RADIATION DOSIMETERS FOR MEDICAL USE

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Abstract – The several personal radiation dosimeter types for medical use, which look like promising for this kind of application, as pMOS (RADFET) dosimeter, direct ion storage (DIS) dosimeters, thermoluminescent (TL) and optically stimulated luminescent (OSL) dosimeters, are described, and their advantages and disadvantages are analyzed. The p-channel metal-oxide-semiconductor (pMOS) dosimetric transistors allow dose measurements in vivo in real time, and they are especially important for radiotherapy. Direct ion storage (DIS) dosimeters are a hybrid of ion chamber and floating gate MOSFETs (FGMOSFETs), show very high sensitivity. Radiative processes that happen during the exposure of crystal to radiation are classified as prompt luminescence or radioluminescence (RL). In the case of an emission during stimulation, this phenomenon is referred to thermoluminescence or optically stimulated luminescence depending on whether the stimulation source is heat or light. TL and OSL dosimeters are natural or synthetic materials, which the intensity of emitted light is proportional to the irradiation dose.

Keywords – radiation dosimeters, pMOS dosimeters, DIS dosimeters, luminescent dosimeters

1. INTRODUCTION

The chosen dosimeters types belong a new dosimeter generation, looking very promising, as radiation sensitive field – effect - transistors (RADFETs), direct ion storage dosimeters (DISD), and optically stimulated luminescent dosimeters (OSLD), and widely used dosimeter, as thermoluminescent dosimeters (TLDs). They are described, emphasizing their advantages and disadvantages. RADFETs are especially important for radiotherapy radiation since they have extremely small sizes and allow dose measurements in vivo in real time. DIS dosimeter is a hybrid of ion chamber and floating gate MOSFETs (FGMOSFETs), having very high sensitivity. The difference between OSLD and TLD in the stimulation source: heat or light. TLD is mainly used as a personal dosimeter in hospitals, changing the old film dosimeter.

2. DOSIMETERS DESCRIPTION

2.1. pMOS dosimeter (RADFET)

p-channel metal-oxide-semiconductor (pMOS) dosimetric transistors (the second name is Radiation Sensitive Field-Effect-Transistors - RADFETs) are unique radiation dosimeters that have extremely small sizes (the dimensions of sensor elements are ~ 1 mm x 1 mm), and allow dose measurements in vivo in real time, which is specially important for radiotherapy.

The basic concept of pMOS dosimeter is to convert the threshold voltage shift, \( \Delta V_T \), induced by radiation, into absorbed radiation dose, \( D \). This dependence can be expressed in the form: \( \Delta V_T = A \cdot D^n \), where \( \Delta V_T = V_T - V_{T0} \), \( V_T \) is the threshold voltage after irradiation, \( V_{T0} \) before radiation, \( A \) is a constant, and \( n \) is the degree of linearity. \( n \) depends on oxide thickness, electric field and absorbed dose, and, ideally, \( n \) is linear, i.e., \( n = 1 \).

Figure 1 shows the cross section of pMOS transistors with the defects created by radiation. These defects are the oxide charge and interface traps, and their contributions to the threshold voltage shift could be expressed in the form [1]:

\[
\Delta V_T = \pm \frac{q}{C_{ox}} \Delta N_{ot} + \frac{q}{C_{ox}} \Delta N_{it},
\]

where \( \Delta N_{ot} \) and \( \Delta N_{it} \) are the areal densities of oxide charge and interface traps, respectively, \( q \) absolute value of electron charge, and \( C_{ox} \) oxide capacitance per unit area. The signs "+" and "-" are for p-channel and n-channel MOSFETs, respectively. It means that both the oxide charge and the interface states contribute to the increase of absolute threshold voltage shift of pMOS transistors. This is a reason why pMOS transistors, instead of nMOS transistors, are used as radiation dosimeters.
The increase in sensitivity to radiation is one of the main objectives when designing pMOS dosimetric transistors. This can be achieved by increasing the gate oxide thickness or stacking more transistors. The investigation of pMOS transistors with a thick gate oxide has been intensified because of their large radiation sensitivity. An interesting idea of thick gate oxide fabrication is the ‘sandwich’ structure, consisting of a layer of thermal and a layer of CVD oxide [1].

The pMOS dosimeter advantages, in comparison with other dosimetric systems, include immediate, non-destructive read out of dosimetric information, extremely small size of the sensor element, the ability to permanently store the absorbed dose, wide dose range, very low power consumption, compatibility with microprocessors, and competitive price (especially if cost of the read out system is taken into account). The disadvantages are a need for calibration in different radiation fields ("energy response"), relatively low resolution (starting from about 1 cGy) and nonreusability.

