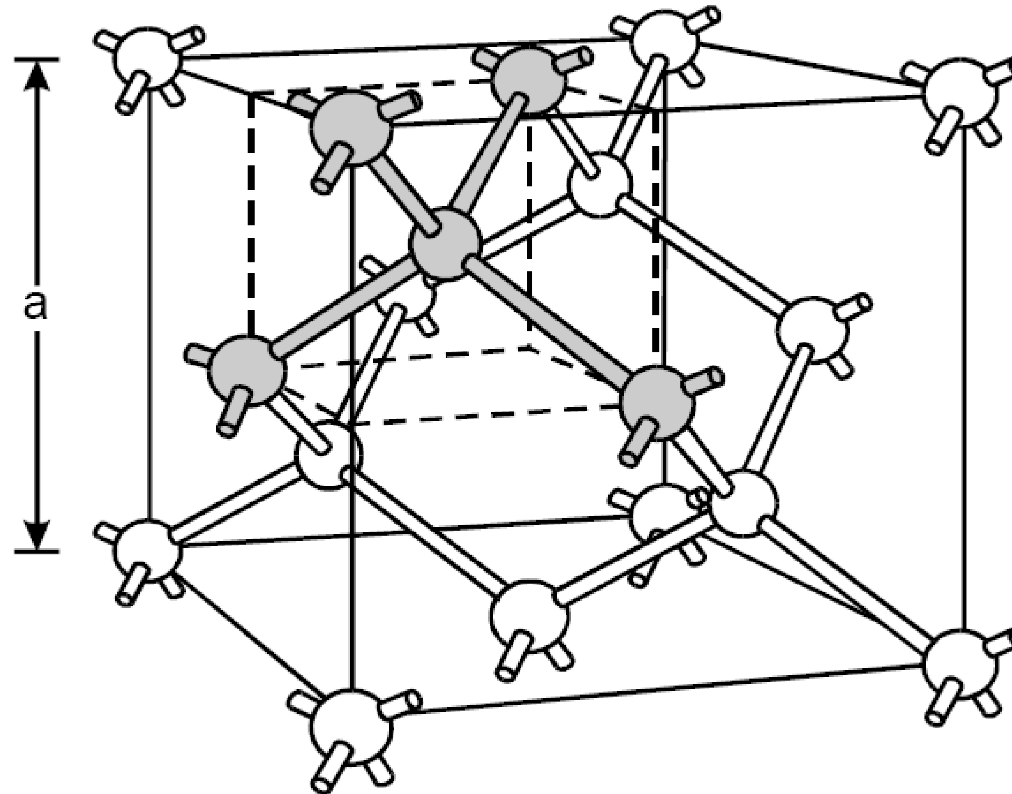
Plan de la présentation

- Lattice structure of silicon
- Band Structure in Crystals (→ Energy band structure)
- Doping → wider Depletion Region & High-Field Region
  - PN junction, PIN diode
- Photoelectric effect
- Ionization effect
  - Fano Factor
- Signal formation
  - Ramo's theorem
  - Weighting field
- Trapping & Ballistic deficit
- Detector system
- Detector model
- Signal amplification
- Small review semiconductor detectors
  - Ionisation
  - APD
  - SiPM

Remerciements :
K. Arisaka, Philippe Bourgeois, Jean-François Genat, Akli Karar, Yuri Musienko,, Helmuth Spieler.

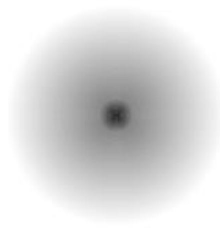
Example: Lattice structure of diamond, Si, Ge ("diamond lattice")



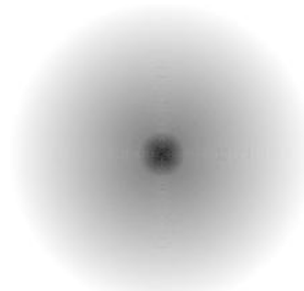
dimension a:	lattice constant	Diamond:	3.56 Å
		Ge:	5.65 Å
		Si:	5.43 Å

Extent of wavefunctions of typical constituent atoms:

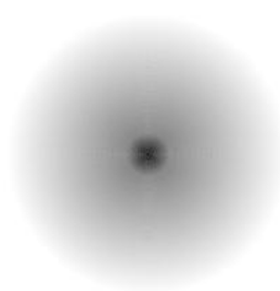
APPROXIMATE SCALE: ← 1 Å →



CARBON (Z = 6)

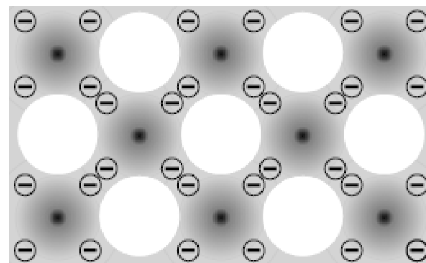


SILICON (Z = 14)

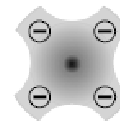


GERMANIUM (Z = 32)

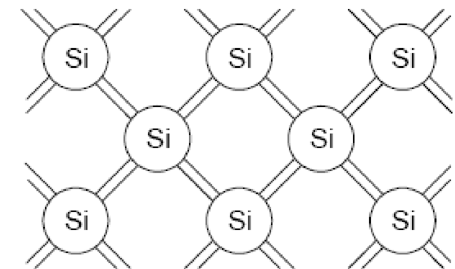
Crystal Bonds



SILICON "CORES" WITH ELECTRON "CLOUDS" SHOWING VALENCE PAIR BONDS



SILICON ATOM WITH FOUR VALENCE ELECTRONS



SYMBOLIC PLANE VIEW USING LINES TO REPRESENT BONDS

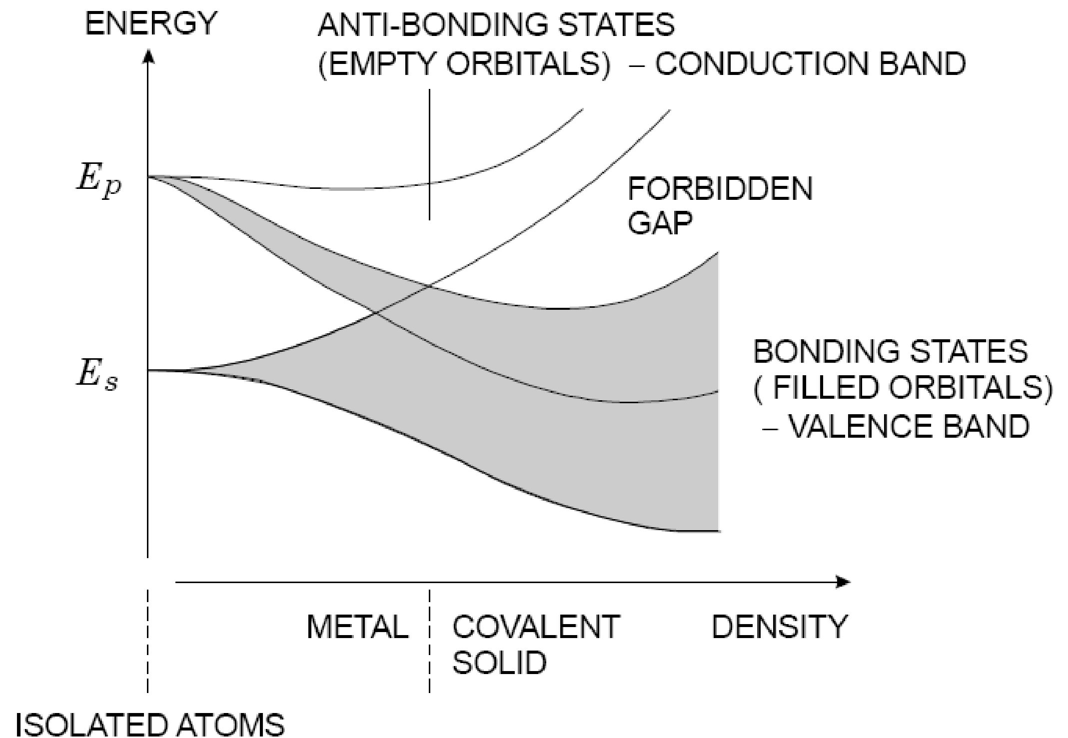
When isolated atoms are brought together to **form a lattice**, the discrete atomic states shift to form energy bands:

Filled band formed by bonding states: $\Psi = \Psi_a + \Psi_a$

(Ψ_a = wavefunction of individual atom)

Empty band formed by anti-bonding states: $\Psi = \Psi_a - \Psi_a$

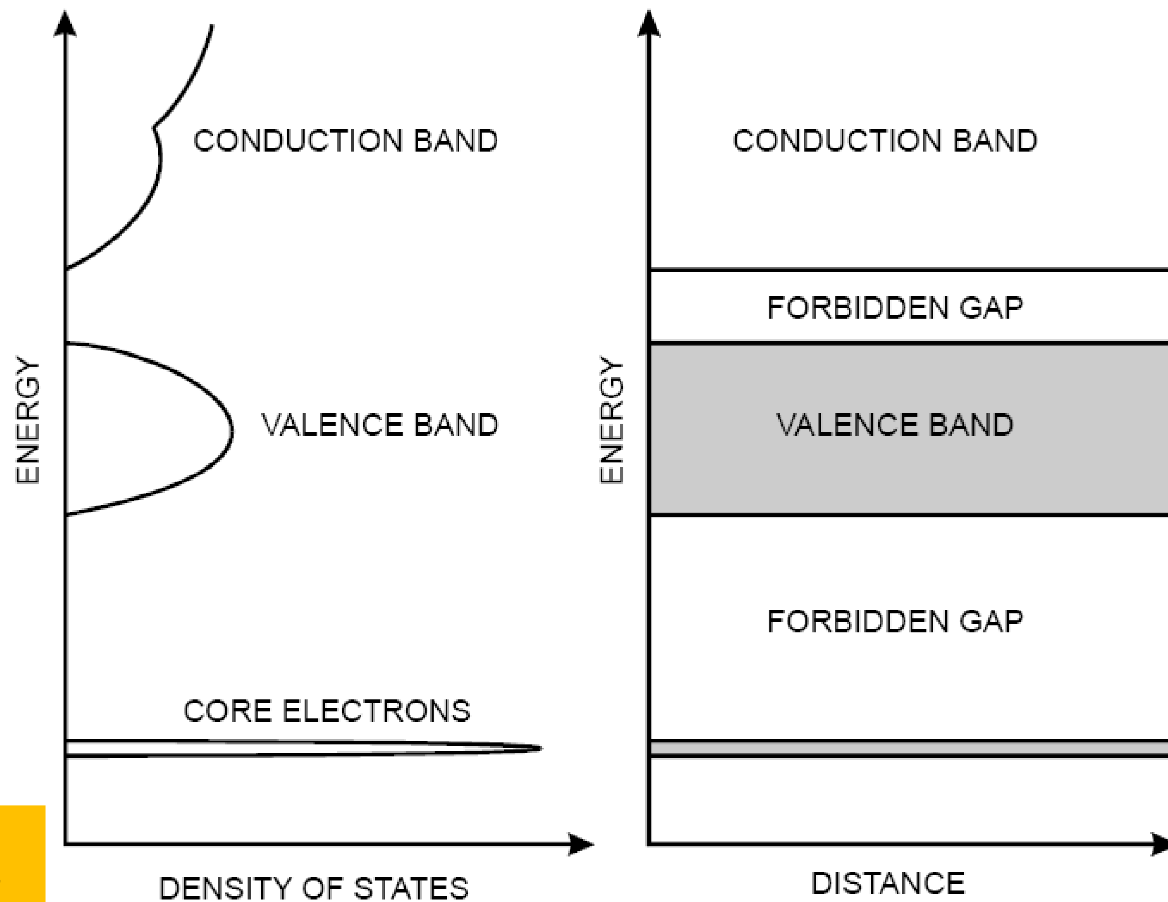
(vanishing occupancy at mid-point between atoms)



Energy band structure

Typical band gaps
(valence – conduction band)

Ge	0.7 eV
GaAs	1.4 eV
Si	1.1 eV
Diamond	5.5 eV



(following Shockley)

At 0°K all electrons occupy bonding states, completely filling the valence band. If an electric field is applied to the crystal, no current can flow,

Ionization energy in solids is proportional to the band gap

small band gap ⇒ ~ conductor

electric field small

DC current >> signal current

large band gap ⇒ insulator

high electric field

small signal charge
+ small DC current

example: diamond

moderate band gap ⇒ semiconductor

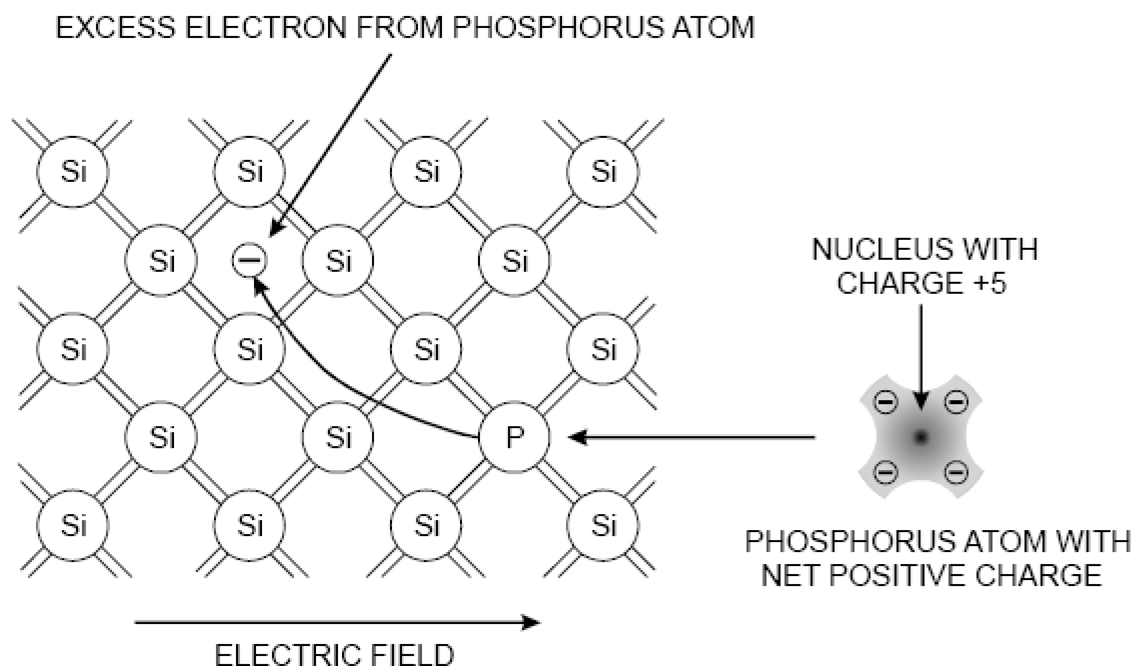
high electric field

"large" signal charge
small DC current, but
"pn-junction" required.

examples: Si, Ge, GaAs

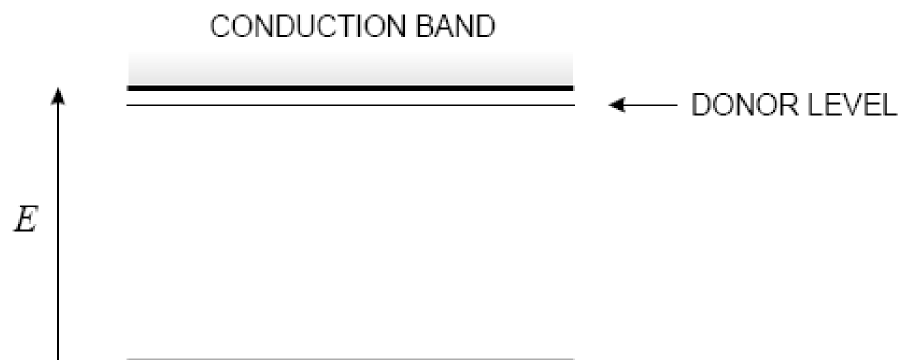
➔ Introduction of impurities to control conductivity → **Doping**

The conductivity of semiconductors can be controlled by introducing special impurities.
Required concentrations: ~10^{12} – 10^{18} cm^{-3}

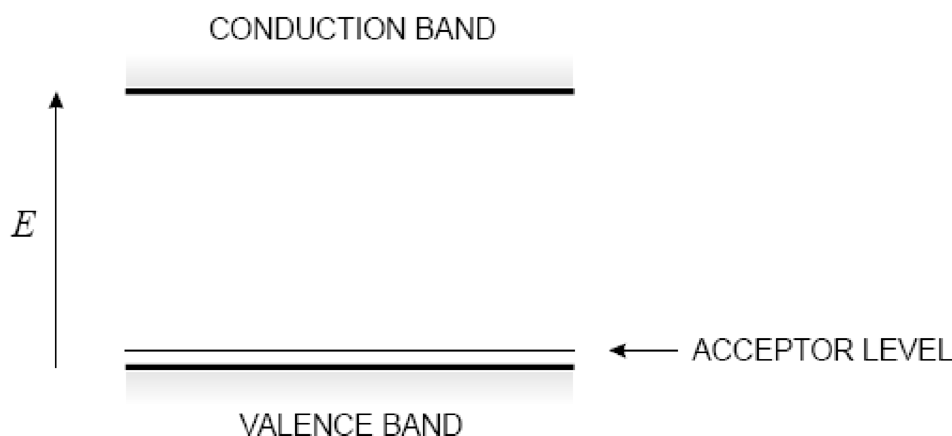


Replacing a silicon atom (group 4 in periodic table, i.e. 4 valence electrons) by an atom with 5 valence electrons, e.g. P, As, Sb, leaves one valence electron without a partner.

Since the impurity contributes an excess electron to the lattice, it is called a **donor**.



➔ substantial ionization probability at room temperature → electrons in conduction band



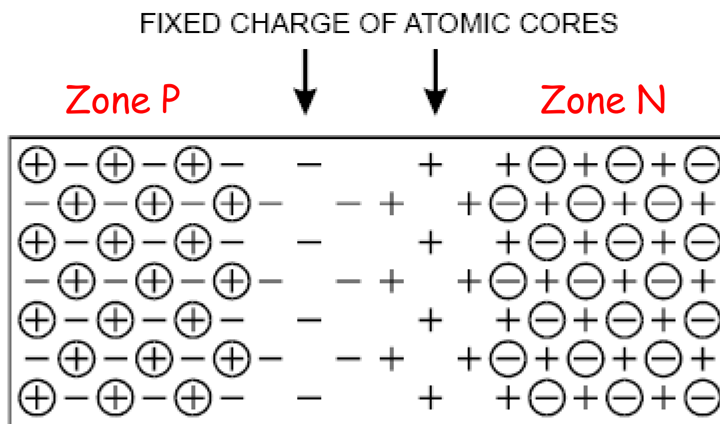
Conversely, introducing a group 3 atom (B, Al, Ga, In) leaves a Si valence electron without a partner.
This type of dopant is called an **"acceptor"**.

The electrons missing from the valence band form mobile charge states called "holes", which behave similarly to an electron in the conduction band, i.e. they can move freely throughout the crystal.

