II. Signal Formation and Acquisition

II. Signal Formation and Acquisition

We consider detectors that provide electrical signal outputs.

To extract the amplitude or timing information the electrical signal is coupled to an amplifier, sent through gain and filtering stages, and finally digitized to allow data storage and analysis.

Optimal signal processing depends on the primary signal.

In general, the signal can be

1. a continuously varying current or voltage
2. a sequence of pulses, occurring
   - periodically
   - at known times
   - randomly

All of these affect the choice of signal processing techniques.

First steps in signal processing:

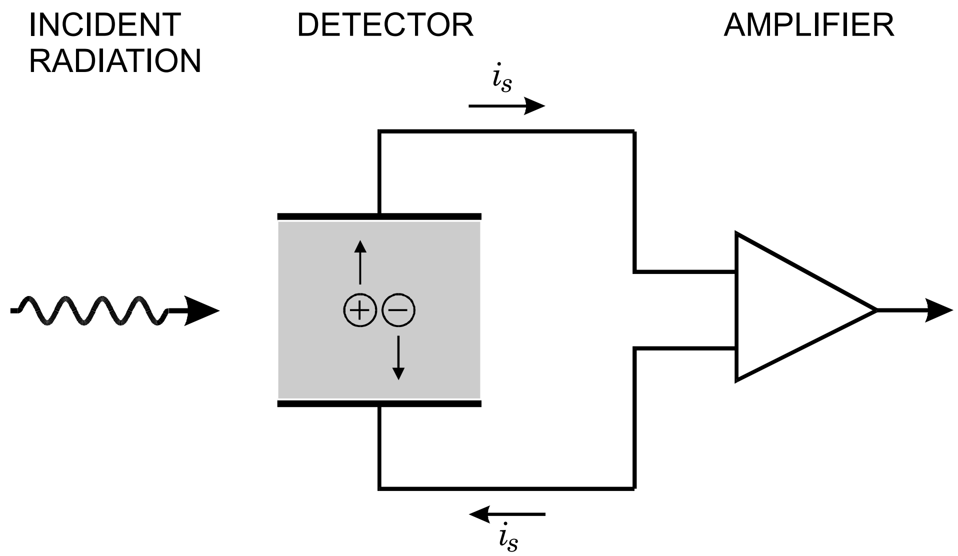
- Formation of the signal in the detector
- Coupling the sensor to the amplifier

Radiation detectors use either

- direct detection or
- indirect detection

Examples:

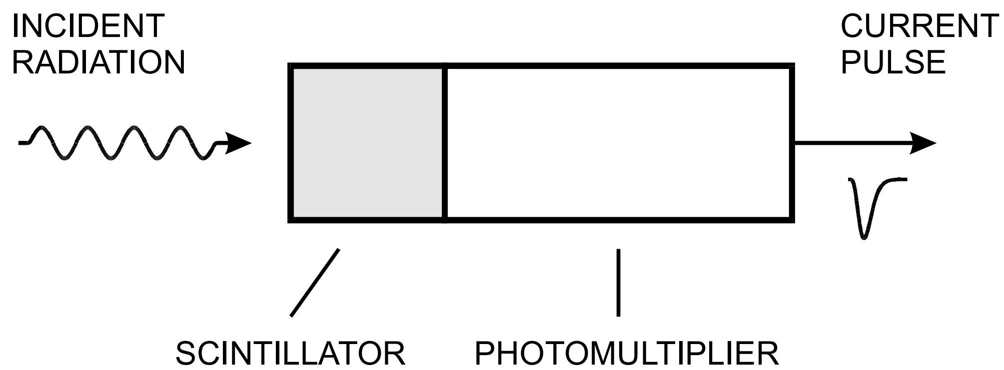
1. Direct Detection



Ionization chamber

Radiation is converted directly to charge pairs.

2. Indirect Detection

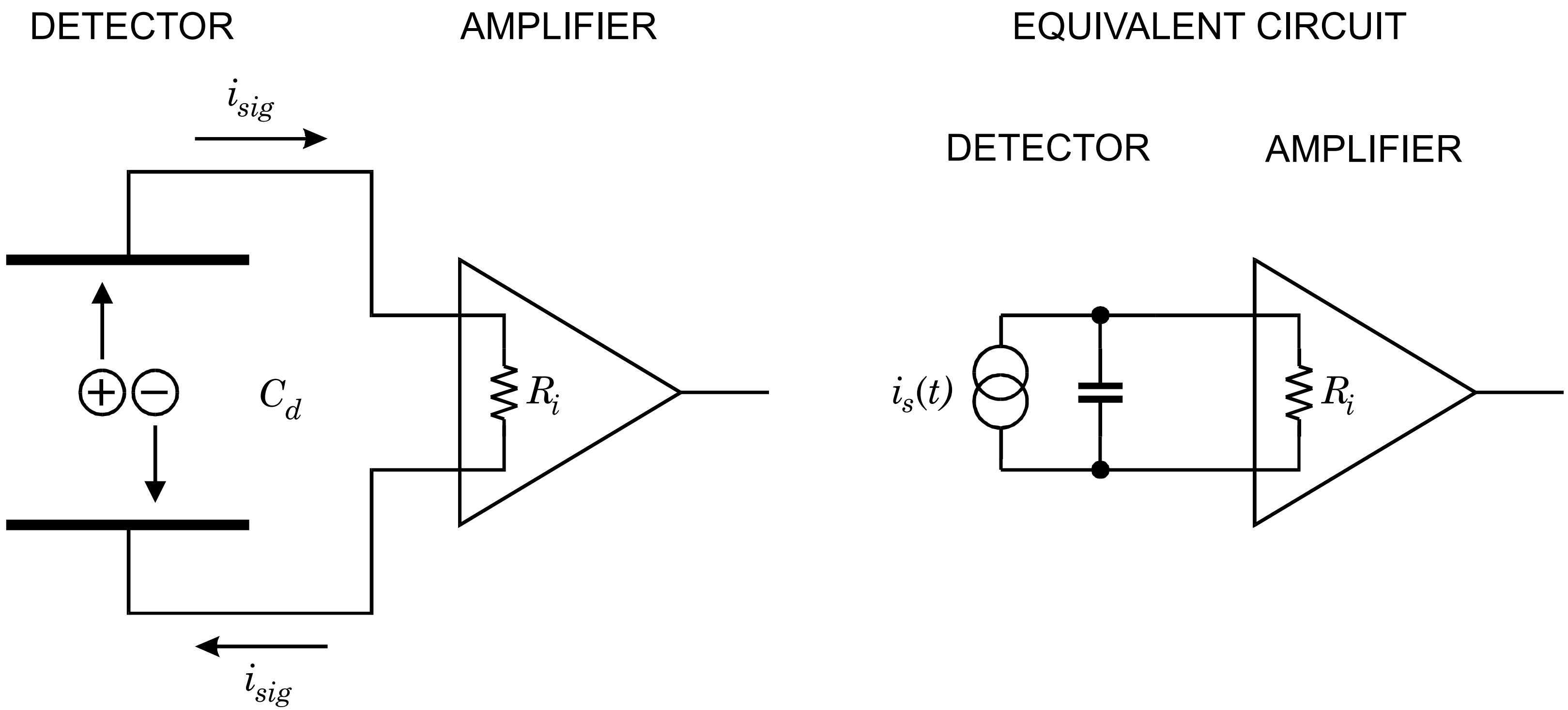


Scintillation detector

Radiation is converted to light (scintillation photons).

Scintillation light is converted to an electrical signal.

2. Signal Formation



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. As the charges move the induced charge changes, i.e. a current flows in the electrode circuit.

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.

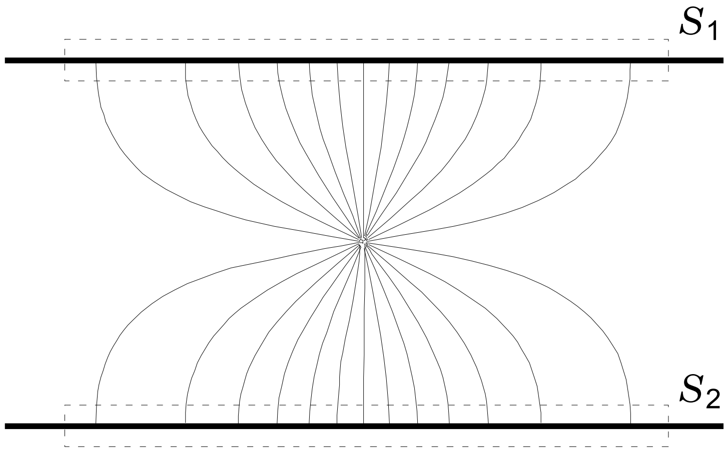
The effect of the amplifier on the signal pulse will be discussed in the Electronics part.

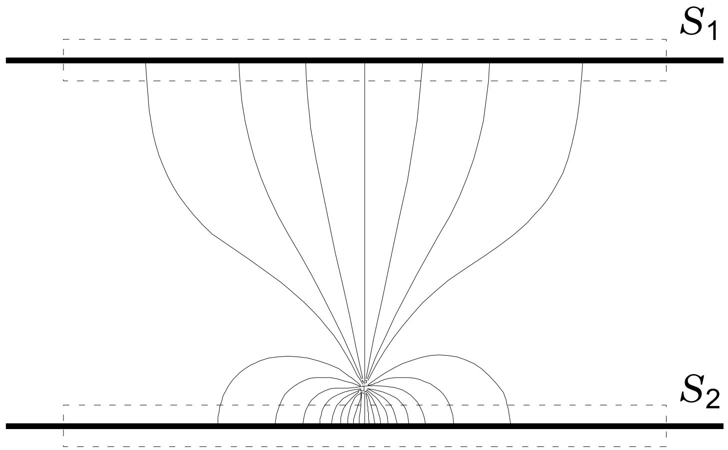
Induced Charge

Consider a charge q in a parallel plate capacitor:

When the charge is midway between the two plates, the charge induced on one plate is determined by applying Gauss' law. The same number of field lines intersect both S_1 and S_2, so equal charge is induced on each plate (= q / 2).

When the charge is close to one plate, most of the field lines terminate on that plate and the induced charge is much greater.

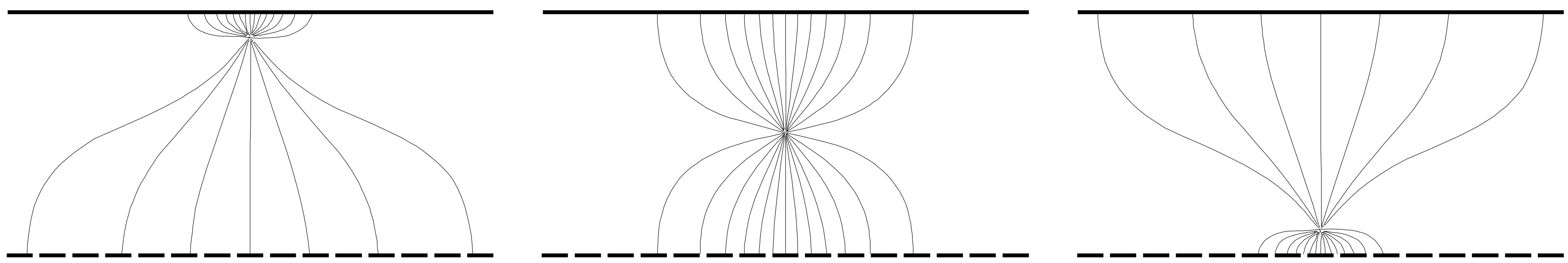




As a charge traverses the space between the two plates the induced charge changes continuously, so current flows in the external circuit as soon as the charges begin to move.

