Measurements with radiation detectors

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Energy dispersive radiation analysis

The energy dispersive radiation analysis, which detects the spectral composition of a radioactive source or material is on extremely important application of radiation detectors. A fundamental concept is the energy resolution, which refers to the ability of a spectrometry system to detect closely spaced spectral lines.

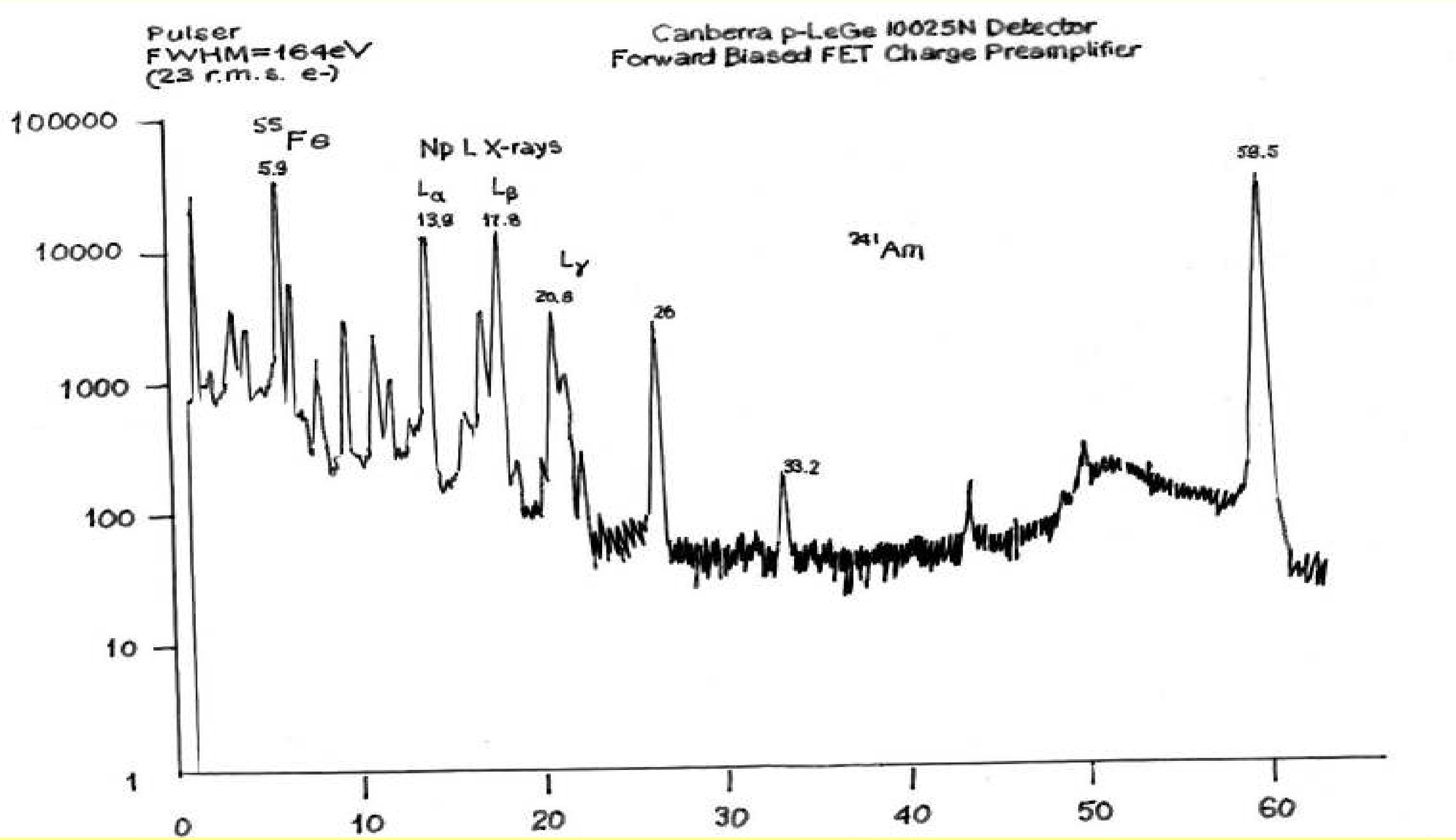
The advent of semiconductor detectors has resulted in an extremely remarkable improvement in energy resolution over gas filled ionization chambers in alpha particle spectrometry and scintillation detectors in gamma-ray and X-ray analysis.