The range of possibilities of pMOS dosimeter practical application is indeed wide: as a personal dosimeter (potentially), in the laboratory, radiation therapy, spacecraft, nuclear equipment and so on. Fig. 2 shows the using of pMOS dosimeter in radiation therapy (\(^{60}\text{Co}, \text{LINAC}, \text{hadron therapy} \ldots\)). This kind of application is possible since sensors (pMOS dosimetric transistors) are extremely small (~1 mm\(^2\)) and allow the measurement of dose in vivo in real time.

A new concept is implantable wireless pMOS dosimeter [2]. Each detector is composed of a single pMOSFET with 400 nm oxide, produced by Tyndall Institute, a data acquisition chip, a microprocessor and a copper coil, all encapsulated in a glass tube 3.25 mm in diameter and 25 mm in length (Fig. 3). The circuit is powered by a current induced in the coil by an external handheld antenna connected to an RF reader. The dosimeter is powered during irradiation and powered only for measurement of VT. The microprocessor controls both data acquisition and reader–dosimeter communication. A 12-bit analogue-to-digital converter in the data acquisition chip provides 1 mV resolution in the voltage measurements. A computer controls the RF reader and converts the digital signal to a decimal voltage (Fig. 4).

Direct ion storage (DIS) dosimeters

Direct ion storage (DIS) dosimeter is a hybrid of ion chamber and floating gate MOSFETs (FGMOSFETs) [3]. Fig. 5 shows the cross sections of FGMOSFET and DIS. Before irradiation, i.e., before dosimeter using the fully charge is collected in the floating gate (FG), and the \(V_T\) is shifted. For this purpose, an uncovered area is formed on the surface of the floating gate of the MOSFET transistor (Fig. 5a). The radiation dose is determined by change which takes place in the charge of the gate.

This principle for information storage is used in a non-volatile FAMOS (Floating gate Avalanche-injected MOS) memory cell, known as EPROMS, EEPROMS and Flash-Memories. In a non-volatile solid state memory cell the information is stored in the form of electronic charge being trapped on the floating gate of a MOSFET transistor. Original memory designs were only used to store digital information (there was either a low amount or a high amount of charge stored to represent one of the two binary digits 0 or 1). In recent years new types of non-volatile memories have been developed and made commercially available to be used for storing analogue information. This means that the amount of charge in each memory cell can be made fully...
variable and, therefore, these memory cells can be used to store analogue information directly.

The radiation sensitivity of normal solid state memory cells is inherently too low for use as detectors in radiation protection applications. The main reason for this is that these devices are specifically designed to be as insensitive as possible to ionizing radiation so that they could be used in space, military and nuclear industry applications without damage. In an analogue EEPROM memory cell, the charge on the floating gate can be set to a predetermined level by injecting electrons through the oxide layer. The charge is then permanently stored on the gate because in the normal operating temperature range the electrons have a very low probability of exceeding the energy barriers in the metal–oxide and oxide–silicon interfaces. These types of memory cells are expected to retain the stored charge for hundreds of years.

The operating voltage of an ionization chamber based on DIS is 25 to 30 V. To obtain electric field strength of the order of 10 kV/m, necessary for linearity up to high dose rates, the distance between electrodes has to be 2 to 3 mm. The extremely high sensitivity of the DIS methods allows, for the use of chamber volumes less than 1 cm³, with a resulting detection limit well below 10 µSv.

Although DIS dosimeter has many similarities to pMOS dosimeter, and many similar characteristics, the main advantages are very high sensitivity and reusability, but disadvantages are difficult using in real-time radiotherapy, and a complicating design.

2.3. TL and OSL dosimeters

Many crystalline materials produce luminescence (emit light) when either heated or stimulated with a visible light spectrum after exposure to ionizing radiation. The general name for these materials is phosphor. The promptly emitted luminescence observed during radiation is called radioluminescence (RL). Since RL is produced continuously when the material is irradiated, information about the irradiation can be obtained in real-time.

During irradiation, the free holes and free electrons are realized in the valence and conductive band, respectively. The free electrons could be captured at the traps (e.g. electronic trap in Fig. 6). Traps are defined as “crystal defects” which are able to capture a charge carrier and release it to its original band. Their energy levels are within the crystal forbidden band (band gap). Some particular defects that can hold both electrons and holes are referred to as recombination centers. A trapped electron will remain so until it is provided with enough stimulation energy to overcome the trap and eventually recombine with a hole at a recombination center. This recombination can result in the emission of light, i.e. luminescence. Several factors compete with the production processes: some hole traps are classified as non-radiative recombination centers (a hole-electron recombination in those traps will not lead to emission of light). Similarly some electron traps are not responsive to thermal or light stimulations (thermally/optically deep traps). Shallow traps on the other hand are unstable at ambient temperature, and may release their trapped electrons even without external stimulation. The electron captured at recombination centre is in exited state firstly, and then is spontaneously released to ground state recombining with the hole and emitting the visible photon.

