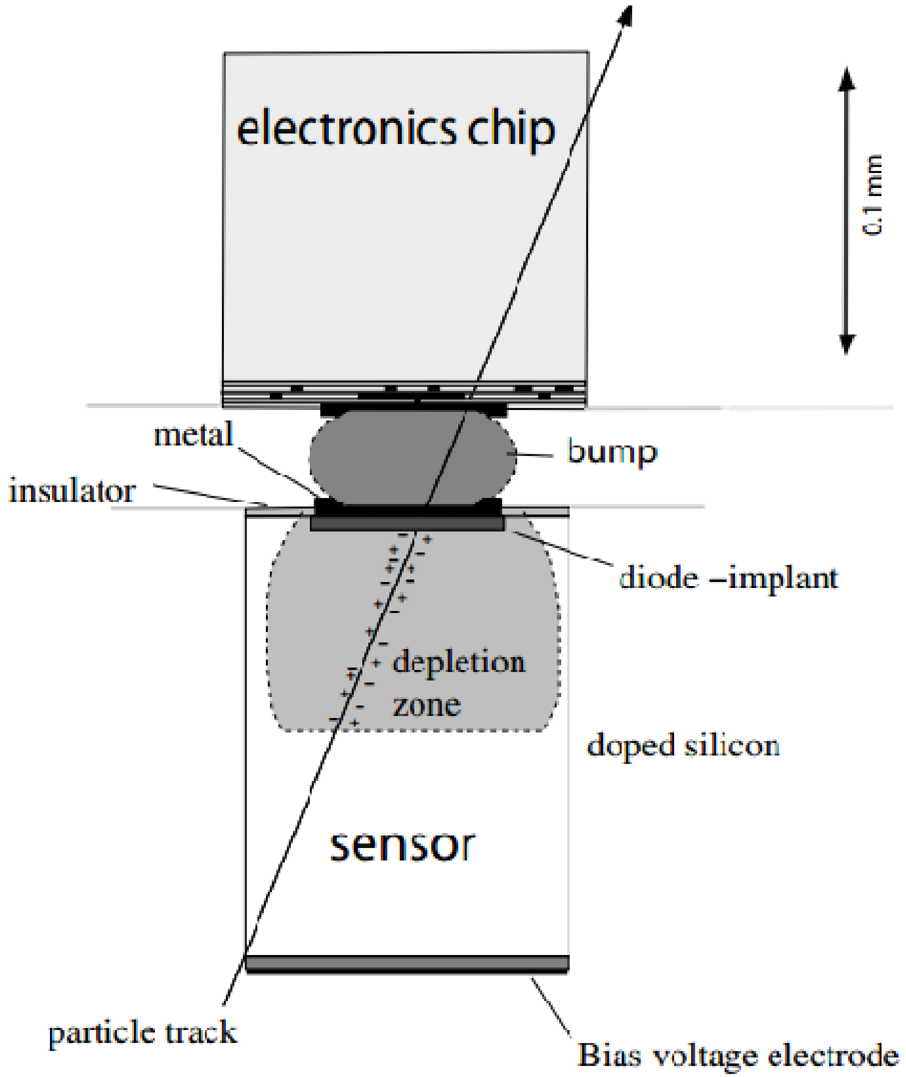
# Pixel detector

## 1.1 Generalities on Pixel Detectors

1) 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.
2) In particular, detectors are discussed where the image is generated in a semiconductor and is processed electronically and where data are readout in parallel.
3) Planar integration technology allows one to put together several thousands of those building blocks in a matrix covering few square centimeters.
4) Particle physics applications demand high speed, good time resolution, and the ability to select hit patterns, while applications in other fields emphasize more high sensitivity and stability.

- This is the so-called hybrid pixel detector (hybrid because electronics and sensors are fabricated separately and then mated)
- The ionizing particle crosses the sensor and generates charges that, moving in the depletion region under the action of an electric field, produce signals.



