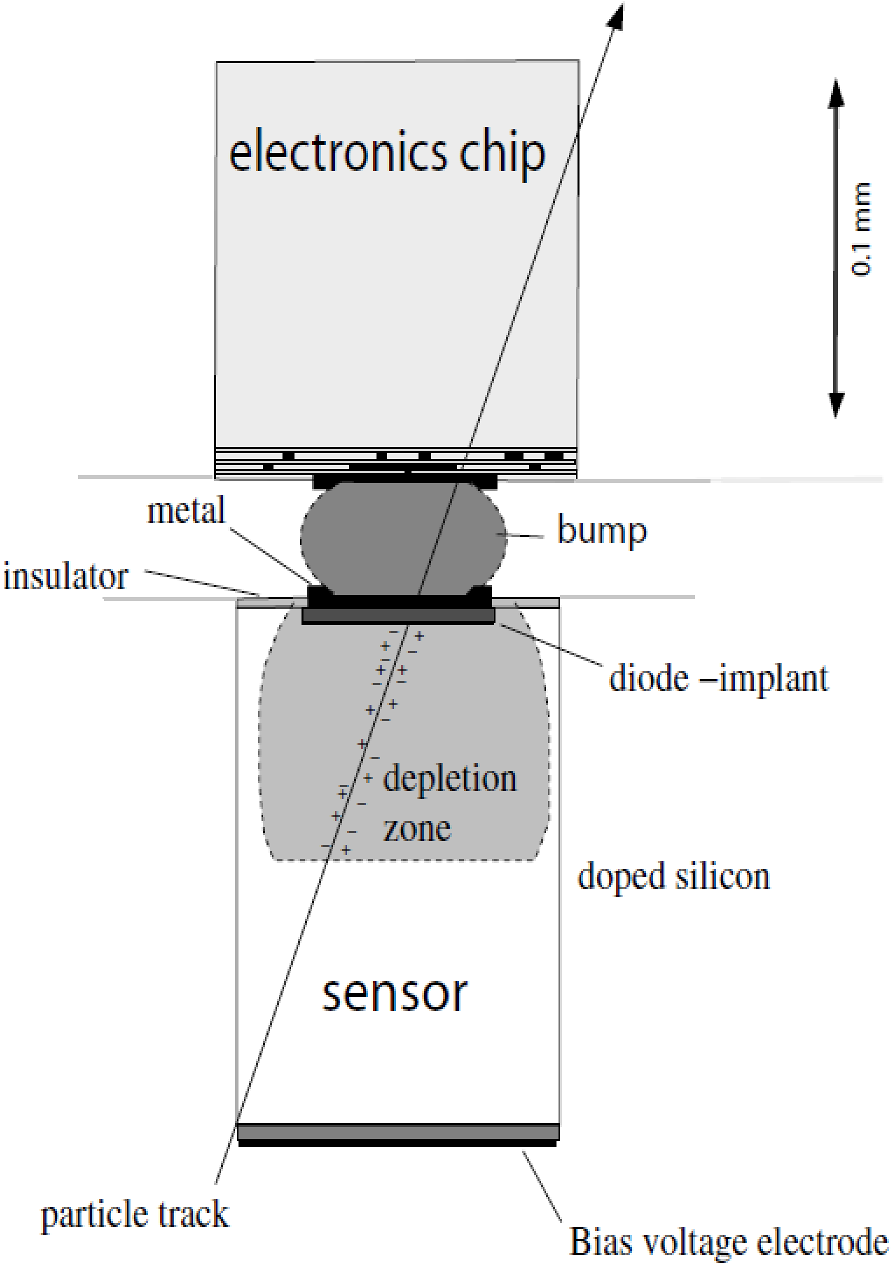
<<Pixel detectors>> from fundamentals to applications

Generalities on Pixel Detectors

- The notion of pixel (short for "picture element") has been introduced in image processing to describe the smallest discernable element in a given process or device
- A pixel detector is therefore a device able to detect an image and the size of the pixel corresponds to the granularity of the image

