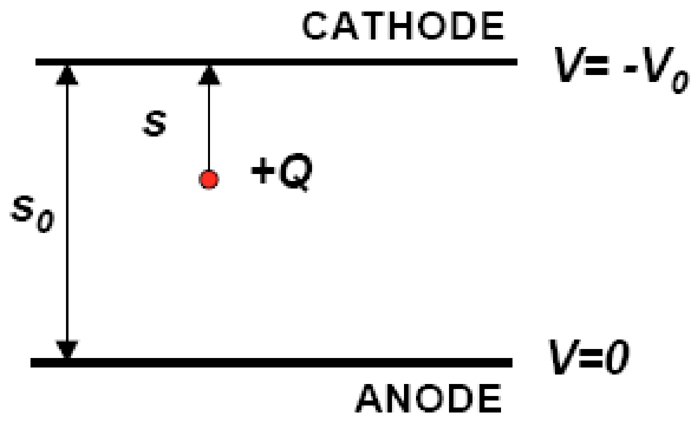
Lecture 3

- Part 1 (Electronics)
    - Signal formation
    - Readout electronics
    - Noise
- Part 2 (Semiconductor detectors =sensors + electronics)
    - Segmented detectors with pn-junction
        - Strip/pixel detectors
    - Drift detectors
    - Photodiodes
    - Monolithic detectors (CCD, CMOS)
    - DEPFET

Literature

- Glen F. Knoll, Radiation Detection and Measurement, chapters 11,13
- Semiconductor Radiation Detectors, Gerhard Lutz, Springer-Verlag, 1999

Single charge +Q:



Charge induced on each electrode by +Q moving through the difference of potential dV:

$$dq = Q\frac{dV}{V_0} = Q\frac{ds}{s_0}$$

Integrating over s (or time t):

$$q(s) = \frac{Q}{s_0}s \qquad q(t) = \frac{Q}{s_0}wt$$

w: drift velocity

Electrons- ion pair (-Q and +Q) released at the same distance s from the cathode :

$$q(t) = Q\left(\frac{w^- t}{s_0} + \frac{w^+ t}{s_0}\right) \quad 0 \le t \le T^-$$

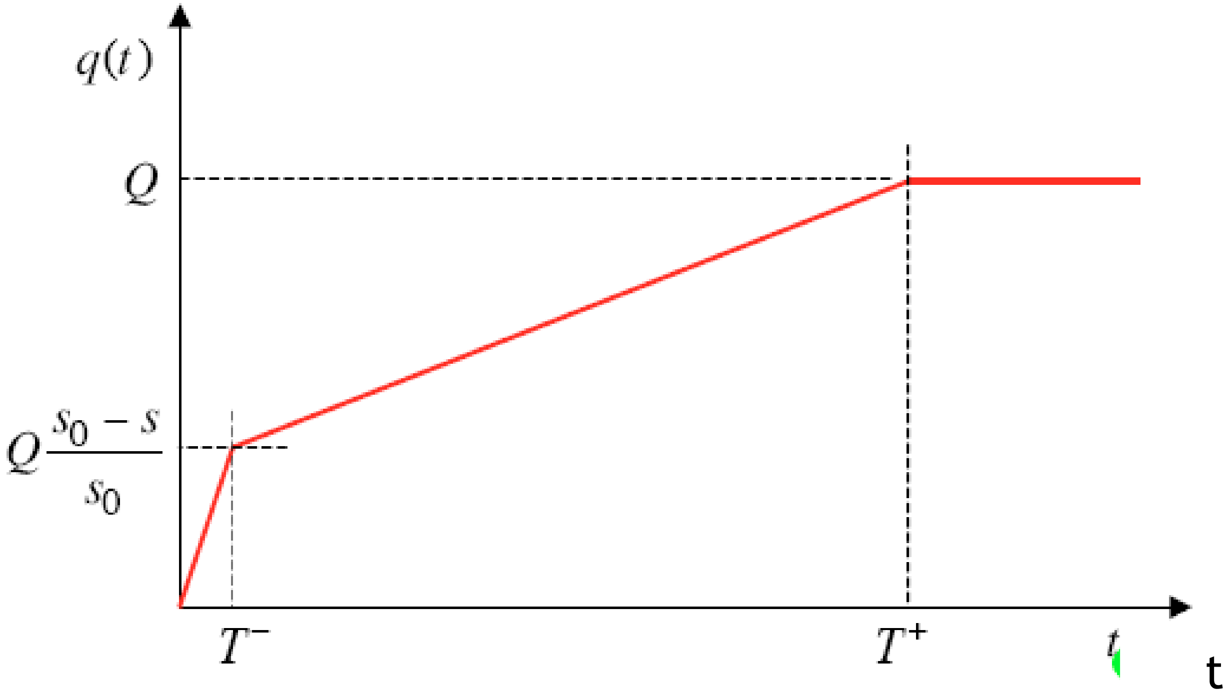
$$q(t) = Q\left(\frac{s - s_0}{s_0} + \frac{w^+ t}{s_0}\right) \quad T^- \le t \le T^+$$

w^- (w^+) : electron (ion) drift velocity

T^- (T^+) : total electron (ion) drift time

Total signal: $q(T^+) = Q$

(+Q on cathode , -Q on anode)



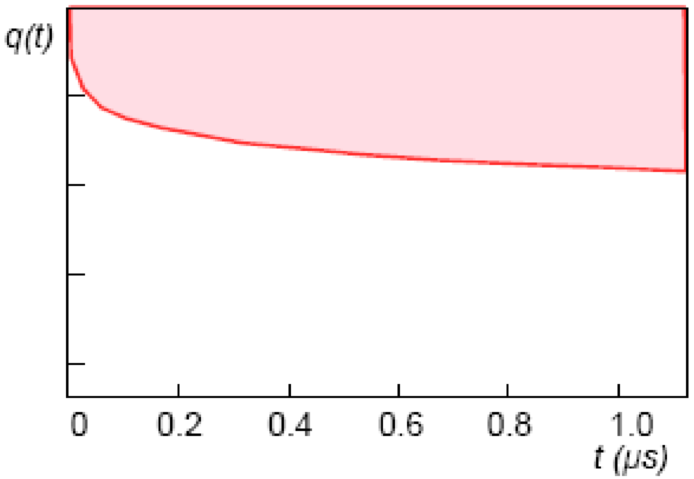
In wire chambers with avalanche amplification near anode wire the relation is:

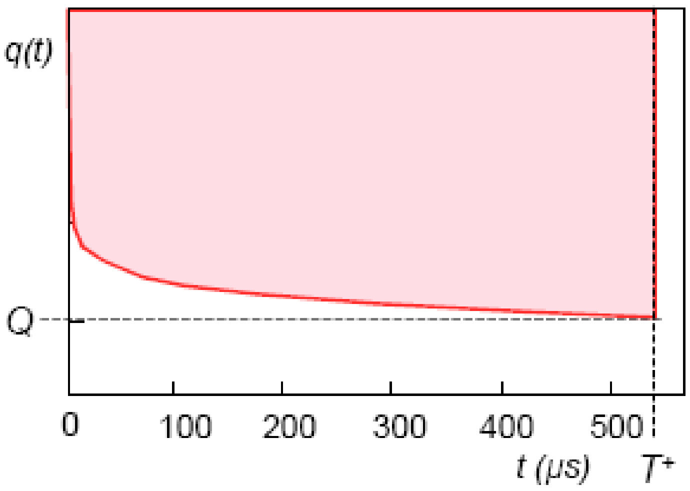
$$V^{signal}_{electron} = -\frac{Q}{lCV_0}\int_{r_0}^{r_0+\lambda}\frac{dV}{dr}dr = -\frac{Q}{2\pi\varepsilon_0 l}\ln\frac{r_0+\lambda}{r_0}$$

$$V^{signal}_{ion} = +\frac{Q}{lCV_0}\int_{r_0+\lambda}^{R}\frac{dV}{dr}dr = +\frac{Q}{2\pi\varepsilon_0 l}\ln\frac{R}{r_0+\lambda}$$

lC=total capaitance

since λ << R the positive ions contribute (~100x) more to the signal formation than electrons