### 1.1.1 Motivations for Pixel Detectors in Particle Physics

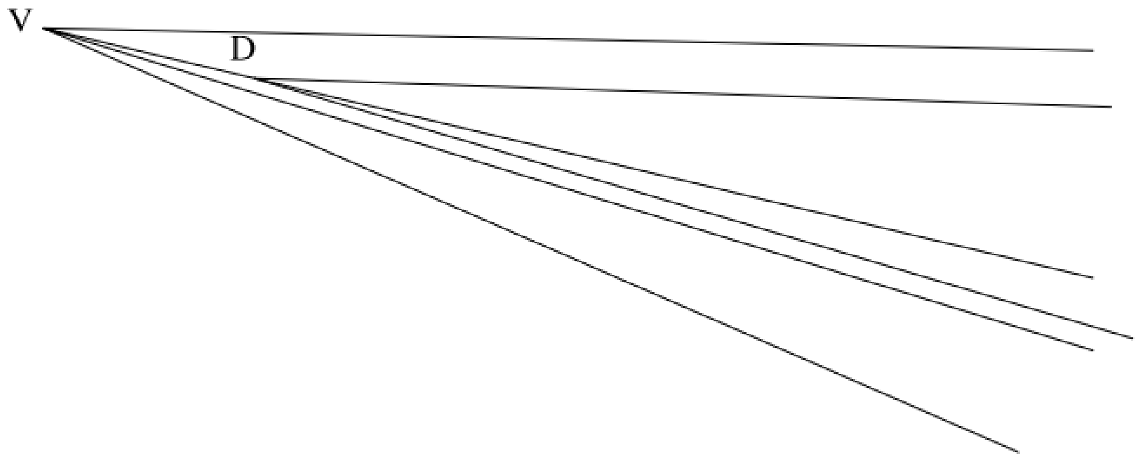
The development of pixel detectors in particle physics has been primarily triggered by two specific requirements :

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

High-energy accelerators generate elementary 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 ($10^{-12}$ s) and then decay into a few daughter particles.

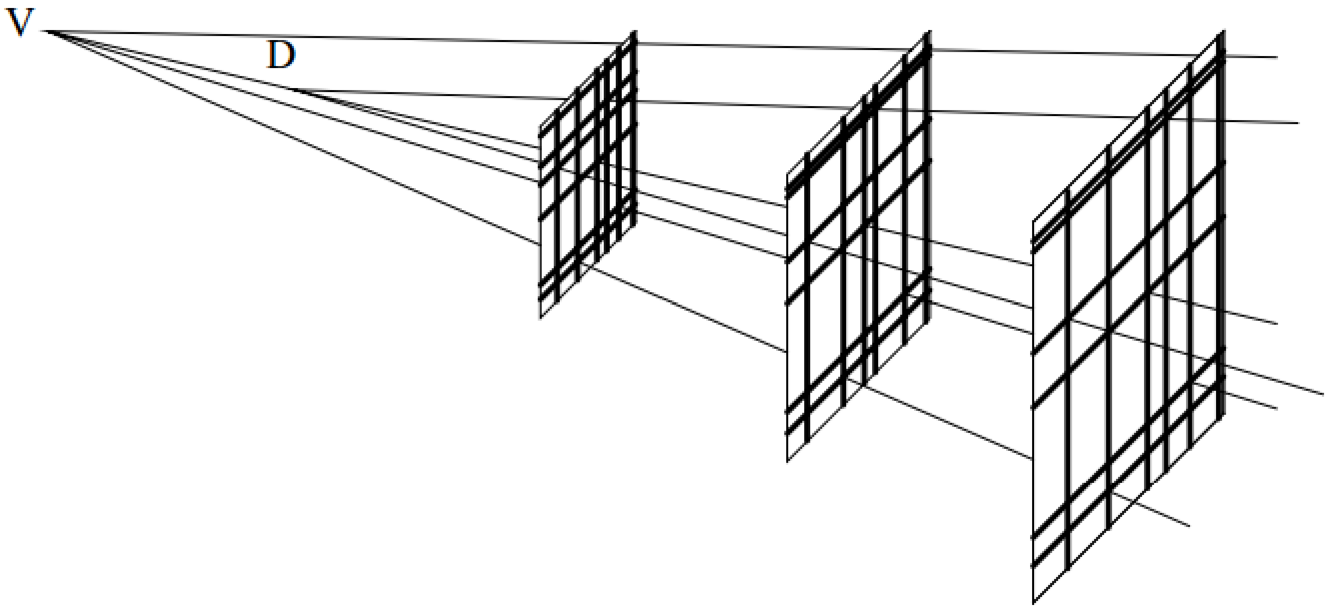
Topology of a short-lived particle decay, with ordinary particles emerging from the same collision. The collision vertex (V) and the decay vertex (D) are indicated.