detectors

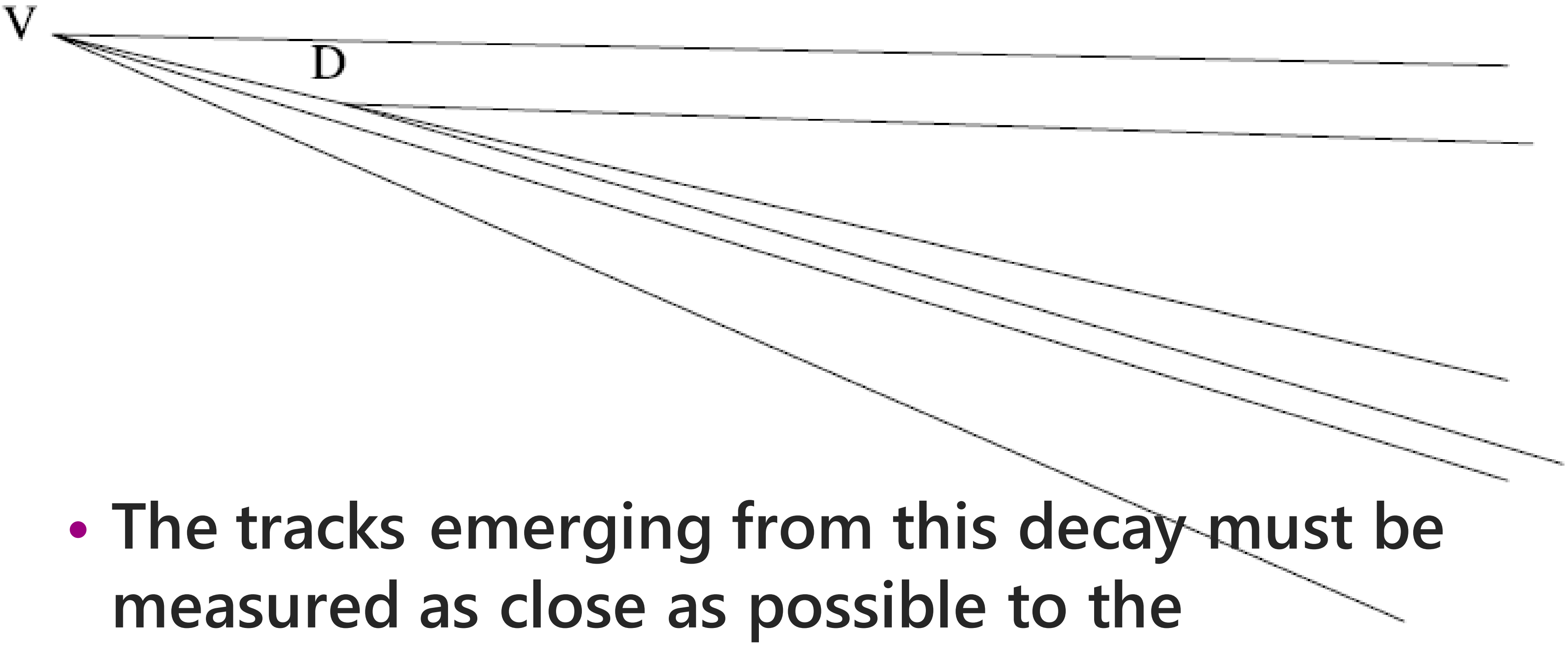
- In particular,detectors are discussed where the image is generated in a semiconductor and is processed electronically and where data are readout in parallel
- This is the so-called hybrid pixel detector (hybrid because electronics and sensors are fabricated separately and then mated)



- Planar integration technology allows one to put together several thousands of those building blocks in a matrix covering few square centimeters
- This kind of device has been developed for the needs of particle physics and in many other fields

Motivations for Pixel Detectors in Particle Physics

1. The possibility of studying short-lived particles
2. The capability of coping with the increasing interaction rates and energies(and therefore the number of particles produced per collision) of modern particle accelerators
    - particle collisions at a rate of 10–100 MHz,with 10–100 particles emerging from every collision
    - Some rare, but interesting,particles live about 1 ps (10 ps) and then decay into a few daughterparticles.



- The tracks emerging from this decay must be measured as close as possible to the interaction point, with an accuracy of $\approx$0.1 $c\tau$(where τ is the particle proper lifetime and c is the speed of light)
- This gives a required measurement accuracy of $\approx$ 0.03mm for a lifetime in the order of a picosecond