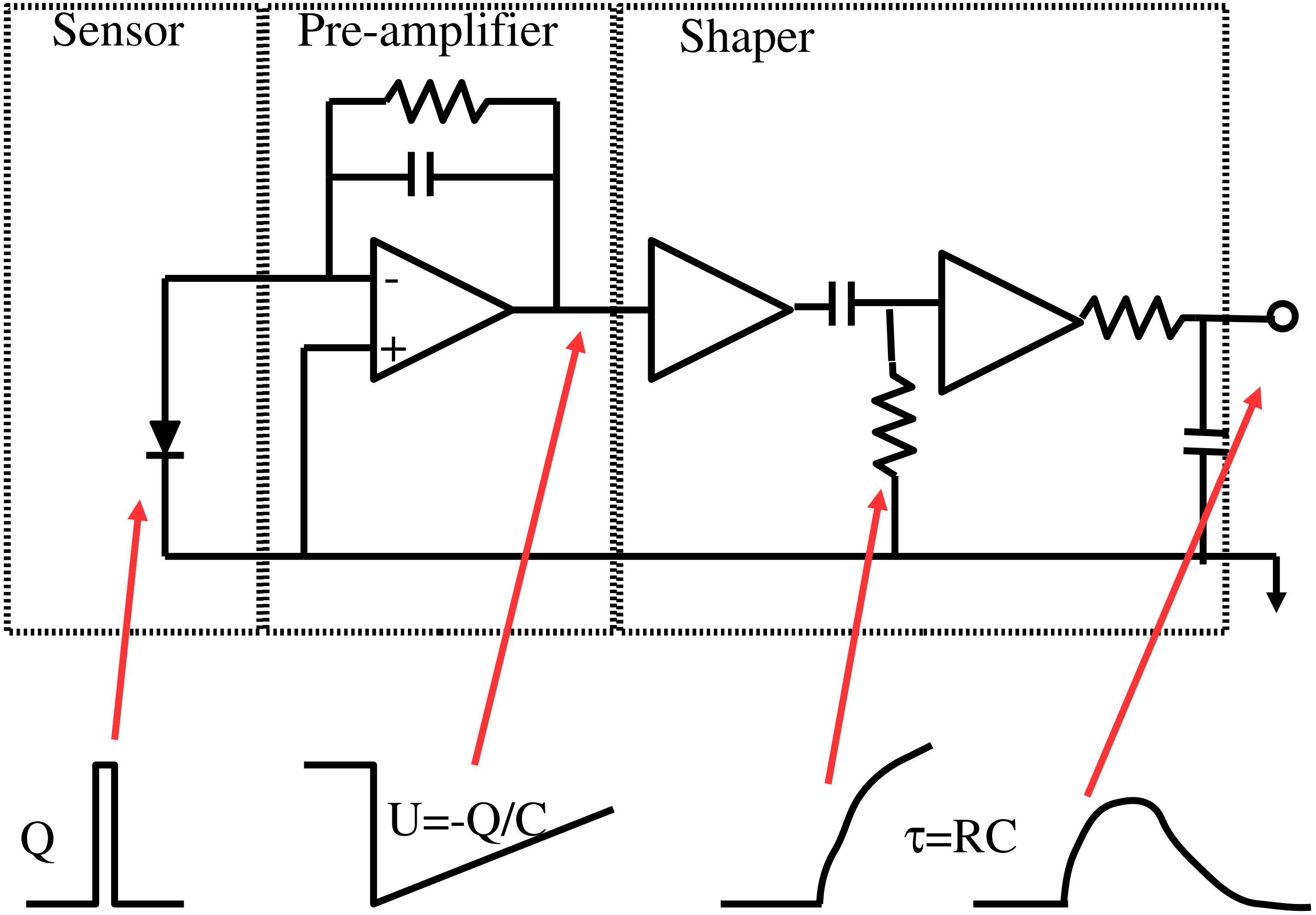




Readout Electronics Basics

- The readout electronics is needed for converting the charge pulse from the sensor to a voltage signal which can be discriminated or converted to a digital form in an Analogue to Digital Converter circuit (ADC)
- The readout electronics consist typically of a chain with a pre-amplifier which is charge sensitive and a shaper. The pre-amplifier is integrating the charge impulse over a time interval →peaking time. The shaper is shaping the pulse to match the needs of the electronics further down the chain→ shaping time. The shaper is also filtering noise improving the signal to noise ratio S/N.

CR-RC shaping

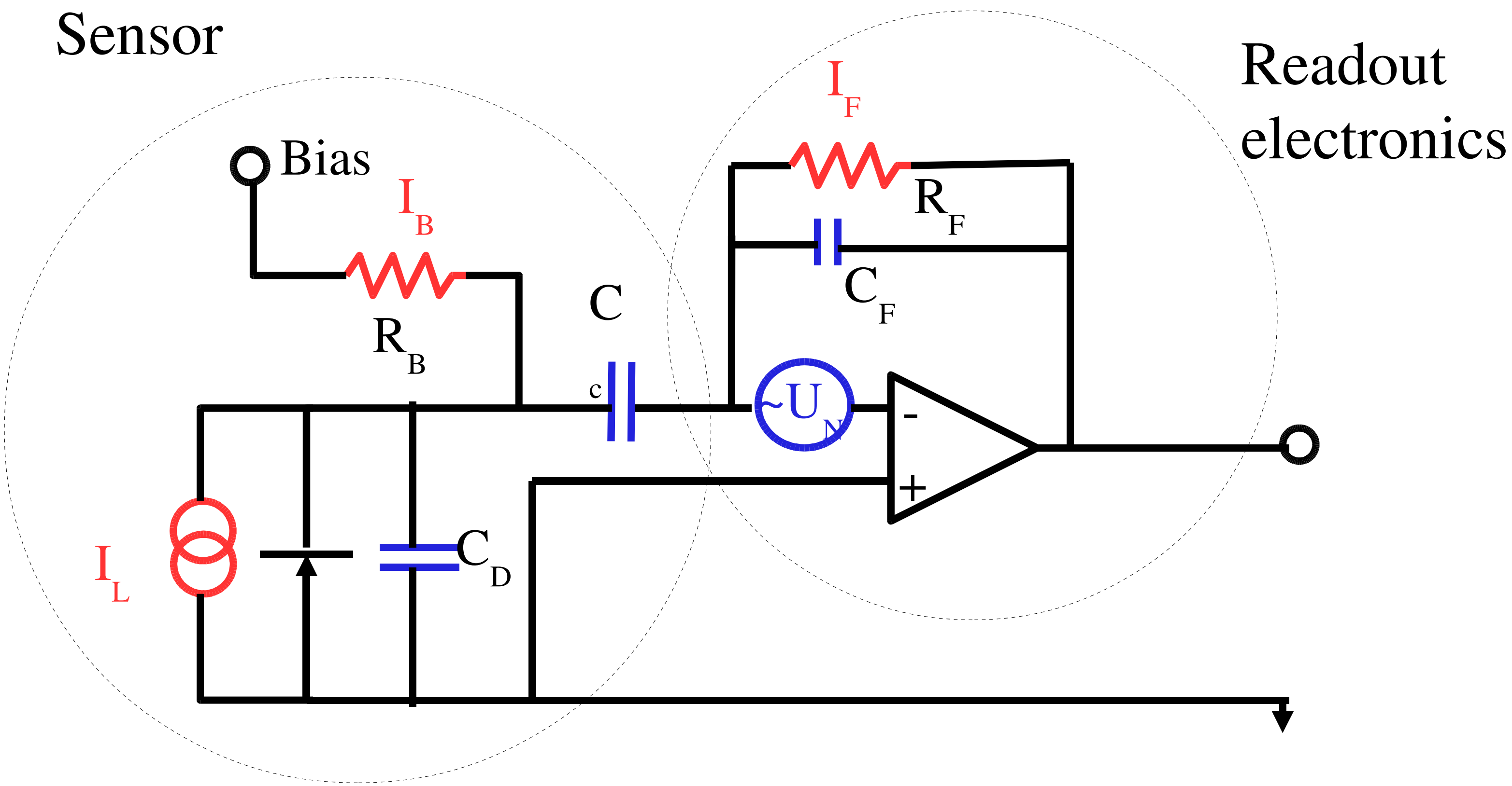


Cut-off frequency: $f_C = \dfrac{1}{2\pi RC}$

Noise (1)

- The noise of a charge sensitive amplifier can be described like a voltage source (in series) on and a current in (parallel) with the input of the amplifier, hence we call them:
  - ✔ serial noise: The voltage on the input of the amplifier fluctuates and even if there is no signal on the input. Noise is injected because of the load created by the sensor capacitance.
  - ✔ parallel noise: Noise created by mainly the leakage current in the sensor (shot noise) and the noise from the biasing circuit.
- For CR-RC shaping the relation between shaping time and S/N is:

$$\frac{S}{N_{serial}} = \sqrt{\tau} \qquad \frac{S}{N_{para}} = \frac{1}{\sqrt{\tau}}$$



🟥 Contributes to parallel noise

🟦 Contributes to serial noise

Noise (3)

- Serial noise *(for circuit on the previous slide)*

$$-Q_N(S) = U_N\left(\frac{1}{\frac{1}{C_D}+\frac{1}{C_C}}+C_F\right)=U_N C_{tot}$$

U_N is given by the amplifier design,processing etc.

C_C coupling capacitance need to be large
C_D we want to keep small
C_F is small to give good amplification

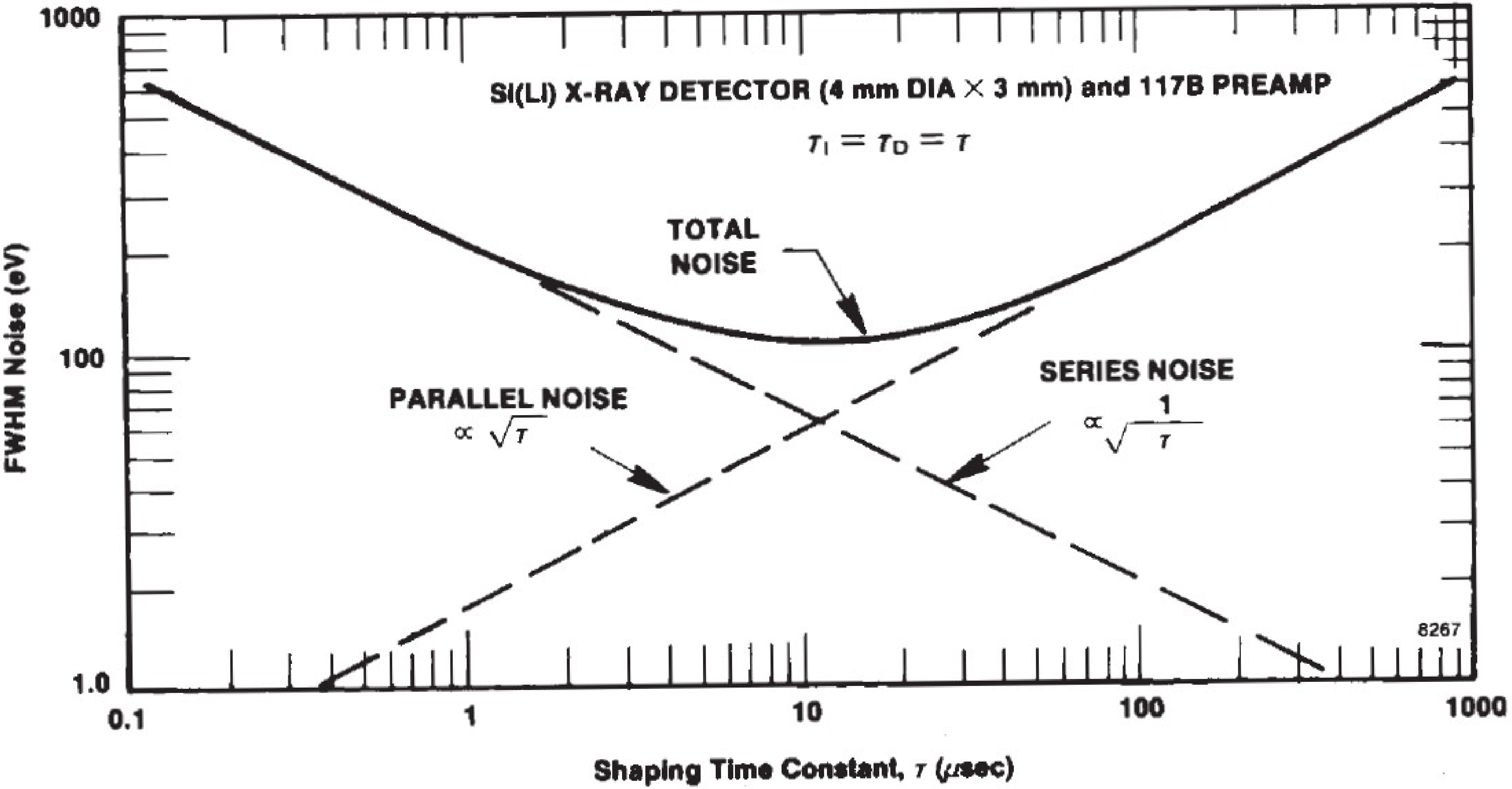
In segmented sensors we will get an additional capacitance to the neighbouring cells which may dominate the total capacitance