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

- Tracks emerging from the decay of a relativistic particle, once extrapolated back to the primary interaction vertex, miss this vertex on average by a distance $c\tau$ . This distance is known as impact parameter. In order to discriminate the tracks coming from the rare heavy quark decays from other tracks emerging directly from the interaction, the impact parameter must be measured with an accuracy sensibly smaller than $c\tau$ : 10% $c\tau$ is commonly assumed.

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.




- The same space resolution is obtained using two planes of microstrip detectors rotated by 90∘, but, together with the N true strip coincidences due to the N tracks, one must also take into account (N^2 − N) ghosts strip coincidences which can severely hamper the track reconstruction capability. (strip 交叉的部分會導致信號被多算了一次，因此要 (N^2-N) 減去多算的信號)

## Requirement of pixel detector

1) 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 μm2 can cover areas as large as a few square meters with 108 pixels.

2) Electronics of pixel detector should be capable of selecting the interesting patterns.

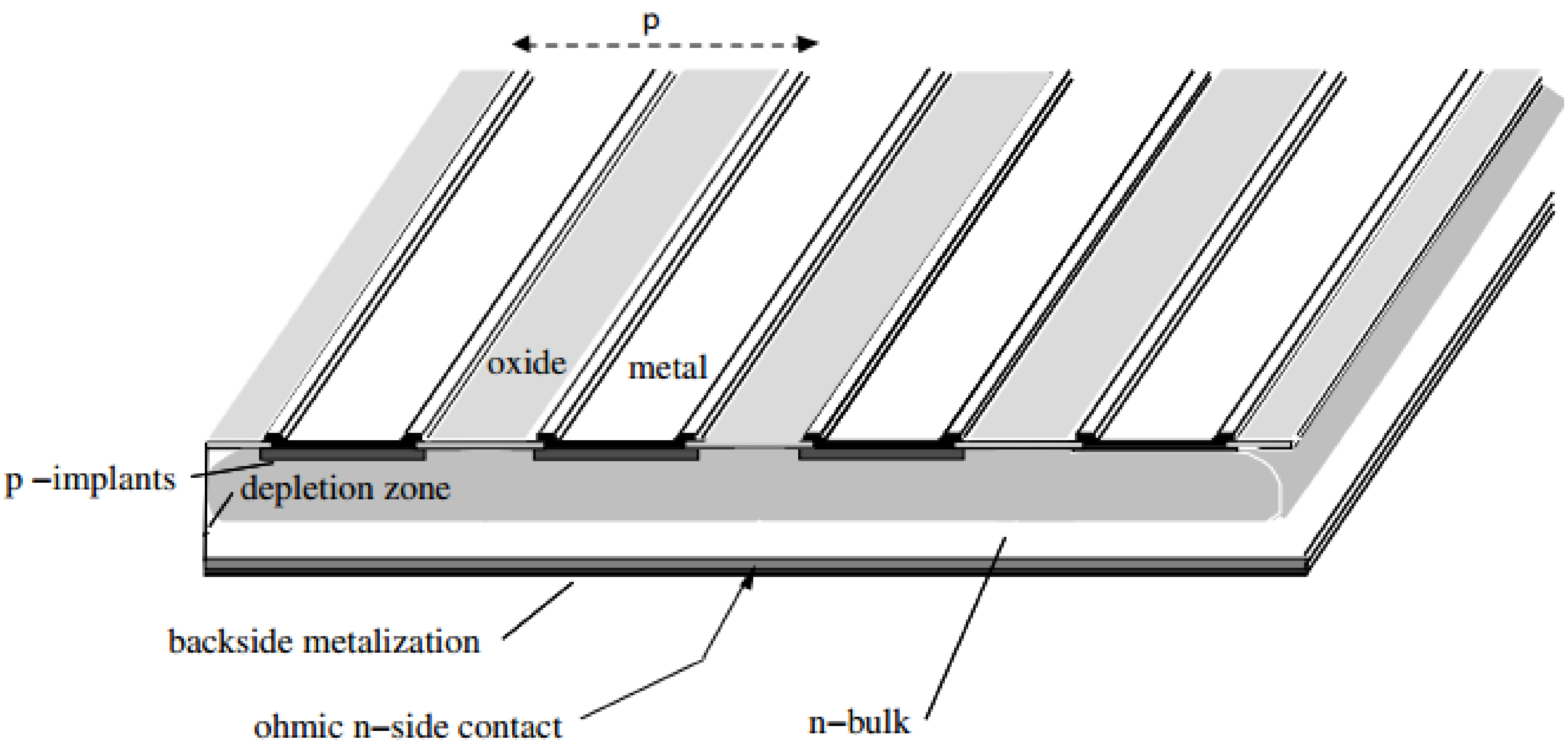
The readout electronics should be designed to temporarily store the hit pattern belonging to an individual event which is judged possibly interesting on the basis of its topological or dynamical variables.