Induced Signal Currents in a Strip Detector

Consider a charge originating near the upper contiguous electrode and drifting down towards the strips.



Initially, charge is induced over many strips.

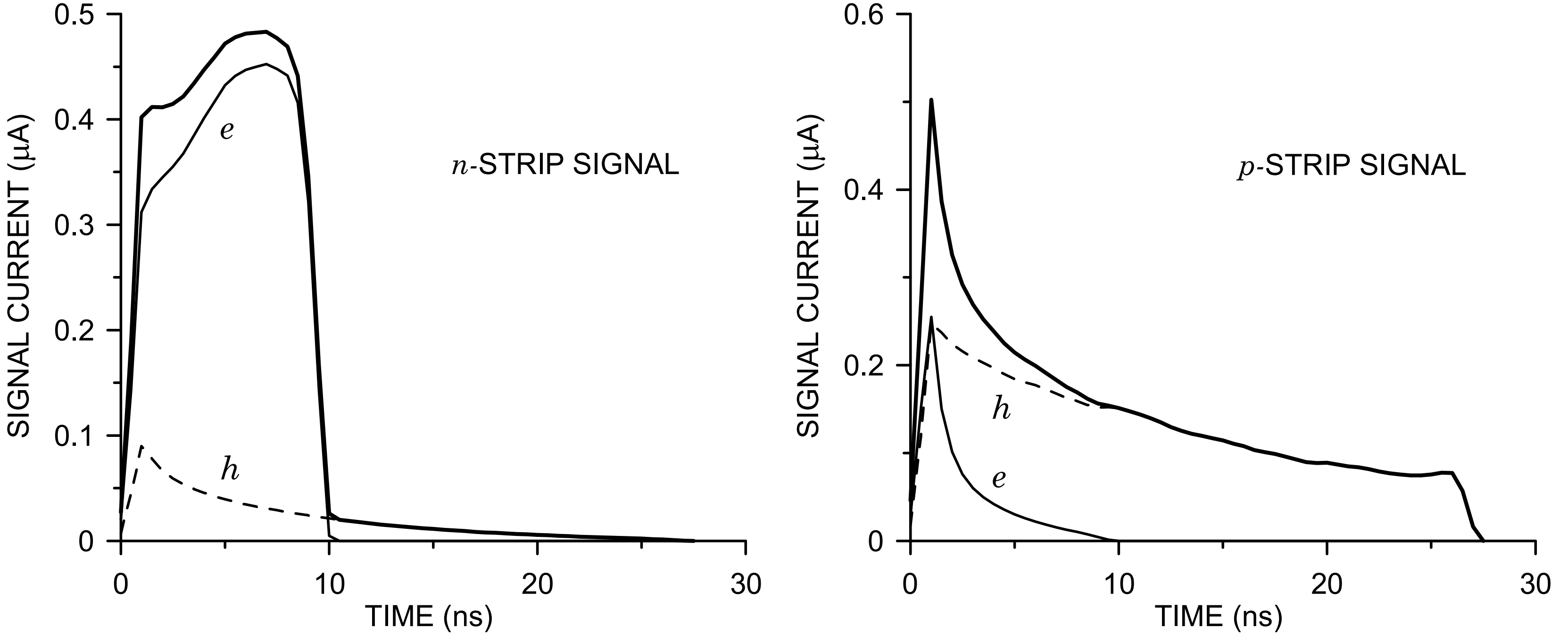
As the charge approaches the strips, the signal distributes over fewer strips.

When the charge is close to the strips, the signal is concentrated over few strips

The magnitude of the induced current due to the moving charge depends on the coupling between the charge and the individual electrodes.

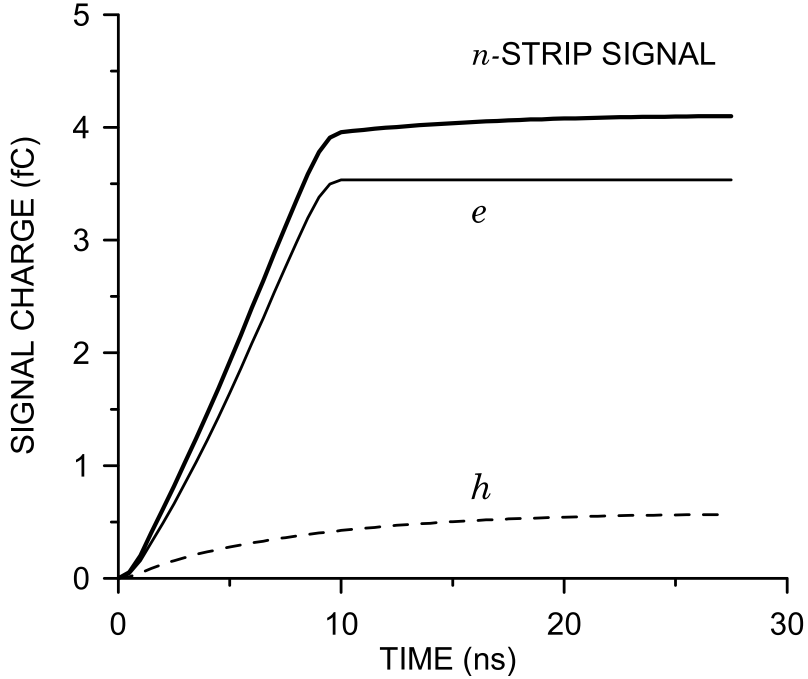
Mathematically this can be analyzed conveniently by applying Ramo's theorem.
(Chapter 2, pp 71-82)

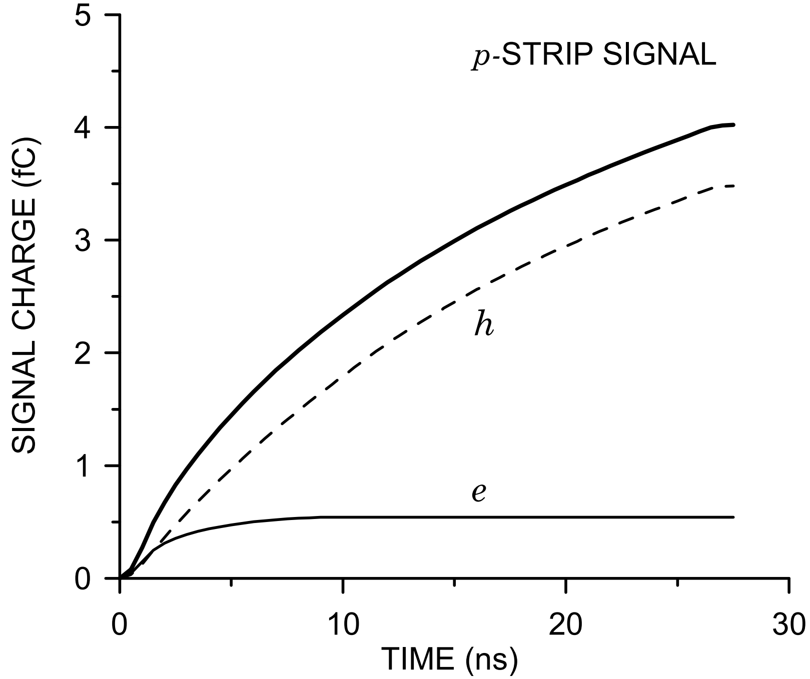
Current pulses in strip detectors (track traversing the detector)



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.

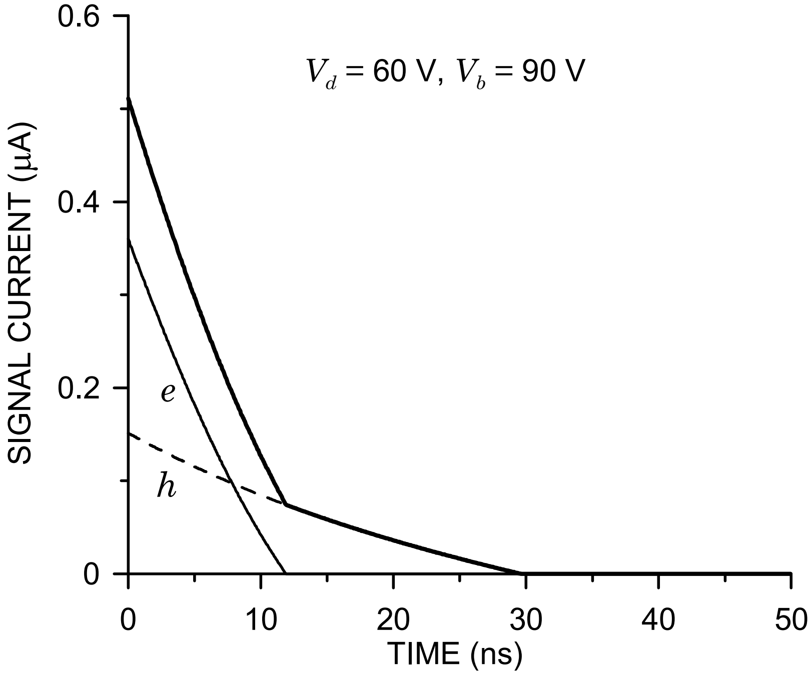
Strip Detector Signal Charge

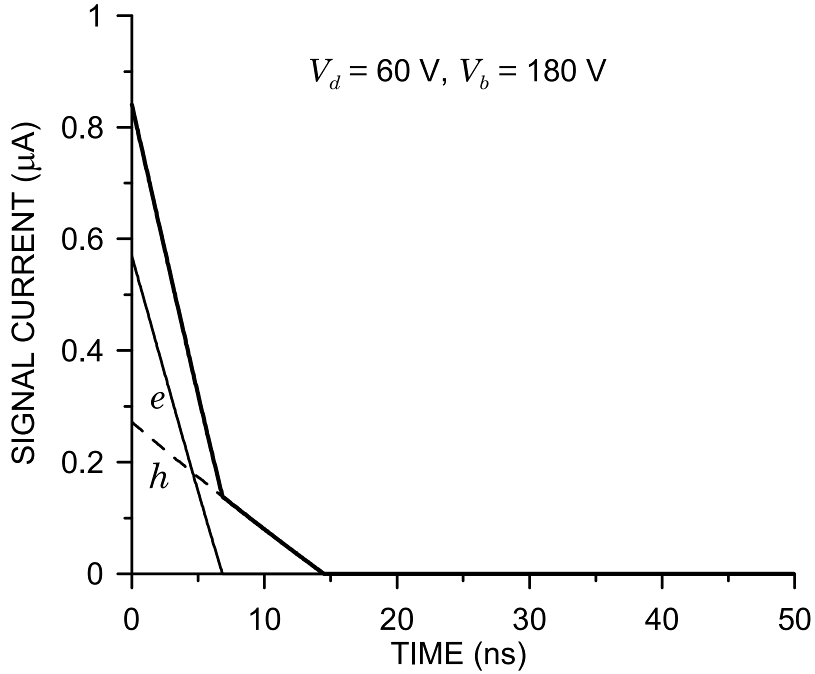




For comparison:

Current pulses in pad detectors (track traversing the detector)





For the same depletion and bias voltages the pulse durations are the same as in strip detectors, although the shapes are very different.