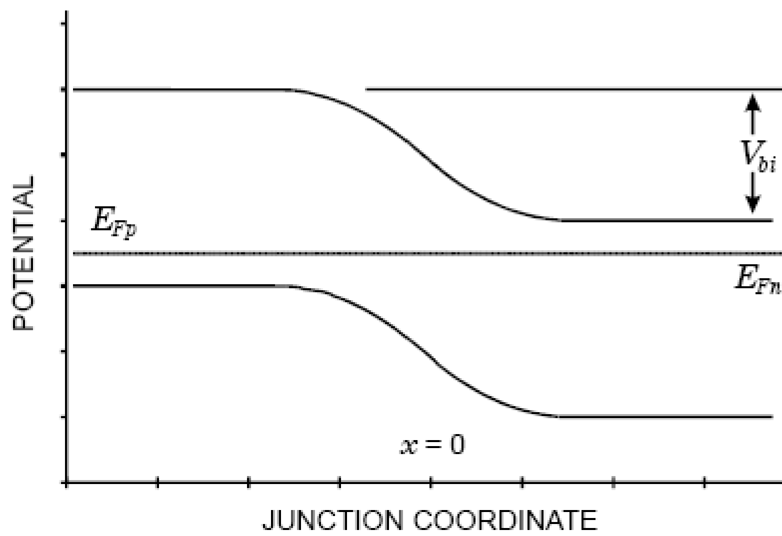
Since the charge carriers in the donor region are electrons, i.e. negative, it is called "*n-type*". Conversely, as the charge carriers in the acceptor region are holes, i.e. positive, it is called "*p-type*".

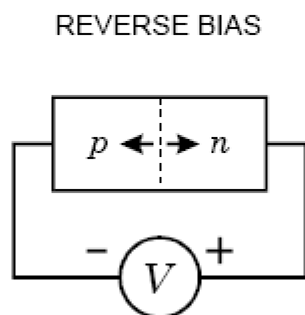
Thermal diffusion

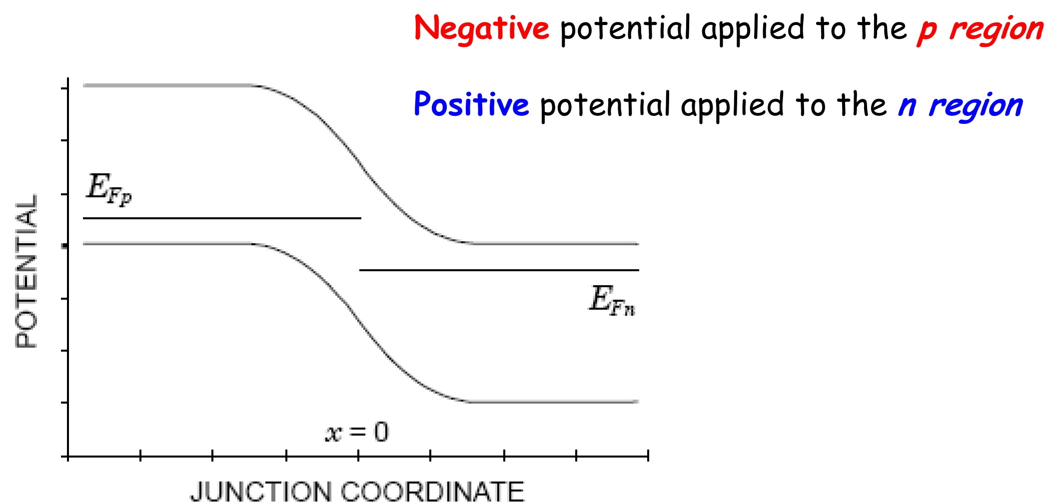
Built in field



The diffusion depth is limited when the space charge potential exceeds the available energy for thermal diffusion







Negative potential applied to the ***p region***

Positive potential applied to the ***n region***

Potential across junction is increased ➔ wider depletion region

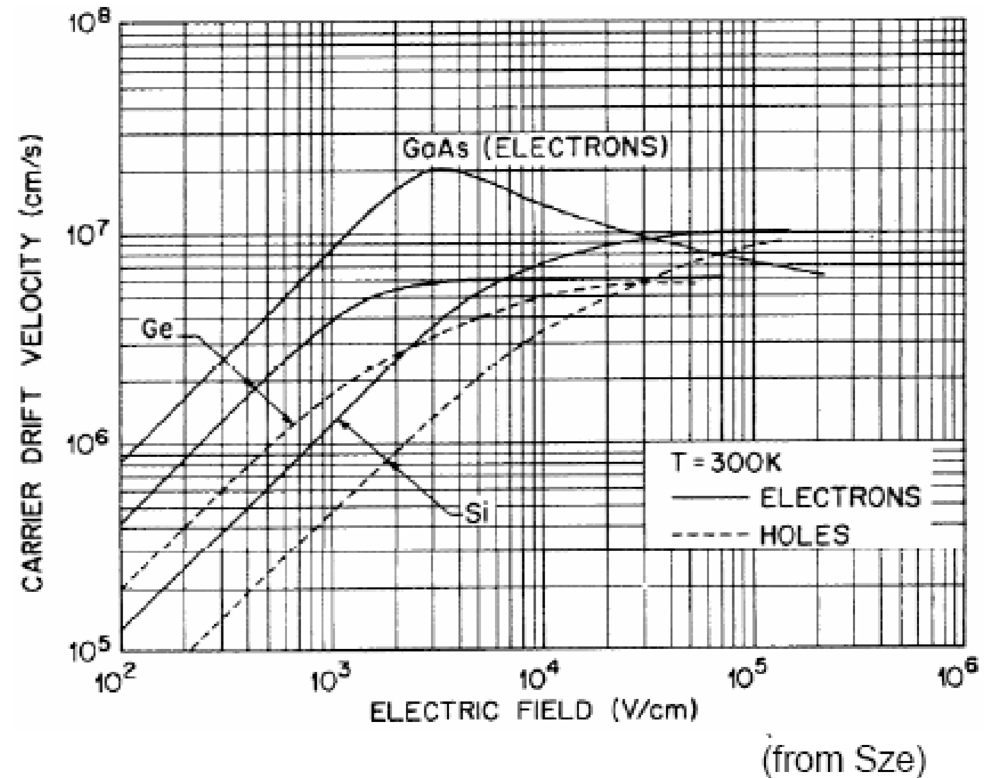
Depletion width and electric field in p-n junction :

Assume a reverse bias voltage V_b *and that the potential changes only in the direction perpendicular to* the *n-p interface.* ***Poisson's equation is then***

$$\frac{d^2V}{dx^2} + \frac{Nq_e}{\varepsilon} = 0$$

N = dopant concentration
q_e *= electron charge.*

$$v(x) = \mu E(x)$$

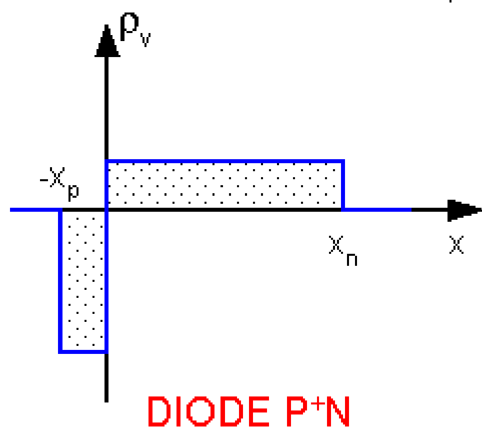


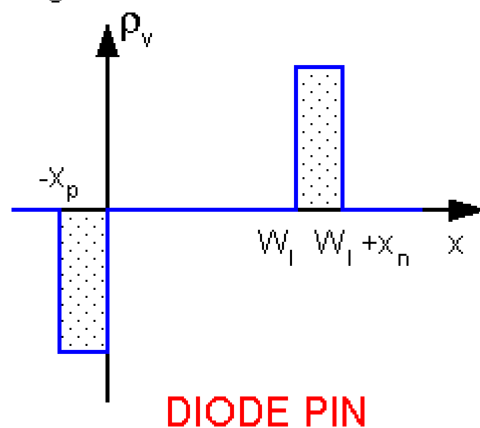
(from Sze)

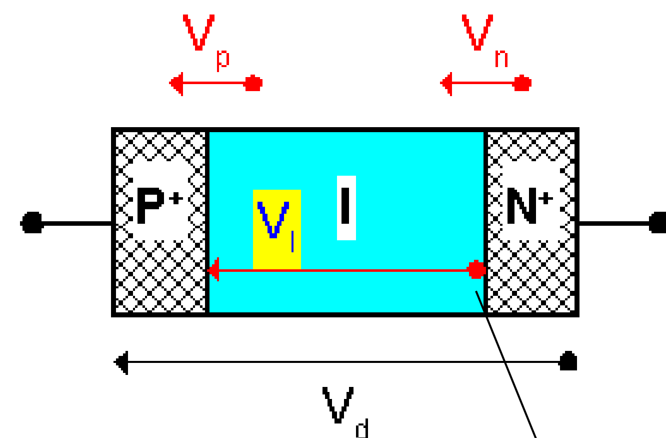
In Si at 300K at low fields the mobility is 1350 cm^2/Vs for e- and 480 cm2/ Vs for holes.

At high fields E > 10^5 V/cm the mobility is proportional to 1/E and carriers attain a constant drift velocity of 10^7 cm/s.

Densité volumique des charges

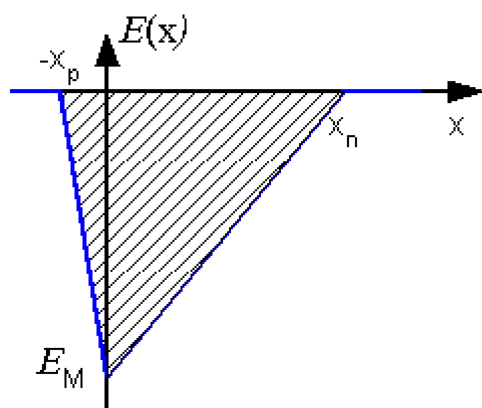


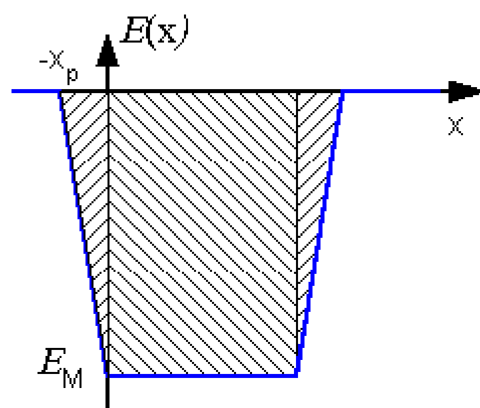




DIODE P+N

DIODE PIN

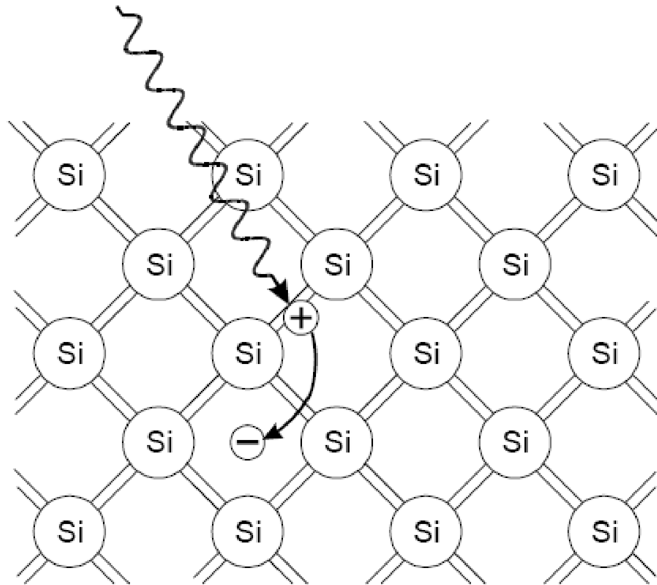




Champ électrique

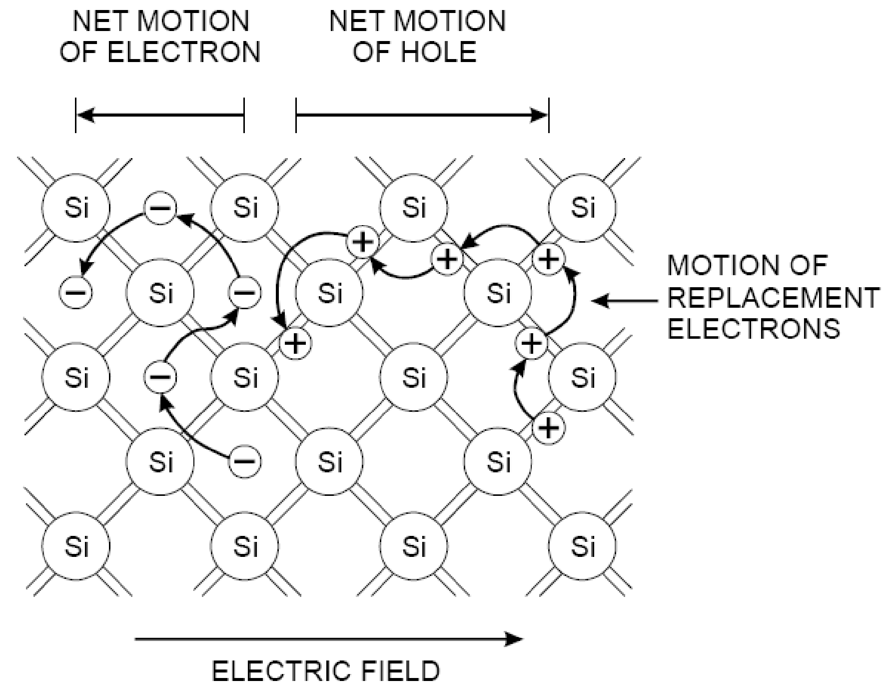
Région intrinsèque (non dopée)

Signaux et modélisation des détecteurs à Semi-conducteur



If energy is imparted to a bond by incident radiation, for example a photon, the bond can be broken:

- exciting an electron into the conduction band and
- leaving back a vacant state in the valence band, a "hole".

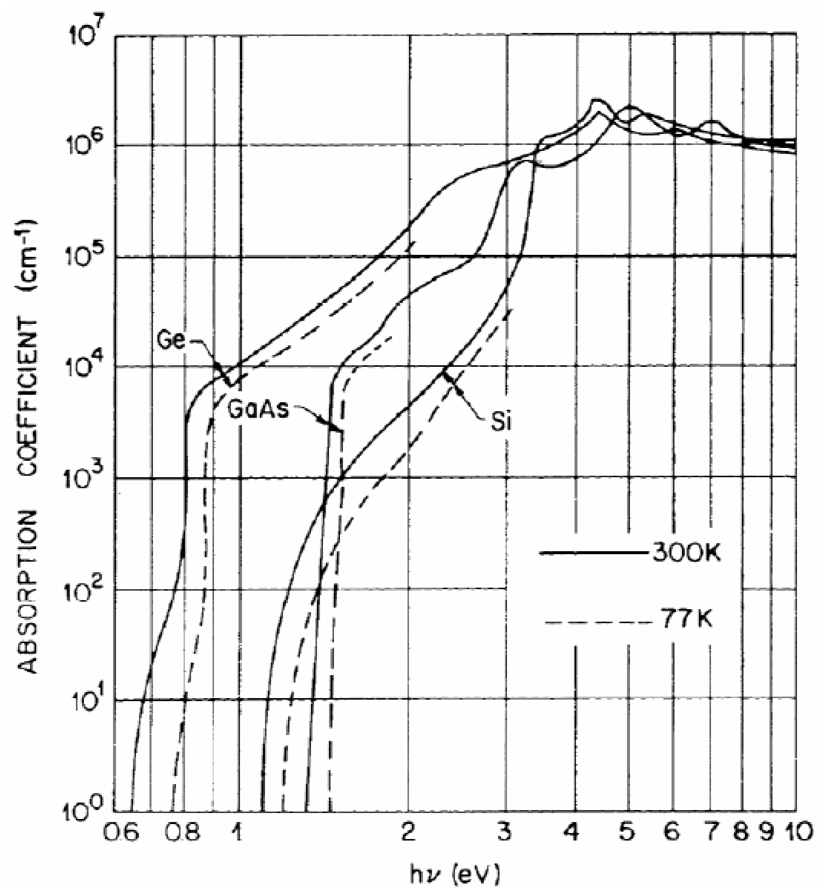


The motion of the electron and hole can be directed by an electric field.

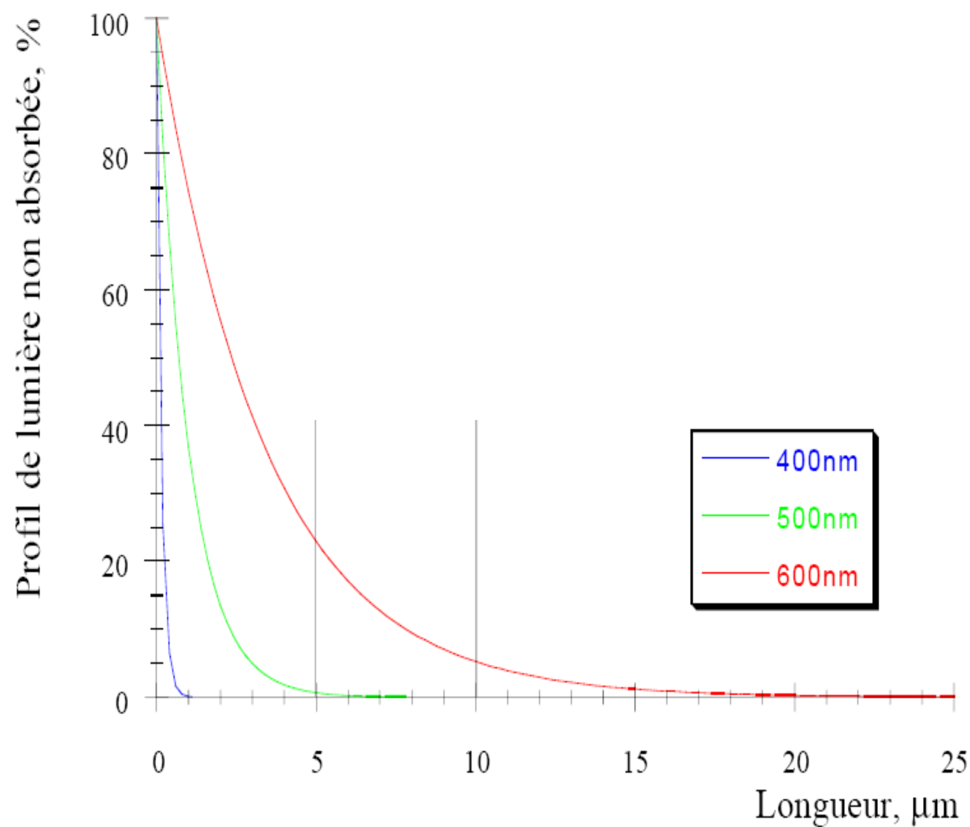
Holes can be treated as positive charge carriers just like the electrons (more slowly).