Noise (4)

- Parallel noise

The noise contribution from the bias resistor need to be added to the noise arising from the leakage current in the sensor (Lecture 2). The noise from the bias and feedback resistors is temperature dependent (Nyqvist noise). The resistance of the feedback resistor is typically large, hence the contribution from the feedback resistor can be neglected.

$$I_B = \frac{4kT}{2qR}$$

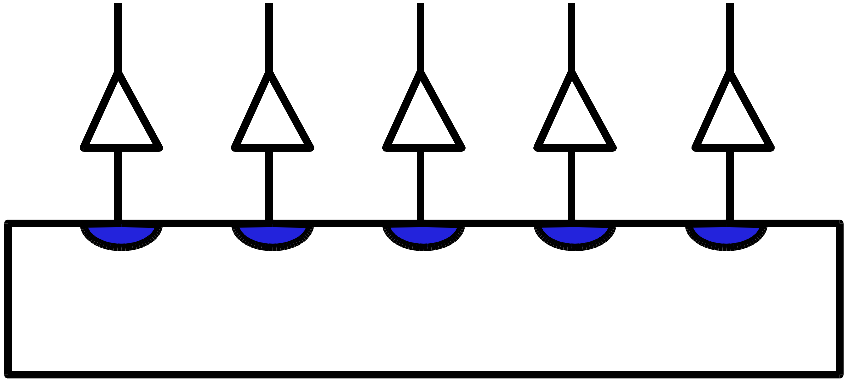

SI(LI) X-RAY DETECTOR (4 mm DIA × 3 mm) and 117B PREAMP
$\tau_I = \tau_D = \tau$
TOTAL NOISE
PARALLEL NOISE
$\propto \sqrt{\tau}$
SERIES NOISE
$\propto \sqrt{\frac{1}{\tau}}$
8267
FWHM Noise (eV)
1000
100
1.0
0.1
1
10
100
1000
Shaping Time Constant, τ (μsec)

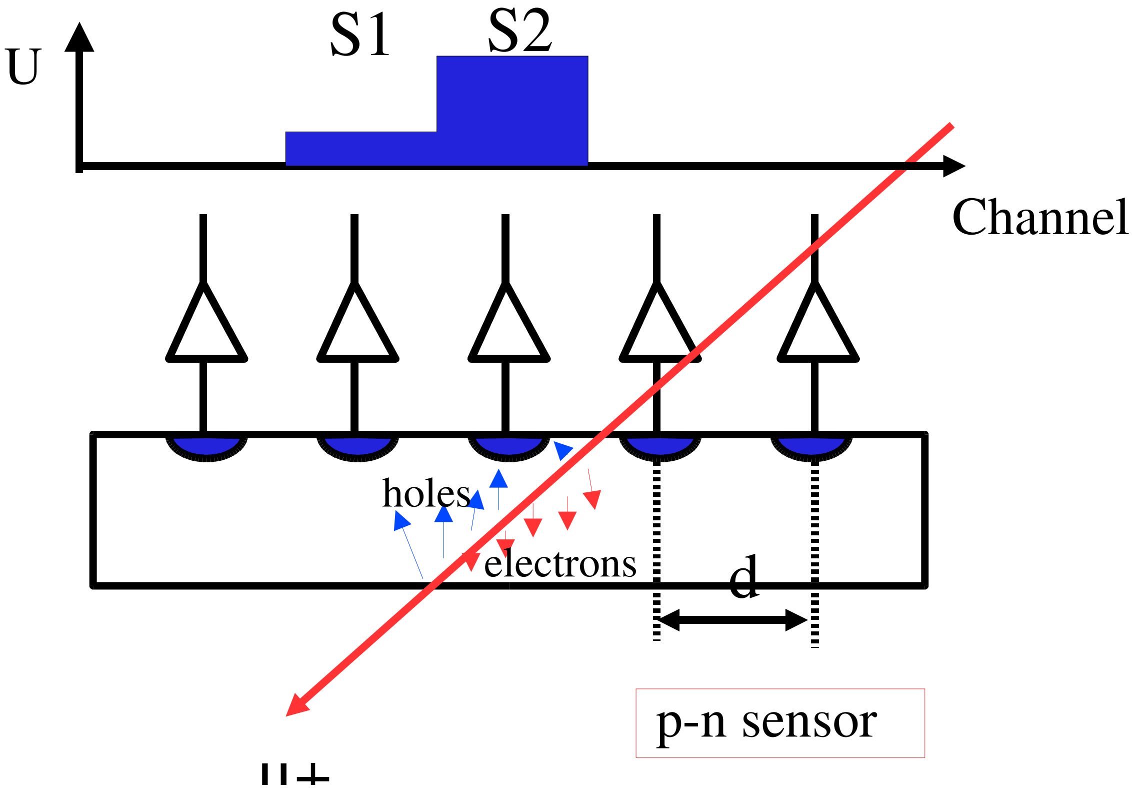
For completeness

- Other less significant noise sources are:
  - Shot-noise: comes from statistical fluctuation in conduction. The effect is more prominent at very low currents. The effect is independent of temperature and frequency
  - 1/f (flicker) noise: A noise dominating at low frequencies. The noise originates from the input transistor (FET) in the amplifier and depends on transistor dimension and processing quality.

Segmented pn-junction based semiconductor detectors

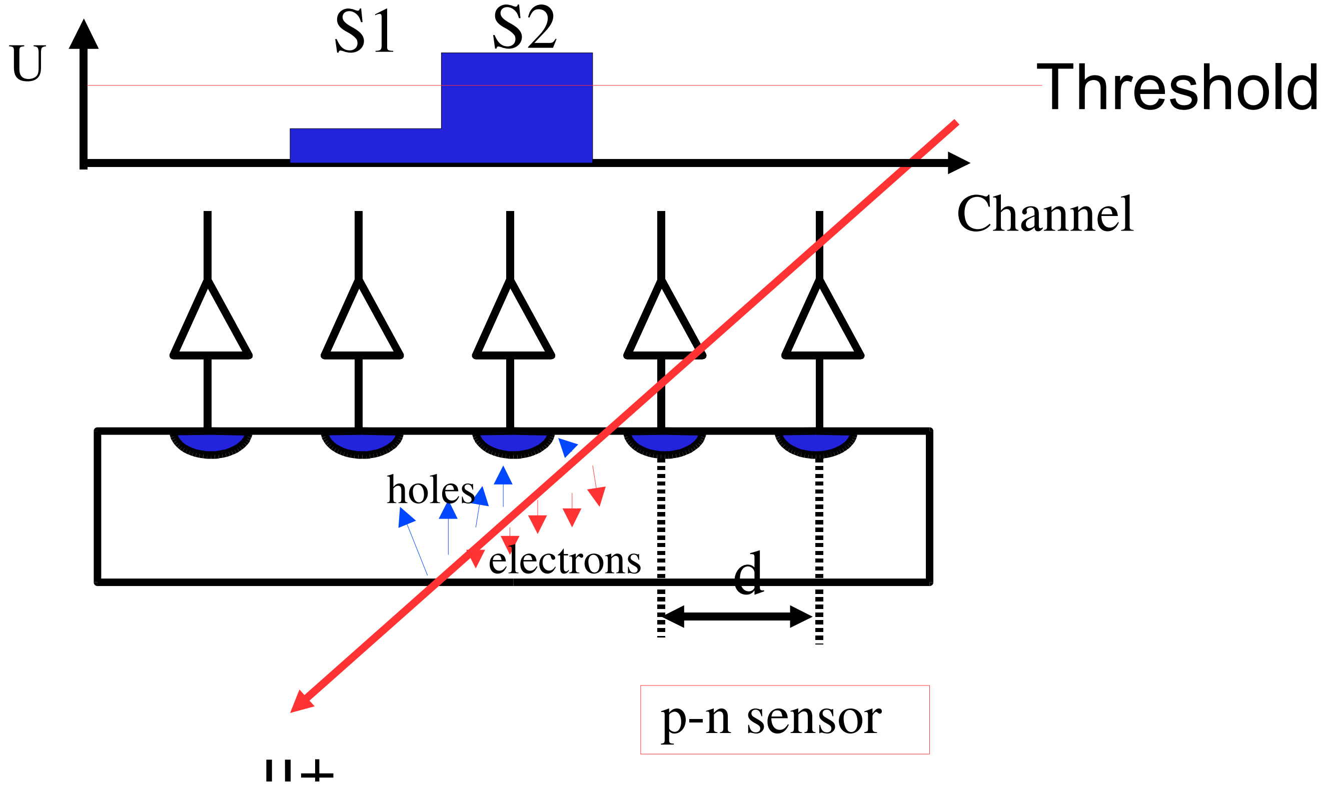
- Apart from the excellent spectroscopic properties of the semiconductor detectors they are very frequently used because they can be segmented. Segmented detectors can be used for measuring the position of a track or to measure a intensity distribution (imaging) e.t.c.
- The sensors can be segmented in 1-dimension → strip (in xy), circles (radially), or in 2-dimension → pixelised





- The position of the track/interaction can be determined from the output pulse from the amplifiers *(This requires that all pulse height information is read out)*. The resolution, σ, is proportional to the S/N. (1 μm resolutions have been demonstrated)

$$x = \frac{S_2}{S_1 + S_2} d$$



- Many times the pulse height information is not read out. The signal is discriminated by a threshold in the readout circuit. This readout method is called binary. The resolution for such system is given by

$$\sigma_{Binary} = \frac{d}{\sqrt{12}}$$

Diffusion

- For segmented detectors the diffusion of free charge carriers in the semiconductor sensor will smear the resolution of the system. The interaction in a semiconductor creates a charge cloud with high concentration of free charge carriers. The probability for charge carriers to move from a region of high concentration to a region with lower concentration is higher than in the opposite direction → diffusion.