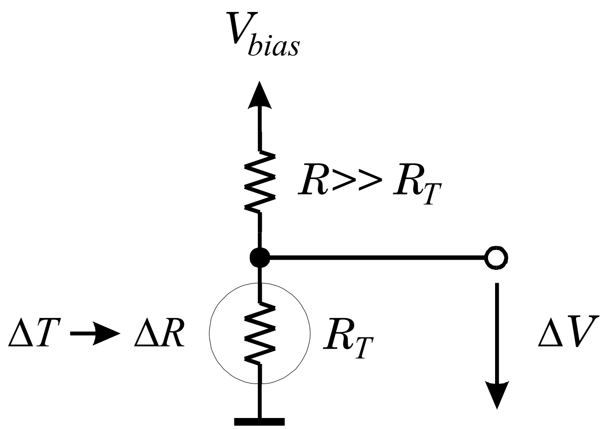
Overbias decreases the collection time.

Example Detector Models

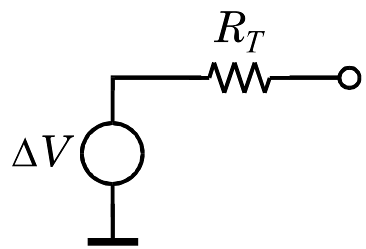
Although detectors take on many different forms, one can analyze the coupling to the amplifier with simple models.

2.1 Thermistor detecting IR radiation

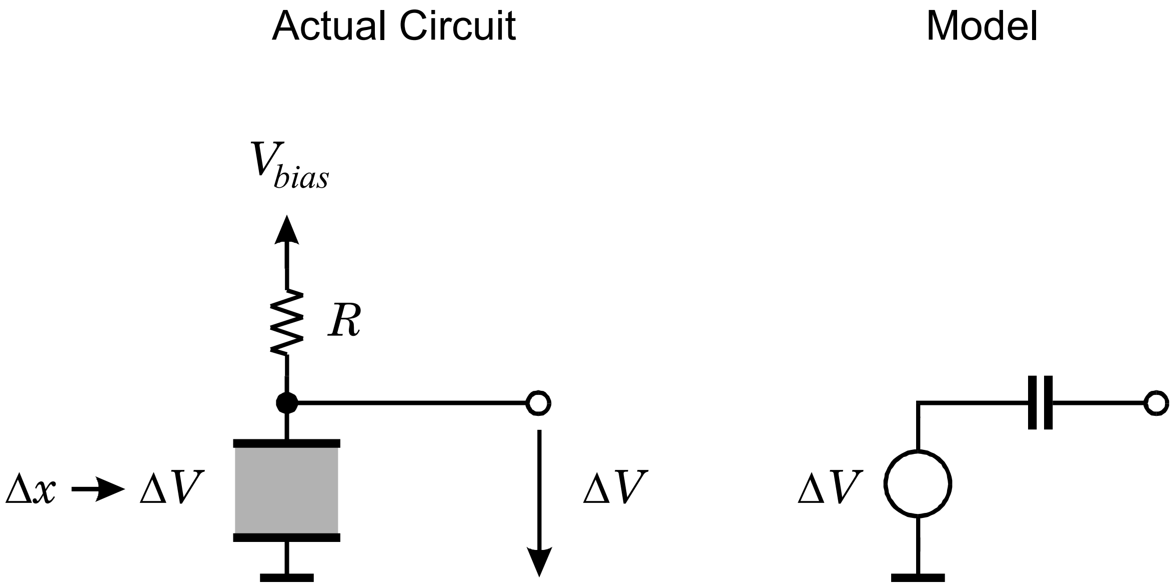
Actual Circuit



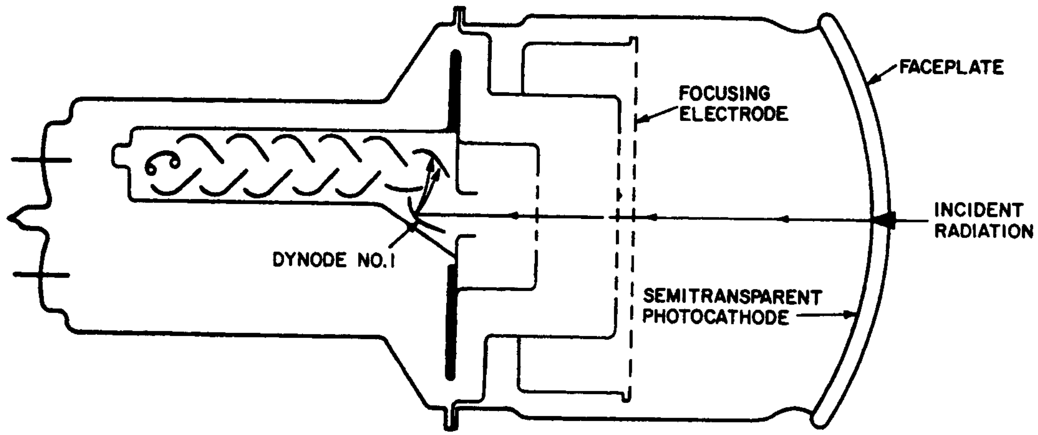
Model



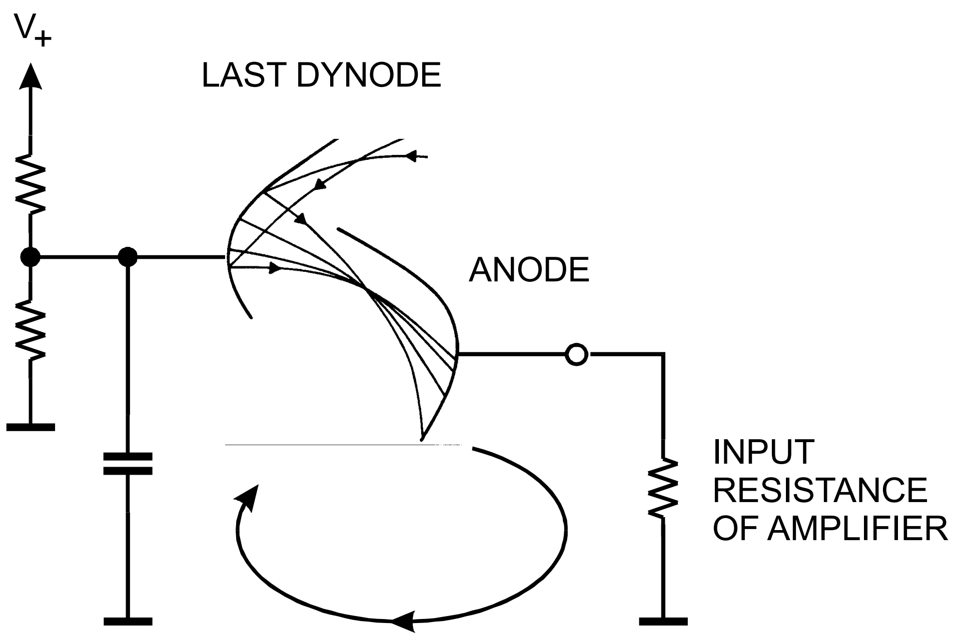
2.2 Piezoelectric Transducer



2.3 Photomultiplier Tube

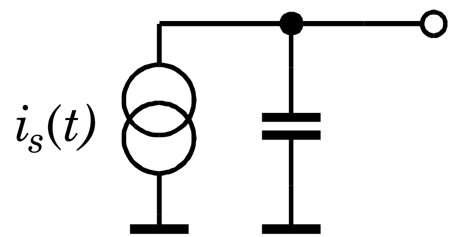


Detail of output circuit



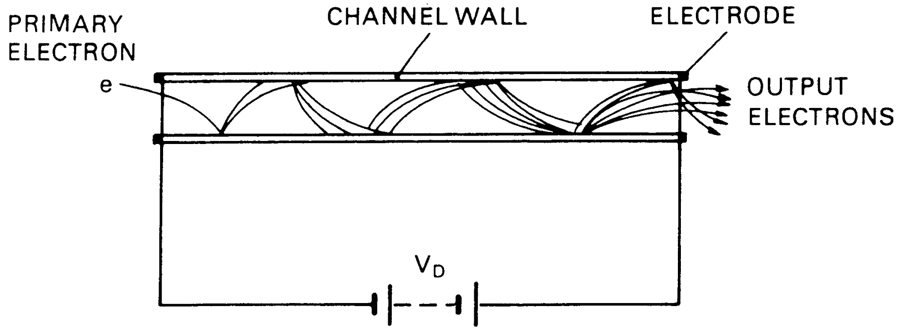
Output Current Loop

Model

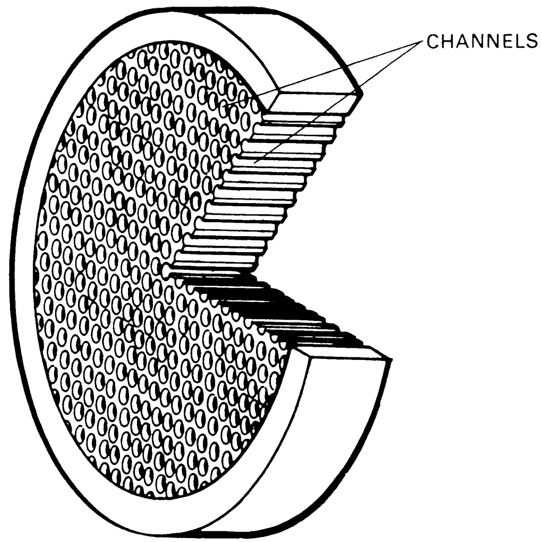


2.4 Channeltrons and Microchannel Plates

Channel electron multiplier
The inside of a glass capillary is coated with a secondary electron emitter that also forms a distributed resistance. Application of a voltage between the the two ends sets up a field, so that electrons in the structure are accelerated, strike the wall, and form secondaries.

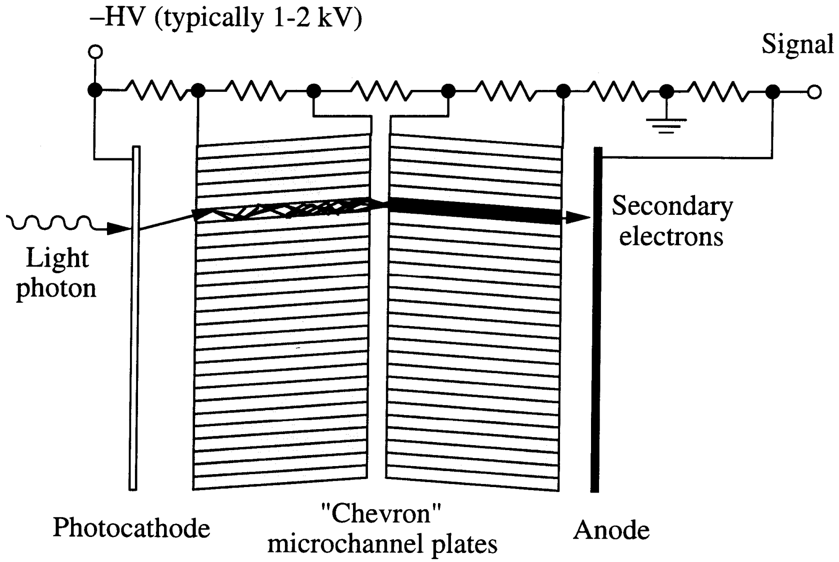


Channel electron multipliers are used individually ("channeltrons"), with tube diameters of ~1 mm, and in arrays called "micro-channel plates", which combine many small channels of order 10 μm diameter in the form of a plate.
Microchannel plates are fabricated by stretching bundles of glass capillaries and then slicing the bundle to form 2 – 5 cm diameter plates of several hundred microns thickness.



