# Chapter X:
# Optically stimulated luminescence dosimeters

# Optically stimulated luminescence dosimeters

- Again → luminescence process → now stimulation by light (UV, visible, IR)
- When optically stimulated luminescence is used in radiation dosimetry → OSL dosimeter
- Fast-expanding during last years
- Remark → when a default is **excited** by light → radiophotoluminescence (RPL) → end of the chapter

- References:
  - L. Bøtter-Jensen, S.W.S. McKeever, A.G. Wintle, *Optically stimulated luminescence dosimetry* (Elsevier Science) 2003
  - S.W.S. McKeever, *Optically stimulated luminescence dosimetry*, Nuclear Instruments and Methods in Physics Research B: 184 (2001) 29–54

# History

- First « practical » OSL measurements have been made in 1985 with quartz and feldspar → via the determination of the environmental dose absorbed by these materials → determination of the age of archeological or geological materials
- The measure of the luminescence of the material is a measure of the dose absorbed since the last exposition to the light → by comparison with reference samples → dating
- For personal dosimetry → late development due to the absence of « good » materials (sensitivity to radiation, small $Z_{eff}$, weak fading,…)
- Currently → development of « good » materials → $Al_2O_3$:C, quartz,…

# Advantages of OSL

- Techniques of reading simpler than for TLD → only optical
- No heating → no thermal quenching
- Possible multiple reading → no necessary to stimulate all traps during the first reading
- Fast reading process

# Escape probability *p*

- Thermoluminescence →

$$p = s \exp\left(-\frac{E}{kT}\right)$$

- Optical stimulation at a fixed wavelength $\lambda$ →

$$p(E_0) = \Phi\sigma(E_0)$$

with $\Phi$, the optical stimulation intensity, $\sigma$, the photoionization cross section for interaction of the metastable state and $E_0$, the threshold optical stimulation energy required to release the $e^-$ from the trap

# Photoionization cross section (1)

- $\sigma(E_0)$ has an energy threshold → for $E < E_0 \rightarrow \sigma(E_0) = 0$
- ≠ expressions have been derived for the dependence as a function of the frequency of $\sigma(E_0) \rightarrow \sigma(h\nu, E_0)$ as a function of the potential energy in the vicinity of the defect
- For a shallow trap → hydrogenic potential (and planewave for the $e^-$) →

$$\sigma(h\nu, E_0) \propto \frac{(h\nu - E_0)^{3/2}}{(h\nu)^5}$$

- For a deep trap → delta-function potential for the defect (model of Lucovsky) with the assumption that the mass of the $e^-$ in the localized state is equal to the effective mass ($m_e$) of the $e^-$ in the conduction band →

$$\sigma(h\nu, E_0) \propto \left[\frac{4(h\nu - E_0)E_0}{(h\nu)^2}\right]^{3/2}$$

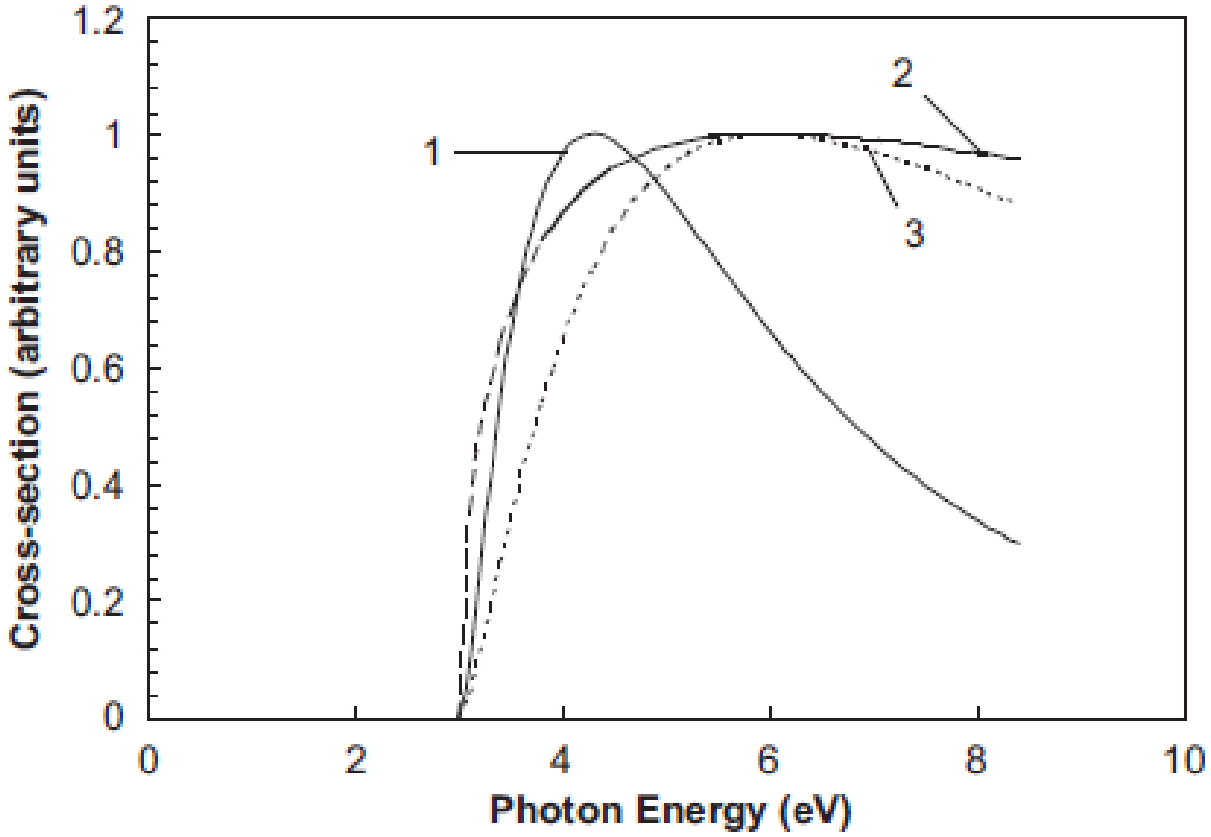
# Photoionization cross section (2)

- For a deep trap → model of Grimmeis and Lebedo considering a mass $m_0$ (rest mass) for the $e^-$ in the localized state →

$$\sigma(h\nu, E_0) \propto \frac{(h\nu - E_0)^{3/2}}{h\nu[h\nu - E_0(1 - m_0/m_e)]^2}$$

- Other models exist but for OSL → deep traps → the models of Lucovsky or of Grimmeis and Lebedo are most often used

# Photoionization cross section (3)




$\sigma(h\nu,E_0)$ for $E_0$ = 3.0 and $m_0/m_e$ = 2 (normalized functions to reach $\sigma_{max} = 1$): 1: hydrogenic, 2: Lucovsky, 3: Grimmeis and Lebedo

# Modes of optical stimulation

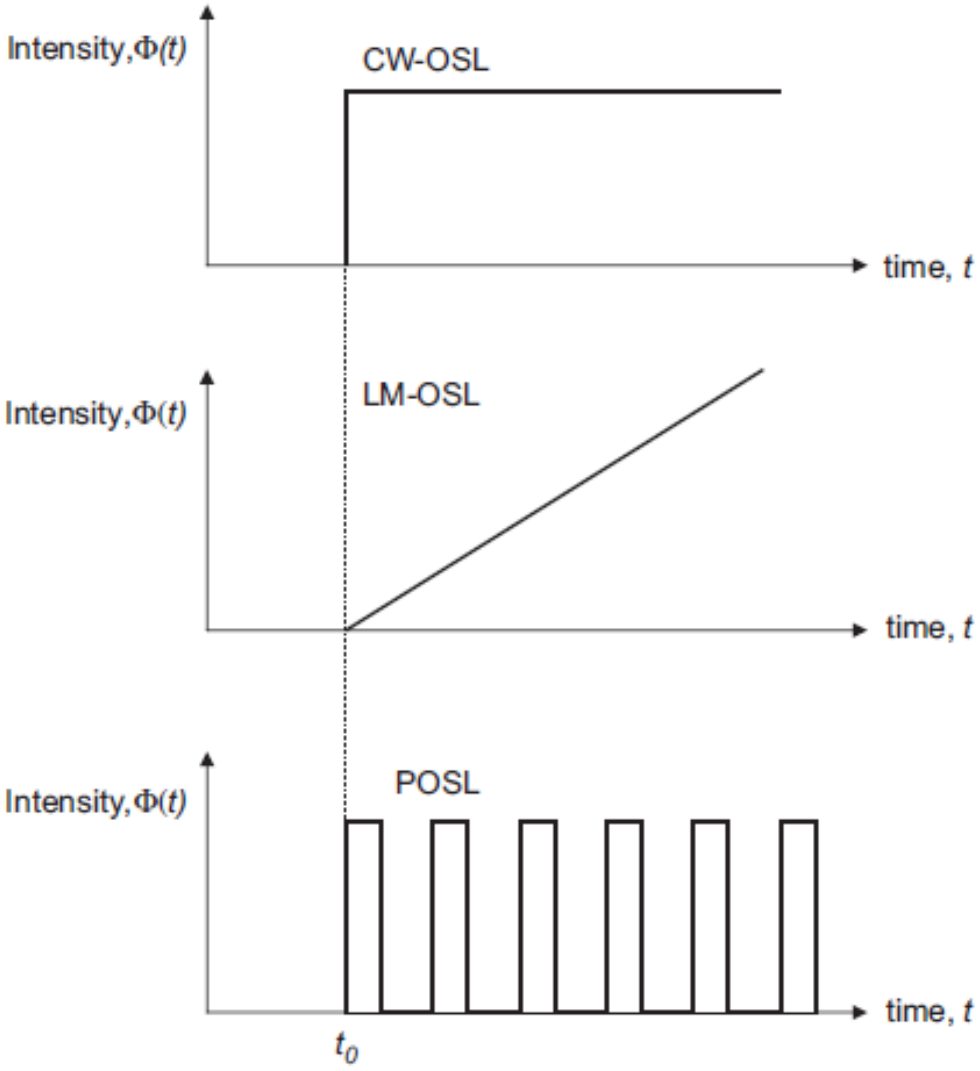
1. $\Phi$ = constant (and $\lambda$ is constant also) → optically stimulated luminescence in continuous mode (continuous-wave OSL: CW-OSL)
2. Introduction of a time-dependence for $\Phi$(t) or $\lambda$(t) → example 1: linear increase in the intensity of optical stimulation at a fixed $\lambda$ (with $\beta_\Phi = d\Phi/dt$ ) →

$$\Phi(t) = \Phi_0 + \beta_\Phi t$$

   → optically stimulated luminescence in linear mode (linear modulation OSL: LM-OSL)
3. → example 2: pulsed stimulation → optically stimulated luminescence in pulsed mode (pulsed OSL: POSL) with $\Delta t$, the pulse width and $\tau$, the period →

$$\begin{cases} \Phi(t) = \Phi_0 \quad \text{for} \quad t_0 \leq t < t_0 + \Delta t \\ \Phi(t) = 0 \quad \text{for} \quad t_0 + \Delta t \leq t < t_0 + \tau \end{cases}$$

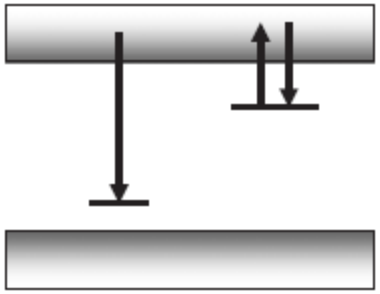
# Schematic representation of the three main OSL stimulation modes



# CW-OSL

- Most often used mode in practice because of its ease of application

- Simplest model: 1 trap – 1 recombination center (as for TL)



- Additional complexities can be subsequently considered

# 1 trap – 1 recombination center: 1st order

- Quasi-equilibrium assumption (QE)
- Negligible retrapping
- Equation similar to equations obtained for TL →

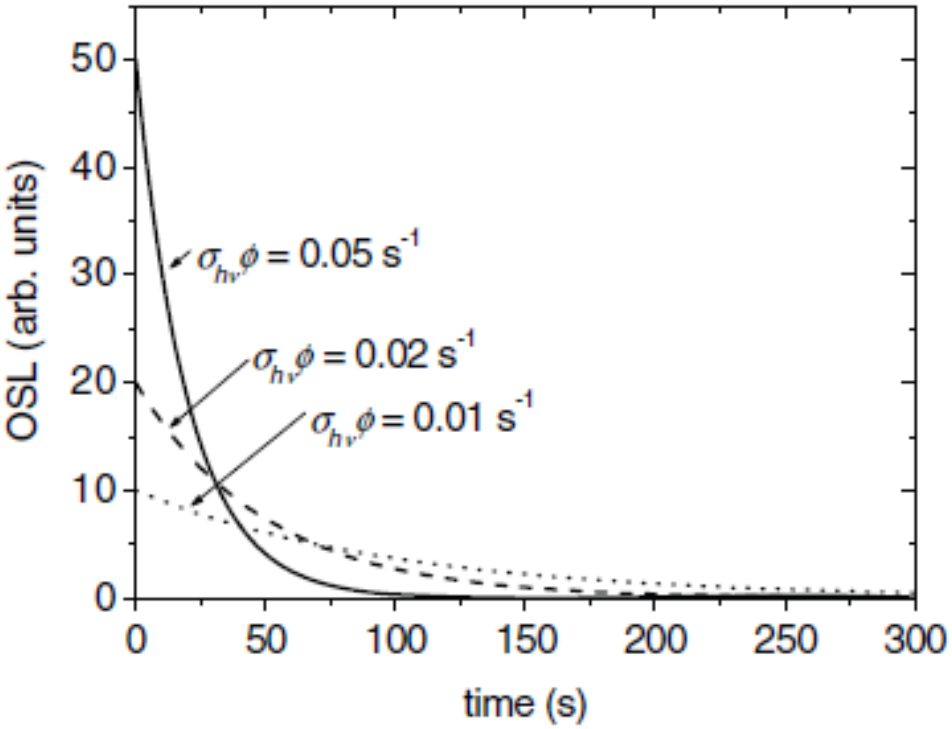
$$I_{OSL}(t) = -\frac{dm}{dt} = -\frac{dn}{dt} = np$$

$$I_{OSL}(t) = n_0 p \exp(-tp) = I_0 \exp(-t/\tau_d)$$

with $\tau_d^{-1} = p = \Phi\sigma$ with $\tau_d$ the CW-OSL decay constant

- 1st order model and exponential decrease of the light intensity
- When all traps are empty $I_{OSL} = 0$

