V.4. Semiconductor Detectors - Summary

Energy required to form an electron-hole pair greater than band gap:

Si: $\varepsilon_i = 3.6$ eV

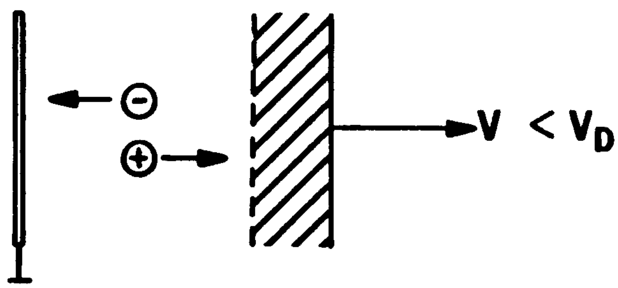
Ge: $\varepsilon_i = 2.9$ eV

Detection volume formed by reverse-biased *pn*-junction.

⇒ energy deposited in depletion region translates into signal

Detector diodes are usually asymmetrically doped.

⇒ depletion extends predominantly into lightly doped region



↑ *pn*-junction ↑ undepleted bulk

where $\varepsilon \equiv \varepsilon_r \varepsilon_0$

Depletion width: $$W = \sqrt{\frac{2\varepsilon V}{q_e N}}$$

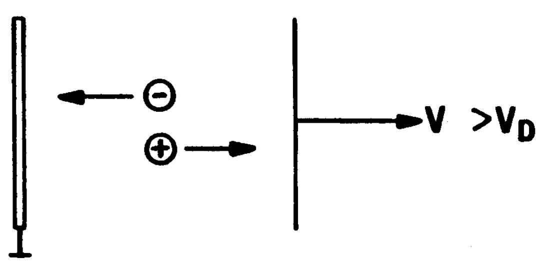
ε_r(Si)= 11.9, ε_r(Ge)= 16.0

$\varepsilon_0 = 8.85 \times 10^{-14}$ F/cm

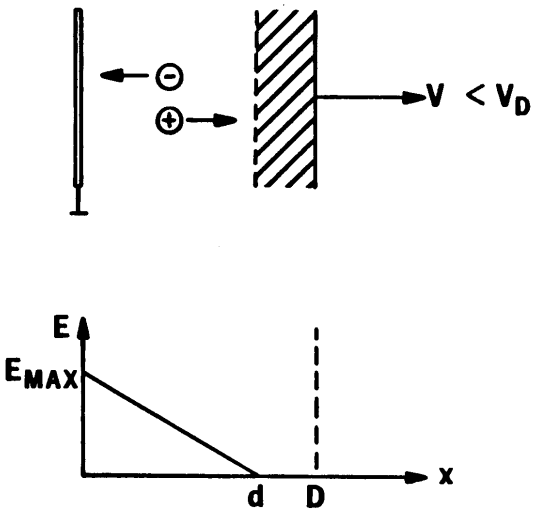
Capacitance: $$C = A\sqrt{\frac{\varepsilon q_e N}{2V}}$$

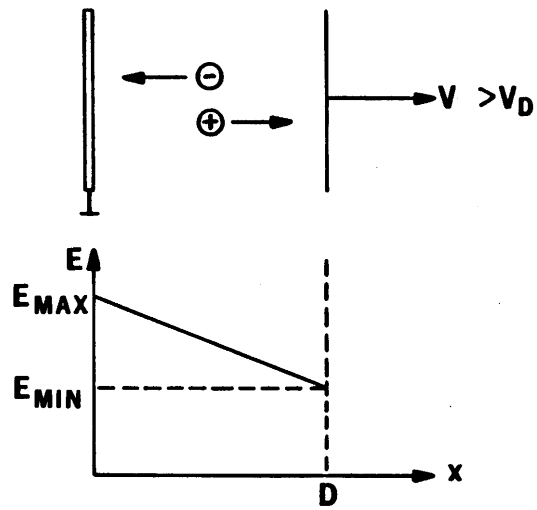
Si: W= 100 µm ⇒ 1 pF/mm^2

If the reverse bias voltage is raised to extend the depletion region throughout the bulk, the detector is "fully depleted" and energy loss in the whole volume contributes to the signal.



Electric field profiles in partial and full depletion





$$E(x) = -\frac{q_e N}{\varepsilon}(d - x)$$

$$E(x) = \frac{2V}{d}\left(1 - \frac{x}{d}\right)$$

$$E_{\max} = \frac{2V}{d}$$

$$E(x) = \frac{2V_D}{D}\left(1 - \frac{x}{D}\right) + \frac{V - V_D}{D}$$

$$V_D = \frac{D^2 q_e N}{2\varepsilon}$$

$$E_{\min} = \frac{V - V_D}{D}, \quad E_{\max} = \frac{V + V_D}{D}$$

Mobile charges move under the influence of the field with the velocity

$$\vec{v} = \mu\vec{E}$$

where the mobility μ in Si at 300K is 1350 cm^2/Vs for electrons and 480 cm^2/Vs for holes.

The mobility is constant up to about 10^4 V/cm, but then decreases and becomes proportional to $1/E$ at $E > 10^5$ V/cm, where carriers attain a constant drift velocity of 10^7 cm/s.

The collection time is the time required for all charges to reach their respective electrodes. The maximum collection time is the time required for electrons and holes to traverse the depletion region.