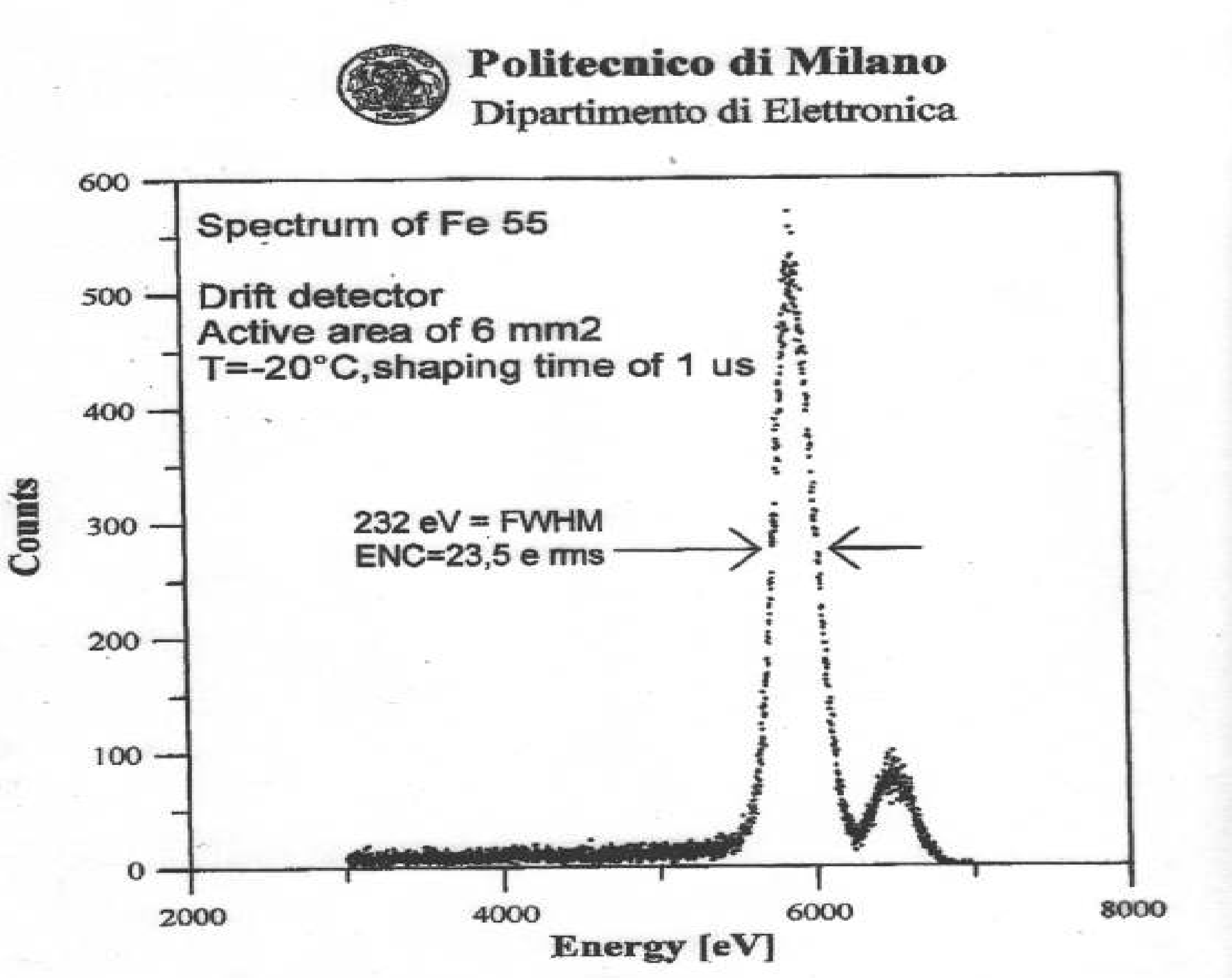
High purity Germanium detectors are nowadays providing superb resolution in gamma-ray analysis up to a few MeV.

Silicon, lithium drifted detectors constitute the best choice for high resolution X-ray analysis in the energy range form a few keV to about 100 keV.

The next slide shows high resolution photon spectra obtained with solid-state detectors.

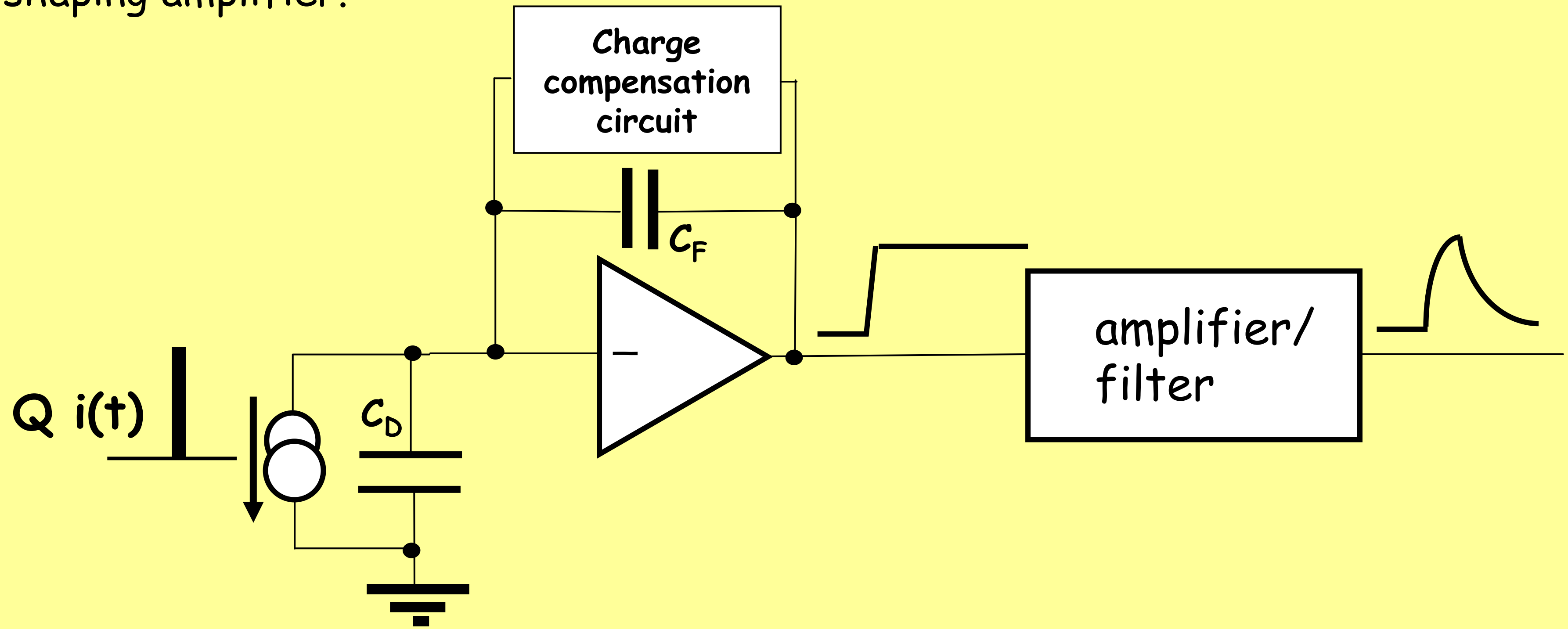
The achievement of such features in terms of energy resolution results from a deep knowledge of all the possible causes of resolution degradation and of their careful control.