# Determination of $n_0$




- $n_0$ is equal to the area of $I_{OSL}(t)$ →

$$\int_0^\infty I_{OSL}(t)dt = n_0$$

- The initial intensity is $\propto$ to $n_0$ and $\Phi$ → $I_{OSL}(0) = n_0 \Phi\sigma$

# 1 trap – 1 recombination center: 2nd order

- Significant retrapping rate →

$$I_{OSL}(t) = np - n_c(N-n)A_n$$

- For $N \gg n$ and $R = A_n/A_m \gg n/(N-n)$ → we obtain the 2nd order shape →

$$I_{OSL}(t) = \frac{n^2 p}{NR} = -\frac{dn}{dt}$$

$$\Rightarrow \quad I_{OSL}(t) = I_0 \left(1 - \frac{n_0 p t}{NR}\right)^{-2}$$

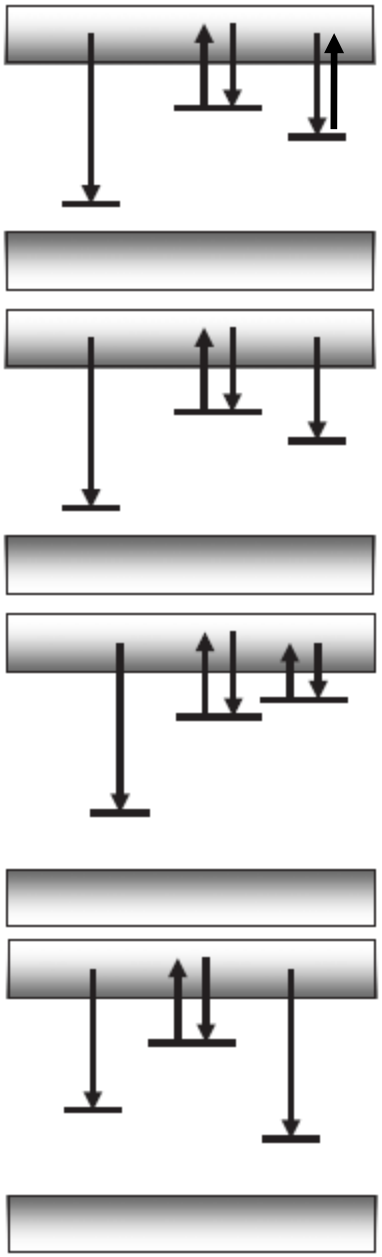
with $I_0 = \dfrac{n_0^2 p}{NR}$

# 1 trap – 1 recombination center: general-order

$$I_{OSL}(t) = I_0 \left(1 - \frac{n_0 p t}{NR}\right)^{\frac{b}{1-b}}$$

with $I_0 = \frac{n_0^b p}{NR}$

# Models with multiple traps and centers



2 independent traps

2 traps including one deep trap not sensitive to the optical stimulation

2 traps including one shallow trap for which thermoluminescence is possible

2 recombination centers including a non-radiative center

# Independent traps

- We consider 2 traps (1 and 2) optically sensitive and independent → we have the traps concentrations $n_1$ and $n_2$ and the escape probabilities $p_1 = \tau_{d1}^{-1}$ and $p_2 = \tau_{d2}^{-1}$ → superposition principle →

$$-\frac{dm}{dt} = -\frac{dn_1}{dt} - \frac{dn_2}{dt}$$

$$\begin{aligned} I_{OSL}(t) &= n_{10}p_1 \exp(-tp_1) + n_{20}p_1 \exp(-tp_2) \\ &= I_{01} \exp(-t/\tau_1) + I_{02} \exp(-t/\tau_2) \end{aligned}$$

- Superposition principle can be applied to more than 2 traps

# Additional deep trap without optical stimulation

- Additional deep trap without optical stimulation (trap 2) occurs for a stimulation with long wavelength and thus with insufficient energy to empty the deep traps→ the deep trap is a competitor to the recombination center
- The OSL intensity can be written (with $N_2$, $n_2$ and $A_{n2}$, the concentration of available traps, of filled traps and the trapping probability for the deep trap) →

$$I_{OSL}(t) = n_{10} p \exp\left(-t/\tau_d\right) - n_c A_{n2}(N_2 - n_2)$$

- The intensity is reduced due to the trapping in the deep trap
- The decrease is no more exponential

# Additional shallow trap with thermoluminescence

$$I_{OSL}(t) = n_{10} p \exp\left(-t/\tau_d\right) + n_2 s \exp\left(-E/kT\right) - n_c A_{n2}(N_2 - n_2)$$

- The last 2 terms combine to produce a long-lived and temperature-dependent component to the OSL decay curve

- That may imply (as a function of the parameters) an initial increase of $I_{OSL}$ followed by a decrease → in such circumstances the terms « OSL decay curve » is inappropriate

# Second recombination center (non-radiative)

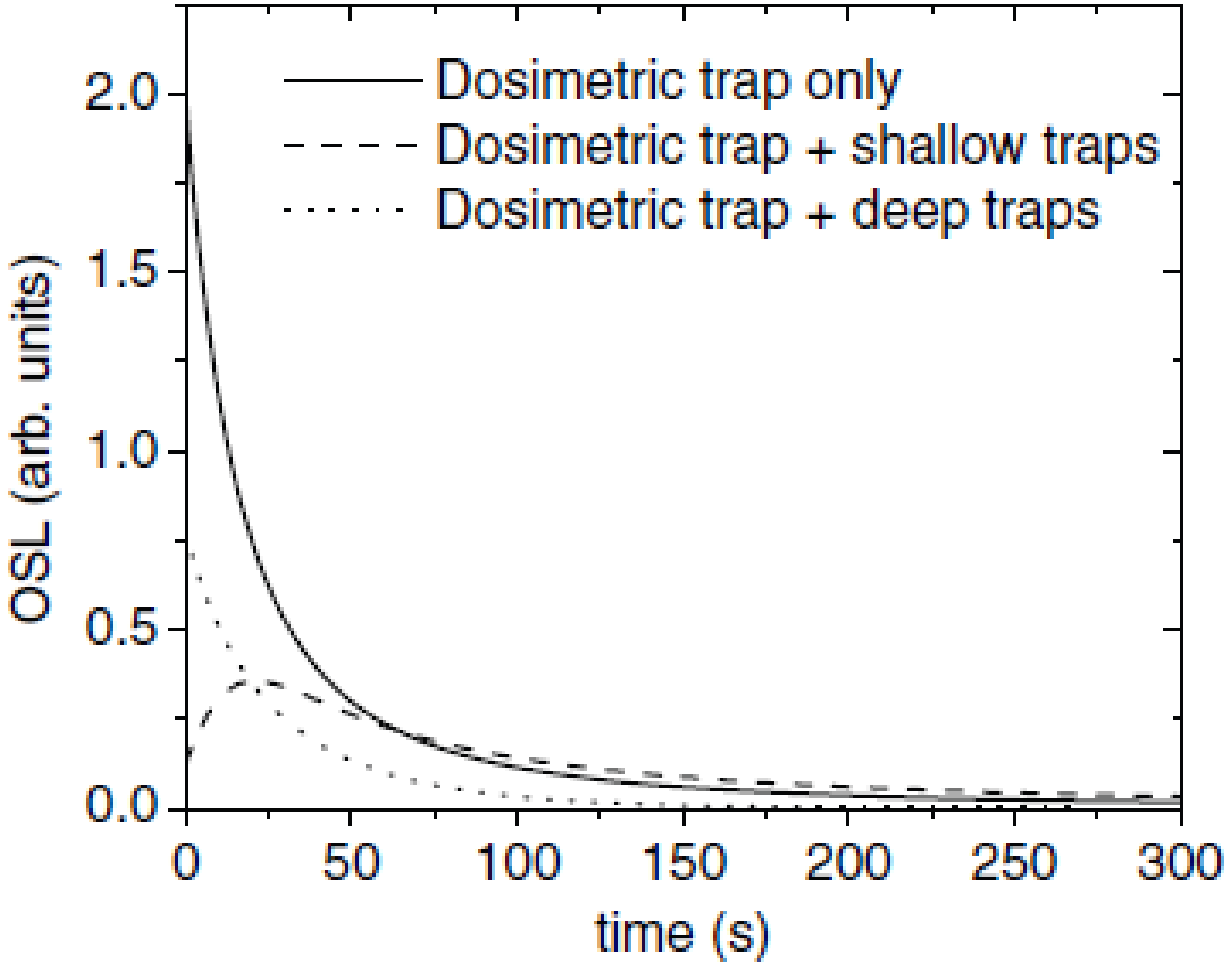
- A second recombination center (2) may exist and be non-radiative (or if radiative, outside the detector sensitivity window)
- Let be $m_1$ and $m_2$, the $h^+$ concentrations at $R_1$ and $R_2$
- As only the recombination $e^-$- $h^+$ at 1 is radiative →

$$I_{OSL}(t) = -\frac{dm_1}{dt}$$

$$I_{OSL}(t) = np\exp\left(-t/\tau_d\right) - \frac{dm_2}{dt}$$

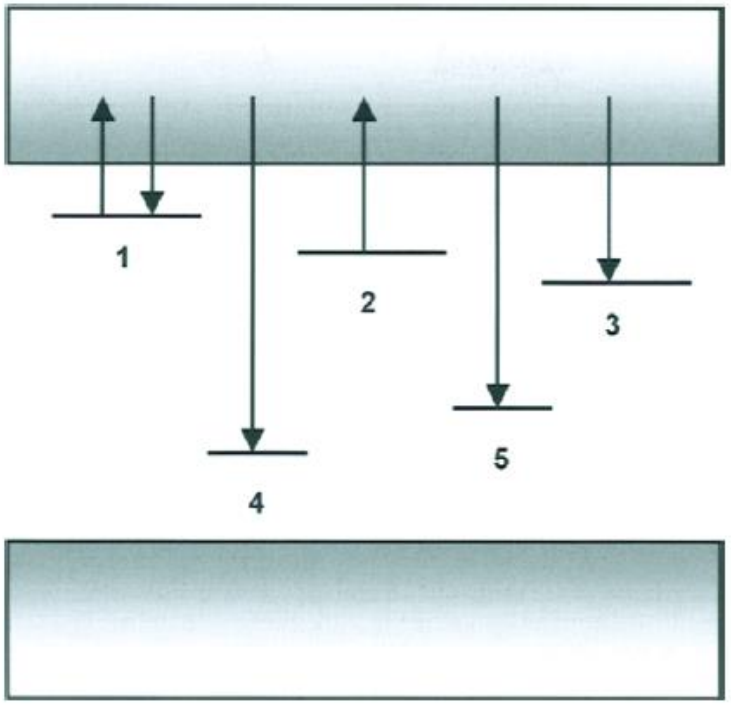
- Again decrease of $I_{OSL}$

# Comparison between the ≠ models

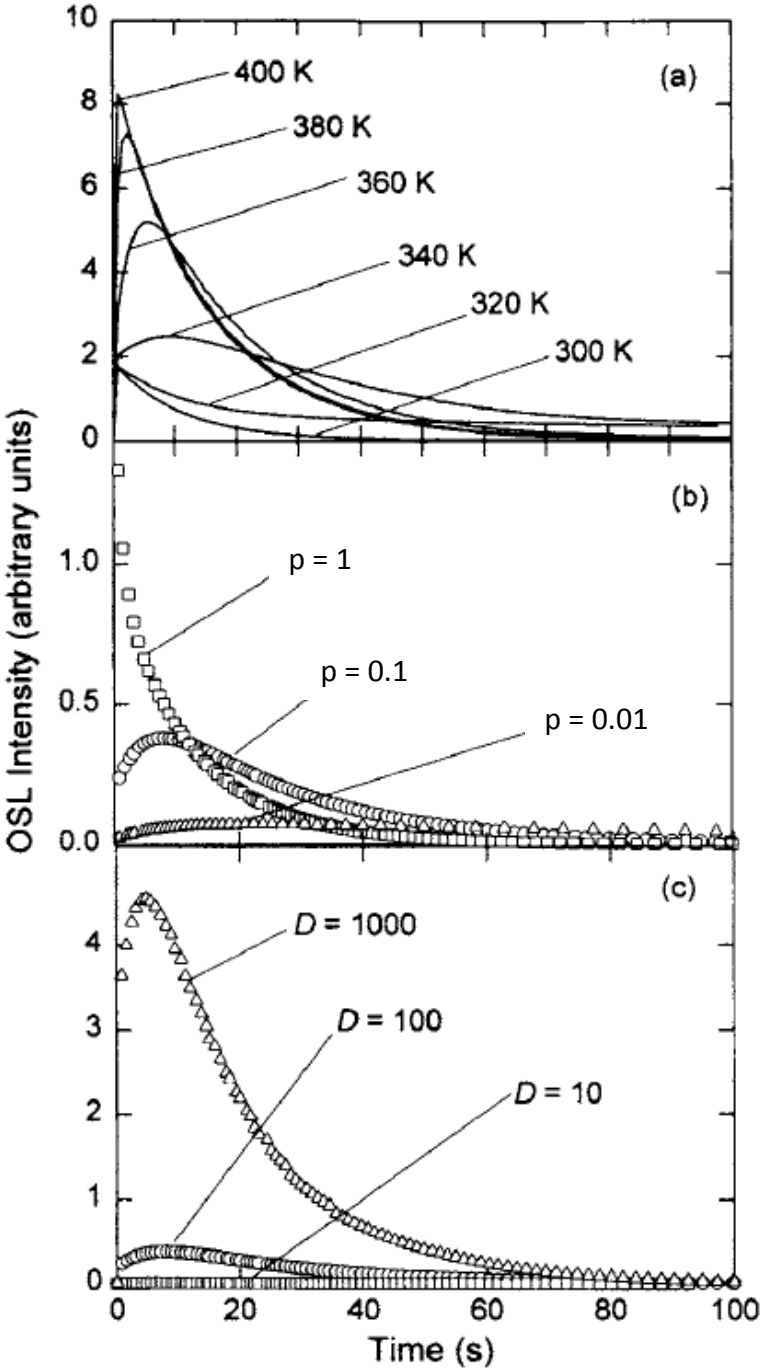


# More complex models

- In previously models → we add 1 deep trap or 1 shallow trap or 1 recombination center
- For realistic materials → they contain multiple traps, deep or shallow, and multiple recombination centres (radiative or not) → model with all these elements →



