Chapter XI:
Electronic dosimeters

Types of electronic dosimeters

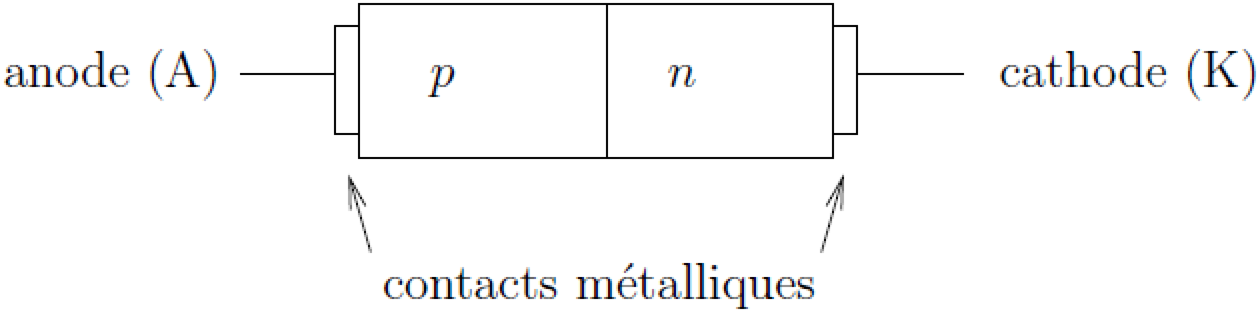
- Electronic dosimeters include both passive (integrators) or active (real-time measurement) dosimeters
- We discuss here about dosimeters made of silicon (even though dosimeters made of germanium, diamond, etc. also exist → less used or more expensive)
- 2 devices will be considered (→ **no** bipolar transistors, **no** solid ionization chambers) →
  - Diode
  - MOSFET (Metal-Oxide Semiconductor Field Effect Transistor)
- References:
  - J. Barthe, *Electronic dosimeters based on solid state detectors*, Nuclear Instruments and Methods in Physics Research B: 184 (2001) 158–189
  - A. Holmes-Siedle, L. Adams, *Handbook of radiation effects* (Oxford Science Publication) 1994

Introduction

- Electronic dosimeter → personal dosimeters, dosimeters for radiotherapy, for curietherapy,…
- Si is used for electronic dosimeters → well known material
- Several advantages of the electronic dosimeter :
    1. Z = 14 → « relatively » tissue-equivalent → for E < 150 keV → increase of the interaction cross section compared to tissues (photoelectric effect)
    2. Better sensitivity than a gas (factor 20000) due to its larger density (factor 2000) and to its smaller ionization energy (factor 10)
    3. Smaller size → B-G conditions satisfied and possibly placed into a confined volume (human body)
    4. Good mechanical stability
    5. Possibility to measure doses or dose rates
    6. Possibility to make neutrons dosimetry (not studied here)

Diode dosimeter: Definition of the diode

- Si diode → junction of 2 types of semiconductors →
  - p-type diode: crystal of p-type (excess of h^+) with a thin layer at the surface of n-type (excess of e^-)
  - n-type diode: crystal of n-type with a thin layer at the surface of p-type
- Thin metal layers are deposited on the semiconductors to make the anode (contact with the p-region) and the cathode (contact with the n-region)



n-type semiconductor

- Silicon and Germanium are tetravalent
- If a pentavalent impurity (doping) atom as arsenic, phosphorus, antimony (donor element) is introduced → replacing an atom lattice → an extra electron does not fit into the valence band
- This extra e^- is weakly bound → easily excited to the conduction band → localized level just below the bottom of the conduction band
- Ionization energy of this extra level: a few 0.01 eV → comparable to thermal energy → e^- in the conduction band without h^+ in the valence band → **n-type semiconductor**
- Practically concentration of donor $N_D \gg n_i$ → electron concentration $n \approx N_D$ ($N_D \sim 10^{15}$ atoms/cm^3) →

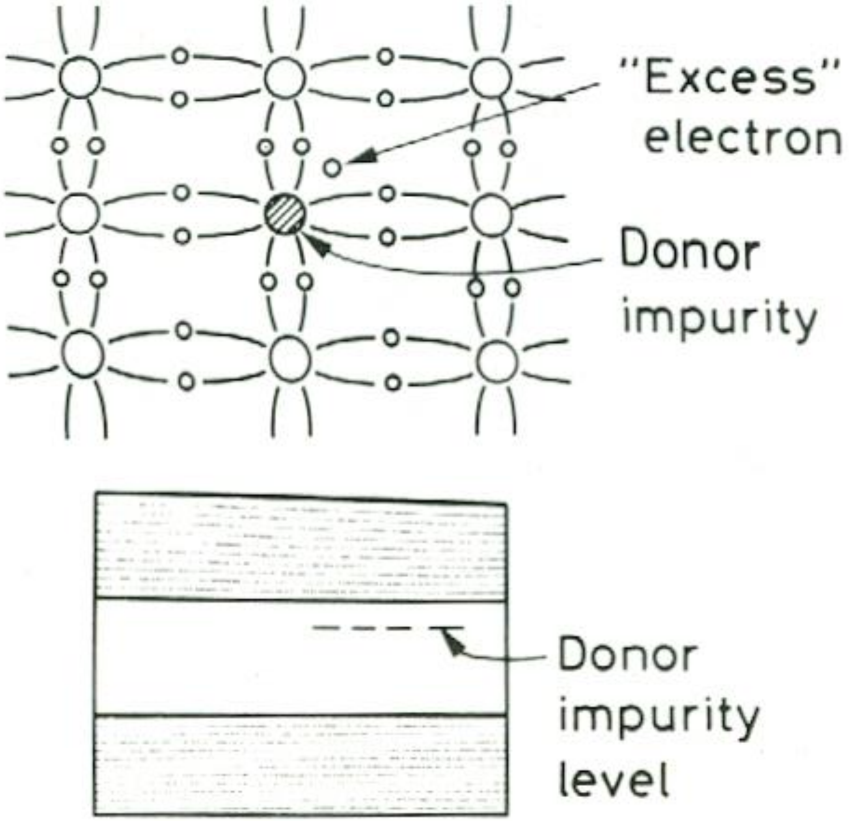
$$\sigma = eN_D\mu_e$$

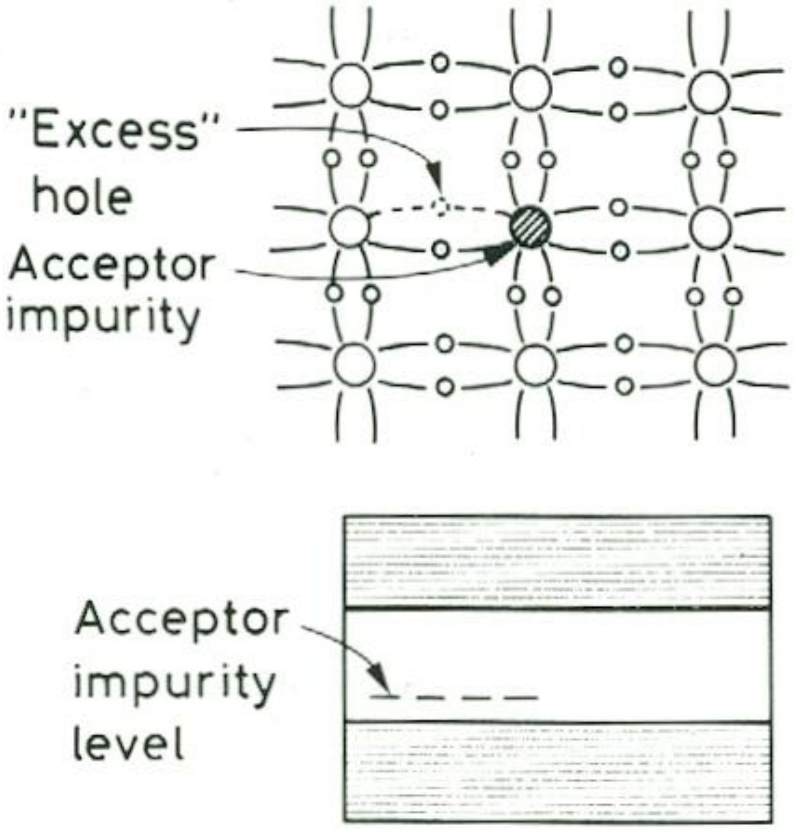
p-type semiconductor

- If a trivalent impurity atom as gallium, boron indium (acceptor element) is introduced → replacing an atom lattice → no enough electron to fill the valence band → excess of hole
- A captured e^- in this hole is less bound than normal e^- → localized level just above the top of the valence band
- e^- in the valence are easily excited to this level → extra hole in the valence band without e^- in the conduction band → **p-type semiconductor**
- Practically concentration of acceptor $N_A \gg n_i$ → hole concentration $p \approx N_A$ ($N_A \sim 10^{15}$ atoms/cm^3) →

$$\sigma = eN_A\mu_h$$

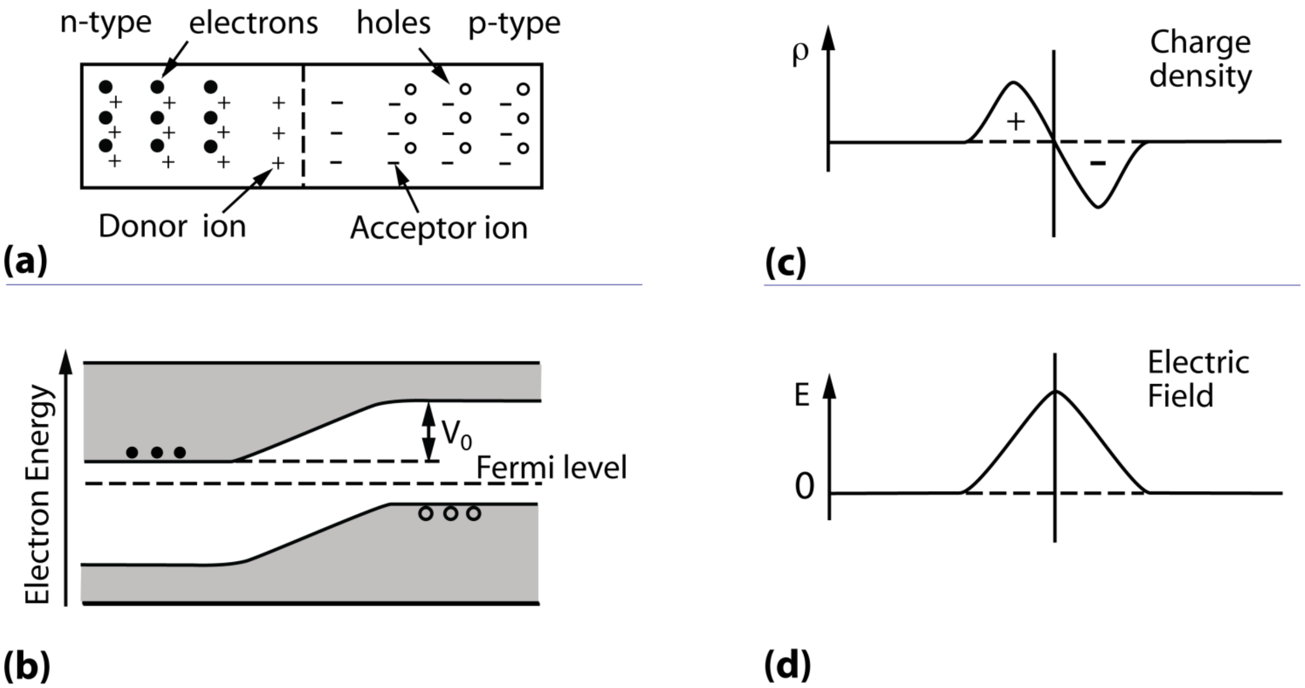
Representation of doped (extrinsic) semiconductors





Principle of the diode

≠ density of charge → diffusion of majority e^- from n-region to p-region and of majority h^+ from p-region to n-region → in the junction zone: recombination of e^- and h^+ → positive ions in the n-region and negative in the p-region → electric field (10^3 V/cm) in this region (called *depletion region*)



Depletion depth (1)

- The width of the depletion zone (= *d*) depends on the concentration of n and p impurities. It can be determined from Poisson's equation (with ε the dielectric constant):

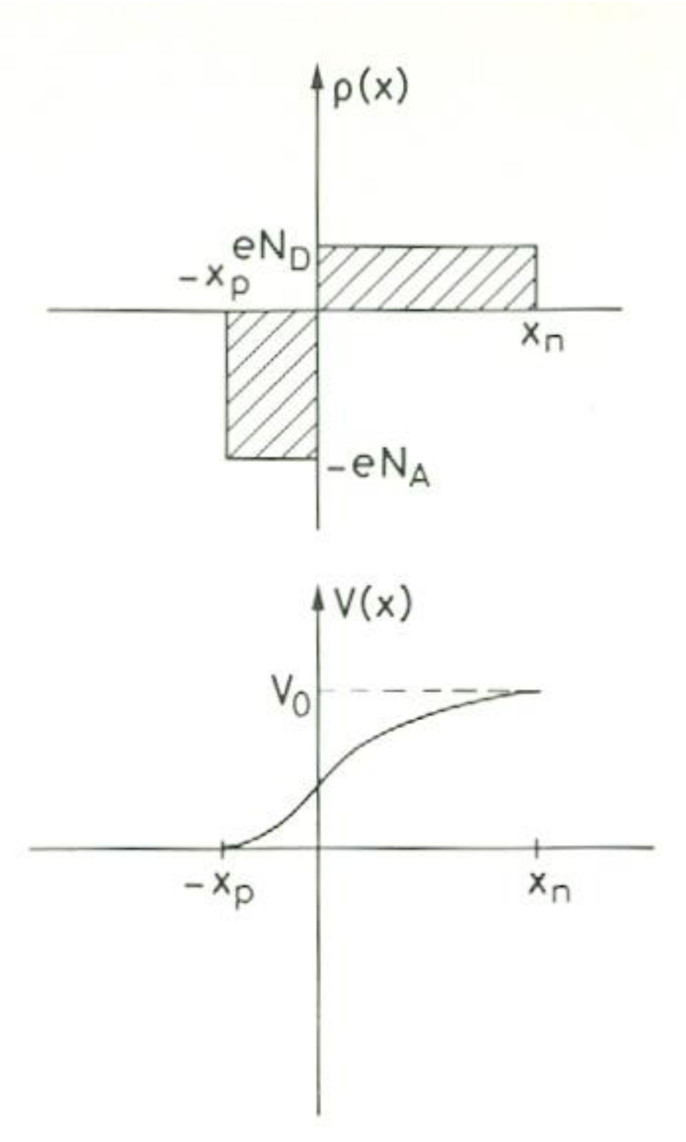
$$\frac{d^2V}{dx^2} = -\frac{\rho(x)}{\varepsilon}$$