Radiative processes that happen during the exposure of the crystal to radiation are classified as prompt luminescence or radioluminescence (RL). In case of an emission during stimulation, this phenomenon is
referred to as thermoluminescence (TL) or optically stimulated luminescence (OSL) depending on whether the stimulation source is heat or light. The presence of shallow, deep traps, as well as non-radiative traps are grouped under the term competing processes, because they interfere with the type of luminescence which is of dosimetric interest. In Fig. 6 the processes in TL and OSL dosimeters are shown. The mechanisms (1) and (2) are for TL/OSL, and RL effects, respectively. An electron in conduction band could be relaxed to the valence band directly, emitting photon that is not visible (mechanism (3)). As is could be easily concluded the physical mechanisms for TL and OSL are very similar.

2.3.1. TL dosimeters (TLDs)

TL detectors are natural or synthetic materials, which emit light which intensity is proportional to the dose of irradiation when heated after having been exposed to radiation. For many years the most commonly used TLDs were LiF phosphor doped with Mg and Ti (LiF:Mg,Ti). The commercial names are TLD-100 (produced by Harshaw), and MTS-N produced in Poland. Then, the following dosimeters produced by Harshaw company: LiF:Mg,Cu,P (TLD-100H), CaF2:Dy/Tm/Mn (TLD-200/TLD-300/TLD-400), Al2O3:C (TLD-500). Nowadays LiF:Mg,Cu,P phosphor detector is produced by different laboratories sometimes under different commercial names, for instance, in the Solid Dosimetric Detector and Method Laboratory, Beijing, China (GR-200 or GR-200A), the Institute of Nuclear Physics, Krakow, Poland (MCP-N). In addition, CaF2:Mn (produced by the Jozef Stefan Institute, Ljubljana, Slovenia), LiB4O7 with different dopants (the Institute for Nuclear Science, Vinca, Serbia), a high sensitive LiF:Mg,Cu,Na,Si (KLT-300) phosphor with a low residual signal, good thermal stability and high sensitivity (the Korean Atomic Energy Research Institute, South Korea), and so on. These commercial dosimeters exhibit an emission maximum at 380 – 480 nm, which corresponds to spectral range of common photomultipliers. The luminescence peak is at 180 – 260 °C, making it easy to read. The shape of the TL curve is also very important. For example, LiF-based dosimeters have complex curves (up to ten peaks). A large number of peaks in TL curves complicates the heating procedure. The heating process should include preheating for the depletion of shallow traps and an additional high-temperature annealing for the depletion of deep traps. CaF2:Mn and Al2O3, which are high sensitive to radiation, show the simplest TL curves. Fig. 7 shows typical TL glow curves with (a) one peak, and (b) more peaks.

2.3.2. OSL dosimeters (OSLDs)

Ionizing radiation creates a large amount of electron-hole pairs in the OSL material. A fraction of these carriers are trapped on energy levels (recombination centers) located in the wide band gap of the insulator. Some of this charge will remain trapped for a period of time depending on both the temperature and the activation energy of the traps. Unlike the thermal anneal used for TL materials, an optical stimulation will provide the energy necessary to release the charges. A subsequent radiative recombination, which emits visible photon, may be observed. Quantifying the amount of emitted light makes it possible to evaluate the dose.

The most famous phosphor for OSLDs is Al2O3:C (synthetic sapphire) produced by Landauer, USA, which luminescence is characteristic of the oxygen vacancy centers, representing recombination center, introduced by the presence of carbon impurities (in concentrations up to 5000 ppm). The occupancy of an oxygen vacancy center by two electrons gives rise to a neutral F center, whereas occupancy by one electron forms a positively charged F+ center. The main luminescence emission occurs around 420 nm and is believed to be caused by:

\[ F^+ + e \rightarrow F^0 \rightarrow F + \hbar \nu, \]

(2)

where F* is an excited F center, which decays to the ground state with the emission of a photon at 420 nm. This process is associated with a relaxation time of approximately 35 ms.
In addition, BaFX materials (X = Br, F, Cl) have been used commercially in OSL for many years, especially for x-ray dose imaging (they are using for x-ray digital radiography as storage phosphors). The best OSL material the wavelengths of stimulation light is strictly divided from wavelengths of emission light (Fig. 8).