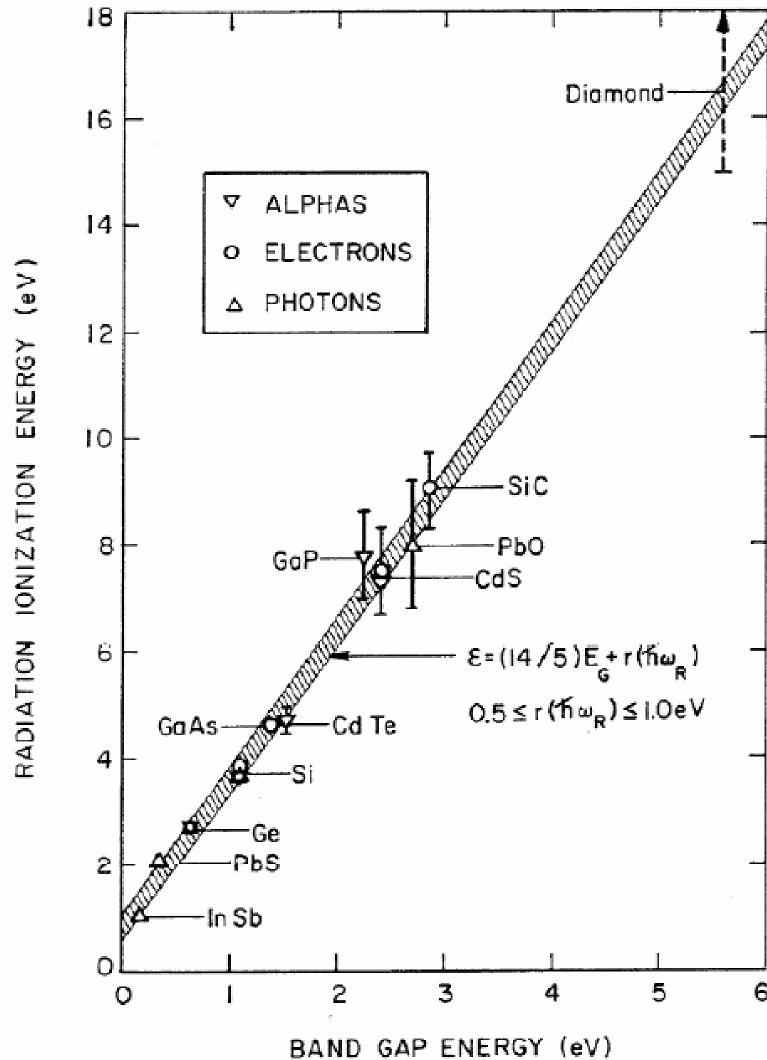
Photoelectric effect ➔ energy required to produce an electron-hole pair ≈ band gap (Silicium: 1.1 eV)

Signaux et modélisation des détecteurs à Semi-conducteur



(from Sze)





C.A. Klein, J. Applied Physics **39** (1968) 2029

High energy quanta (*E » Eg) :*

It is experimentally observed that the energy required to form an electron-hole pair exceeds the bandgap.

Why?

When particle deposits energy one must conserve both energy and momentum. Momentum conservation not fulfilled by transition across gap ➔ excite phonons

Ionization effect ➔ energy required to produce an electron-hole pair > band gap (Silicium: ~3.6 eV)

Signaux et modélisation des détecteurs à Semi-conducteur

The Fano Factor

The mean ionization energy exceeds the band gap for two reasons

1. Conservation of momentum requires excitation of lattice vibrations
2. Many modes are available for the energy transfer with an excitation energy less than the band gap.

Two types of collisions are possible:

a) Lattice excitation, i.e. phonon production (with no formation of mobile charge).

b) Ionization, i.e. formation of a mobile charge pair.

Assume that in the course of energy deposition

N_x excitations produce N_P phonons (or molecular vibrations, for example) and
N_{ion} ionization interactions form N_Q charge pairs.

On the average, the sum of the energies going into excitation and ionization is equal to the energy deposited by the incident radiation :

$$E_0 = E_{ion} N_{ion} + E_x N_x$$

where E_{ion} *and* E_x *are the energies required for a single excitation or ionization.*

If for a given event more energy goes into charge formation, less energy will be available for excitation:

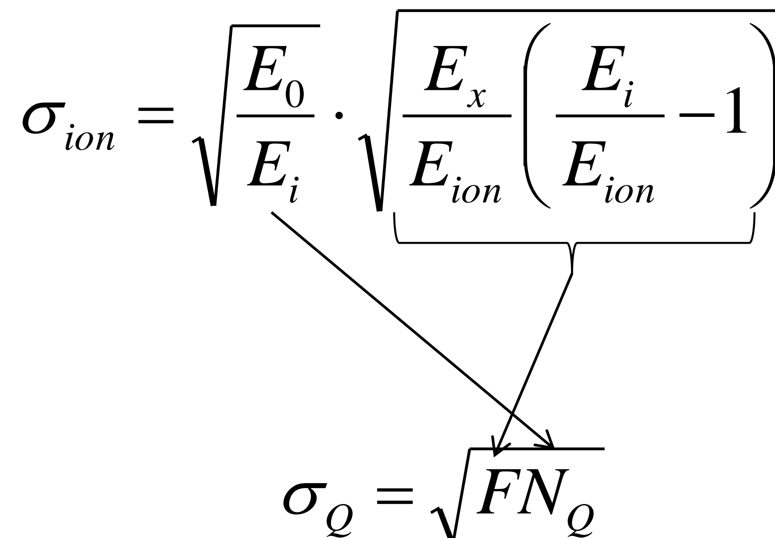
$$E_x \Delta N_x + E_{ion} \Delta N_{ion} = 0$$

Averaging over many events this means that the variances in the energy allocated to the two types of processes must be equal:

$$E_x \sigma_x = E_{ion} \sigma_{ion} \Leftrightarrow \sigma_{ion} = \frac{E_x}{E_{ion}} \sqrt{N_x}$$

Where: $\sigma_x = \sqrt{N_x}$ and $\sigma_{ion} = \sqrt{N_{ion}}$ (Gaussian statistic)

One can then obtain:



$$\sigma_{ion} = \sqrt{\frac{E_0}{E_i}} \cdot \sqrt{\frac{E_x}{E_{ion}}\left(\frac{E_i}{E_{ion}} - 1\right)}$$

$$\sigma_Q = \sqrt{F N_Q}$$

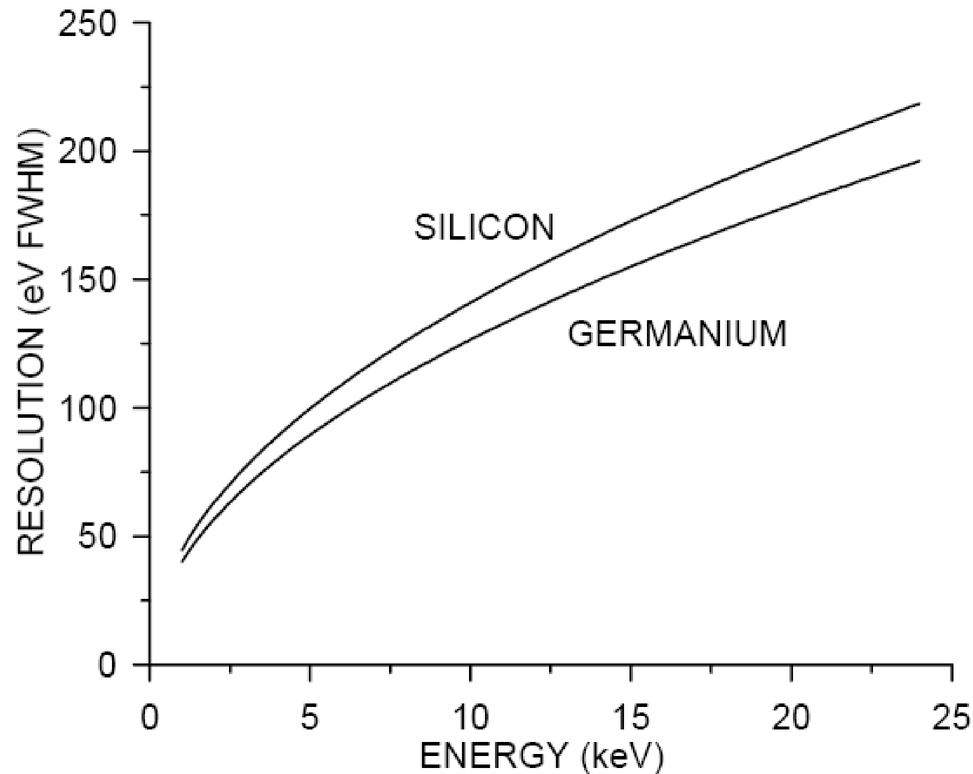
In Silicon:

$E_x = 0.037$ eV
$E_{ion} = E_{gap} = 1.1$ eV $\Leftrightarrow F = 0{,}08$
$E_i = 3.6$ eV

The variance of the signal charge is smaller than naively expected: $\sigma_Q \approx 0{,}3\sqrt{N_Q}$

The Fano Factor

$$\Delta E_{FWHM} = 2.35 \cdot \varepsilon_i \sqrt{FN_Q} = 2.35 \cdot \varepsilon_i \sqrt{F \frac{E}{E_i}} = 2.35 \cdot \sqrt{FEE_i}$$



Si: $E_i = 3.6$ eV $F = 0.1$

Ge: $E_i = 2.9$ eV $F = 0.1$

Detectors with good efficiency for this energy range have sufficiently small capacitance to allow electronic noise of ~100 eV FWHM, so the variance of the detector signal is a significant contribution.

At energies >100 keV the detector sizes required tend to increase the electronic noise to dominant levels.

When does the signal current begin ?

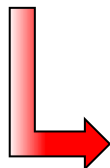
a) when the charge reaches the electrode ?

or

b) when the charge begins to move ?

Although the first answer is quite popular (encouraged by the phrase "charge collection"), the second is correct. When a charge pair is created, both the positive and negative charges couple to the electrodes and **induce mirror charges of equal magnitude**.

The following discussion applies to ALL types of structures that register the effect of charges moving in an ensemble of electrodes, i.e. not just semiconductor or gas-filled ionization chambers, but also resistors, capacitors, photoconductors, vacuum tubes, etc.

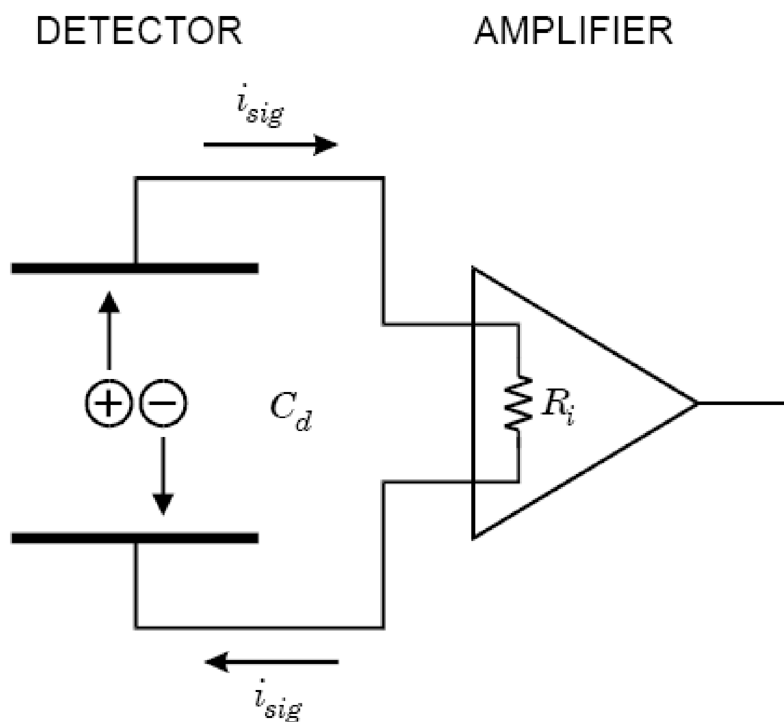


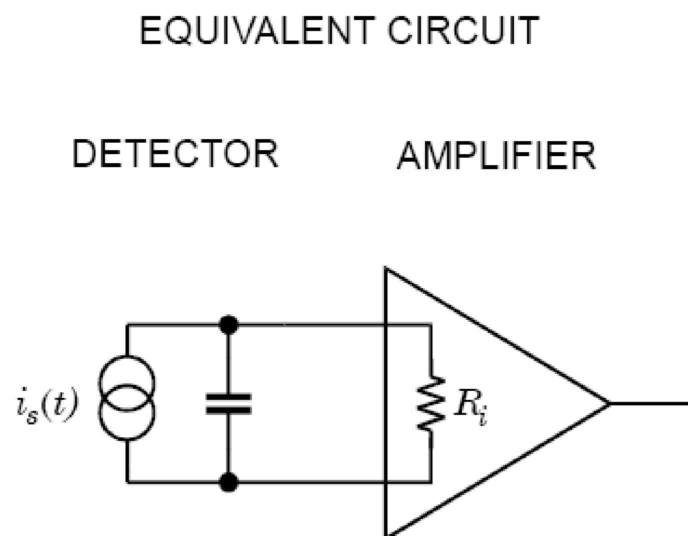
This can be analyzed conveniently by applying Ramo's theorem.

W. Shockley, J. Appl. Phys. ***9 (1938) 635***
S. Ramo, Proc. IRE ***27 (1939) 584***

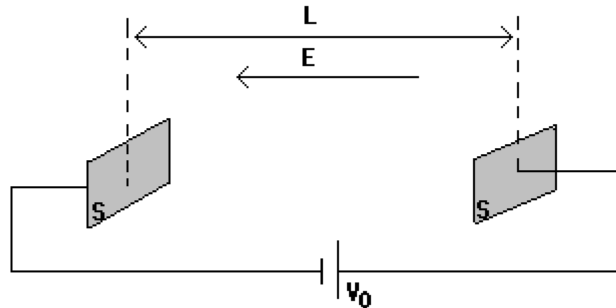
Signal Formation

Time Dependence of the Signal Current

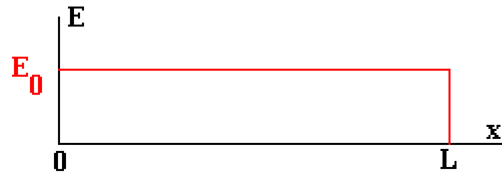




THEOREME DE RAMO-SHOCKLEY



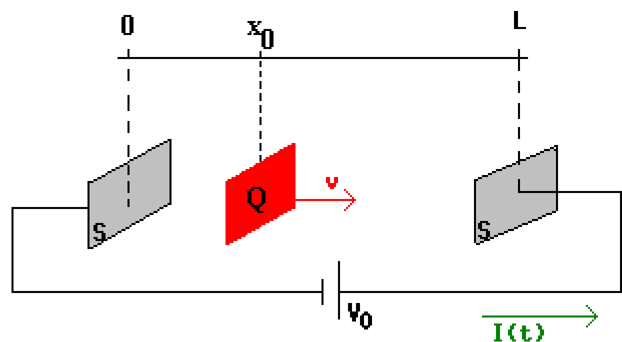
$$E_0 = \frac{V_0}{L}$$

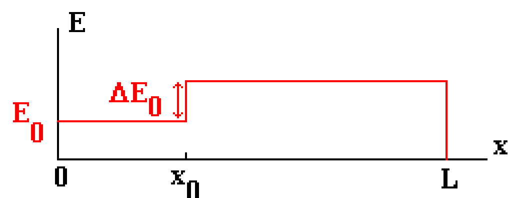


La valeur de la densité surfacique de charge σ_0 sur l'armature métallique est lié au champ éléctrique par :

$$E_0 = \frac{\sigma_0}{\varepsilon} \Leftrightarrow d\sigma_0 = \varepsilon dE_0$$

Théorème de Gauss : $\int_S E\,dS = \frac{1}{\varepsilon_0}\sum_i q_i = \frac{1}{\varepsilon_0}\int_V \rho\,dV$





Supposons qu'à l'instant $\mathbf{t_0}$, on crée brutalement, à l'abscisse $\mathbf{x_0}$, un plan de charge **Q**, de surface **S** et largeur infinitésimale $\mathbf{dx_0}$.

La loi de Gauss nous permet d'écrire :

$$\Delta E_0 = \frac{Q}{S\varepsilon}$$

La tension étant maintenue constante on a alors :

$$V_0 = E_0 L + \Delta E_0 (L - x_0)$$

En remplaçant ΔE_0 par sa valeur et en traduisant le fait que la différence de potentiel est maintenue constante, on peut écrire :

$$dV_0 = 0 = LdE_0 - \frac{Q}{S\varepsilon}dx_0$$

La variation de la densité surfacique de charge sur l'armature métallique à la position L est alors :

$$d\sigma_0 = \varepsilon dE_0 = \frac{Q}{SL}dx_0$$

et la variation du nombre de charge **dQ_L** sur l'armature métallique à la position L est alors :

$$dQ_L = Sd\sigma_0 = \frac{Q}{L}dx_0$$

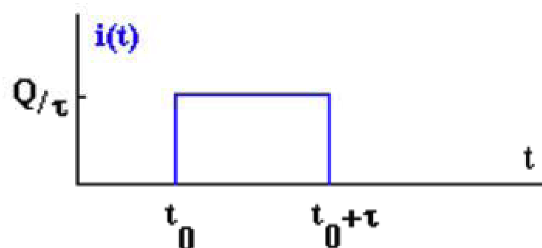
Finalement, on obtient le courant circulant dans le circuit extérieur :

$$I = \frac{dQ_L}{dt} = \frac{Q}{L}\frac{dx_0}{dt} = \frac{Q}{L}v$$

v étant la vitesse du plan de charge sous l'action de la force $\vec{F} = Q\vec{E}$

Le courant induit dans le circuit extérieur a donc l'allure d'un créneau d'amplitude :

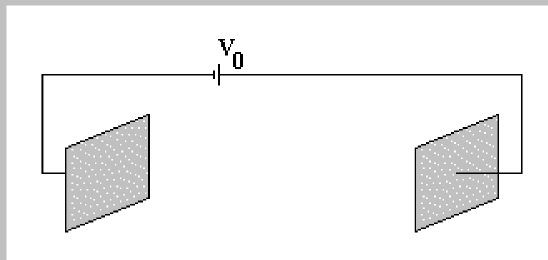
$$I = \frac{Q}{\tau}$$



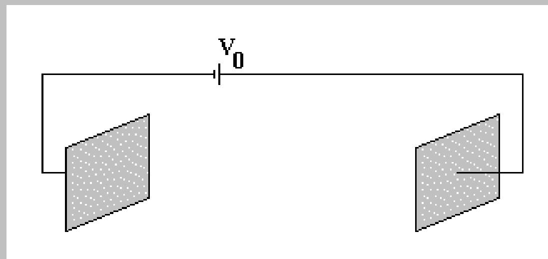
et de durée : temps de transit de la charge entre les deux armatures.

$$\tau = \frac{L}{v}$$

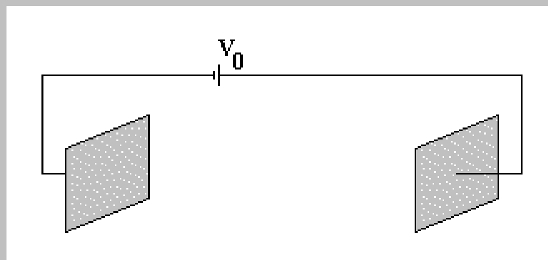
A vitesse de déplacement constante et à même quantité de charge injectée, le courant induit a donc une amplitude inversement proportionnelle au temps de transit (donc à la longueur de transit), et une durée proportionnelle au temps de transit.



longueur de transit = 1



longueur de transit = 2



longueur de transit = 4

The instantaneous current can be expressed in terms of a weighting field :

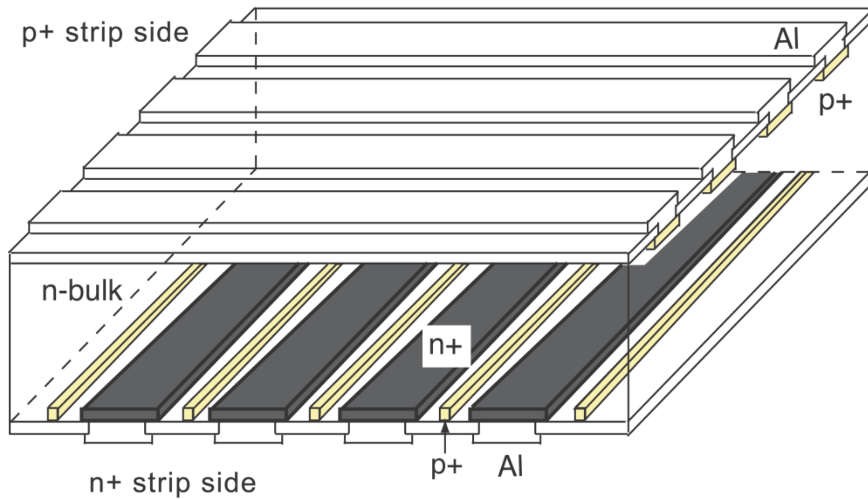
$$i_k = -q\vec{v} \cdot \vec{F}_k$$

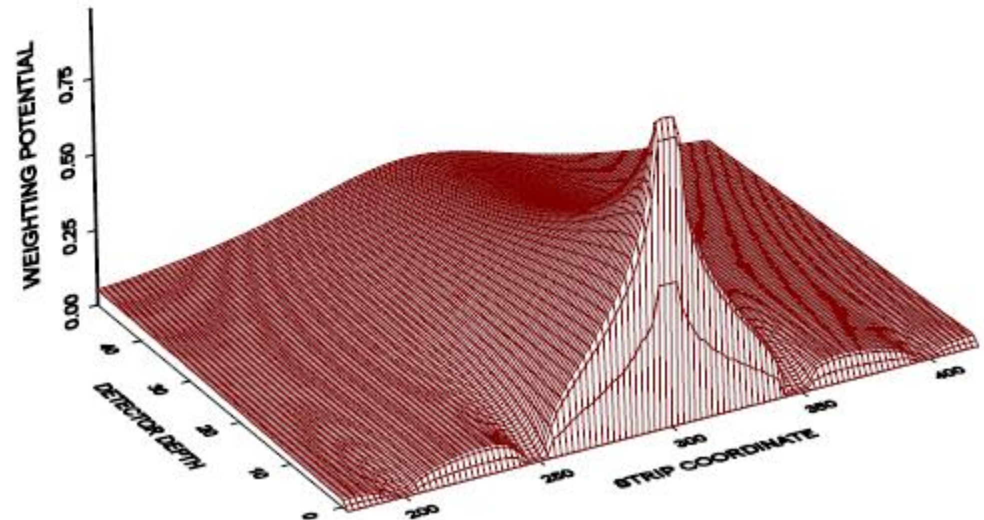
The weighting field is determined by applying unit potential to the measurement electrode and 0 to all others.