# Results for this complex model



# LM-OSL

- Alternative method introduced in 1996 by Bulur → the intensity of the stimulation linearly increases

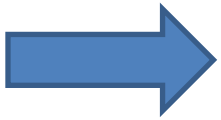
$$\Phi(t) = \Phi_0 + \beta_\Phi t$$

- The OSL response is a series of peaks, each peak corresponding to the optical escape of charge from a given type trap → the traps with the largest photoionization cross section are empty first
- The traps characterized by slow, medium or fast escape are more easily discriminate than for CW-OSL
- Not very often used in practice due to a larger technical complexity than for CW-OSL but also to a larger mathematical complexity

# 1 trap – 1 recombination center: 1st order

- 1er ordre → hypothèses de quasi-équilibre et de repiégeage négligeable
- Considérons comme forme pour $\Phi(t)$ →

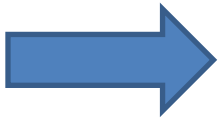
$$\Phi(t) = \gamma t$$



$$\frac{dn}{dt} = -\sigma\gamma t n$$

- Cette équation a comme solution une fonction gaussienne →

$$n = n_0 \exp\left(-\frac{\sigma\gamma}{2}t^2\right)$$



$$I_{OSL} = n_0\sigma\gamma t \exp\left(-\frac{\sigma\gamma}{2}t^2\right)$$

# Caractéristiques du 1er ordre

- The OSL curve shape starts from 0 at *t = 0*
- The curve shows a maximum at

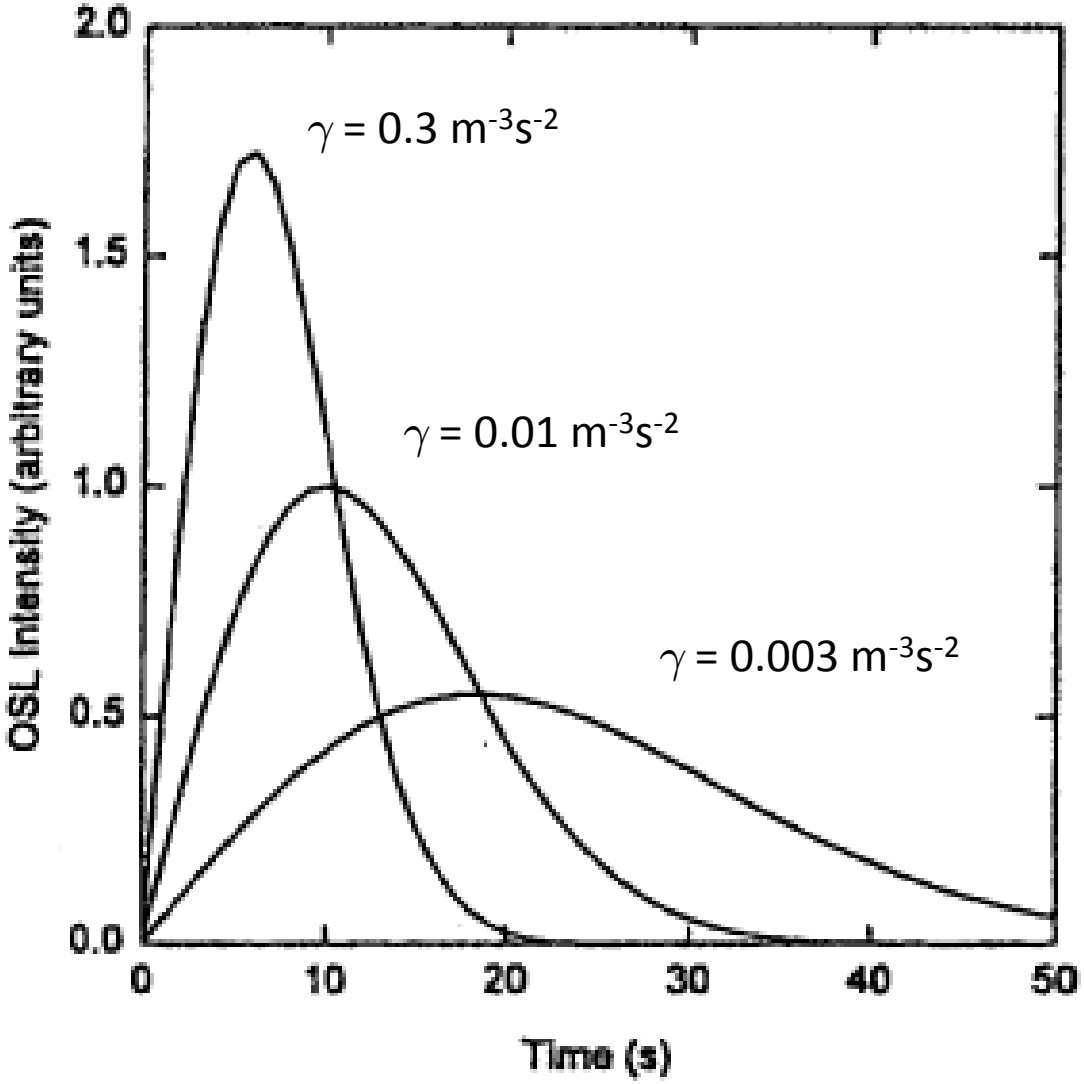
$$t = t_{max} = \sqrt{1/\sigma\gamma}$$

- For known $\gamma$ → it is possible to obtain $\sigma$
- The maximum intensity of the curve is →

$$I_{OSL}^{max} = \frac{n_0}{t_{max}} \exp\left(-\frac{1}{2}\right)$$

- The integration of $I_{OSL}$ gives $n_0$

# Examples of LM-OSL curves

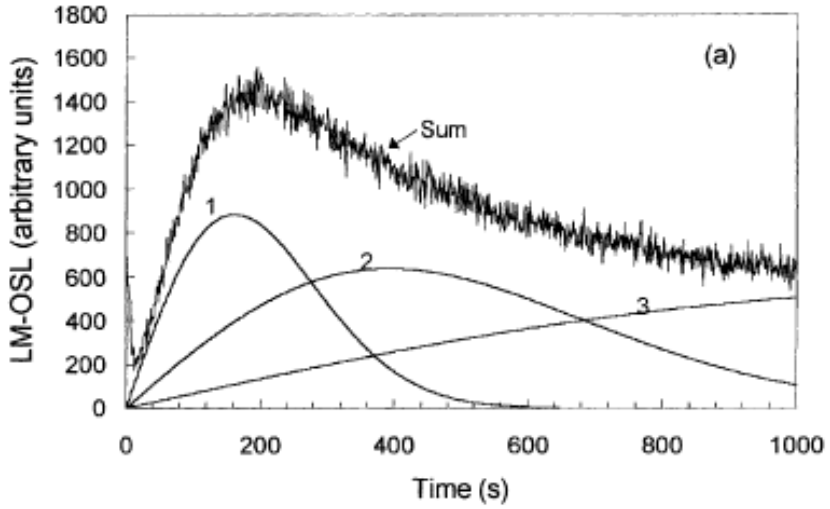


# Multiple independent traps

- The superposition principle can be applied → for k traps characterized by their occupation $n_i$ and their photoionisation cross section $\sigma_i$ →

$$I_{OSL} = \gamma t \sum_{i=1}^{k} n_{0i}\sigma_i \exp\left(-\frac{\sigma_i \gamma}{2} t^2\right)$$

- OSL curve → sum of k curves having each a maximum dependent on $\sigma_i$ →




OSL response of quartz

# Characteristics at general-order

- QE but important retrapping rate
- For 1 type of trap →

$$\frac{dn}{dt} = -\frac{\sigma\gamma t n^b}{n_0^{b-1}}$$

$$\Rightarrow \quad I_{OSL} = n_0\sigma\gamma t\left[(b-1)\frac{\sigma\gamma t^2}{2}+1\right]^{b/(1-b)}$$

- Maximum $t_{max}$ for a value of $I^{max}$ →

$$t_{max} = \sqrt{\frac{2}{\sigma\gamma(b+1)}} \quad \text{and} \quad I_{OSL}^{max} = \left(\frac{2n_0}{b+1}\right)\left(\frac{1}{t_{max}}\right)\left(\frac{2b}{b+1}\right)^{b/(1-b)}$$

- Attention → for several types of traps → retrapping implies that the traps are **not** independent → the superposition is not possible as for 1st order → complexity

# POSL

- POSL allows to efficiently separate luminescence and stimulation lights
- Important decrease of the background due to the scattered stimulation light
- Very powerful method for weak dose dosimetry

# Principles of POSL (1)

- We consider several stimulation pulses (supplied by LED or laser) of different intensities $\Phi_i$ and durations $T_i$ such that $\Phi_i T_i = \Phi T =$ constant (fixed absorbed energy by pulse).
- By considering the 1st order model →

$$\Delta n = \int_0^T n\sigma\Phi dt$$

- For a weak stimulation ($\Delta n \ll n$ → *the* concentration of charges released by pulse is negligible compared to the concentration of trapped charges) → $\Delta n \propto \Phi T$ → the charge released from the traps is approximately equal after each pulse

# Principles of POSL (2)

- Normally when writing rate equations → we consider that each recombination event leads **instantly** to a photon emission event
- In reality → the recombination center is first excited (luminescence center) before relaxation by light emission → existence of a built-in delay $\tau$ (lifetime of the excited state)
- If we have $n_e$, the concentration of excited states →

$$\frac{dn_e}{dt} = \frac{dm}{dt} - \frac{n_e}{\tau}$$

- One photon is emitted when the excited state relaxes →

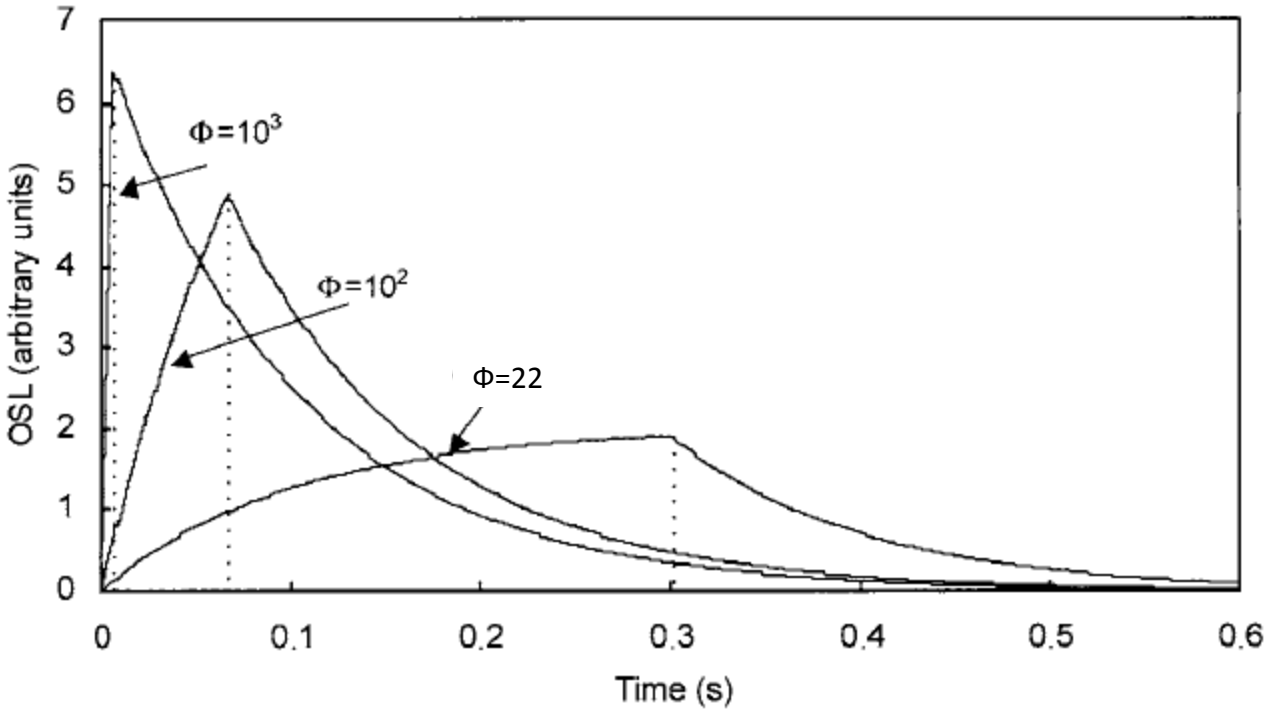
$$I_{OSL} = \frac{n_e}{\tau}$$

# Principles of POSL (3)

- If $\tau \ll$ T → conditions of quasi-equilibrium → $dn_e/dt \approx 0$ and $I_{OSL} \approx -dm/dt$ as usual (as for CW-OSL)
- If $\tau \geq$ T → ≠ situation → a certain number of centers relaxe **after** the end of the stimulation pulse
- If $\tau \gg$ T → most of the photons are emitted after the pulse (for $Al_2O_3$:C → 90% of the light emerges after the pulse if it is narrow enough)