- If we consider an uniform charge distribution about the junction and with x_n and x_p the extents of the depletion zone on the n- and p-sides and a contact potential V_0 →

$$\rho(x) = \begin{cases} eN_D & 0 < x < x_n \\ -eN_A & -x_p < x < 0 \end{cases}$$

- Since the charge is conserved: $N_A x_p = N_D x_n$ (with $N_A \approx p$ the acceptors concentration and $N_D \approx n$ the donors concentration)

Depletion depth (2)



Depletion depth (3)

- Integrating Poisson's equation:

$$\frac{dV}{dx} = \begin{cases} -\frac{eN_D}{\varepsilon}x + C_n & 0 < x < x_n \\ \frac{eN_A}{\varepsilon}x + C_p & -x_p < x < 0 \end{cases}$$

- Since *dV/dx = 0* at *x = x$_n$* and *x = -x$_p$*:

$$\frac{dV}{dx} = \begin{cases} -\frac{eN_D}{\varepsilon}(x - x_n) & 0 < x < x_n \\ \frac{eN_A}{\varepsilon}(x + x_p) & -x_p < x < 0 \end{cases}$$

- One more integration:

$$V(x) = \begin{cases} -\frac{eN_D}{\varepsilon}\left(\frac{x^2}{2} - x_n x\right) + C & 0 < x < x_n \\ \frac{eN_A}{\varepsilon}\left(\frac{x^2}{2} + x_p x\right) + C' & -x_p < x < 0 \end{cases}$$

Depletion depth (4)

- As solutions are equal at $x = 0 \rightarrow C = C'$ and as $V(x_n) = V_0$ and $V(-x_p) = 0$:

$$\begin{aligned} V_0 &= \frac{eN_D}{2\varepsilon}x_n^2 + C \\ 0 &= -\frac{eN_A}{2\varepsilon}x_p^2 + C \end{aligned}$$

- Eliminating C:

$$V_0 = \frac{e}{2\varepsilon}(N_D x_n^2 + N_A x_p^2)$$

- Using the charge conservation equation:

$$x_n = \left(\frac{2\varepsilon V_0}{eN_D[1 + N_D/N_A]}\right)^{1/2} \quad \text{and} \quad x_p = \left(\frac{2\varepsilon V_0}{eN_A[1 + N_A/N_D]}\right)^{1/2}$$

➡ $d = x_n + x_p$

Depletion depth (5)

- Considering for instance $N_A \gg N_D$ → $x_n \gg x_p$ →

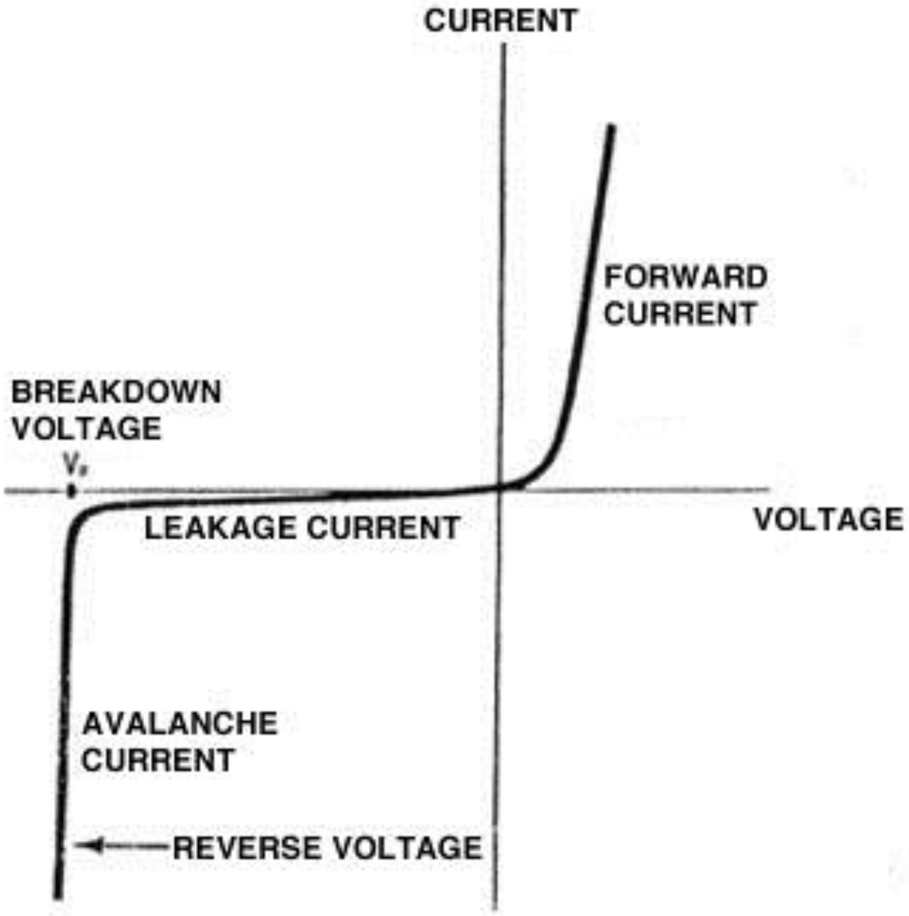
$$d \simeq x_n \simeq \left(\frac{2\varepsilon V_0}{eN_D}\right)^{1/2}$$

- Extension of the depletion zone to the n-side
- For Si with ρ = 20000 Ωcm and V_0 = 1V → d ≈ 75 µm

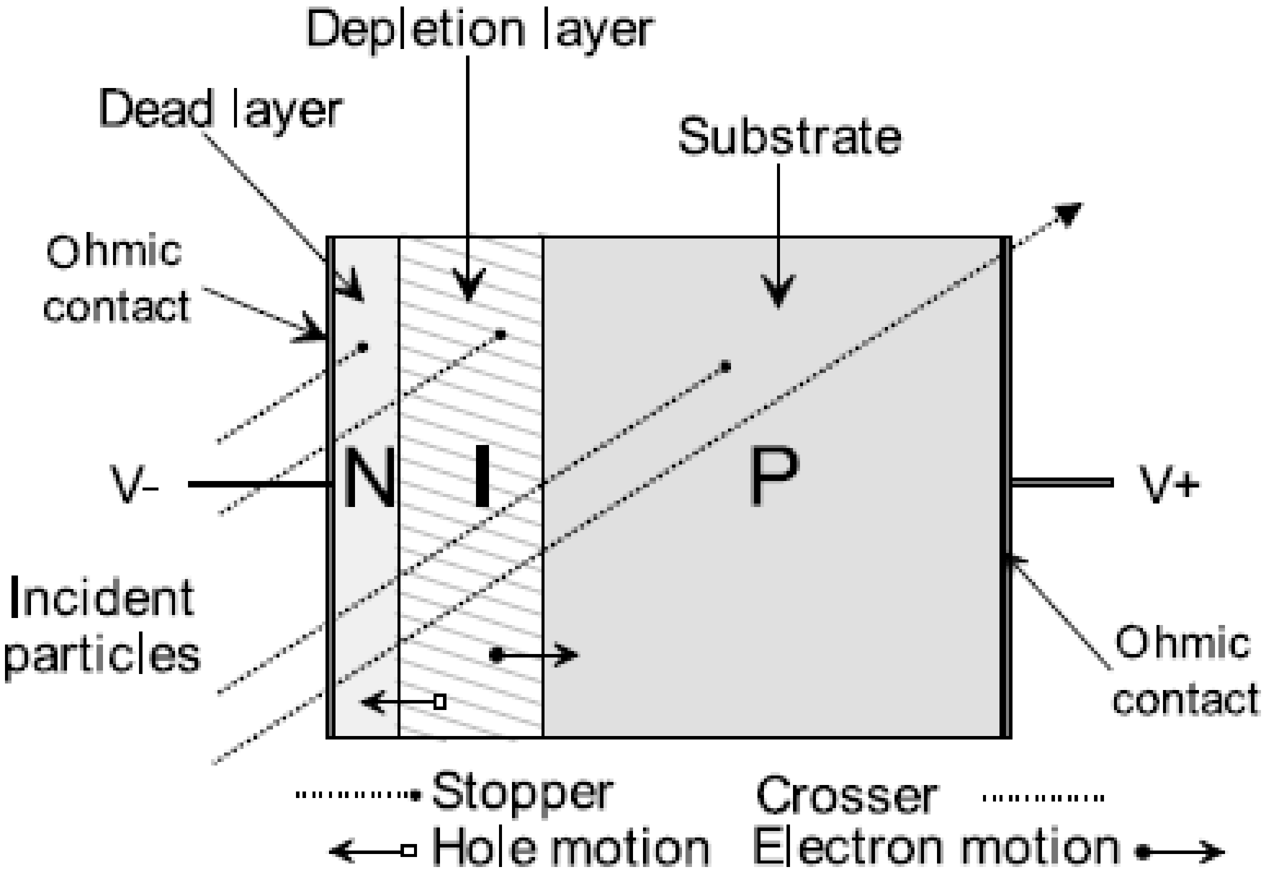
Applied voltage

- If an external voltage is applied such as the anode is at a larger potential than the cathode potential (direct polarization) → decrease of the potential at the junction → a current will flow → no use in in dosimetry
- If an external voltage is applied such as the anode is at a smaller potential than the cathode potential (inverse polarization) → re-enforcement of the potential difference at the junction → no current
  1. This voltage attracts h^+ in the p-region away from the junction and similarly for the e^- in the n region → enlarge the depletion zone (use in previous equation $V_B+V_0 \approx V_B$ because $V_B \gg V_0$) → 5 mm in Si
  2. *V_B* is limited → attention to the breakdown (by Zener or avalanche effect)

Current – voltage feature



Principle of diode detector (1)



Principle of diode detector (2)

- When an ionizing radiation passes through the diode → creation of e^- - h^+ pairs
- When the pairs are created in the depletion zone or at a distance < $L_{p,n}$ (the diffusion lengths of the carriers) of the depletion zone (« sensitive part » of the diode) → they undergo the electric field → they reach the boundaries of the depletion zone → voltage pulse is collected
- Only pairs created in the sensitive part of the diode ($d + L_p + L_n$) will be collected → sensitivity of the diode $\propto$ depth of the depletion zone
- The diode is used in reverse bias for the measurement of small doses and without polarization for high doses (in radiotherapy) → depth of the depletion zone reduced to minimum
- For diodes used in spectrometry → difference → the particle has to deposit all its energy in the depletion zone → size ↗

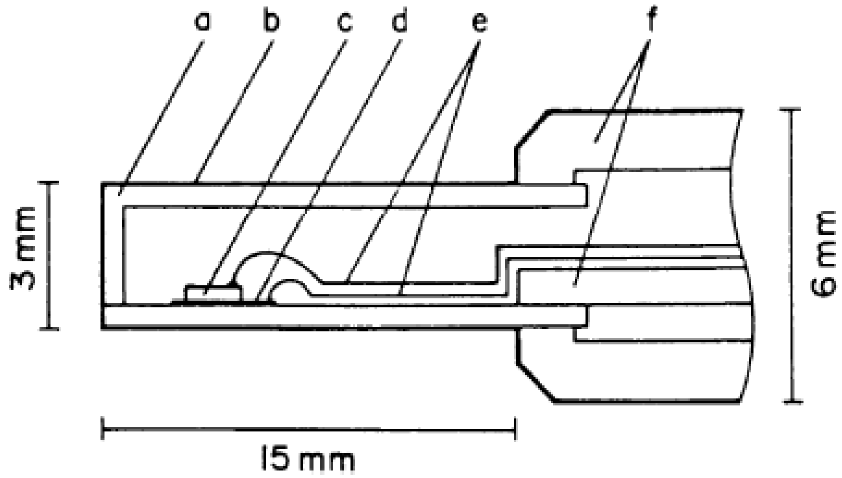
Type of diode used in dosimetry (1)

- The sensitivity of a diode detector is linked to the life time of the charge carriers created → if recombination → charge is lost → sensitivity ↘
- The life time is itself linked to the concentration of defects (= traps) in the diode
- The irradiation will introduce additional defects in the material (radiative damages) → sensitivity depends on the dose and on the dose rate
- It is possible to show that the number of additional traps as a function of the dose rate created in a n-type semiconductor is larger than for a p-type → the irradiation affects more importantly the life time of the e^- than the one of the h^+
- In practice in dosimetry → p-type diode (« large » volume of p-type associated with a « small » volume of n-type) because the loss of sensitivity is largely more important for n-type diodes than for p-type

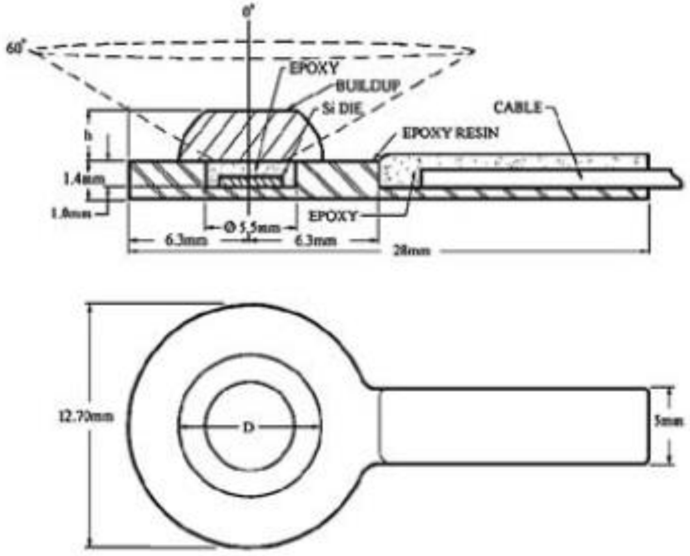
Type of diode used in dosimetry (2)

- Diodes for dosimetry are ≠ of diodes used in spectrometry
- To minimize the perturbations in the medium (Bragg rule: no perturbation of the fluence by the detector) → diode smallest as possible (classical dimensions: $1 \times 1 \times 1$ mm^3)
- Size not too small anyway → sensitivity $\propto$ size of the depletion zone → compromise must be found
- The material surrounding the diode is also important → generation of secondary charged particles → as tissue-equivalent as possible: electric contacts in Al, supports in plastic, carbon,…