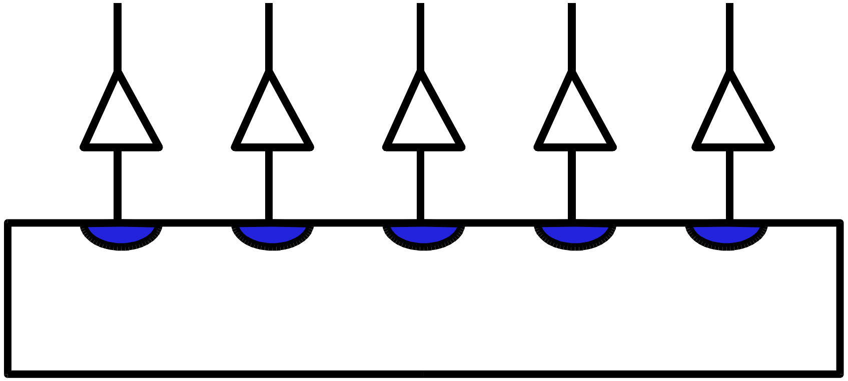
$$\sigma_{Diff} = \sqrt{\frac{2kT}{q}\mu_{h(e)} t_{drift}}$$

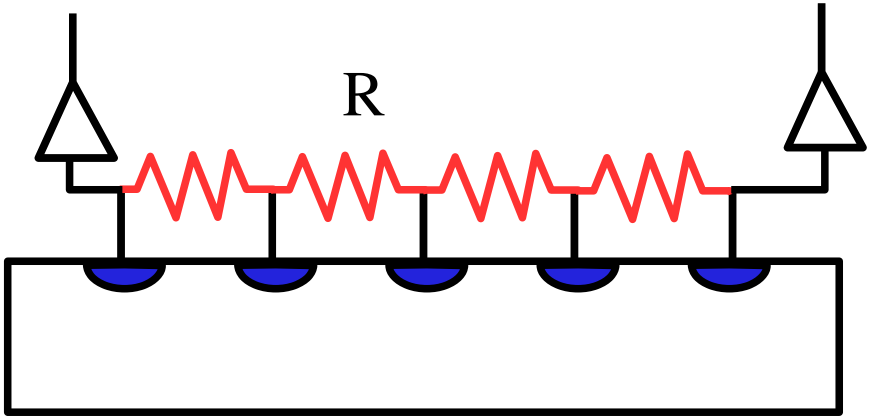
t_{drift} = time for the charge to drift out to the readout electrode

$m_{h(e)}$ = mobility of hole or electron *(depending upon what we collect)*

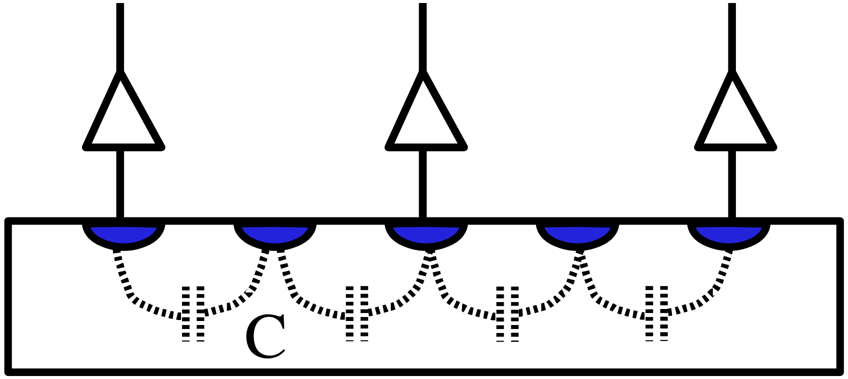
Strip (array) detectors

- Strip detectors are commonly used in particle physics and in event driven applications with high multiplicity. Characteristics
    - Fully depleted sensor for good signal efficiency
    - Low number of readout channels for a large active surface
    - Fast readout speed
    - If energy information is no critical the readout channel number can be reduced by capacitive and resistive charge division
    - 1-dimensional position information orthogonal to strip direction. *(2-dimensional position information can be achieved with double sided sensors)*
    - The strip electronics can contain complex electronics (discriminator, de-randomise buffer, counter e.t.c.)
    - Typical strip pitch 25 μm to 1mm, position resolution down to 1 μm
    - Used in high energy physics, autoradiography (betas), scanning devices in medicine (X-rays) e.t.c.





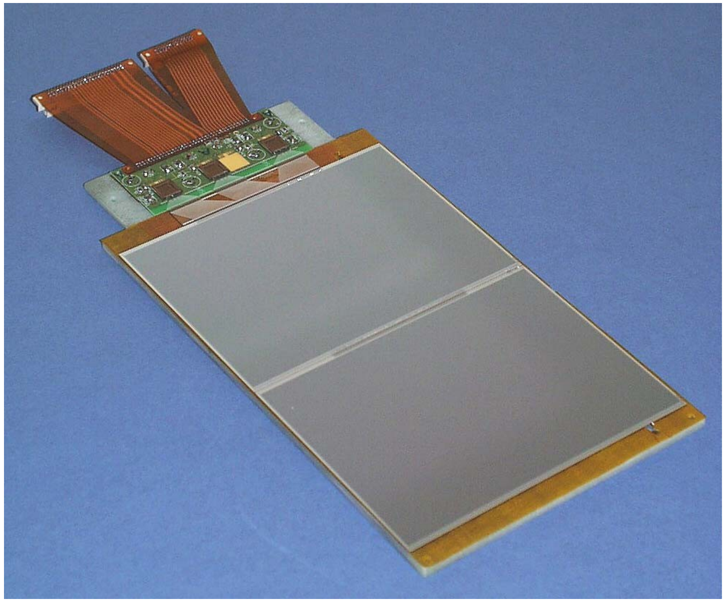
Resistive charge division:
Resistance will degrade noise performance, hence only applicable to large charge signals

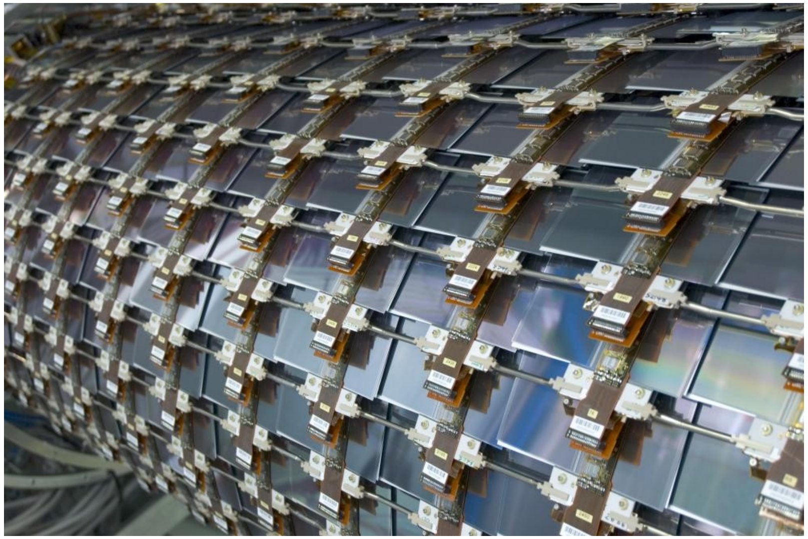


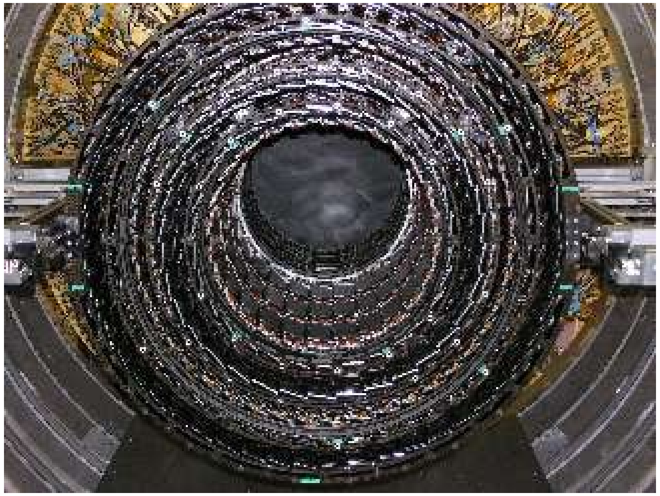
Capacitive charge division:
Small loss in S/N but only limited reduction of readout channels