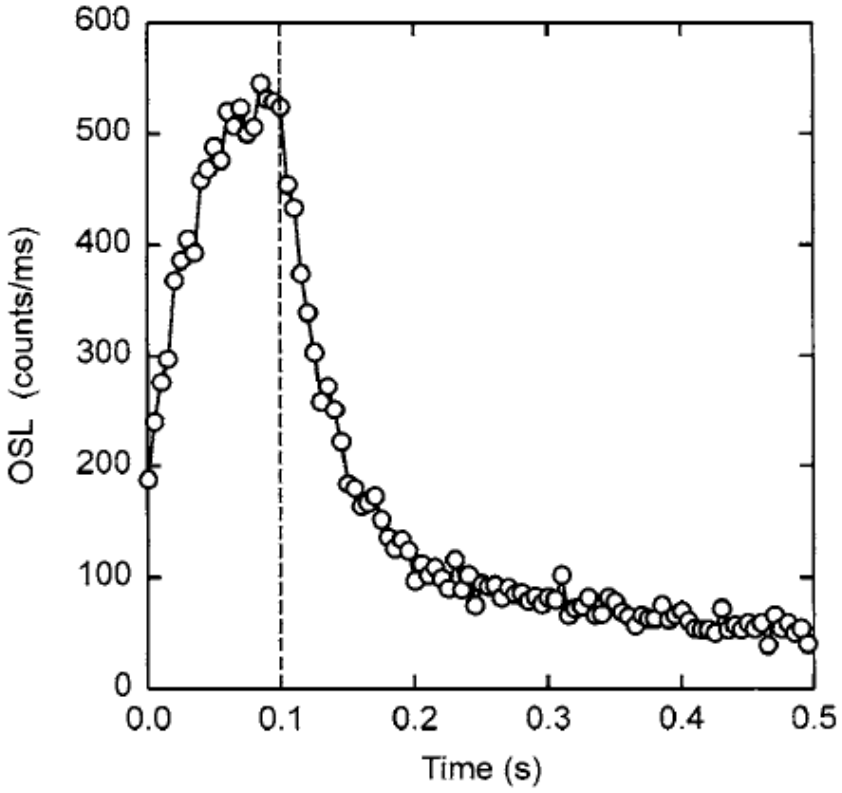
- For t < T → $I_{OSL}$ ↗ when t ↗ (optical stimulation of the traps)
- For t > T → $I_{OSL}$ ↘ when t ↗ (relaxation with a time constant $\tau$)

# Schematic illustration of POSL

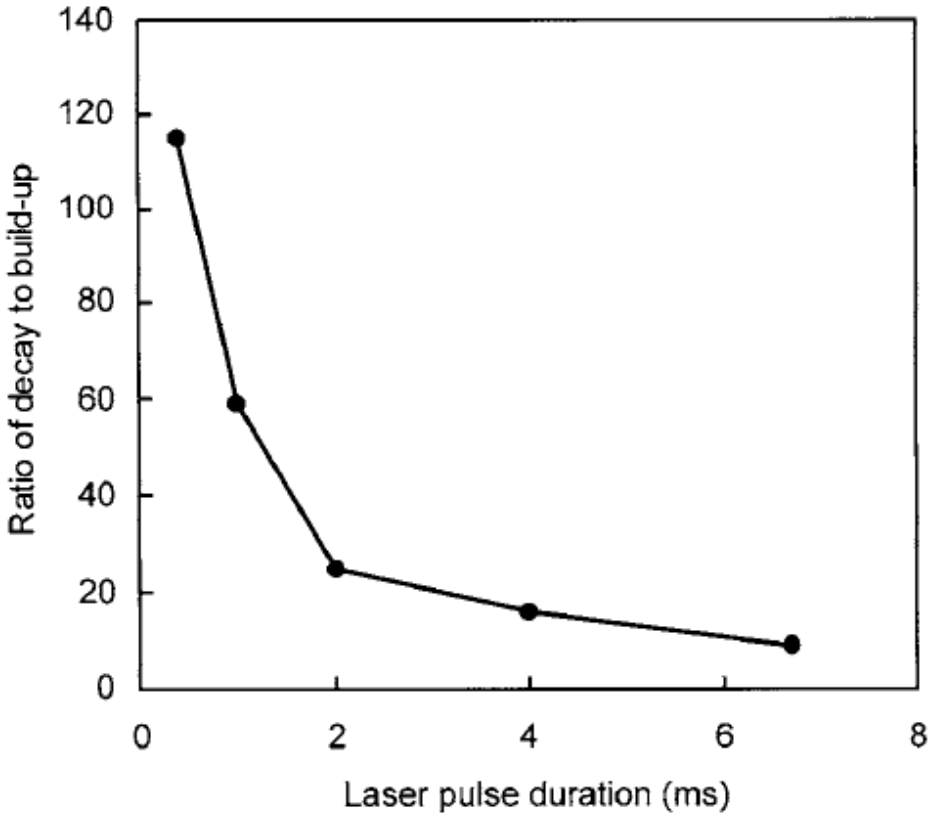



- POSL after pulses with $\Phi$ = $10^3$, $10^2$ and 22 u.e./s → we have the corresponding T: T = 6.6, 66 and 300 ms ($\tau$ = 100 ms was chosen)
- The ratio of the areas after during the pulse ↗ for T ↘

# Experimental illustration of POSL




POSL for $Al_2O_3$:C stimulated by laser during 0.1 ms




Ratio of the areas after and during the pulse for $Al_2O_3$:C

# Determination of the dose by POSL

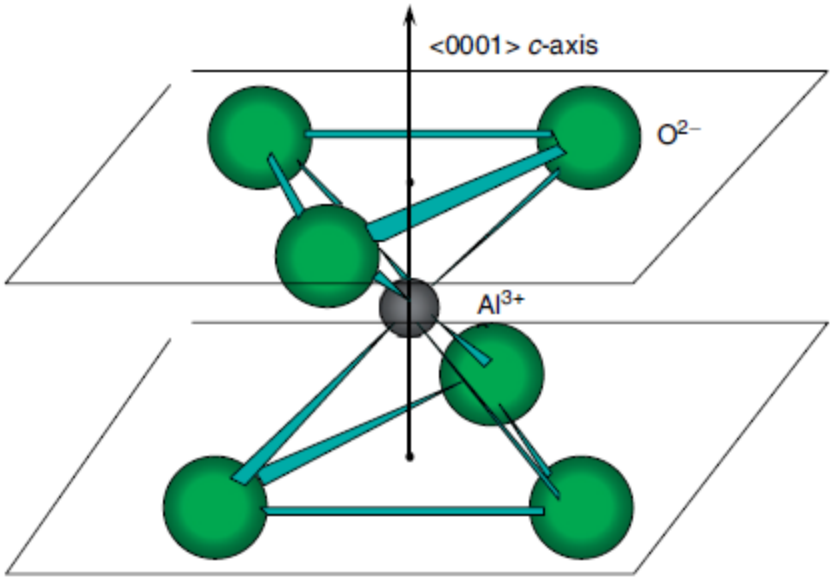
- The total integration of the POSL curve corresponding to 1 pulse is equal to the charges released from the traps and is thus $\propto$ to $n_0$
- The integration of the curve after the end of the pulse is also $\propto$ to the charges released from the traps and is thus also $\propto$ to $n_0$ but the proportionality coefficient changes as a function of the width T of the pulses
- With $\Delta n \ll n \rightarrow$ only a few stimulation pulses are enough $\rightarrow$ to make several measurements is possible
- POSL especially applied with $Al_2O_3$:C but very promising

# $Al_2O_3$:C

- $Al_2O_3$ → as $\alpha$-$Al_2O_3$ : corundum or alpha alumina
- $Al_2O_3$:C is the material most often used in OSL
- $Al_2O_3$:C is the only material used in POSL

# $Al_2O_3$:C: Structure of $\alpha$-$Al_2O_3$

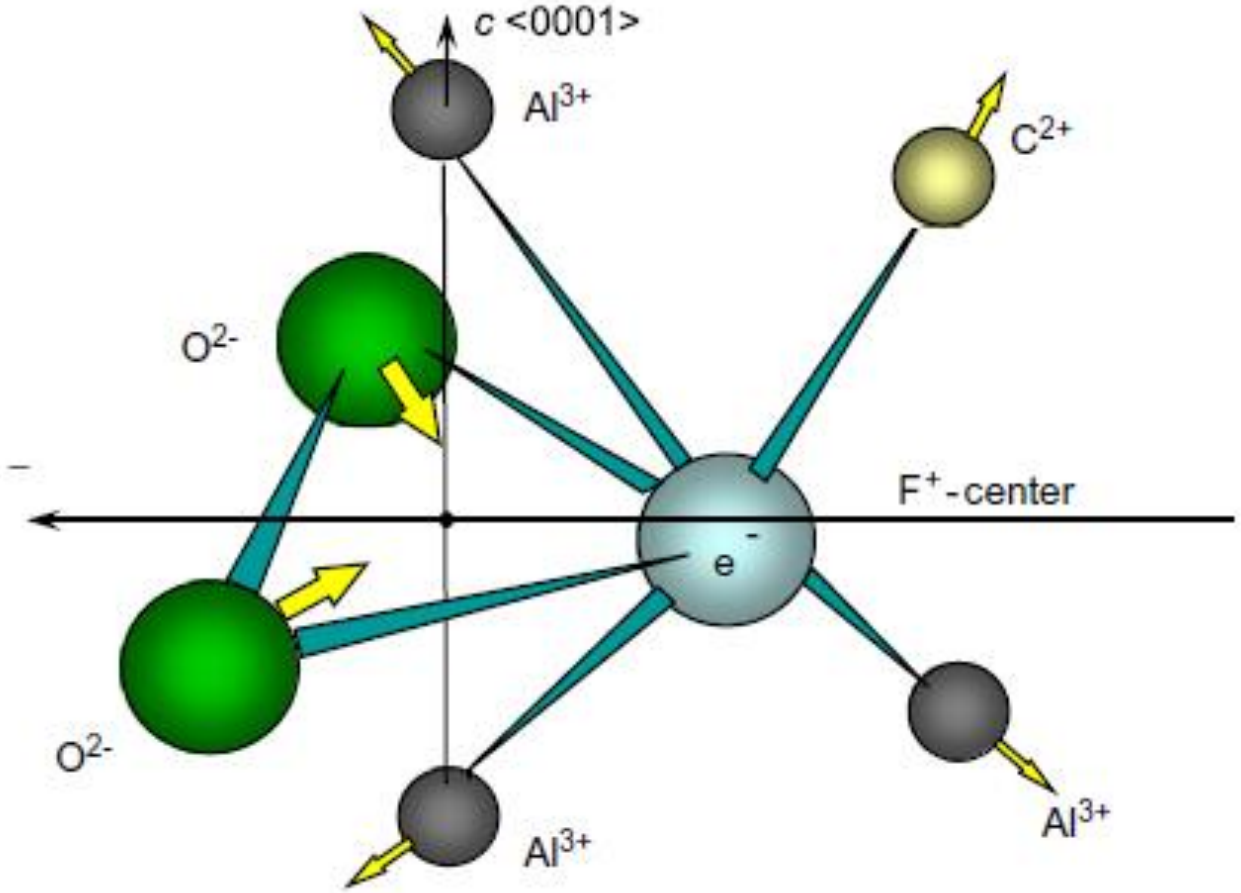
- The crystalline structure of $\alpha$-$Al_2O_3$ is a slightly distorted hexagonal-closepacked $O^{2-}$ lattice with $Al^{3+}$ ions occupying two out of every three octahedral interstices
- Each $Al^{3+}$ ion is surrounded by 6 octahedral nearest-neighbor $O^{2-}$ ions



# Defects and impurities

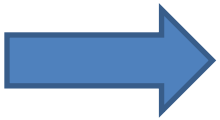
- The thermodynamic defects are oxygen or aluminium vacancies → centers of type F and V, respectively
- The $O^{2-}$ vacancy implies a charge compensation →
  - the occupancy of the vacancy by 2 $e^-$ gives rise to a neutral F-center
  - the occupancy of the vacancy by 1 $e^-$ gives rise to a positive $F^+$-center
- The addition of carbon impurities causes significant increase the sensitivity of the material
- The divalent $C^{2+}$ carbon ion replaces a trivalent $Al^{3+}$ ion → charge compensation → creation of oxygen vacancies as $F^+$-center