Note that the electric field and the weighting field are distinctly different:

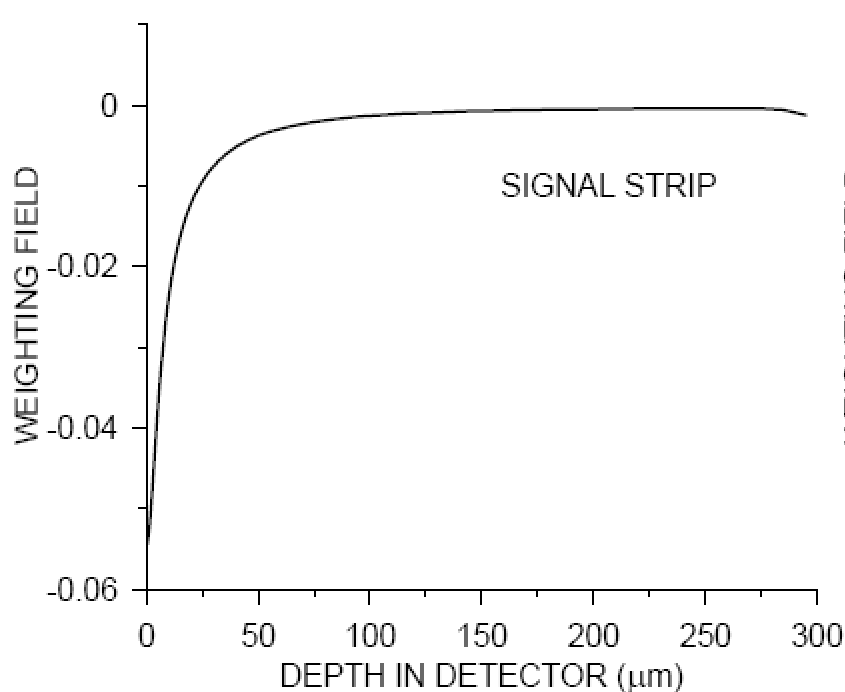
- The electric field determines the charge trajectory and velocity
- The weighting field depends only on geometry and determines how charge motion couples to a specific electrode.
- Only in 2-electrode configurations are the electric field and the weighting field of the same form.

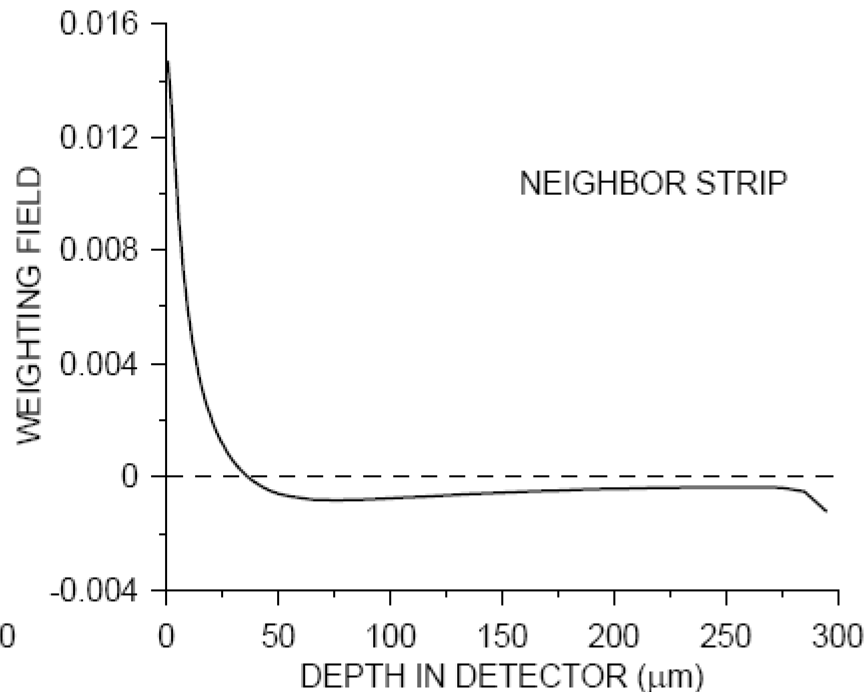
Double-sided silicon strip detector





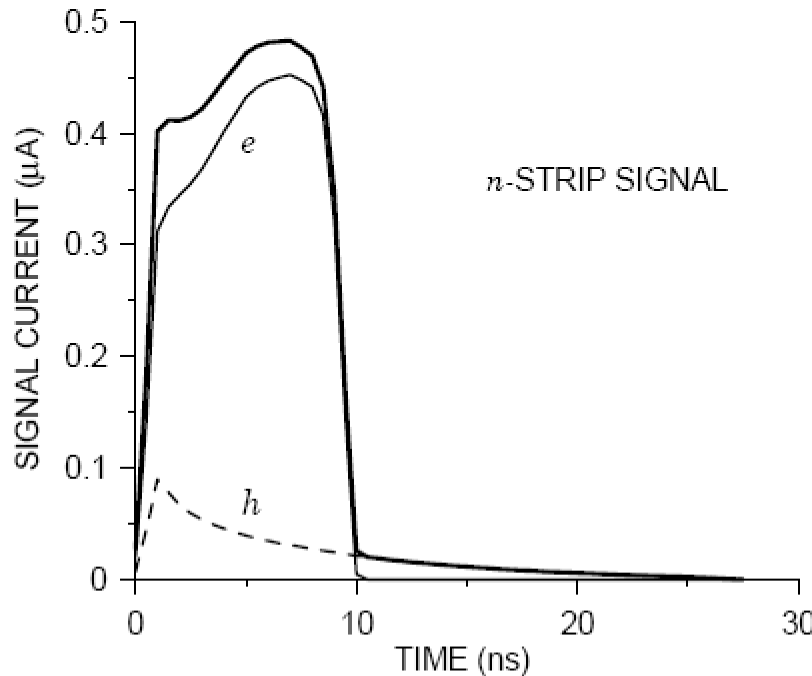
Weighting potential for a 300 µm thick strip detector with strips on a pitch of 50 µm. Only 50 µm of depth are shown.

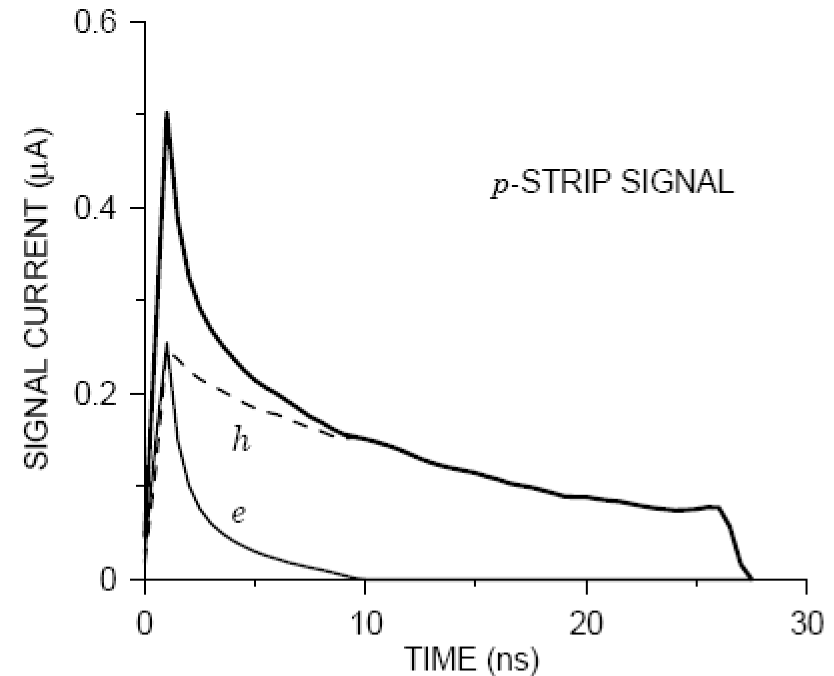




In general, if moving charge does not terminate on the measurement electrode, signal current will be induced, but the current changes sign and integrates to zero.

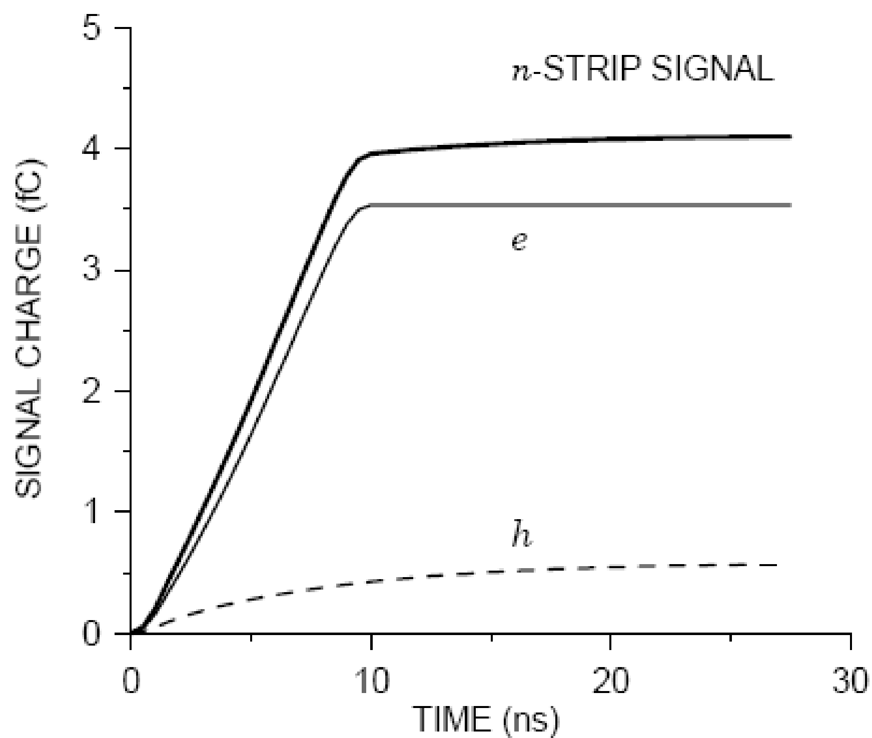
Current pulses in strip detectors (track traversing the detector)

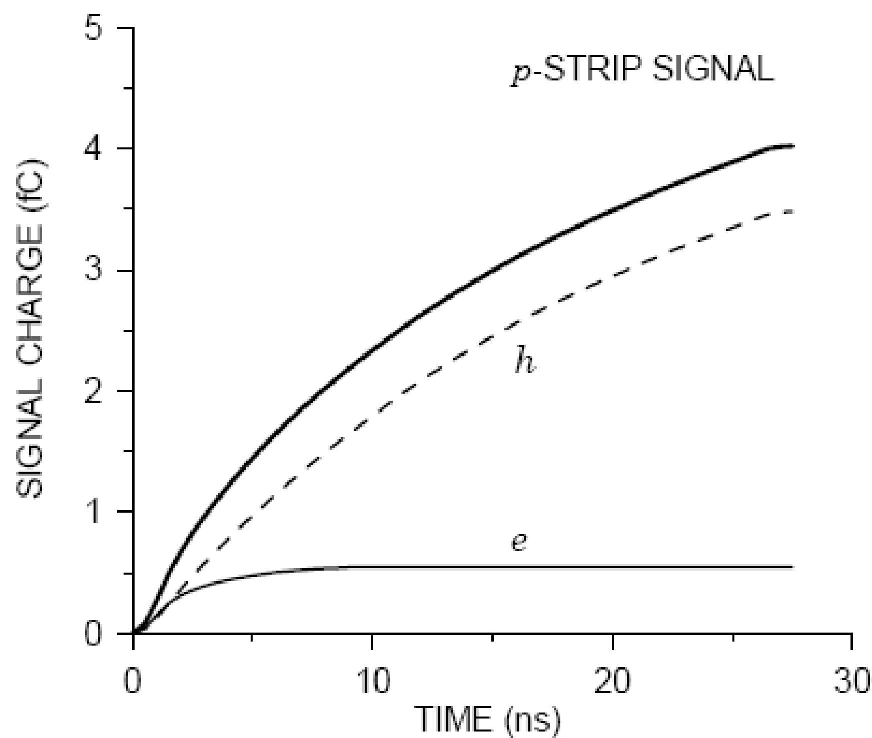




The duration of the electron and hole pulses is determined by the time required to traverse the detector as in a parallel-plate detector, but the shapes are very different.

Strip Detector Signal Charge Pulses





Charge Collection in the Presence of Trapping

Practical semiconductor crystals suffer from imperfections introduced during crystal growth, during device fabrication, or by radiation damage.

Defects in the crystal

- impurity atoms
- vacancies
- structural irregularities (e.g. dislocations)
- radiation damage

introduce states into the crystal that can trap charge.

Charge trapping is characterized by a carrier lifetime, the time a charge carrier can "survive" in a crystal before trapping or recombination with a hole.

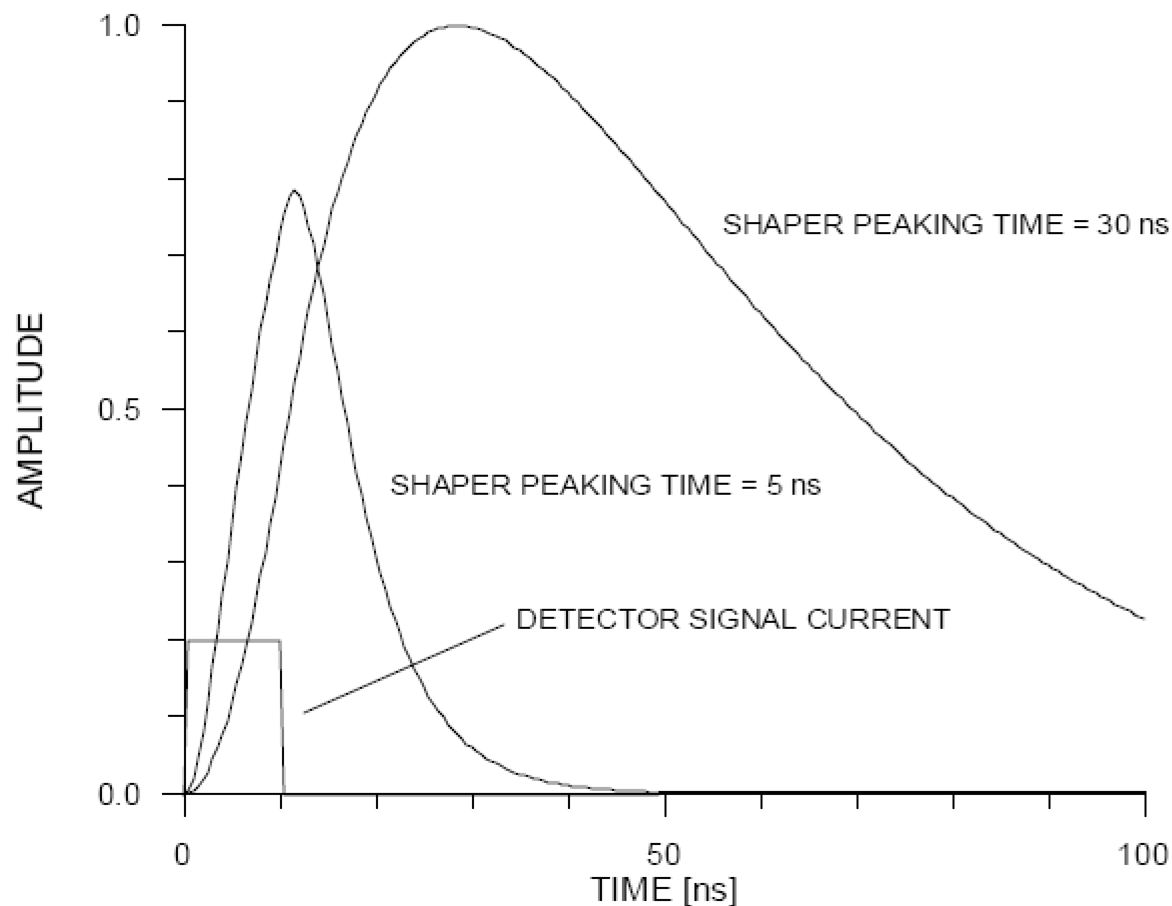
Trapping removes mobile charge available for signal formation.

Depending on the nature of the trap, thermal excitation or the externally applied field can release the carrier from the trap, leading to delayed charge collection.

Ballistic Deficit

Loss in Pulse Height (and Signal-to-Noise Ratio) if

Peaking Time of Shaper < Detector Collection Time



1. Radiation deposits energy in a detecting medium.

The medium may be gas, solid or liquid.

In a tracking detector one wishes to detect the presence of a particle without affecting its trajectory, so the medium will be chosen to minimize energy loss and particle scattering.