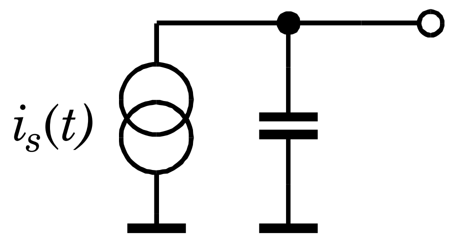
Microchannel plates are compact and fast. Transit time dispersion is < 1 ns due to the small dimensions of an individual channel. Pairs of microchannel plates can be combined to provide higher gain.

Connection scheme of a photon detector using microchannel plates



(from Derenzo)

Model

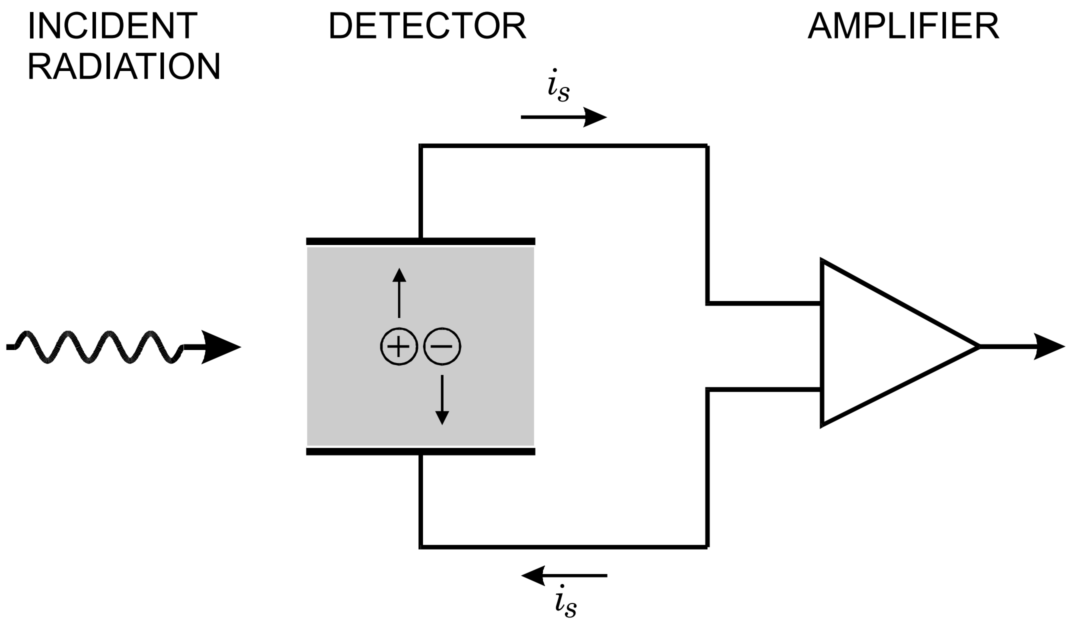


The shunt capacitor represents the capacitance between the exit face of the MCP and the anode.

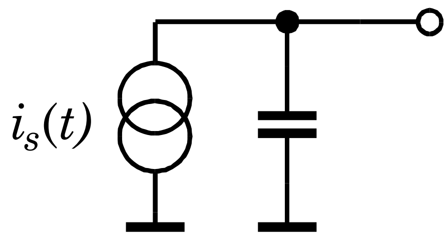
2.5 Ionization Chamber

Semiconductor detectors (pad, strip, pixel electrodes)

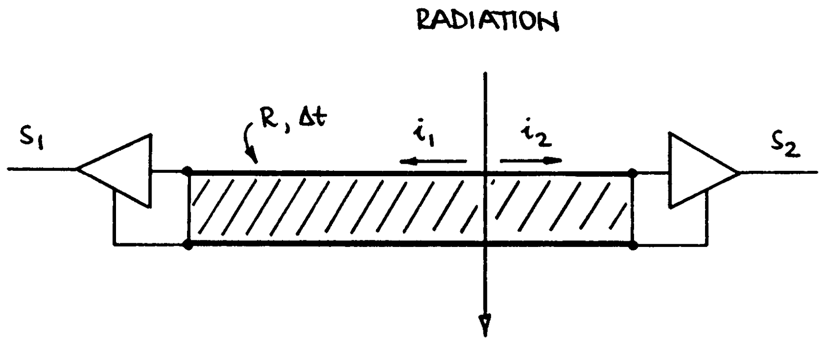
Gas-filled ionization or proportional chambers, ...



Model:



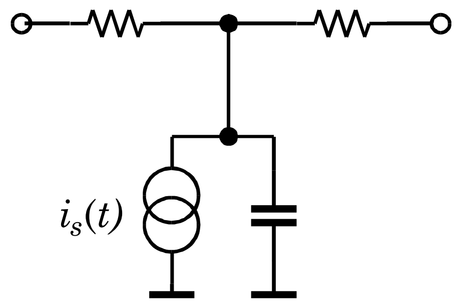
2.6 Position-Sensitive Detector with Resistive Charge Division



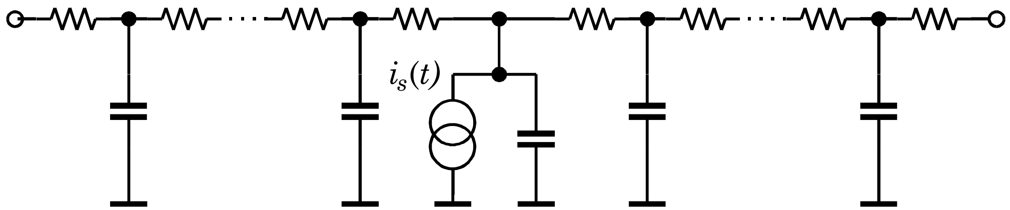
Electrode is made resistive with low-impedance amplifiers at each end. The signal current divides according to the ratio of resistances presented to current flow in the respective direction

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

Simplest Model:



Depending on the speed of the amplifier, a more accurate model of the electrode includes the distributed capacitance:



Signal Magnitude

Any form of elementary excitation can be used to detect the radiation signal.

An electrical signal can be formed directly by ionization.

Incident radiation quanta impart sufficient energy to individual atomic electrons to form electron-ion pairs (in gases) or electron-hole pairs (in semiconductors and metals).

Other detection mechanisms are

Excitation of optical states (scintillators)

Excitation of lattice vibrations (phonons)

Breakup of Cooper pairs in superconductors

Formation of superheated droplets in superfluid He

Typical excitation energies

Ionization in gases	~30 eV
Ionization in semiconductors	1 – 5 eV
Scintillation	~10 – 1000 eV
Phonons	meV
Breakup of Cooper Pairs	meV

Detector Sensitivity

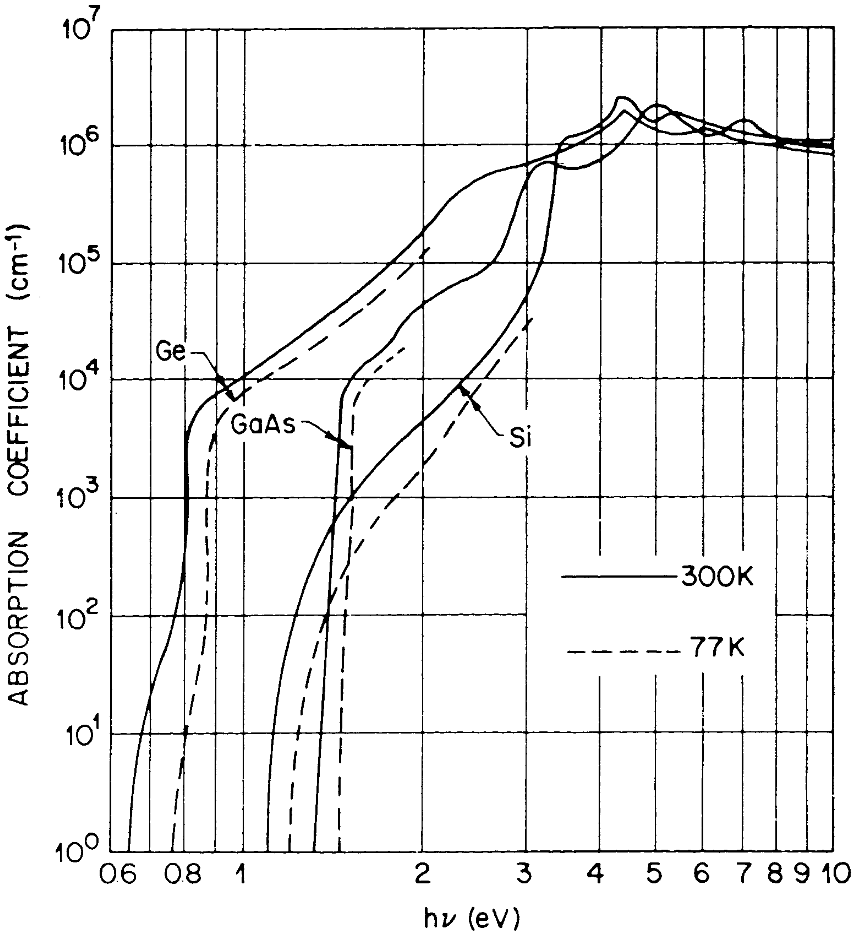
Example:

Ionization signal in semiconductor detectors

a) Visible light (energies near band gap)

Detection threshold = energy required to produce an electron-hole pair
≈ band gap

In indirect bandgap semiconductors (Si), additional momentum required: provided by phonons



(from Sze)

b) High energy quanta ($E \gg E_g$)

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

In Si: $E_i = 3.6$ eV ($E_g = 1.1$ eV)

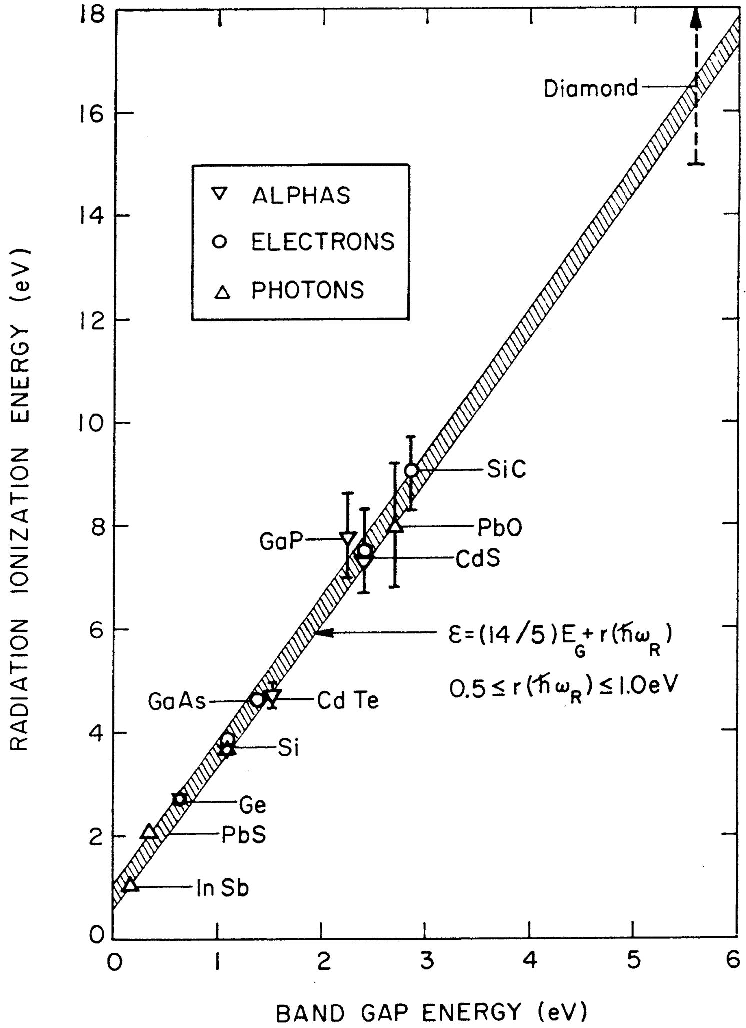
Why?