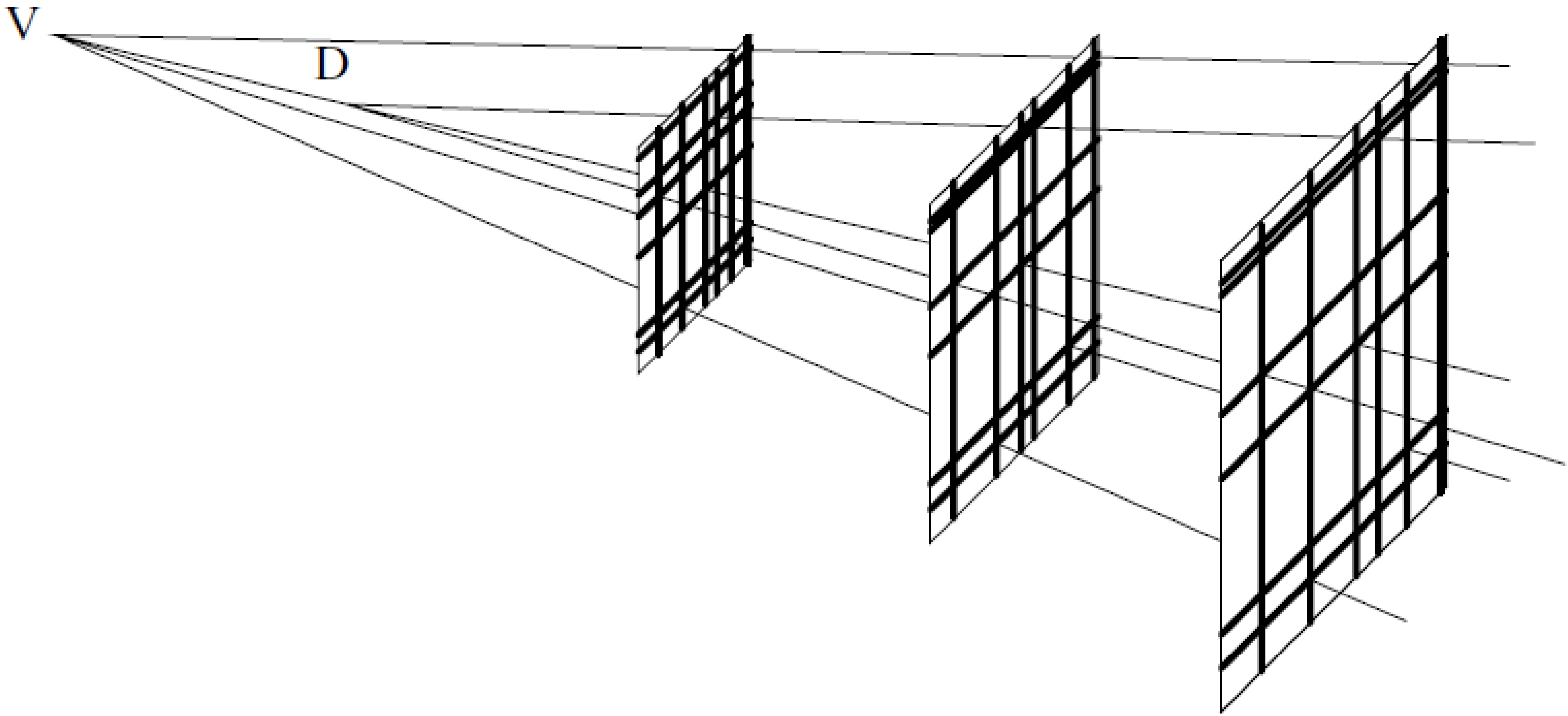


Fig. 1.4. Same decay topology as shown in Fig. 1.2. The tracks are measured by three double-sided microstrip detectors with 100-µm strip pitch. The hit strips (i.e. the pattern "seen" by the detectors) are highlighted