2 examples of diode dosimeters



(a) polyethylene
(b) carbon cover
(c) Si diode
(d) carbon epoxy
(e) cables in Al
(f) PMMA

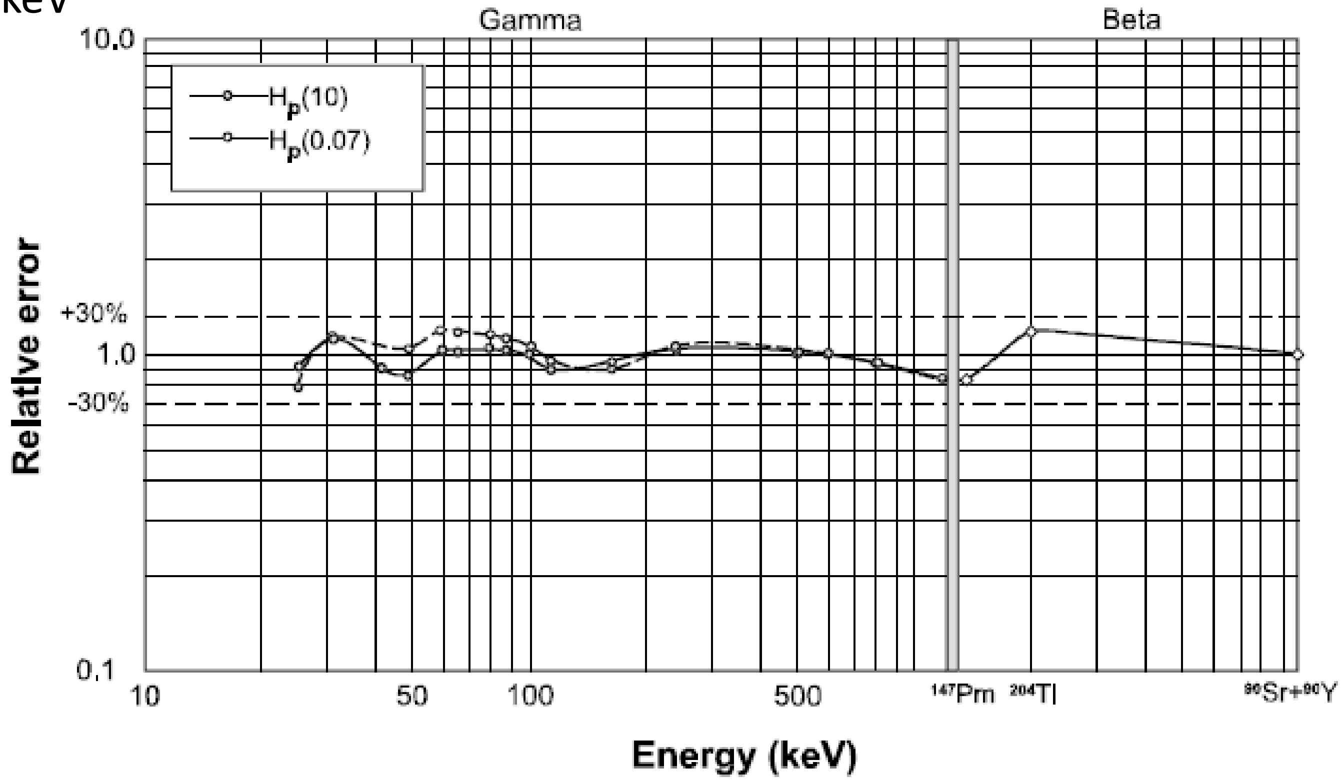


Diode developed by Sun Nuclear Corporation

Energy response

- Difficulty for small energy γ → photoelectric effect is dominating → overestimation of the dose → problem → use of filters

X, γ rays: 20 keV to 6 MeV

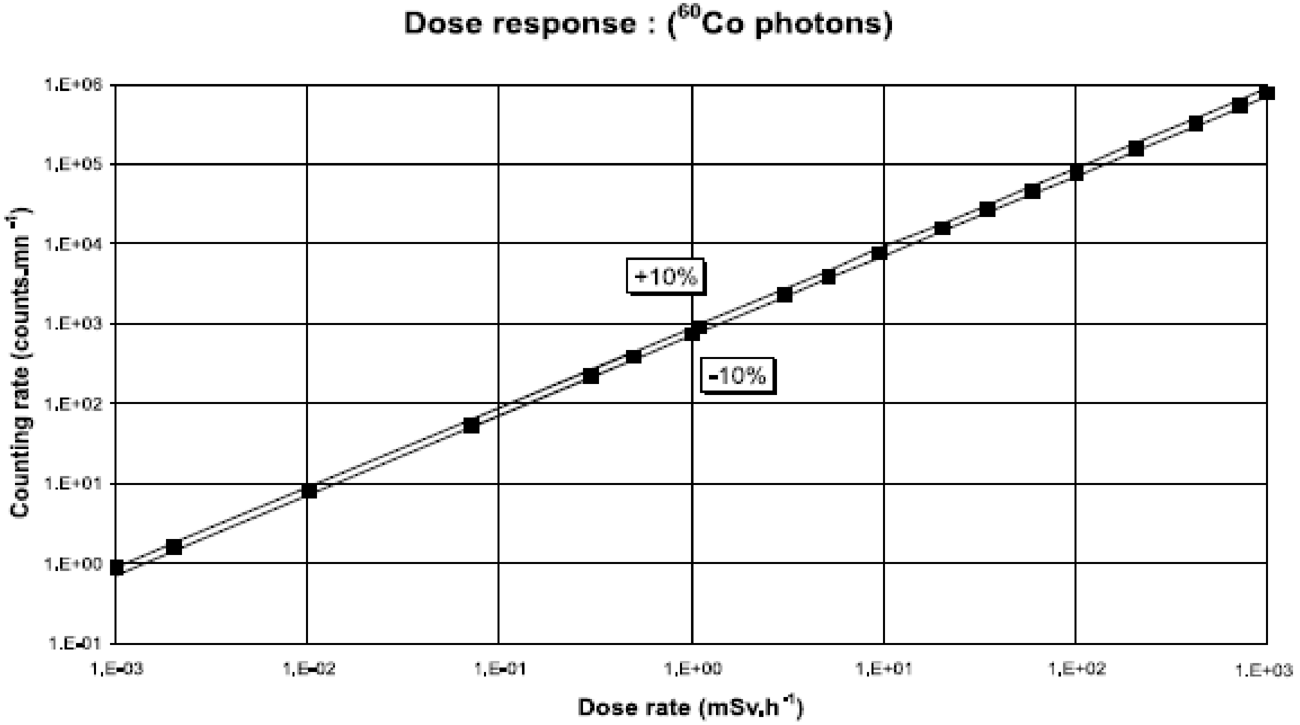


β: > 60 keV

Dosimeter DMC-2000 XB: MGP Instruments

Response in dose

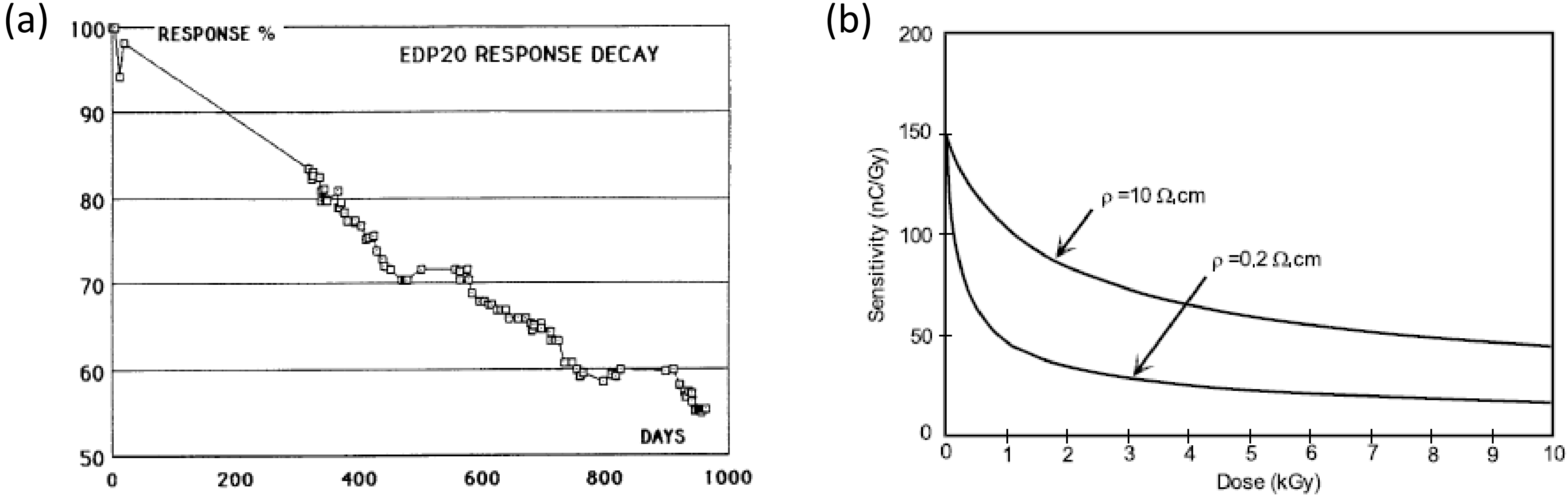
- In pulse mode (for not too important dose rates → not for radiotherapy) → linear dose response



Dosicard: Canberra

Effect of cumulated dose (1)

- As written above → irradiation produces additional defects in the material
- When the dose ↗ (remark: high doses) → sensitivity ↘



(a) Diode EDP-20: Scanditronix - Wellhöfer → dose rate: 45 Gy/j, γ of 25 MeV
(b) Response as a function of the cumulated dose for 6 MeV γ

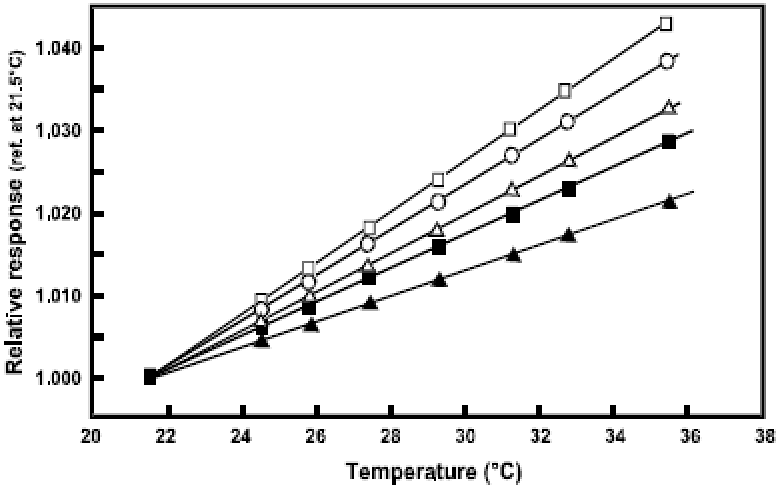
Effect of cumulated dose (2)

- To precisely determine the dose at a given time → the decay curve of the sensitivity and the previous irradiation level should ne known → problem

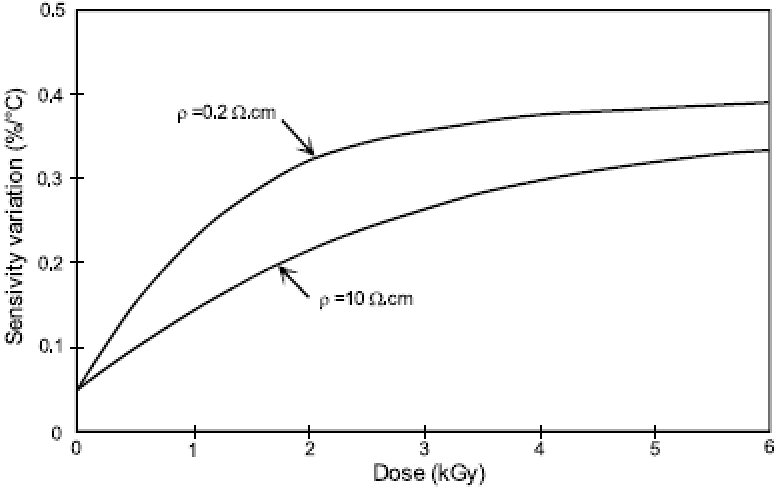
- Solution → pre-irradiation before use to reach a (about) constant level of sensitivity

Temperature effect

- When T ↗ → the concentration of carriers ↗ → large dependence of the diode response as a function of T → problem
- In practice → SVWT (*sensitivity variation with temperature*) = 0.1%/°C for a non pre-irradiated diode
- For p-type diode pre-irradiated at 5 kGy (20 MeV γ) → SVWT = 0.35-0.4 %/°C → SVWT depends on the cumulated dose (and also on the dose rate)



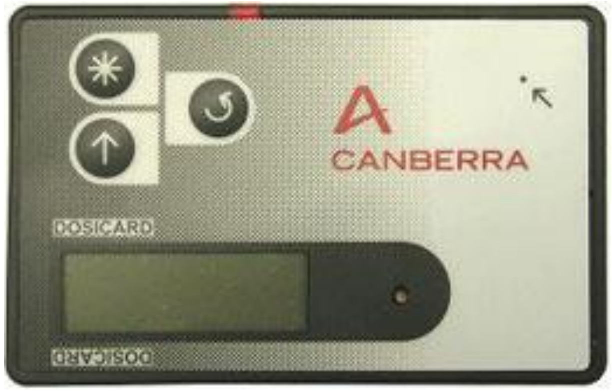
Response in T for ≠ diodes



SVWT as a function of the cumulated dose for 6 MeV γ

Examples of available personal dosimeters

ES600 of Labomoderne



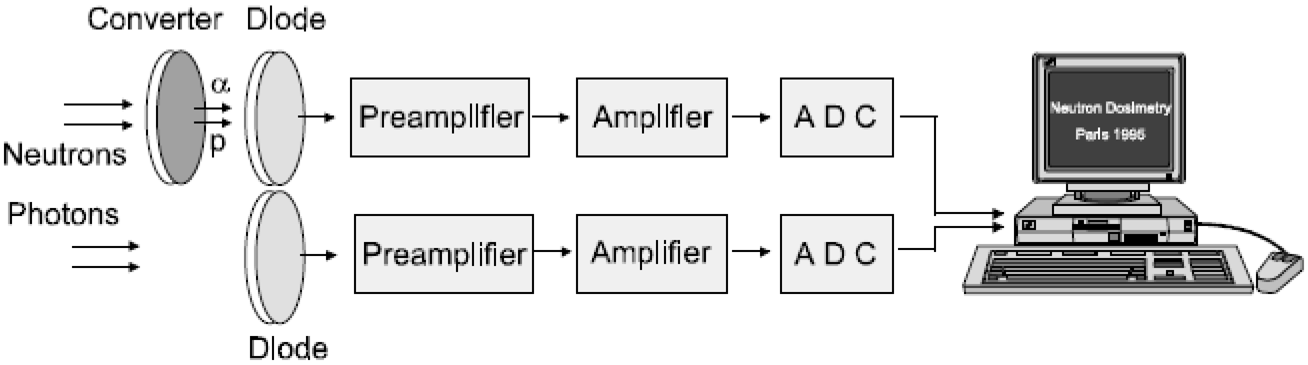
Dosicard of Canberra

Characteristics of ES600 and of dosicard

- Very similar
- For β and γ
- Measure of dose: 1 μGy < D < 10 Gy
- Measure of dose rate: 1 μGy/h < D/h < 1 Gy/h
- Accuracy: < ± 15% at ^{137}Cs, up to 1 Sv/h
- Non-volatile EEPROM memory
- Digital readout of the dose and of the dose rate
- Alarm
- Storage of data