3) The typical particle physics application 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 individual X-ray conversions in the detecting medium). The readout electronics should therefore not select events, but accumulate them for a preset period of time under known and stable conditions.

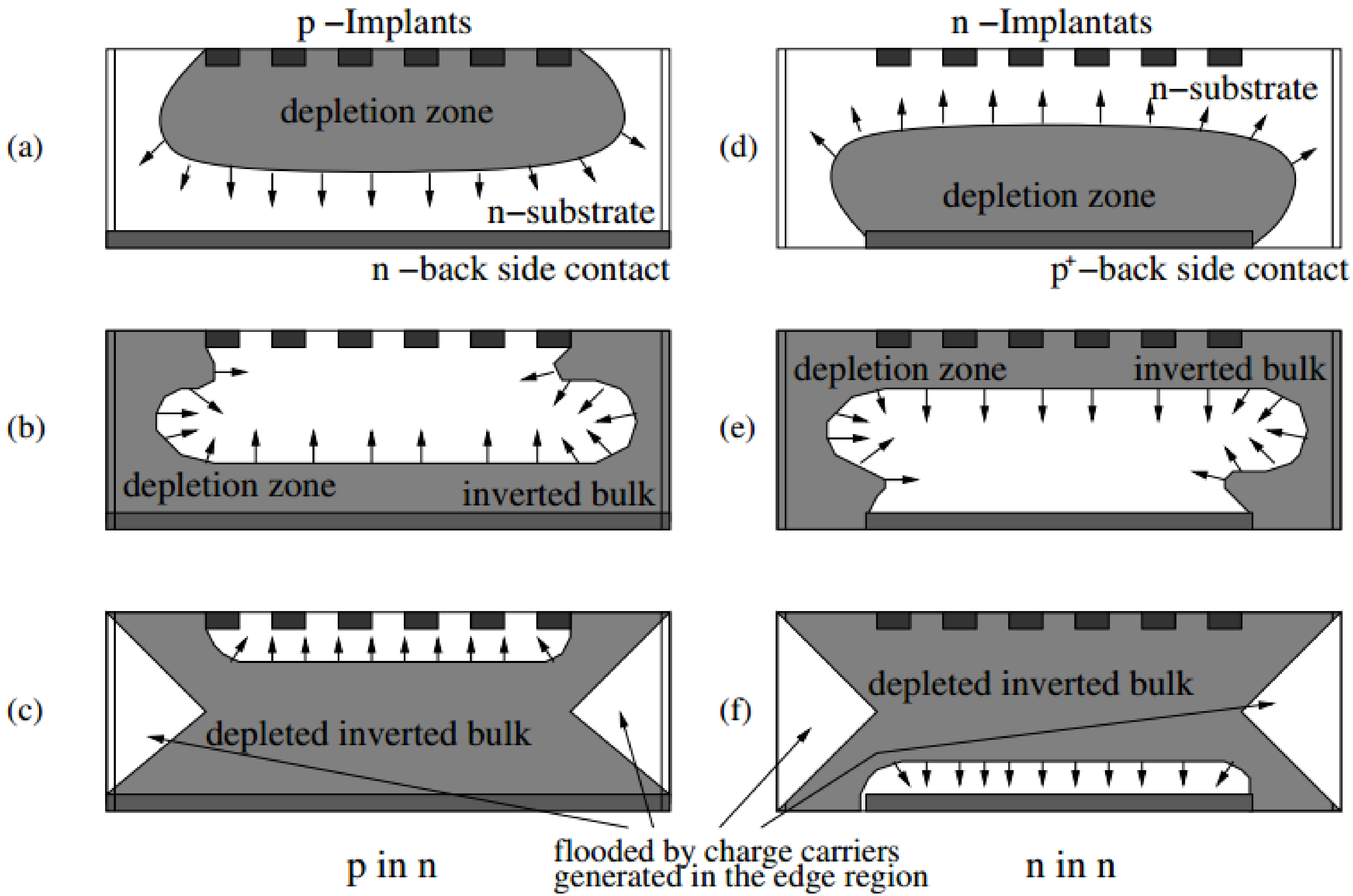
### 1.1.2 Working Principle and Operating Characteristics of Segmented Silicon Detectors