Pulser
FWHM=164eV
(23 r.m.s. e-)
Canberra p-LeGe 10025N Detector
Forward Biased FET Charge Preamplifier
100000
10000
1000
100
10
1
55Fe
5.9
Np L X-rays
L_α
13.9
L_β
17.8
L_γ
20.8
26
241Am
33.2
59.5
0
10
20
30
40
50
60

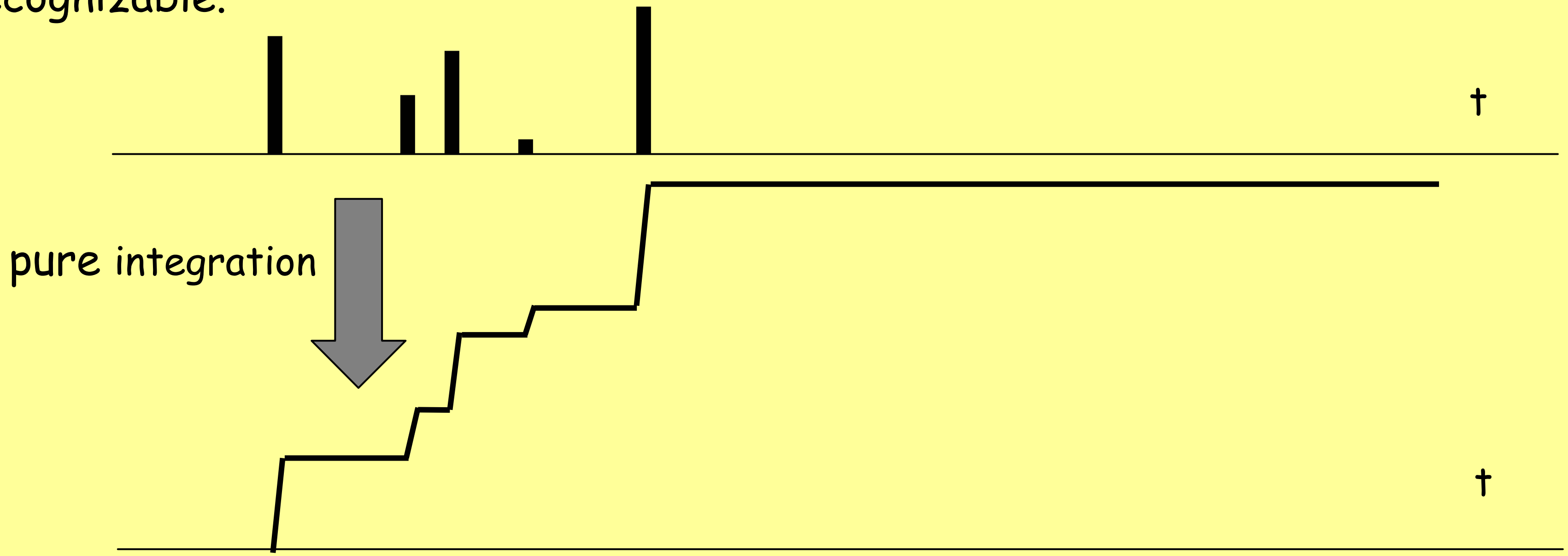

Politecnico di Milano
Dipartimento di Elettronica
Spectrum of Fe 55
Drift detector
Active area of 6 mm2
T=-20°C,shaping time of 1 us
232 eV = FWHM
ENC=23,5 e rms
Counts
Energy [eV]
600
500
400
300
200
100
0
2000
4000
6000
8000

Energy measurements with radiation detectors consist in measuring the charge induced on the signal electrode by the drift of the mobile carriers.

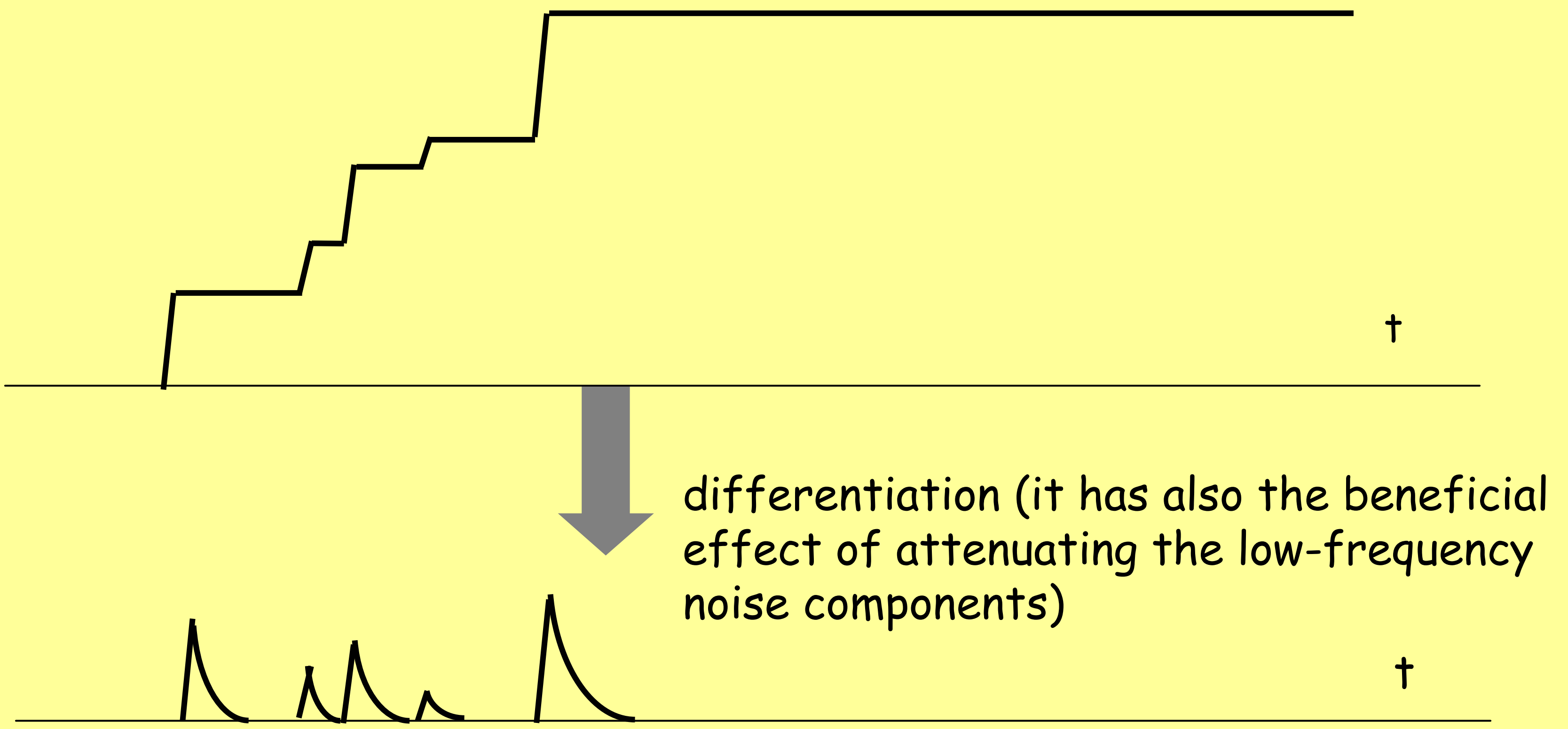
The analog section of a charge measuring system is shown below. In its more usual configuration, it consists of an operational integrator followed by a shaping amplifier.