# Configuration of an $F^+$-center charge-compensated by a divalent carbon ion



# Emission mechanisms

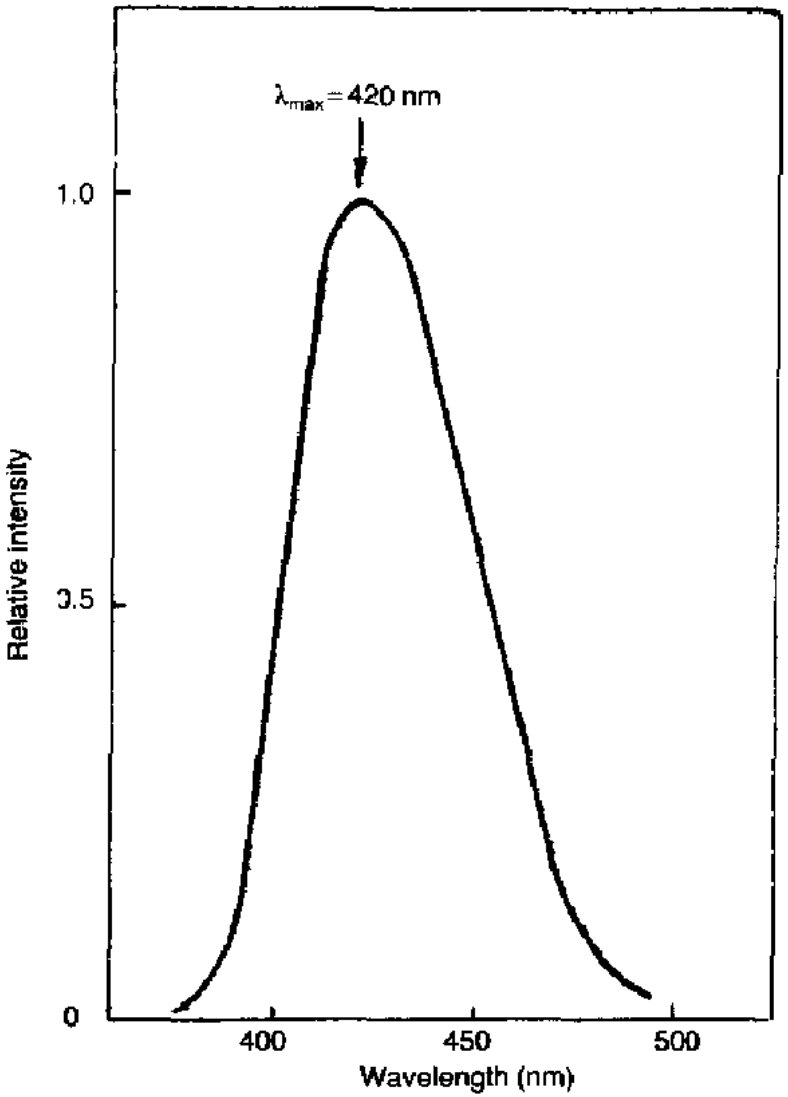
- The sensitivity of $Al_2O_3$:C depends on the concentration of $F^+$-centers that are the recombination centers
- The main emission band of the $Al_2O_3$:C is a quite large band centered at 420 nm and ascribed to a F-center of luminescence
- The $e^-$ are released from the traps and recombine with $F^+$-center → creation of excited F-center relaxing and giving luminescence
- The lifetime of the excited F-center is 35 ms at ambient T



$$F^+ + e^- \longrightarrow F^* \overset{\tau = 35\ \mathrm{ms}}{\longrightarrow} F + h\nu_{420\mathrm{nm}}$$

- The identity of the defects responsible for the capture of the charge carriers during the ionization is not known

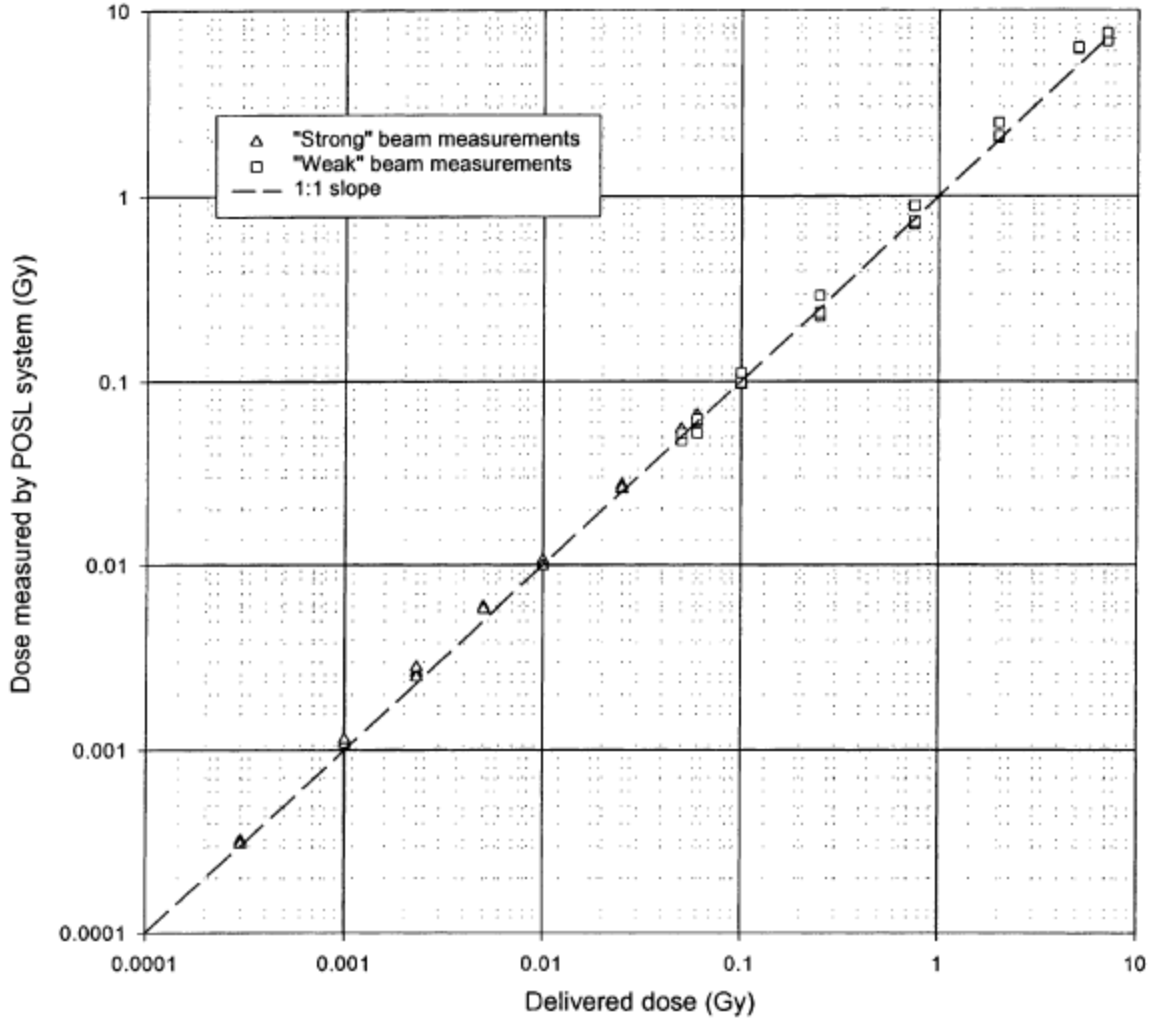
# Emission spectrum of $Al_2O_3$:C



# Dosimetric properties of $Al_2O_3$:C (1)

- The energy band-gap of $Al_2O_3$ is wide ($\sim$ 9.5 eV) → allows to engineer deep and thermally stable traps and color centers (little sensitive to T)
- $Al_2O_3$:C is very sensitive to radiation (sensitivity → ratio between the number of emitted photons and the absorbed dose) because of the absence of thermal quenching and of very small noise (especially for POSL) → 60 $\times$ more sensitive than the TLD-100 which is the reference
- This very good sensitivity allows to make measurements at very small doses → $D$ = 1 $\mu$Gy
- $Al_2O_3$:C shows a linear response to the dose in a large range → 1 $\mu$Gy < D < 10 Gy → on 5 decades (supralinearity appears at 10 Gy and sublinearity at 100 Gy)

# Dose response of $Al_2O_3$:C



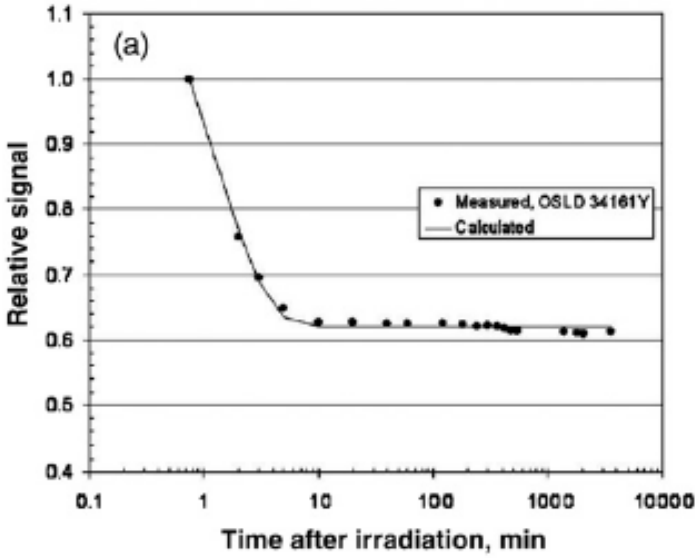

« strong » and « weak » characterize the stimulation power (1.2 W and 0.01 W)

# Dosimetric properties of $Al_2O_3$:C (2)

- Possible rereading of the dosimeter → due to the large sensitivity of $Al_2O_3$:C → in CW-OSL a measurement is precise enough if only a part of the traps is emptied → by considering the fraction of charges released during the 1st measurement, a second measurement is possible (or a 3th, etc.)
- In POSL, rereading is more obvious → only a few stimulations pulses are enough → such as $\Delta n \ll n$ → measure could be redo
- Also possibility to reuse the OSL dosimeter after heating at high T to empty the traps
- $Al_2O_3$:C is not tissue-equivalent ($Z_{eff}$ = 10.2 ≠ 7.35) → energy dependence (overestimation) for E < 200 kEV → 1 filter could correct this problem

# Fading

- Fading comparable to TLD-100 (5%/an)




- A transient signal appears for $t < 10$ min → due to shallow traps which are quickly empty → afterwards stable signal

# Characteristics of $Al_2O_3$:C and other OSL

| OSL material | Rel. OSL Sensitivity | Linear dose range | Stimulation wavelength (nm) | Main emission wavelength (nm) | Fading rate in dark | Effective Z (Tissue =7.4) |
|---|---|---|---|---|---|---|
| $Al_2O_3$:C (Landauer Inc.) | 1.00 | µGy-10 Gy | 450-550 | ~420 | <5% /y | 10.2 |
| $Al_2O_3$:C (BARC, India) | ~0.3 | 50 µGy-1 Gy | 470 | 420 | negligible in a month | 10.2 |
| **$Al_2O_3$:B | ~0.17 | 100 µGy-15 Gy | 470 | 420 | Negligible in a month | 10.2 |
| BeO sintered pellets (Germany) | ~1.00 | µGy-10 Gy | ~435 | ~335 | 1% in six months | 7.2 |
| MgO:Tb | weak | 100 µGy-10 Gy | 500-560 | 375,420,440, 470,500,650 | 43% in 1st 36h and then nil | 10.8 |
| $NaMgF_3$:Eu | ~10.0 | µGy-100 Gy | ~470 | 360 | 40% in 1st 24h and then nil | 10.4 |
| $Mg_2SiO_4$:Tb | ~0.11 | 30 µGy-10 Gy | <532 | 370,420 and 440 | 30% in 1st 10h and then nil | 11.23 |
| *$LiMgPO_4$:Tb,B (BARC, India) | ~1.00 | 20 µGy -1 kGy | 470 | 380,417,440 | 16% in 4 days and stable thereafter | 11.20 |

# $Al_2O_3$:C dosimeters in practice

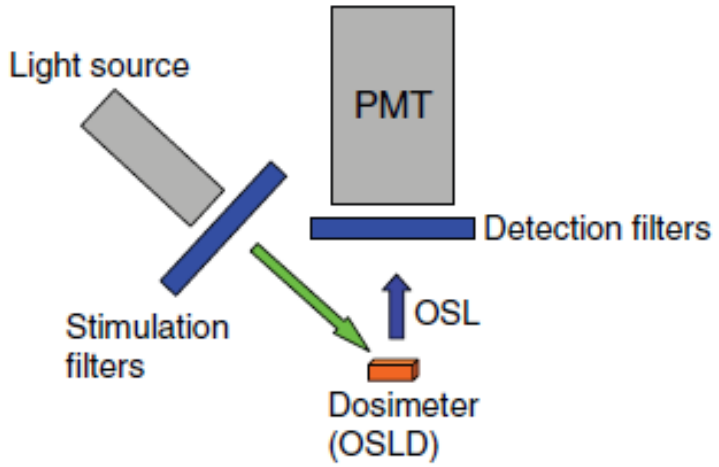
- As monocrystal
  - → very sensitive → excellent for the measurement of small doses
  - → may be heated → deep traps are emptied → may be indefinitely reused
  - → lack of uniformity between 2 crystals → large variability between dosimeters of this type → individual calibration
- As powder (Landauer Inc.) → crystals grinded into powder and embedded in a plastic matrix
  - → very good uniformity
  - → cannot be heated → deep traps are not emptied → loss of sensitivity in the end
- Microcrystals and optical fiber
  - → in-vivo dosimetry
  - → real-time dosimetry
  - → to be investigated