1) Single-sided microstrip detectors are a special case of semiconductor detectors in which one electrode is segmented in thin parallel strips.
2) Ion implantation and photolithographic techniques are used to selectively dope the surfaces of the semiconductor wafer of typically 300-μm thickness and to deposit the metallization patterns necessary to extract the signals.



- Sketch of a single-sided microstrip detector. In this example strips are p+ implants on n type silicon. They are repeated at a pitch p. In between the strips, metallizations are regions with a silicon dioxide layer. The detector is operated by applying a voltage between the backside metallization and the strips. In this example the detector is only partially depleted. Increasing the voltage would extend the depletion zones toward the backside and toward the neighboring strips.
- Resistivity : $\rho=1/eN\mu$ ,where e is the elementary charge, μ is the majority carrier mobility
- Depletion zone thickness : $W = \sqrt{2\varepsilon_0\varepsilon_{si}(V/eN)} = \sqrt{2\varepsilon_0\varepsilon_{si}(V\mu p)}$
- The depletion zone can be seen as a charged capacitor of value C per unit area : $C = \frac{\varepsilon_0\varepsilon_{si}}{W} = \sqrt{e\varepsilon_0\varepsilon_{si}N/2V}$

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).



p –Implants
n –Implantats
(a)
depletion zone
n–substrate
n –back side contact
(d)
n–substrate
depletion zone
p+–back side contact
(b)
depletion zone
inverted bulk
(e)
depletion zone
inverted bulk
(c)
depleted inverted bulk
(f)
depleted inverted bulk
p in n
flooded by charge carriers
generated in the edge region
n in n

- Dark current or thermal background current

If diodes are reversely polarized, very little current flows through them. 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. 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 with standard deviation

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

assuming a typical electron diffusion constant of 35 cm2/s and a transit time of the carriers of 10 ns

$$\sigma = \sqrt{2Dt} = \sqrt{2 \times 35 \times (10 \times 10^{-9})} = 8.37 \times 10^{-4} cm = 8.37 \mu m$$

- 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

$$\tan\theta_L = \mu_H B_\perp \approx \mu B_\perp$$

where $B_\perp$ is the magnetic field component perpendicular to the electric field, $\mu_H$ is the Hall mobility, and μ is the carrier mobility. Typical Lorentz angles range from a few to 20◦.

