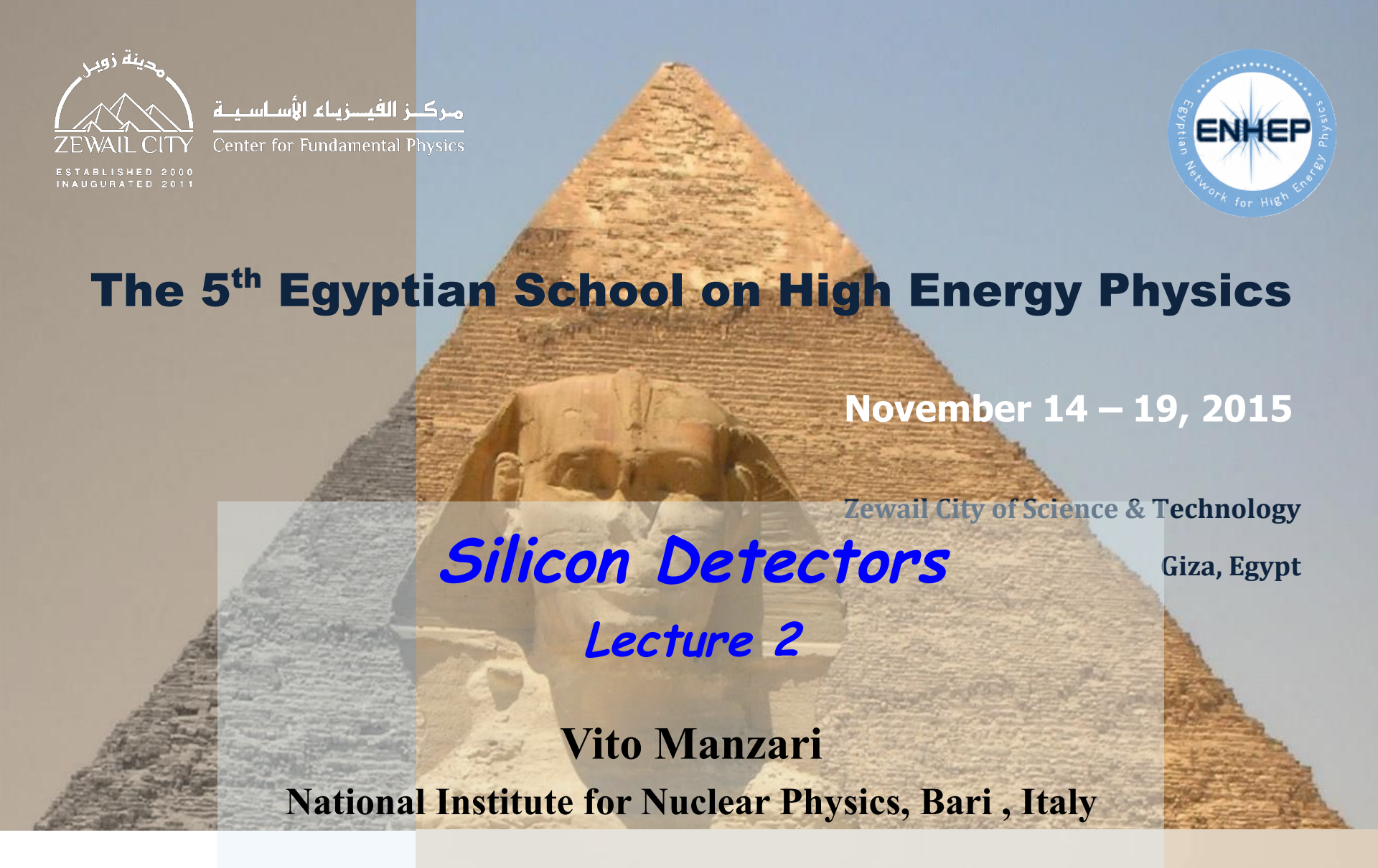

The 5th Egyptian School on High Energy Physics

November 14 – 19, 2015

Zewail City of Science & Technology

Giza, Egypt

Silicon Detectors

Lecture 2

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National Institute for Nuclear Physics, Bari , Italy

Outline

Lecture 2

Semiconductor Detectors, Signal, Noise and Electronics

Why silicon?

Moderate band gap

E_g = 1.12 eV ⇒ E(e-h pair) = 3.6 eV

≈30 eV for e-ion in gas detectors, ≈100 eV for photon in scintillators

High carrier yield

Better energy resolution and high signal

High specific density

2.33 g/cm^3 → High specific energy loss

dE/dx (M.I.P.) ≈3.8 MeV/cm, ≈108 e-h/μm (average)

Thin detectors

Reduced range of secondary particles

Better spatial resolution

High carrier mobility

μ_e=1450 cm^2/Vs, μ_h= 450 cm^2/Vs

fast charge collection (<10 ns)

Very pure

<1ppm impurities and <0.1ppb electrical active impurities

Rigidity

allows thin self supporting structures

Detector production

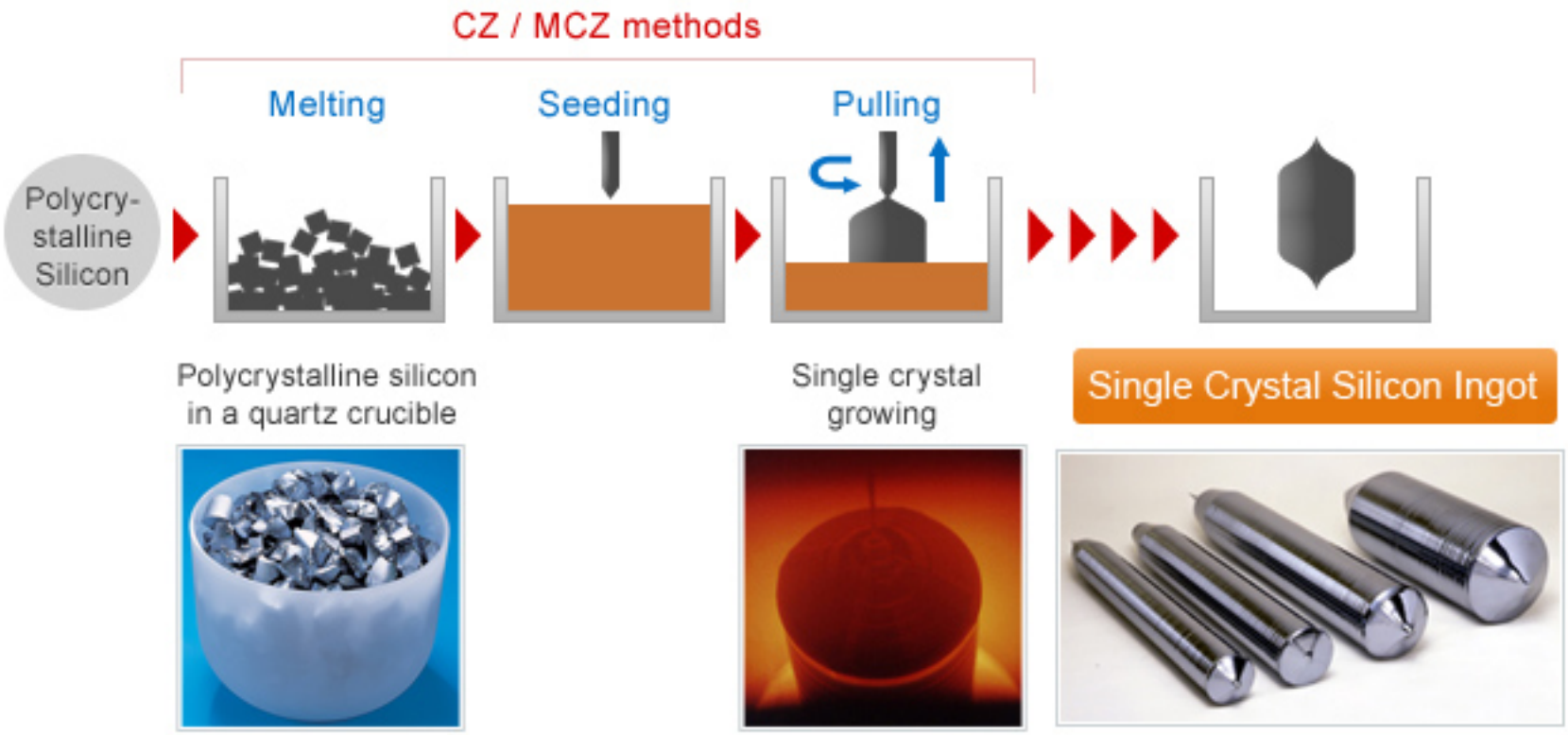
by microelectronic techniques

well known industrial technology, relatively low price, small structures workable

High intrinsic radiation hardness

Raw material for silicon detectors

- Silicon used in semiconductor device, including ionizing radiation detectors, is currently fabricated into ingot that are large enough in diameter to allow the production of 300 mm (12 in.) wafers.

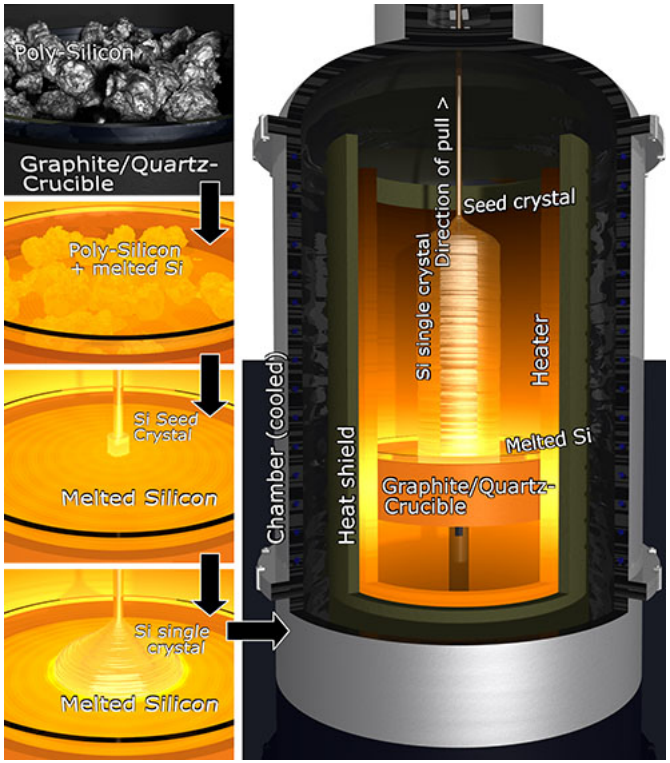


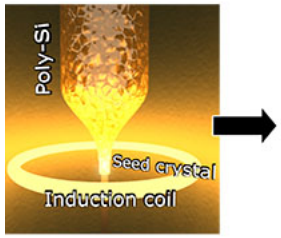
Examples of raw silicon material

The different process steps of **Czochralski** crystal growth: melting of polysilicon with dopants, immersion of the seed crystal, crystal growth.

Advantages: big crystal diameters (up to 18 inch = 46 cm), lower production cost

Disadvantages: impurities such as oxygen and carbon, low homogeneity of axial and radial dopant concentration





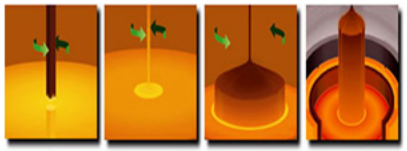
Schema of the **Float-zone** technique: a seed crystal is attached to the end of a polysilicon ingot (top) which is the starting point for the crystallization of the entire ingot.

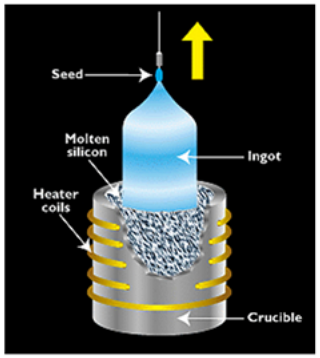
Advantages: very low impurity concentration, the dopant concentration in the final crystal is rather homogeneous and manageable

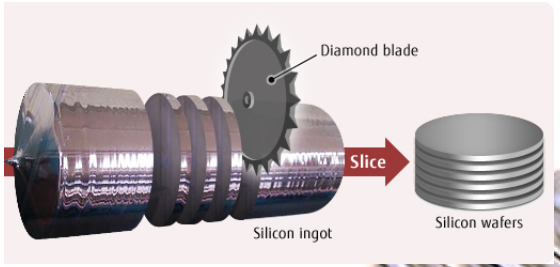
Disadvantages: more expensive, crystal diameter limited to 8 inch

Silicon wafers

Ingot production



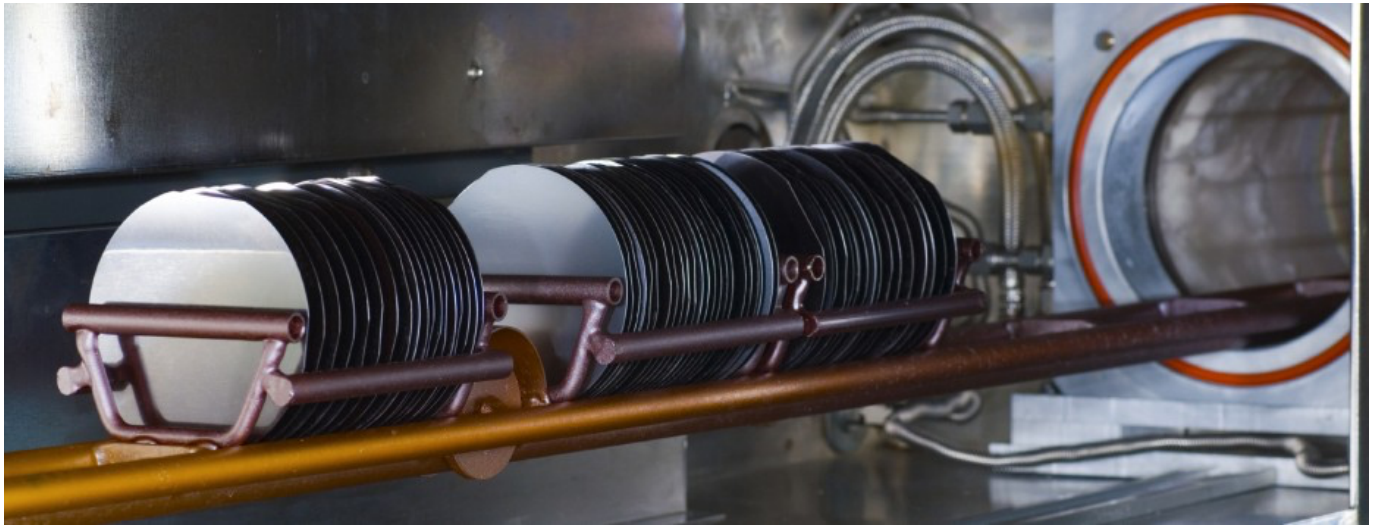




Wafer production

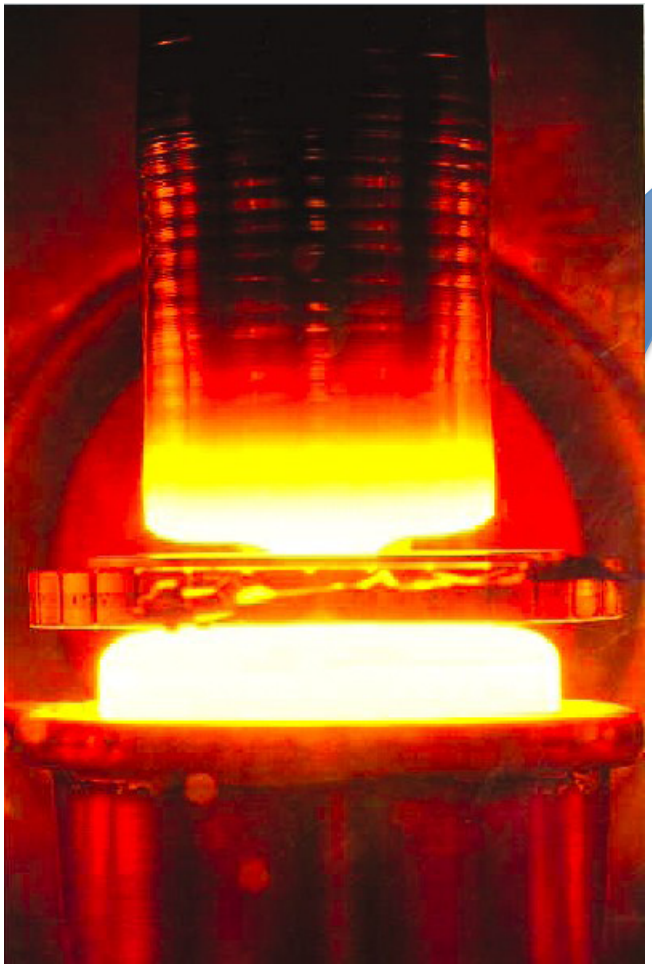
- Slice into wafer of 3-500 µm
- Lapping
- Etching
- Polishing

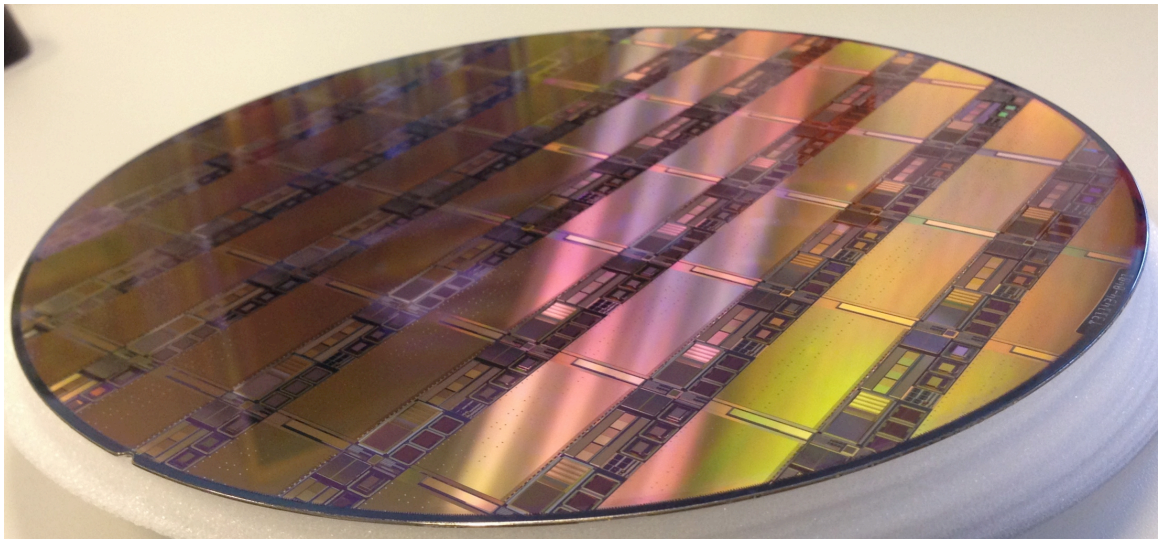
… at this stage almost all detectors look still the same