Ø = 300 $\mu$m

# OSL Readers: Basic properties

A basic installation requires:

1. A light source for the stimulation (LED, laser,…)
2. Filters to select the wavelength of the light source
3. Filters to select the wavelength of the luminescence light
4. A light detector (photomultiplier,…)
5. The associated electronics



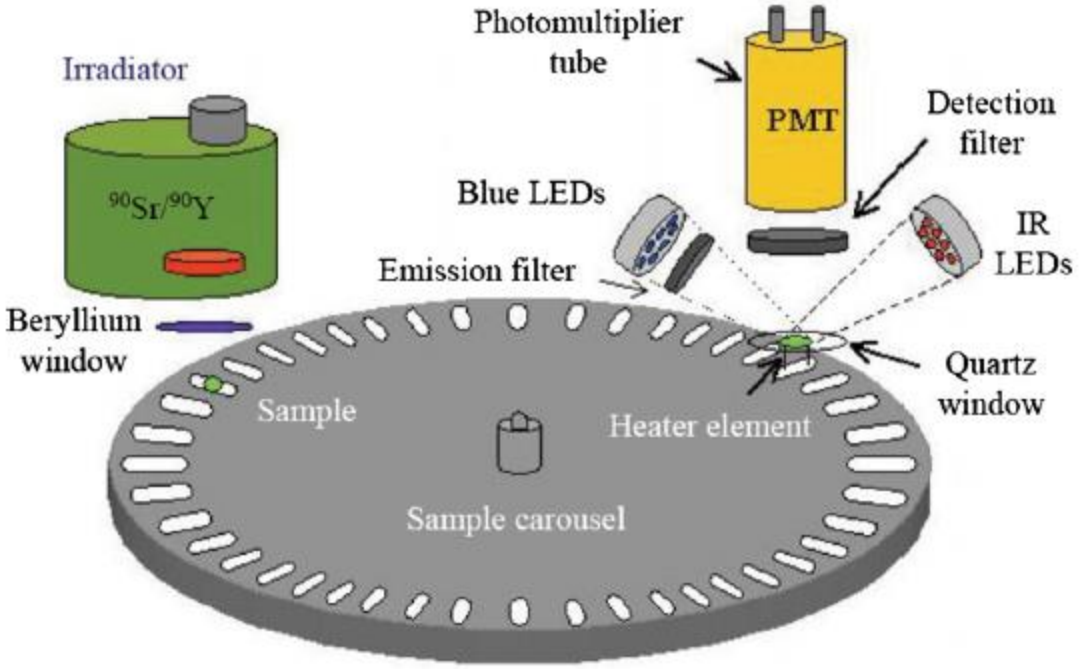
# Wavelength of the stimulation light

- The more efficiency wavelength of the stimulation light is blue ($\lambda \approx 470$ nm) but it too close of the maximum of luminescence ($\lambda = 420$ nm)

- In practice in dosimetry green is used ($\lambda \approx 525$ nm)

# OSL reader in practice (1)

- OSL reader for research
  - → High-capacity automatization
  - → allows OSL or TLD measurements
  - → calibration source is often incorporated
  - → equipped with blue and/or green LEDs



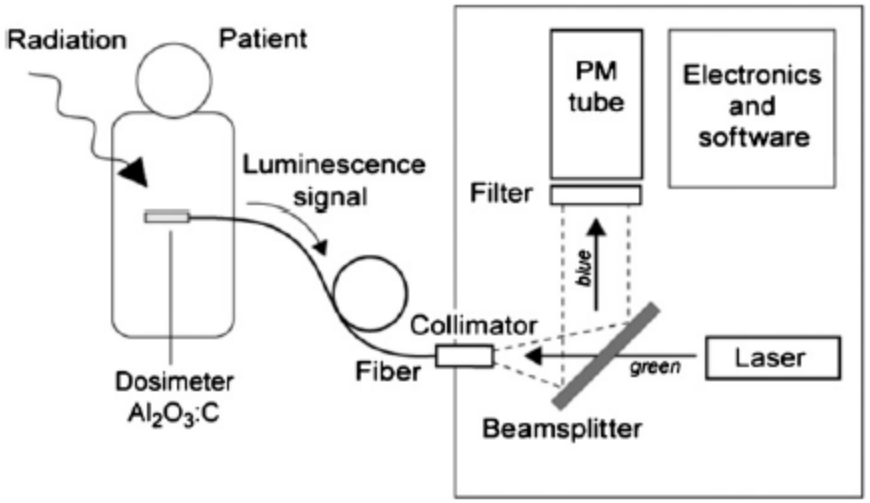
# OSL reader in practice (2)

- OSL Landauer reader → in POSL mode
  → OSL stimulated by laser Nd:YAG (532 nm) with short period
  → the OSL intensity is measured between pulses
  → as a function of the dose → ≠ stimulation powers

- OSL Landauer reader → in CW-OSL mode
  → short stimulation (1s) by green LEDs
  → number of LEDs (and thus power) depending as a function of the dose to be measured

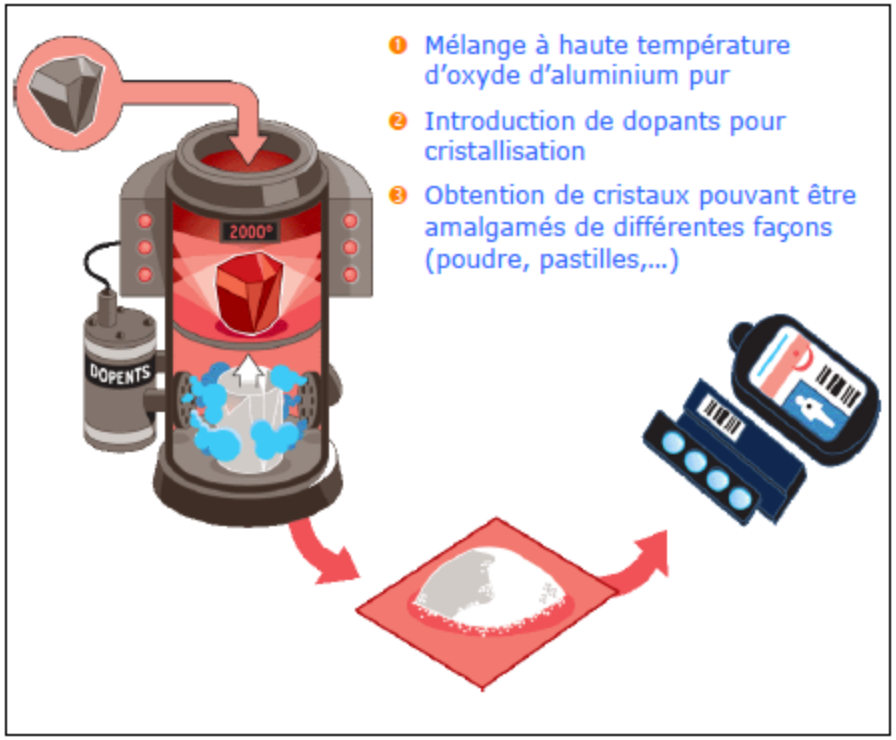
# OSL reader in practice (3)

- System with optical fiber
  - → the optical fiber delivers the OSL stimulation OSL and carries back the luminescence
  - → green laser for stimulation
  - → also POSL mode
  - → allows  in-vivo and real-time measurements



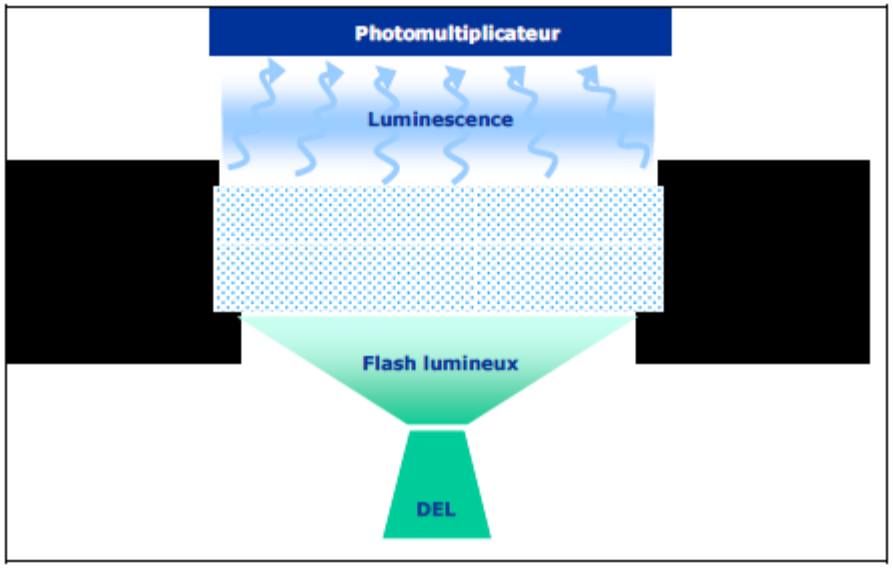
# OSL dosimeter: In practice at ULB (1)

- Dosimeters Landauer IPLUS in $Al_2O_3$:C
- From crystals in aluminium oxide → aluminium oxide powder applied between 2 plastic films



# OSL dosimeter: In practice at ULB (2)

- For IPLUS → optical stimulation realized from a set of electro luminescent diodes emitting  continuously a 532 nm light (green) → CW-OSL
- Signal emitted from detectors (blue light of about 420 nm) measured with a photomultiplier



# OSL dosimeter: In practice at ULB (3)

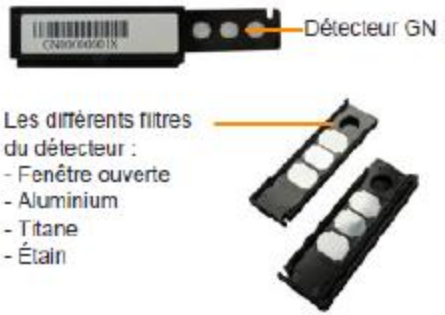
- **Dosimeter re-analyze:** The optical stimulation maintain more than 99% of information in the detector → possible multiple reading and storage of the dosimeter for later investigations
- **No required calibration:** The sensitivity of the detector is determined during the fabrication process → the sensitivity value carved on the detector is automatically taken into account during the reading process
- **Stable sensitivity in time:** Sensitivity defined for ever
- **Very weak fading:** Smaller than 1,5 % / month and <4% / year → the fading does imply to be corrected during the dose estimation
- **Response to neutrons:** No neutron sensitivity highlighted here

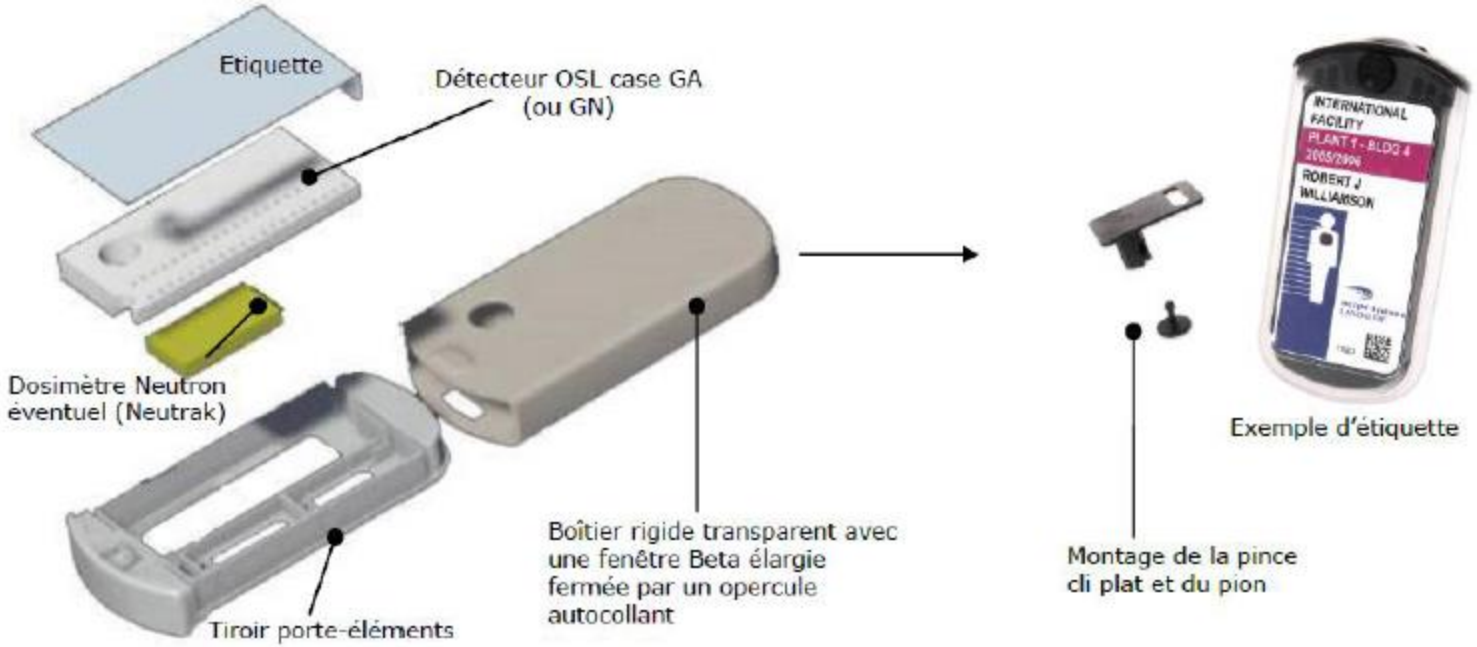
# OSL dosimeter: In practice at ULB (4)