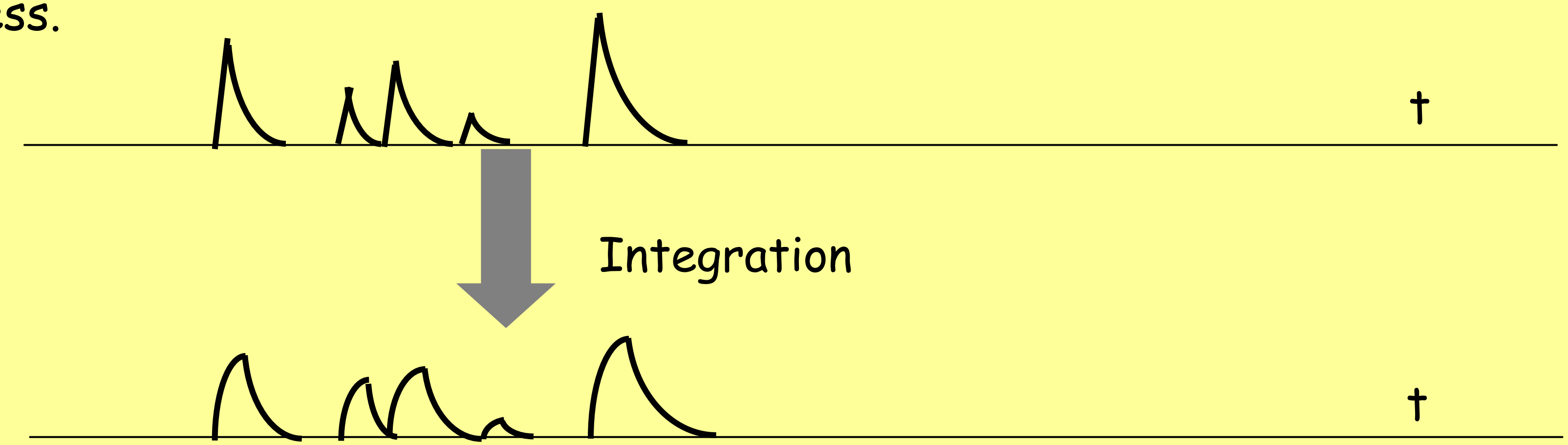
The amplification is required to bring the signal at the preamplifier output to the level required by the further signal processing circuits. The nature of the shaping function will be clear soon. Suppose that the random sequence of detector signals, represented as rectangular current pulses of a short duration arrive at the input of the preamplifier. As a result of the integration carried out by the preamplifier, the staircase voltage waveform shown below would appear at its output and the individual charge contributions wouldn't be recognizable.



So, the first function to be implemented is some kind of differentiation (clipping) at the preamplifier output to restore the features of the individual signals.



One more step is required in the shaping, an integration of the signals which has the purpose of slowing down their leading edges and results in the attenuation of the high frequency noise components. From the point of view of signal-to-noise ratio this is by far the most important operation in the entire shaping process.



All the shaping functions discussed are linear, so that the amplitude of the individual shaped signals are proportional to the charge delivered b the detector and therefore to the energy released by the incoming radiation. As it is obvious that at a given noise level, the best signal-to-noise ratio is acquired by a peak amplitude measurement, the energy measurements with radiation detectors are based on the measurement of the peak amplitudes of the signals shaped according to the described criteria.

Suppose now that a strictly monochromatic radiation falls on the detector and that the amplitude spectrum of the signals appearing at the output of the shaping amplifier is accumulated. A delta-impulse like spectral line would be expected. Instead, a gaussian distribution of finite width would appear. Several physical processes contribute to the width of the observed line. Let σ be the standard deviation of the gaussian distribution and FWHM its full width at half maximum. The following relationship holds:

$$FWHM = 2.355\ \sigma$$

Calling $\sigma_1, \sigma_2, \ldots \sigma_n$ the standard deviations due to the single processes, that are generally statistically independent from each other:

$$\sigma^2 = \sigma_1^2 + \sigma_2^2 + \ldots + \sigma_n^2$$

Some contributions to σ^2 have their origin in the detector and are related to the nature of the interaction of the radiation with the detector, Some other ones are due to defects in the detector. The signal processing electronics is responsible for additional line broadening, a very important contribution of which is the already discussed noise in the preamplifier.

CONTRIBUTIONS TO THE WIDTH OF THE SPECTRAL LINE ARISING IN THE DETECTOR

The fluctuation in the number of pairs created by the radiation constitutes in in some situations an important contributions to the width of the spectral lines.
The statistics of pair creation in the ionization process features a standard deviation lower than the one relevant to a Poisson distribution.
Consider the case of the energy E released in an ionization detector where the energy required to create a pair of carriers is ε. The average number of pairs is $n = E/\varepsilon$. If the statistics were poissonian, la variance σ^2 would be equal to n. Instead, the process of pair creation by ionization exhibits a variance reduced by the Fano factor F:

$\sigma^2 = Fn$ with $F < 1$, that is, $\sigma^2 = F\,E/\varepsilon$ or, referred to the energy,

$$\sigma^2 = \varepsilon\, F\, E$$

Values of Fano factor are 0.1 for Si and 0.08 for high purity Ge.

There are more detector-related sources of spectral line broadening

❖ The energy straggling in the detector entrance window

❖ The trapping of mobile carriers by defects in the detector material. This aspect, which is usually of minor importance in detectors made of high purity materials like silicon or germanium, may become a limitation in a material like CdTe.

❖ Structural defects in the detector, for instance the presence regions of low electric field, where the complete charge collection is not guaranteed or the collection time of carriers is excessively long. In this case, portions of the tracks that enter the detector at random angles may end up in the region of low electric field. The contribution to the induced current brought about by these portions is accordingly a random variable.