- **one must also take into account (*N^2 – N)* ghosts strip coincidences**

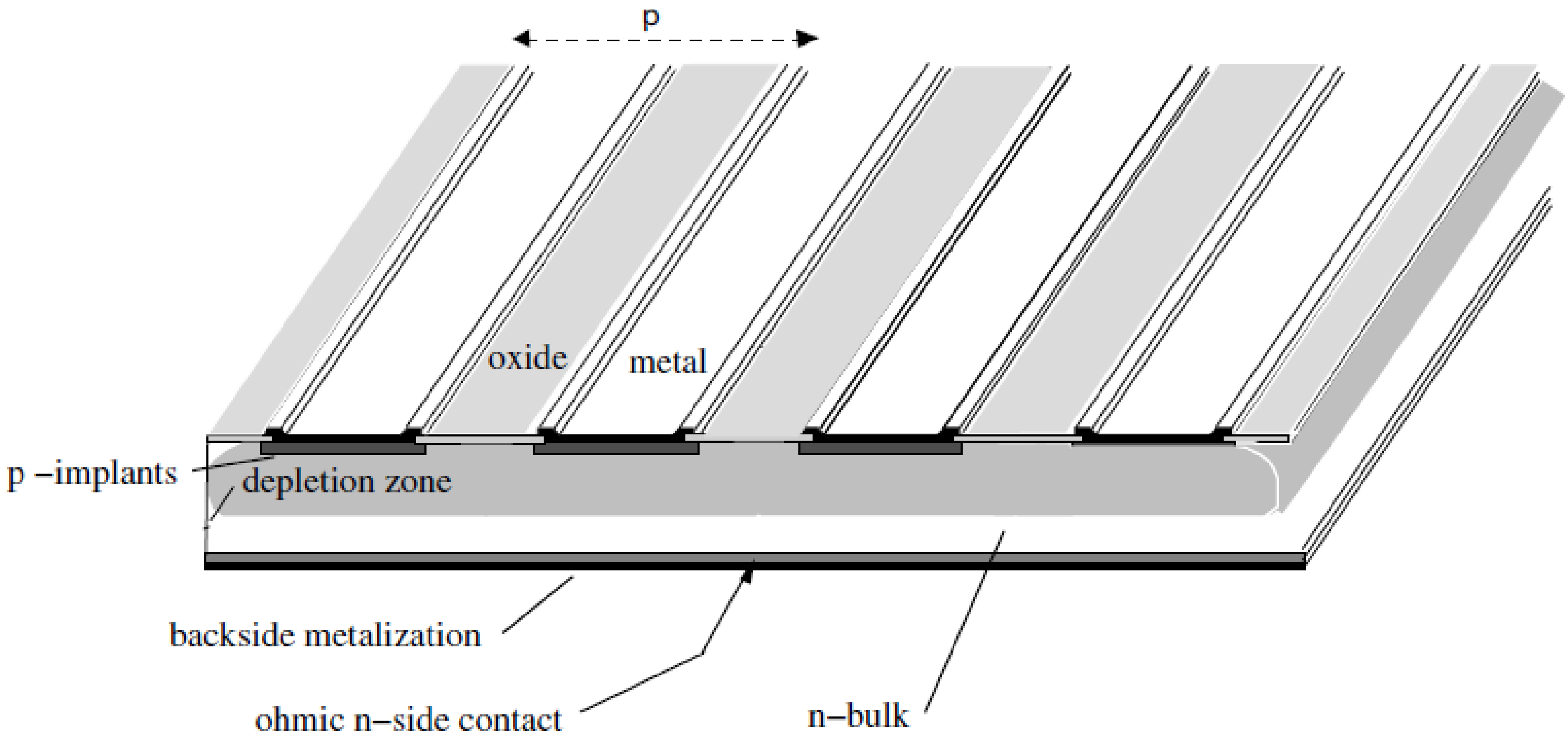
conclusion

- a detector with a high granularity able to detect multiple tracks with good space and time resolution
  - pixel detectors with cell sizes in the order of 100 × 100 µm^2 can cover areas as large as a few square meters with 108 pixels
- its electronics should be capable of selecting the interesting patterns
  - be designed to temporarily store the hit pattern belonging to an individual event which is judged possibly interesting on the basis of its topological or dynamical variables

- The typical particle physics application therefore requires that one hit pattern (image) is one event
- Other applications (like X-ray radiography) require instead that one image is made of
  - many events The readout electronics should therefore not select events , but accumulate them for a preset period of time under known and stable conditions.

Working Principle and Operating Characteristics of Segmented Silicon Detectors

- Single-sided microstrip detectors are a special case of semiconductor detectors in which one electrode is segmented in thin parallel strips.
- Ion implantation and photolithographic techniques are used to selectively dope the surfaces of the semiconductor wafer
- Deposit the metallization patterns necessary to extract the signals


p
oxide
metal
p –implants
depletion zone
backside metalization
ohmic n–side contact
n–bulk

- Resistivity $\rho = \dfrac{1}{eN\mu}$, dopant density *N* majority carrier mobility *μ*
- depletion zone thickness

$$W = \sqrt{2\varepsilon_0\varepsilon_{\mathrm{Si}}(V/eN)} = \sqrt{2\varepsilon_0\varepsilon_{\mathrm{Si}}(V\mu\rho)}$$

- Depletion zone can be seen as a charged capacitor(per area)

$$C = \varepsilon_0\varepsilon_{\mathrm{Si}}/W = \sqrt{e\varepsilon_0\varepsilon_{\mathrm{Si}}N/2V}$$

- Increasing the reverse bias voltage V increases the thickness of the depletion zone and reduces the capacitance of the sensing element, and both these effects increase the signal-to-noise ratio (S/N)

dark current , thermal background current

- diodes are reversely polarized
- The majority carriers experience a barrier due to the voltage applied externally.
- The minority carriers are constantly removed out of the depleted region by the field in the junction thus generating a small current, known as dark current
- As the carriers are thermally generated, this current depends on temperature and is also known as thermal background current

- Particles crossing the silicon detector generate charged carriers
- If these carriers are generated in the depletion zone, they lead to a current signal much larger than the thermal background current
- During the drift the charges do not exactly follow the electric field lines, but diffuse as a consequence of the random thermal motion
  - Spread of the arrival position of the charge can be described as a Gaussian distribution

$$\sigma = \sqrt{2Dt}$$

with standard deviation assuming a typical electron diffusion constant of 35 cm^2/s and a transit time of the carriers of 10 ns

- Intense magnetic fields (B) of up to 4T are often used in particle physics experiments to allow measuring the momenta of the charged particles
- The magnetic field acts on all charged particles and therefore also on the electrons and holes drifting inside the silicon
  - the Lorentz angle

$$\tan\theta_{\mathrm{L}} = \mu_{\mathrm{H}} B_{\perp} \approx \mu B_{\perp} \, ,$$

Hybrid Pixel Detectors

- One speaks of pixel detectors when the area of the sensing element is below 1mm^2 and their number is in the order of 10^3–10^4.
- In this case a two-dimensional connectivity to the electronics as dense as the pixels themselves is necessary

The two-dimensional high-density connectivity

1. The connectivity between the sensor and the mating readout chip must be vertical, i.e. the connections must run out of the sensor plane.
2. There must be exact matching between the size of the pixel and the size of the front-end electronics channel.
3. The electronics chip must be very close (10–20 µm) to the sensor