ATLAS SCT

CMS TRACKER

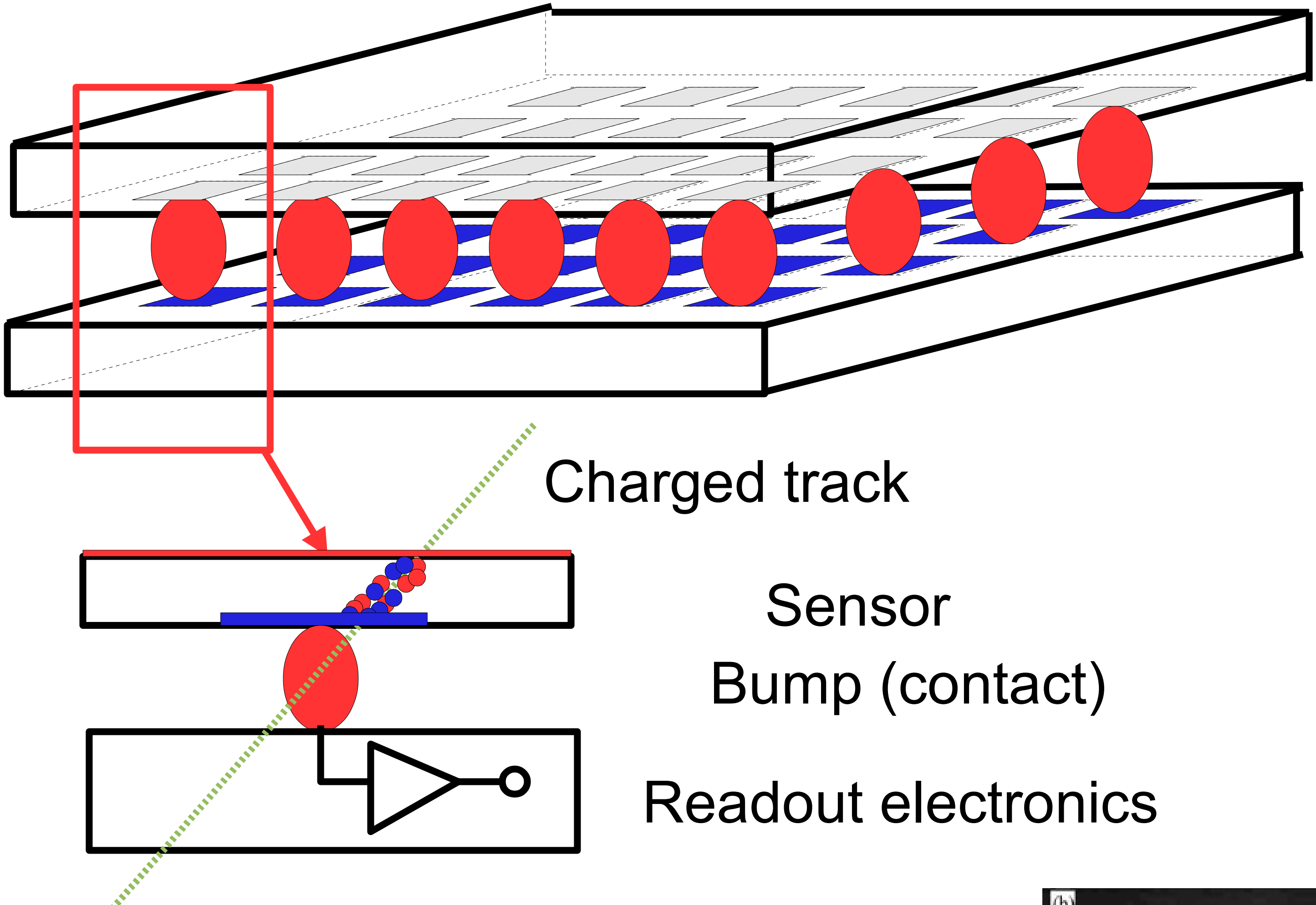






Pixel detectors

- A 2-dimensional sensor with readout electronics in every pixels. The sensor and the readout electronics are laid on top of each other "flip-chip" and connected by interconnecting bumps → hybrid pixel detector. *The monolithic pixel detectors is a recent development with readout electronics integrated into the pixel*. Characteristics of pixel detectors:
    - Fully depleted sensor for good signal efficiency
    - Large number of readout channels
    - Fast readout speed
    - Can be used for imaging (integrating events) and for single event readout
    - The pixel electronics can contain complex electronics (discriminator, de-randomise buffer, counter e.t.c.)
    - Typical pixel pitch 25 μm to 1mm, position resolution down to few μm
    - Used for medical(X-rays), space (X-rays), high energy physics e.t.c.

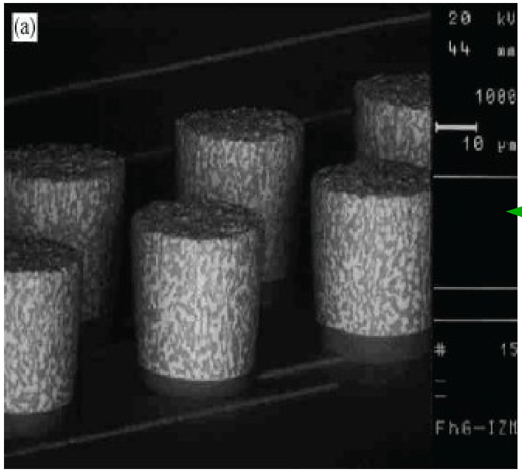


Charged track

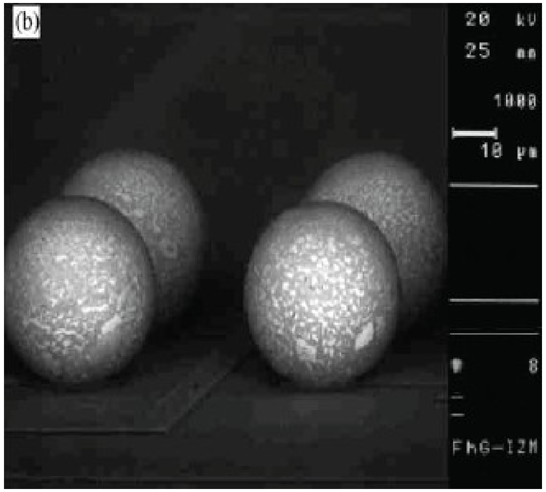
Sensor

Bump (contact)

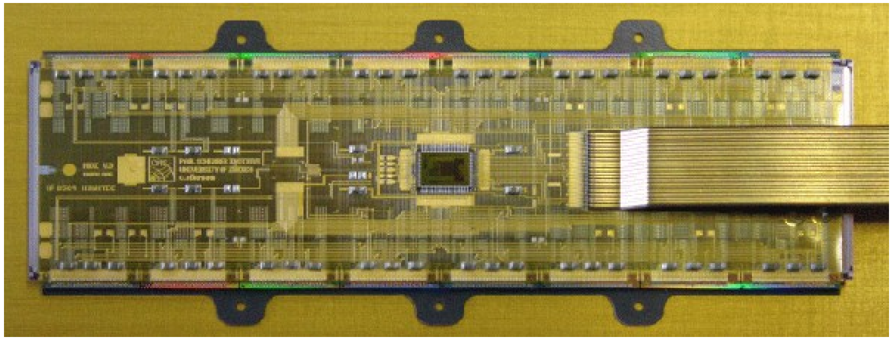
Readout electronics

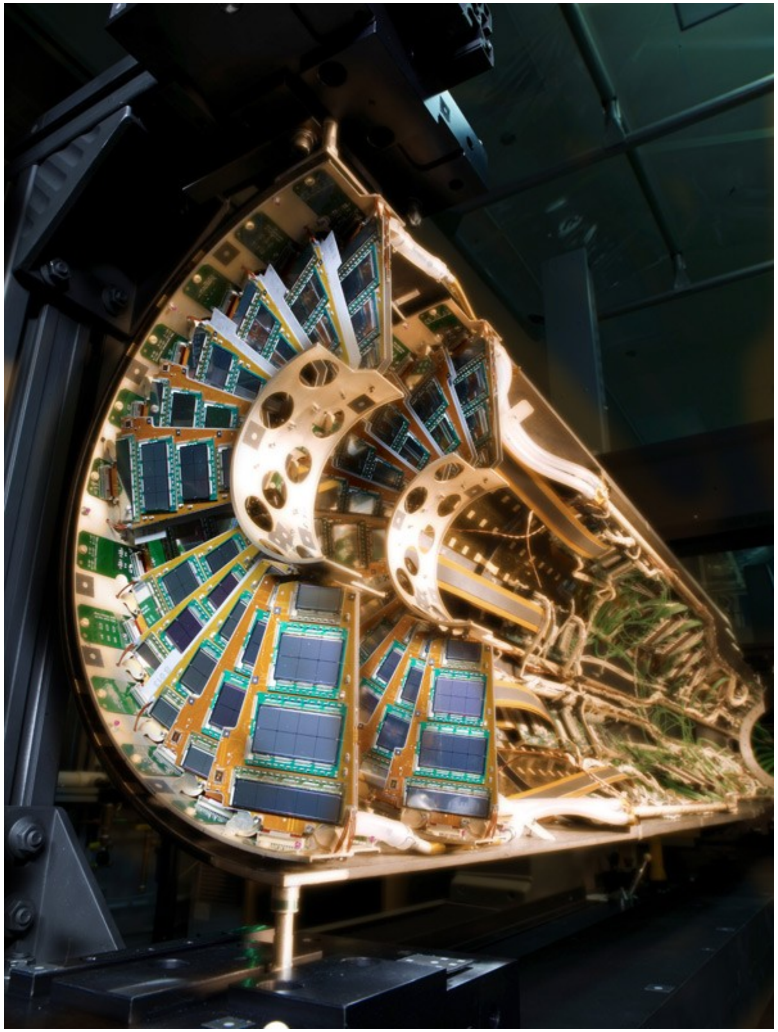


Bumps **before** **after** reflow



CMS





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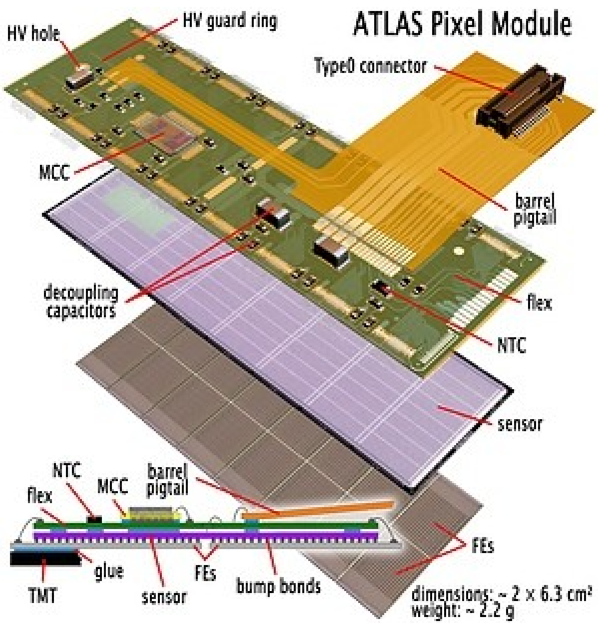
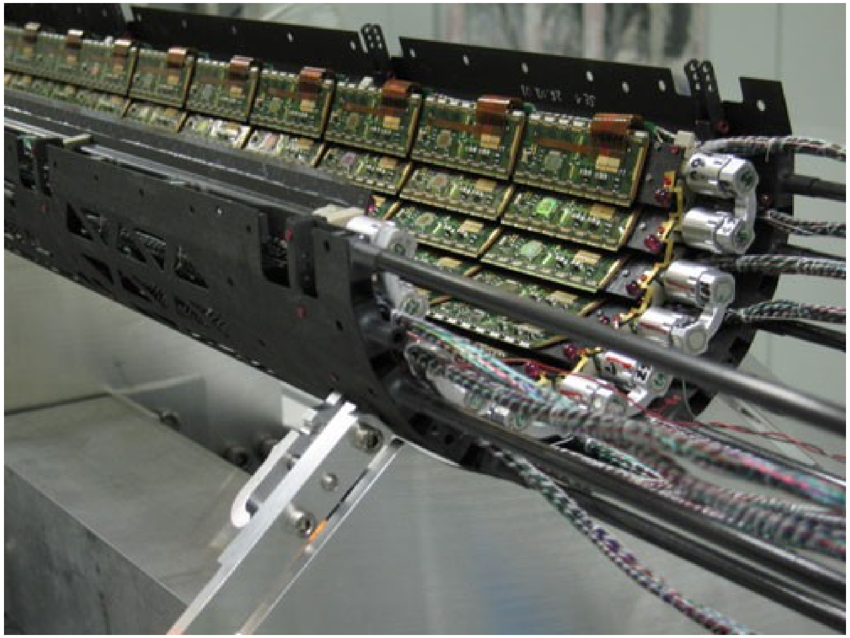