Wafer processing

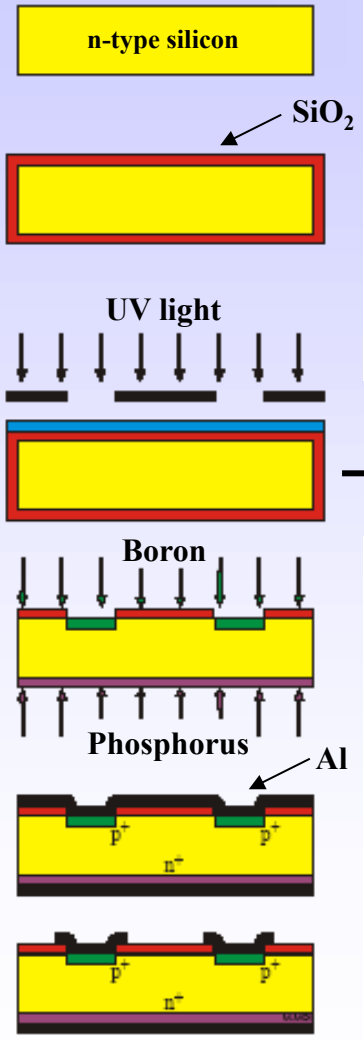
Silicon detector



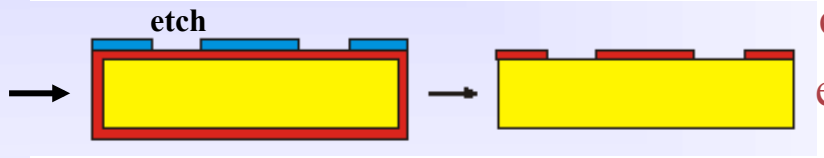


Main fabrication steps

Simplest detector type based on p-on-n structure



- Polished n-type silicon wafer (typical ρ ~ 1-10 KΩcm)
- Grow thermal oxide (800-1200°C)
- Photolithography and etching of SiO_2

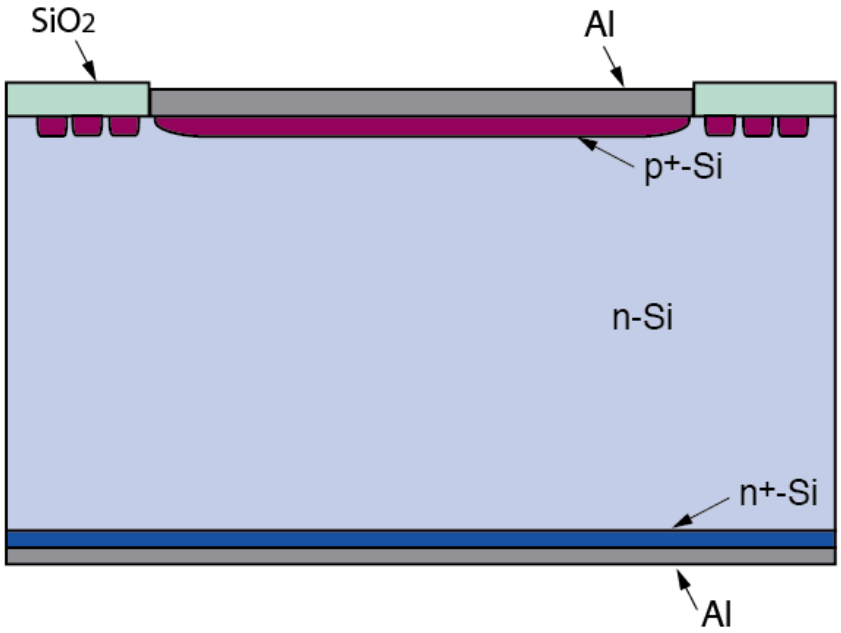


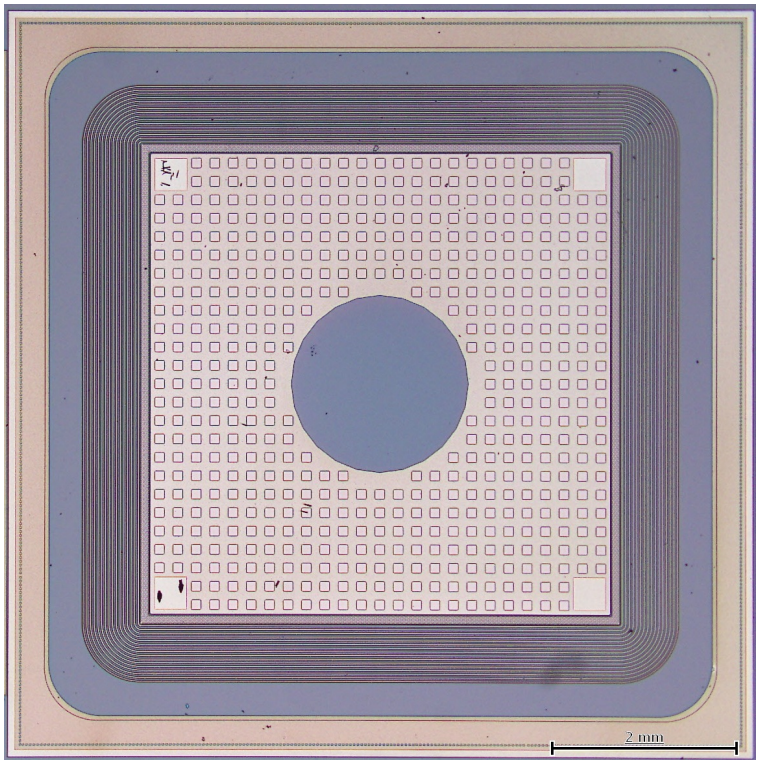
coat with photo resist; align mask,
expose to UV light, develop photoresist
define electrode pattern

- Doping with boron and phosphorus by implantation (or by diffusion)
  Annealing to cure radiation damage and activate dopants
  p^+ n junction on front side
  n n^+ ohmic contact on back side
- Al metallization on both surface (e.g. by evaporation)
- Pattern metal to form contacts

Pad detector

- The most simple detector is a large surface diode with guard ring(s)

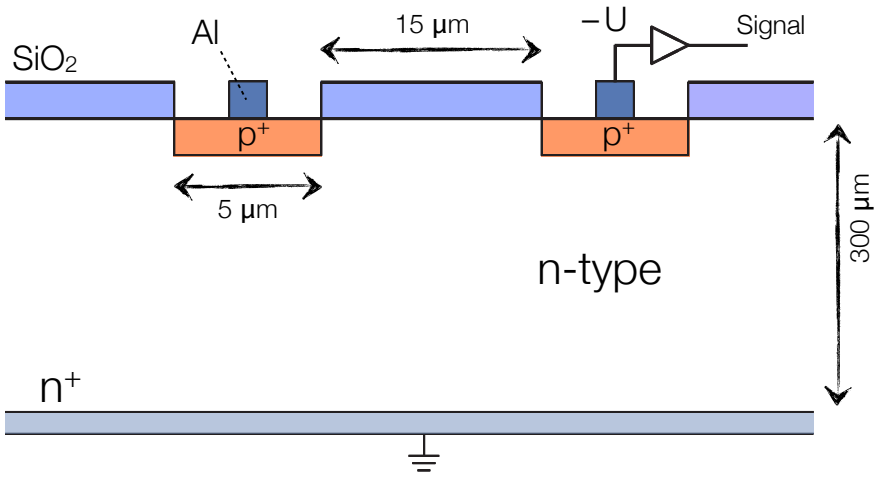




Position sensitive detectors

- Segmentation of one surface (at least) into strips, pads, pixels...

- Typical parameters
  - Thickness 150 - 500 μm
  - Strip separation (pitch) 20 - 150 μm
  - Resolution 5 - 40 μm (pitch/√12)
  - Charge collection 20 ns
  - Charge integration 120 ns
  - Operation voltage <200 V



High resistive n-type silicon onto which p+ diode strips or pixels with aluminum contacts are implanted

- Output signal
  - Average energy loss of MIP: 300 eV/μm; Si: 3.6 eV/pair
  - Thus ≈80 electron-hole pairs per μm
  - 300 μm thickness ➛ 24000 pairs/MIP
  - Total charge: Q_{out} ~ 4 fC

Microstrip Detector – n-type and p-type detectors

The previous slide explains an n-type detector (detector bulk is n-type silicon)

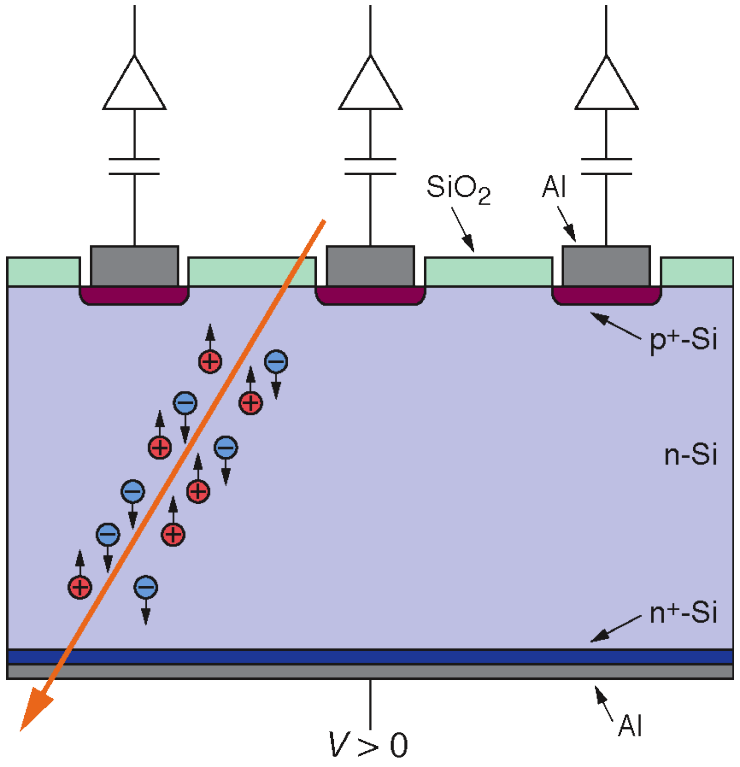
Using p-type silicon and exchanging p^+ and n^+ would give a perfectly working p-type detector

For tradition and production reasons most of the present detectors are n-type detectors.

p-type detectors are discussed as base line detectors for the upgrade experiments CMS and ATLAS, due to their advantages in the high radiation environment

Microstrip Detector - DC coupled strip detector

- Through going charged particles create e^-h^+ pairs in the depletion zone
  - About 25.000 pairs in standard detector thickness
  - Charges drift to the electrodes
  - The drift (current) creates the signal which is amplified by an amplifier connected to each strip
- From the signals on the individual strips the position of the through going particle is deduced
- A typical n-type Si strip detector
  - p^+n junctions
    - $N_a \approx 10^{15}$ cm-3, $N_d \approx 1–5 \cdot 10^{12}$ cm^{-3}
  - n-type bulk
    - $\rho > 2$ kΩcm
    - thickness 300 μm
  - Operating voltage < 200 V.
  - n^+ layer on backplane to improve ohmic contact
  - Aluminum metallization



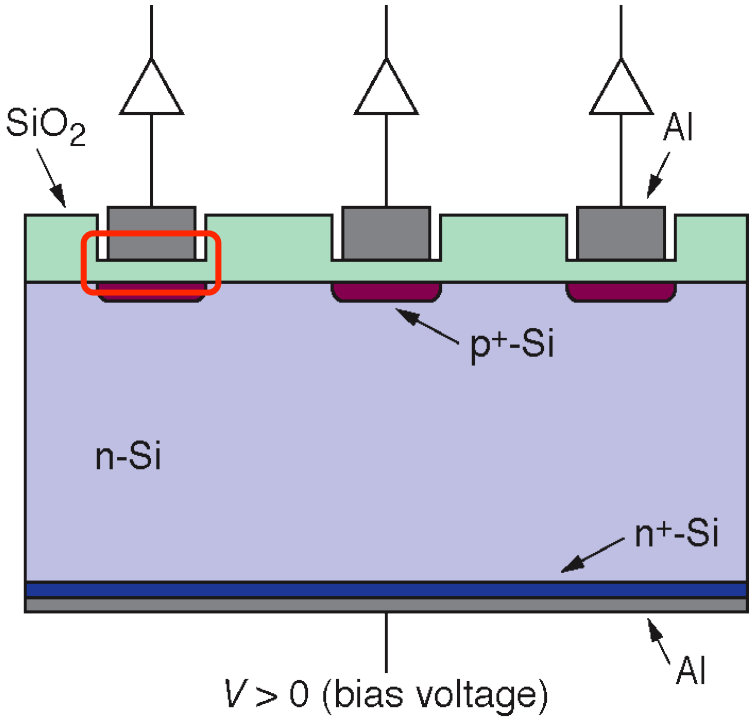
Microstrip Detector - AC coupled strip detector

- AC coupling blocks leakage current from the amplifier
  - Integration of coupling capacitances in standard planar process.
  - Deposition of SiO_2 with a thickness of 100–200 nm between p^+ and aluminum strip
  - Depending on oxide thickness and strip width the capacitances are in the range of 8–32 pF/cm.

- Problems are shorts through the dielectric (pinholes).
  - Usually avoided by a second layer of Si_3N_4

- However, the dielectric cuts the bias connection to the strips
  - Several methods to connect the bias voltage
    - polysilicon resistor
    - punch through bias
    - FOXFET bias

AC coupled strip detector:



Microstrip detector - Polysilicon bias

- Deposition of polycristalline silicon between p^+ implants and a common bias line

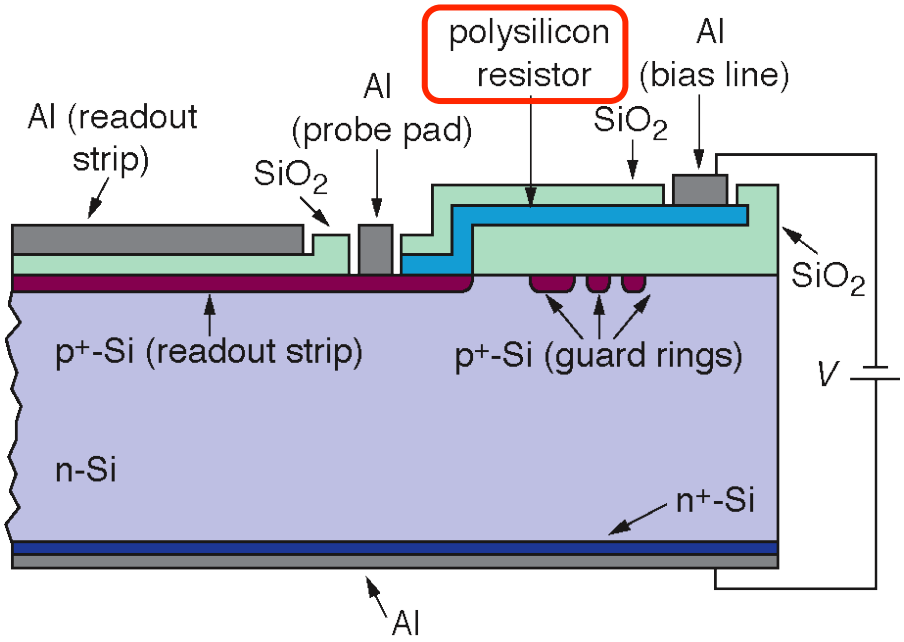
  Sheet resistance of up to $R_s \approx 250$ kΩ/❑

- To achieve high resistor values winding poly structures are deposited

  Depending on width and length a resistor of up to $R \approx 20$ MΩ is achieved ($R = R_s \cdot length/width$)

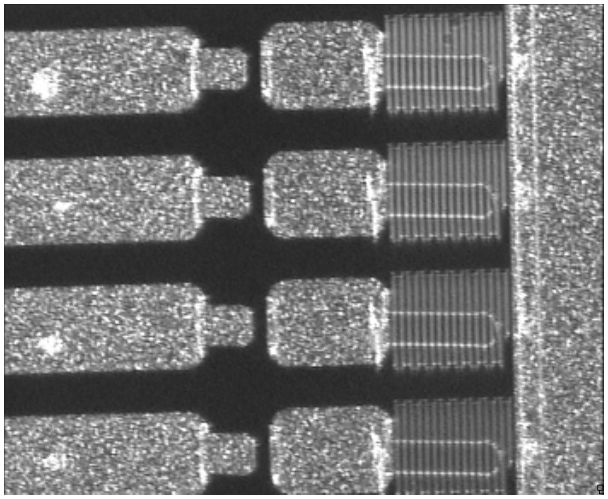
- Drawback: Additional production steps and photo lithograpic masks required

Cut through an AC coupled strip detector with integrated poly resistors



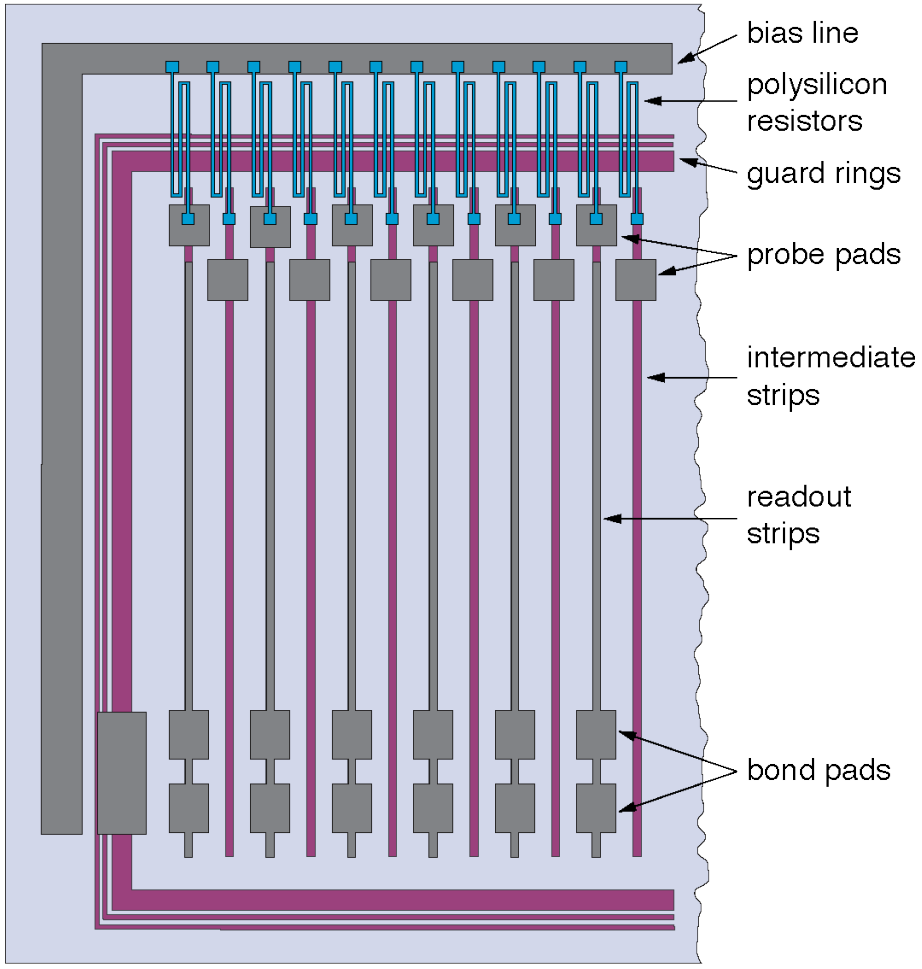
Microstrip detector - Polysilicon bias

CMS-Microstrip-Detector
Close view of area with polysilicon resistors, probe pads, stip ends.