### 1.1.3 Hybrid Pixel Detectors

One speaks of pixel detectors when the area of the sensing element is below 1 mm2 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 is the key characteristics of the hybrid pixel detector and has three main consequences :

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

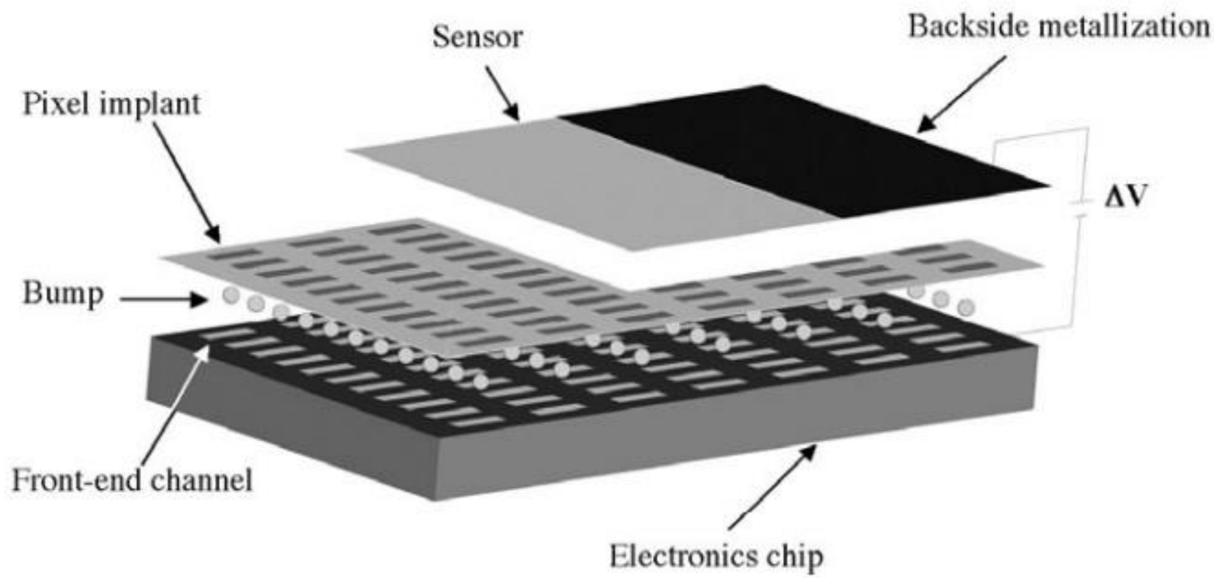



**Fig. 1.7.** Sketch of a "blown-up" hybrid pixel detector

**Electronics chip**

- Any electronics chip must have some ancillary logic to extract the signal from the front-end channels, organize the information, and transmit it out. The electronics chip is placed close to one edge of the chip.
- The chip is very close (≈10 μm) to the sensor, designers must pay special attention to avoid the following:

① 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.

② Large high-frequency signals on the electronics that may induce detectable signals on the pixel metallization.

- Multiple square centimeter electronics chips ($\approx 1cm\hat{}2$) should be mounted on a sensor which is considerably larger (≈10 cm^2) if a high enough yield (>50%) is desired.
- Other peculiar characteristics of the pixel detectors are related to the small dimensions of the sensing elements.

① Each pixel covers, in fact, a very small area (≈10^−4 cm^2) over a thin (≈300 μm) layer of silicon, therefore exhibits a very low capacitance (≈0.2–0.4 pF). (dominated by the coupling to the neighboring pixels rather than to the backside plane)

② The direct interpixel coupling to the neighboring pixels has to be kept to a minimum with proper sensor design to avoid cross talk between pixels.

**Signal shaping**

- The low capacitance is one of the key advantages of pixel detectors since it allows fast signal shaping with very low noise.
- 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.
- The advantage of the excellent S/N is to consider that the detector is robust enough to tolerate even a considerable signal loss.

① To sensors which have a poor charge collection or a limited active thickness
② 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. After 10^15 particles per square centimeter the reverse current density increases to ≈30 μA/cm2, rendering large sensing elements difficult to operate.

## The advantage of Hybrid detector

Hybrid pixel detector is the ideal detector to work in the very hostile environment which exists close to the interaction region.

① It is radiation hard (i.e. it survives high integral flux of particles).
② It provides non-ambiguous three-dimensional measurements with good time resolution (i.e. it operates in high instantaneous particle flux).
③ It provides the space resolution which is needed to measure short-lived particles.
④ It can extract the rare patterns the physicist is looking after (i.e. it memorizes hit patterns and selectively reads out those interesting).