V.2. Signal Acquisition

- Determine energy deposited in detector

- Detector signal generally a short current pulse

  Typical durations

Thin silicon detector (10 ... 300 m thick):	100 ps – 30 ns
Thick (~cm) Si or Ge detector:	1 – 10 μs
Proportional chamber (gas):	10 ns – 10 μs
Gas microstrip or microgap chamber:	10 – 50 ns
Scintillator + PMT/APD:	100 ps – 10 μs

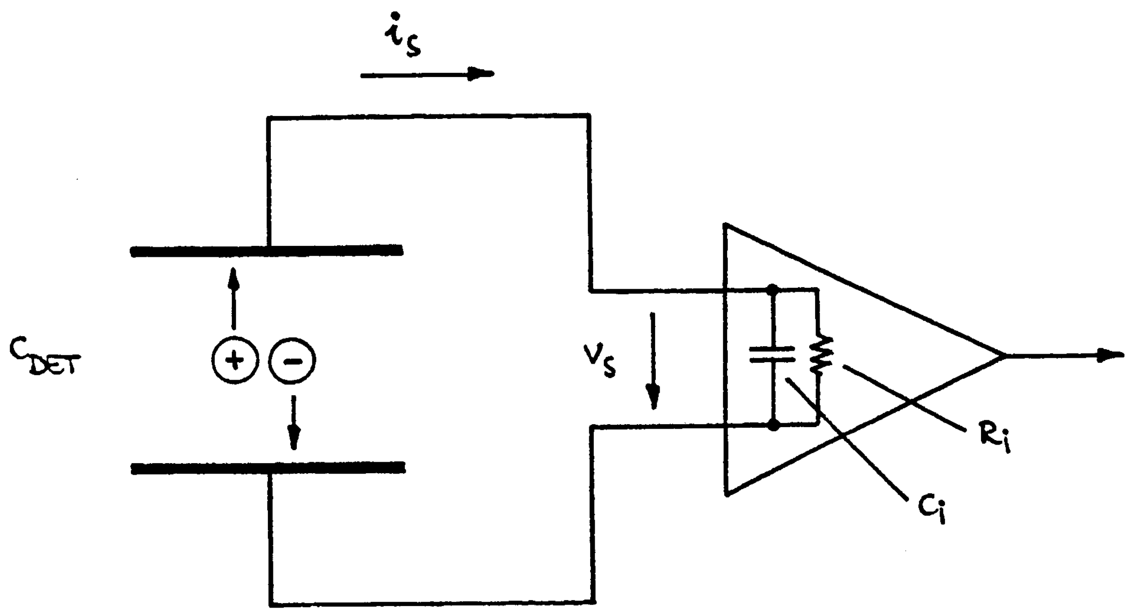
The total charge Q_s contained in the detector current pulse is $i_s(t)$ proportional to the energy deposited in the detector

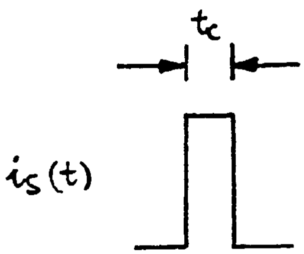
$$E \propto Q_s = \int i_s(t)\, dt$$

- Necessary to integrate the detector signal current.

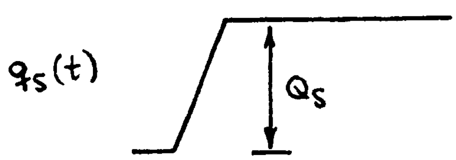
Possibilities:
1. Integrate charge on input capacitance
2. Use integrating ("charge sensitive") preamplifier
3. Amplify current pulse and use integrating ("charge sensing") ADC

Signal integration on Input Capacitance





$R_i \cdot (C_{DET} + C_i) \gg$ COLLECTION TIME t_c



$$\longrightarrow \quad V_s = \frac{Q_s}{C_{DET} + C_i}$$

$\uparrow$

System response depends
on detector capacitance !

Detector capacitance may vary within a system or change with bias voltage (partially depleted semiconductor diode).

$\Rightarrow$ make system whose gain (dV_{out}/dQ_s) is independent of detector capacitance.