ATLAS Pixel Module
HV hole
HV guard ring
Type0 connector
MCC
barrel pigtail
decoupling capacitors
flex
NTC
sensor
NTC
flex
MCC
barrel pigtail
glue
TMT
sensor
FEs
bump bonds
FEs
dimensions: ~ 2 × 6.3 cm²
weight: ~ 2.2 g

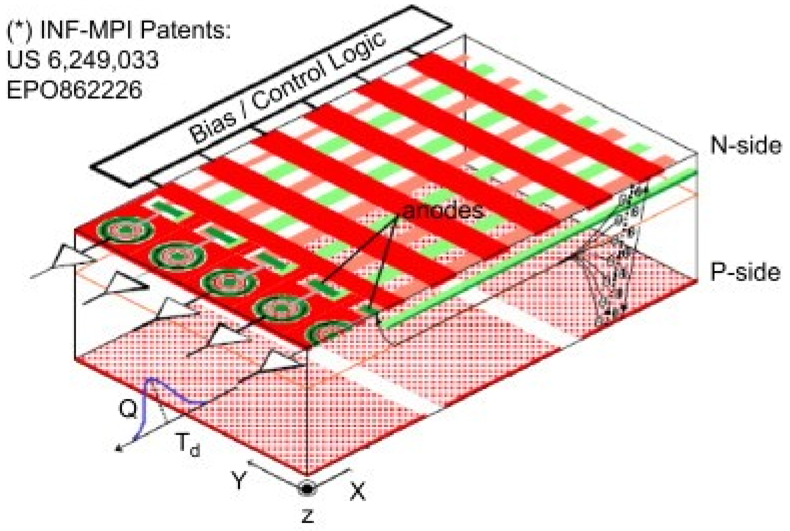


Drift detectors

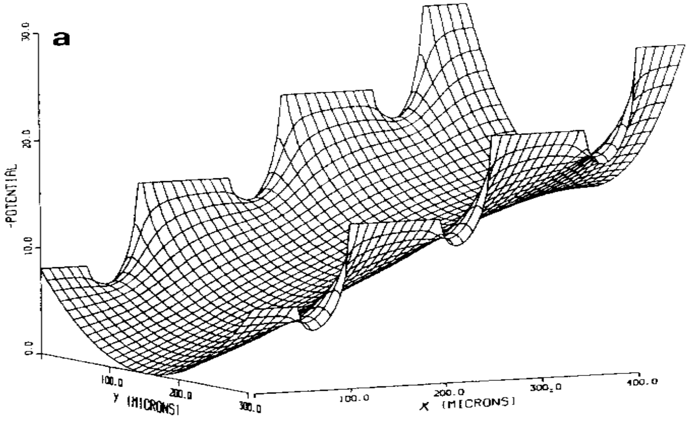
Drift detectors give an alternative way of achieving 2-d readout to pixelised detectors. In the Drift detector the electric filed is horizontal (sidewards). A fully depleted drift detector has p+ strips implanted on both sides and a n+ strip/pad on one side. The p+ strips give the position information with the signal from drifting holes while the n+ strip collect electrons with fast time response and good energy resolution.
Characteristics of a drift detector

- Fully depleted sensor for good signal efficiency
- Slow readout
- Good energy resolution
- Used in space (X.-rays), high multiplicity physics e.g. Heavy Ion and Nuclear Physics

ALICE silicon drift detector



(*) INF-MPI Patents:
US 6,249,033
EPO862226



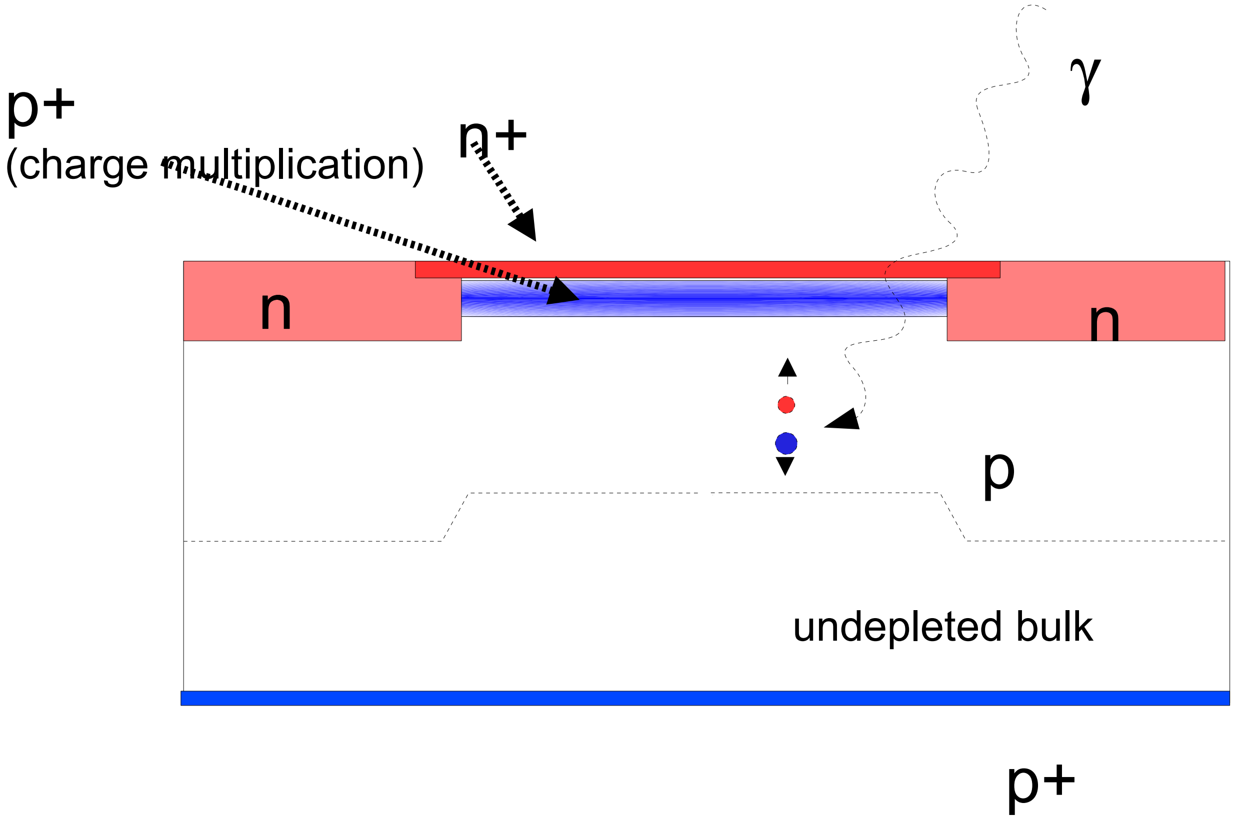
Photodiodes

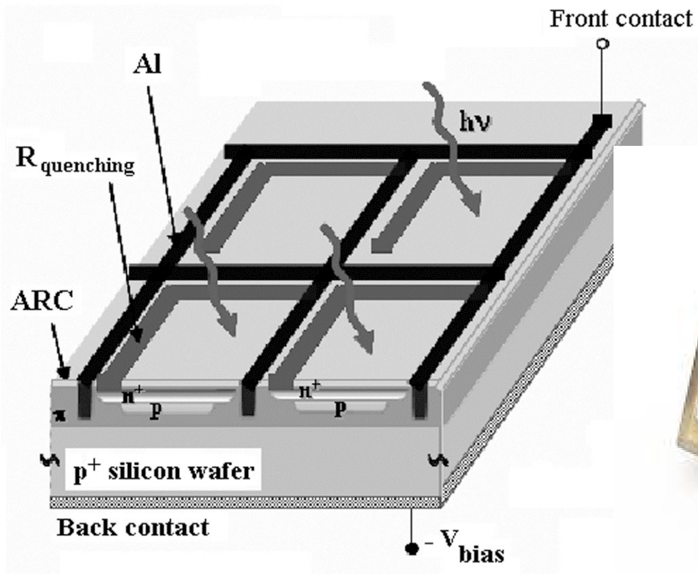
Semiconductors we have discussed have so far only provided the primary ionisation. In some applications (especially detecting low energy photons) the semiconductor sensor is turned into an amplifier by operating the sensor with very high fields causing charge multiplication → Avalanche photodiodes.

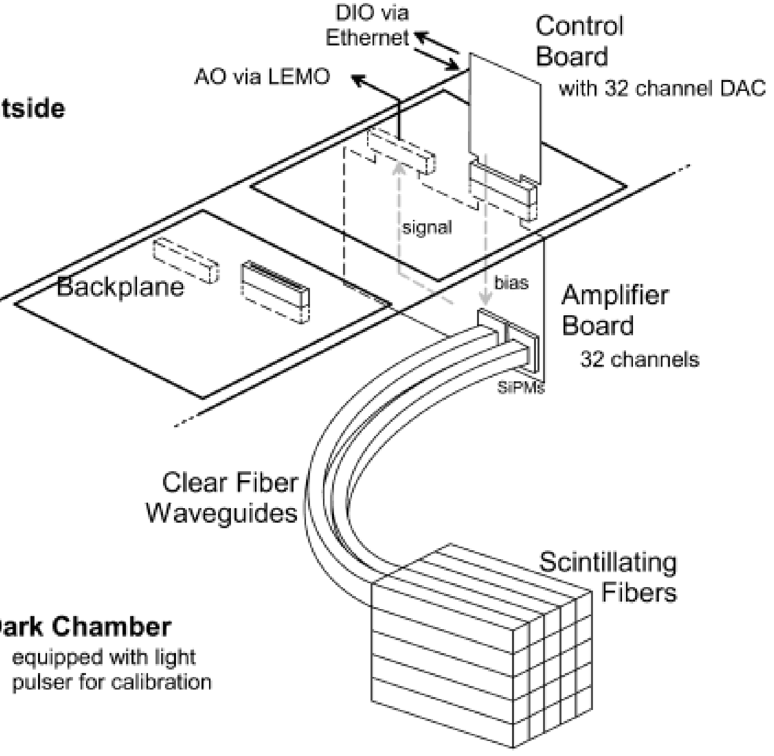
Avalanche photodiodes are widely used in optical data transmission where GaAs is the preferred material.