SPECTRAL LINE BROADENING IN MEASUREMENTS WITH RADIATION SOURCES OF LOW INTENSITY

Consider the case of a radiation detector made of an extremely pure material and manufactured in an ideal way, so to have an extremely thin entrance window, no traps and no regions of low electric field.

Suppose also the radiation source to be extremely well collimated, so that the radiation enters the detector at a fixed angle.

Suppose finally that the intensity of the source is low to such an extent that you can chose the pulse shaping with a comparatively long peaking time.

oThese are the ideal conditions for a high resolution radiation spectrometry. Only two sources of line broadening are to be considered:

o The statistics of pair creation in the detector
o The noise in the front-end electronics

The line broadening due to the front-end noise is expressed by

$$\sigma^2_{noise} = ENC^2$$

which must be compared to the line broadening due to statistics of pair creation in the detector

$$\sigma^2_{statistics} = \varepsilon \, F \, E$$

The following conclusions can be reached.

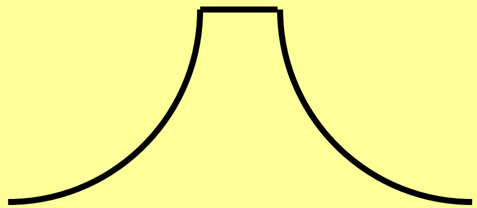
In a Si(Li) detector operating on X-rays of a few tens of keV, small E, the dominant source of line broadening at low counting rates is the front-end noise

In a planar Ge detector operating on gamma-rays of some hundreds of keV up to a few MeV, larger values of E, the dominant source of line broadening is the statistics of pair creation

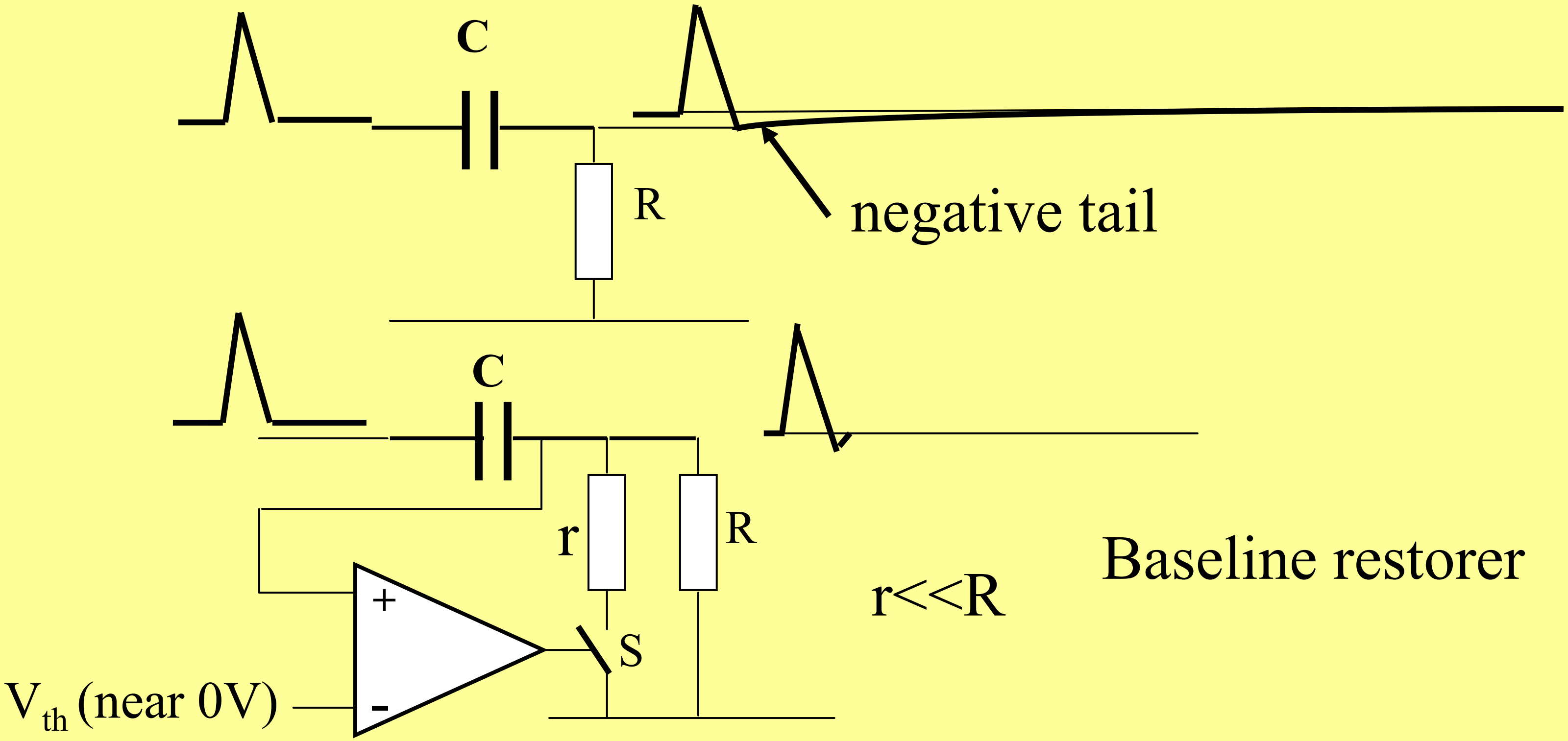
FURTHER SOURCES OF SPECTRAL LINE BROADENING

***Ballistic deficiency*: occurs when the peak value of the signal at the filter output does not correspond to the complete collection of the charge delivered by the detector, but only to a fraction of it. If the duration of the detector current pulses varies from event to event, though all events yield the same charge, the fraction of the charge lost is a random variable which introduces a dispersion in the amplitude of the signal at the filter output.**

To reduce the ballistic deficiency the filter must be chosen with the criterion that the δ-response of the entire analog channel (preamplifier and filter) feature a low curvature at the peaking point. A δ-response with a flat-top is advisable.