When particle deposits energy one must conserve both

energy and momentum

momentum conservation not fulfilled by transition across gap

$\Rightarrow$ excite phonons (lattice vibrations, i.e. heat)



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

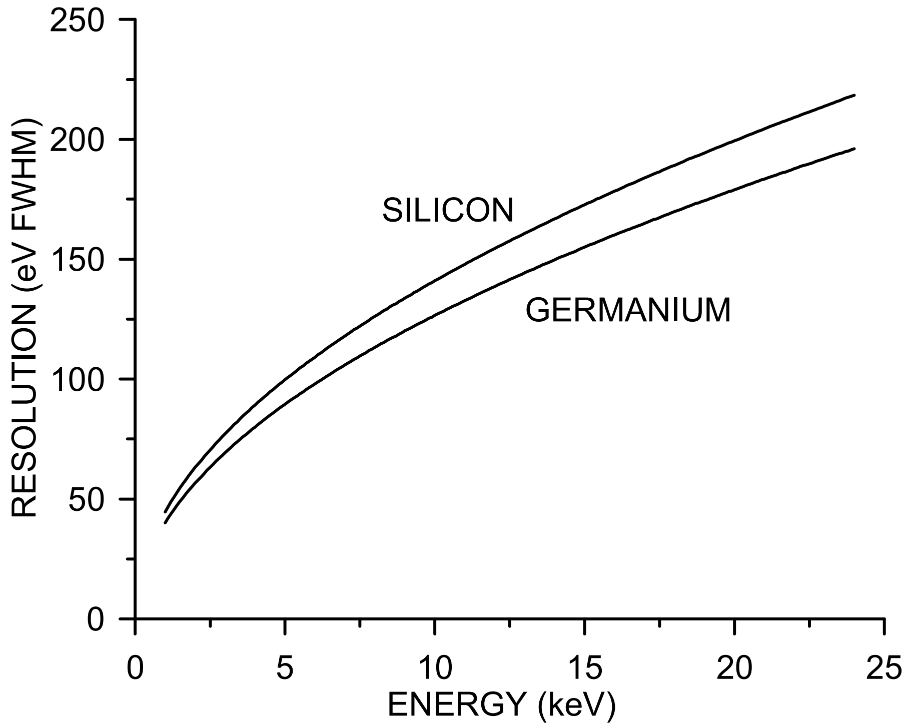
Signal Fluctuations: Intrinsic Resolution of Semiconductor Detectors

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

F is the Fano factor (Chapter 2, pp 52-55).

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

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



Detectors with good efficiency in 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.

Signal Fluctuations in a Scintillation Detector

Example: Scintillation Detector - 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.

In this example

$$\frac{\Delta E}{E} = \frac{1}{\sqrt{3000}} = 2\% \text{ rms} = 5\% \text{ FWHM}$$

511 keV gamma ray

$\Downarrow$

25000 photons in scintillator

$\Downarrow$

15000 photons at photocathode

$\Downarrow$

3000 photoelectrons at first dynode

$\Downarrow$

$3 \cdot 10^9$ electrons at anode

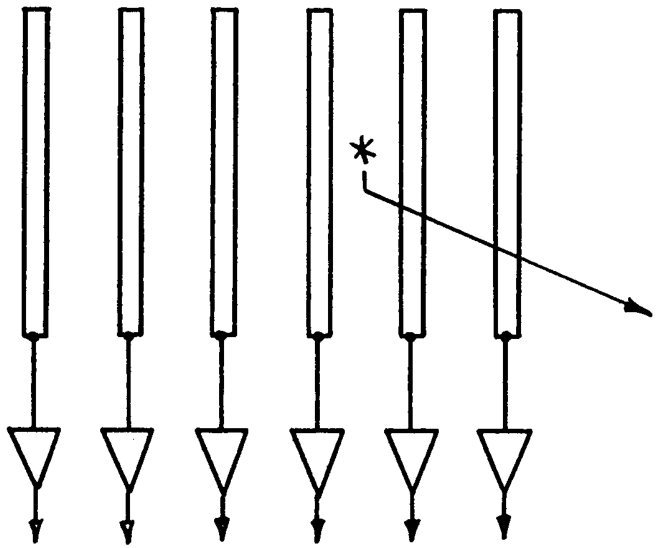
2 mA peak current

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

In addition to energy measurements, semiconductor detectors allow precision position sensing.

Resolution determined by precision of micron scale patterning of the detector electrodes (e.g. strips on 50 μm pitch).

Two options: Binary Readout Analog Readout



Interpolation yields resolution < pitch

Relies on transverse diffusion

$$\sigma_x \propto \sqrt{t_{coll}}$$

to discriminators

Position resolution determined directly by pitch p: $\sigma_x = p/\sqrt{12}$

e.g. in Si: $t_c \approx$ 10 ns $\Rightarrow \sigma_x$= 5 μm

depends on S/N and p

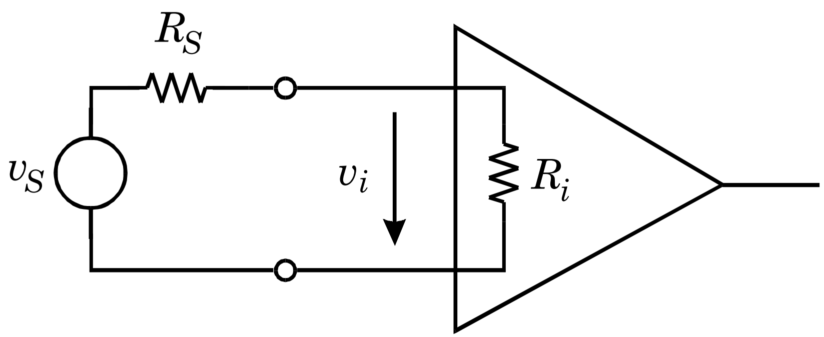
p= 25 μm and S/N=50

$\Rightarrow$ 3 – 4 μm resolution

3. 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

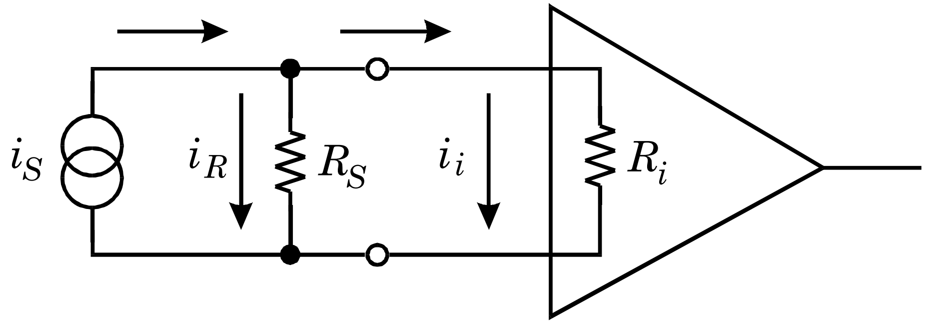
$$v_i \approx v_S \quad \Rightarrow \quad R_i \gg R_S$$

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).

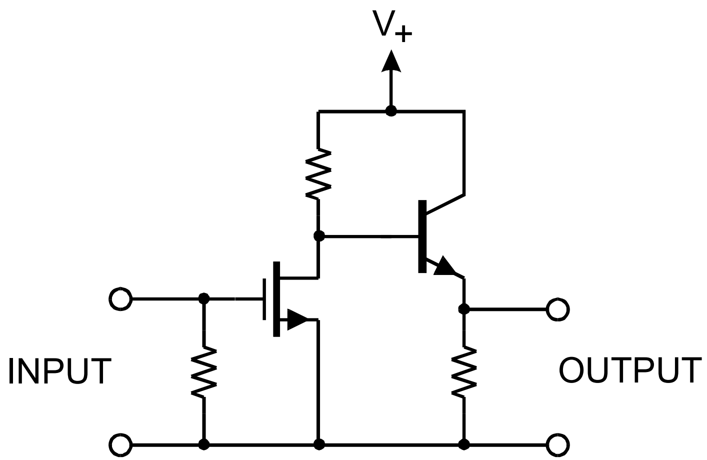
One can also model a current source as a voltage source with a series resistance. For the signal current to be unaffected by the amplifier input resistance, the input resistance must be small compared to the source resistance, as derived above.

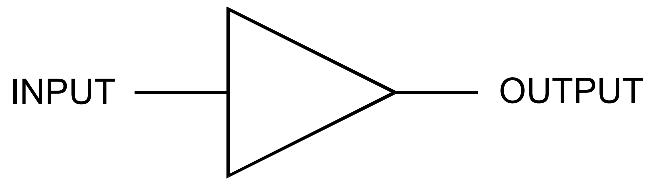
At the output, to provide current drive the output resistance should be high, i.e. large compared to the input resistance of the next stage.

- Whether a specific amplifier operates in the current or voltage mode depends on the source resistance.

- Amplifiers can be configured as current mode input and voltage mode output or, conversely, as voltage mode input and current mode output. The gain is then expressed as V/A or A/V.