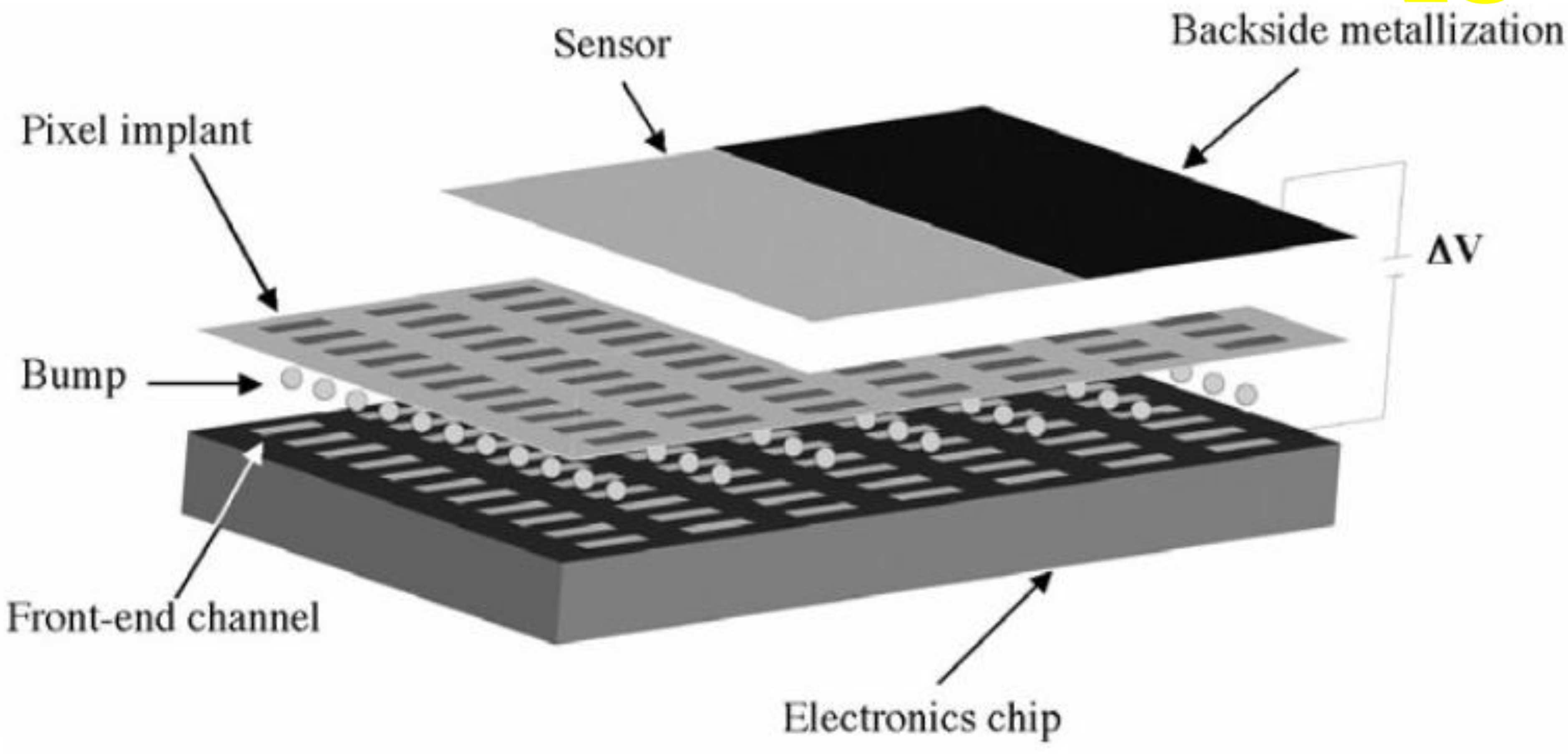


Fig. 1.7. Sketch of a “blown-up” hybrid pixel detector

electronics chip logic

- **Any electronics chip must have some ancillary logic to extract the signal from the front-end channels**
  - placed close to one edge of the chip
- **designers must pay special attention to avoid the following**
  - Large static voltage (i.e. bias voltage) on the front side or on the edge of the sensors that may give rise to destructive sparks.
  - Large high-frequency signals on the electronics that may induce detectable signals on the pixel metallization.

- multiple square centimeter electronics chips should be mounted on a sensor which is considerably larger (≈10 cm^2).(Chap.4)
- Other peculiar characteristics of the pixel detectors are related to the small dimensions of the sensing elements).(Chap.2)
  - Each pixel covers, in fact, a very small area (≈10^−4 cm^2) over a thin (≈300 μm) layer of silicon
  - The direct interpixel coupling to the neighboring pixels has to be kept to a minimum with proper sensor design

fast signal shaping

- The low capacitance is one of the key advantages of pixel detectors since it allows fast signal shaping with very low noise(Chap.3)
- It is common to obtain noise figures of ≈200 e− for electronics operating at 40MHz and therefore an S/N exceeding 100 for fully depleted 300-μm-thick sensors
- taking advantage of the excellent S/N ratio
  - To sensors which have a poor charge collection or a limited active thickness
  - To crystalline silicon sensors damaged by high irradiation flux

- Finally, smallness of the pixel means smallness of the reverse current flowing through it at depletion (typically 0.1 µA/cm^2).
- This reduces the parallel noise and allows operation even after considerable irradiation

summary

- **hybrid pixel detector is the ideal detector to work in the very hostile environment which exists close to the interaction region**
  - It is radiation hard
  - It provides nonambiguous three-dimensional measurements with good time resolution
  - It provides the space resolution which is needed to measure short-lived particles
  - It can extract the rare patterns the physicist is looking after (i.e. it memorizes hit patterns and selectively reads out those interesting).