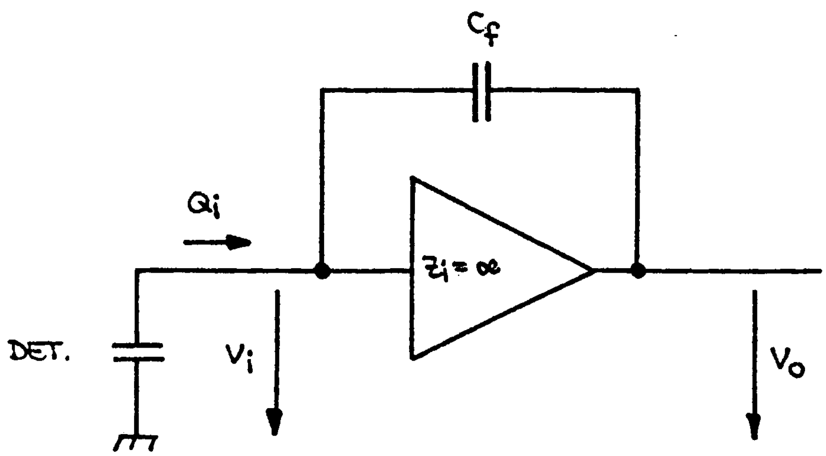
Active Integrator ("charge-sensitive amplifier")

Start with inverting voltage amplifier

Voltage gain $dV_o/dV_i = -A \quad \Rightarrow \quad v_o = -A\, v_i$

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: $\quad Q_f = C_f\, v_f = C_f\, (A+1)\, v_i$

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

$\Rightarrow$ Effective input capacitance

$$C_i = \frac{Q_i}{v_i} = C_f\,(A+1)$$

("dynamic" input capacitance)

Gain

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

Q_i is the charge flowing into the preamplifier ....

but some charge remains on C_{det}.

What fraction of the signal charge is measured?

$$\frac{Q_i}{Q_s} = \frac{C_i v_i}{Q_{\mathrm{det}} + Q_i} = \frac{C_i}{Q_s} \cdot \frac{Q_s}{C_i + C_{\mathrm{det}}}$$

$$= \frac{1}{1 + \frac{C_{\mathrm{det}}}{C_i}} \approx 1 \;\; (\text{if } C_i >> C_{\mathrm{det}})$$

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

$\uparrow$

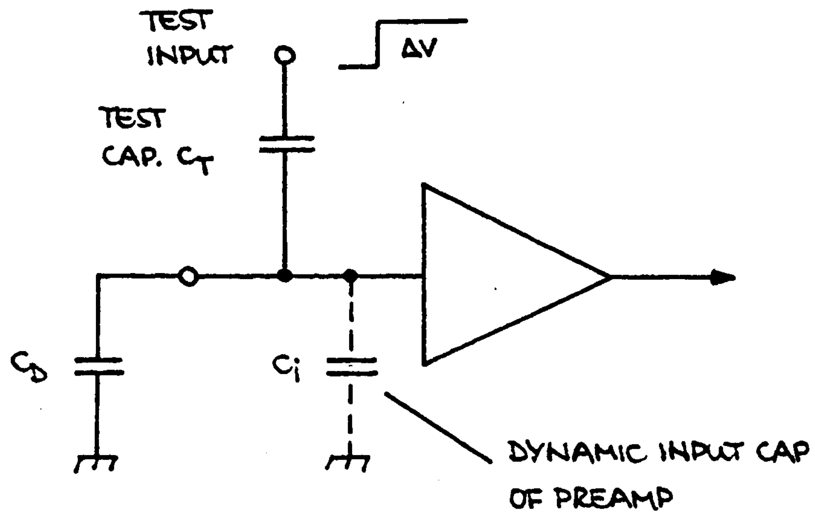
Si Det.: 50 µm thick
500 mm^2 area

Note: Input coupling capacitor must be $>> C_i$ 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.

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

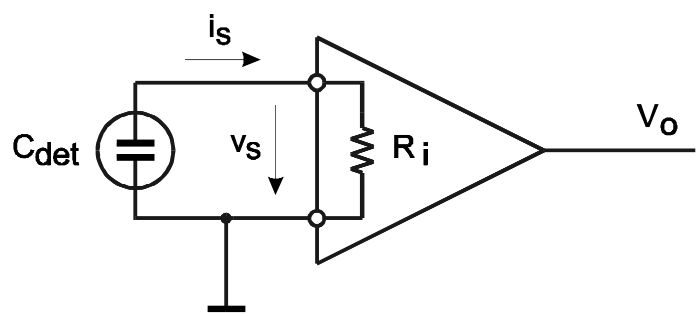
Accurate expression:

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

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

Summary of Amplifier Types

1. Simple Amplifiers



Output voltage V_o = voltage gain $A_v \times$ input voltage v_s.