In partial depletion: $$t_c \approx 3 \cdot \frac{\varepsilon}{\mu q_e N} = 3 \cdot \frac{D^2}{2\mu V}$$

for charge traversing 95% of the depletion width. The collection times for electrons and holes are obtained by inserting the appropriate value of mobility.

- The collection time in partial depletion is independent of the applied voltage.

In operation beyond the full depletion voltage

$$t_c = \frac{D^2}{2\mu V_D} \ln \frac{V + V_D}{V - V_D}$$

which for large values of overbias $V >> V_D$ becomes $t_c \approx \frac{D^2}{\mu V}$

Note: In both partial and full depletion the collection time can be estimated easily by determining the average field

$$\overline{E} = \frac{E_{\min} + E_{\max}}{2}$$

and calculating the transit time $t_c = d/v$ (or $t_c = D/v$), so in

partial depletion	and	full depletion
$\overline{E} = \frac{V}{d}$		$\overline{E} = \frac{V}{D}$
$t_c \approx \frac{d^2}{\mu V}$		$t_c \approx \frac{D^2}{\mu V}$

At a field of 10^3 V/cm electrons require 7 ns to traverse 100 µm.

Energy Resolution and Electronic Noise

- The energy resolution of semiconductor detector systems is determined largely by electronic noise. The principles that set the electronic noise level apply to all types of detectors.

Primary noise sources can be described as

current noise

and

voltage noise

Noise sources are characterized by their spectral noise density

$$\frac{dI_{noise}^2}{df} \equiv i_n^2 \qquad\qquad \frac{dV_{noise}^2}{df} \equiv v_n^2$$

Typical current noise sources:

shot noise from reverse bias current	$i_n^2 = 2q_e I_B$
resistors connected parallel to input	$i_n^2 = 4kT / R_P$
amplifier (equivalent input noise)	i_n^2

Typical voltage noise sources:

series resistance in detector signal path	$v_n^2 = 4kTR_S$
amplifier (equivalent input noise)	v_n^2

The equivalent input noise of the amplifier is determined by measuring the noise at the output vs. input load impedance and deriving an equivalent circuit consisting of a noiseless amplifier with voltage and current noise sources at the input.

For voltage noise, the equivalent input noise voltage is the output noise voltage divided by the amplifier’s voltage gain.

Since the energy deposited in the detector translates directly into charge, it is convenient to express the electronic noise as an Equivalent Noise Charge (ENC).

Equivalent Noise Charge :

signal charge for which the signal-to-noise ratio $S/N = 1$.

$$Q_n^2 = i_n^2 \quad T_s F_i \; + \; C_i^2 v_n^2 \quad \frac{F_v}{T_s} \; + \; C_i^2 A_f \quad F_{vf}$$

↑	↑	↑	↑	↑	↑
front end	shaper	front end	shaper	front end	shaper

where T_s — Characteristic shaping time (*e.g.* peaking time)

F_i , F_v , F_{vf} — Noise indices ("form factors") that are determined by the shape of the output pulse.

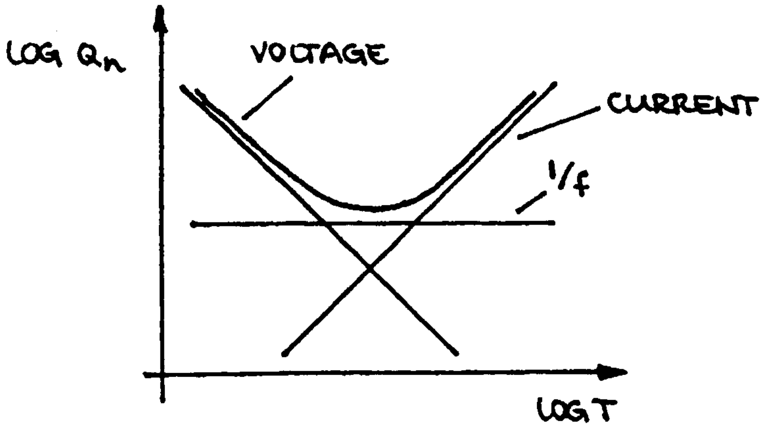
They can be calculated in the frequency or time domain. CR-RC Shaper: $F_i = F_v = 0.9$

C_i — Total capacitance at the input node (detector capacitance + input capacitance of preamplifier + stray capacitance + …)

- Current noise contribution increases with T_s
- Voltage white noise contribution decreases with increasing T_s

  "1/*f* " voltage noise contribution constant in T_s
- Only valid for capacitive signal source
- ENC is the standard deviation of the Gaussian noise distribution and is typically expressed in fC, electrons or eV (using the ionization energy of the detecting medium).
- ENC is a derived quantity – combined effect of noise current and voltage, capacitance at input, and pulse shaper.

Minimum equivalent noise charge is obtained at the shaping time where the current and voltage noise contributions are equal.



Equivalent Noise Charge vs. Detector Capacitance ($C_d = C_i - C_a$)

If current noise $i_n^2 F_i T$ is negligible:

$$\frac{dQ_n}{dC_d} \approx 2v_n \sqrt{\frac{F_v}{T}}$$

Zero intercept (determined by input capacitance of amplifier and stray capacitance at input)

$$Q_n\Big|_{C_d=0} = C_a v_n \sqrt{F_v / T}$$