Monolithic Pixel Detectors

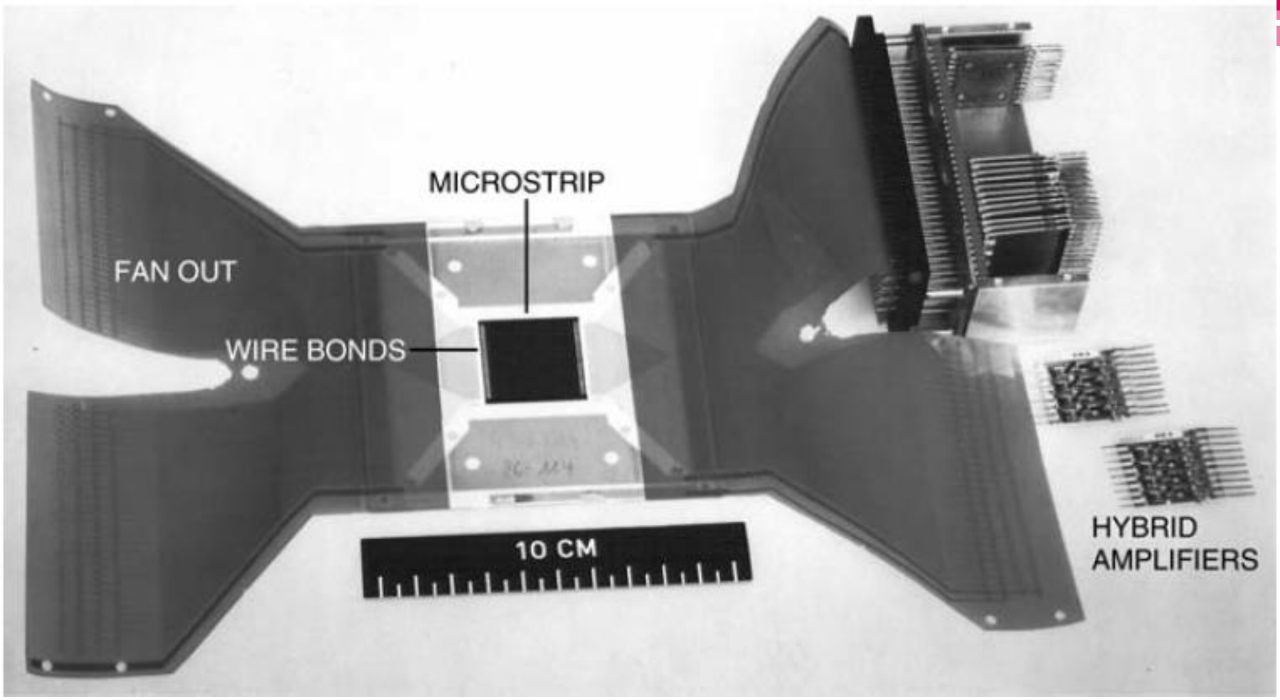
- building both electronics and sensor in the same technological process(Chap. 6)
    - avoids the high-density interconnection technique and the many related manipulations
    - further reduce the capacitance of each pixel and obtain a very low-noise performance

- In some cases (like, for instance, in the DEPFET design) the sensor part is driving the development
  - Simple electronics circuits are integrated on high-resistivity silicon
  - The signal generation is optimal as large thicknesses can be depleted and high electric fields provide fast and efficient charge collection
- In other cases (like, for instance, in the MAPS design) the electronics part is driving the development
  - The detector is realized on a thin layer of low-resistivity p-doped silicon, which is optimal for complex electronics design but does not allow having large depletion volumes and fast charge collection
  - takes about 100 ns(10 times longer than in high -resistivity)

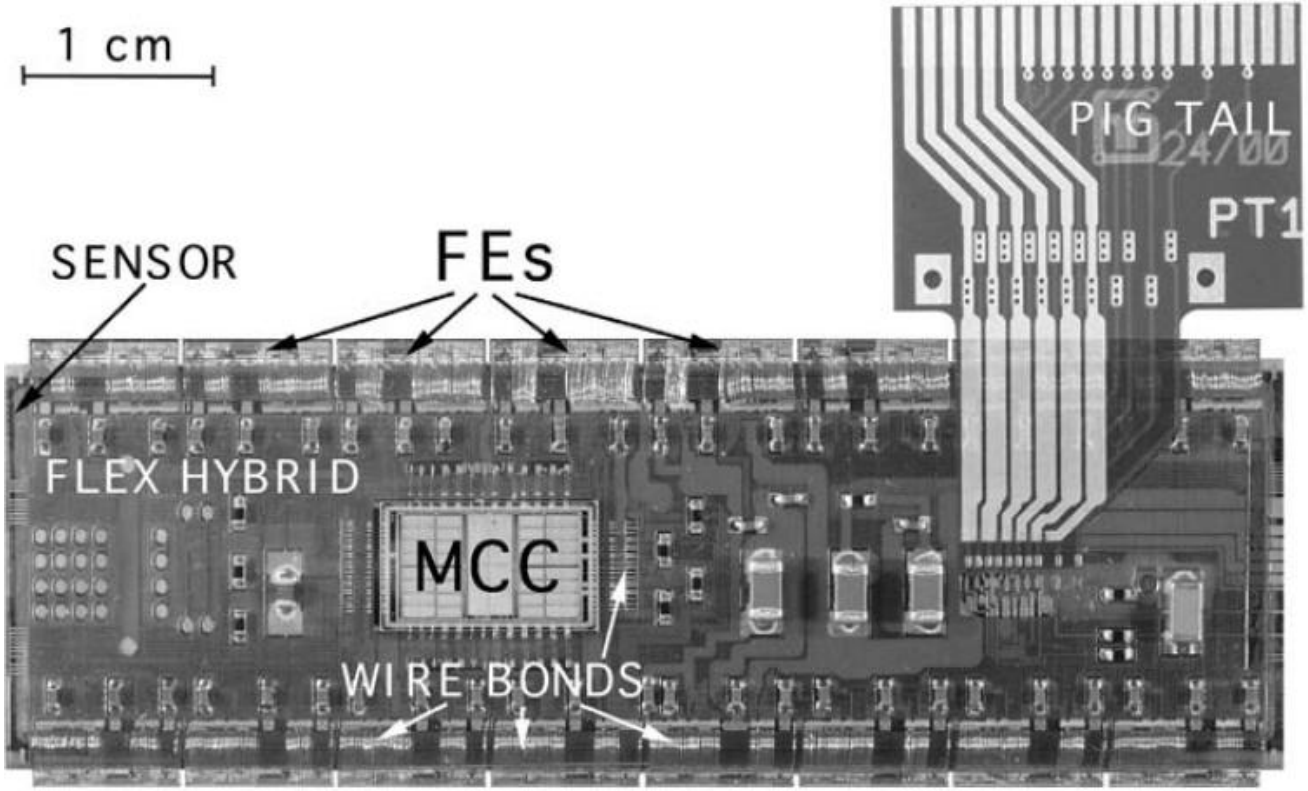
- quasi-monolithic
  - plasma-enhanced chemical vapor deposition of hydrogenated amorphous silicon produces a thin sensor of limited charge collection properties
  - promises to be radiation hard