- **Temperature and hygrometry:** Range of use: -10°C to 40°C and from 0 % to 90%
- **Exposition to light:** no particular restriction in normal conditions
- **Strong and light dosimeter:** Strong, compact, light, fully customize dosimeters
- **Types of radiations**:
  - photon: energies from 16 keV to 6 MeV (with a maximum energy of 18 MeV)
  - beta: energies larger than 250 keV
- **Possible reutilization**: dose maximum of 100 mSv and maximum number of reutilizations: larger than 1000
- **Homogeneity of the pack sensitivity**: < 10% (generally < 2,4%)

# OSL dosimeter: In practice at ULB (5)

- Detector with :
  - A detector card with 4 pastilles in $Al_2O_3$:C
  - A filter holder box with a barcode printed in a legible form and composed of 4 filters: plastic, aluminium, titanium, tin



# Radiophotoluminescence dosimetry (RPL)

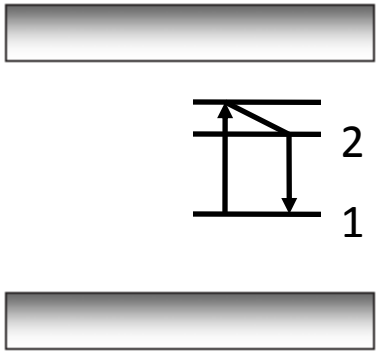
- Again luminescence process stimulated by light
- For radiophotoluminescence (RPL) → no ionization of the defect but excitation of the defect → during relaxation → emission of light
- Main advantage → the trapped carriers are preserved → the measurement can be indefinitely repeated → **storage**
- Process ≠ from OSL → another class of dosimeter (even with optical stimulation)
- Very recent development → this technology need to prove itself
- Reference:

  T. Yamamoto, D. Maki, F. Sato, Y. Miyamoto, H. Nanto, T. Iida, *The recent investigations of rdiophotoluminescence and its application,* Radiations Measurements 46 (2011) 1554-1559

# History

- Discovery and first application in 1951 by Schulman
- Problem → Photoluminescence inherent to considered materials → emission of light without irradiation → important noise → brake on its use while properties are extremely interesting
- Recently → development of a pulsed laser system + perfectly controlled materials + improved electronics → decrease of the noise to a correct level
- Possibly a very valued method in the future (currently: Japan and IRSN in France)

# Simple model for RPL (1)




- We have $n_1$, the concentration of $e^-$ trapped in 1 (ground state of the trap), $n_2$, the concentration of $e^-$ trapped in 2 (excited state of the trap), $\alpha$ and $\beta$, the transition probabilities 1 → 2 and 2 → 1
- The material is exposed to a light source with short wavelength (UV) and with intensity $I_{in}$ (constant) → the result is that a light with a larger wavelength and with intensity $I_{out}$

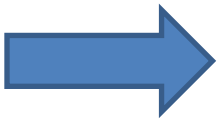
# Simple model for RPL (2)

- The equations of the process are →

$$\begin{cases} \dfrac{dn_1}{dt} = \beta n_2 - \alpha I_{in} n_1 \\ I_{out} = \beta n_2 \end{cases}$$

- By considering stationary state → $dn_1/dt = dn_2/dt = 0$ →

$$n_2 = \frac{\alpha I_{in} n_1}{\beta}$$

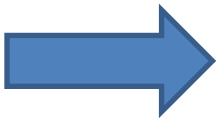


$$I_{out} = \alpha I_{in} n_1$$

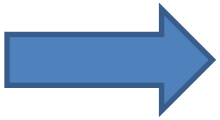
# Simple model for RPL (3)

- The important parameter linked to the dose is $n_t = n_1 + n_2$ →

$$n_t = n_1 + \frac{\alpha I_{in} n_1}{\beta}$$



$$n_1 = \frac{n_t}{1 + \alpha I_{in}/\beta}$$

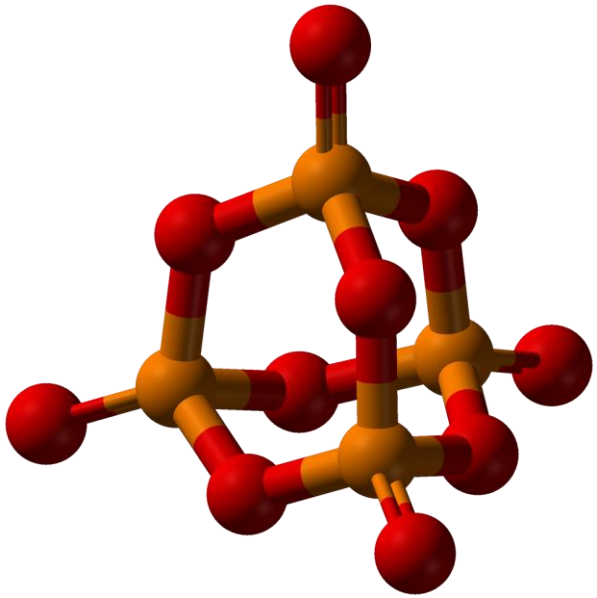


$$I_{out} = \frac{\alpha I_{in}}{1 + \alpha I_{in}/\beta} n_t$$

- If the source is a powerful laser → $I_{in}$ > → important denominator
- If the source is a LED → $I_{in}$ < → $I_{out} = \alpha I_{in} n_t$
- If signal present even though dose = 0 → $I_{out} = \alpha I_{in}(n_t + n_b)$ → effect of pre-dose (photoluminescence)

# RPL dosimeter: Phosphate glass with silver impurities

- Phosphate glass → type of glass in which $SiO_2$ is replaced by $P_2O_5$
- The $P_2O_5$ mainly crystallize into $P_4O_{10}$ → each P atom is surrounded by 4 O atoms as tetrahedron shape →



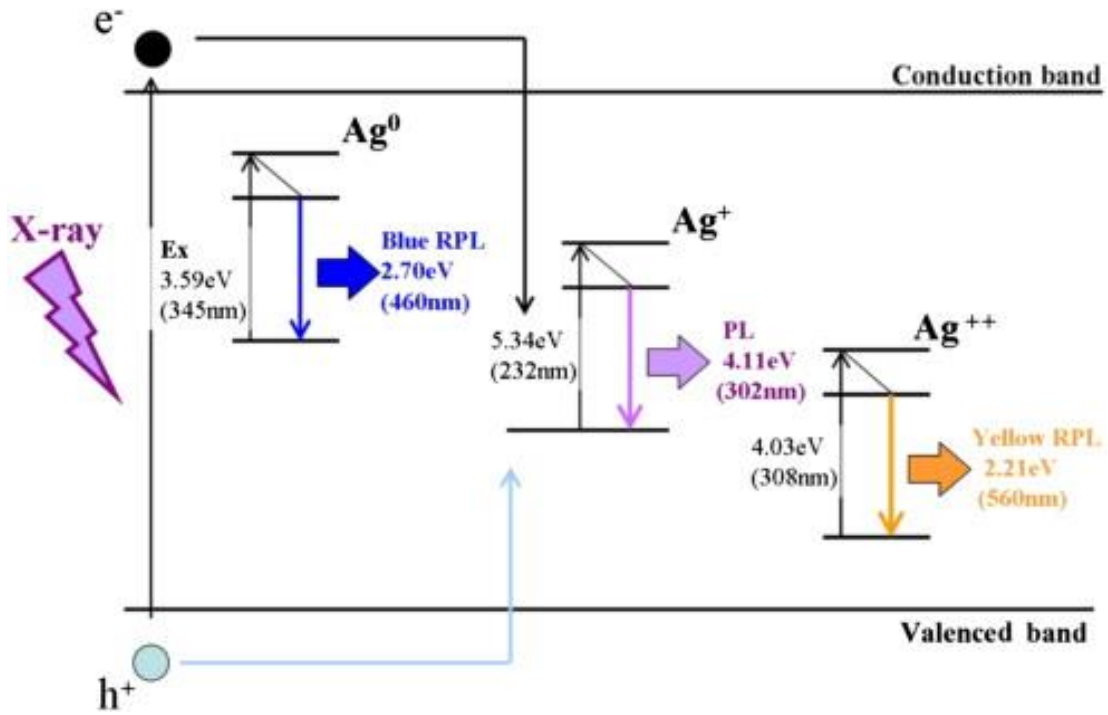
# Phosphate glass: Silver impurities

- Several compositions exist but all of them contain Ag impurities (example: FD-7 → Na: 11.00%, P: 31.55%, 0: 51.16%, Al: 6.12%, Ag: 0.17%)
- The optimum Ag concentration is determined in a phenomenological way
- In the phosphate glass, Ag is stable as $Ag^+$ ion
- The $e^-$ and $h^+$ created by ionizing radiation in the glass are diffused in it and produce at the end the reactions →

$$\begin{cases} \mathrm{Ag}^+ + \mathrm{e}^- \rightarrow \mathrm{Ag}^0 \\ \mathrm{Ag}^+ + \mathrm{h}^+ \rightarrow \mathrm{Ag}^{2+} \end{cases}$$

# Luminescence mechanism

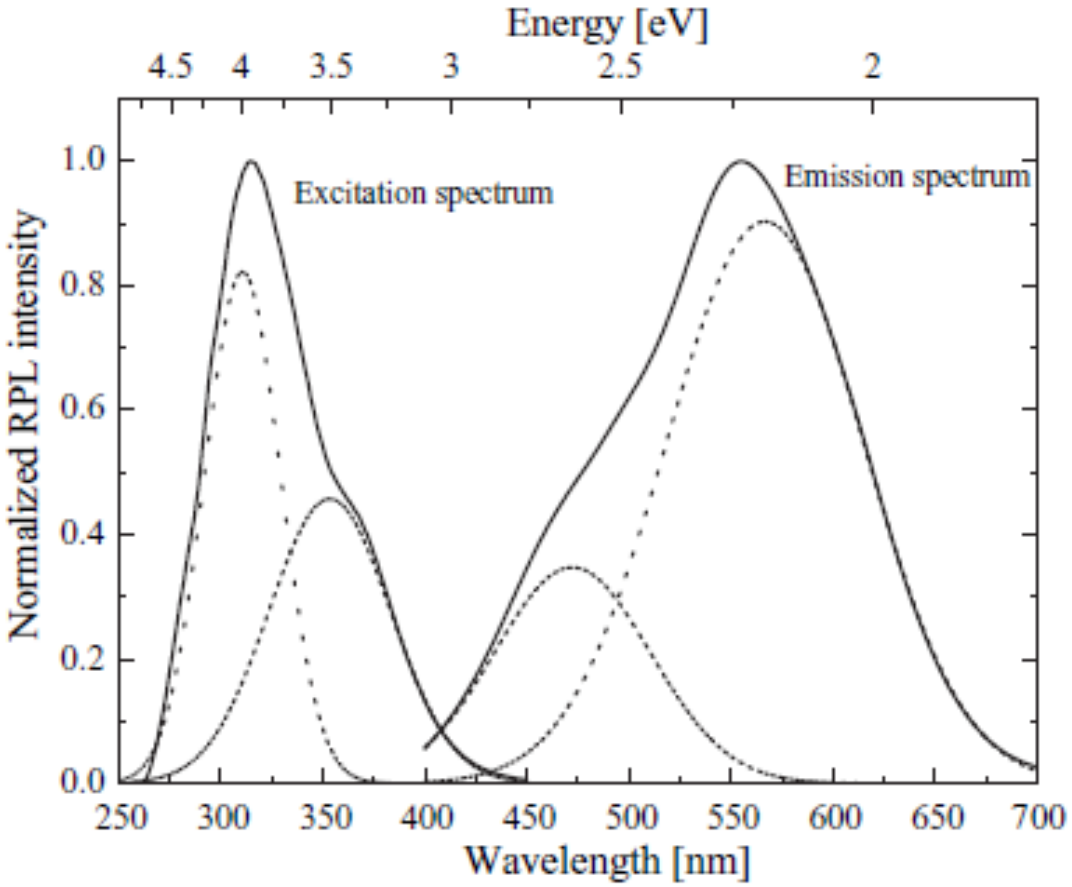
- $Ag^0$ are $Ag^{2+}$ are the stable luminescence centers at ambient T




- When the glass is exposed to UV radiation (345 and 308 nm) → excitation of $Ag^0$ and $Ag^{2+}$ impurities and then relaxation of these impurities by visible light emission (460 nm: blue and 560 nm: yellow-orange)