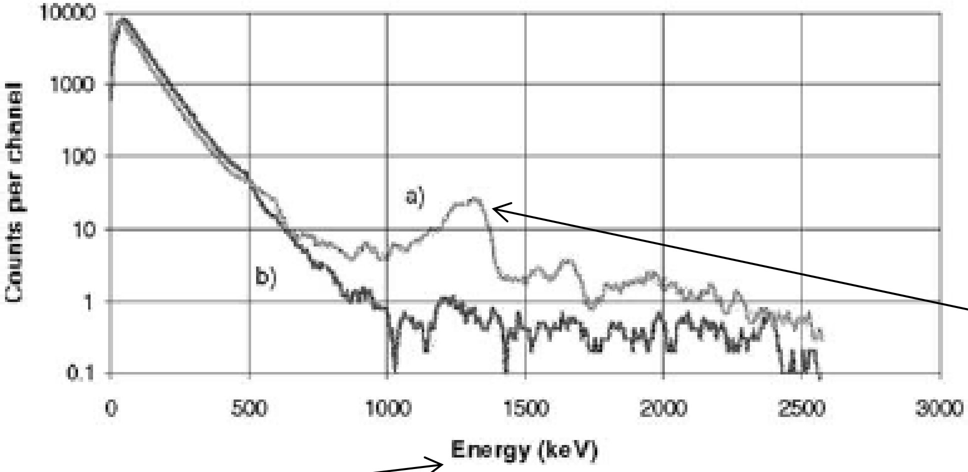
Neutrons detectors with diodes (1)

- Neutrons detectors based on the used of 2 diodes
- Diode 1 (called neutron diode): covered with an organic medium (plastic: PE,…) doped with ^{10}B (≈ 10^{13}/cm^3 B atoms) → sensitive to neutrons and γ
- Diode 2 (called γ diode): « nude » → no sensitive to neutrons and sensitive to γ
- The 2 diodes are side by side and $\perp$ to ionizing radiations (neutrons + γ)



Neutrons detectors with diodes (2)

- Thermal n interact with 1 in 2 ways →
  1. H(n,n)p → emission of protons
  2. $^{10}B(n,\alpha)^{7}Li$ → emission of α
- The ≠ between signals from diodes 1 et 2 allows to discriminate the contribution due γ from the contribution due to neutrons



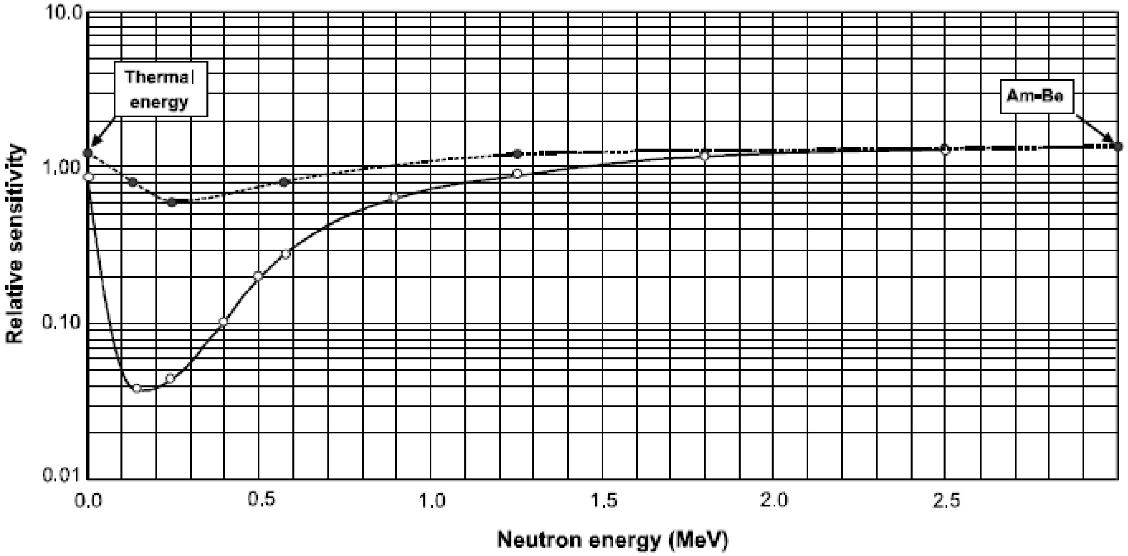
a) Diode 1
b) Diode 2

Pic α

Measured spectrum

Neutrons detectors with diodes (3)

- If the size of the plastic coating is large → important moderation of high energy neutrons → it is possible to study neutrons with high *E*
- The quantity of ^{10}B is chosen to obtain a response to thermal neutrons equal to the response to fast neutrons



Neutrons detectors with diodes (4)

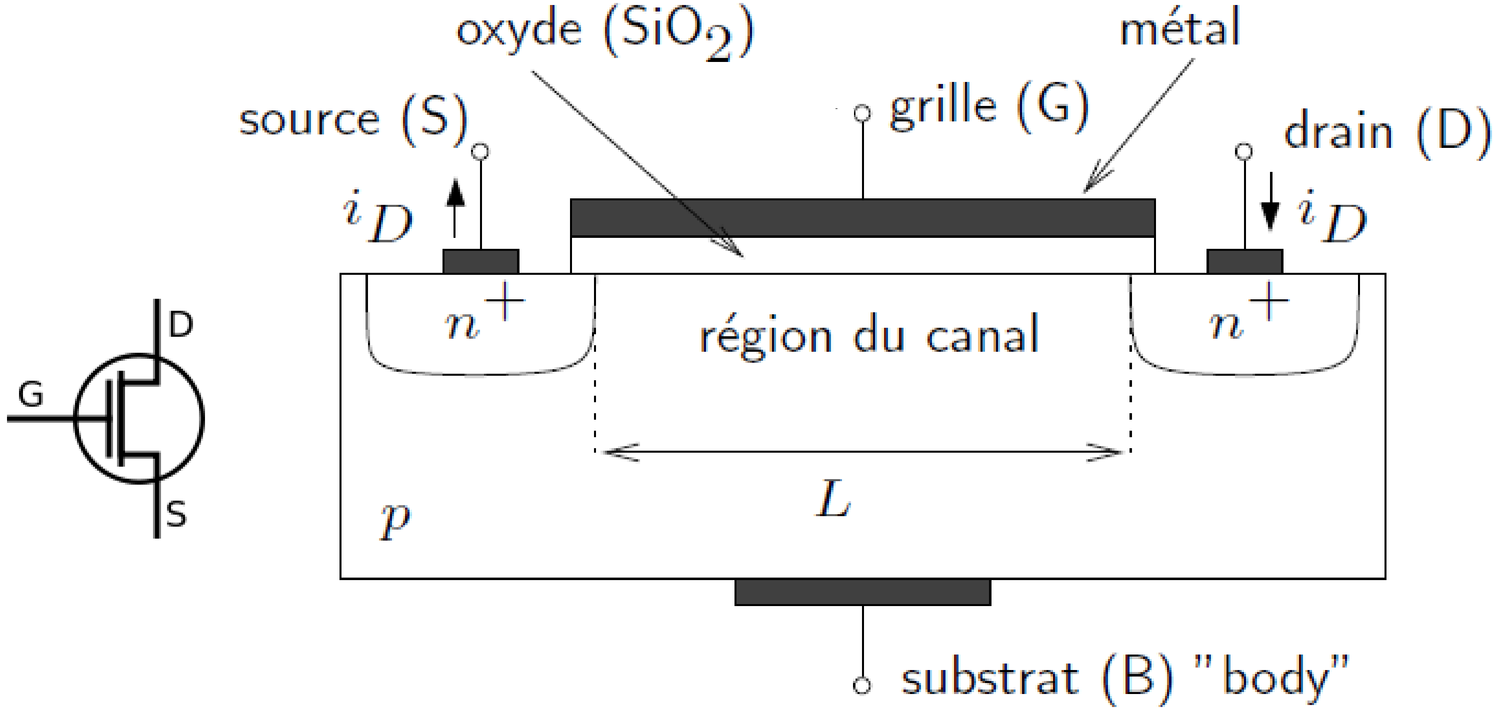
- For very high E (*E* > 10 MEV) → addition of Pb → reaction (n,2n)
- To improve the precision for a large range of *E* → system with 3 or 4 diodes with ≠ coatings → multi-elements detector (Saphydose detector)

Saphydose Detector of Saphymo

MOSFET dosimeter: Definition of MOSFET

- MOSFET → acronym for Metal-Oxide Semiconductor Field Effect Transistor
- Field effect transistor → use of an electric field to control the shape and the conductivity of a « channel » in a semiconductor material → modulation of the current passing through (between the « source » and the « drain ») with a voltage applied on the central electrode called « gate »
- For the MOSFET → the gate (metal or polycrystalline silicon) is electrically isolated from the substrate (semiconductor) by a dielectric (as SiO_2) → no current injected by the gate
- Can be n- or p-type channel

Scheme of a n-type channel MOSFET (nMOS)



Typical characteristics → $L \approx$ 1-40 μm, SiO$_2$ thickness ≈ 0.02-0.1 μm, ⊥ width ≈ 2-500 μm, n regions strongly doped (n$^+$): $n \geq 10^{17}$ cm^{-3}

Principle of operation (n channel)

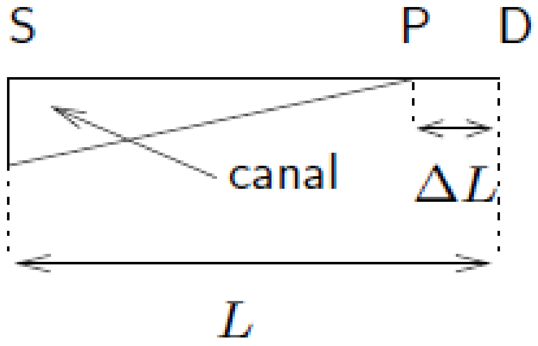
- Assumptions:
  1. $V_S = V_B$
  2. We apply a positive difference of potential $V_{DS} = V_D - V_S > 0$ between the drain and the source
- Without grid polarization → $V_{GB} = V_G - V_B = V_{GS} = 0$ → no current between the source and the drain → $I_D = 0$
- $V_{GS} \nearrow \rightarrow$
  1. $V_{GS} \leq V_{TH} \rightarrow I_D = 0$ → Cutoff mode: when the gate voltage is smaller than the « threshold voltage »

     → h^+ repelled to the substrate → creation of a depletion zone

     → e^- thermally generated in the substrate or coming from n^+ regions are attracted at the surface of the substrate
  2. $V_{GS} > V_{TH}$ and $V_{DS} < (V_{GS} - V_{TH}) \rightarrow I_D$ linearly ↗ → Linear mode (or triode mode or ohmic mode): creation of a conduction channel of e^- → the transistor operates like a resistor
  3. $V_{GS} > V_{TH}$ and $V_{DS} > (V_{GS} - V_{TH}) \rightarrow I_D$ independent of V_{DS}: Saturation mode (or active mode): $I_D \propto (V_{GS} - V_{TH})^2$

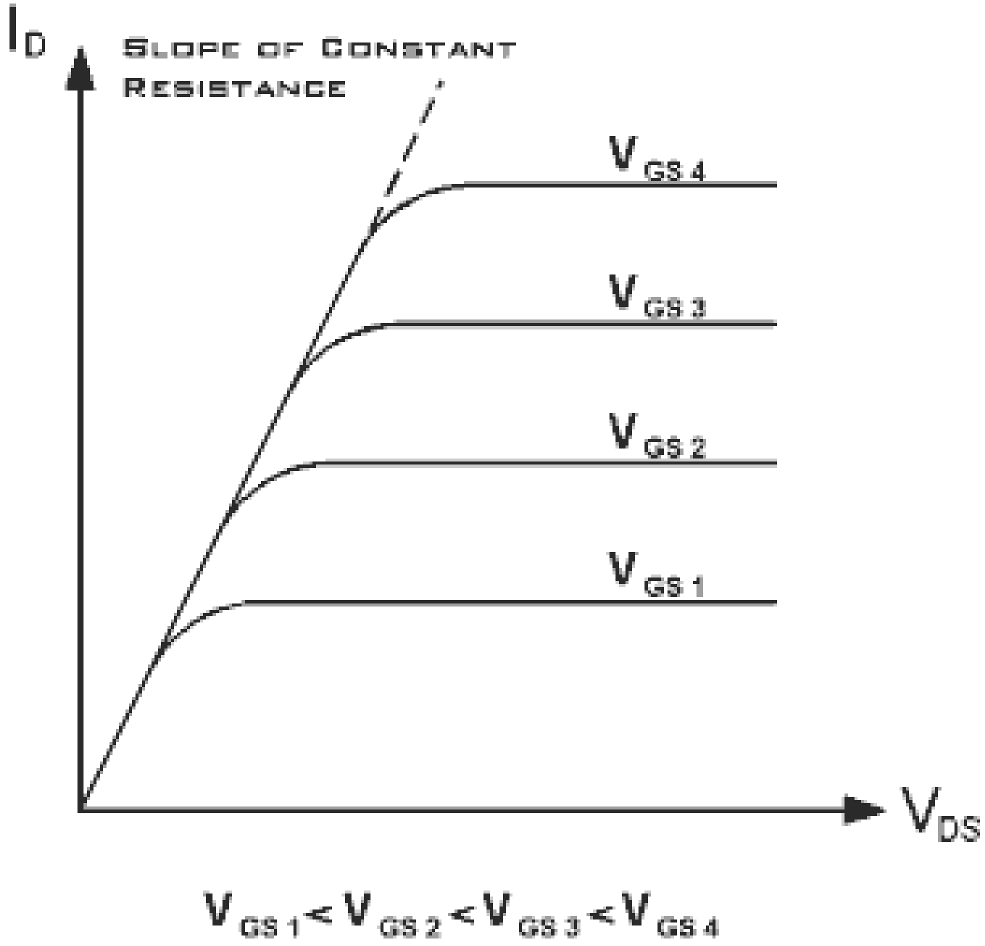
Saturation mode

- We have $V_{GS} > V_{TH}$ → when V_{DS} ↗ → $V_D > V_S$ → $V_G - V_D < V_G - V_S$ → $V_{GD} < V_{GS}$ → the density of e^- decrease in the channel near the drain → the channel is pinched at point P (pinch-off point), close to the drain → ↗ of the resistance of the channel → saturation of I_D