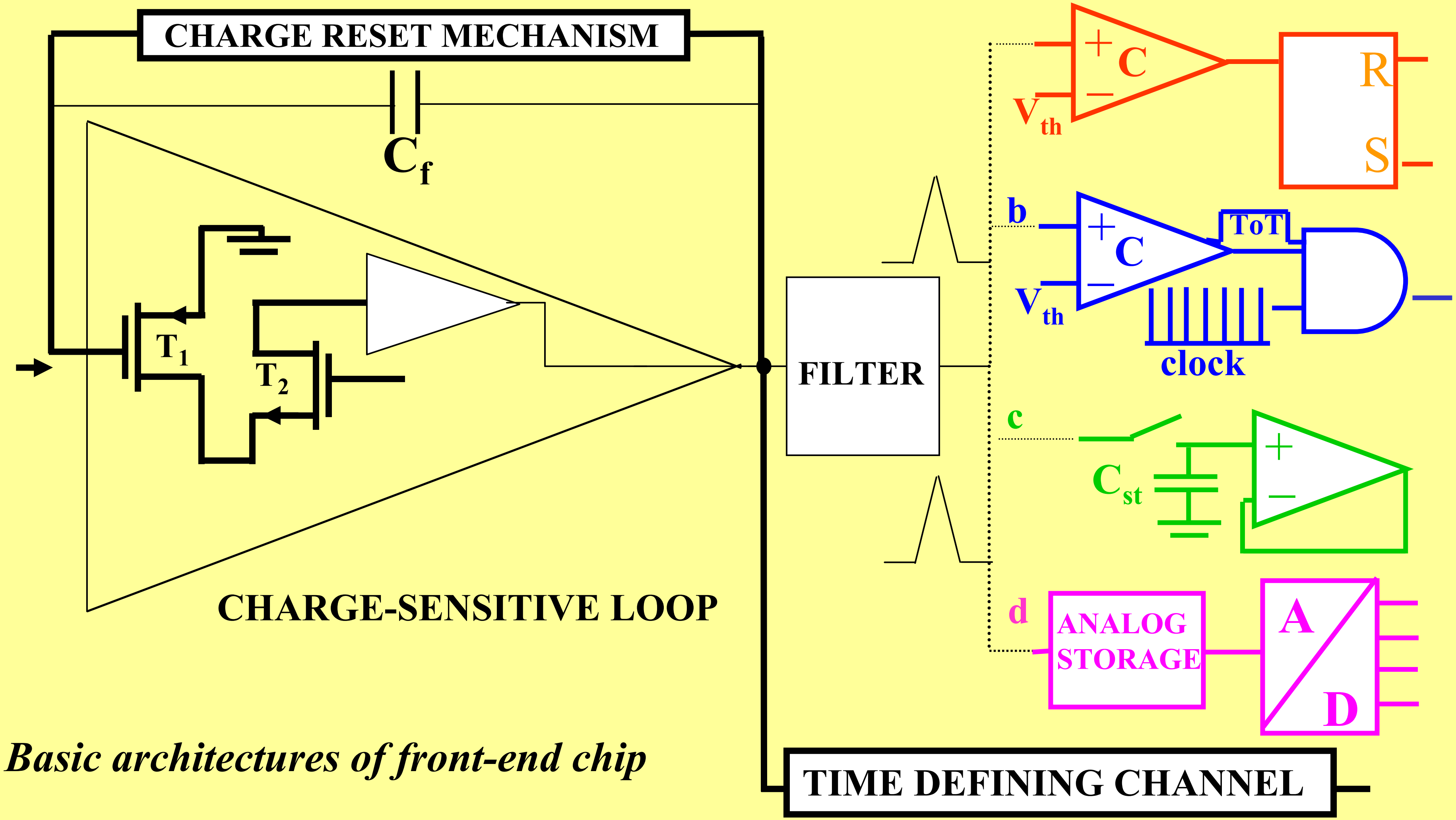
***Baseline shift at high counting rates:** takes place when a long lasting tail of opposite polarity is introduced on the signal by a high-pass filter.*



Front-end electronics for position sensing detectors

Position sensing detectors, based on microstrip or pixel structures, as required by the most advanced applications feature a high segmentation and therefore need a high density front-end electronics.

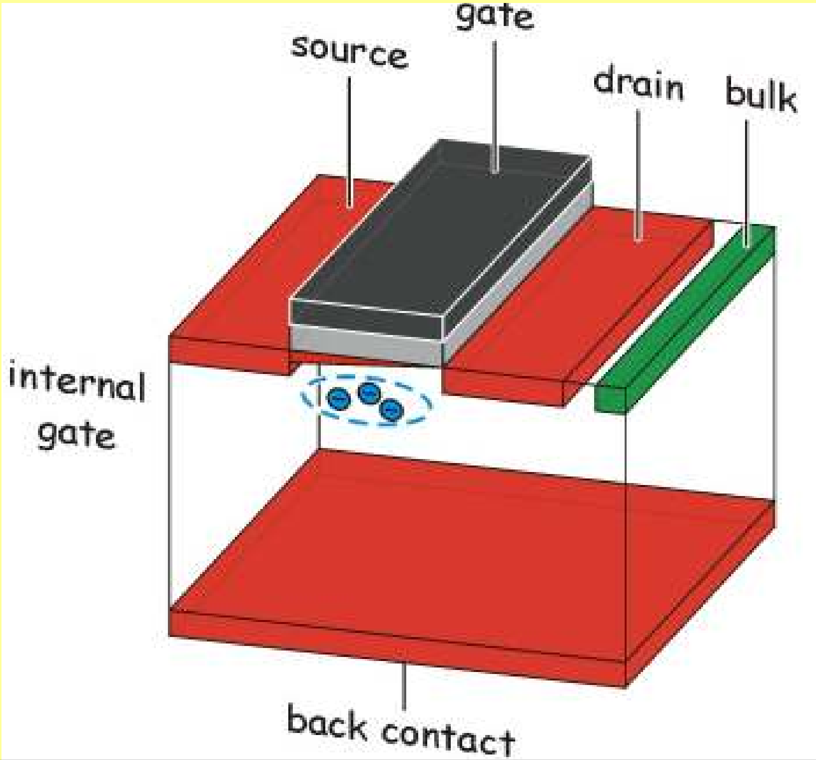
The readout circuits are normally realized in monolithic form and the more widely employed technology is CMOS. The next slide shows some solutions adopted in the readout electronics for position sensing detectors.