Operating mode depends on charge collection time t_{coll} and the input time constant $R_i C_{det}$:

a) $R_i C_{det} << t_{coll}$ detector capacitance discharges rapidly

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

current sensitive amplifier

b) $R_i C_{det} >> t_{coll}$ detector capacitance discharges slowly

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

voltage sensitive amplifier

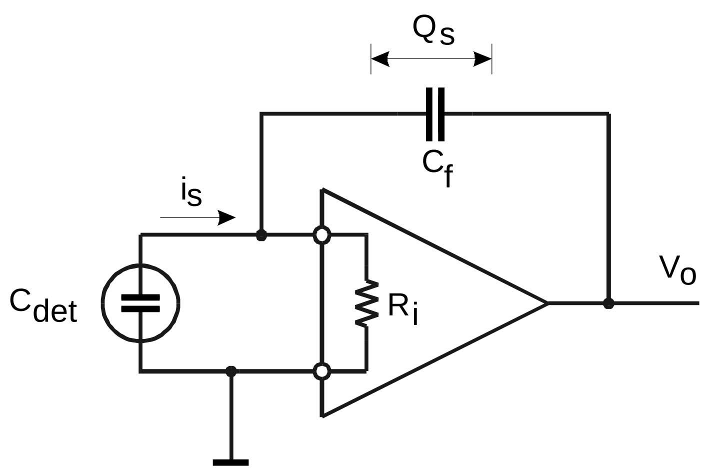
In both cases the ouput signal voltage is determined directly by the input voltage.

2. Feedback Amplifiers

Basic amplifier as used above.

High input resistance: $R_i \, C_{det} >> \; t_{coll}$

Add feedback capacitance C_f



Signal current i_s is integrated on feedback capacitor C_f :

$$V_o \propto \; Q_s / C_f$$

Amplifier output directly determined by signal charge, insensitive to detector capacitance

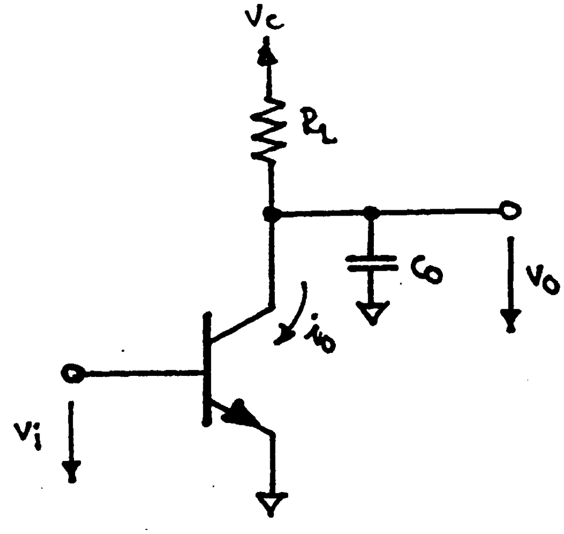
$\Rightarrow$ charge-sensitive amplifier

Realistic Charge-Sensitive Preamplifiers

The preceding discussion assumed idealized amplifiers with infinite speed.

- How do “real” amplifiers affect charge response?
- How does the detector affect amplifier response?

A Simple Amplifier



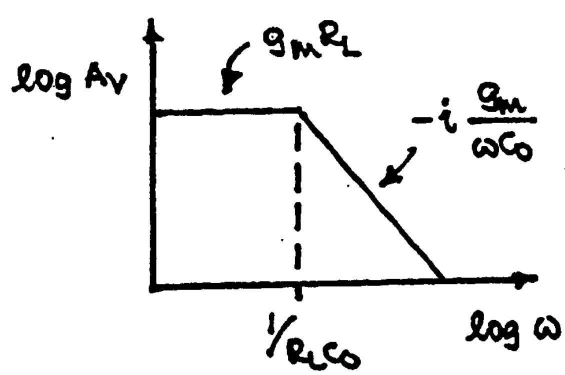
Voltage gain:

$$A_V = \frac{dv_o}{dv_i} = \frac{di_o}{dv_i} \cdot Z_L \equiv g_m Z_L$$

$g_m \equiv$ transconductance

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

$$\frac{1}{Z_L} = \frac{1}{R_L} + i\omega C_o \qquad \Rightarrow \qquad A_V = g_m \left(\underset{\substack{\uparrow \\ \text{low freq.}}}{\frac{1}{R_L}} \; + \; \underset{\substack{\uparrow \\ \text{high freq.}}}{i\omega C_o} \right)^{-1}$$



