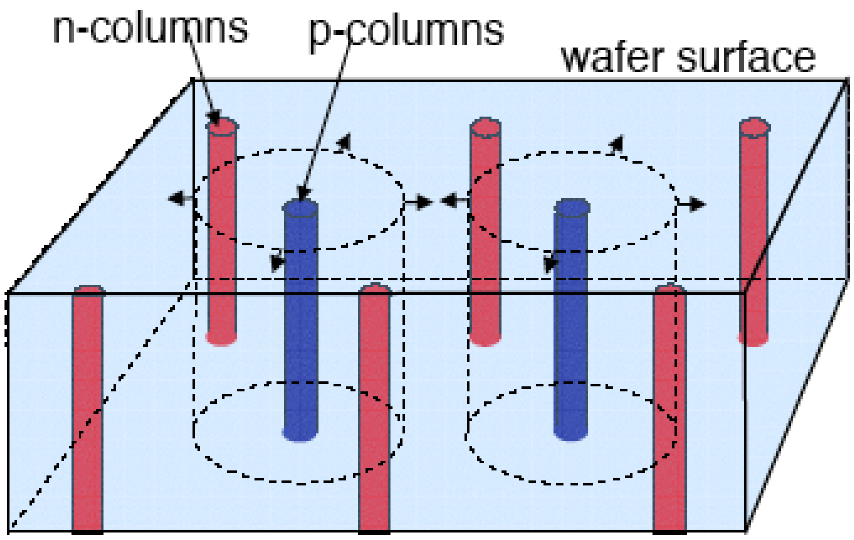

ATLAS Pixel Bare Module

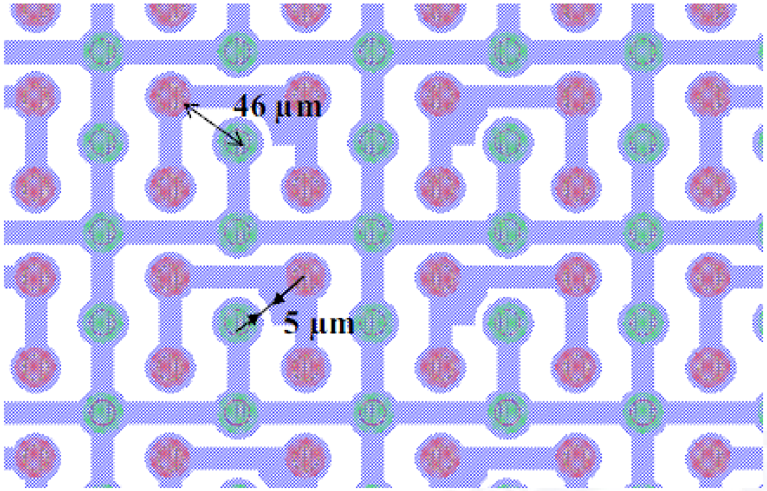


ALICE SPD

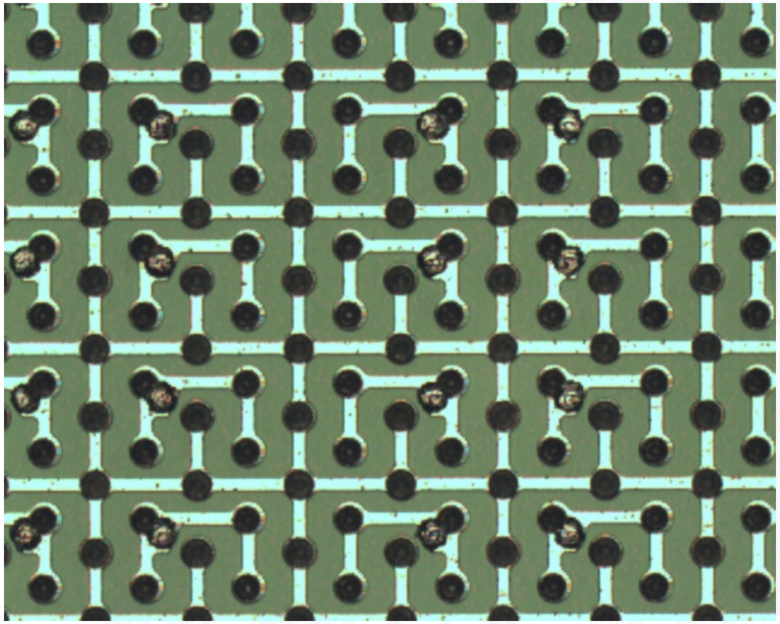
Other sensors than planar silicon sensors…