CMS Collaboration, HEPHY Vienna

Top view of a strip detector with polysilicon resistors:

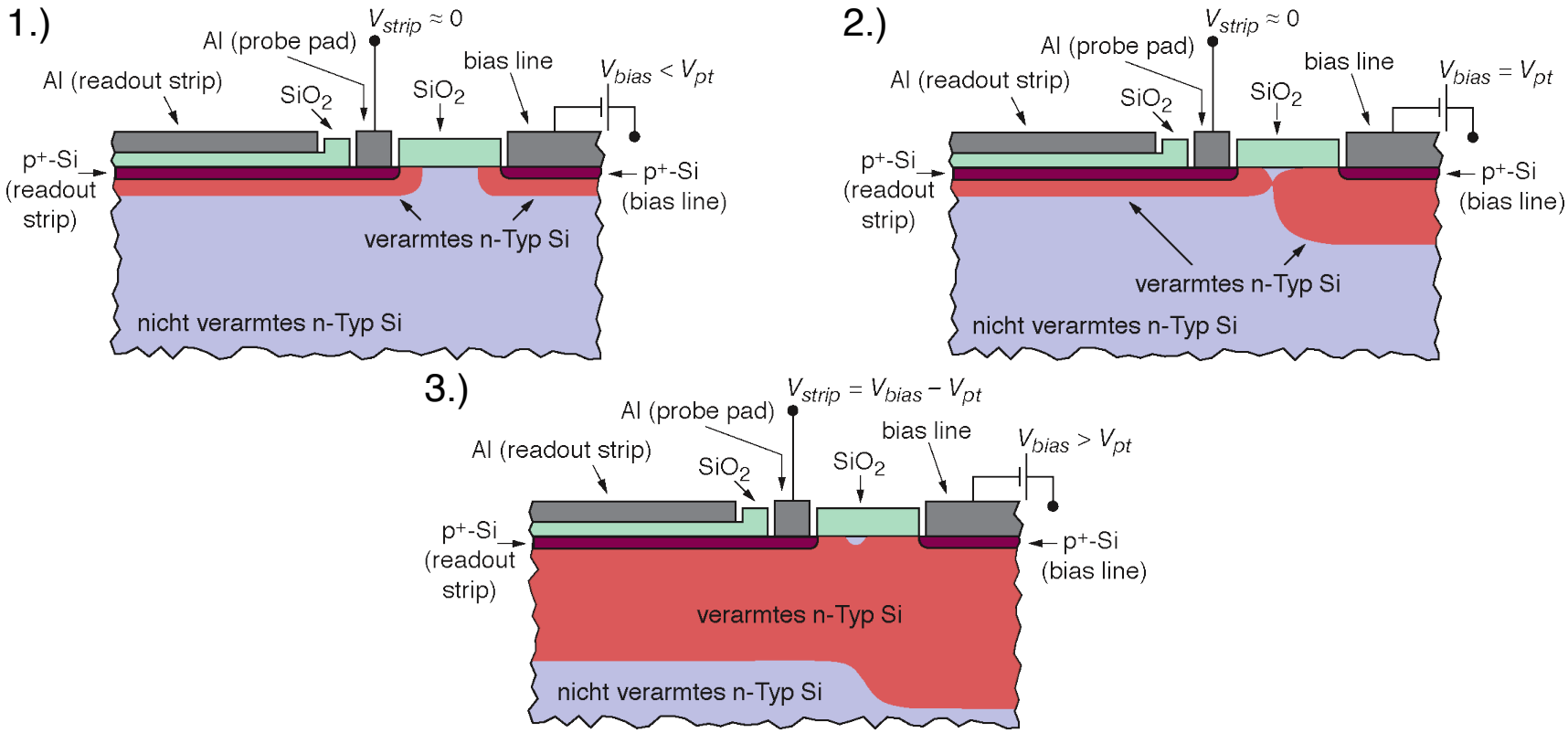


Microstrip detector - Punch through bias

- Punch through effect

  Figures show the increase of the depletion zone with increasing bias voltage

  V_{pt} = punch through voltage



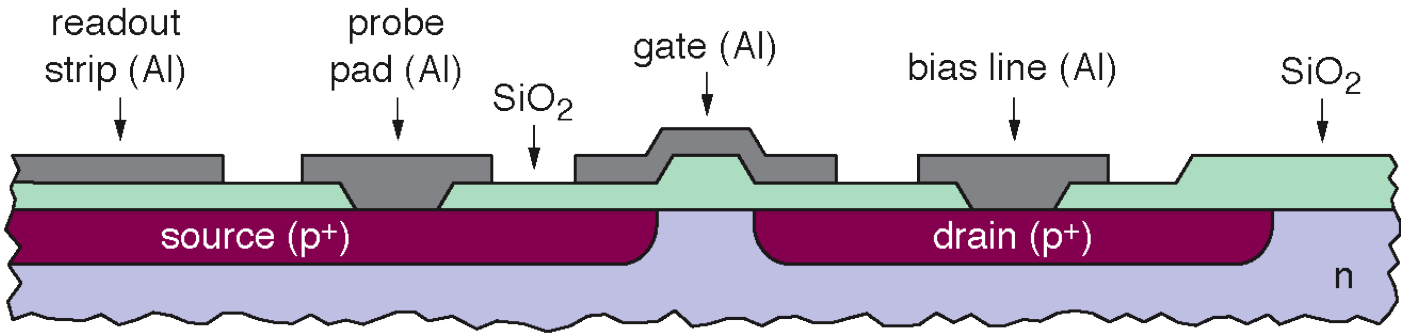
Advantage → No additional production steps are required.

Microstrip detector – FOXFET bias

- Strip p^+ implant and bias line p^+ implant are source and drain of a field effect transistor - FOXFET (Field OXide Field Effect Transistor).

  A gate is implemented on top of a SiO_2 isolation

  Dynamic resistor between drain and source can be adjusted with gate voltage



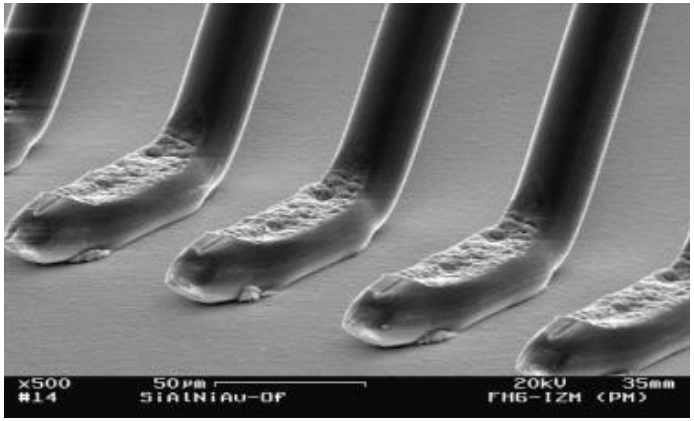
FOXFET biasing

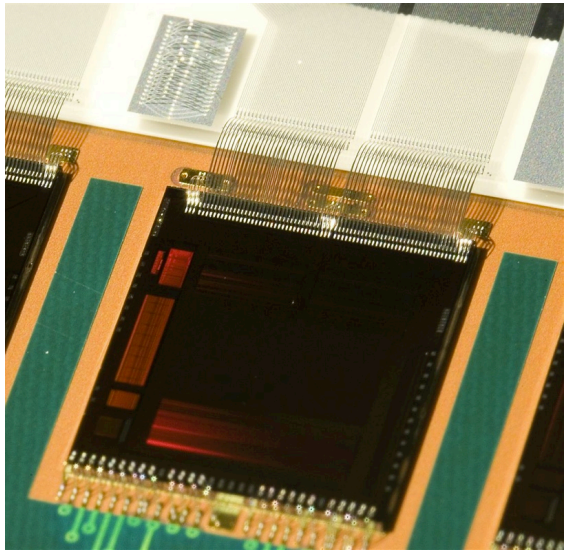
Microstrip detector – Wire bond connection

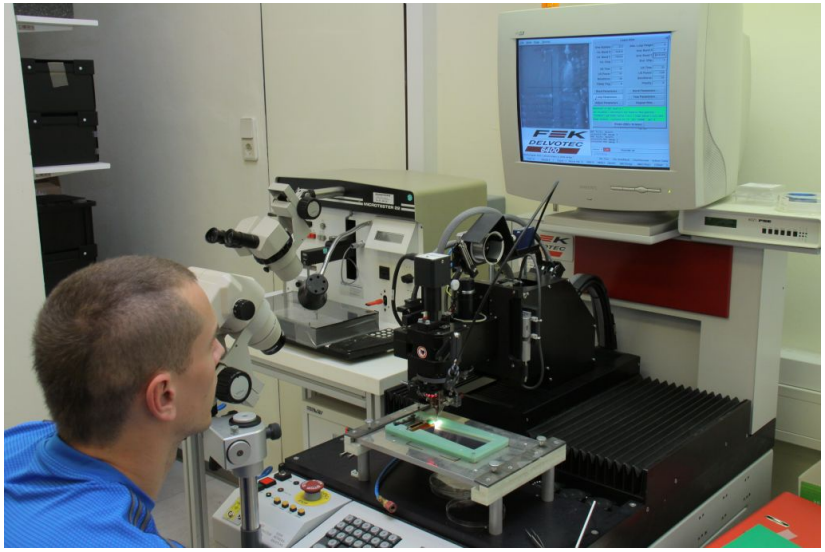
- Ultrasonic welding technique

  Typically 25 micron bond wire of Al-Si-alloy

- Fully-automatized system with automatic pattern recognition







Double-sided microstrip detector

- Single sided strip detector measures only one coordinate

  To measure second coordinate requires second detector layer

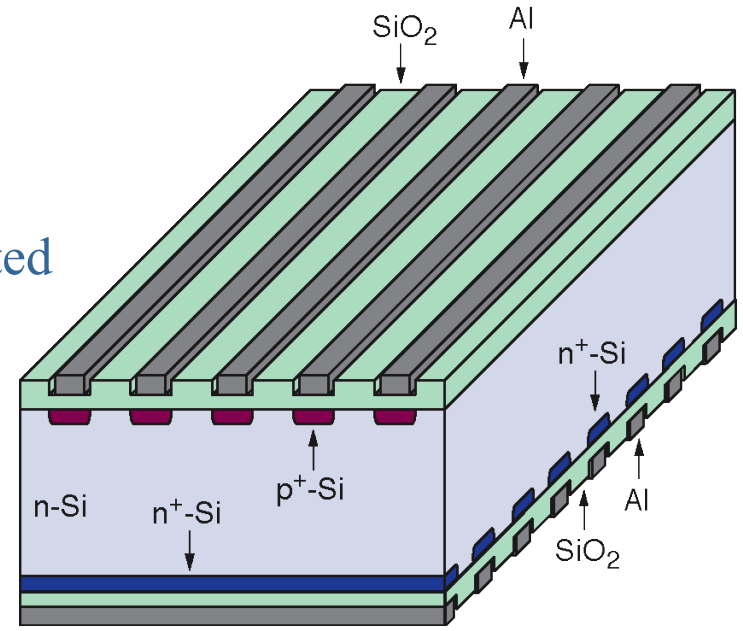
- Double-sided microstrip detector measures two coordinates in one detector layer

  Double-sided microstrip detector minimizes material

- In n-type detector the n^+ backside becomes segmented

  e.g. strips orthogonal to p^+ strips

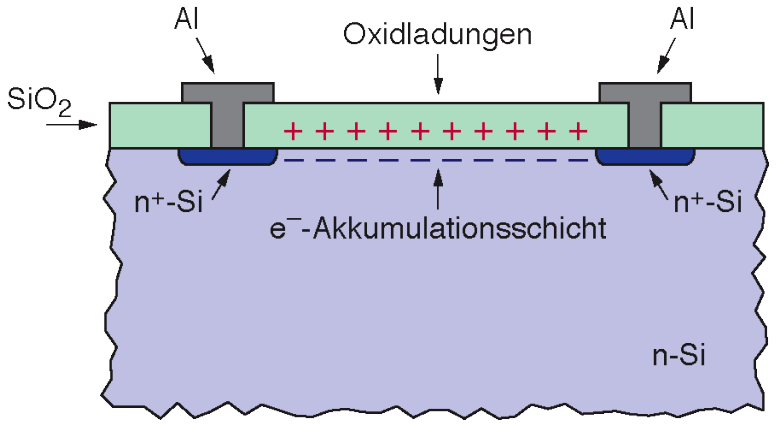
- Drawback: Production, handling, tests are more complicated and hence double sided detector are expensive



Scheme of a double-sided microstrip detector (biasing structures not shown):
Holes drift towards p^+ strips
Electrons drift towards n^+ strips

Double-sided microstrip detector

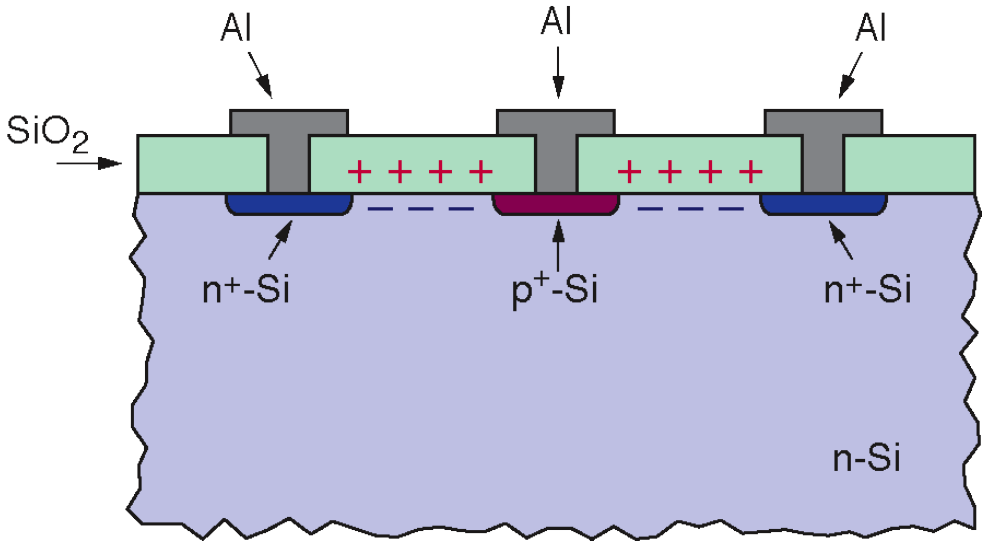
- Consequence of the n^+ segmentation
  - There is always a static positive oxide charges at the Si-SiO_2 interface
  - These positive charges attract electrons
  - The electrons form an accumulation layer underneath the oxide
- n^+ strips are no longer isolated from each other (resistance ≈ kΩ)
  - Charges generated by through going particle spread over many strips
  - Position measurement is not possible
- The solution is to interrupt accumulation layer using p+-stops, p+-spray or field plates



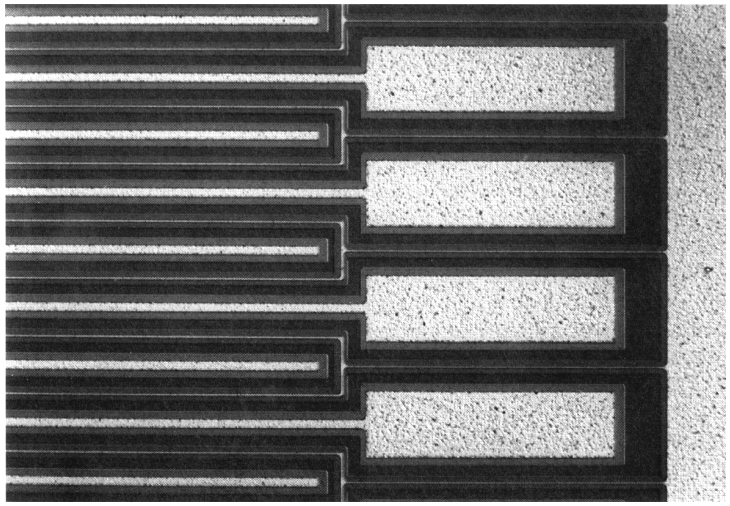
Positive oxide charges cause electron accumulation layer