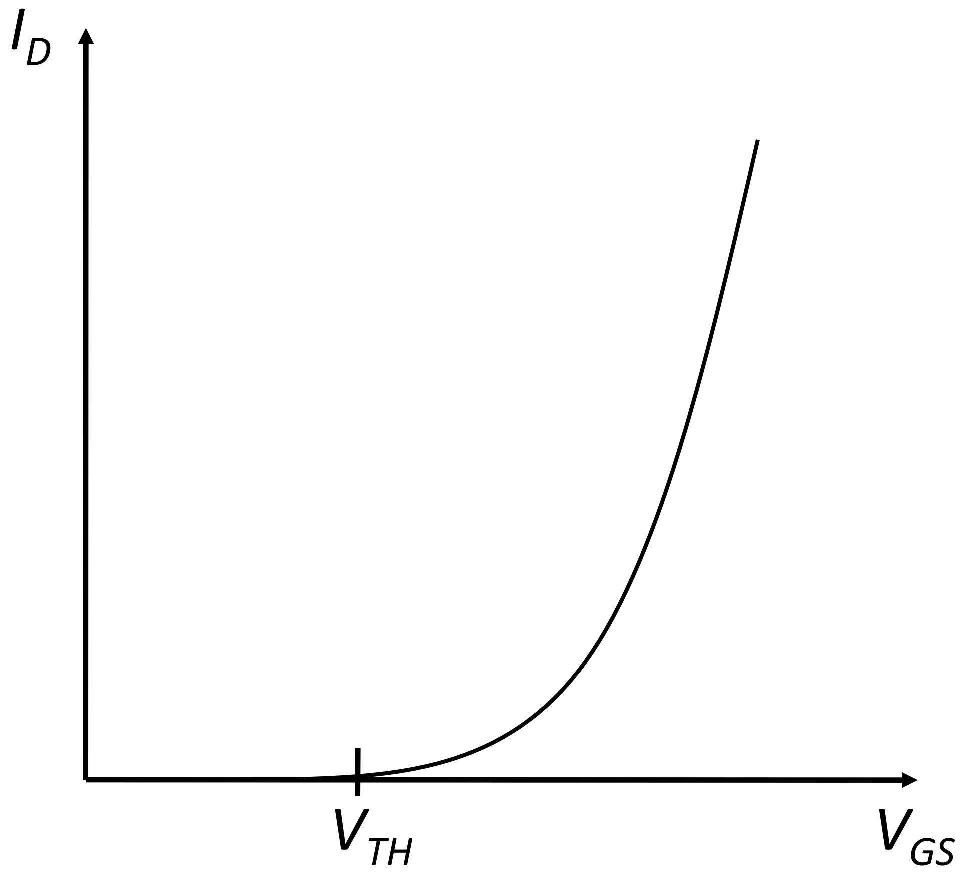


- I_D is thus independent (practically → weakly dependent) of V_{DS} and principally controlled by V_{GS}

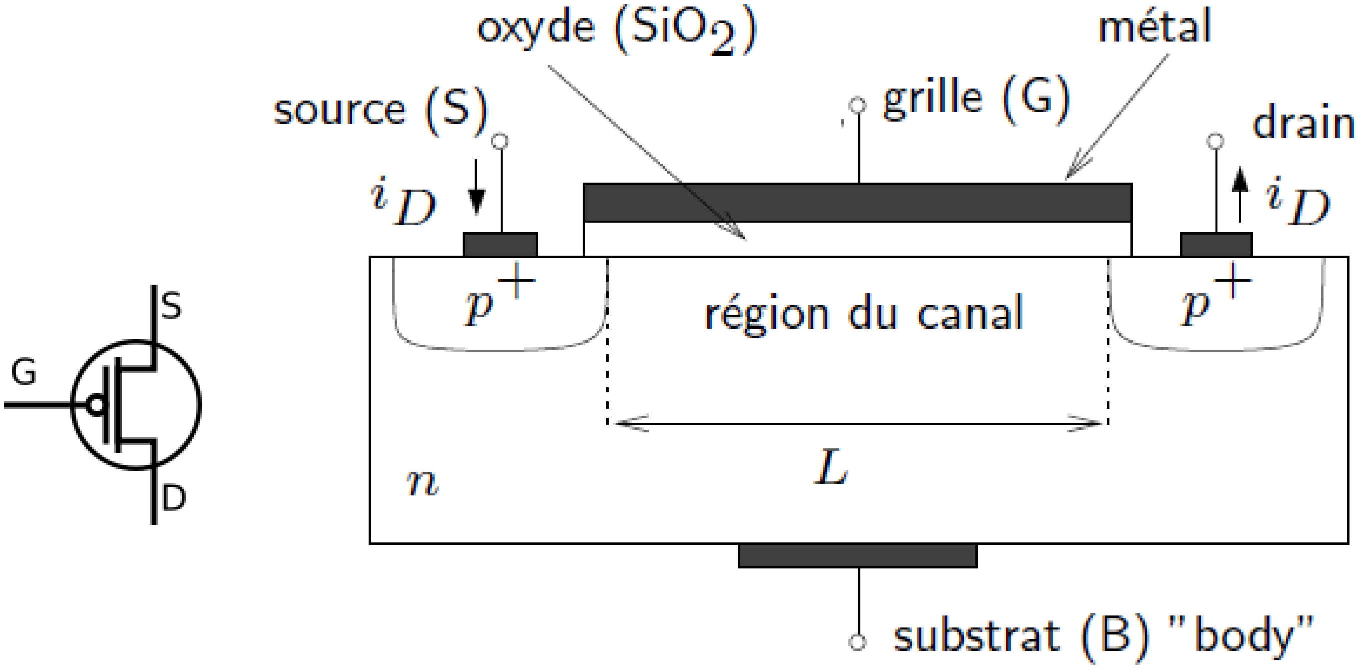
Characteristic curves $I_D = f(V_{DS})$



Characteristic curve $I_D = f(V_{GS})$



Scheme of a p-type channel MOSFET (pMOS)

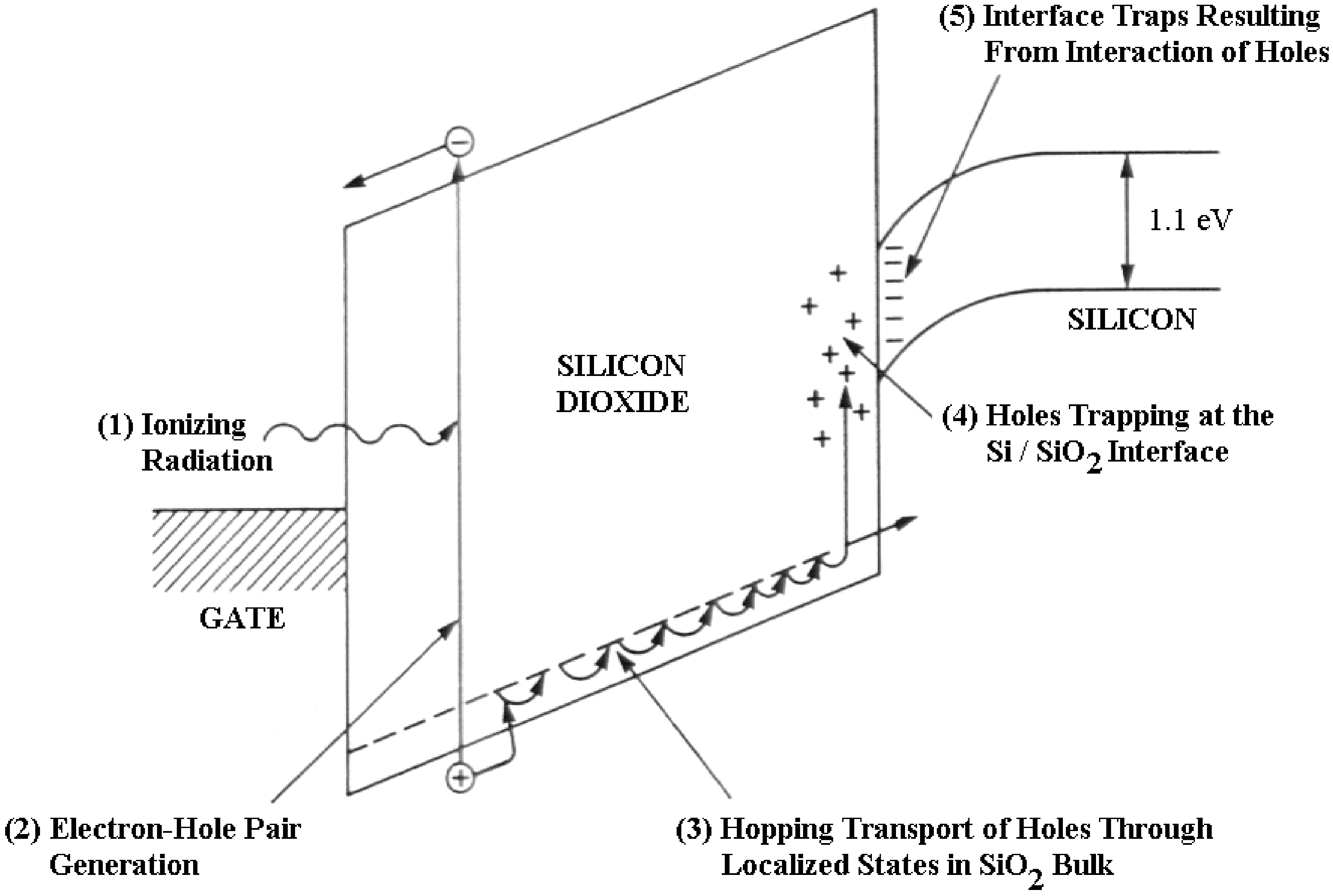


Similar to the n-channel MOSFET but the doped regions are opposite, I_D is opposite, V_{GS} and V_{DS} have opposite polarities and the drain current is made of h$^+$

Effects of radiation on MOSFET (1)

- The MOSFET under irradiation may be in passive mode ($V_{GS} = 0$) or in active mode ($V_{GS} > 0$) → $V_{GS} > 0$ → the recombination ↘ → more sensitive and more linear response
- Ionizing radiations produce e^- - h^+ pairs in the metal, the oxide coating and the semiconductor constituting the MOSFET
- In the metal and in the semiconductor, the e^- - h^+ pairs are quickly removed because these materials have a weak resistance
- On the contrary in the SiO_2 ($W \approx 17 \pm 1$ eV for SiO_2) → the pairs, either immediately recombine, either split off because of the present electric field → however ≠ behaviour due to their ≠ mobility (5 to 12 orders of magnitude)
- If we suppose a voltage $V_{GS} > 0$
  - → the e^- drift to the gate and, because of their large mobility ($\mu = 20$ cm^2 V^{-1}s^{-1}) → they reach the metal and leave the oxide in a time ≤ 1 ps
  - → the h^+ drift to the SiO_2-Si interface more slowly because of their small mobility (strongly dependent on T → $\mu = 10^{-4}$-10^{-11} cm^2 V^{-1}s^{-1}) and are trapped at the interface (always in the oxide) → giving origin to a fixed + charge → modification of the characteristic curve of the MOSFET

Effects of radiation on MOSFET (2)



h^+ transport in the SiO_2

- Due to the small mobility of the h^+ → the transport in the oxide can take a few seconds (depending on T)
- Model for the transport of the h^+ in the SiO_2 → « Small Polaron Hopping » (SPH): transport (or hop) of the small (charge confined in a small volume) polaron (quasi-particle composed of a charge and of its polarization field)
- SPH model based on the strong interaction between the h^+ and the lattice → the interaction gives origin to a distortion of the lattice close to the h^+→ ↘ of the energy of the system
- The h^+ polarizes the medium → this polarization then interacts back on the carrier → implies a large distortion of the lattice in the immediate vicinity of the h^+ → the h^+ becomes localized at a particular site → ↗ of the effective mass of the h^+
- The carrier, which is in practice self-trapped, is called *small polaron*

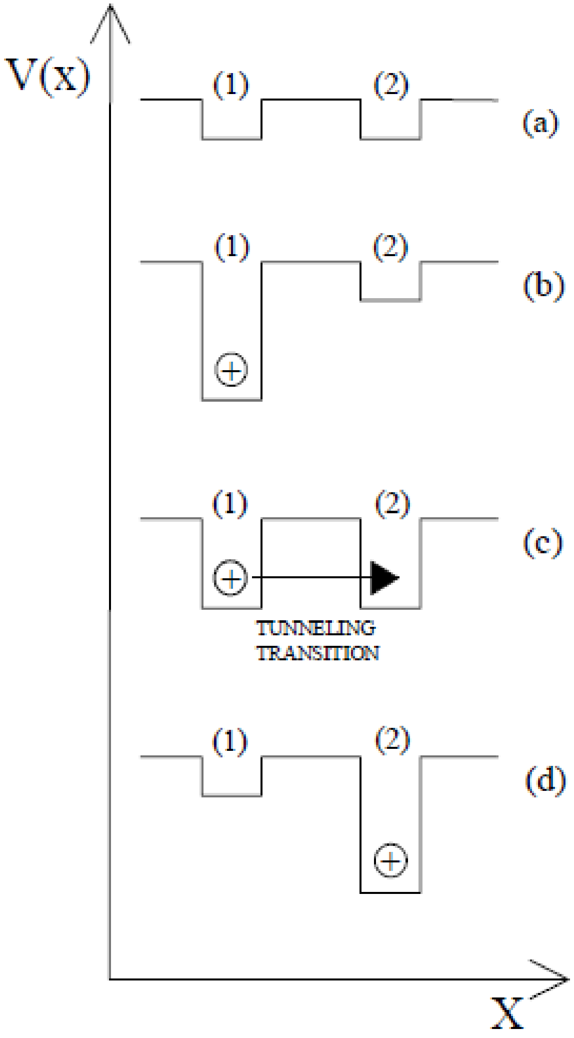
SPH model

a) Initially empty localized trap

b) Capture of a h⁺ by a site → distortion of the lattice potential around the trap site

c) Thermal fluctuations of the system → interaction with another site → transfer of the h⁺ by tunnel effect