3D Pixel Detectors





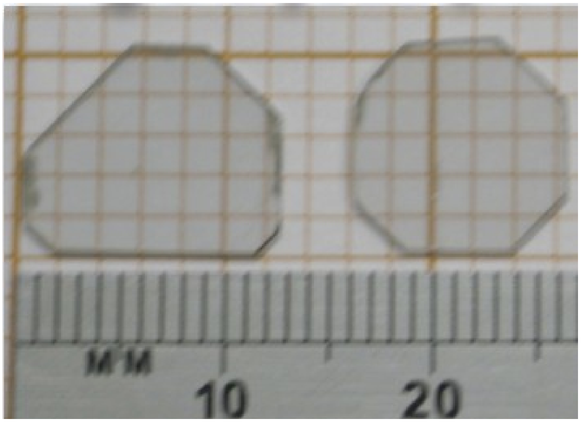
CMS 3D prototype sensor

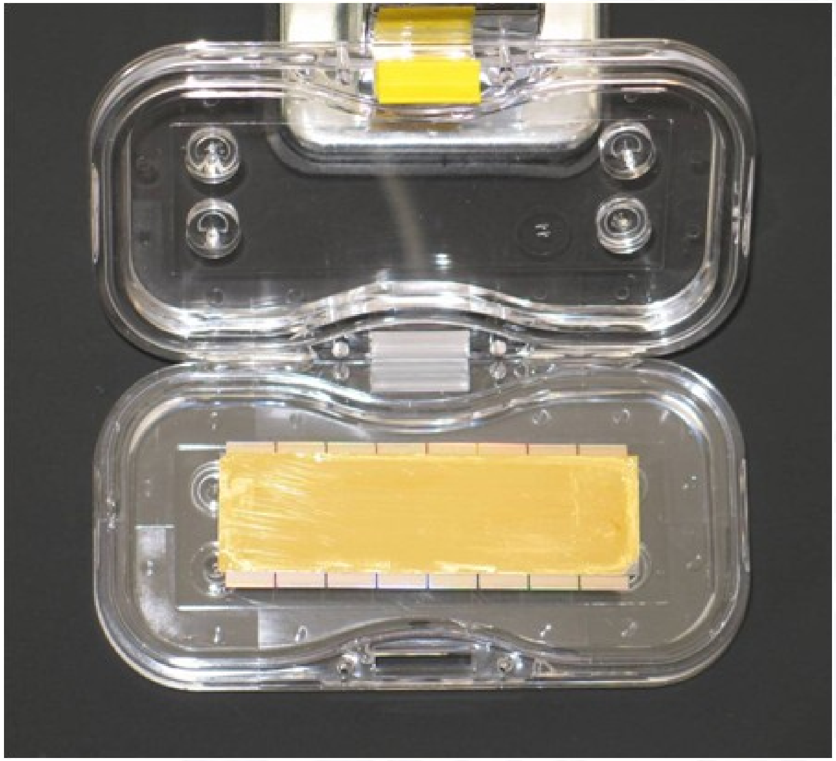


- Lateral depletion ($V_{dep} \leq 10$ V)
- Short charge collection distance
- Pixel metalisation connects several electrodes

Diamond Pixel Detectors

- CVD Diamond: high resistivity → no p-n-junction necessary
- Electrodes (pixels/strips/pads) defined by metallisation only
- Room-temperature operation, radiation hard, but signal height depends on diamond quality (charge collection)





Now: Hands-on…