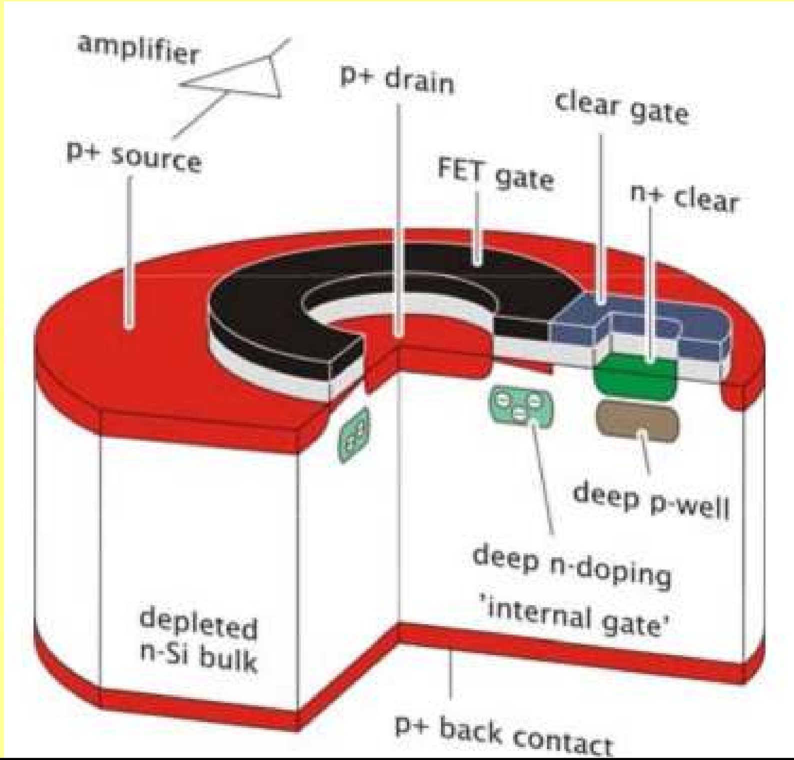


Basic architectures of front-end chip

Speaking about pixel detectors in their active versions, the MAPS (Monolithic active Pixel Sensors) as they are called, a preamble on the DEPFET is necessary because its applications and the extensions of its principle have been important issues.

Different DEPFET geometries



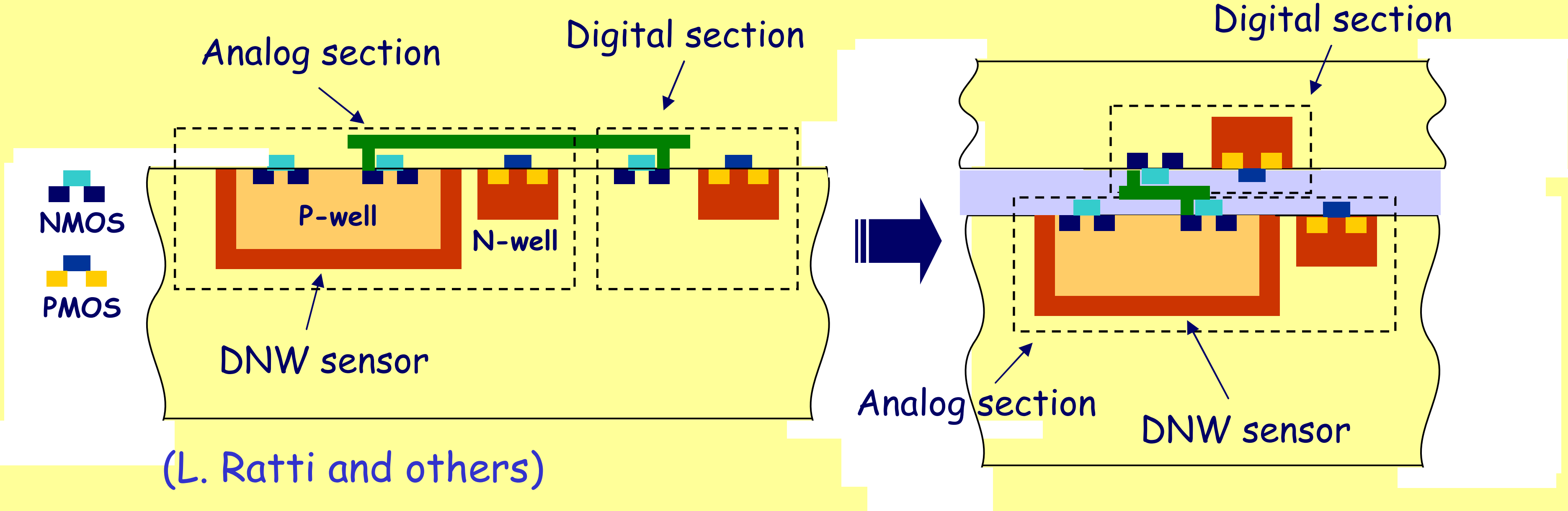


The DEPFET, an idea presented by J. Kemmer and G. Lutz in 1987, is a depletion-type P-channel device which can be integrated on the high resistivity detector material in either version, JFET or MOSFET. The DEPFET is interesting as it behaves as a pixel cell with the additional characteristics:

- it is an active device with switchable features
- it provides the storage of the signal charge for a delayed readout.

MIGRATION to 3D PROCESSES: from SDR0 to SDR1

- First guideline: separate analog from digital section to minimize cross-talk between digital blocks and sensor/analog circuits



(L. Ratti and others)

- Tier 1: collecting electrode (deep N-well/P-substrate junction) and analog front-end and discriminator
- Tier 2: digital front-end (2 latches for hit storage, pixel-level digital blocks for sparsification, 2 time stamp registers, kill mask) and digital back-end (X and Y registers, time stamp line drivers, serializer)

Definition of the time of occurrence of the event

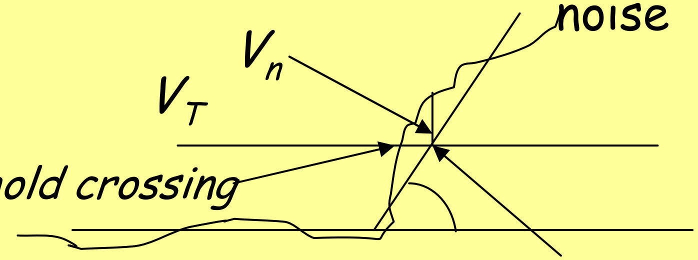
Two effects impair the accuracy in the time definition of the event:

1 – noise (jitter)

2 – systematic dependence on the amplitude (walk).