# Absorption and emission spectra

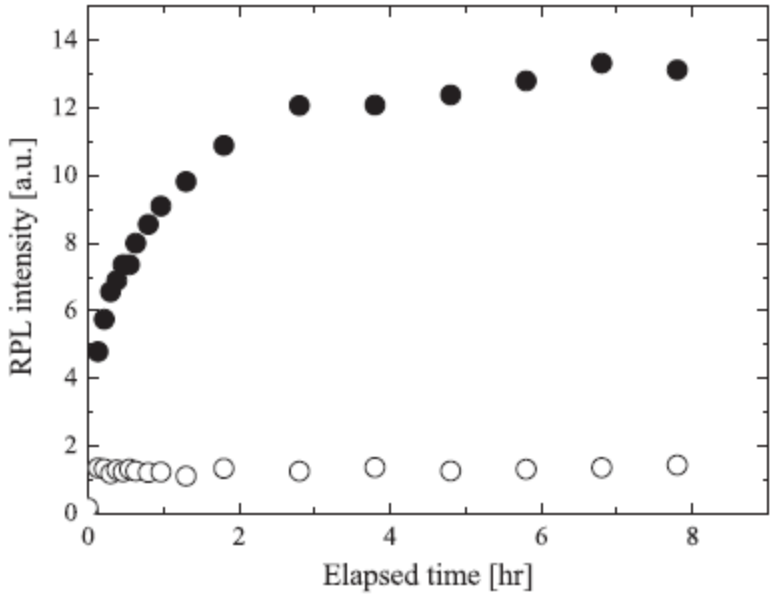
There is thus a combination between the 2 visible radiations emitted → the emission spectrum is dependent on the absorption spectrum




yellow-orange is dominating

# Build-up effect

- Particularly for the emission at 560 nm → a waiting time is needed after the irradiation by ionizing radiation to stabilize the RPL light intensity → « build-up » phenomenon




● : RPL à 560 nm

○ : RPL à 460 nm

- It was suggested that, initially, the $h^+$ is trapped by a $PO_4$ tetrahedron → only after a certain time: $Ag^+ + hPO_4^+ \rightarrow Ag^{2+} + PO_4$

# RPL dosimetry: In practice

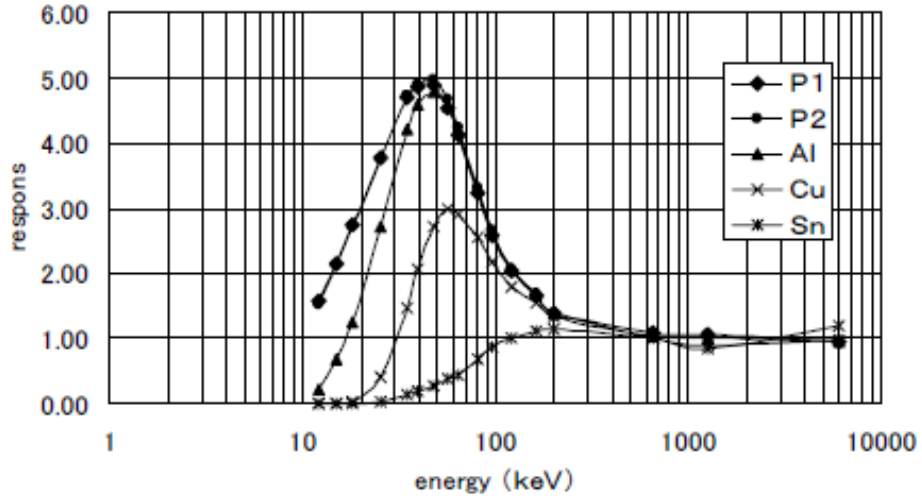
- The dosimeters based on the radiophotoluminescence phenomenon are called RPLD

- For the FD-7 dosimeters: $Z_{eff}$ = 12.0 → not tissue-equivalent ($Z_{eff}$ = 7.35) → energy dependence for small energies (photoelectric effect)

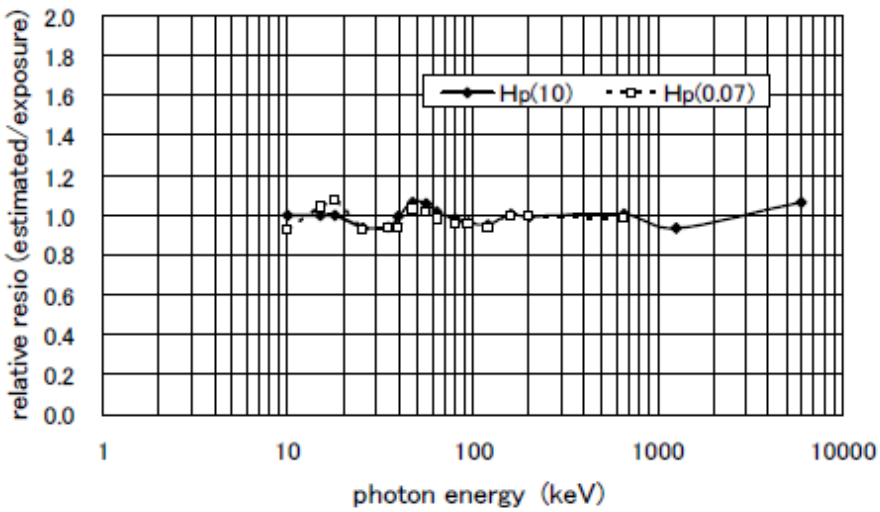
- To correct this non-linearity → addition of filters (for instance: Sn, Al, Cu, PE,…)

# Energy response

(a)




(b)

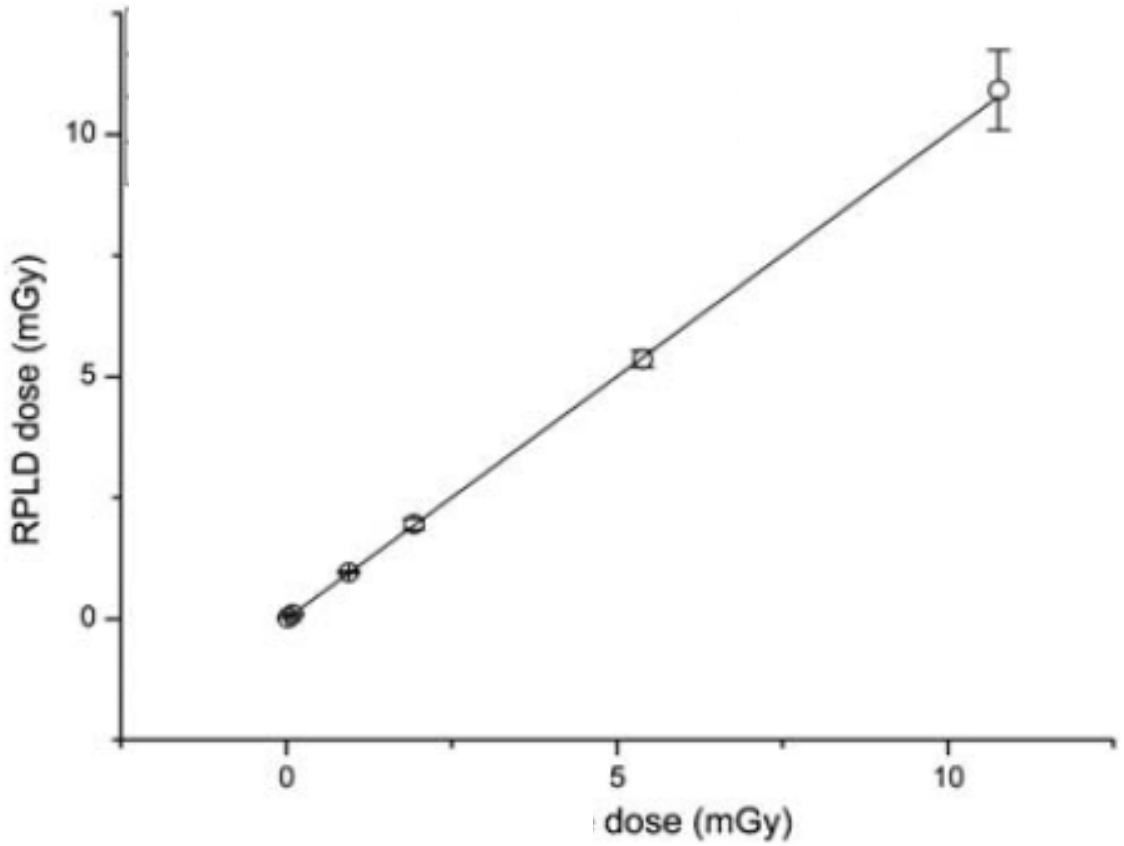



(a) Energy response for incident $\gamma$ with ≠ filters

(b) corrected response of the dosimeter ($R = \sum_i k_i R_i$)

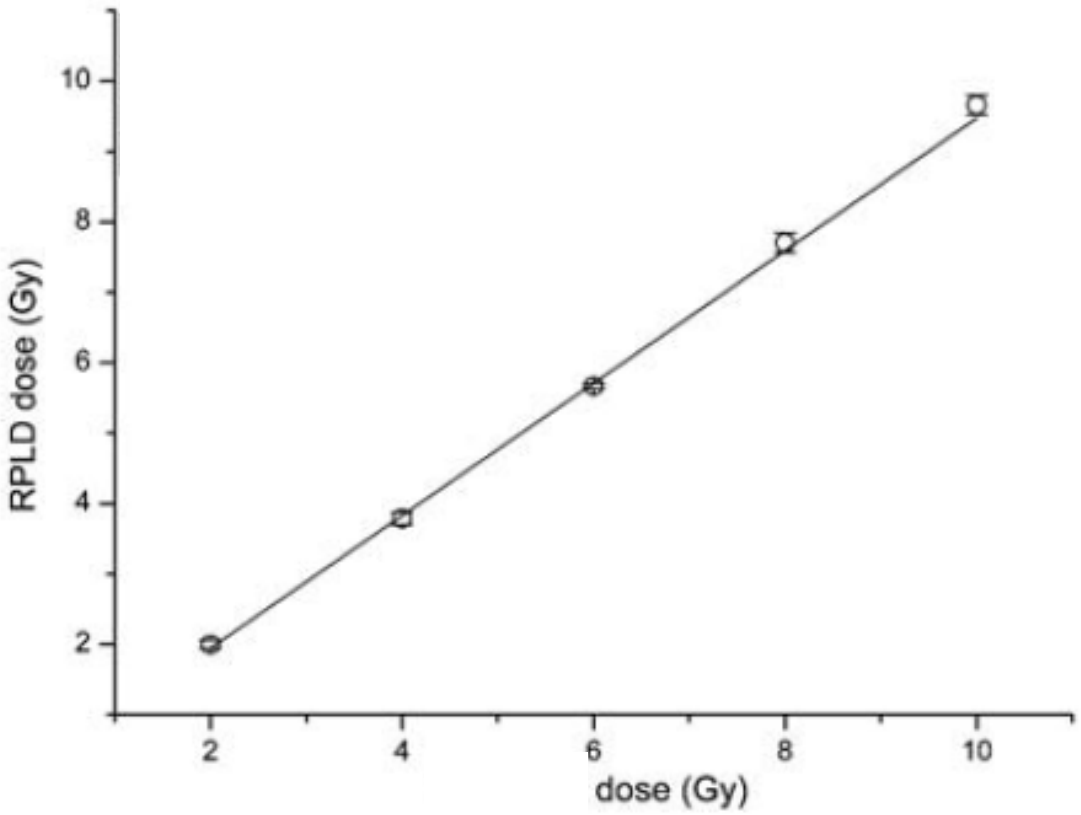
→ Linear response equal to 1 (with corrections)

# Response in dose: Small doses




- Linear response for small doses

# Response in dose: high doses




- Linear response for high doses
- Linear response for 20 $\mu$Gy < *D* < 10 Gy

# Fading - Reproducibility

- The fading data depend on the considered materials (and on measurement laboratories) but fading ≤ 1%/month is generally observed

- The measurements are reproduced several times after various waiting times (t < 10 days) and various doses (20 $\mu$Gy < *D* < 10 Gy) give identical results (with variation of 1.5%)

| TL dosimeters | OSL dosimeters | RPL dosimeters |
|---|---|---|
| High sensitivity of materials: LiF:Mg,Cu,P, LiF:Mg,Cu,Si, $CaSO_4$:Dy | High sensitivity due to absence of thermal quenching and IR background: $Al_2O_3$:C and BeO | High sensitivity of materials such as silver-activated phosphate glass |
| Stable sensitivity possible | Stable sensitivity possible | Stable sensitivity possible |
| Easy handling (no light sensitivity using LiF:Mg,Cu,P, LiF:Mg,Ti. | Highly light sensitive, but can be managed with appropriate precautions during storage and use. | No light sensitivity for visible light ($\lambda$>366nm), as RPL emission is stimulated by UV light. |
| Dose re-estimation possible. Doses as low as 0.2 mGy can be re-estimated using PTTL in LiF:Mg, Cu,P* | Multiple dose re-estimations possible. Multiple measurements of OSL from $Al_2O_3$:C using either pulsed or continuous wave stimulation have been reported.** | Dosimeter can be read as many times as necessary without depleting the signal. |
| Flat photon energy response for LiF:Mg, Cu,P (100keV – 3MeV) | Flat photon energy response for BeO OSL dosimeters. (100keV – 3MeV) | Use of appropriate filters gives nearly flat photon energy response: 10 keV to 10 MeV. |
| Identification of static/dynamic exposure is somewhat difficult | Identification of static/dynamic exposure is possible. | Identification of static/dynamic exposure is possible. |
| Dose imaging difficult | Dose imaging possible. | Dose imaging possible. |
| Complex thermal annealing steps for some TL materials | Elimination of thermal annealing steps, as heating of samples is not required during OSL readout | The RPL dosimeter must undergo heat treatment at 70°C to stabilize the build-up of colour centers before readout. |
| Real-time measurements- not possible | Using Optical Fiber based OSL dosimetry system: real-time (on-line) measurements. | No published report on this aspect of use is available. |
| Readout time for commercial systems: acquisition time:13.3s per readout using hot air # | ~1-2s per readout, 12-13s per 4-element dosimeter (using CW-OSL mode). | <1s per readout |
| Dose range: 1μGy to 100Gy | 10μGy to 10 Gy | 14μGy–10 Gy |
| Post-irradiation fading: <2% in 6months | <5% per year | 1% per month |