Conversely, if one wishes to measure the total energy (energy spectrometry or calorimetry), the absorber will be chosen to optimize energy loss (high density, high *Z*).

2. Energy is converted into an electrical signal, either directly or indirectly. Each detected particle will appear as a pulse of electric charge.

Direct conversion: incident radiation ionizes atoms/molecules in absorber, creating mobile charges that are detected. (ionization chambers)
Indirect conversion: incident radiation excites atomic/molecular states that decay by emission of light, which in a second step is converted into charge. (scintillation detectors)

- **The primary signal charge is proportional to the energy absorbed.**

Some typical values of energy required to form a signal charge of 1 electron:

gases 30 eV
semiconductors 1 to 10 eV
scintillators 20 to 500 Ev

Typical pulse durations: 1 ns – 10 µs

3.The electrical signal is amplified.

a) electronic circuitry

b) gain by secondary multiplication
Primary charge is accelerated to sufficient energy for it to liberate additional charge carriers by impact ionization.
Examples: proportional chambers, avalanche photodiodes, photomultiplier …

Both techniques may introduce significant random fluctuations (electronic noise, avalanche noise).

Ideally, a gain stage would increase only the magnitude of the detector pulse, without affecting its time dependence.

This ideal behavior is never strictly realized in practice, as it would require amplifiers with infinite bandwidth.

4. Pulse shaping

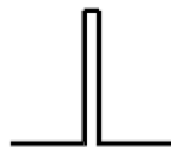
(not always necessary, but always present in some form)

The time response of the system is tailored to optimize the measurement of signal magnitude or time and the rate of signal detection.

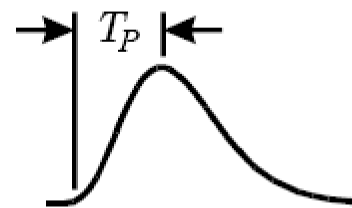
Typically, the pulse shaper transforms a narrow detector current pulse to
- a broader pulse
(to reduce electronic noise),

- with a gradually rounded maximum at the peaking time *TP*
(to facilitate measurement of the amplitude)

SENSOR PULSE



SHAPER OUTPUT



5. Digitization

5.1 Signal Magnitude

analog-to-digital converter

Example: Flash ADC

5.2 Time difference between the detected signal and a reference signal

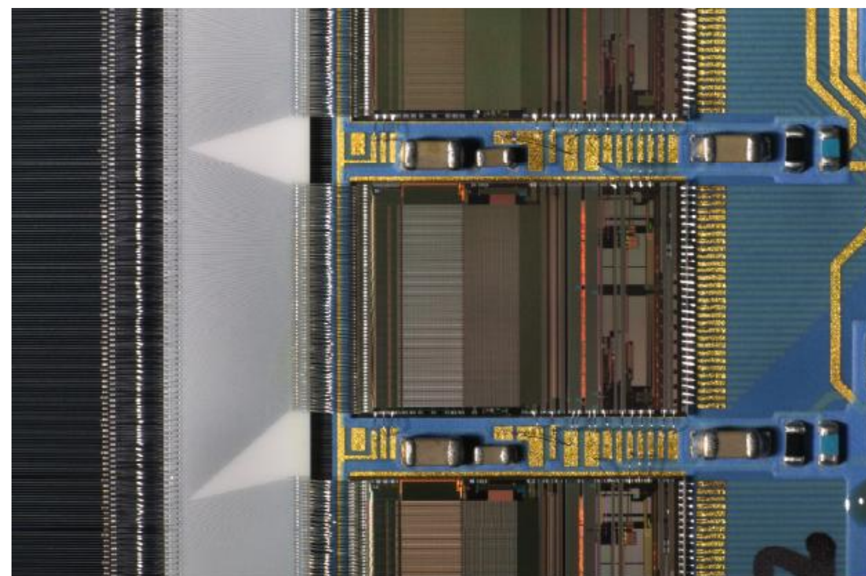
time-to-digital converter, TDC

6. Data Readout

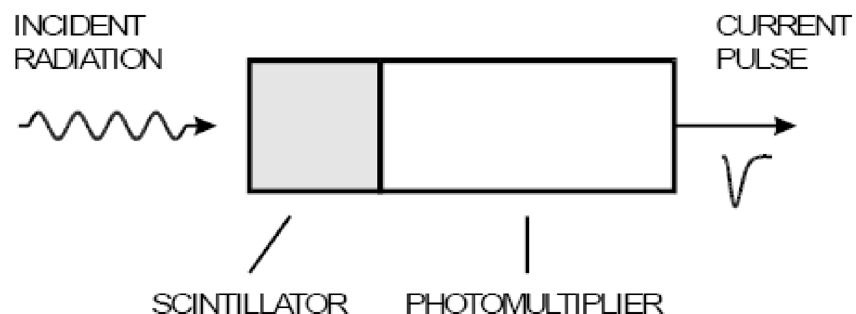
In complex detector systems the individual digitized outputs may require rather complex circuitry to combine the signal associated with a specific event and "package" them for efficient transfer.

Example: Silicon-Strip Detector Module

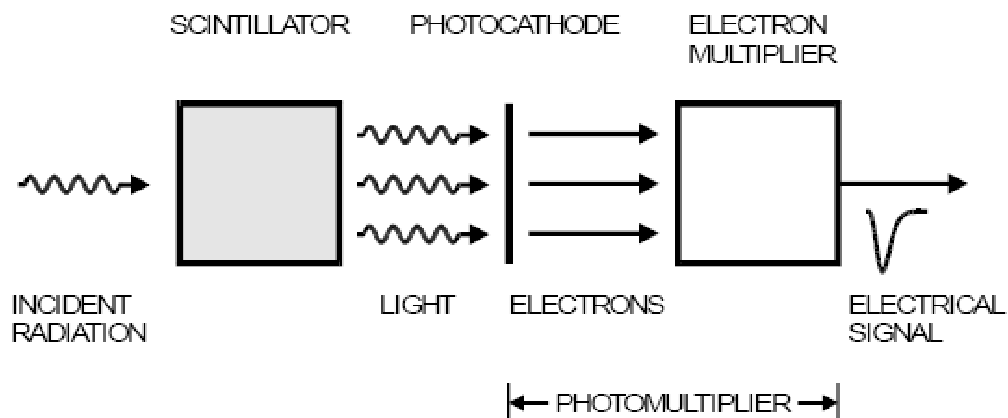
128 channels on 50 µm pitch of low-noise preamplification, pulse shaping, analog-todigital conversion, and zero-suppressed data readout



A Typical Detector System – Scintillation Detector



Processes in Scintillator – Photomultiplier



number of photons ∝ absorbed energy

number of photoelectrons ∝ absorbed energy

charge in pulse ∝ abs. energy

Precision of signal magnitude is limited by fluctuations

Two types of fluctuations

1. Fluctuations in signal charge for a given energy absorption in detector

Signal formed by many elementary excitations

$$\text{Average number of signal quanta} = \frac{\text{absorbed energy}}{\text{excitation energy}} \Rightarrow N = \frac{E}{E_i}$$

Number of signal quanta fluctuates statistically. $\Delta N = \sqrt{FN}$

where F is the Fano factor (0.1 in Si, for example), so the energy resolution

$$\Delta E = E_i \Delta N = \sqrt{FEE_i} \quad \text{r.m.s.}$$

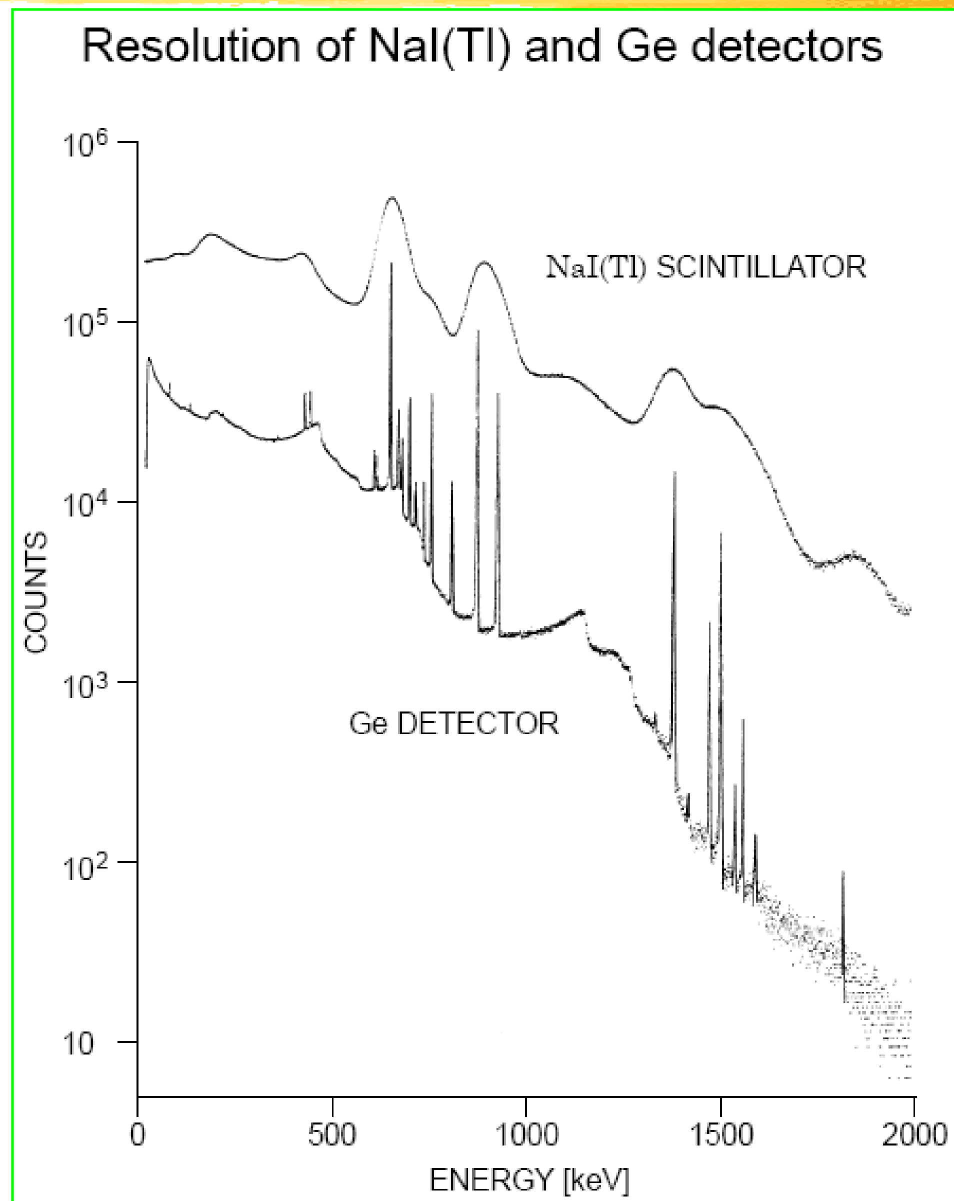
$$\Delta E_{FWHM} = 2.35 \times \Delta E_{rms}$$

2. Baseline fluctuations in the electronics: “electronic noise”

The overall resolution is often the result of several contributions. Individual resolutions add in quadrature, for example

$$\Delta E = \sqrt{\Delta E_{fluc}^2 + \Delta E_{elec}^2}$$

If one contribution is 20% of the other, the overall resolution is increased by 10%.



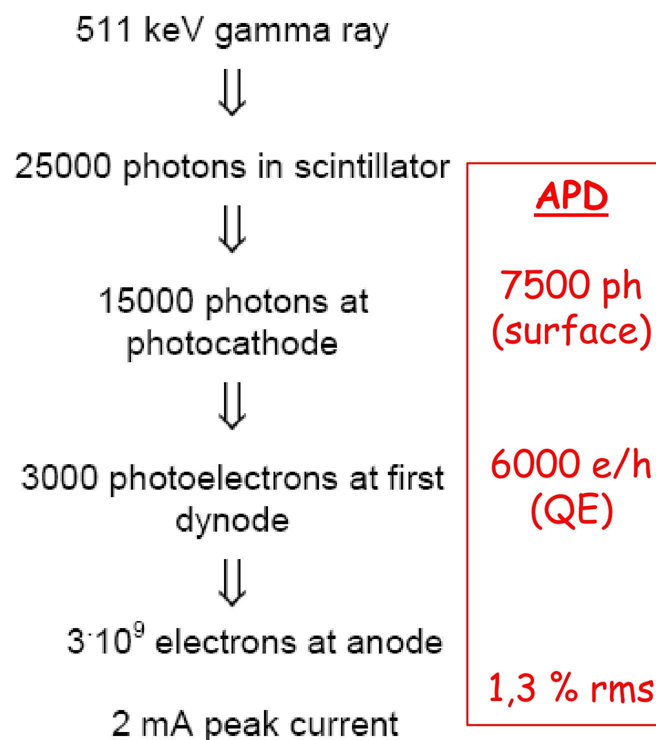
NaI(Tl) scintillation detector:
signal fluctuations

Ge detector:
predominantly electronic noise

Signal Fluctuations in a Scintillation Detector

Example:

a typical NaI(Tl) system (from Derenzo)



Resolution of energy measurement determined by statistical variance of produced signal quanta.

$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

Resolution determined by smallest number of quanta in chain, i.e. number of photoelectrons arriving at first dynode.

$$\frac{\Delta E}{E} = \frac{1}{\sqrt{3000}} = 2\% \text{ r.m.s.} = 5\% \text{ FWHM}$$

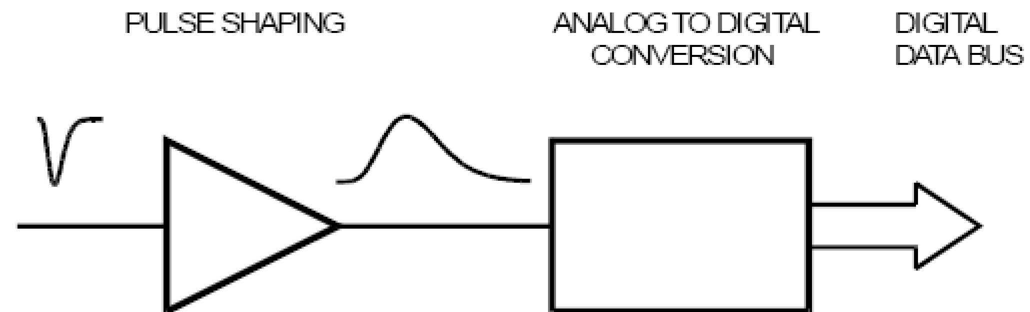
In this example

Typically 7 – 8% obtained, due to non-uniformity of light collection and gain.

Signal Processing

charge in pulse
∝ abs. energy

pulse height
∝ absorbed energy



Purpose of pulse processing and analysis systems

1. Acquire electrical signal from detector

   typically a short current pulse

2. Tailor the time response (i.e. "shape" the output pulse) of the system to optimize

   - minimum detectable signal (detect hit/no hit)
   - energy measurement (magnitude of signal)
   - event rate
   - time of arrival (timing measurement)
   - insensitivity to detector pulse shape
   - some combination of the above

   Generally, these cannot be optimized simultaneously

   ⇒ compromises

   Position-sensitive detectors use presence of hit, amplitude measurement or timing.

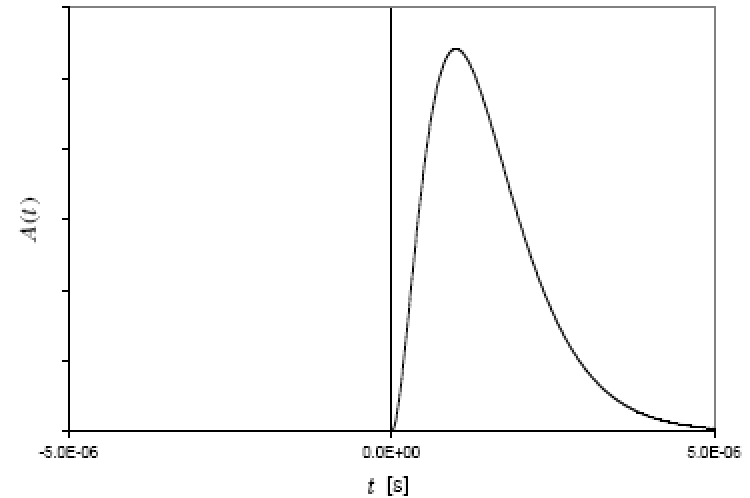
   ⇒ same problem

3. digitize the signal and store for subsequent analysis

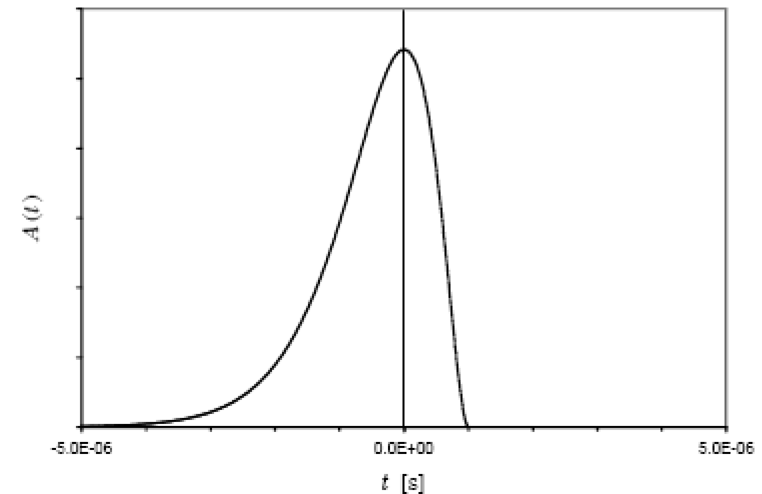
Tailor frequency response of measurement system to optimize signal-to-noise ratio.
Frequency response of measurement system affects both
- signal amplitude and
- noise.

There is a general solution to this problem:
Apply a filter to make the noise spectrum white (constant over frequency).
Then the optimum filter has an impulse response that is the signal pulse *mirrored in time and shifted by the measurement time.*

For example, if the signal pulse shape is:



The response of the optimum filter:



This is an "acausal" filter, i.e. it must act before the signal appears.

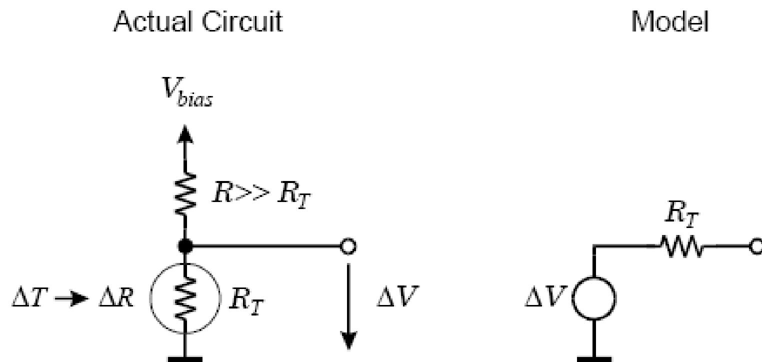
- Only useful if the time of arrival is known in advance.
- Not good for random events
- Need time delay buffer memory

complexity!