Arrays of avalanche photodiodes are used in Silicon Photo Multipliers (used in calorimeters)

- Benefits:
    - large signal from the sensor
    - high speed
    - compact (compared with other methods)
    - work in magnetic field
- Penalty:
    - linearity
    - different amplification onset for electrons and holes. This effect is large for Si but small for GaAs.


p+
(charge multiplication)
n+
γ
n
n
p
undepleted bulk
p+

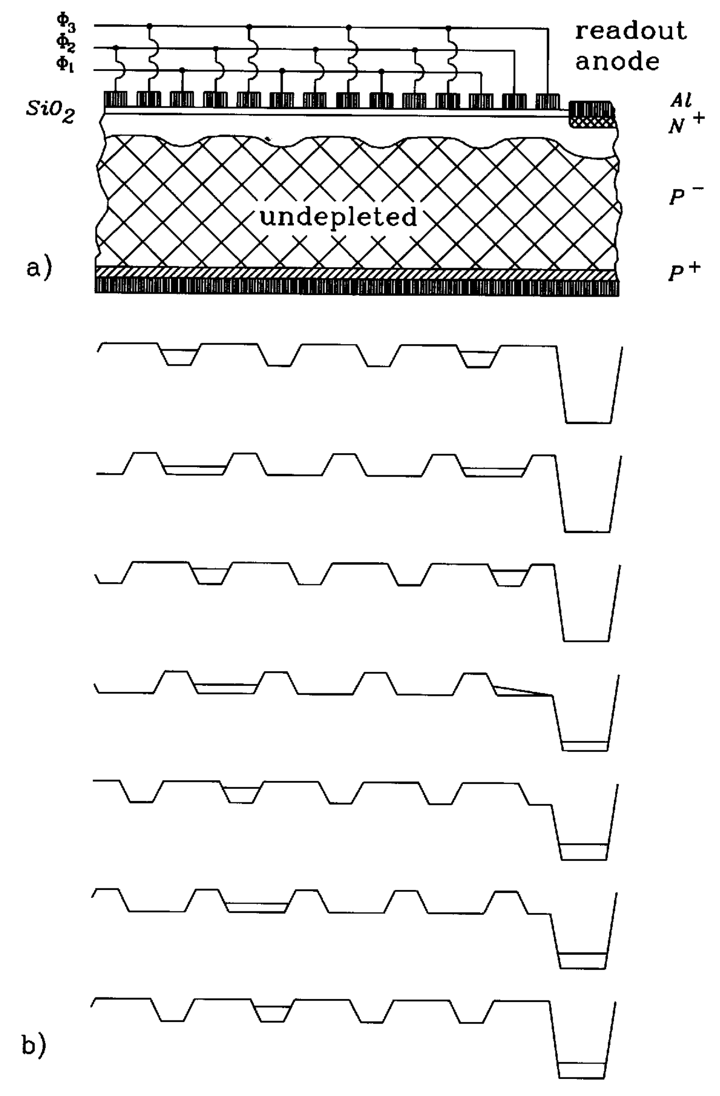

Front contact
Al
hν
R quenching
ARC
n+
p
n+
p
p+ silicon wafer
Back contact
- V bias


DIO via Ethernet
Control Board
with 32 channel DAC
AO via LEMO
Outside
signal
bias
Backplane
Amplifier Board
32 channels
SiPMs
Clear Fiber Waveguides
Scintillating Fibers
Dark Chamber
equipped with light pulser for calibration

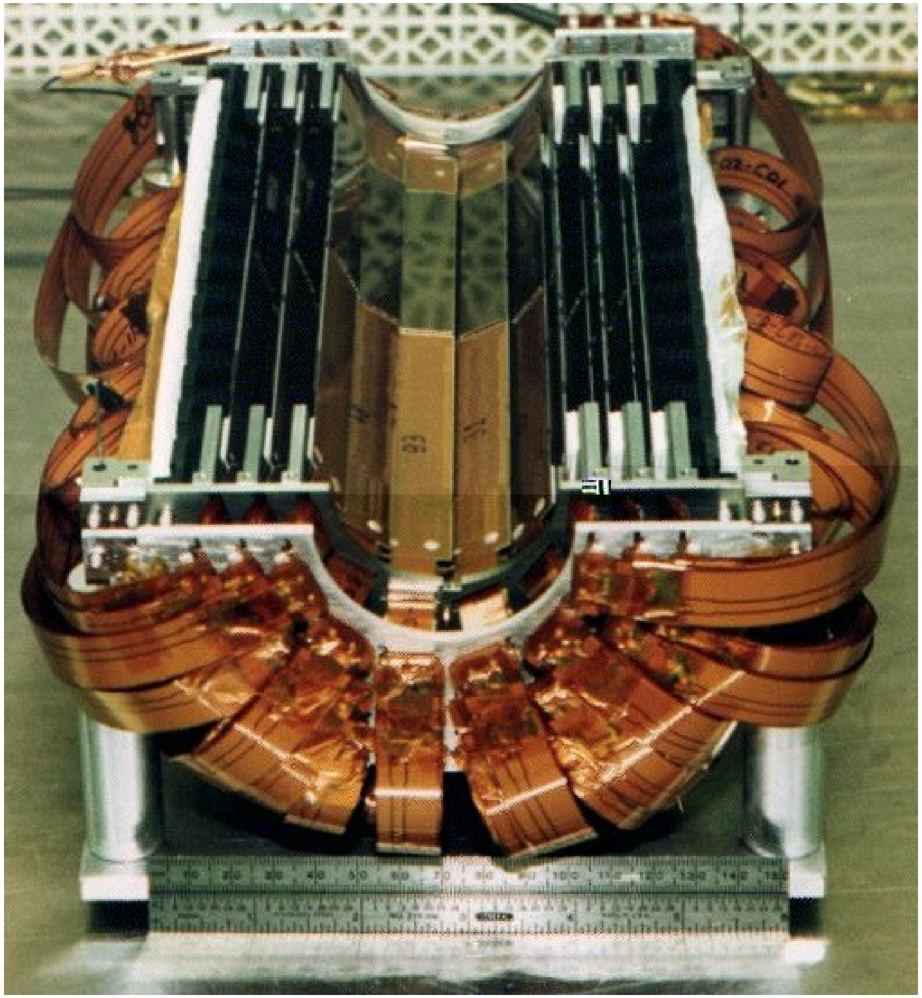
Charge Couple Devices

- CCD's are widely used in video cameras. The sensors are not depleted structures but works with MOS depletion layers. For low noise and with low particle fluxes (like in astronomy) the CCD's must be cooled. In medicine CCD's are used together with converters like scintillators. The CCD's are pixelated by metal electrodes in one direction and by implants in the other direction. By changing the potential of the electrodes the charged collected by the CCD can be transported to the amplifier which is integrated with the CCD (monolithic). Characteristics of a CCD
  - Non depleted (low efficiency for X-rays)
  - Slow (since the charge has to be transported through many pixels)
  - Pixels do not contain electronics hence no processing like setting threshold can be done in the pixel.
  - Large number of pixels
  - Typical pixel pitch 10 μm, position resolution down to μm
  - Limited radiation tolerance
  - Special processing that differs from industry road map.