Double-sided microstrip detector – p^+-stops

- p^+-implants (p^+-stops, blocking electrodes) between n^+-strips interrupt the electron accumulation layer
- Resistance between adjacent strips reaches again GΩ



Picture showing the n^+-strips and the p^+-stop structure

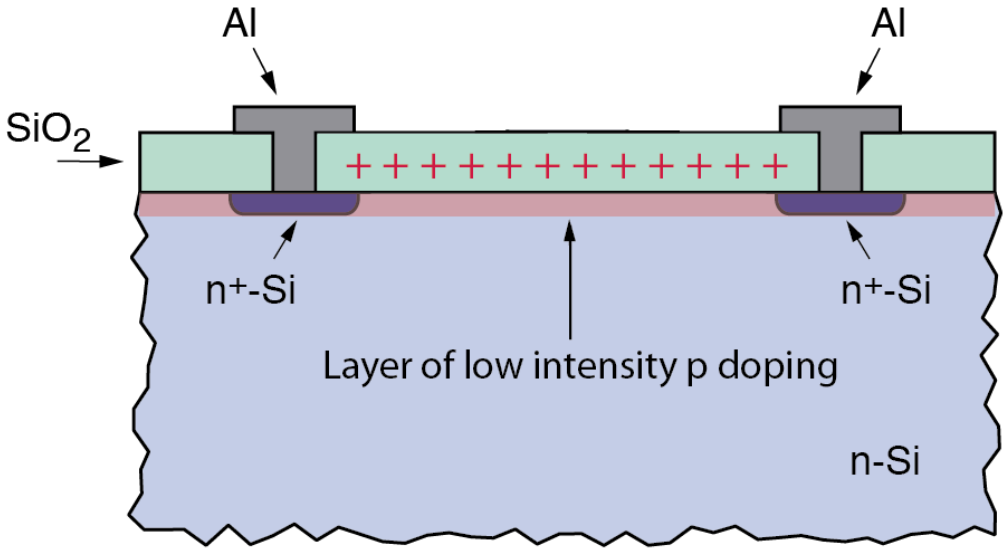


J. Kemmer and G. Lutz, *New Structures for Position Sensitive Semiconductor Detectors*, Nucl. Instr. Meth. A **273**, 588 (1988)

Double-sided microstrip detector – p-spray

- p doping as a layer over the whole surface

  Disrupts the e^- accumulation layer



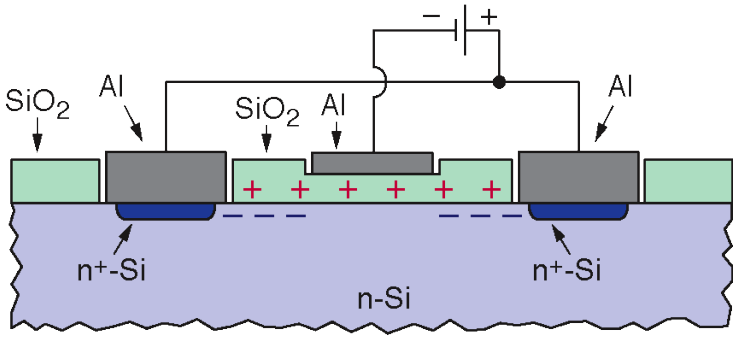
- Some sensor producers use a combination of p^+ stops and p spray

Double-sided microstrip detector – Field plates

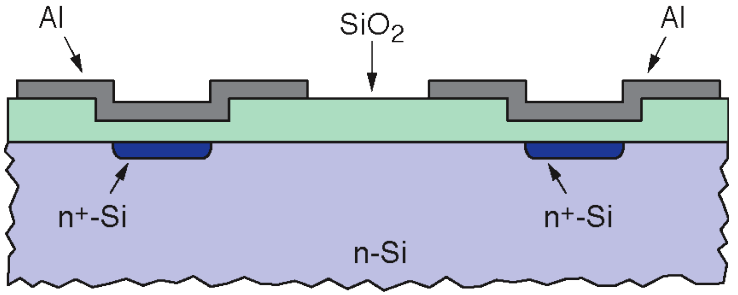
- Metal of MOS structure at negative potential compared to the n^+-strips displace electrons below Si-SiO_2 interface

  Above a threshold voltage n^+-strips become isolate

- A simple realization of AC coupled sensors with wide metal lines with overhang in the region between adjacent strips acts as field plates



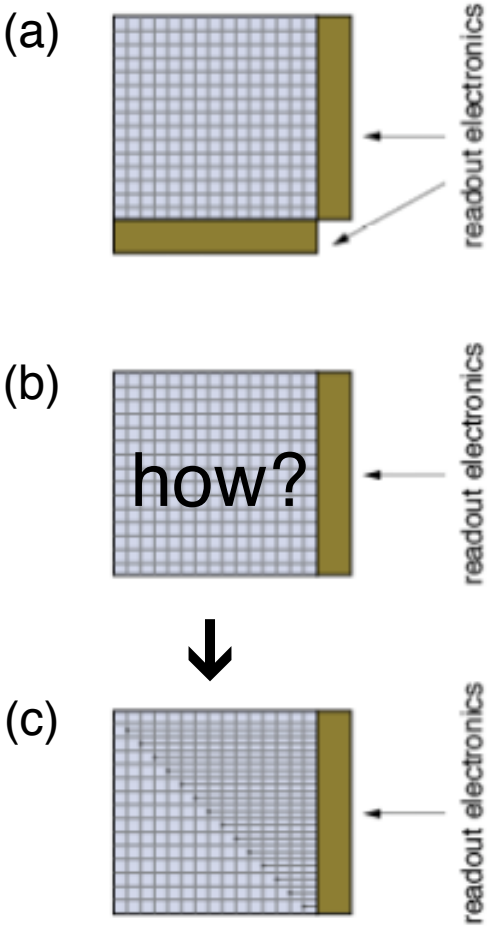
A field plate at negative potential interrupts accumulation layer

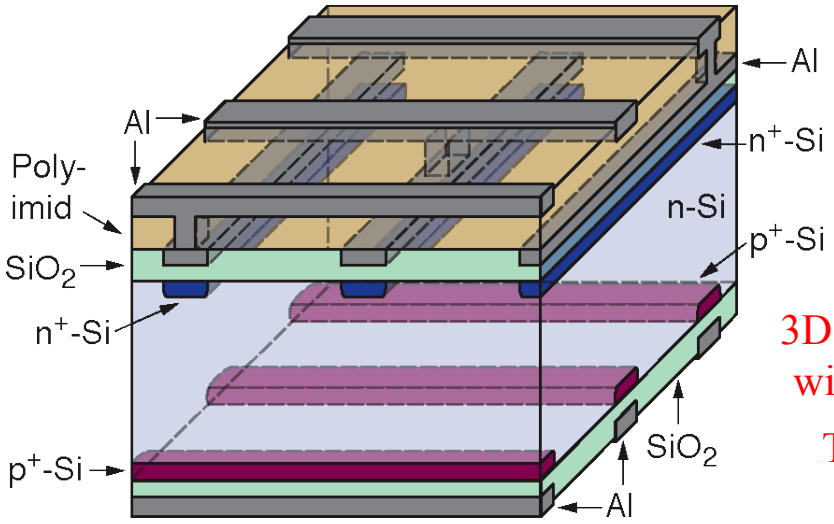


n^+-strips of an AC coupled detector. The aluminium readout lines act as field plates:

Double-sided microstrip detector – 2nd metal layer

- In the case of double sided strip detectors with orthogonal strips the readout electronics is located on two sides (fig. a)
- Many drawbacks for construction and material distribution, especially in collider experiments
- Electronics only on one side is a preferred configuration (fig. b)
- Possible by introducing a second metal layer. Lines in this layer are orthogonal to strips and connect each strips with the electronics (fig. c). The second metal layer can be realized by an external printed circuit board, or better integrated into the detector





3D scheme of an AC coupled double sided strip detector with 2nd metal readout lines (bias structure not shown).

The isolation between the two metal layers is either polyimide or SiO_2

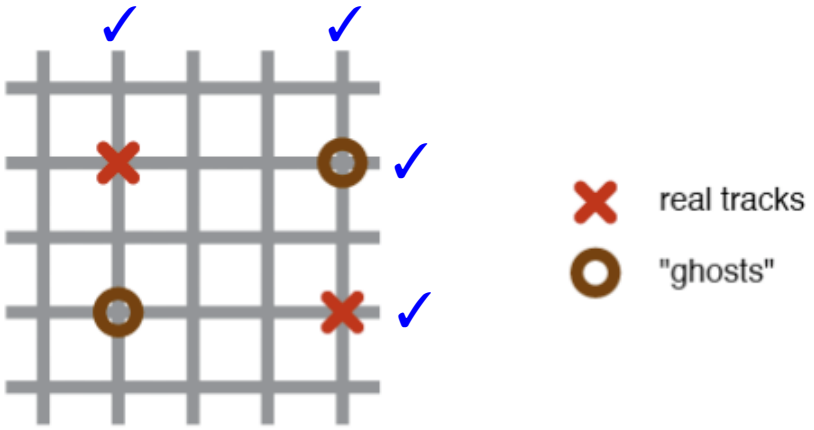
Pixel detector

- Double sided strip sensors measure the 2 dimensional position of a particle track

  If more than one particle hits the strip detector the measured position is no longer unambiguous

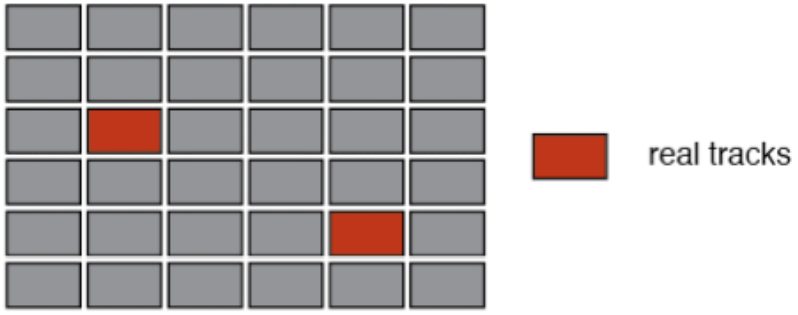
  "Ghost"-hits appear!

True hits and ghost hits in a double sided strip detector in case of two particles traversing the detector



- Pixel detectors produce unambiguous hits

Measured hits in a pixel detector in case of two particles traversing the detector



Pixel detector

- Typical pixel size is 50 µm x 50 µm
- If signal pulse height is not recorded, resolution is the digital resolution: ~14 µm (50 µm pixel pitch).
- Better resolution achievable with analogue readout

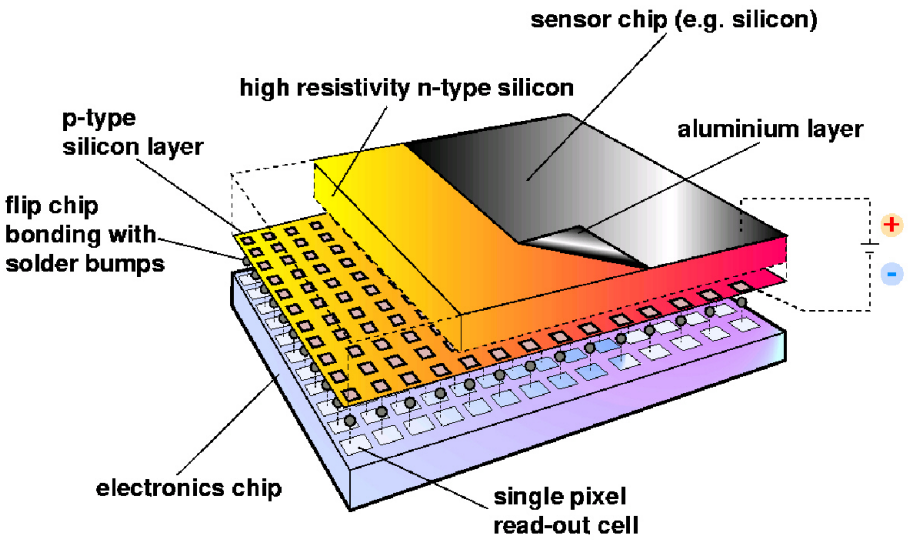
$$\sigma_x \approx \frac{d}{\sqrt{12}}$$

d=pixel dimension

- Advantages
  - Small pixel area
    - low detector capacitance (≈1 fF/pixel)
      - large signal-to-noise ratio (e.g. 150:1)
  - Small pixel volume
    - low leakage current (≈1 pA/Pixel)
- Drawbacks, usually
  - Large number of readout channels
  - Large number of electrical connections
  - Large power consumption of electronics

Hybrid pixel detector

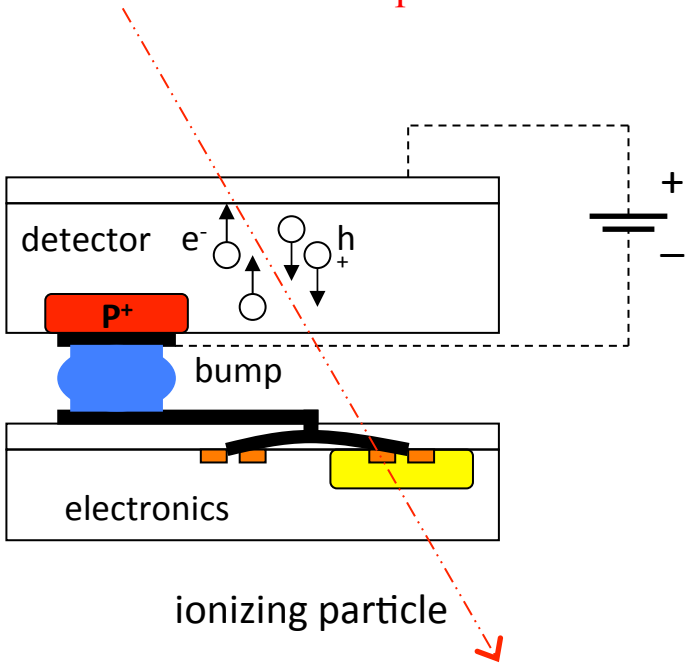
"Flip-Chip" pixel detector



On top the Si detector, below the readout chip, bump bonds make the electrical connection for each pixel.

Detail of bump bond connection.

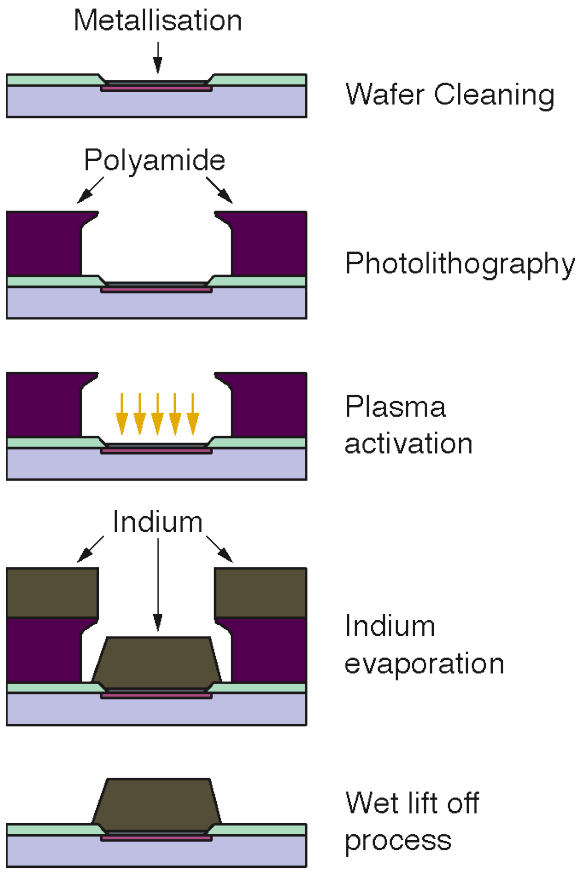
Bottom is the detector, on top the readout chip



Hybrid pixel detector – Bump-bonding process

- A typical bump bonding process (array bump bonding)

1. Deposition of an "underbump metal layer", plasma activated, for a better adhesion of the bump material
2. Photolithography to precisely define areas for the deposition of the bond material
3. Deposition, by evaporation, of the bond material (e.g. In or SnPb) producing little "bumps" (≈ 10 μm height)
4. Edging of photolithography mask leaves surplus of bump metal on pads
5. Reflow to form spheres



Hybrid pixel detector – Bump-bonding process

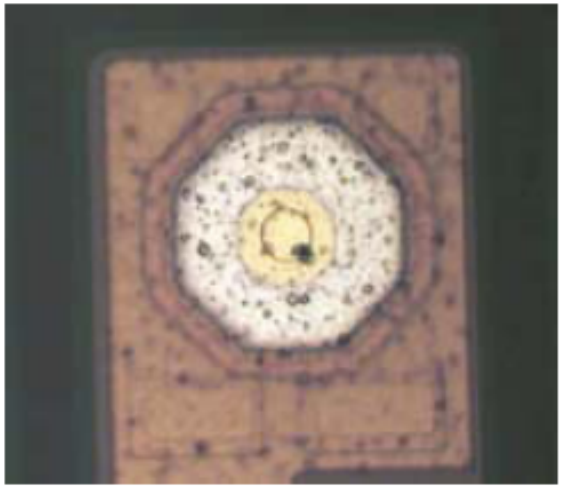
- Electron microscope pictures before and after the reflow production step.