Evolution of Pixel Detectors in Particle Physics

- looking for an alternative to the widely used bubble chamber detector, which suffered from data rate limitations
- The integrated circuit technology accessible to particle physicists was, however, not yet mature enough in the 1960s
- In the late 1970s,The first trials were done with multiple layers of closely spaced silicon surface barrier diodes
  - A charmed particle decay happens after few millimeters of flight path and increases, on average, this number
  - The detection and localization of the charm decay point could then be done through a charge measurement



- microstrip detector(built in the year 1984 for the CERN experiment WA82)
  - The microstrip detector has a sensitive area of about 2.5×2.5 cm^2 and 512 channels at 50-μm pitch
  - each circuit measures 2.5×2.5 cm2 and contains four amplifiers
  - The use of integrated electronics became possible a few years later



- Pixel detectors, built in the year 2000 for the CERN experiment ATLAS
  - on the contrary, needed more sophisticated technologies even to start-up and stayed longer in the conceptual phase
  - 1.6×6.4 cm^2 and 46,080 rectangular pixels at pitches of 50 and 400 µm respectively

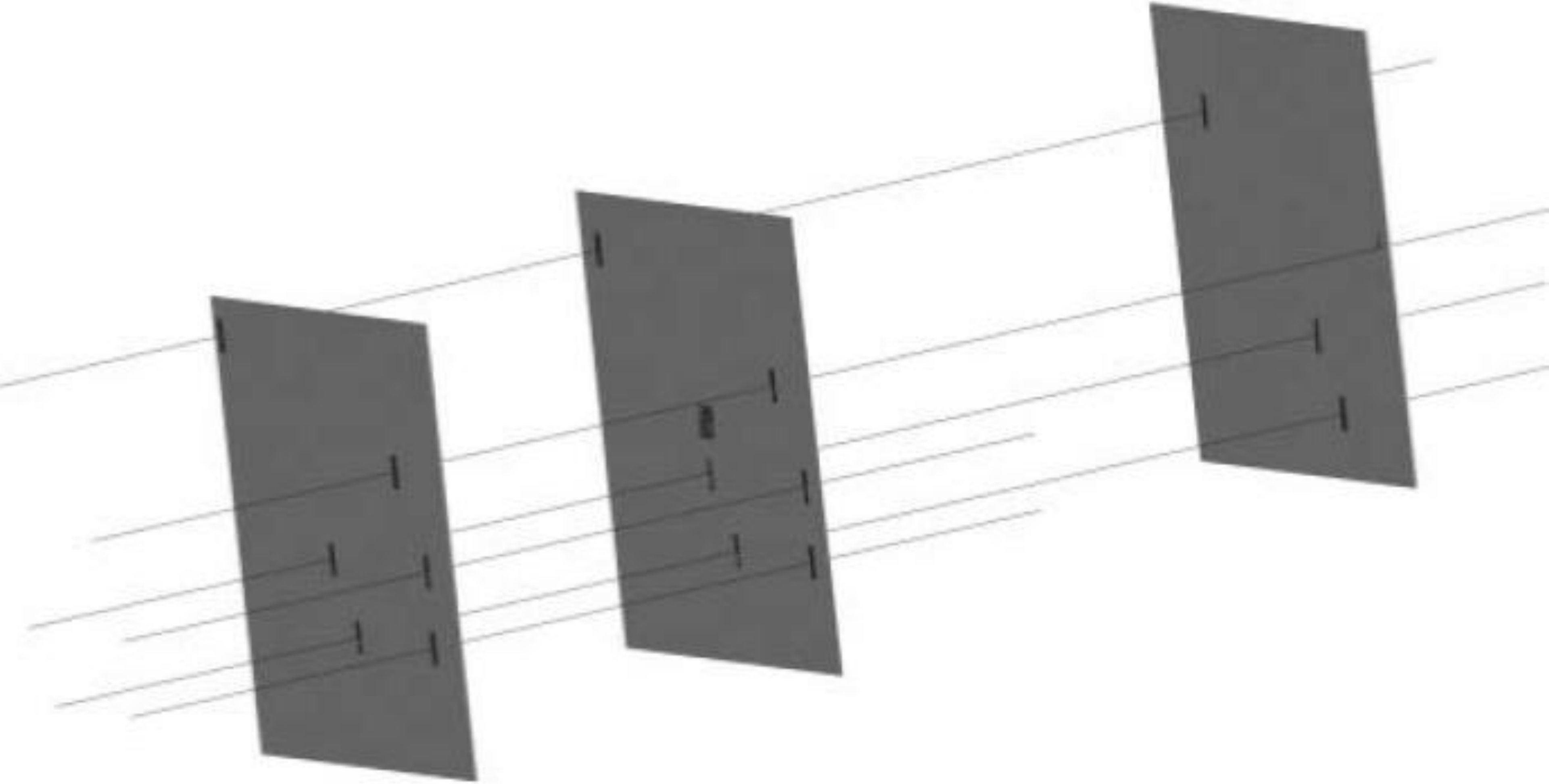
- The most noticeable difference
  - the level of integration of the electronics
  - and the related connectivity problems
- One can say that the evolution has eliminated most of the inactive material that was necessary before to connect hybrid electronics to multichannel sensors
  - The pixel detector has ≈100 times more channels than does the microstrip detector
  - weights only 1% of microstrip detector