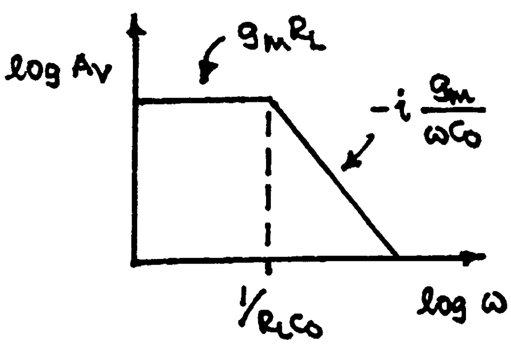
$\uparrow$ upper cutoff frequency $2\pi f_u$

Pulse Response of the Simple Amplifier

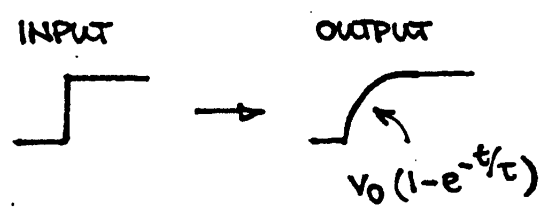
A voltage step $v_i(t)$ at the input causes a current step $i_o(t)$ at the output of the transistor.

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

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



Frequency Domain



Time Domain

Note that τ is the inverse upper cutoff frequency $1/(2\pi f_u)$

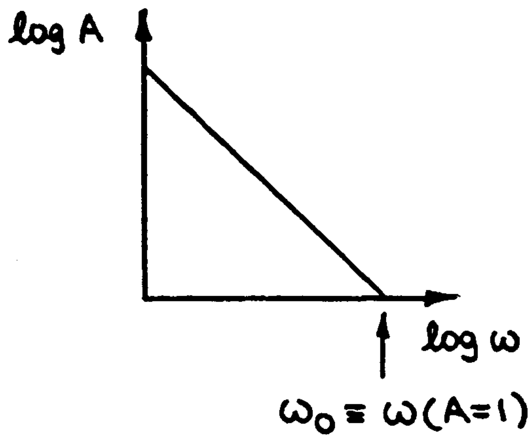
Input Impedance of a Charge-Sensitive Amplifier

Input impedance

$$Z_i = \frac{Z_f}{A+1} \approx \frac{Z_f}{A} \quad (A >> 1)$$

Amplifier gain vs. frequency

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



Gain-Bandwidth Product

Feedback Impedance

$$Z_f = -i\ \frac{1}{\omega\, C_f}$$

$\Rightarrow$ Input Impedance

$$Z_i = -\frac{i}{\omega\, C_f} \cdot \frac{1}{-i\,\dfrac{\omega}{\omega_0}}$$

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

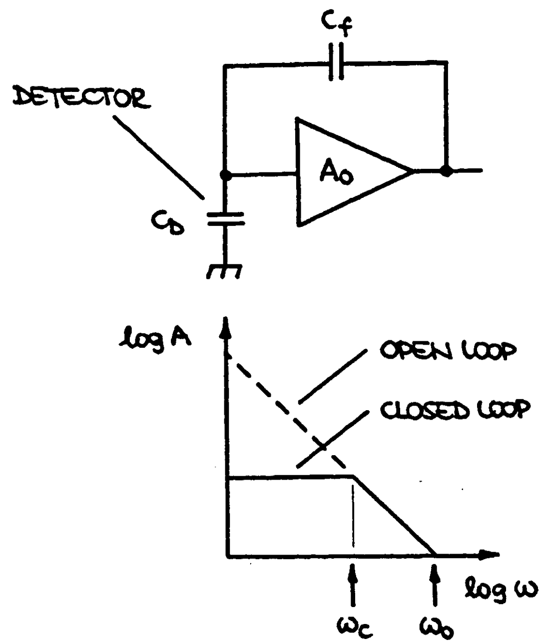
Imaginary component vanishes $\Rightarrow$ *Resistance:* $Z_i \to R_i$

Time Response of a Charge-Sensitive Amplifier

Closed Loop Gain

$$A_f = \frac{C_D + C_f}{C_f} \quad (A_f << A_0)$$

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



Closed Loop Bandwidth

$$\omega_C A_f = \omega_0$$

Response Time

$$\tau_{amp} = \frac{1}{\omega_C} = C_D \; \frac{1}{\omega_0 C_f}$$

Alternative Picture: Input Time Constant

$$\tau_i = R_i C_D$$

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

Same result as from conventional feedback theory.