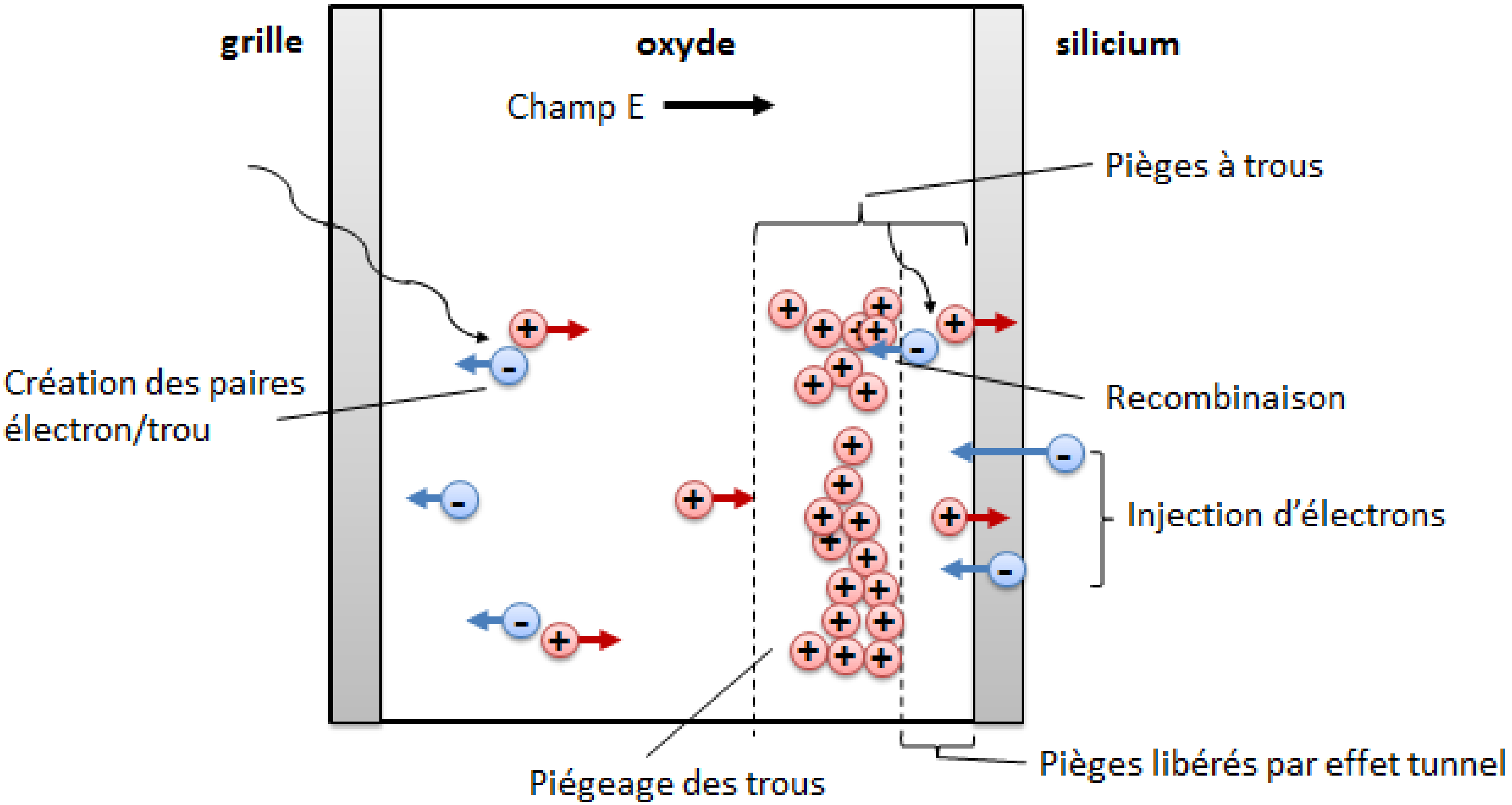
d) Final state



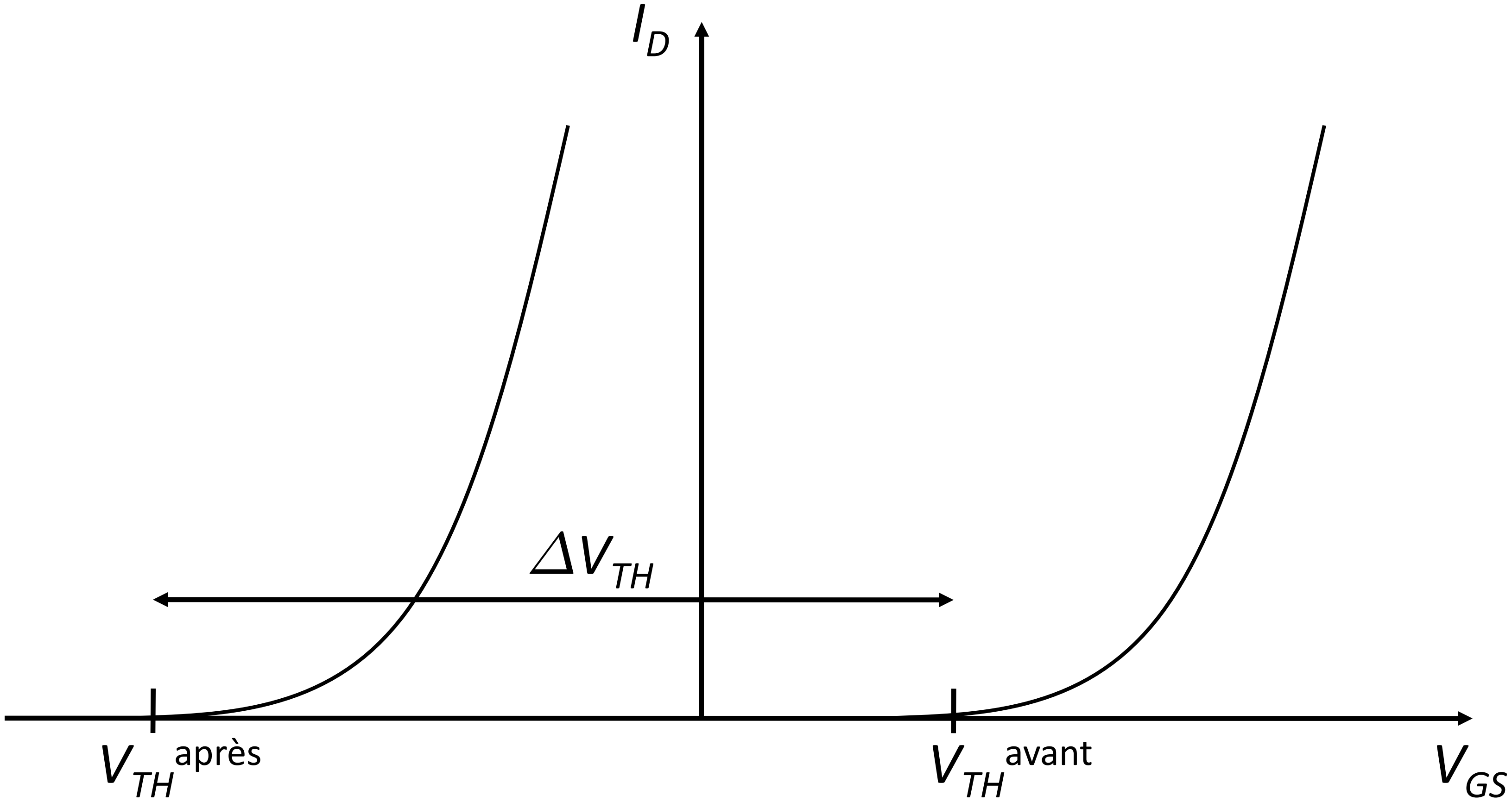
Trapping of the h^+ at the interface SiO_2-Si (1)

- When the radiation-induced h^+ have completed the crossing of the oxide → they are trapped at the SiO_2-Si interface → production of a + charge Q_T at the SiO_2-Si interface
- Consequently → production of a - image charge at the surface of the semiconductor
  - → has a positive role in the formation of the n-channel for a nMOS → the voltage to be applied to the gate to create the n-channel is smaller → V_{TH} ↘
  - → has a negative role in the formation of the p-channel for a pMOS → ↗ of the $|V_{GS}|$ to be applied to have the formation of the p-channel p → V_{TH} ↘
- Q_T implies thus a (negative) modification ΔV_{TH} of the threshold voltage V_{TH} (but also to a lesser extent of the leakage current) → shift of the I_D - V_{GS} characteristic curve
- This modification ΔV_{TH} can stay for a period of time varying from milliseconds to years
- ΔV_{TH} is a measure of the dose absorbed in the oxide

Trapping of the h^+ at the interface SiO_2-Si (2)



Modification of the I_D - V_{GS} characteristic curve



Modification of the I_D - V_{GS} characteristic curve for a nMOS exposed to ionizing radiation

Mathematical expression of ΔV_{TH}

- In active mode ($V_{GS} > 0$) → we consider q: the e^- charge, ε_{ox}: the permittivity of the oxide, ρ_{ox}: the density of the oxide, W: the energy necessary to create one e^- - h^+ pair, $f_y(E)$: the fraction of created charges which do not recombine, $f_t(E)$: the fraction of trapped holes, d_{ox}: the thickness of the oxide coating, D: the dose →

$$\Delta V_{TH} = -\frac{q}{\varepsilon}\frac{\rho_{ox}}{W} f_y f_t d_{ox}^2 D$$

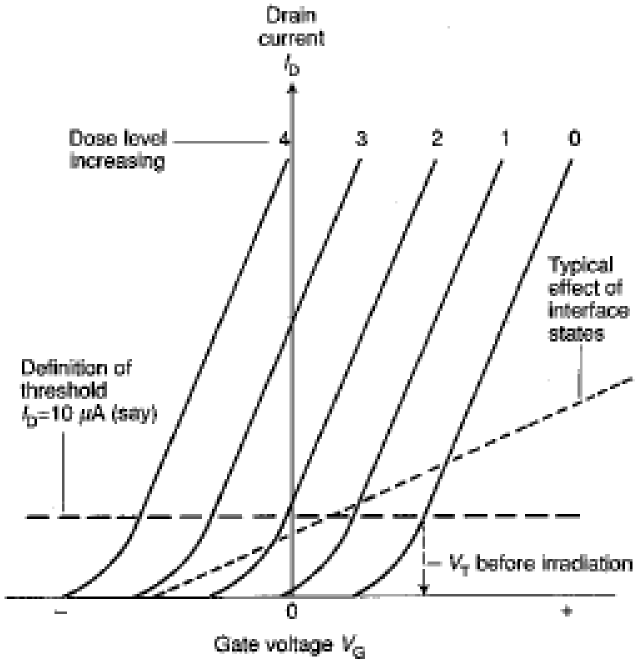
- In passive mode ($V_{GS} = 0$) → decrease of sensitivity and loss of linearity →

$$\Delta V_{TH} \propto d_{ox}^2 D^{0.4}$$

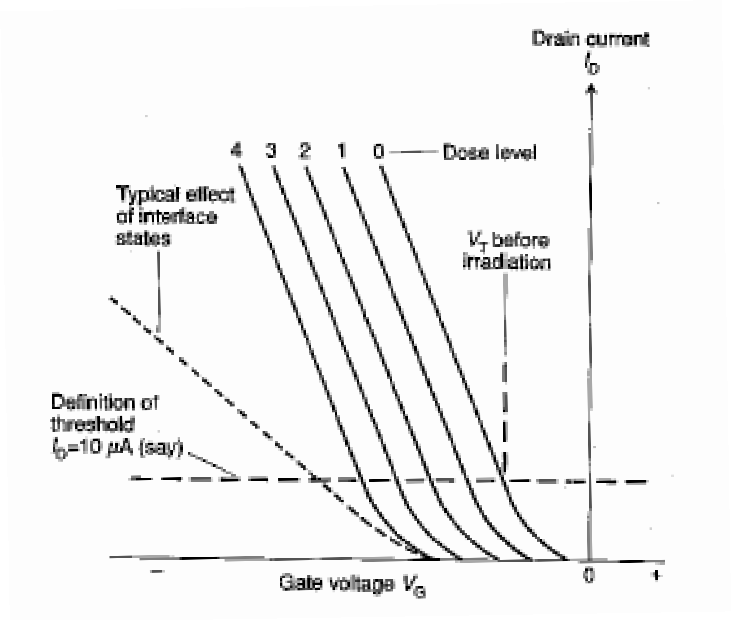
Another effect of irradiation on a MOSFET

- Another effect of irradiation on a MOSFET → ↗ of the number of traps (several orders of magnitude) at the SiO_2-Si interface (« interface » means on both sides → in the Si and in the SiO_2)
- Phenomenon not completely explained
- Observation → ½ of the traps created by the irradiation are donors and ½ are acceptors → in the Si more traps (of 2 types) → whether for a nMOS or for a pMOS → more difficulties to obtain the channel → $|V_{TH}|$ ↗ (+ distortion of the characteristic)
- For a pMOS → this effect adds up to ΔV_{TH} (because $\Delta V_{TH} < 0$) because of h^+ trapping
- For a nMOS → this effect offsets ΔV_{TH}
- In practice → use of a pMOS