The First Pixel Detectors and Their Use in Experiments

- The birth of pixel detectors can be traced back to the 1984 IEEE Nuclear Science Symposium where Gaalema pointed out that an integrated circuit for focal plane imaging sensors, developed by Hughes Aircraft Co., could be connected, through bump bonding, to a semiconductor diode array to detect and localize X-rays
- The charge “seen” by each pixel is integrated for hundreds of microseconds on a capacitor to minimize the serial electronics noise.

- works under the following conditions
  - Each pixel must draw very low current to avoid saturating the readout amplifier and to contribute significantly to the parallel electronics noise.
  - The data rate should be limited to 1 kHz
  - The device must be continuously “interrogated, ” i.e. it cannot react to an external trigger
- were not acceptable for particle physics applications

- Designs of pixel readout circuits with much shorter integration times and the ability to react to external trigger were developed in the early 1990s
- An R&D program was launched by CERN in 1990, because collider reach unprecedented particle collision energies and beam intensities
  - first use in experiments CERN experiment WA94



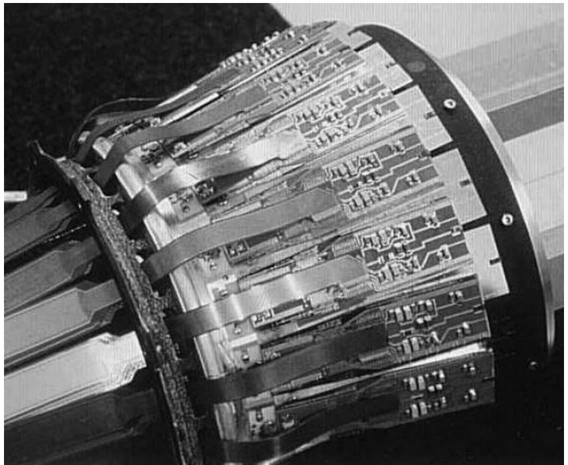
The OMEGA Pixel Detectors

- The first pixel matrix, OmegaD, had 1,024 pixels of size 75 × 500 µm^2
- Each channel had a continuously sensitive preamplifier followed by an asynchronous comparator and a digital delay line through which the discriminated signals travel waiting for an external trigger
- When the trigger is received all pixels with a coincident delay line signal are read out

- The power dissipation was 30 µW per pixel
- Electronics noise was just below 100 e− rms while the threshold variation between channels was around 500 e− rms
    - one individual pixel circuit can have excellent performance, but it is difficult to get by design a correspondingly good response uniformity over the whole chip area
- the adoption of deep submicron (DSM) technologies featuring 0.25-µm structure sizes, 3 µm technology used for the OmegaD chip
    - Smaller feature size also means thinner silicon oxide layers, which, in turn, implies smaller parameter shifts caused by radiation in MOS transistors(1000 times than 3 µm)

The DELPHI Pixel Detector

- The first use of pixel detectors in a colliding beam environment
- The LEP energy increase above the threshold ofW+W− production required to also increase the DELPHI angular acceptance to cover
- Two crowns of pixel detectors have been added to the microstrip vertex detector already operational in the experiment in order to extend its acceptance to the forward and backward regions
- The pixel modules have been designed to minimize material too



- This was the first attempt for a more compact layout and then evolved in the multichip module deposited approach to pixel module construction (Chap.6)
- The relatively large size of the pixels (330× 330 μm^2) allows one to use an industrial standard for the bump-bonding process
- Detectors are operated at a typical threshold of 10 ke−, which is comfortably high compared to the few hundred electrons noise