![Fig. 8 – Principle of OSL dosimeter](image)

Fig. 8 shows an active OSL sensor [4]. The power consumption is limited to the bias current in the LED during stimulation, that is, 50 mA during a few seconds under a 2 V bias voltage. The whole sensor fits in half a sugar cube volume (4 mm × 4 mm × 7 mm), and it weights no more than 3 g.

![Fig. 9 – One type of OSL active sensor](image)

The RL/OSL optical fiber dosimeter system shown in Fig. 10, developed at RisØ [5], is real-time system for radiotherapy. It can be divided into three major components: i) a sensor crystal, ii) an optical detection system, and iii) the signal-processing electronics. The sensor $\text{Al}_2\text{O}_3$:C crystal is connected to the optical system via a plastic fiber. To produce OSL, a green laser beam is focused through a beam splitter and transported via the optical fiber into the $\text{Al}_2\text{O}_3$:C dosimeter. The OSL signal is then transported back along the same fiber. The dosimeter system is controlled using a standard laptop, and uses only one optical fiber to reduce the size of the probe inserted into a patient for in vivo dosimetry.

A problem is that the signal generated by ionizing radiation in the optical fiber during exposure introduces a noise component in all real-time measurements. Extensive literature attests to the presence of this so-called stem-effect in optical fiber dosimeters using both plastic and silica fibers. The main contributor is Cerenkov radiation, which is generated in a dielectric medium when a charged particle with a velocity greater than that of light in the medium is passing through the medium. In addition, the big lack of system is its emphasized complication.

The RL is collected during irradiation, while the OSL is measured by switching the laser on after the irradiation is completed. This approach allows the investigation of the respective properties of the RL and the OSL signals (see Fig. 11).

Because of their very good characteristics, firstly the high sensitivity, TLDs&OSLDs are irreplaceable in personal, medical and environmental dosimetry.

The advantages of TL&OSL dosimeters relating to others are very high sensitivity, very good linearity to even seven orders of magnitude, re-usability, low energy dependence, low fading (the ability to store dosimetric information for a long time), and reproducibility. The sensitivity threshold is even ~5 – 10 µGy (=µSv for gamma and x photons), which is much bellow 100 µGy required by international standard. Manufacturers of TL&OSL dosimeters claim that they may be re-used at least 2000 times without noticeable change in sensitivity.

![Fig. 20 – The RL/OSL real-time dosimetry system](image)

The disadvantages are the saturation of response curve after ~ 1 Gy, and impossibility of real time using (for TLDs). TL curves with one isolated peak are desirable; otherwise, if several peaks are present, the dosimeter heating protocol is complicated. Although this is still under debate whether TLD or OSLD is better, it seems that OSLDs have some advantages. Besides real time possibility, the main advantages are ability: 1) of multiple measurements of dose, and 2) to provide imaging information. 1) The measuring of the TL signal completely empties the filled traps, and re-reads are not possible. With optical stimulation, however, one has fine control over the degree to which the traps are emptied and, by varying the intensity and the wavelength of the...
stimulation light, multiple measurements are possible—up to 15 independent measurements of the absorbed dose have been demonstrated. It should be emphasized that each re-evaluation of the dose is a completely independent fresh analysis. As a result, dosimeters may be retained and archived for re-analysis at a future date, at the request of the customer or other agency. 2) An additional advantage of the OSL technique is its ability to provide imaging information. One of the most desirable features of film badge technology is the ability to ‘image’ the radiation field. Imaging requires the use of large area detectors in order to allow the spatial variations in the radiation field to be monitored. Spatial imaging is not so feasible with TLDs, which are small in order that they may be heated uniformly.

3. CONCLUSION

The pMOS dosimeter advantages, in comparison with other dosimetric systems, include immediate, non-destructive read out of dosimetric information, extremely small size of the sensor element, the ability to permanently store the absorbed dose, wide dose range, very low power consumption, compatibility with microprocessors, and competitive price (especially if cost of the read out system is taken into account). The disadvantages are a need for calibration in different radiation fields (“energy response”), relatively low resolution (starting from about 1 cGy) and nonreusability.

The DIS dosimeters have many similarities to pMOS dosimeter, and their main advantages are very high sensitivity and reusability, but disadvantages are difficult using in real-time radiotherapy, and a complicating design, as well as relatively high operating voltage (25 - 30 V).

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4. REFERENCES