Modification of I_D - V_{GS} (global effect)



nMOS



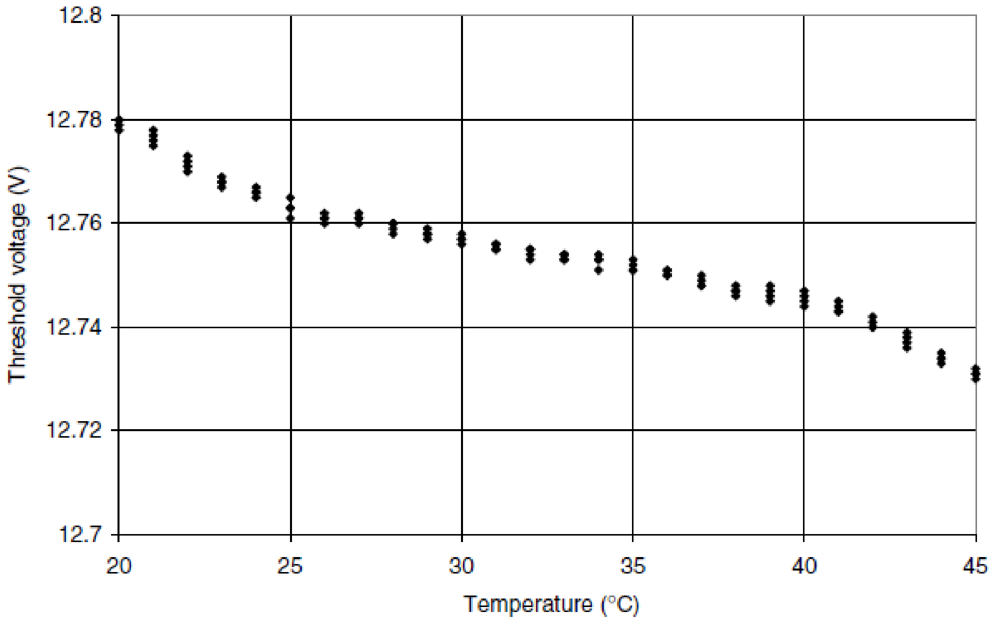
pMOS

Remarks on the use of a MOSFET

- Lower detection limit « relatively high » → main use in radiotherapy and curietherapy
- For « classical» available MOSFET dosimeters → lower limit ≈ 1 cGy
- Investigations for an improvement of this lower limit → currently: ≈ 100 μGy
- Measurements are available at any moment → dose or dose rate
- The ΔV_{TH} shift caused by previous measurements must be known (because of the accumulation of the h^+ in the insulator)
- Limited life time of a MOSFET detector

Temperature effect

- Very sensitive to temperature (→ as for diodes) → apparition of a term ΔV_{TH}^{temp}



D = 100 Gy

- Between 20 °C and 40 °C → ≠ of 50 mV for ΔV_{TH} → ≠ of 10 cGy
- Generally → 1 °C → $\Delta V_{TH}^{temp} = 4 - 5$ mV

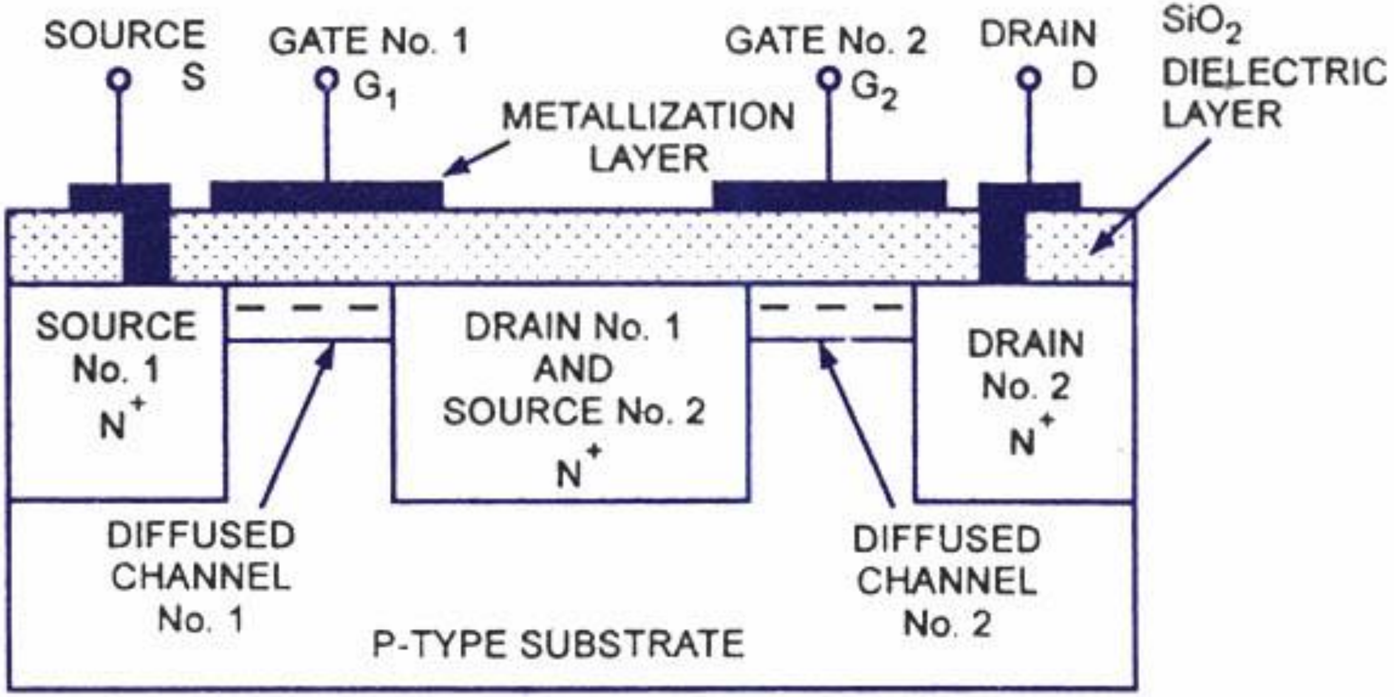
Solution to the T problem: dual MOSFET

- Dual MOSFET: 2 identical MOSFET, build on the same Si chip and operating at 2 ≠ gate voltages
- During irradiation → each element gives a voltage shift → the ≠ between the 2 voltage shifts gives a signal $\propto$ to the dose

$$\begin{aligned} \Delta V_{TH} &= (\Delta V_{TH}^{1} - \Delta V_{TH}^{temp}) - (\Delta V_{TH}^{2} - \Delta V_{TH}^{temp}) \\ &= \Delta V_{TH}^{1} - \Delta V_{TH}^{2} \end{aligned}$$

- For a dual MOSFET → variation of ≈ 0.015 mV/°C

Dual MOSFET

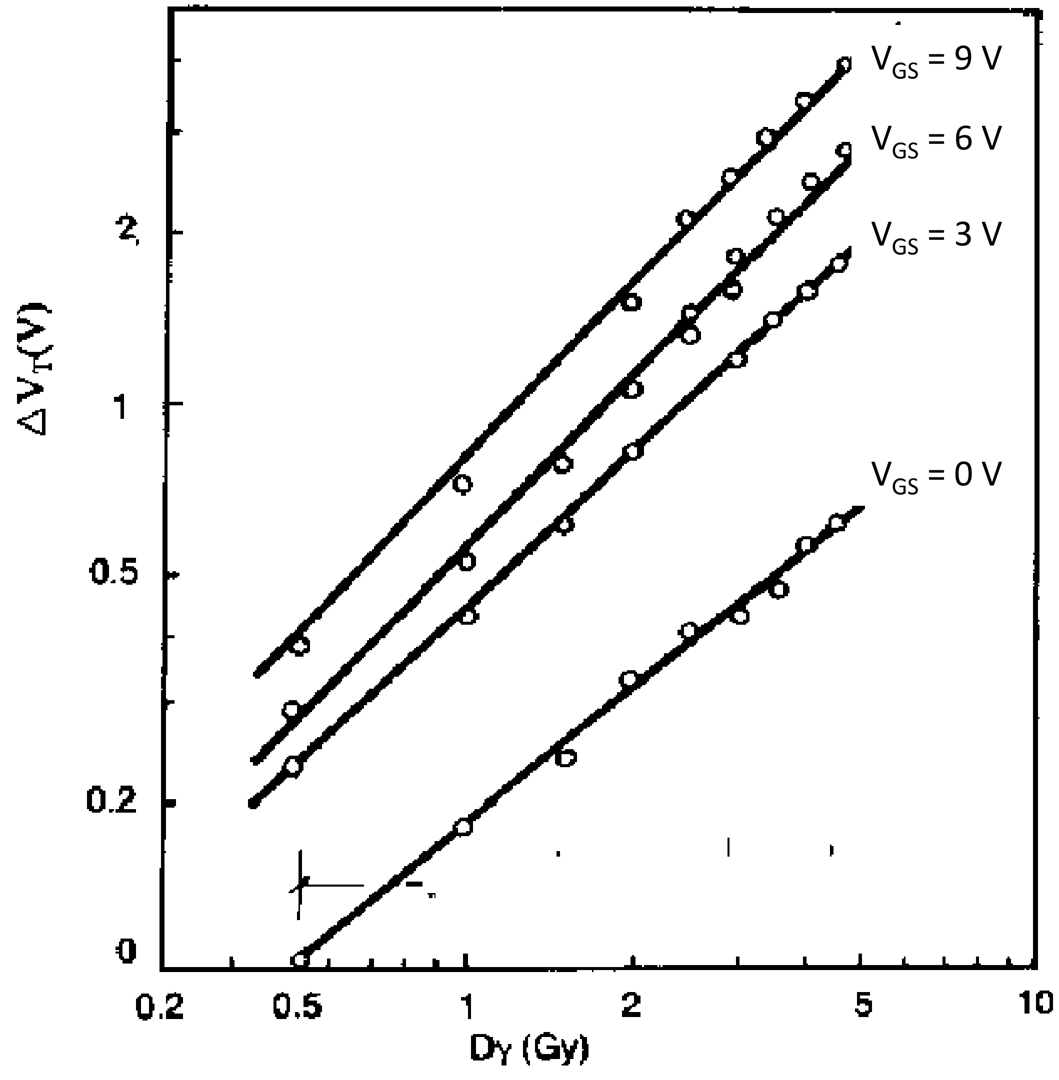


Dual-Gate N-Channel Depletion Type MOSFET

RADFET

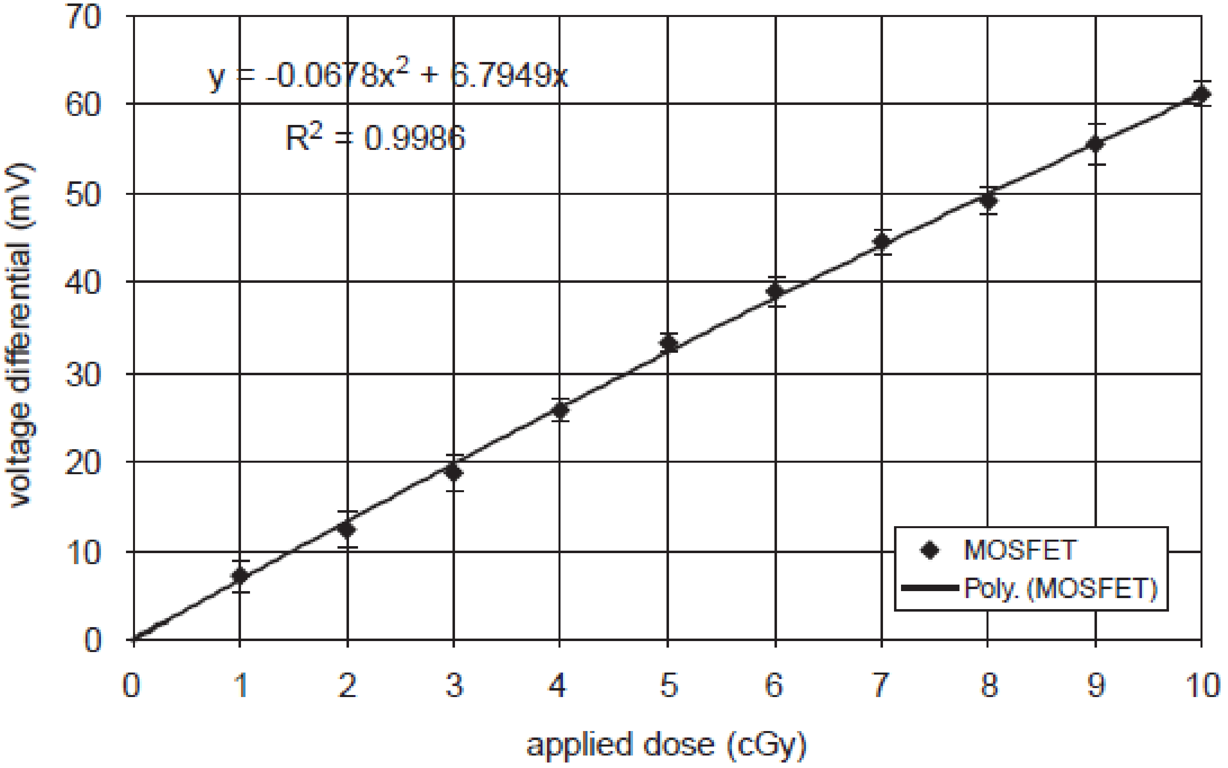
- To improve the sensitivity of the detector → several linked MOSFET → RADFET (RADiation-sensing Field-Effect Transistor)
- Properties identical to the dual MOSFET but larger sensitivity: « theoretically » < μGy → practically less good