Although an amplifier has a pair of input and a second pair of output connections, since the two have a common connection a simplified representation is commonly used:

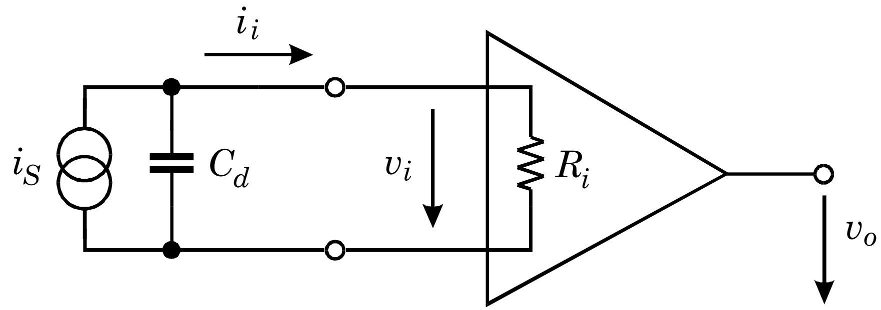




c) Voltage and Current Mode with Capacitive Sources

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 $R_i C_d$:

a) $R_i C_d \ll t_c$

detector capacitance discharges rapidly

$\Rightarrow \quad v_o \propto i_s(t)$

current sensitive amplifier

b) $R_i C_d \gg t_c$

detector capacitance discharges slowly

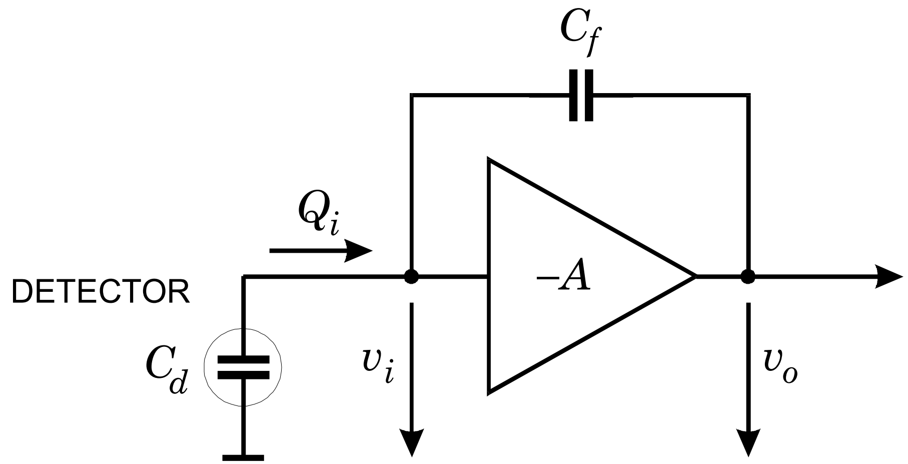
$\Rightarrow \quad v_o \propto \int i_s(t)dt$

voltage sensitive amplifier

Note that in both cases the amplifier is providing voltage gain, so the 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 $dv_o / dv_i = -A \Rightarrow$

$$v_o = -Av_i$$

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

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

Charge gain set by a well-controlled quantity, the feedback capacitance.

Q_i is the charge flowing into the preamplifier .... but some charge remains on C_d.

What fraction of the signal charge is measured?

$$\frac{Q_i}{Q_s} = \frac{C_i v_i}{Q_d + Q_i} = \frac{C_i}{Q_s} \cdot \frac{Q_s}{C_i + C_d}$$

$$= \frac{1}{1 + \frac{C_d}{C_i}} \approx 1 \quad (\text{if } C_i >> C_d)$$

Example: $A = 10^3$

$C_f = 1$ pF $\Rightarrow$ $C_i = 1$ nF

$C_{det} = 10$ pF: $Q_i / Q_s = 0.99$

$C_{det} = 500$ pF: $Q_i / Q_s = 0.67$

↑

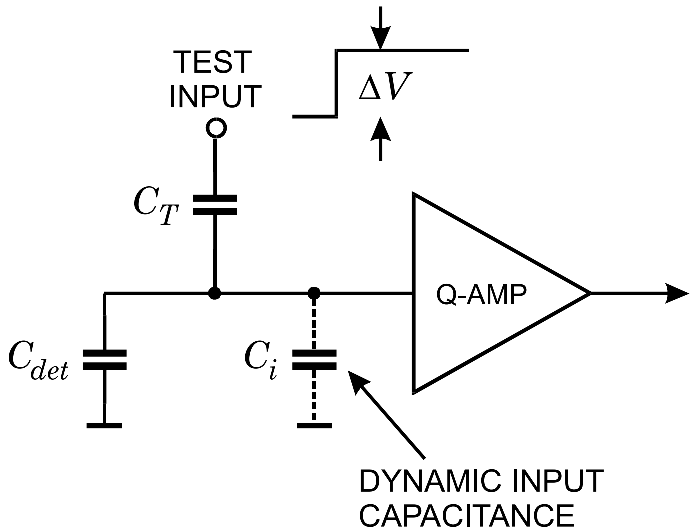
Si Det.: 50 μm thick, 250 mm^2 area

Note: Input coupling capacitor must be $\gg C_i$ for high charge transfer efficiency.

Calibration

Inject specific quantity of charge - measure system response

Use voltage pulse (can be measured conveniently with oscilloscope)



C_i >> C_T $\Rightarrow$ Voltage step applied to test input develops over C_T.

$\Rightarrow$ $Q_T = \Delta V \cdot C_T$

Accurate expression: $$Q_T = \frac{C_T}{1+\frac{C_T}{C_i}} \cdot \Delta V \approx C_T \left(1 - \frac{C_T}{C_i}\right) \Delta V$$

Typically: $C_T / C_i = 10^{-3} - 10^{-4}$

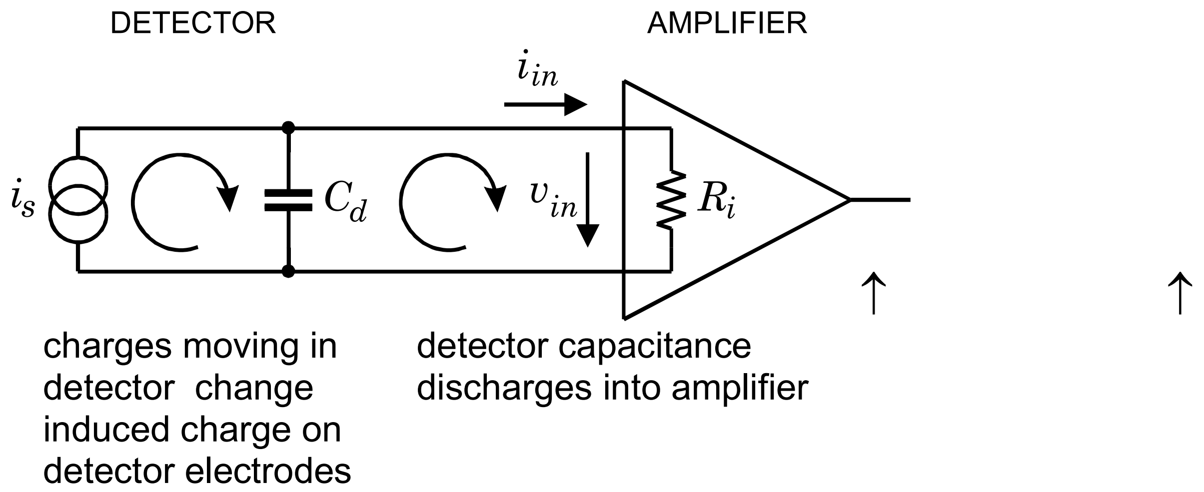
Realistic Charge-Sensitive Preamplifiers

The preceding discussion assumed idealized amplifiers with infinite speed.

In reality, amplifiers may be too slow to follow the instantaneous detector pulse.

Does this incur a loss of charge?

Equivalent Circuit:



Signal is preserved even if the amplifier responds much more slowly than the detector signal.

However, the response of the amplifier affects the measured pulse shape.

- How do “real” amplifiers affect the measured pulse shape?
- How does the detector affect amplifier response?

Although detector signals are commonly viewed in the time domain, the analysis of readout systems is facilitated by utilizing both the time and frequency domain.

Detectors are current sources, so we have to consider how the current will flow.

In a purely resistive path $$I = \frac{V}{R}.$$

In a capacitive path
$$Q = CV$$
$$I = \frac{dQ}{dt} = C\frac{dV}{dt}$$

If the voltage signal is sinusoidal $$V(t) = V_0 \sin \omega t$$
$$I(t) = V_0 \cdot C\omega \cdot \cos \omega t = V_0 \cdot C\omega \cdot \sin(\omega t + 90°),$$

so the magnitude of the resistance (impedance) presented by the capacitor

$$|Z_C| = \frac{1}{\omega C} \; ,$$

but there is also a +90° phase shift between the driving voltage and the current.

In an inductance the current flow gives rise to an opposing voltage

$$V(t) = -L\frac{dI}{dt} \; .$$

For a sinusoidal current $I = I_0 \sin \omega t$,

$$V(t) = -I_0 \cdot \omega L \cdot \cos \omega t = I_0 \cdot \omega L \cdot \sin(\omega t - 90°)$$

so the magnitude of the resistance (impedance) presented by the inductor

$$|Z_L| = \omega L \, ,$$

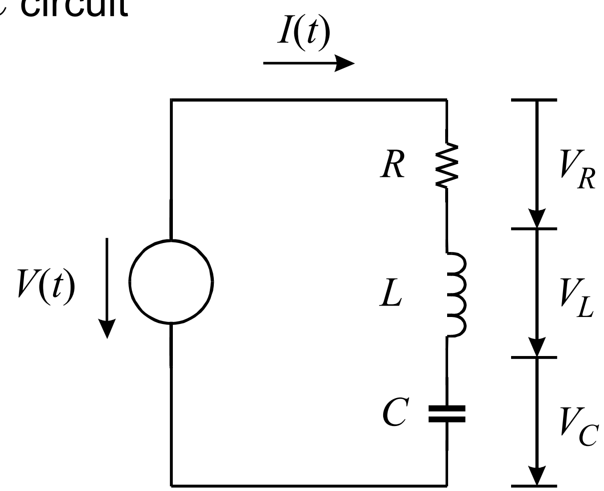
but there is a negative -90° phase shift between the voltage and current.

Nomenclature: Impedance Z is the resistance presented to alternating currents or voltages. The DC resistance can be infinite.

The impedance presented by an inductance or capacitance alone is called reactance (X_L or X_C)

How to simplify calculations that involve phase shifts:
Phasors and Complex Algebra in Electrical Circuits

Consider the RLC circuit



$$V = V_R + V_L + V_C$$

$$V = IR + L\frac{dI}{dt} + \frac{Q}{C}$$

$$\frac{dV}{dt} = \frac{dI}{dt}R + L\frac{d^2I}{dt^2} + \frac{I}{C}$$

Assume that $V(t) = V_0 e^{\mathbf{i}\omega t}$ and $I(t) = I_0 e^{\mathbf{i}(\omega t+\varphi)}$

Then

$$\mathbf{i}\omega V_0 e^{\mathbf{i}\omega t} = \mathbf{i}\omega R I_0 e^{\mathbf{i}(\omega t-\varphi)} - \omega^2 L I_0 e^{\mathbf{i}(\omega t-\varphi)} + \frac{1}{C} I_0 e^{\mathbf{i}(\omega t-\varphi)}$$

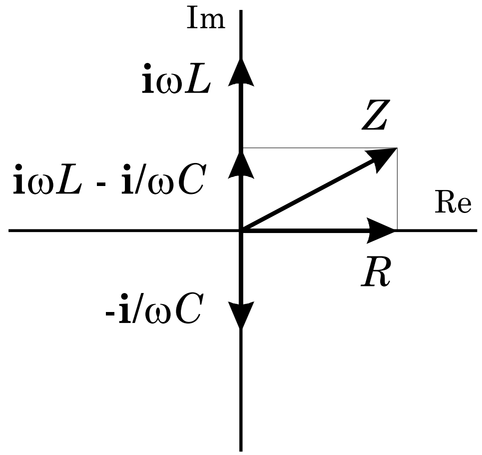
$$\frac{V_0}{I_0} e^{\mathbf{i}\varphi} = R + \mathbf{i}\omega L - \mathbf{i}\frac{1}{\omega C}$$

Thus, we can express the total impedance $Z \equiv (V_0 / I_0)\ e^{\mathrm{i}\varphi}$ of the circuit as a complex number with the magnitude $|Z| = V_0 / I_0$ and phase φ.