1 – Noise

Consider the signal coming from the linear section of an analog processor, which consists of a preamplifier and a filter. The signal can be represented in its initial portion as $V_0 t/\tau$, where τ is the integration time constant in the filter.



The inaccuracy in the time definition can be expressed

$$\Delta t = V_n/(V_o/\tau) = V_n\tau/V_o$$

Passing to the variance:

$$\sigma_t^{\,2} = \langle V_n^2 \rangle\, \tau^2 / V_o^2$$

Assuming the noise due to a white source of spectral power density S_w passed through a low-pass filter of time constant τ:

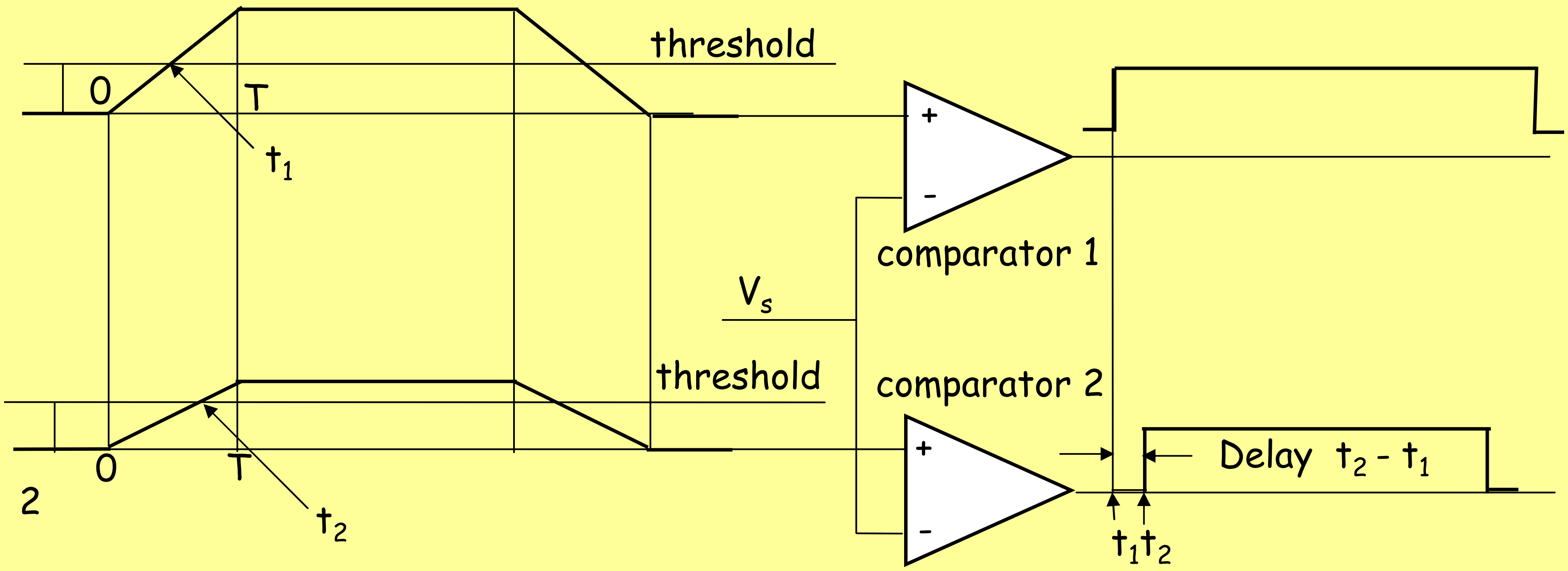
$$\langle V_n^2 \rangle = S_w/\tau$$

Which yields the following expression for the variance:

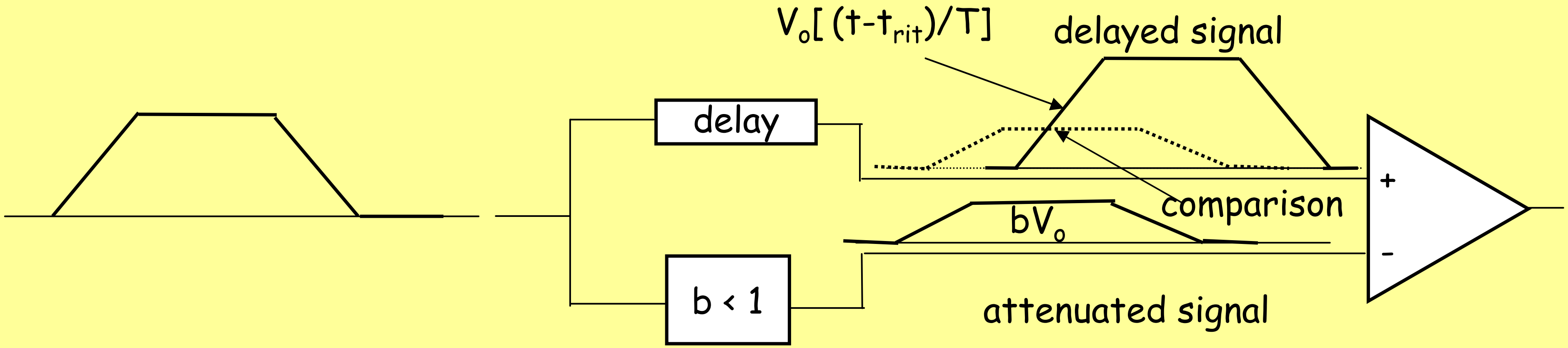
$$\sigma_t^2 = S_w\tau/V_o^2$$

2 –Systematic dependence on the amplitude

Nature of the problem. Consider two signals of the same shape and different amplitude that are presented simultaneously to two identical comparators set at the same threshold. The larger signals crosses the threshold before the smaller one does. Because of this effect, the signals at the output of the comparators are not simultaneous.



To remove this type of inaccuracy, an adaptive threshold, that is, dependent on the signal amplitude is employed, as shown below.



The same principle can be based upon a zero-crossing approach, as shown below