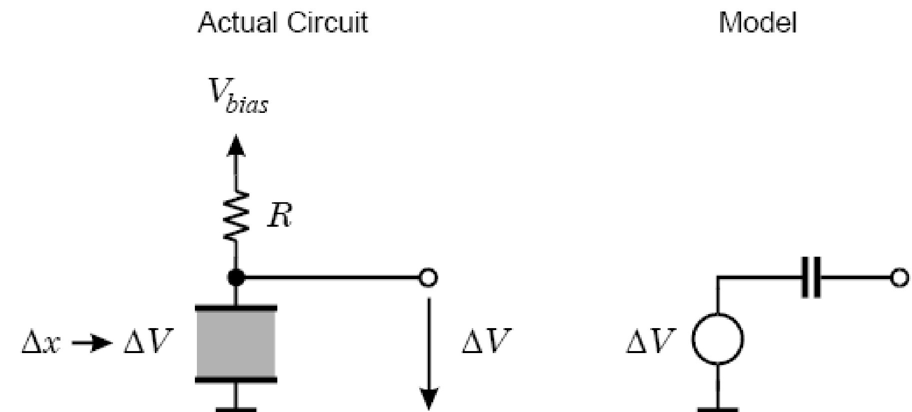
Detector Models

Although detectors take on many different forms, one can analyze the coupling to the amplifier with simple models.

Thermistor detecting IR radiation

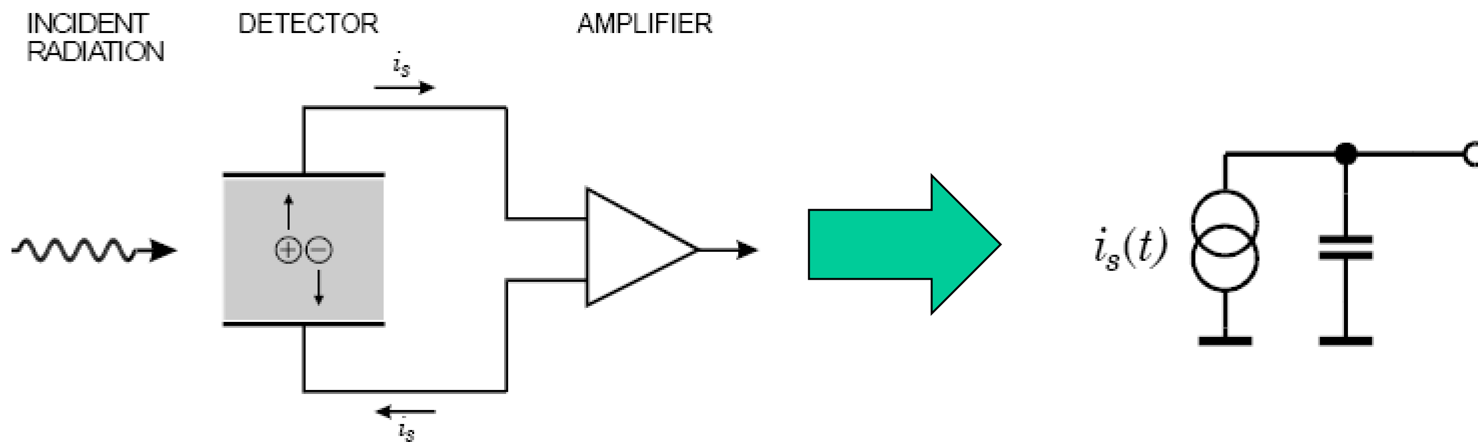


Piezoelectric Transducer

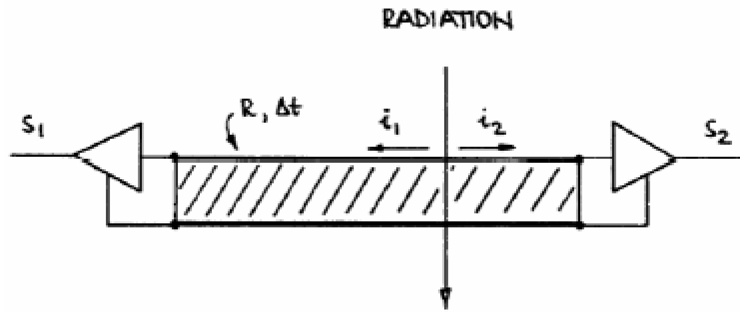


Ionization Chamber

semiconductor detectors (pad, strip, pixel electrodes)
gas-filled ionization or proportional chambers, ...

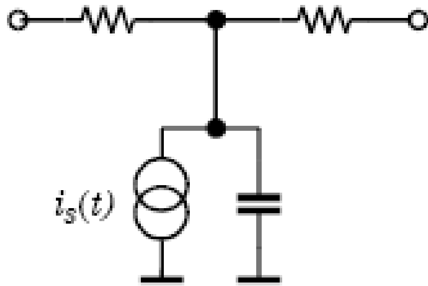


Position-Sensitive Detector with Resistive Charge Division

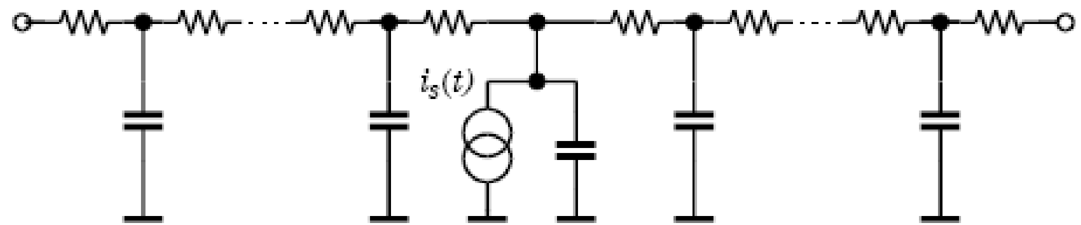


$$\frac{i_1(x)}{i_2(x)} = \frac{R_2(x)}{R_1(x)}$$

Simplest Model



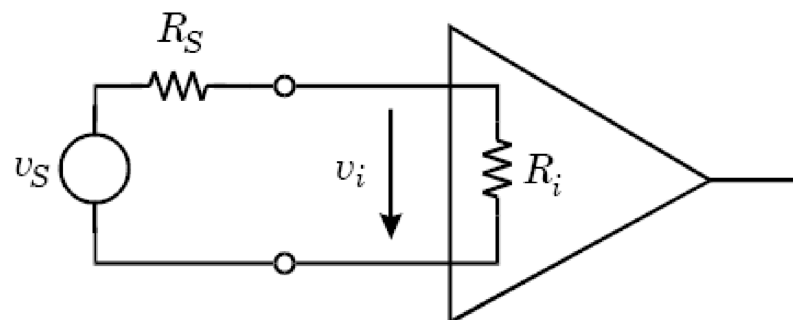
A more accurate model of the electrode includes the distributed capacitance



4. Signal Acquisition

Amplifier Types

a) Voltage-Sensitive Amplifier



The signal voltage at the amplifier input

$$v_i = \frac{R_i}{R_S + R_i} v_S$$

If the signal voltage at the amplifier input is to be approximately equal to the signal voltage

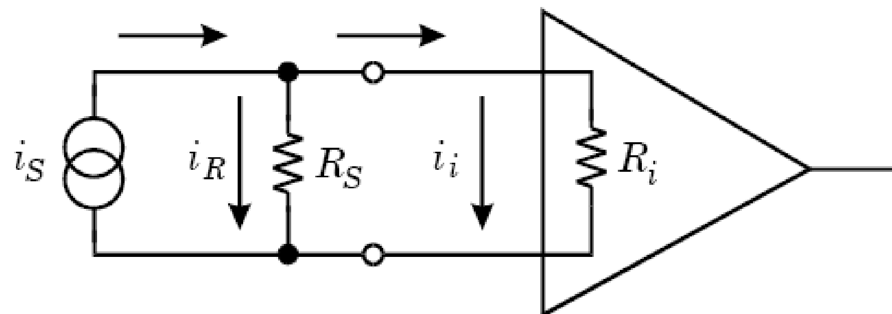
$$v_i \approx v_S \quad \Rightarrow \quad R_i \gg R_S$$

To operate in the voltage-sensitive mode, the amplifier's input resistance (or impedance) must be large compared to the source resistance (impedance).

In ideal voltage amplifiers one sets $R_i = \infty$, although this is never true in reality, although it can be fulfilled to a good approximation.

To provide a voltage output, the amplifier should have a low output resistance, i.e. its output resistance should be small compared to the input resistance of the following stage.

b) Current-Sensitive Amplifier



The signal current divides into the source resistance and the amplifier's input resistance. The fraction of current flowing into the amplifier

$$i_i = \frac{R_s}{R_s + R_i} i_S$$

If the current flowing into the amplifier is to be approximately equal to the signal current

$$i_i \approx i_S \qquad \Rightarrow \qquad R_i \ll R_S$$

To operate in the current-sensitive mode, the amplifier's input resistance (or impedance) must be small compared to the source resistance (impedance).

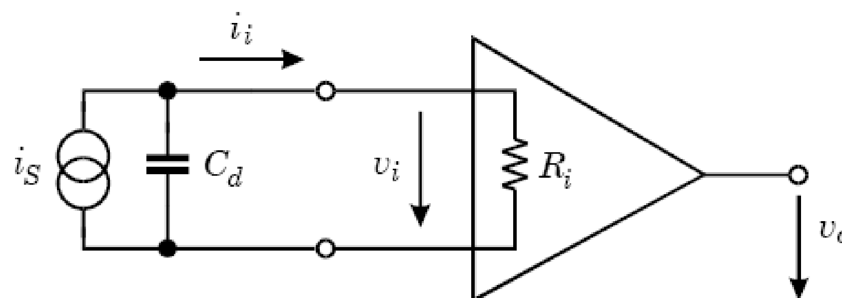
One can also model a current source as a voltage source with a series resistance. For the signal current to be unaffected by the amplifier input resistance, the input resistance must be small compared to the source resistance, as derived above.

At the output, to provide current drive the output resistance should be high, i.e. large compared to the input resistance of the next stage.

c) Voltage and Current Mode with Capacitive Sources

Output voltage:

v_o = (voltage gain A_v) × (input voltage v_i).



Operating mode depends on charge collection time t_c and the input time constant R_iC_d :

a) $R_iC_d \ll t_c$	b) $R_iC_d \gg t_c$
detector capacitance discharges rapidly	detector capacitance discharges slowly
$\Rightarrow \quad v_o \propto i_s(t)$	$\Rightarrow \quad v_o \propto \int i_s(t)dt$
current sensitive amplifier	voltage sensitive amplifier

Note that in both cases the amplifier is providing voltage gain, so output signal voltage is determined directly by the input voltage. The difference is that the shape of the input voltage pulse is determined either by the instantaneous current or by the integrated current and the decay time constant.

Goal is to measure signal charge, so it is desirable to use a system whose response is independent of detector capacitance.

Active Integrator ("charge-sensitive amplifier")

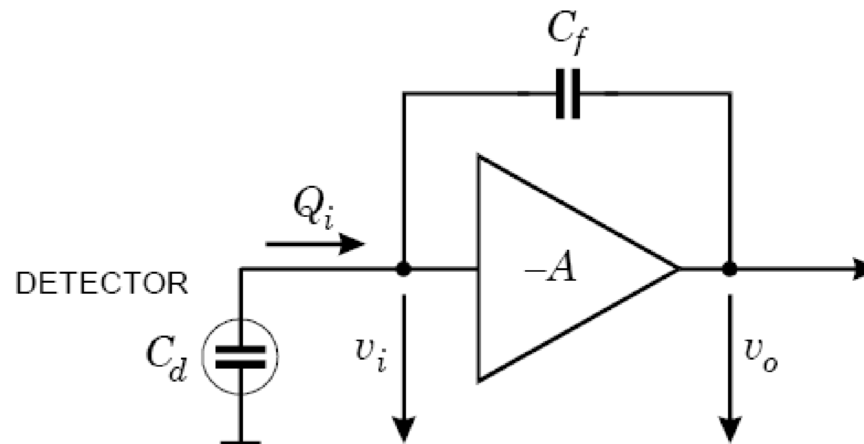
Start with inverting voltage amplifier

Voltage gain $dv_o / dv_i = -A \quad \Rightarrow$

$v_o = -A v_i$

Input impedance = ∞ (i.e. no signal current flows into amplifier input)

Connect feedback capacitor C_f between output and input.



Voltage difference across C_f: $\quad v_f = (A+1) v_i$

$\Rightarrow$ Charge deposited on C_f: $\quad Q_f = C_f v_f = C_f (A+1) v_i$

$Q_i = Q_f \quad$ (since $Z_i = \infty$)

$\Rightarrow$ Effective input capacitance $\quad C_i = \dfrac{Q_i}{v_i} = C_f (A+1)$ ("dynamic" input capacitance)

Gain
$$A_Q = \frac{dV_o}{dQ_i} = \frac{A \cdot v_i}{C_i \cdot v_i} = \frac{A}{C_i} = \frac{A}{A+1} \cdot \frac{1}{C_f} \approx \frac{1}{C_f} \quad (A >> 1)$$

Dependent on a well-controlled quantity, the feedback capacitance.

Détecteurs Semi-conducteur : Performances

- Ionisation du matériau: Silicium, Germanium, GaAs…
- Collection par un champ électrique:
  Drift, électrodes (CCDs),
  Jonction PN polarisée en inverse.

Sensibilité — MIP: 8000e- / 100 μm

Résolution en énergie —
5-100eV @ 6 keV
50 keV @ 5.5 MeV
2 keV @ 1 MeV

Résolution spatiale —
~1.5 μm (MAPS pixels 10 μm)
à 15 μm (Hybrides pixels 125 μm)

Transparence — 0.1% X_0 / 100 μm

Tenue aux radiations — O(100) kRad (CCD) - 50 Mrad (Hybrides)

Géométrie

- "Bulk" Spectroscopie nucléaire
  Résolution en énergie, trajectographie
  Identification, charge

- Planaire

  - Strips Localisation, Trajectographie

  - Pads Calorimétrie électromagnétique

  - Pixels Vertex, Astronomie, Imagerie médicale

Strips de Silicium

Détecteur: Silicium de haute résistivité O(kΩ/cm)

Électronique: Silicium Sub-micronique profond

Intégration sur détecteur

Résolution: *~O(10)μm (pitch > 100 μm)*

Lecture: *shaping long O(μs) -> charge*

shaping court O(20 ns) -> time

Transparence: *0.1 X_0 / 100 μm*

Alice, CMS, MUST2

Détecteurs à Pixels

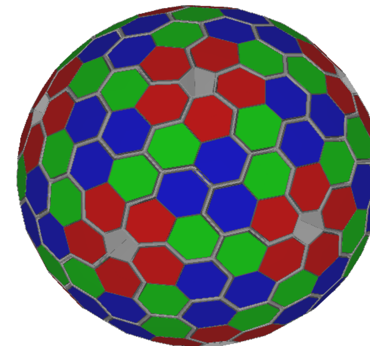
- CCD Transfert de Charge
- HPS Pixels "Hybrides"
- MAPS Pixels "Monolithiques"

Applications: Détecteurs de Vertex
Télescopes
Bolomètres
Imagerie médicale

Détecteurs pour la Spectroscopie

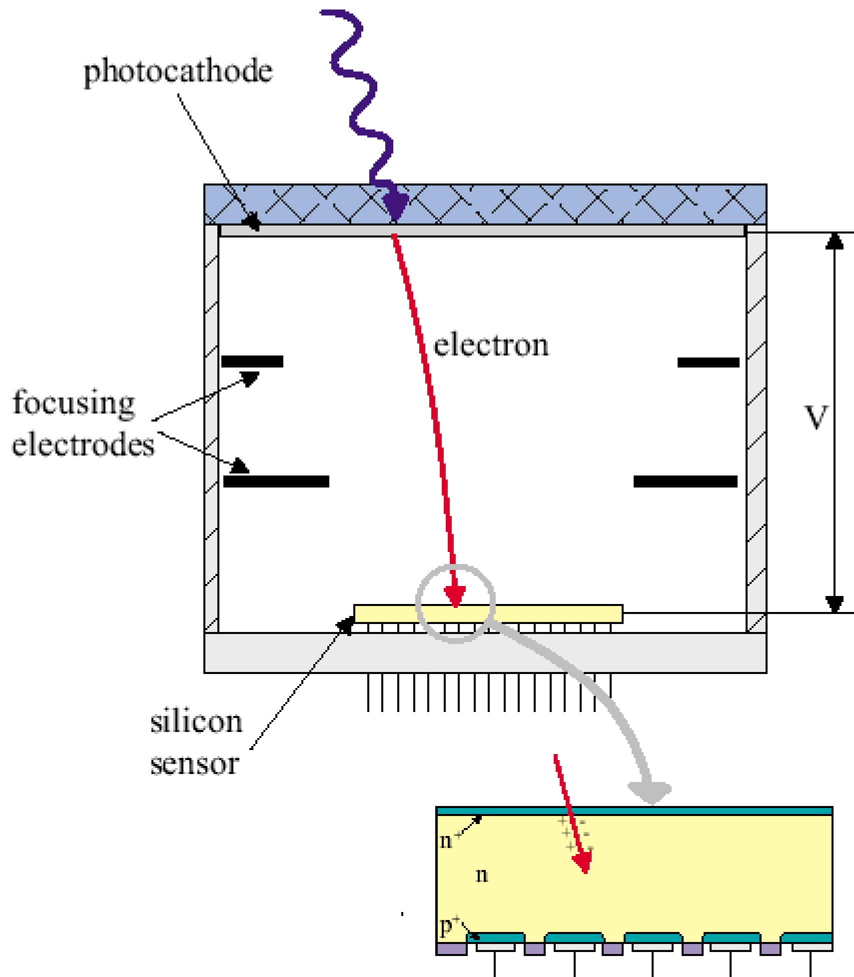
- Germanium
- CdTe, CdZnTe
- Silicium

Spectroscopie γ : Agata



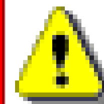
Excellente résolution spectrale:
1.2 keV @ 100 keV
2 keV @ 1 MeV
*Pixels de 2cm * 2cm*

HPD (Hybrid PhotoDetector)



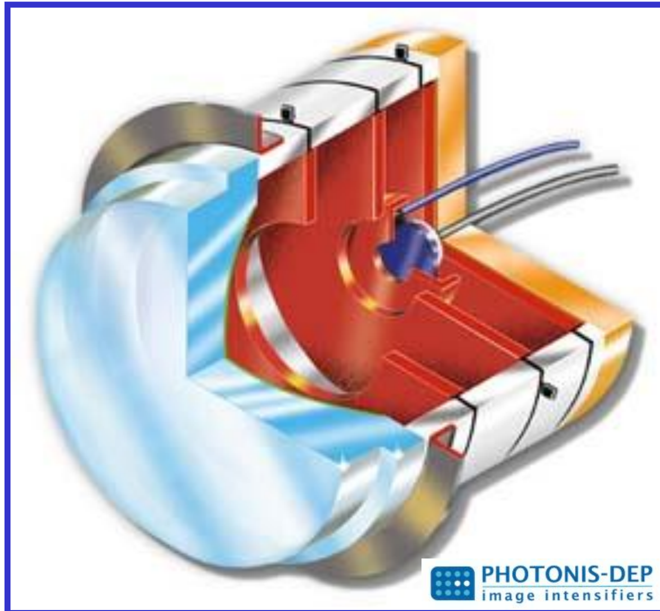
Interest : Additive noise
whereas for the PM it is multiplicative noise.