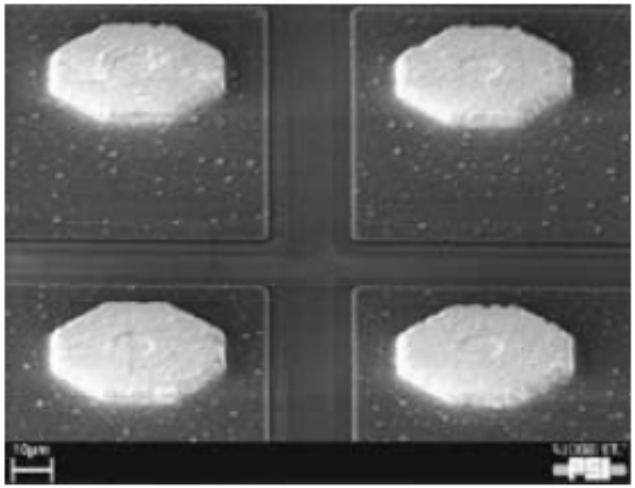
  Indium bump

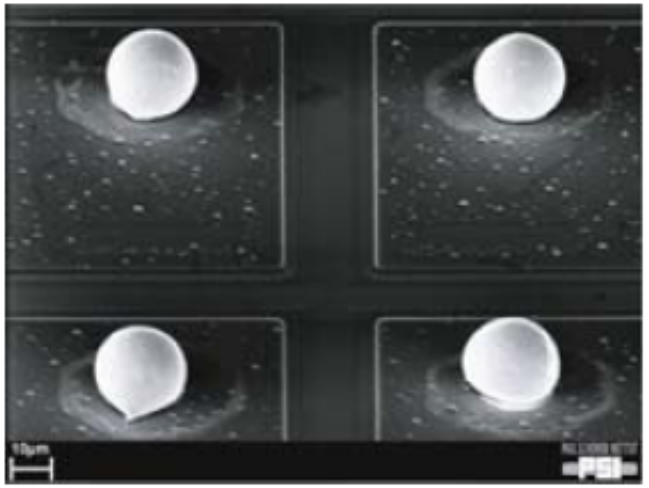
  The distance between bumps is 100 μm

  The deposited indium is 50 μm wide

  The reflowed bump is only 20 μm wide.



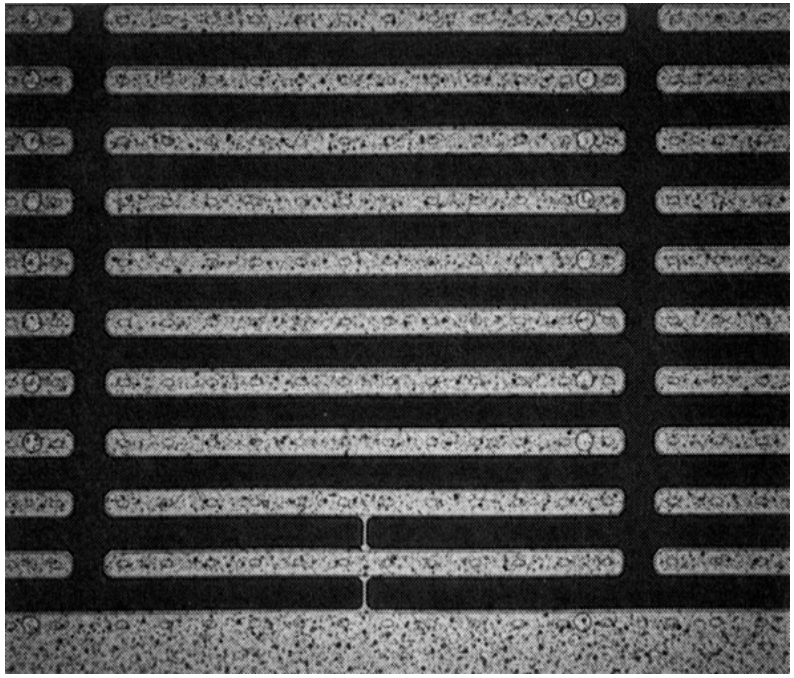




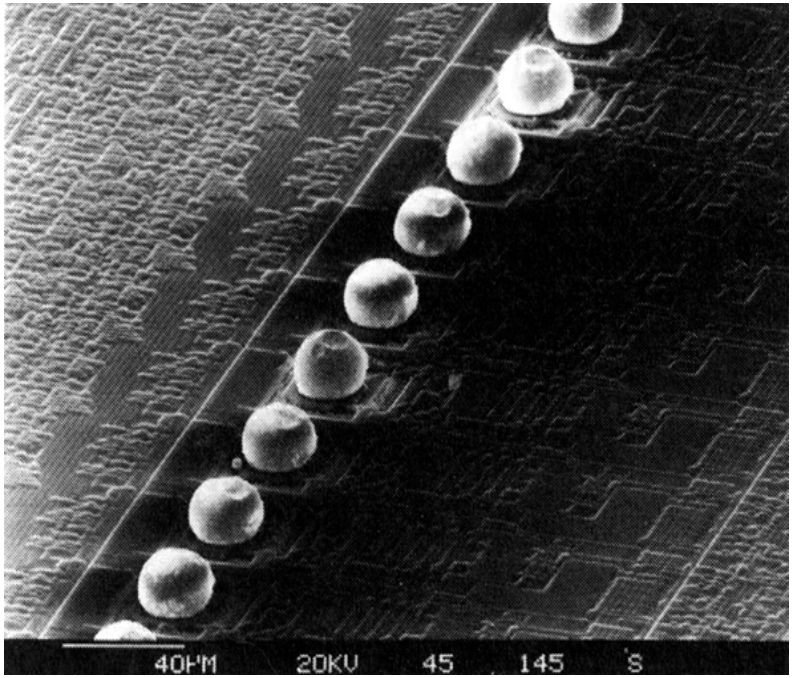
Hybrid pixel detector – Bump-bonding process

Electron microscope picture of pixel detector with long strip

Pixel Sensor



Readout chip with bump bonds applied



Other Si detector structures

- Strip and hybrid pixel detectors are mature technologies employed in almost every experiment in high energy physics
- Additional interesting silicon detector structures are:

  Silicon Drift Detectors (SDD)

  Monolithic Active Pixels (MAPS)

  3D detectors

  Charged Coupled Devices (CCD)

  Depleted Field Effect detectors (DEPFET)

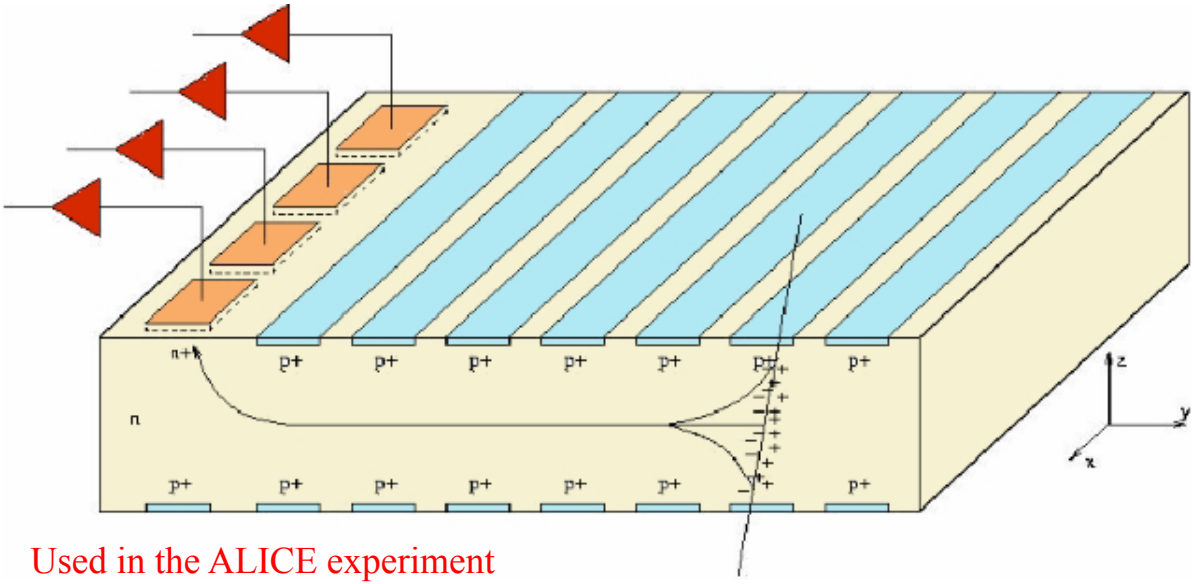
  Silicon On Oxide (SOI)

  Avalanche Photo Diodes (APD) and Silicon Photo Multiplier (SiPM)

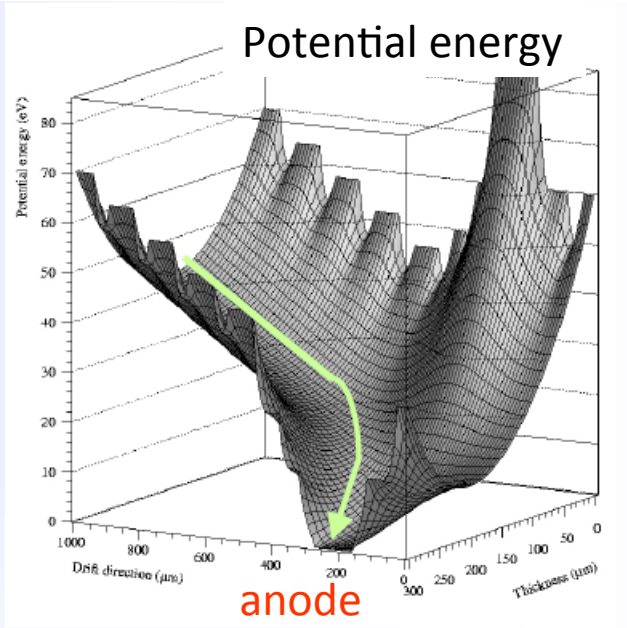
Silicon Drift Detector

- In silicon drift detectors p^+ strips are implanted on both surfaces of the sensor
  complete depletion of the bulk from segmented n+ anodes located at one side of sensor
- A drift field transports the generated electrons parallel to the sensor surface to the readout electrodes n^+

  voltage divider network (resistors) connected to p-strips provides uniform drift field
- One coordinate is measured by signals on n+ anodes, the second by the drift time



Used in the ALICE experiment at CERN-LHC



Silicon Pixel Detectors

- Hybrid Pixel detectors

  Sensor based on pn junction detectors produced in planar process

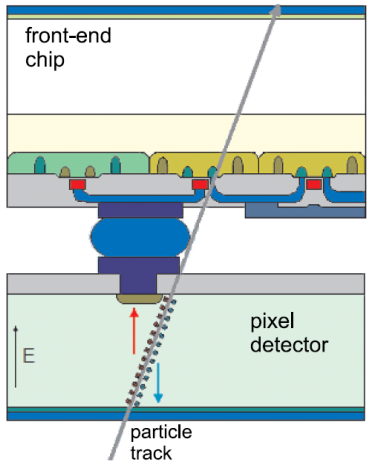
  High resistivity wafers (few kΩcm) with diameters 4”-6”

  Specialized producers (~10 world wide)

  Readout Chip: CMOS chip fabricated in sub-micron technology

  Interconnect technology based on flip-chip bonding

Hybrid Pixel Detector



- Monolithic Pixel detectors

  Combine sensor and all or part of the readout electronics in one chip

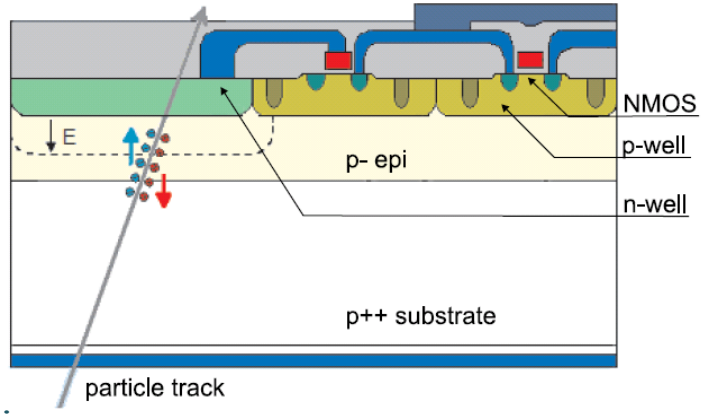
  Charge generation volume integrated into the ASIC

  No interconnection between sensor and chip needed

  Many different flavours with different levels of integration of sensor and readout parts

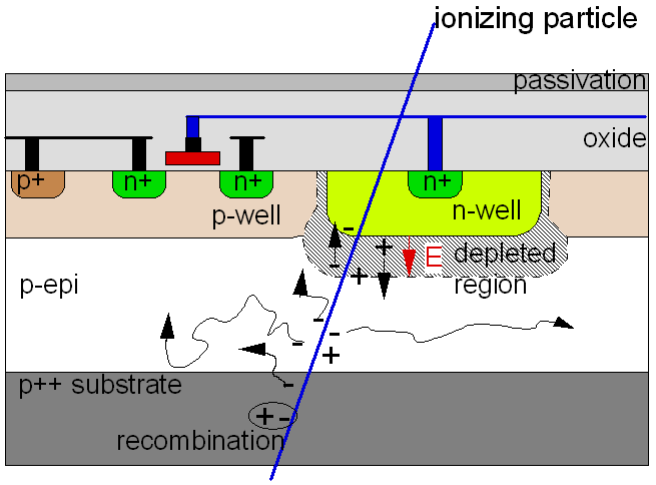
  CCDs, CMOS MAPS, HV/HR CMOS , DEPFET, SOI, ...

Monolithic Pixel Detector



Monolithic Active (CMOS) Pixels

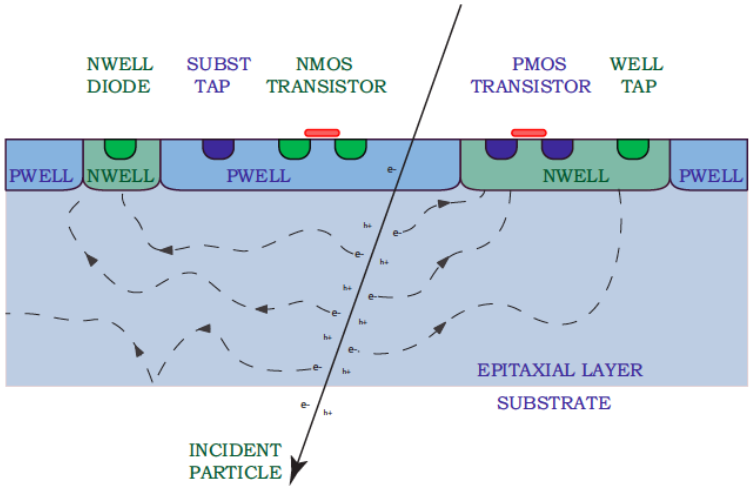
- Sensor volume and signal processing are integrated in the same silicon wafer
  - Commercial standard CMOS technologies
  - Wafer diameter (10")
  - Many foundries available
  - Lower cost per area
- Signal created in thin epitaxial layer (10-30 μm)
  - MIP signal <1000 electrons
    - challenge for IC readout design
- Charge carriers collected by thermal diffusion (~100 ns)
  - Collection at n-well/epi junction
  - Reflective boundaries at p-well and substrate
  - Charge spread to several pixels
- 100% fill factor
- Low material budget: 50 μm thin detector
- Very high-granularity
  - Pixel pitch ~20÷30 μm
    - Intrinsic spatial resolution ~few microns

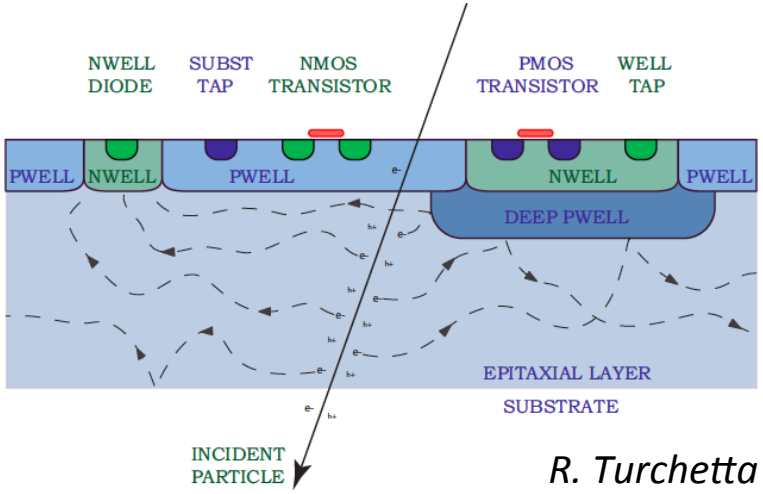


MAPS vs Hybrid Pixels	MAPS	Hybrid
Granularity	+	-
Material budget	+	-
Readout speed	+	++
Radiation tolerance	+	++

Monolithic Active CMOS Pixels

- Due to n-well/epi collection diode, only NMOS transistors can be embedded in active area
  n-wells for PMOS transistors compete with the collection diodes
- Special quadruple-well process available to shield PMOS transistors
  Allows in-pixel truly CMOS circuitry





R. Turchetta - RAL

- Breakthrough in monolithic pixel detectors
  The new Silicon Tracker for the upgrade of the ALICE experiment will be entirely based on this technology

SOI Monolithic Active Pixels

- A Silicon on Insulator (SOI) monolithic active pixel detector consists of a thick fully depleted high-resistivity Si bulk and a thin low resistivity n-type Si wafer bonded to a very thin silicon dioxide SiO_2 referred to as buried oxide (BOX).