In this representation the equivalent resistances (reactances) of L and C are imaginary numbers

$$X_L = \mathbf{i}\omega L \quad \text{and} \quad X_C = -\frac{\mathbf{i}}{\omega C}\ .$$

Plotted in the complex plane:



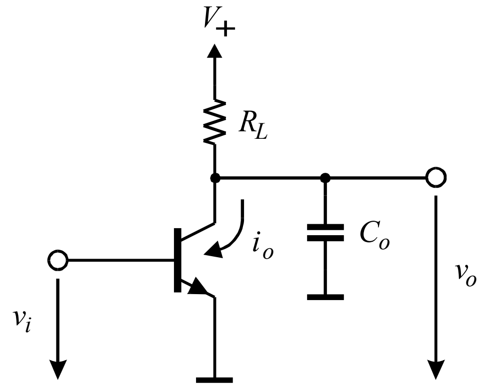
Relative to V_R, the voltage across the inductor V_L is shifted in phase by +90°.

The voltage across the capacitor V_C is shifted in phase by -90°.

Use to represent any element that introduces a phase shift, e.g. an amplifier. A phase shift of +90° appears as $+\mathbf{i}$, -90° as $-\mathbf{i}$.

In the above example when $|X_L| = |X_C|$ the two cancel, presenting the minimum impedance as expected in a series resonant circuit.

A Simple Amplifier



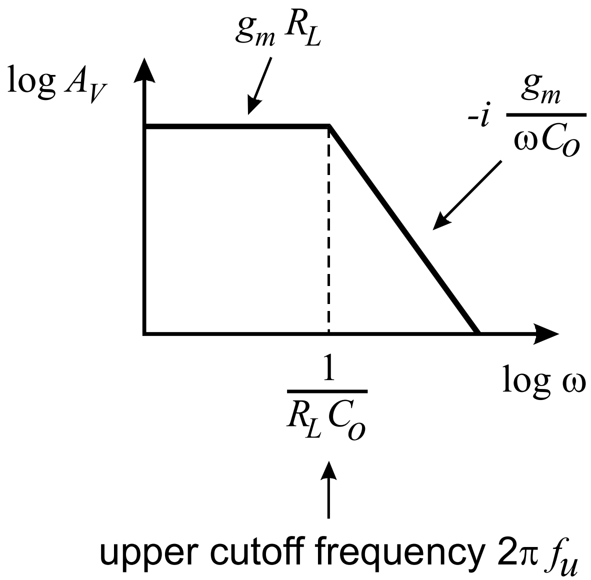
Voltage gain: $A_V = \dfrac{dv_o}{dv_i} = \dfrac{di_o}{dv_i} \cdot Z_L \equiv g_m Z_L$

$g_m \equiv$ transconductance

$$Z_L = R_L \,/\,/\, C_o$$

$$\frac{1}{Z_L} = \frac{1}{R_L} + \mathbf{i}\omega\, C_o$$

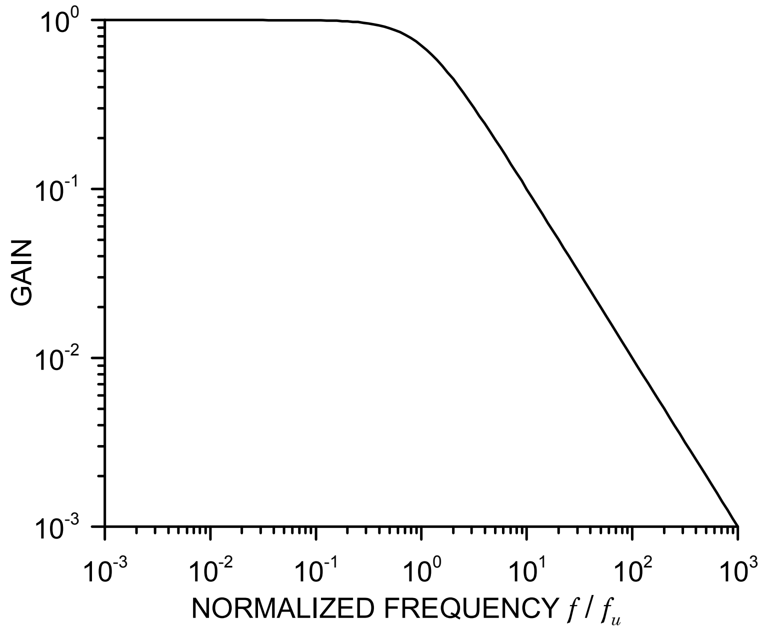
Gain vs. Frequency

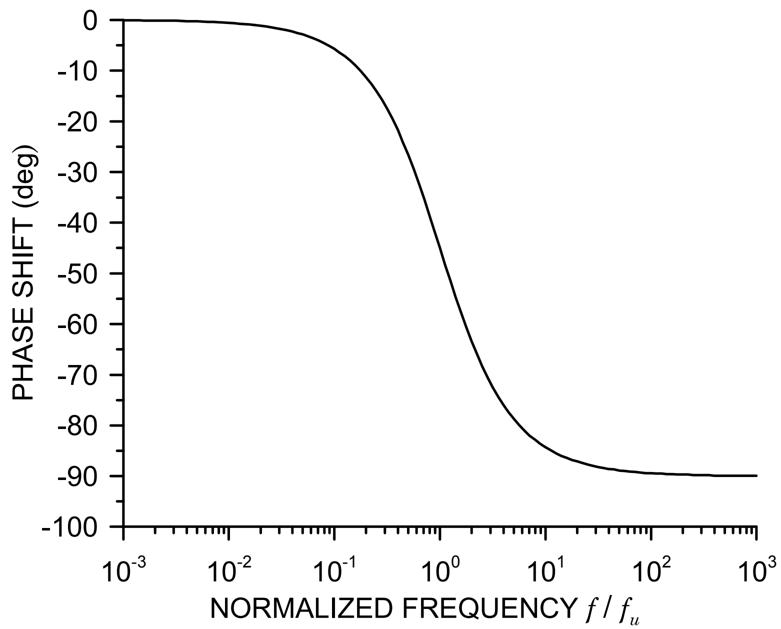


$$\Rightarrow \quad A_V = g_m \left(\frac{1}{R_L} + \mathbf{i}\omega\, C_o \right)^{-1}$$

low freq. high freq.

Frequency and phase response:





Phase shows change from low-frequency response. For an inverting amplifier add 180°.

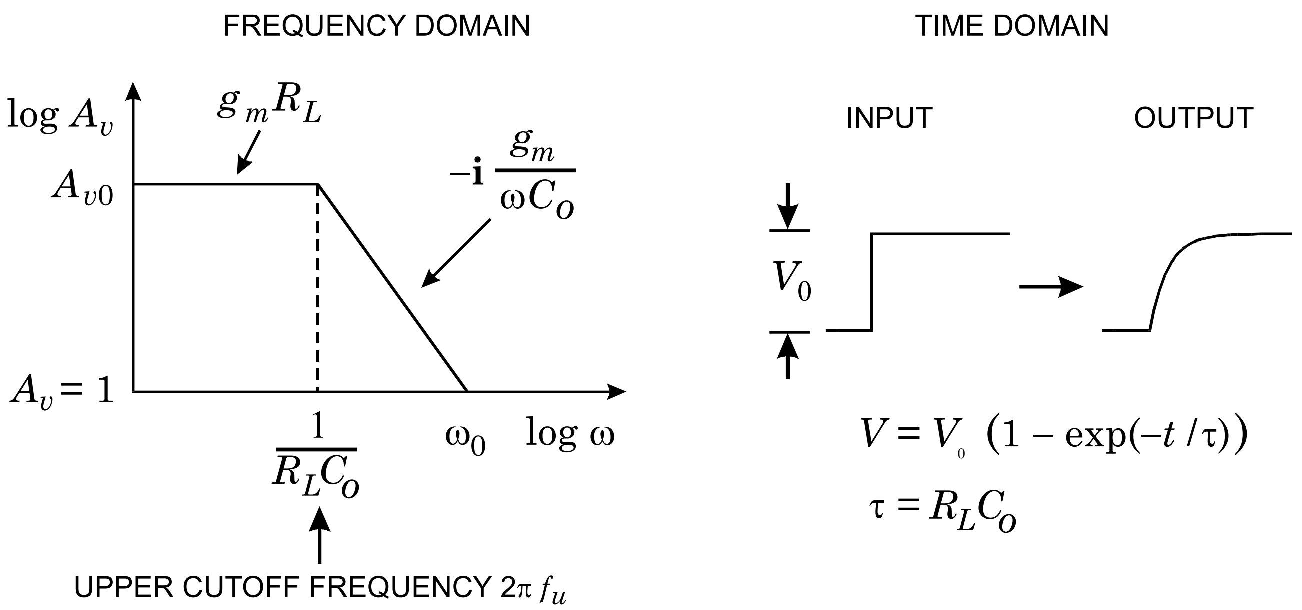
The corner (cutoff) frequency is often called a “pole”.

Pulse Response of the Simple Amplifier

A voltage step $v_i(t)$ at the input causes a current step $i_o(t)$ at the output of the transistor.

For the output voltage to change, the output capacitance C_o must first charge up.

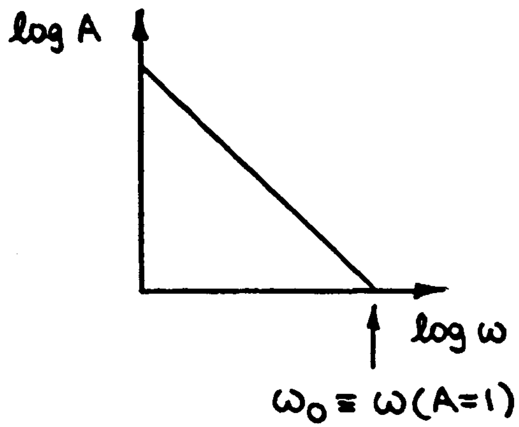
$\Rightarrow$ The output voltage changes with a time constant $\tau = R_L C_O$



The time constant τ corresponds to the upper cutoff frequency : $\tau = \frac{1}{2\pi f_u}$

Input Impedance of a Charge-Sensitive Amplifier

Input impedance $$Z_i = \frac{Z_f}{A+1} \approx \frac{Z_f}{A} \quad (A \gg 1)$$



Gain-Bandwidth Product

Amplifier gain vs. frequency beyond the upper cutoff frequency

$$A = -\mathbf{i}\ \frac{\omega_0}{\omega}$$

Feedback impedance $$Z_f = -\mathbf{i}\ \frac{1}{\omega\ C_f}$$

$\Rightarrow$ Input Impedance $$Z_i = -\frac{\mathbf{i}}{\omega\ C_f} \cdot \frac{1}{-\mathbf{i}\frac{\omega_0}{\omega}} = \frac{1}{\omega_0 C_f}$$