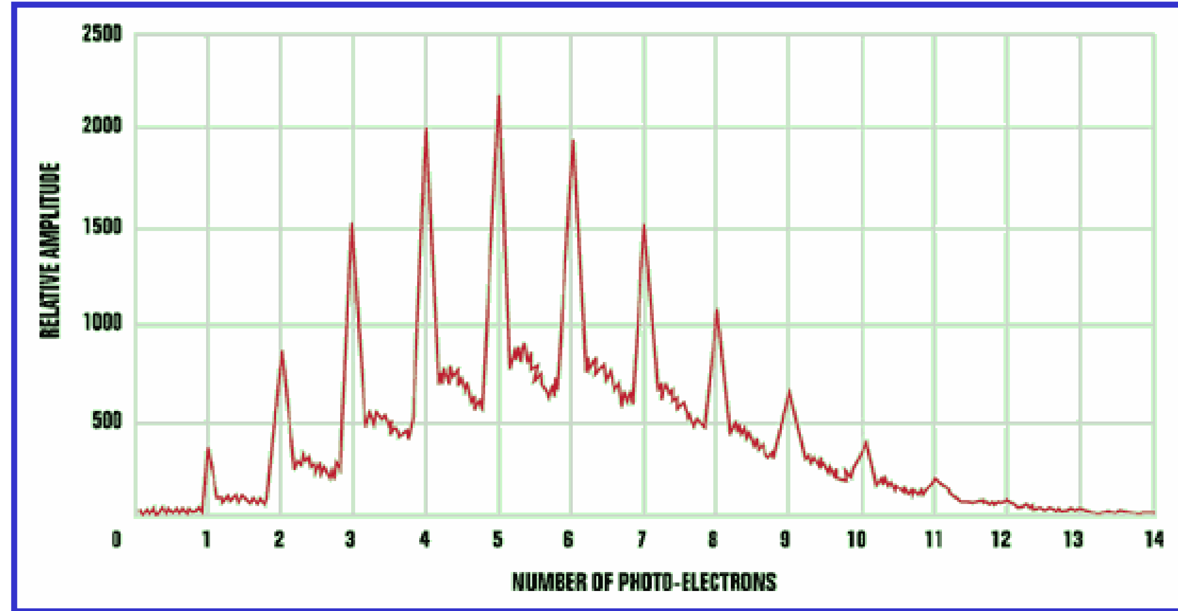
$$\delta_1 > 1000 \Rightarrow ENF = 1$$



Pairs production by **ionization**
(3,6 eV / e^--h pair in silicon)

HPD (Hybrid PhotoDetector)



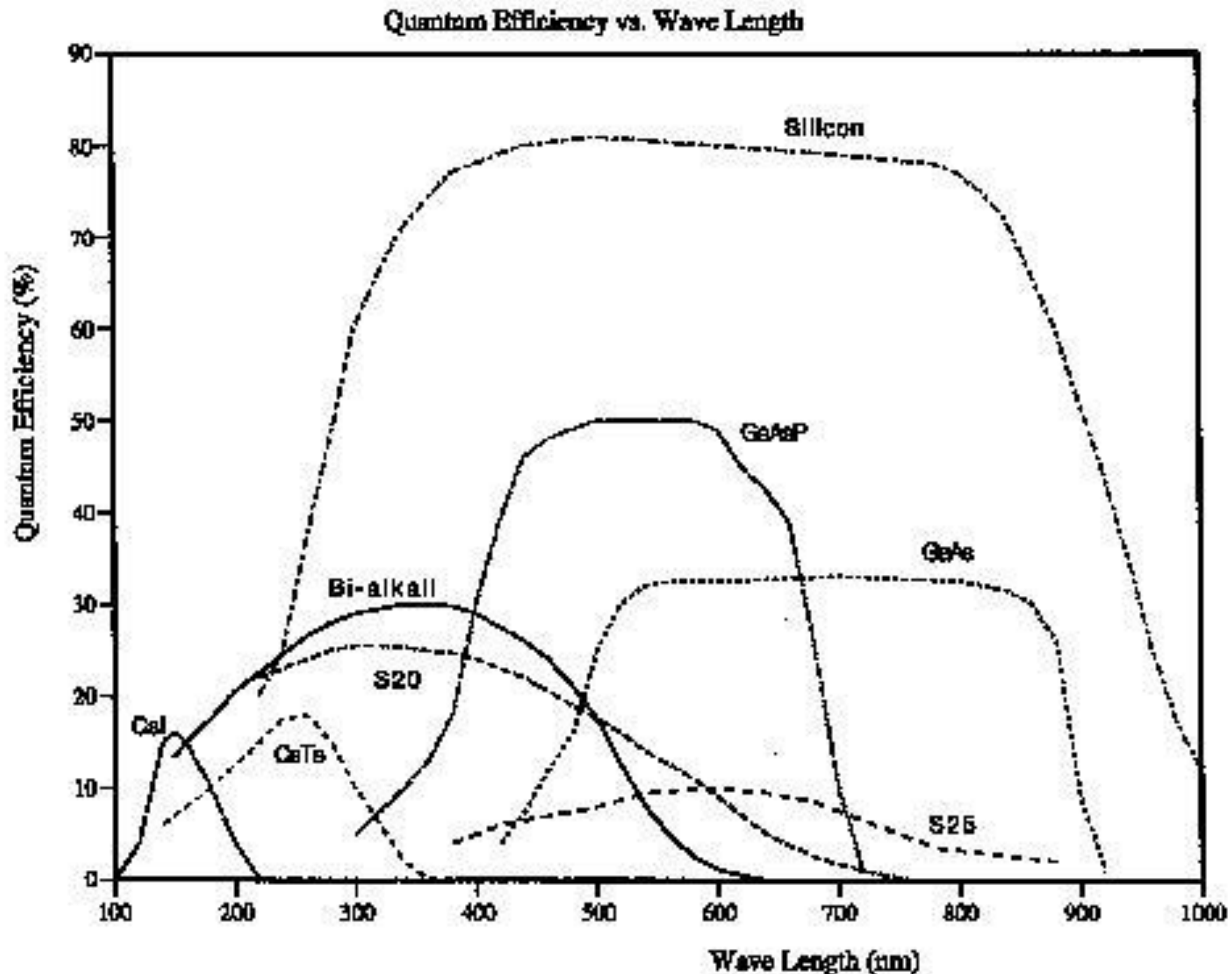


Excellent photon resolution → Single photo-electron → Absolute calibration of the gain
(Not a calibration for QE and CE)

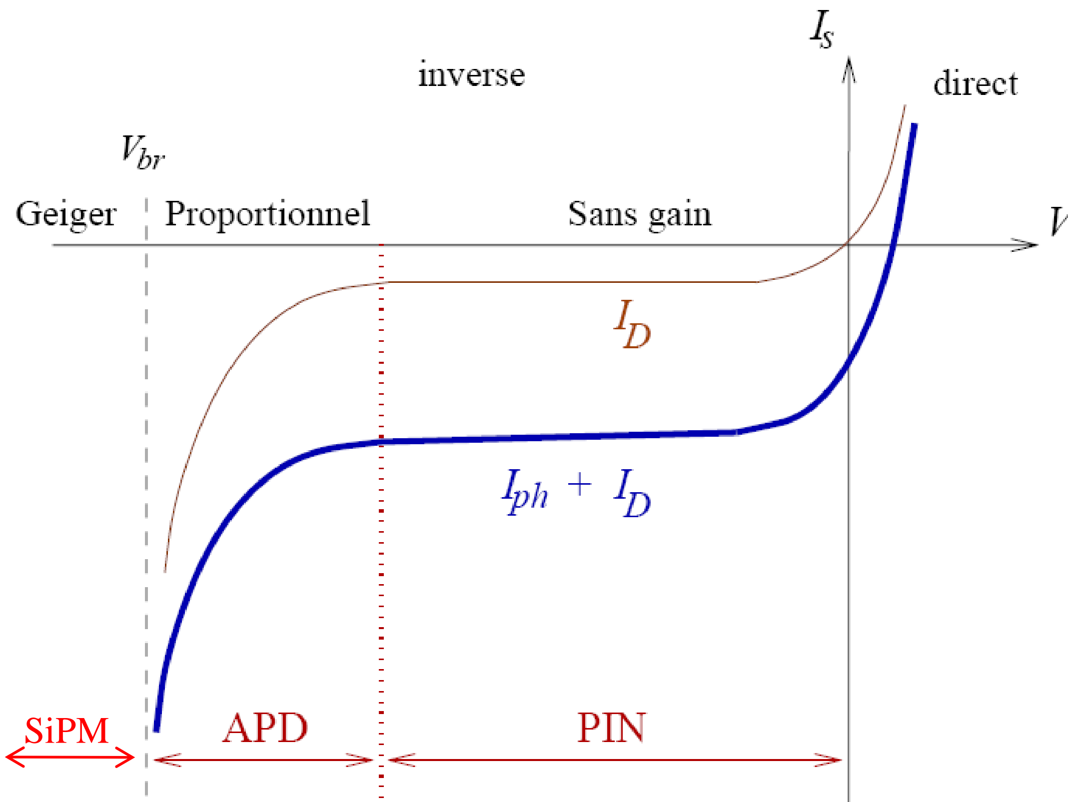
Low gain : 3500 @ 15 kV → needs low noise electronics

From Joël Pouthas (IPN Orsay)

Higher Quantum Efficiency with solid state devices



Ref : K. Arisaka

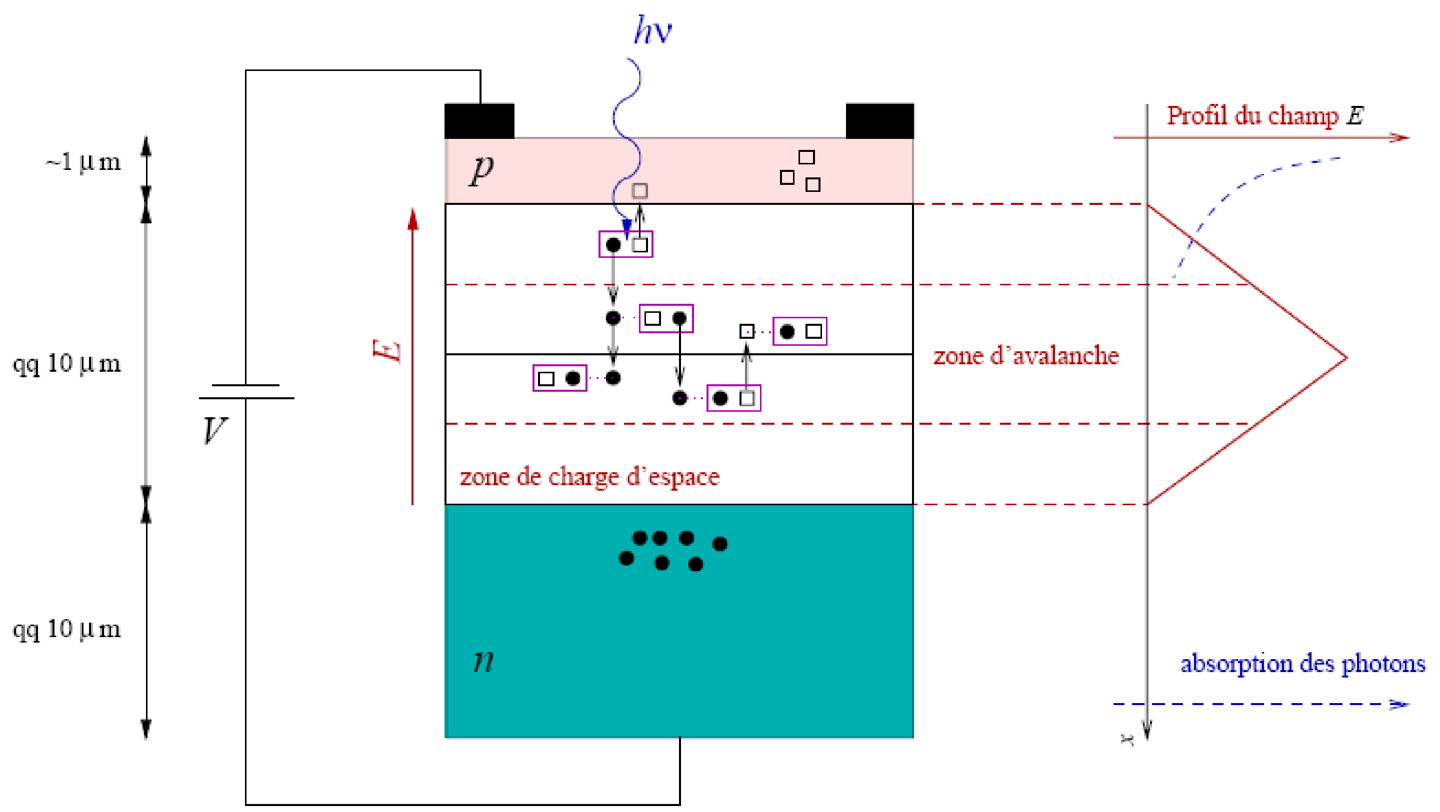


❑ Régime d'amplification proportionnelle au nombre de porteurs de charge primaire lorsque :

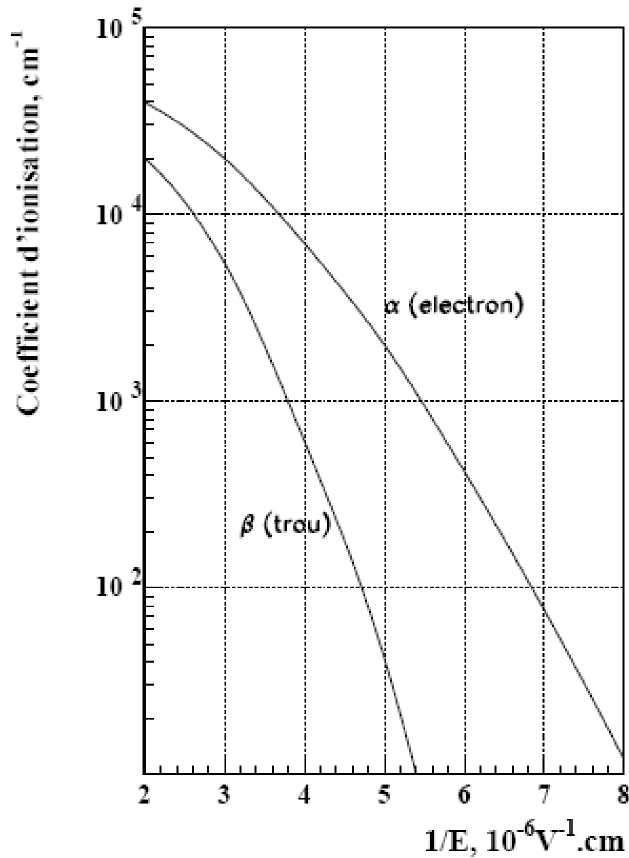
$$|\vec{\varepsilon}| > 10^5 V.cm^{-1}$$

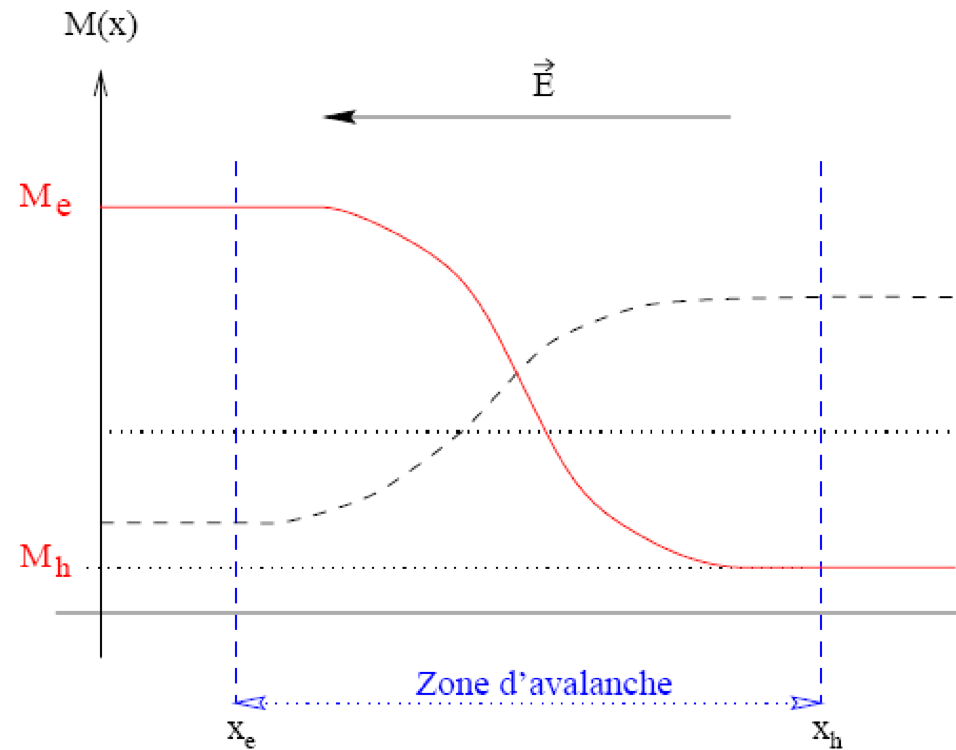
Processus d'ionisation par impact

❑ Pour une tension > Vbr l'amplification n'est plus proportionnelle
➔ fonctionnement en mode Geiger

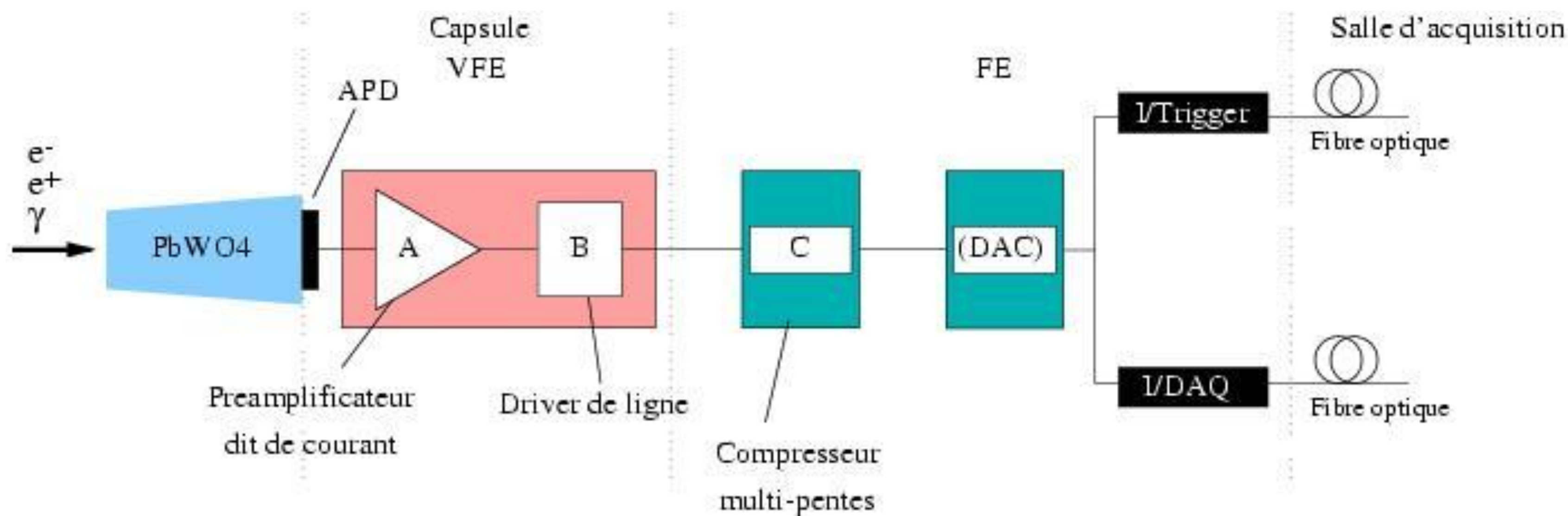

hν
~1 µm
qq 10 µm
qq 10 µm
V
p
E
zone d'avalanche
zone de charge d'espace
n
Profil du champ E
absorption des photons
x

On appelle coefficient d'ionisation l'inverse de la distance moyenne que doit parcourir un porteur pour réaliser une ionisation par impact.