  The front-end electronics, NMOS and PMOS transistors, are manufactured in the thin, low resistivity layer, using standard IC methods, over a buried oxide

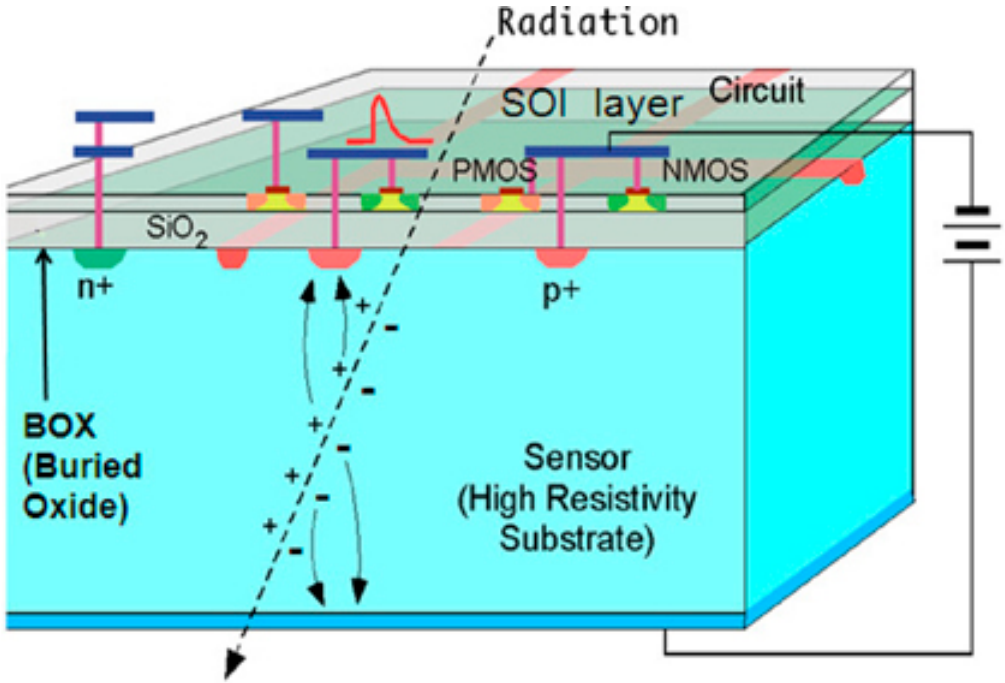
  The pixel matrix is created in the high resistive wafer

  Both parts of the sensor are connected by a metal line that passes through the upper silicon layer and the buried oxide.

The silicon-on-insulator (SOI) sensor's basic structure

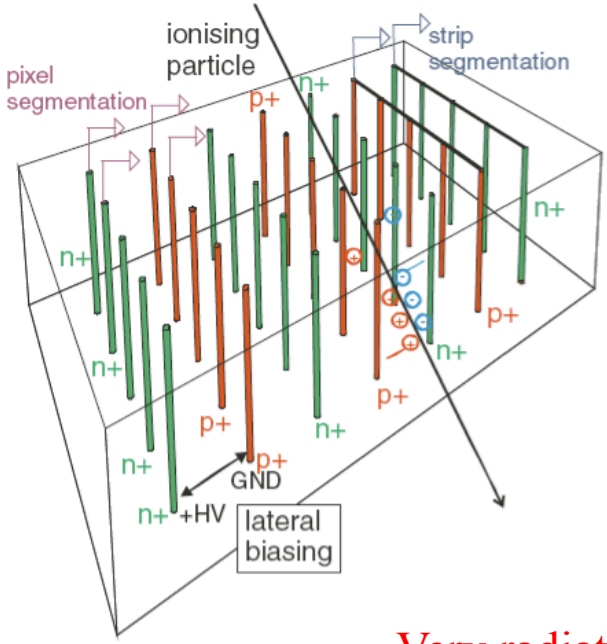
The thickness of the top silicon layer and BOX is ~40nm and 200nm, respectively.

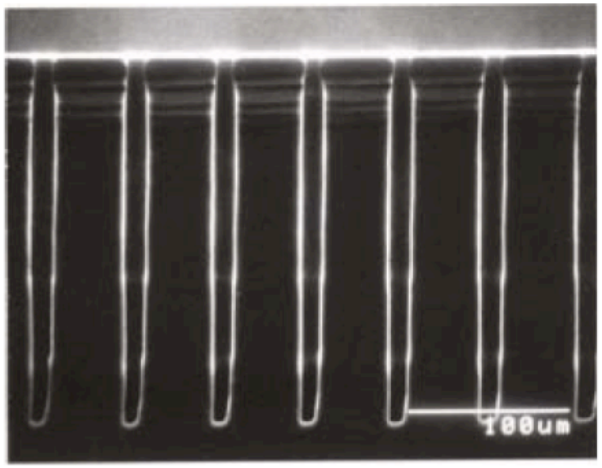
The sensor can be thinned from 700µm to tens of microns, depending on the application.



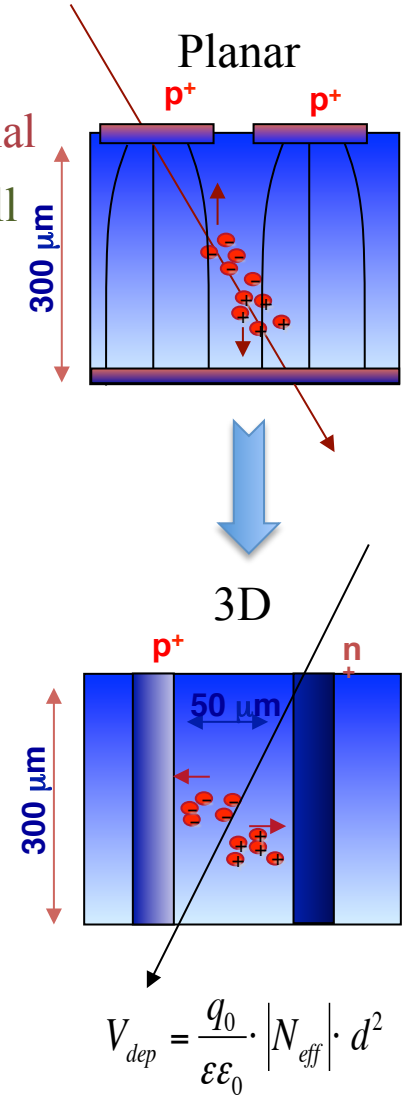
3D Hybrid Pixel Detectors

- 3D hybrid pixel detectors are non-planar sensors
  - Deep holes are etched into the silicon bulk and filled with n^+ and p^+ material
  - Depletion is sideways and the distances between the electrodes are small
    - Depletion voltage can be much smaller and charge carries travel much short distances





Picture from CNM-IMB (CSIC), Barcelona



$$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0} \cdot |N_{eff}| \cdot d^2$$

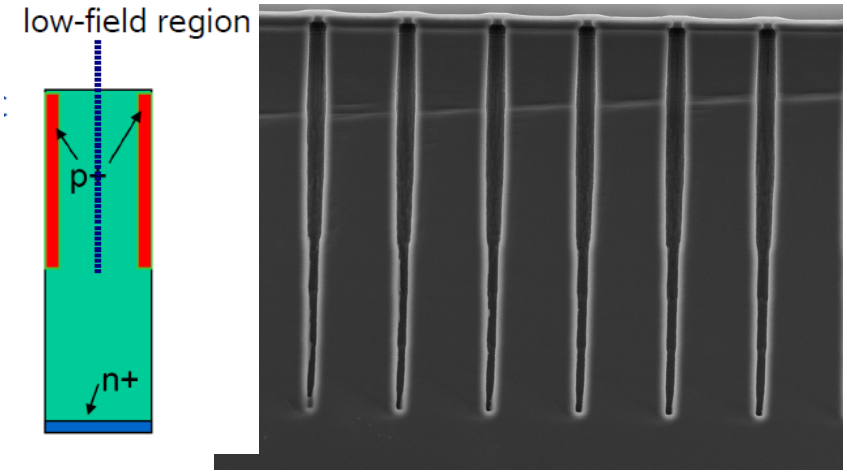
Very radiation tolerant detectors

First use in ATLAS IBL layer

3D Hybrid Pixel Detectors

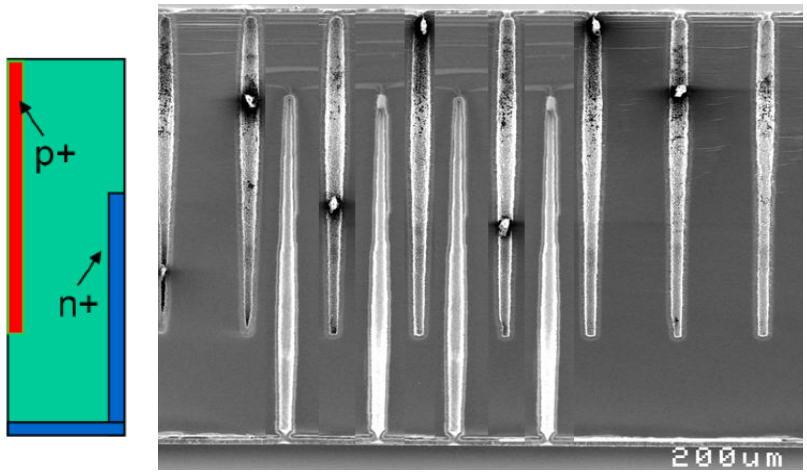
- Two different approaches

Single column



Low field region between columns

Double-sided double column



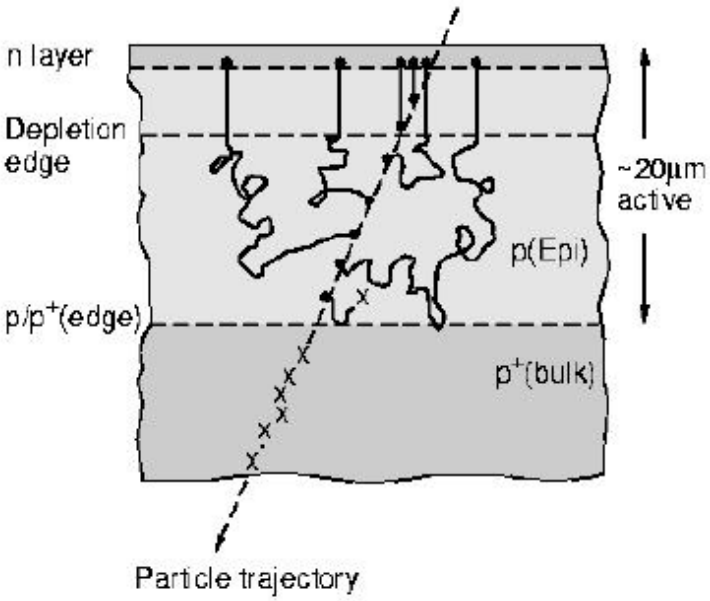
High field, but more complicated

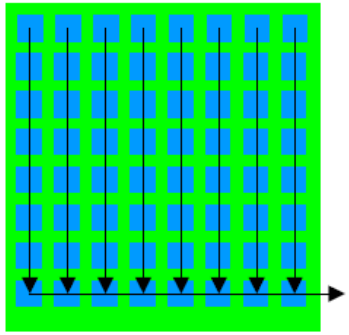
Charge Coupled Devices

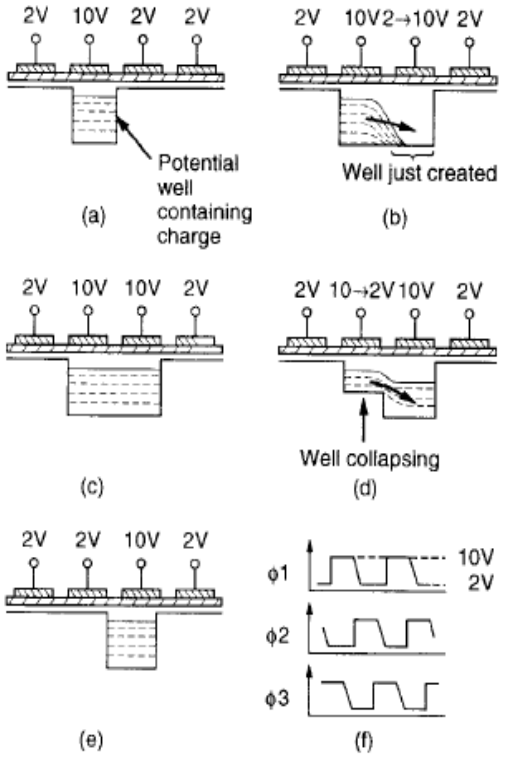
- The charge is kept in the pixel and during readout shifted through the columns and through final row to a single signal readout channel

  Shallow depletion layer, typically ~15μm

  Relatively small signal



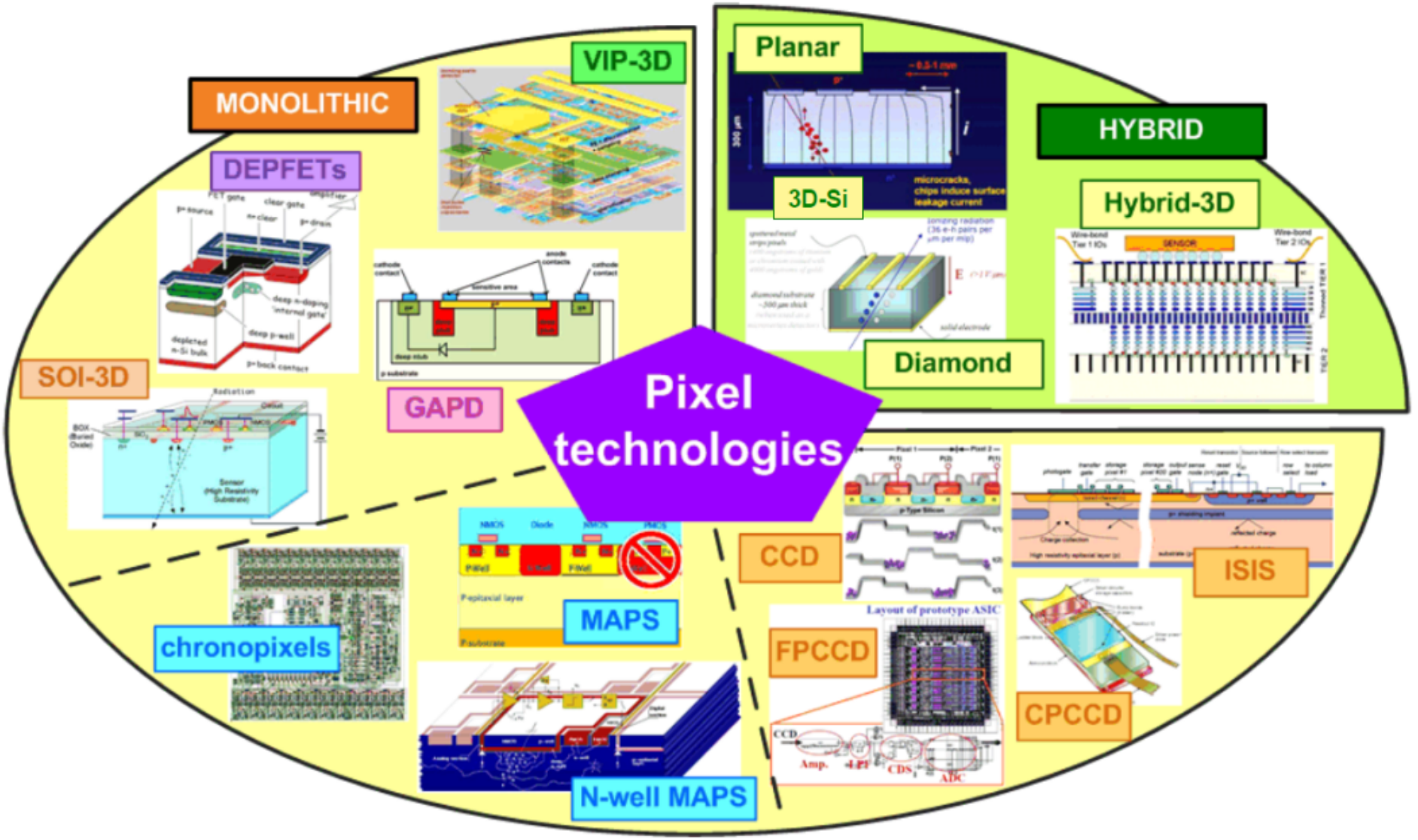




- Slow device, hence not suitable for fast detectors

  Possible improvement, e.g. parallel column readout

The variety of pixel technologies



Slide: N.Wermes at annual workshop of the Helmholtz Alliance Dec.2011, Bonn

Detector Performance

Signal and noise

- The **signal** generated in a silicon sensor depends essentially only on the thickness of the depletion zone and the dE/dx of the particle

  Reminder

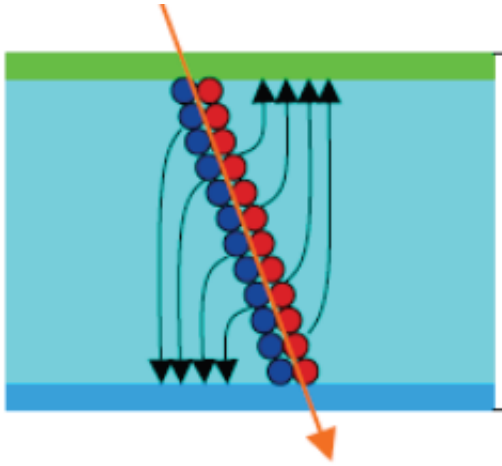
  Mean energy loss per flight path of a mip

  $dE/dx = 3.87$ MeV/cm

  Fluctuations give the famous "Landau distribution"

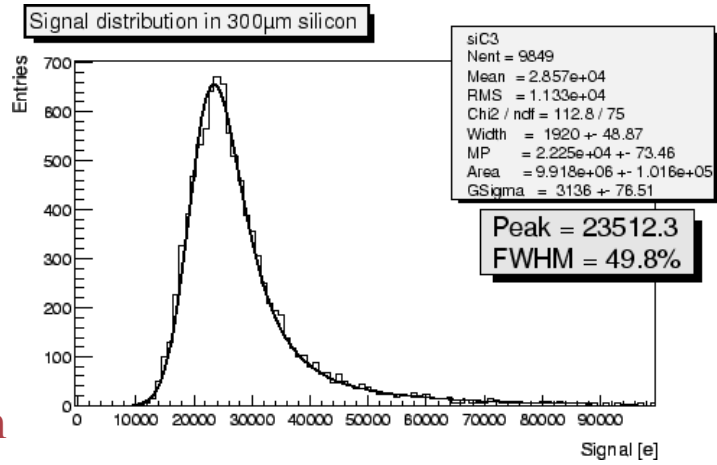
  The "most probable value" is 0.7 of the peak

  For 300 µm of silicon, most probable value is ~24000 e^--h^+ pairs



- The **noise** in a silicon detector system depends on various parameters: geometry of the detector, the biasing scheme, the readout electronics, etc.