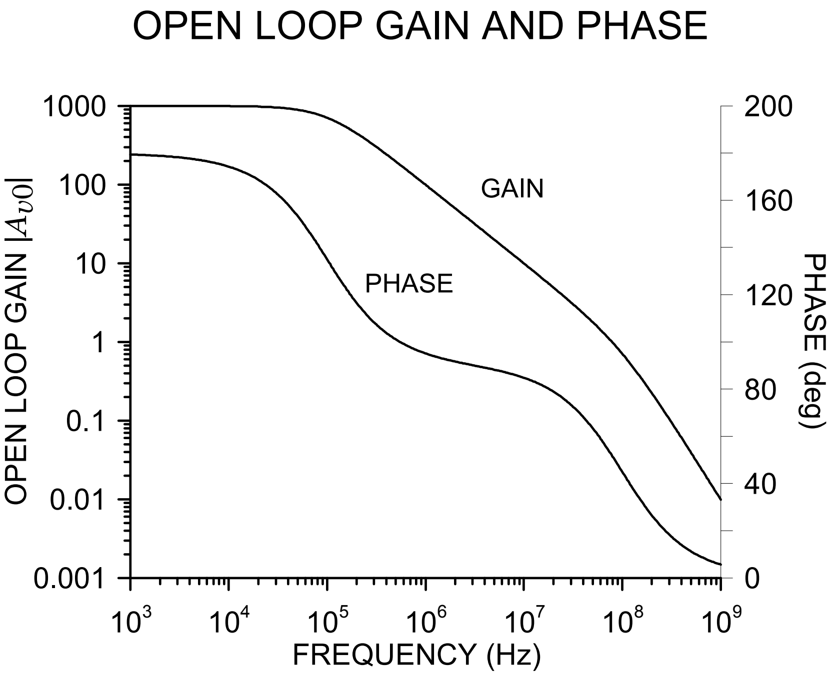
Imaginary component vanishes $\Rightarrow$ *Resistance:* $Z_i \to R_i$

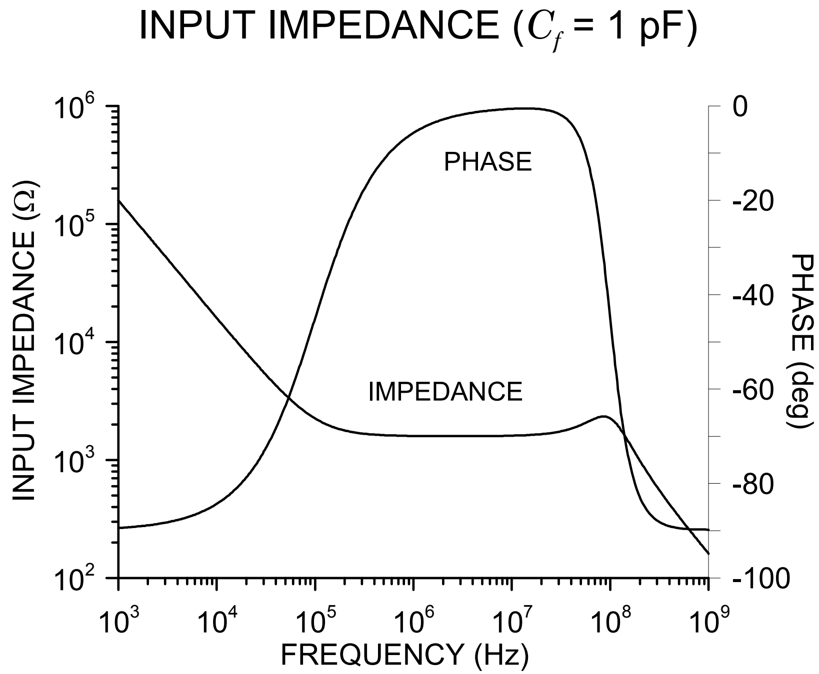
$\Rightarrow$ low frequencies ($f < f_u$): capacitive input
high frequencies ($f > f_u$): resistive input

Practically all charge-sensitive amplifiers operate in the 90° phase shift regime.
$\Rightarrow$ Resistive input

However ... Note that the input impedance varies with frequency.

Example: cutoff frequencies at 10 kHz and 100 MHz, low frequency gain = 10^3

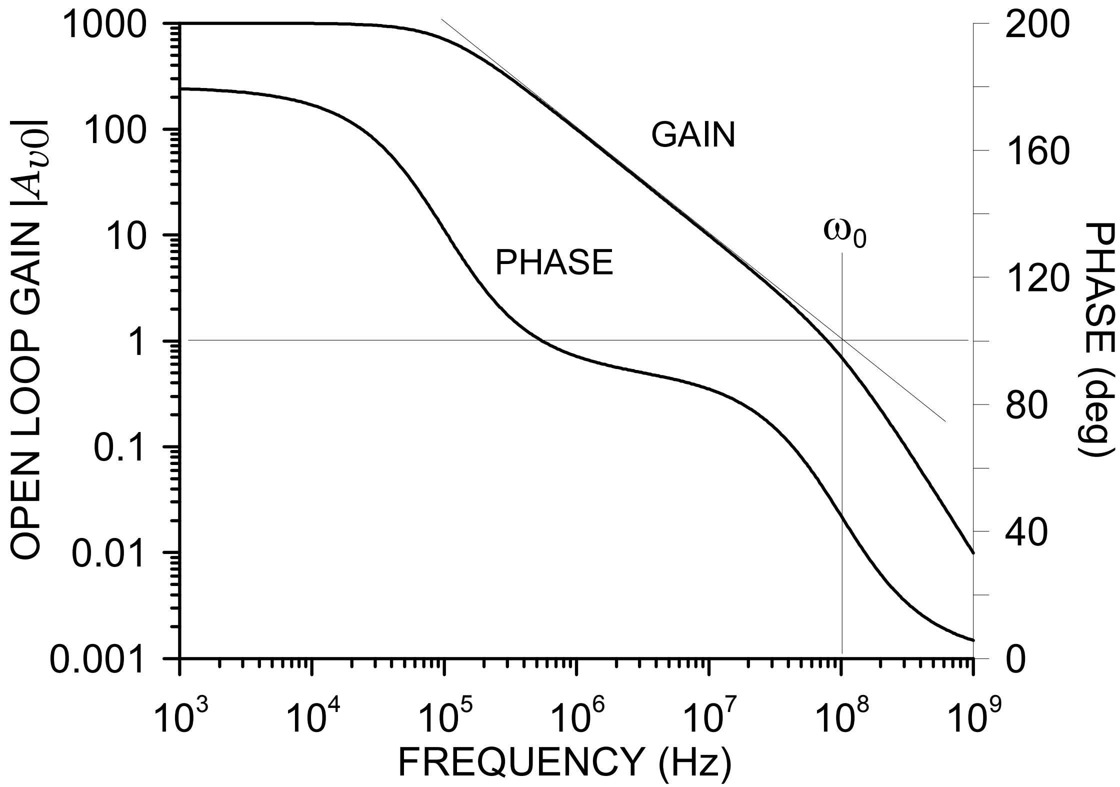




In the resistive regime the input impedance

$$Z_i = \frac{1}{\omega_0 C_f} ,$$

where C_f is the feedback capacitance and ω_0 is the extrapolated unity gain frequency in the 90° phase shift regime.



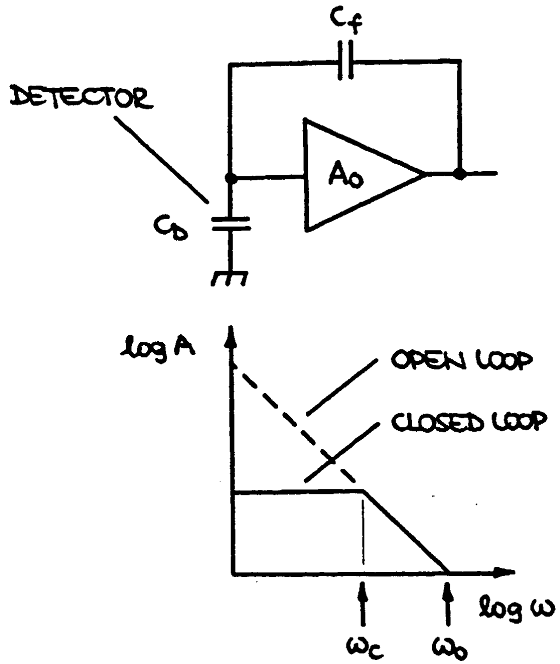
Time Response of a Charge-Sensitive Amplifier

Input resistance and detector capacitance form RC time constant: $\tau_i = R_i C_D$

$$\tau_i = \frac{1}{\omega_0 C_f} \cdot C_D$$

$\Rightarrow$ Rise time increases with detector capacitance.

Or apply feedback theory:



Closed Loop Gain $A_f = \dfrac{C_D + C_f}{C_f} \quad (A_f << A_0)$

$$A_f \approx \frac{C_D}{C_f} \quad (C_D >> C_f)$$

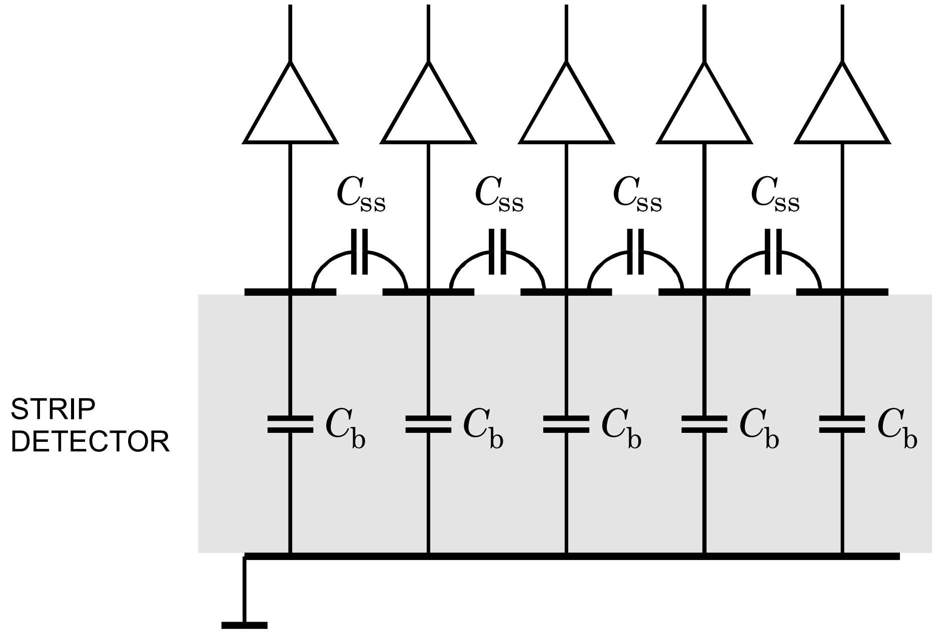
Closed Loop Bandwidth $\omega_C A_f = \omega_0$

Response Time $\tau_{amp} = \dfrac{1}{\omega_C} = C_D \, \dfrac{1}{\omega_0 C_f}$

Same result as from input time constant.

Importance of input impedance in strip and pixel detectors:

Amplifiers must have a low input impedance to reduce transfer of charge through capacitance to neighboring strips



In the previous example at
8 MHz ($\hat{=}$ ~20 ns peaking time)
$Z_i \approx$ 1.6 kΩ, corresponding to 12 pF

$\Rightarrow$ with 6 cm long strips about half of the signal current will go to the neighbors.

For strip pitches that are smaller than the bulk thickness, the capacitance is dominated by the fringing capacitance to the neighboring strips C_{SS}.

Typically: 1 – 2 pF/cm for strip pitches of 25 – 100 μm on Si.

The backplane capacitance C_b is typically 20% of the strip-to-strip capacitance.

Negligible cross-coupling at shaping times $T_P > (2\ ...\ 3) \times R_i C_D$ and if $C_i \gg C_D$.