Operation



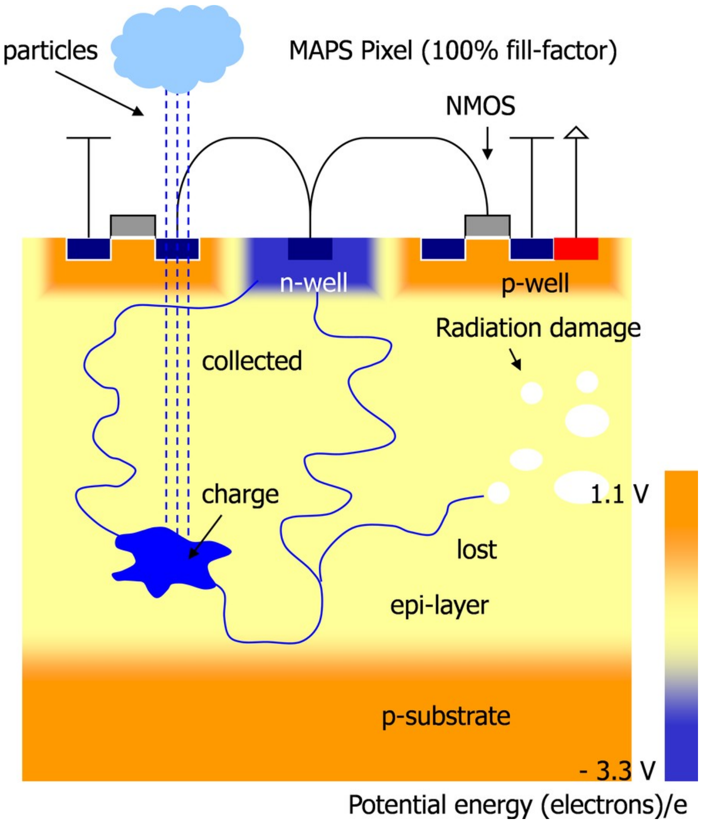
SLD pixel detector at SLAC

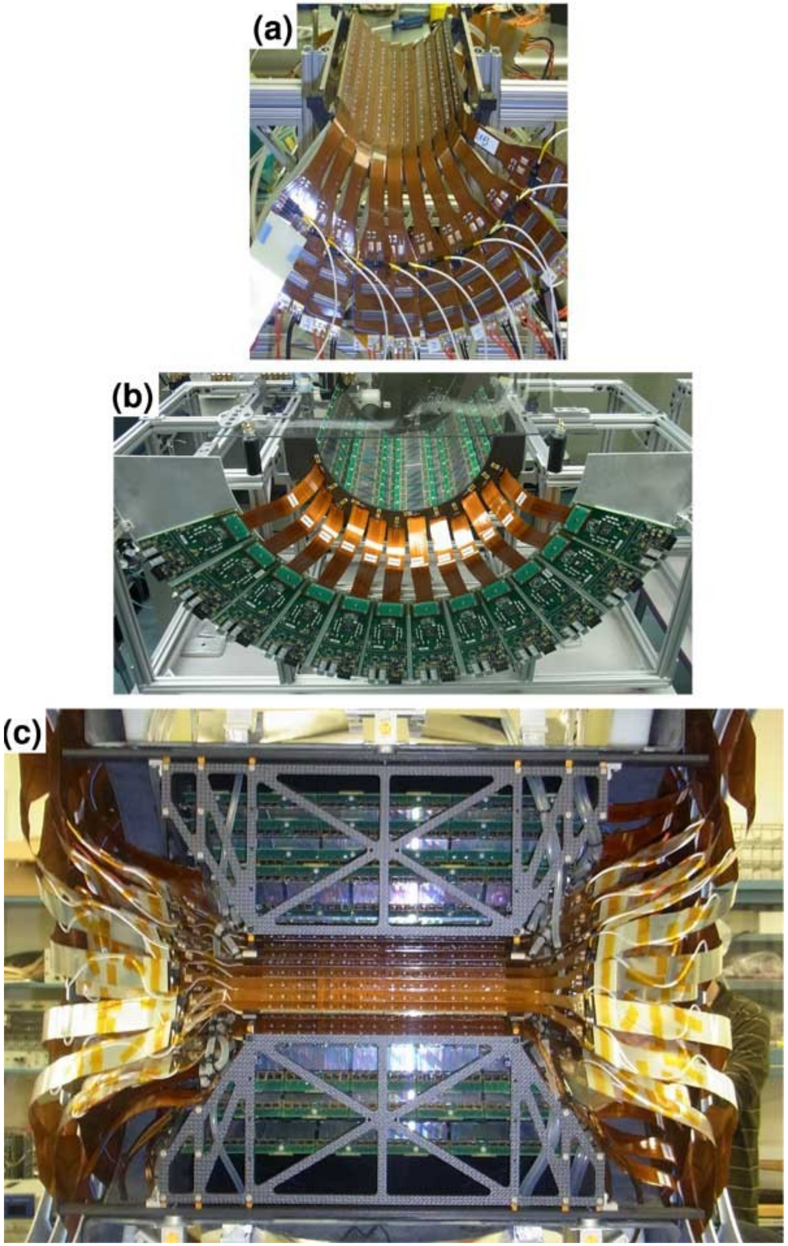


CMOS sensors

- Monolithic Analogue Pixel Sensors/CMOS sensors is a new emerging technology which is rapidly competing with CCDs in consumer products and HEP applications.
    - Non depleted (low efficiency for X-rays)
    - Faster than CCD but still slow for LHC-type usage.
    - Charge transport with diffusion (=> slow charge collection)
    - Sufficient S/N at room temperature
    - Uses CMOS processing technology and processes widely supported by industry
    - Electronics in every pixel with common readout.
    - Large number of pixels
    - Typical pixel pitch 10 μm, position resolution down to μm
    - Better radiation tolerance than CCDs but still too low for LHC-type applications
    - Technology preferred by Heavy Ion and Linear Collider communities.
    - Can be made very thin => low X/X0

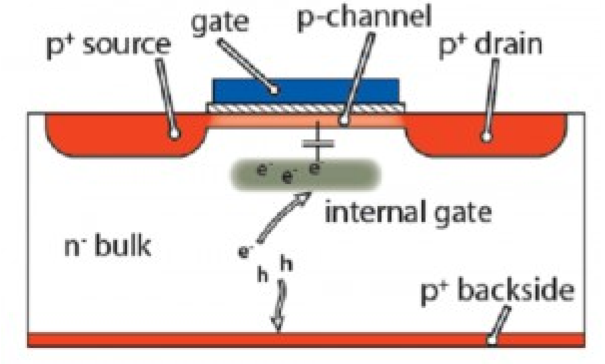
STAR CMOS pixel detector at RHIC and ALICE

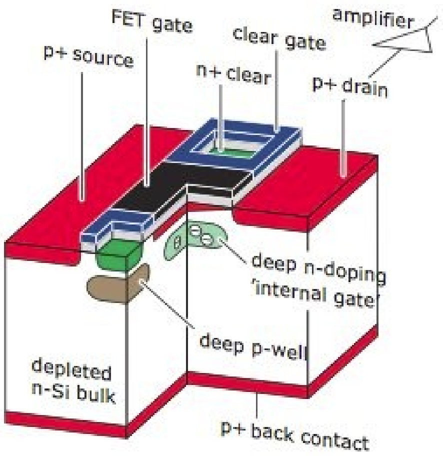


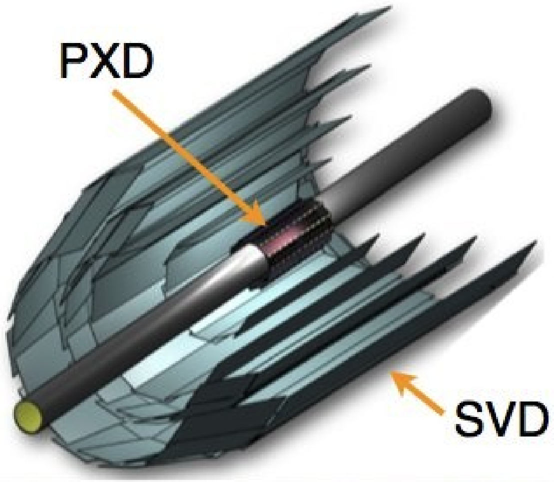


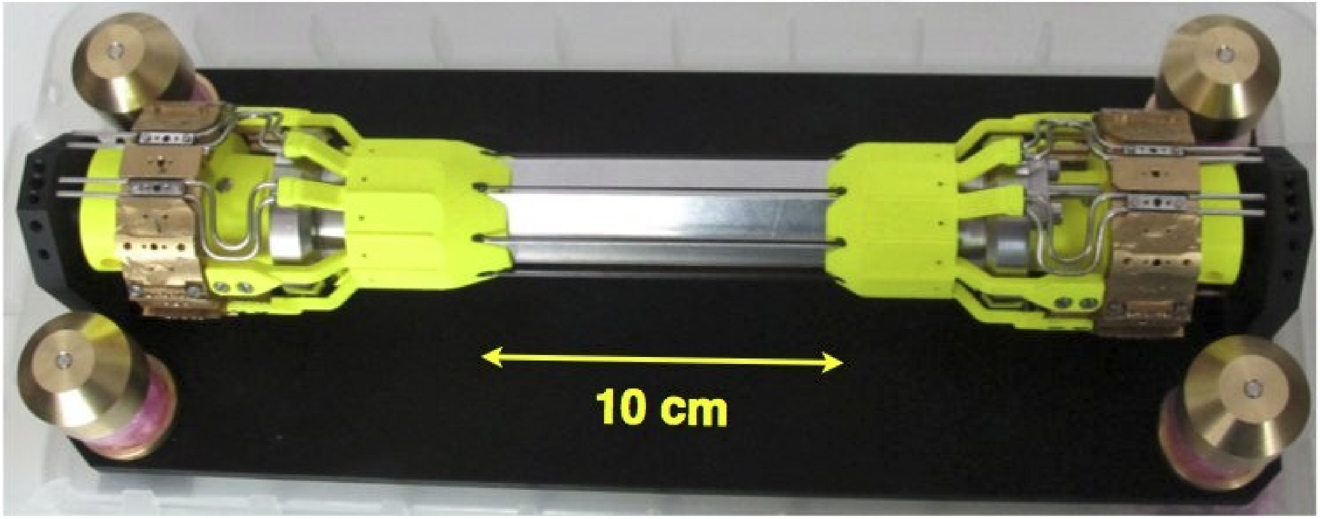
DEPFET (DEpleted Field Effect Transistor structure)

Each channel has an integrated FET to amplify the signal already in the detector which allow for building extremely thin sensors. MPI in Munich is building the vertex detector for Belle upgrade with this technology.





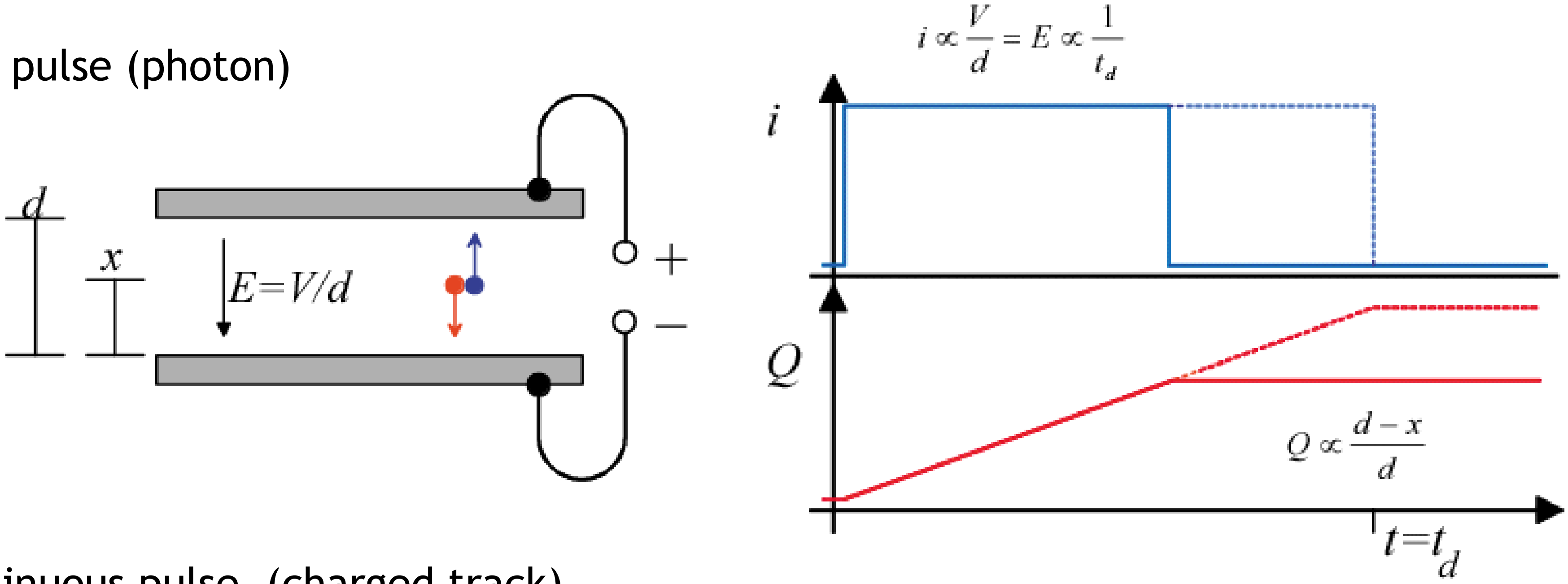




END LECTURE

Signal formation in the detector

Delta pulse (photon)



Continuous pulse (charged track)