  Noise is typically given as *equivalent noise charge* ENC corresponding to the noise at the input of the amplifier in elementary charges



Introduction

Signal processing is a way of converting an obscure signal into useful information

Signal processing includes:

- signal formation due to a particle passage within a detector
- signal amplification
  - Semiconductor detectors need signal amplification since they usually do not have any built-in amplification
- signal shaping (filtering)
- readout

The basic goal is to extract the desired and pertinent information from the obscuring factors (e.g. noise, pile-up)

The two quantities of greatest importance to be extracted from detector signals are:

- amplitude ⟹ energy, nature of the particle, localization
- time of occurrence ⟹ localization

Signal

- The signal on the electrodes arises from induction caused by the movement of the charges due to the incident radiation rather than the actual collection of the charge itself on the electrode

  e^- and h^+ drift apart in the electric field of the depletion region and hence they produce extra voltage across the region

  the external bias circuit maintains a constant voltage across the detector

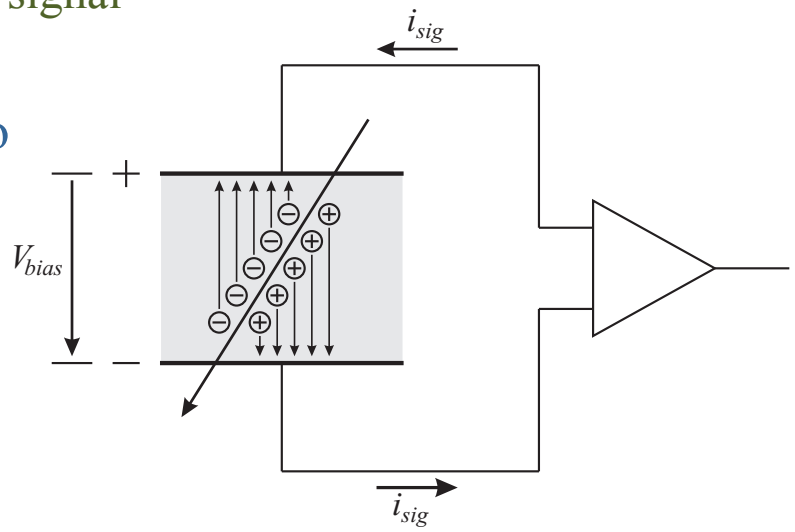
  a charge will flow onto the electrodes to produce a compensating potential

  this induced charge gives the externally detectable signal

- Assuming a simple model of the detector as two parallel electrodes separated by d

  Charge induced on the electrodes by a charge *q* travelling a distance *dx* within the gap between electrodes

$$dQ = \frac{q}{d} dx$$



Signal

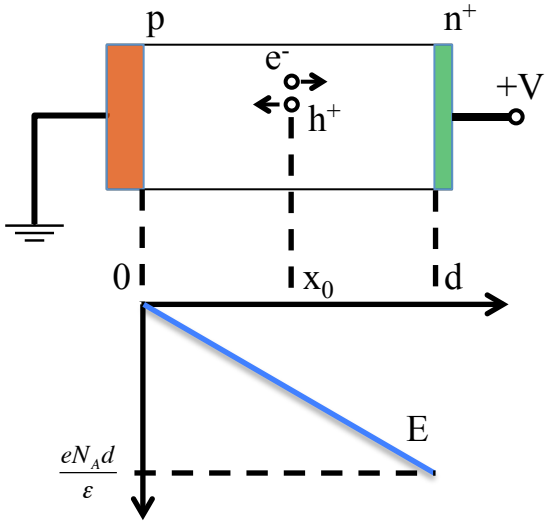
- The time development of the signal

e^--h^+ pair created at the position x in the depletion region, moving towards the respective electrodes

$$v_e = -\mu_e E(x) \qquad v_h = \mu_h E(x)$$

The charge induced by the electron as a function of *t* is

$$Q_e(t) = -\frac{e}{d}\int \frac{dx}{dt}dt = \frac{e}{d}x_0\left(1 - \exp\frac{\mu_e t}{\mu_h \tau}\right)$$



The charge induced by the hole as a function of *t* is

$$Q_e(t) = -\frac{e}{d}x_0\left(1 - \exp\frac{-t}{\tau}\right)$$

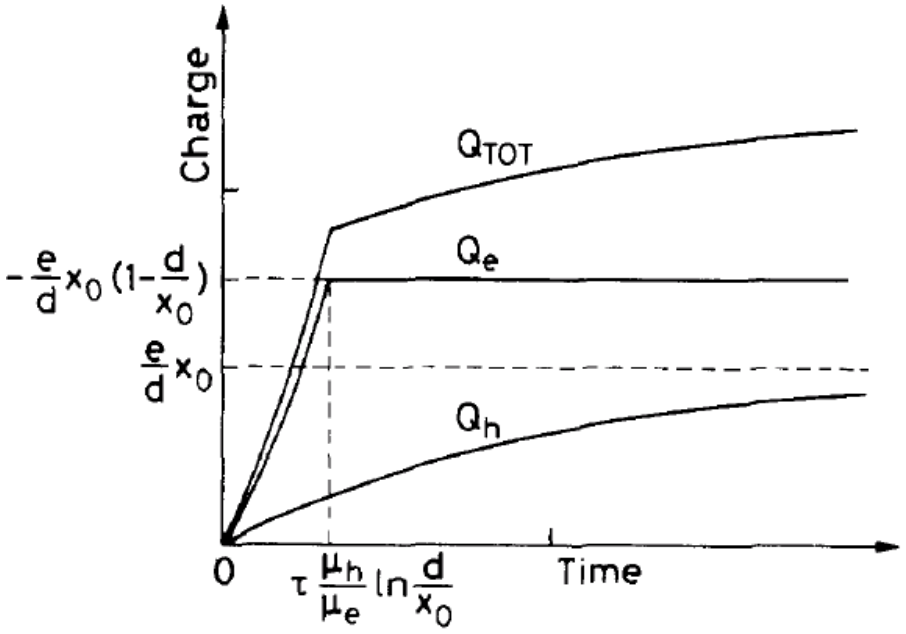
The time taken by the electron to reach the electrode at x = d

$$t = \tau\frac{\mu_h}{\mu_e}\ln\frac{d}{x_0}$$

The hole moves towards the electrode at x = 0 and because the E field goes to zero, the drift velocity drops to zero also and the hole would never reach the electrode (infinite collection time)

Signal

- The overall pulse shape is the sum of the charge induced both by the electron and the hole



The parameter τ determines the rise time of the signal

In silicon, $\tau \approx \rho \cdot 10^{-12}$ s where ρ is the resistivity in Ωcm.

Typically, $\rho \sim k\Omega cm$ ⟹ $\tau \sim ns$

Charge signal

Statistical fluctuations of the energy loss

- Silicon position detectors are thin (300–500 μm) and absorb only a small fraction of the total energy of through going particles
- The energy loss *dE/dx* follows a Landau distribution

  Asymmetric probability function with a long "tail" to large energy deposits
- Example of a mip measured in a 300 μm thick silicon detector

  Most probable energy loss (peak)

  86 keV in 300 μm →

  → ≈80 e^-h^+ pairs per μm

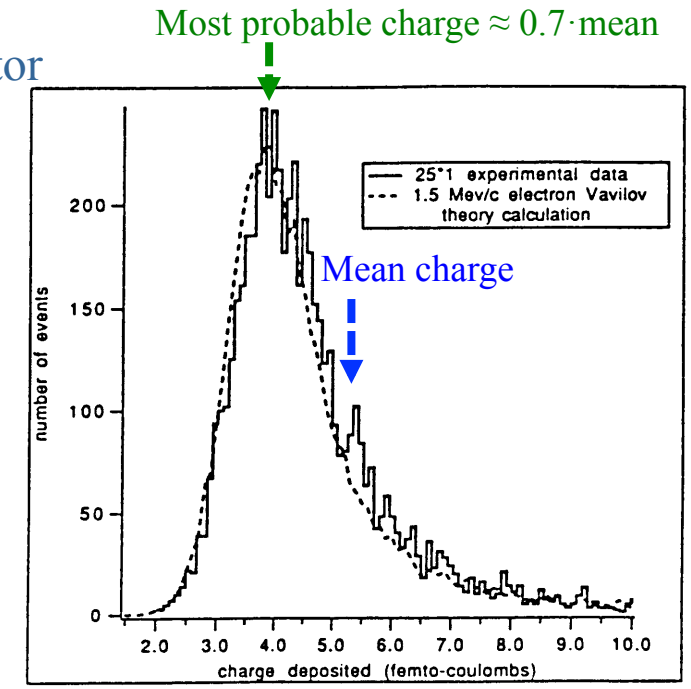
  Mean of the energy loss:

  123 keV in 300 μm →

  → ≈114 e^-h^+ pairs per μm

  Most probable charge (300 μm)

  ≈ 24000 e ≈ 4 fC



Measured Landau distribution in a 300 μm thick Si detector (Wood et al., Univ. Oklahoma)

Noise

- What is **noise**?

  Any unwanted signal obscuring signal we want to observe

- Two main origins

  Extrinsic noise

  Pickup from external sources

  RF interference from system or elsewhere, power supply fluctuations

  Ground currents

  Small voltage differences => currents can couple into system

  May be hard to distinguish from genuine signals but avoidable

  Assembly & connections, especially to ground, are important

  Intrinsic noise

  Fundamental property of detector or amplifying electronics

  Can't be eliminated but can be minimised

Noise contributions

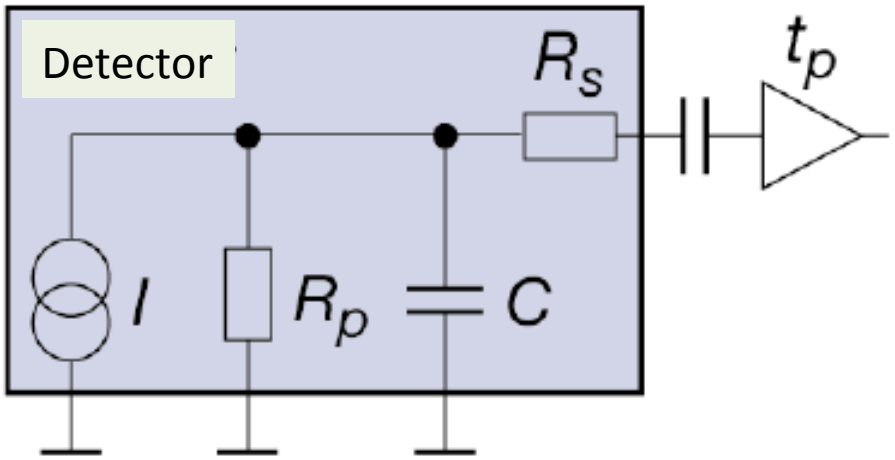
- The most important noise contributions are:

  Detector capacitance (ENC_C)

  Leakage current (ENC_I)

  Detector parallel resistor (ENC_{Rp})

  Detector series resistor (ENC_{Rs})



Alternate circuit diagram of a silicon detector

- t_p is the preamplifier integration time

- The overall noise is the quadratic sum of all contributions

$$ENC = \sqrt{ENC_C^2 + ENC_I^2 + ENC_{Rp}^2 + ENC_{Rs}^2}$$

Detector capacitance ENC_C

- The detector capacitance at the input of a charge sensitive amplifier is usually the dominant noise source in the detector system

- This noise term can be written as $ENC_C = a + b \cdot C$

  The parameter a and b are given by the design of the preamplifier

  C is the detector capacitance at the input of the preamplifier channel

  The integration time t_p plays a crucial role

    short integration time leads usually to larger a and b values

    integration time depends on the accelerator time structure

- Typical values are (amplifier with ~ 1 μs integration time):

    a ≈ 160e

    b ≈ 12 e/pF

To reduce this noise component segmented detectors with short strip or pixel structures are preferred

Leakage current ENC_I

- The detector leakage current comes from thermally generated electron holes pairs within the depletion region, which are separated by the electric field and generate the leakage current

  The fluctuations of the leakage current are the source of noise

  In a typical detector system (good detector quality, no irradiation damage) the leakage current noise is usually negligible

- Assuming an amplifier with an integration time t_p followed by a CR-RC filter the noise contribution by the leakage current I can be written as

$$ENC_I = \frac{e}{2}\sqrt{\frac{I t_p}{e}}$$

e = Euler number (2.718...)
E = Electron charge

- Using the physical constants, the leakage current in units of nA and the integration time in μs the formula can be simplified to

$$ENC_I \approx 107\sqrt{I t_p} \qquad [I \text{ in nA},\ t_p \text{ in } \mu s]$$

To minimize this noise contribution the detector should be of high quality with small leakage current.

Parallel resistor ENC_{Rp}

- The parallel resistor R_p in the alternate circuit diagram is the bias resistor
- The noise term can be written as

$$ENC_{Rp} = \frac{e}{e}\sqrt{\frac{kTt_p}{2R_p}}$$

e = Euler number (2.718...)
E = Electron charge

- Assuming a temperature of T=300K, t_p in μs and R_p in MΩ the formula can be simplified to

$$ENC_{Rp} \approx 772\sqrt{\frac{t_p}{R_p}} \qquad [R_p \text{ in M}\Omega,\ t_p \text{ in } \mu\text{s}]$$

To achieve low noise the parallel (bias) resistor should be large

However the value is limited by the production process and the voltage drop across the resistor, which increases in irradiated detectors

Series resistor ENC_{Rs}

- The series resistor R_s in the alternate circuit diagram is given by the resistance of the connection between sensors and amplifier input (e.g. aluminum readout lines, hybrid connections, etc.).
- This noise term can be written as

$$ENC_{Rs} \approx 0.395\, C \sqrt{\frac{R_s}{t_p}}$$

C = Detector capacitance in pF
t_p = Integration time in μs
R_s = Series resistor in Ω

- Note that, in this noise contribution t_p is inverse, hence a long t_p reduces the noise

The detector capacitance is again responsible for larger noise

To avoid excess noise the interconnection lines should have low resistance (e.g. thick aluminum layer) and all other connections as short as possible

Noise contributions - Summary

- To achieve a high signal to noise ratio in a silicon detector system the following conditions are important

  Low detector capacitance (i.e. small pixel size or short strips)

  Low leakage current

  Large bias resistor

  Short and low resistance connection to the amplifier

  Usually long integration time

- Some of the conditions above are contradictory, therefore

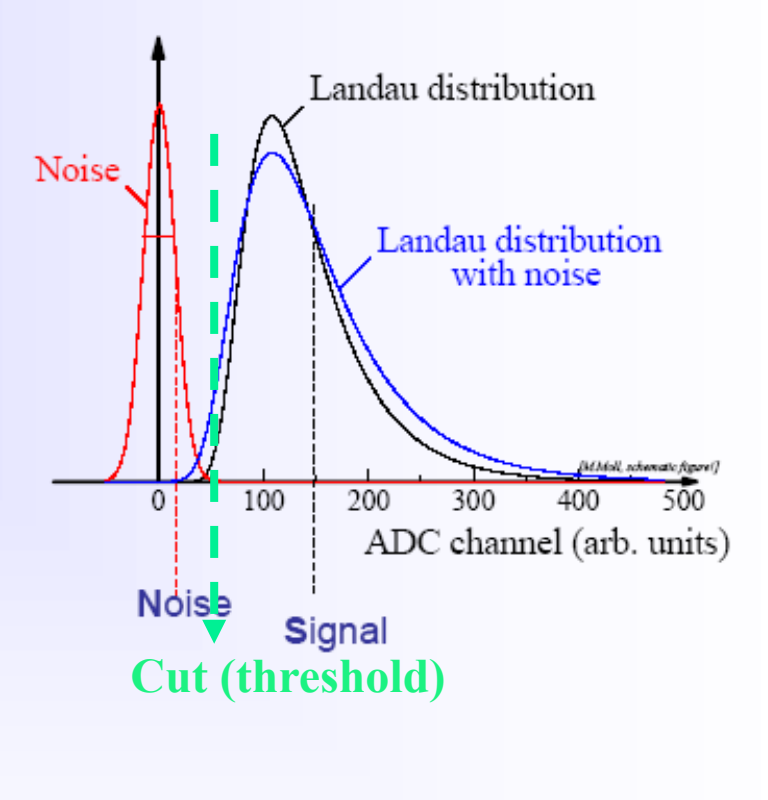
  Detector and front end electronics have to be designed as one system

  The optimal design depends on the application

Signal to noise ratio (SNR)

- **Landau distribution** has a low energy tail
  Even lower by noise broadening

- Good hits selected by requiring N_{ADC} > noise tail
  If cut too high ⇒ efficiency loss
  If cut too low ⇒ noise occupancy



- Figure of Merit: Signal-to-Noise Ratio S/N
  Typical values >10-15, people get nervous below 10
  ⇒ Radiation damage severely degrades the S/N

Position resolution

- The position accuracy - which is one of the main parameter of a tracking detector - depends on various factors, some due to physics constraints and some due to the external parameters such as the design of the system

  Physics processes

    Statistical fluctuations of the energy loss

    Diffusion of charge carriers

  External parameters

    Binary or analogue signal readout

    Distance between strips or pixels (detector pitch)

    Signal to noise ratio

Position resolution

Statistical fluctuations of the energy loss

- Long tail in energy loss distribution is due to δ-electrons

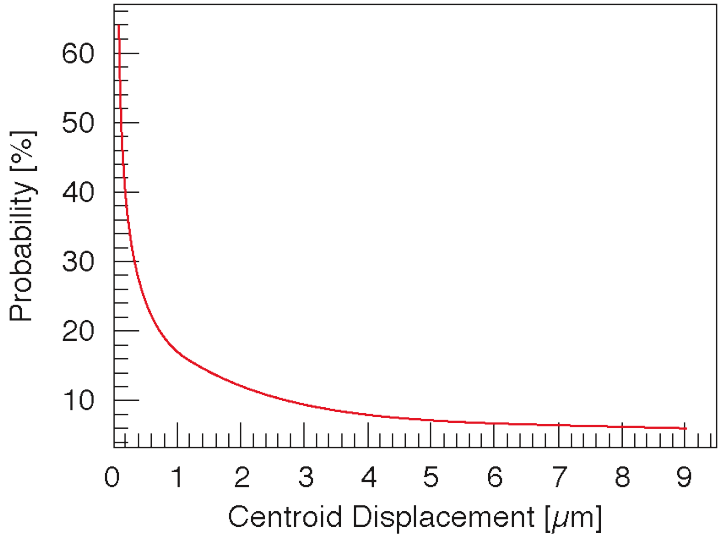
  δ-electrons have a high energy (keV) and are produced by rare, hard collisions between incident particle and electrons from the detector material