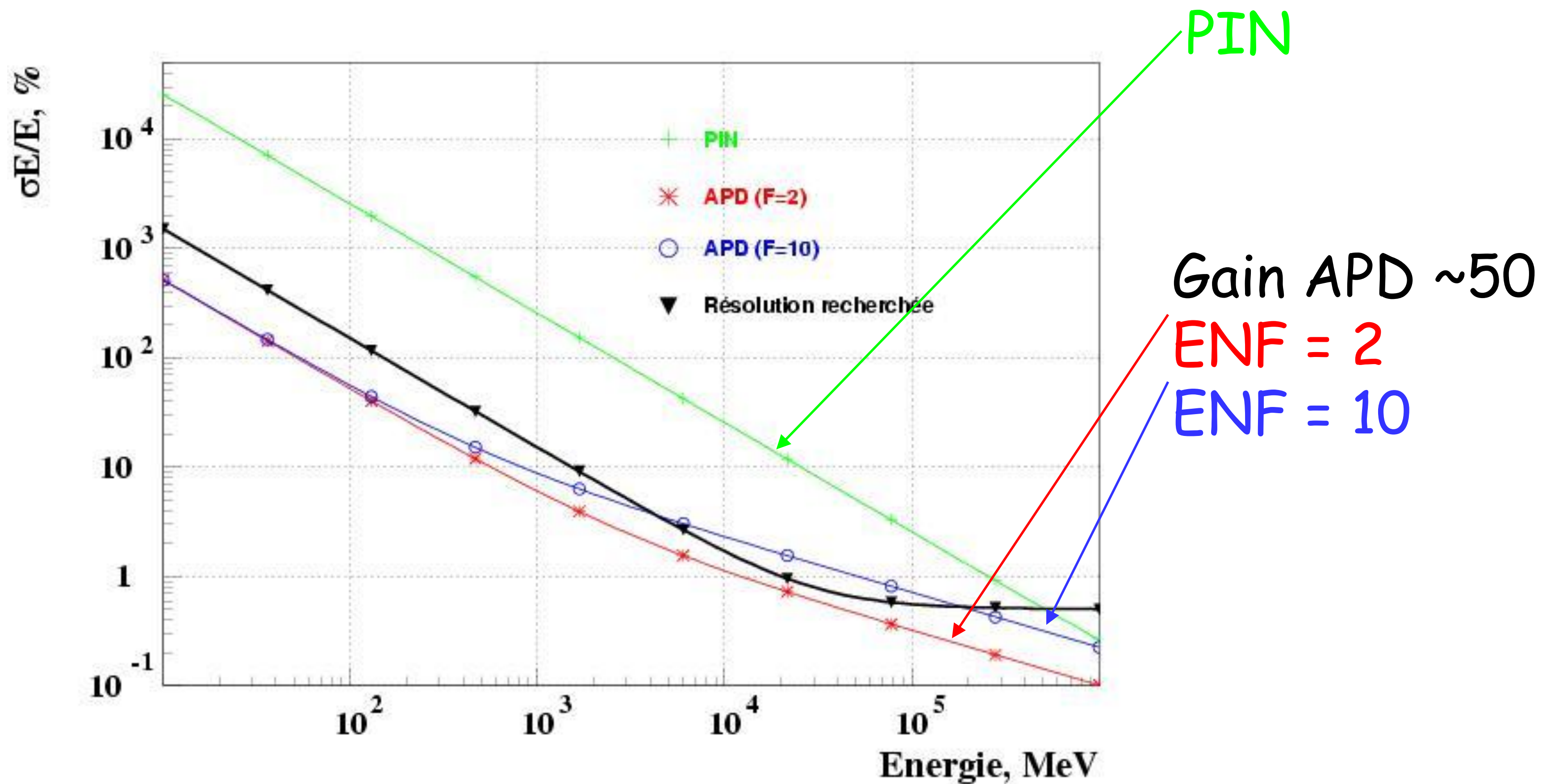




Calorimètre électromagnétique : expérience CMS



Calorimètre électromagnétique : résolution



Signaux et modélisation des détecteurs à Semi-conducteur

Bruit Schottky d'une photodiode PIN :

$$\langle i_s^2 \rangle = 2q(I_{ph} + I_D)$$

Bruit d'une photodiode à avalanche :

$$\langle i_s^2 \rangle = 2q\{I_{DS} + (I_{ph} + I_{DV})M^2 F\}$$

Facteur de bruit en excès (*excess noise*):

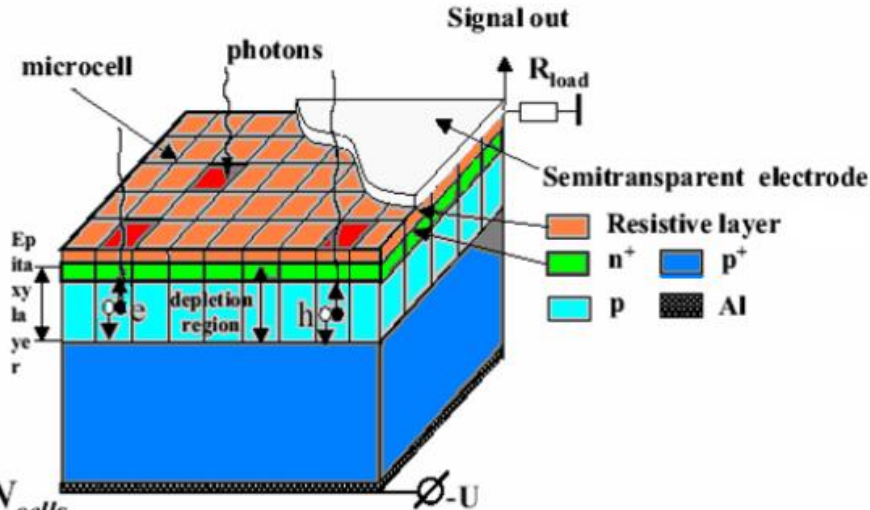
$$F = 1 + \frac{\sigma^2}{M^2}$$

$\Rightarrow$ F caractérise les fluctuations du gain (Pour un PM $F \sim 1.2$)

$\Rightarrow$ $F \equiv$ qualité de l'APD en tant qu'amplificateur ($F \simeq 2$)

Solid State Photomultipliers

Microcells are identical and independent.



$$Q_{tot} = \sum_{i=1}^{N_{fired}} G_i$$

$$\text{Dynamic range} < N_{cells}$$

Picture from talk of E. Grigoriev at Como 2001

- *Geiger avalanche is quenched by an individual pixel resistor (from 100kΩ to several MΩ)*
- *It contains 100÷20 000 pixels/mm2, made on common substrate and connected together*
- *Each pixel works as a binary device*
- *G-APD is pixellated silicon avalanche photodiode operated in Geiger mode (~10-20% over breakdown voltage)*
- *For small light pulses ($N\gamma \ll N_{pixels}$) device as a whole works as an analog detector*

SiPM

Each pixel works as a digital device 1,2,3... photons produce the same signal $Q_1=C_{pixel}*(V-V_b)$ (or Single Pixel Charge).

Multi-pixel structure works as a linear device, as long as $N_{pe}=N\gamma*QE<<N_0$, where N_0 is a total number of pixels/device

Measured charge :

$$Q_{output}=N_{pe}*Gain$$

It was found by many groups that : Gain ≠ Q1 ,
More than 1 pixel is fired by one primary photoelectron!

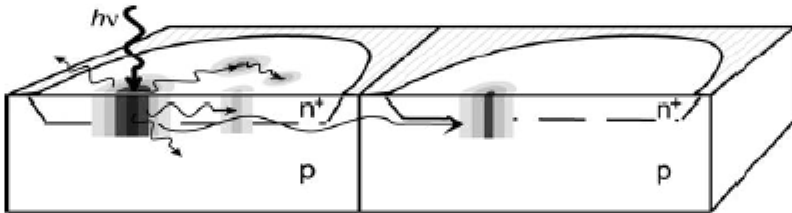
$$Gain=Q1*n_p$$

where n_p is average number of pixels fired by one primary photoelectron.

There are 2 reasons for this discrepancy:

- optical cross-talk between pixels
- after-pulsing (one pixel can be fired more than 1 time during light flash)

Optical cross-talk

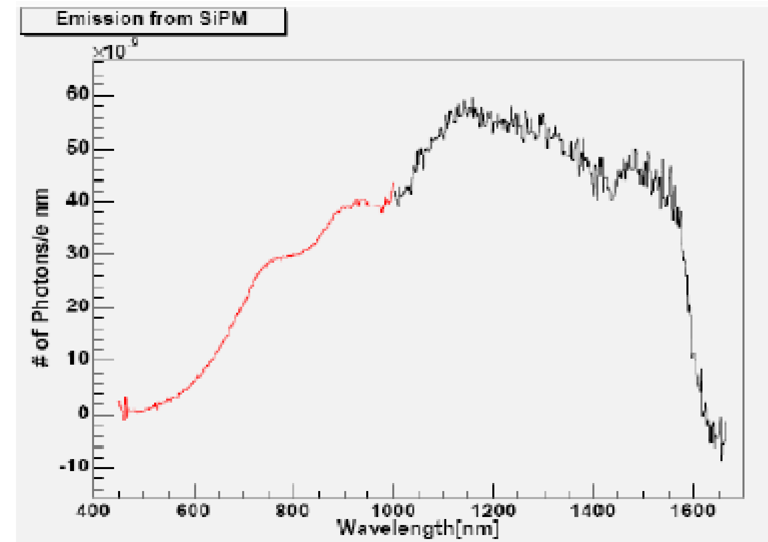


A. Lacaita et al, IEEE TED (1993)

Hot-carrier luminescence:
10^5 carriers produces ~3 photons with an wavelength less than 1 μm

Increases with the gain !

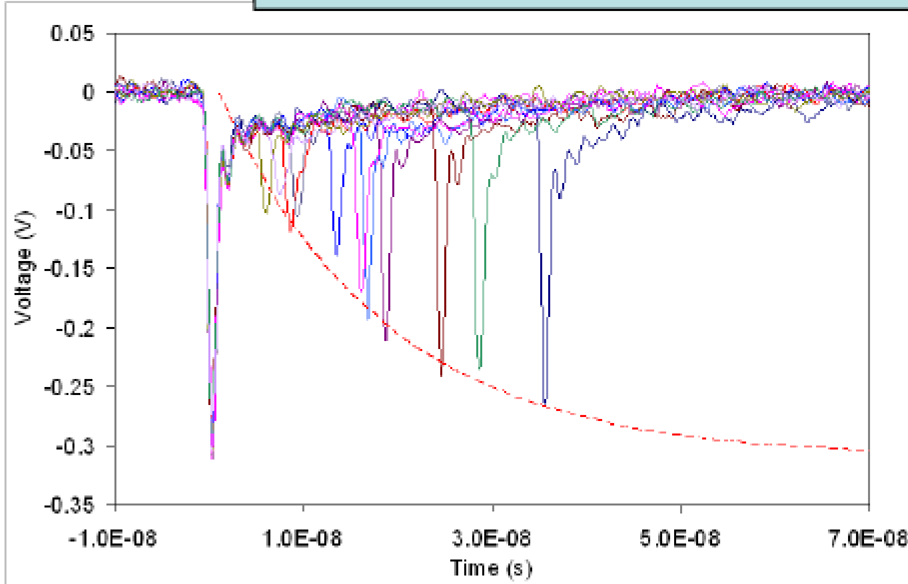
Optical cross-talk causes adjacent pixels to be fired → increases gain fluctuations → increases noise and excess noise factor !

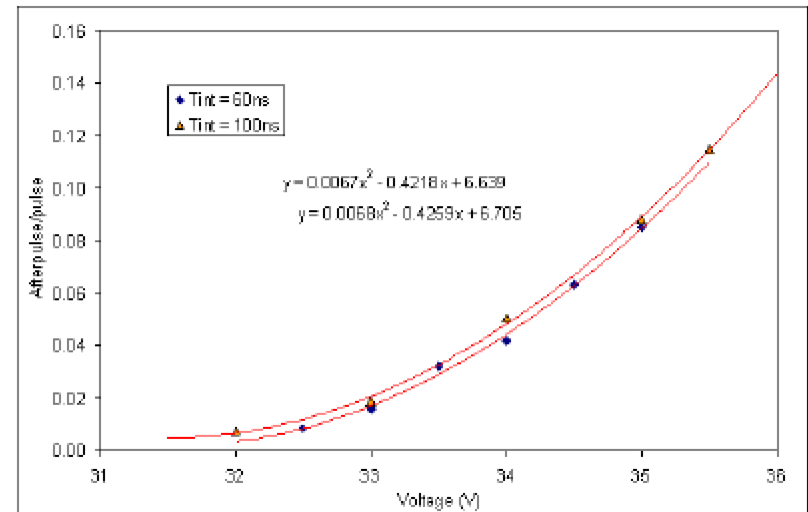


(R. Mirzoyan, NDIP08, Aix-les-Bains)

After-pulsing

C. Piemonte: June 13th, 2007, Perugia



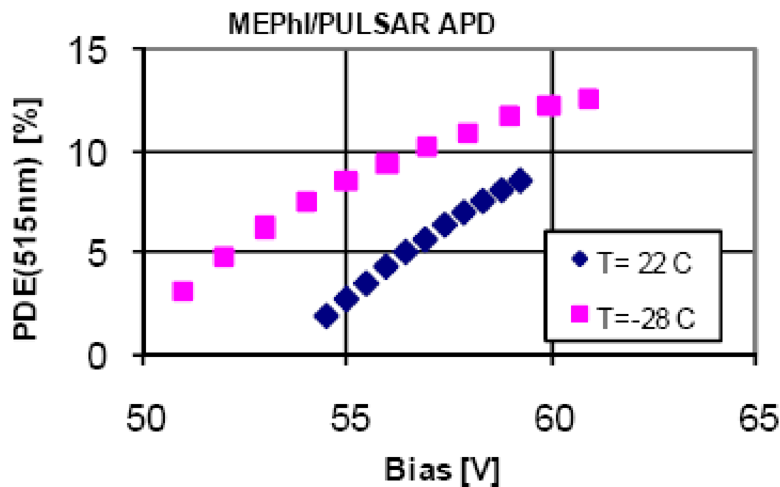


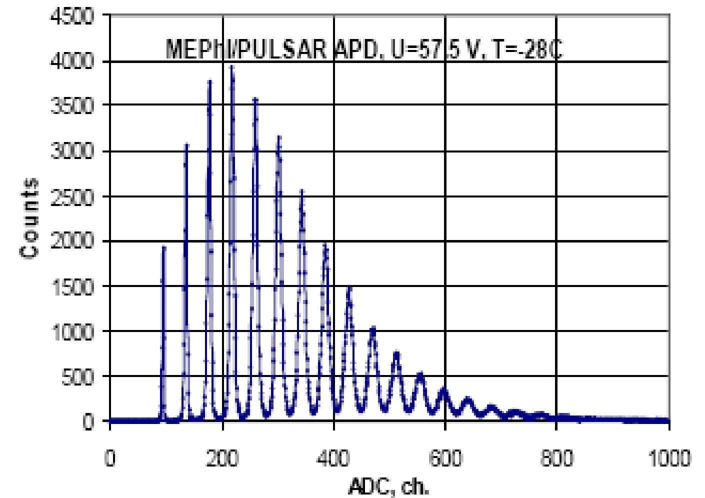
Events with after-pulse measured on a single micropixel.

After-pulse probability *vs* bias

Solution: “cleaner” technology or longer pixel recovery time

Photon detection efficiency





Photon detection efficiency (PDE) is the probability to detect single photon when threshold is < Q1 . It depends on the pixel active area quantum efficiency (QE), geometric factor and probability of primary photoelectron to trigger the pixel breakdown P_b (depends on the $V-V_b$!!, V_b – is a breakdown voltage) .

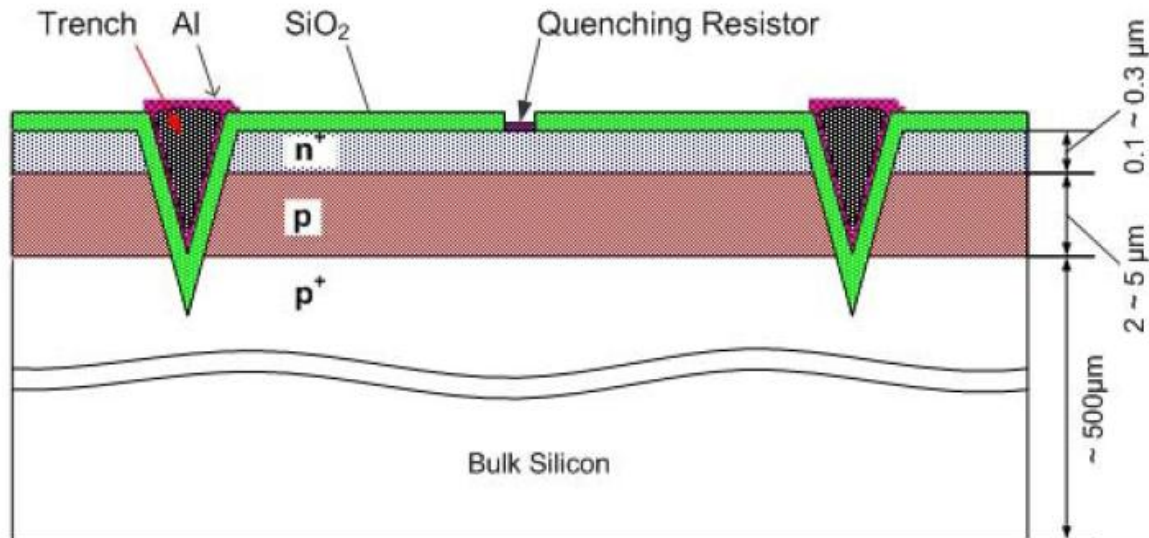
$$PDE(\lambda, U,T) = QE(\lambda)*G_f*P_b(\lambda,U,T)$$

Signaux et modélisation des détecteurs à

SiPM

Silicon PM are very promising and still have a great potential of improvement

Solution: optically separate cells with trenches



(D. McNally, G-APD workshop, GSI, Feb. 2009)

To reduce optical cross-talk CPTA /Photonique was the first to introduce trenches separating neighbouring pixels

Developers and producers

Since 1989 many MG APD structures were developed by different developers:

- CPTA/Photonique(Moscow/Geneva)
- Zecotek(Singapore)
- MEPhI/Pulsar (Moscow)
- Amplification Technologies (Orlando, USA)
- Hamamatsu Photonics (Hamamatsu, Japan)
- SensL(Cork, Ireland)
- RMD (Boston, USA)
- MPI Semiconductor Laboratory (Munich, Germany)
- FBK-irst(Trento, Italy)
- STMicroelectronics (Italy)
- ……

Every producer uses its own name for this type of device: MRS APD, MAPD, SiPM, SSPM, SPM, DAPD, PPD, G-APD (D. Renker, E. Lorenz"Advances in solid state photon detectors" 2009 JINST 4 P04004) …