Response as a function of the dose: High doses



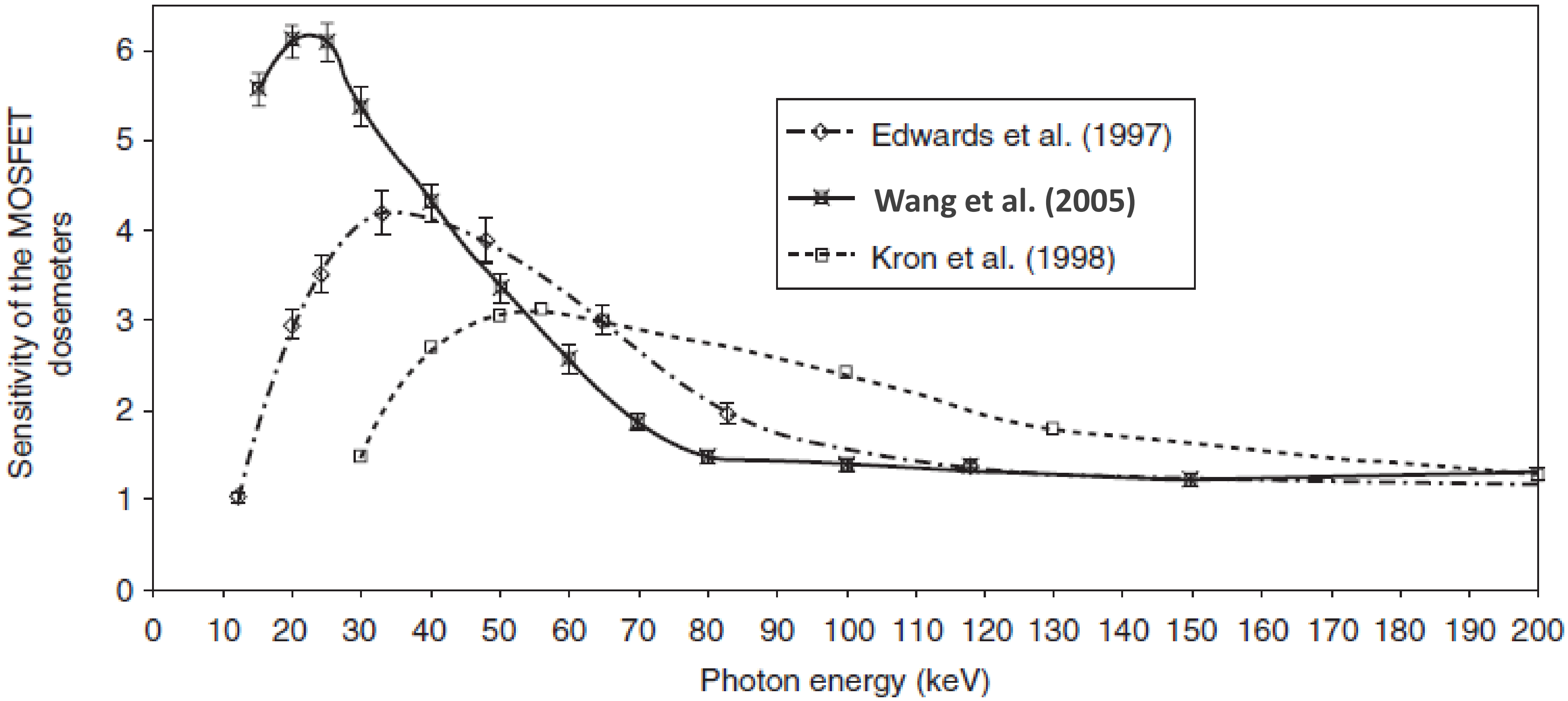
nMOS for 1 MeV γ

Response as a function of the dose: Small doses



Dual pMOS for 6 MeV γ

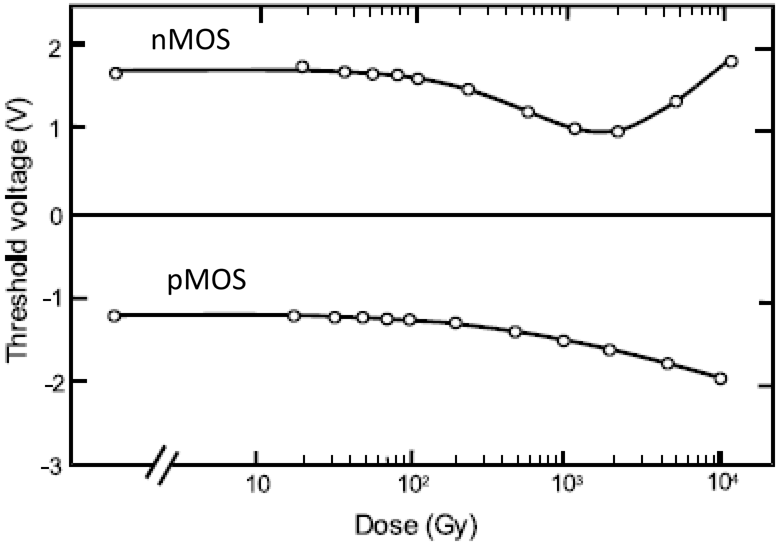
Energy response



Energy responses obtained in ≠ studies (6 MeV γ) for ≠ MOSFET → in all cases → non-linearity for E < 100 keV

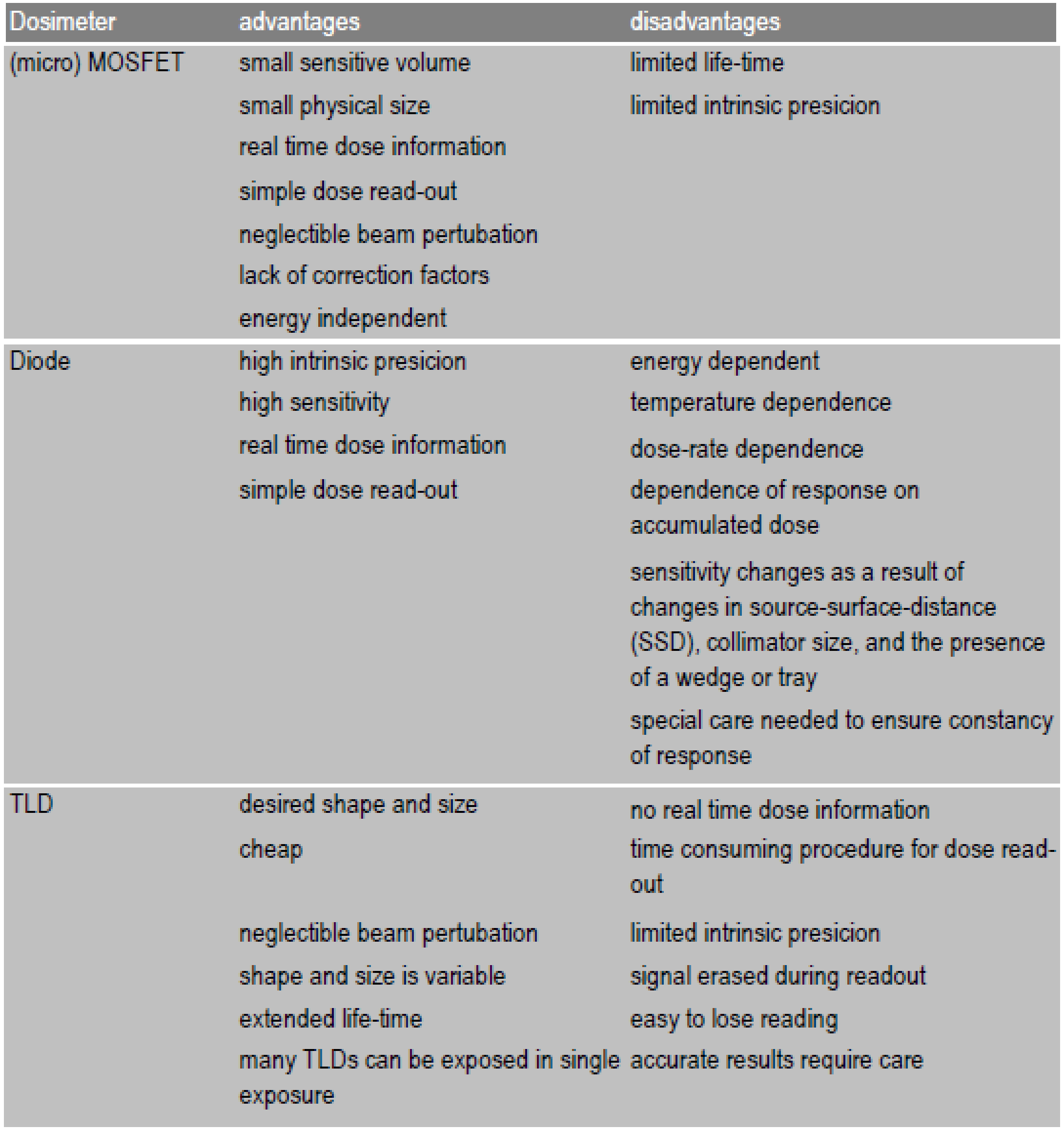
Effect of the cumulated dose

- As for diodes → the irradiation introduces supplementary defects in the material → modification of the sensitivity as a function of the dose (for high doses)



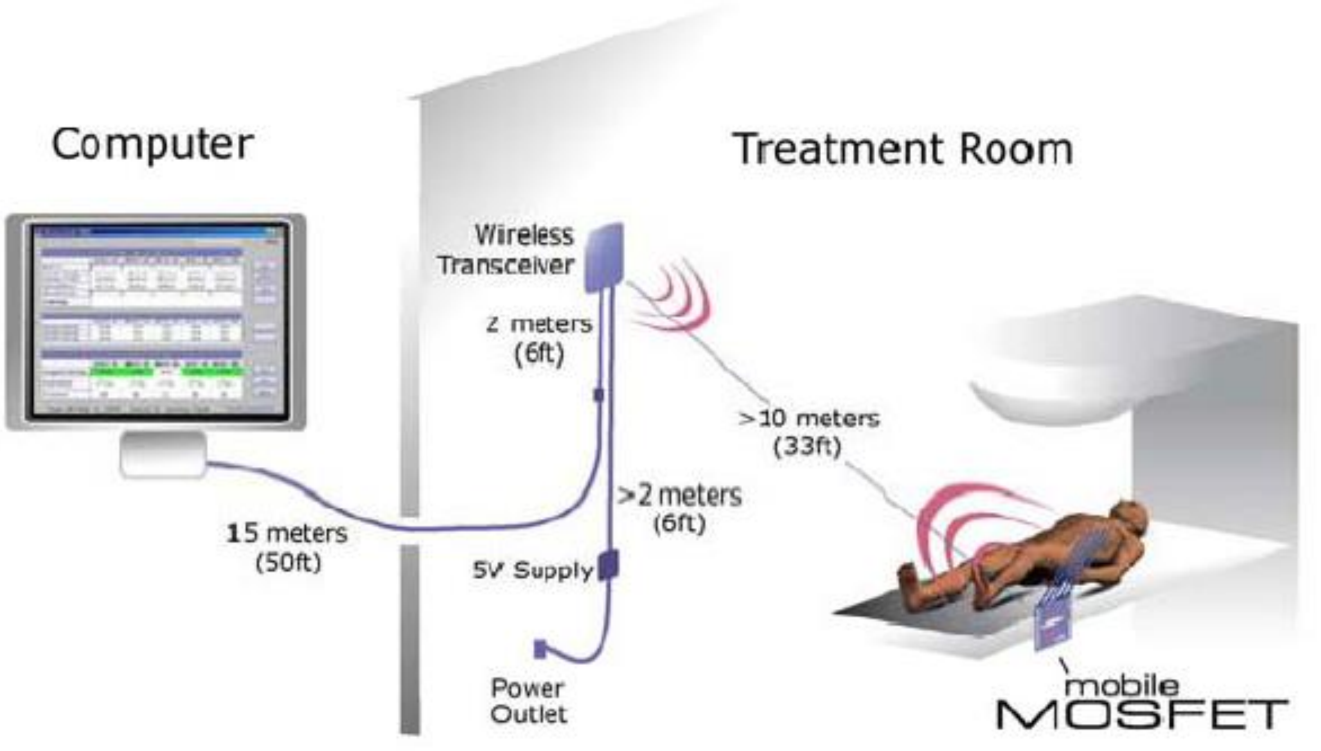
- ≠ Behaviour for nMOS and pMOS ↔ because ≠ types of defects and thus of traps

Comparison TLD-Diode-MOSFET



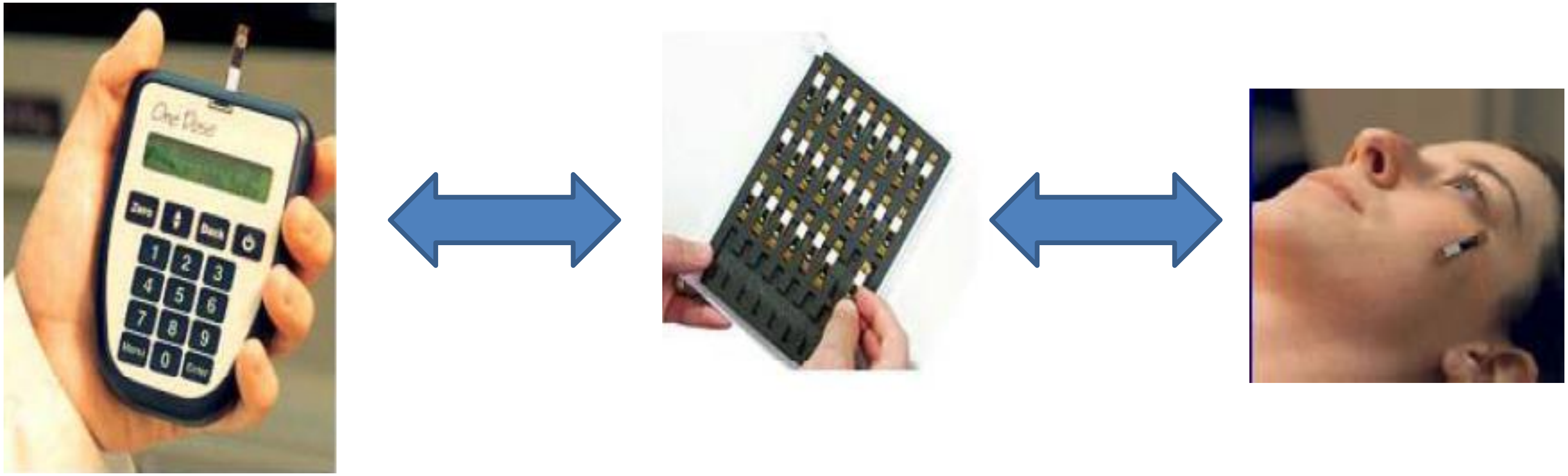
Dosimeter	advantages	disadvantages
(micro) MOSFET	small sensitive volume	limited life-time
	small physical size	limited intrinsic presicion
	real time dose information	
	simple dose read-out	
	neglectible beam pertubation	
	lack of correction factors	
	energy independent	
Diode	high intrinsic presicion	energy dependent
	high sensitivity	temperature dependence
	real time dose information	dose-rate dependence
	simple dose read-out	dependence of response on accumulated dose
		sensitivity changes as a result of changes in source-surface-distance (SSD), collimator size, and the presence of a wedge or tray
		special care needed to ensure constancy of response
TLD	desired shape and size	no real time dose information
	cheap	time consuming procedure for dose read-out
	neglectible beam pertubation	limited intrinsic presicion
	shape and size is variable	signal erased during readout
	extended life-time	easy to lose reading
	many TLDs can be exposed in single exposure	accurate results require care

Applications (1)



Mobile MOSFET system from Best Medical → wireless

Applications (2)



OneDose MOSFET system from Sicel Technologies Inc. → wireless