  The probability to produce δ-electrons is relatively small

  δ-electrons may have a long path in the detector material and may produce e^-h^+ pairs along the track

    Dislocate the measured track

    Measurement errors in the order of few μm are unavoidable



Probability of the displacement of the charge center of gravity due to δ-electrons:

Position resolution

Diffusion of charge carriers

- After the ionizing particle has gone through the detector, the e^-h^+ pairs are produced close to the original track
- While the clouds of e^- and h^+ drift towards the respective collecting electrodes, the diffusion due to random thermal motion widens the charge carrier distribution.
- The rms width σ_D of the charge distribution after a time t is given by

$$\sigma_D = \sqrt{2Dt} \qquad \text{with:} \qquad D = \frac{kT}{e}\mu$$

t = drift time
K = Boltzmann constant
e = electron charge

D = diffusion coefficient
T = temperature
μ = charge carrier mobility

- Note that $D \propto \mu$ and $t \propto 1/\mu$, hence σ_D is equal for e^- and h^+
- Typical values

Drift times for d=300 μm and E = 2.5Kv/cm

$t_d(e) = 9$ ns and $t_d(h) = 27$ ns

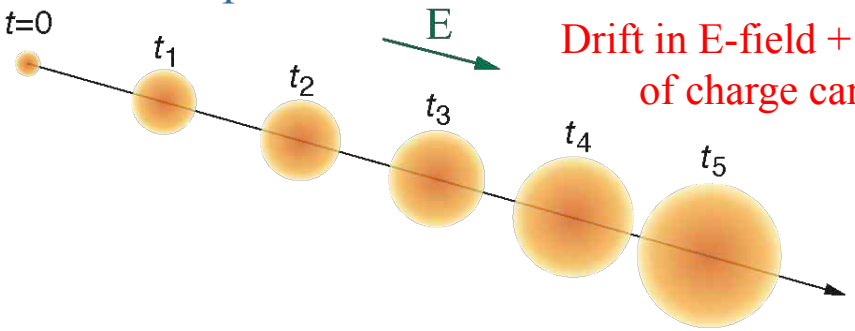
Diffusion for 300 μm drift

$\sigma_D \approx 8$ μm

Position resolution

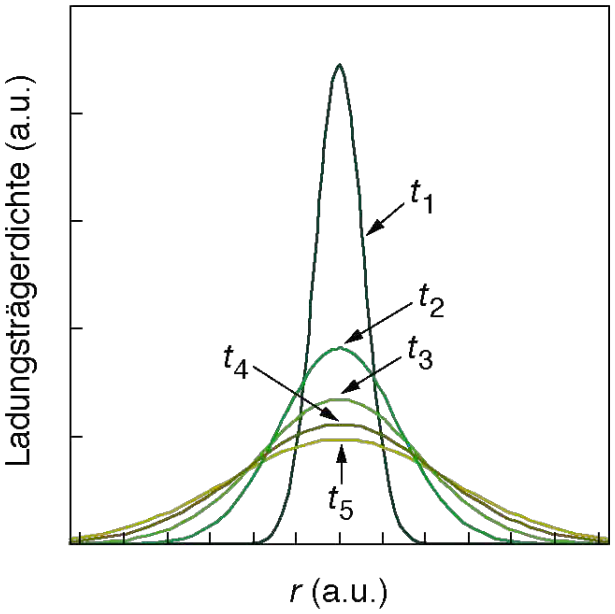
Diffusion of charge carriers

- h^+ created close to the anode, i.e. the n^+ backplane, and e^- created close to the cathode, i.e. the p^+ strips or pixels, have the longest drift path and hence the diffusion acts much longer on them compared to e^- and h^+ with short track paths



Drift in E-field + diffusion of charge carriers

Charge density distribution for 5 equidistant time intervals



- The signal measured comes from many overlapping Gaussian distributions

  Charge carrier diffusion can be exploited to improve the position resolution

  Charge is distributed over more than one strip/pixel (charge sharing)

  Interpolation, i.e. calculation of the charge center of gravity, allows to achieve a better position measurement

  Interpolation is more precise the larger the signal to noise ratio is

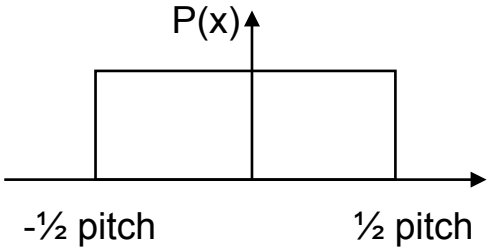
Strip/Pixel pitch and signal to noise ratio determine the position resolution

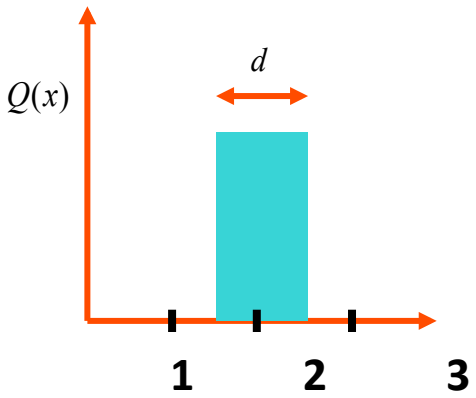
Position resolution

- The position resolution is related to the dimension of the readout elements, pixel size or microstrip pitch.
- The worst possible case for the resolution is the whole charge collected on a single element

The residuals, i.e. measured position minus true position,

is a uniform distribution with an extension equal to the pitch p





Position x = strip position

x = position of particle track

p = distance between strips/pixels (readout pitch)

Resolution σ measured as the rms of the residuals distributions

<x> = 0 $\quad \sigma_x^2 = \int_{-1/2}^{1/2} \left(x - \langle x \rangle\right)^2 P(x)\,dx = \int_{-1/2}^{1/2} x^2 P(x)\,dx$

$$\sigma = \frac{1}{\sqrt{12}} = \frac{p}{\sqrt{12}}$$

Position resolution

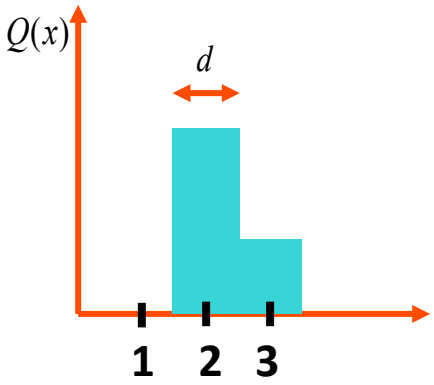
- A position resolution significantly better is obtained if charge sharing and analogue readout

  The hit is between elements 2 and 3, and closest to 2

  Probability function narrower then previous (some times pitch/10)

  For every point between elements 2 and 3 there is a unique value of (Q2-Q3)/(Q2+Q3)

  By measuring this quantity we can reconstruct the position



- Charge center of gravity (analogue readout) assuming signal on two strips/pixels and output signal amplitude proportional to the deposited energy

Position

$$x = x_1 + \frac{h_1}{h_1 + h_2}(x_2 - x_1) = \frac{h_1 x_1 + h_2 x_2}{h_1 + h_2}$$

x_1, x_2 = position of 1st and 2nd strip

h_1, h_2 = signal amplitude on 1st and 2nd strip

Resolution

$$\sigma_x \propto \frac{p}{SNR}$$

SNR = signal to noise ratio

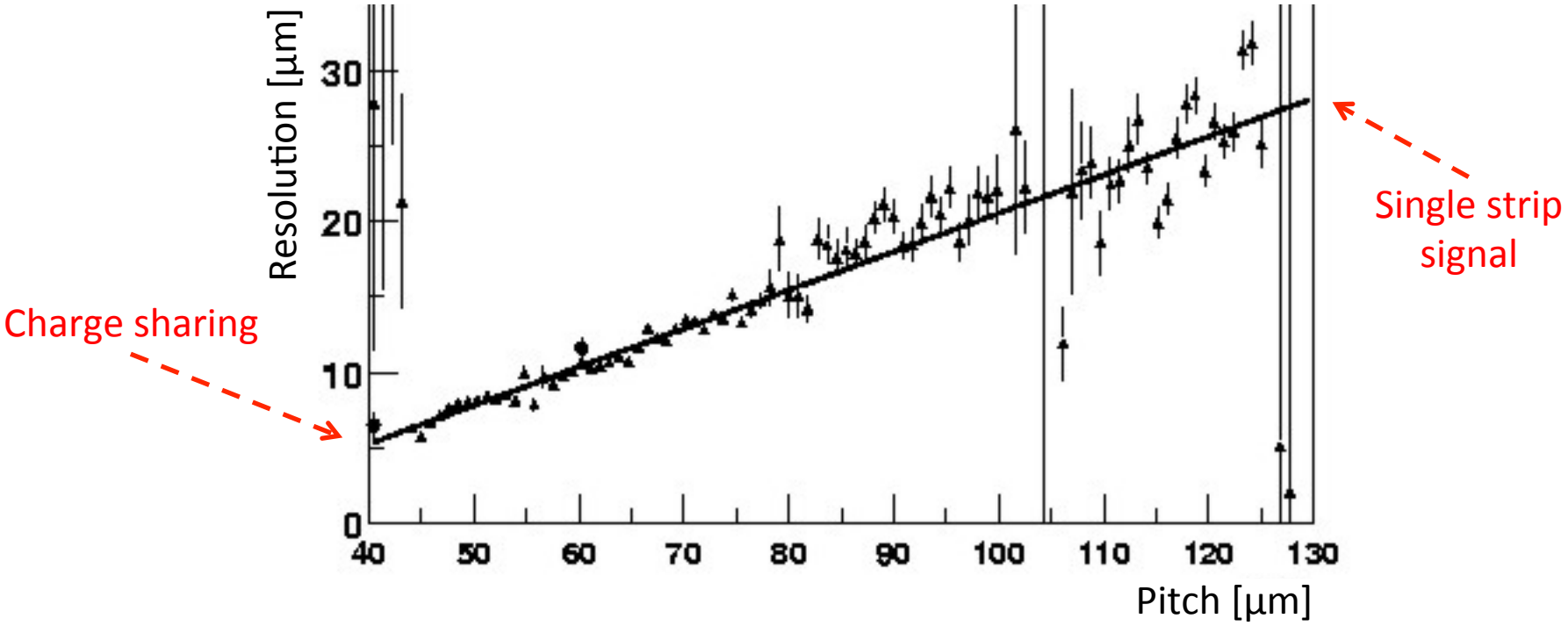
Position resolution

- In real life, position resolution is degraded by many factors

  Relationship of strip pitch (25÷150 μm) and diffusion width (5-10 μm)

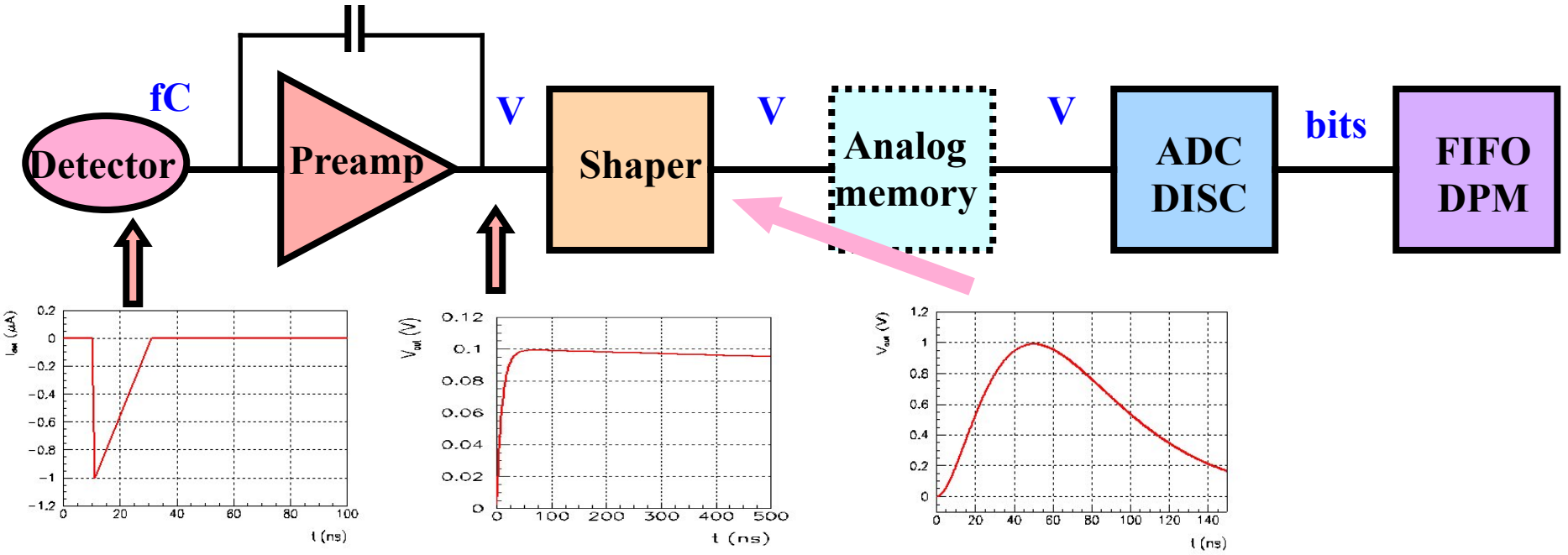
  Statistical fluctuations on the energy deposition

- Typical values of the position resolution for a 300μm thick sensor with **S/N=20**



Overview of readout electronics

- Most front-ends follow a similar architecture



Very small signals (fC) → need **amplification**

Measurement of **amplitude** and/or **time** (ADCs, discriminators, TDCs)

Several thousands to millions of channels

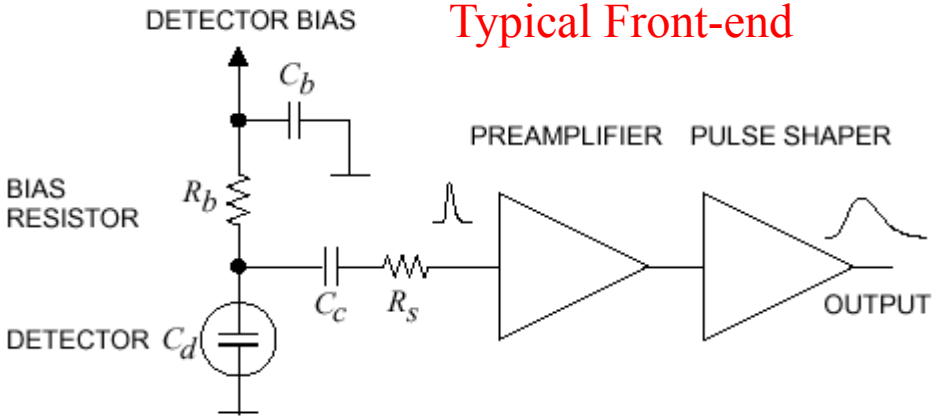
Trends → high speed**, low power**

Front-end electronics

- Most detectors rely critically on low noise electronics

The detector is represented by the capacitance C_d, bias voltage is applied through R_b, and the signal is coupled to the amplifier through a capacitance C_c

The resistance R_s represent all the resistances in the input path. The preamplifier provides gain and feed a shaper which takes care of the frequency response and limits the duration of the signal



- The equivalent circuit for noise analysis includes both current and voltage noise sources labelled i_n and e_n respectively

The two most important noise sources are the detector leakage current (fluctuating, some times called shot noise) and the electronic noise of the amplifier, both unavoidable and therefore important to control and reduce

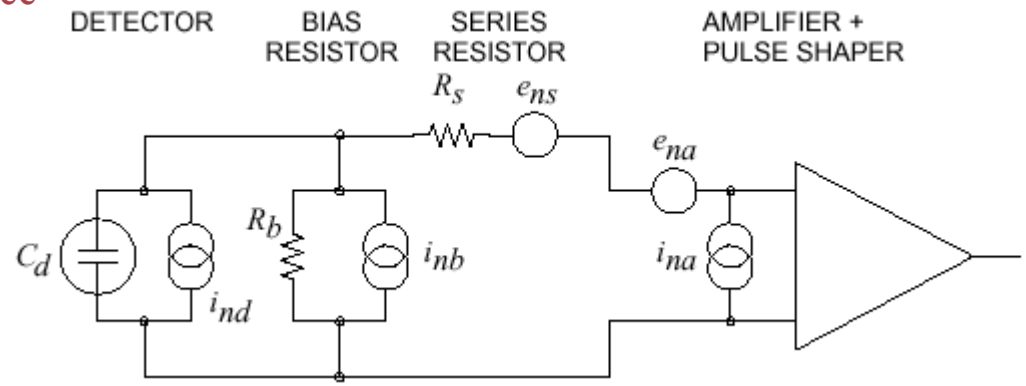


Diagram showing the noise sources and their representation in the noise analysis

Front-end electronics

- The critical parameters are
  - Detector capacitance
  - Shaping time τ
  - Resistances in the input circuit
  - Noise parameters of the amplifier
    - Depend mostly on the input device (transistor)
      - To be optimized for the specific load and use
  - Additional critical parameter is the current drawn
    - Important contribution to the power consumption of the electronics

Silicon detector radiation damage

- Prolonged exposure to radiation creates some permanent damage

  Surface damage ⟹ extra positive charge collects in oxide

  All ionising particles generate surface damage

  MOS devices are particularly prone to surface damage

  Larger signal sharing and increased interstrip capacitance → noise

  Bulk damage ⟹ atomic displacement damages lattice and creates traps in the band-gap

  Only heavy particles (p, n, π, ...) cause significant damage

  Increased leakage current → noise

  Change of the substrate doping