pMOS dosimeters (RADFETs)

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Abstract— **p-channel metal-oxide-semiconductor (pMOS) dosimetric transistors are unique radiation dosimeters that have extremely small sizes (the dimensions of sensor elements are $\approx 1\,mm \times 1\,mm$) and allow the dose measurement *in vivo* in real time, which are specially important for radiotherapy.**

I. Basic concept

The idea of using metal-oxide-semiconductor field-effect transistor (MOSFET), or shorter MOS transistor, as a MOS dosimeter of ionizing radiation is very old [1]. The basic concept of MOS dosimeter is to convert the threshold voltage shift, ΔV_T, induced by radiation, into absorbed radiation dose, D. This dependence can be expressed in the form:

$$\Delta V_T = A \cdot D^n, \qquad (1)$$

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. Ideally, this dependence is linear, i.e $n = 1$, and then A represents the sensitivity, S, of MOS dosimeter:

$$S = \frac{\Delta V_T}{D}\left(\frac{V}{Gy}\right). \qquad (2)$$

The threshold voltage shift ΔV_T is caused by radiation-induced oxide charge and interface traps. Irradiation results in the trapping of holes (generated by the radiation) in the SiO, and the creation of interface states at the Si/SiO$_2$ boundary. Both the trapped holes and interface states contribute to the ΔV_T in the same direction in the case of p-channel MOS (pMOS) transistors and opposite to each others in the case of n-channel MOS (nMOS). Namely, the positive oxide trapped charge decreases, but interface traps increases ΔV_T in nMOS transistors, compensating the effect of each others. Both the positive oxide trapped charge and interface traps increase the absolute values of ΔV_T in pMOS transistors. It is reason that pMOS transistors, instead of nMOS transistors, have been used as a radiation dosimeter. It should be noted that the electrons, generated by the radiation, could be also trapped in the oxide, but it is less probable, and the net oxide charge induced by radiation is always positive.

The sensitivity increasing to the radiation is one of the main objectives when designing pMOS transistors for radiation dosimetric purposes (so called *pMOS dosimetric transistors*). This can be achieved by increasing the gate oxide thickness [2] – [6] or stacking more transistors [7], [8]. The investigation of pMOS transistors with a thick gate oxide has been intensified because of their enhancement radiation sensitivity. An interesting idea of the thick gate oxide fabrication is two-layer structure (so-called the "sandwich" structure), consisting of a layer of thermal and a layer of CVD oxide [2], [4], [9], [10]. It has been shown [11] the advantages of the two-layer oxide structures in comparison to a one-layer oxides, if their thicknesses are the same. Also, it is easier to fabricate thick CVD than thick thermal oxide.

So, the basic idea is to produce a radiation sensitive pMOS transistor (pMOS dosimetric transistor) that could me used as a radiation dosimeter [12], [13]. The name of this radiation dosimeter is *pMOS dosimeter* or *RADFET* (Radiation-Sensitive Field Effect Transistor).

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 rad) and nonreusability.

The range of possibilities of pMOS dosimeter practical application is indeed wide: as a personal dosimeter, in the laboratory, radiation therapy, spacecraft, nuclear equipment and so on [14]. Fig. 1 shows the using of pMOS dosimeter in radiation therapy (^{60}Co, LINAC, hadron therapy, ...) [15]. This kind of application is possible since sensors (pMOS dosimetric transistors) are extremely small ($\approx 1\,mm^2$) and allow the measurement of dose *in vivo* in real time.

Figure 2 shows the cross section of pMOS transistors with the defects created by radiation.

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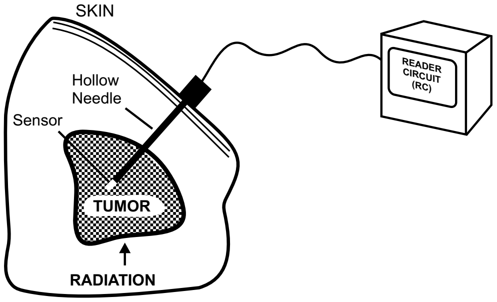

Fig. 1. An application of pMOS dosimeter in radiotherapy [15].

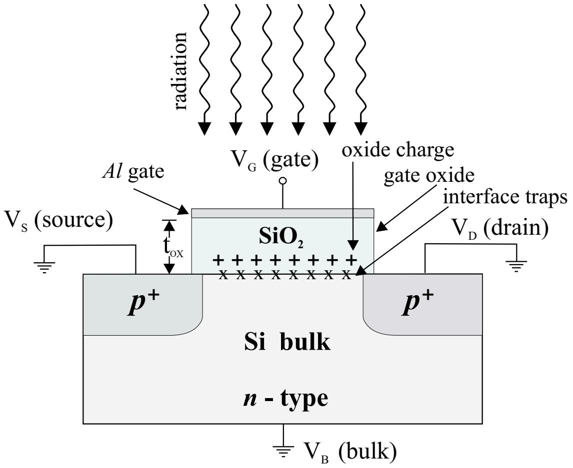

Fig. 2. Cross section of pMOS transistors after irradiation with $V_G = 0$ or $V_G > 0\,V$.

II. The ionizing source

${}^{60}_{27}Co$ is the most commonly used source for the simulation of ionizing effects in silicon devices and is utilized for industrial irradiation, sterilization, radiotherapy and biological research. ${}^{60}Co$ in each disintegration emits β particle and two photons of energy $E_1 = 1.17$ MeV ($99.86\,\%$) and $E_2 = 1.33$ MeV ($99.98\,\%$), transforming itself into ${}^{60}_{28}Ni$. These two gamma photons with different energies are usually consider as two photons with the same energy of $E = 1.25\,MeV$ $((1.17 + 1.33)\,MeV/2)$, so that the total photon energy liberated in each disintegration is $2 \cdot E = 2 \cdot 1.25$ MeV $= 2.5$ MeV. The half-life of ${}^{60}_{27}Co$ is 5.27 years.

III. The basic dosimetric units

The absorbed dose D (also often called *total dose* or only *dose*) represents the mean energy absorbed per unit mass of irradiated matter at the point of interest, and for a constant incident photon flux is:

$$D = \frac{E_{ab}}{m} \left[\frac{J}{kg}\right], \tag{3}$$

where E_{ab} is the mean absorbed energy in the matter and m is the mass of matter. If an incident photon (radiation) flux is not constant over whole both mass of irradiated matter and irradiation time, the dose should be represented in differential form: $D = dE_{ab}/dm$. Absorbed dose is the best physical indicator of biological response. Absorbed dose to water, since it is similar to human tissue, is used to specify the amount of radiation to be used in clinical practice [16].

The SI unit of dose is the *Gray* (*Gy*): $1\,Gy = 1\,J/1\,kg$, and the customary unit is *rad* (*rad*): $1\,Gy = 100\,rad$. Since the dose depends on the matter of interest, the specific matter should be always referenced: $rad(Si)$, $Gy(SiO_2)$, $rad(air)$, etc.

Absorbed dose rate (*dose rate*) $\dot{D}$ represents the time rate of the absorbed dose change, and for the constant photon flux is

$$\dot{D} = \frac{D}{t} \left[\frac{Gy}{s}\right]. \tag{4}$$

In practice, $\dot{D}$ is calculated by the expression:

$$\dot{D} = 33.85 \frac{\mu_{me}(E)}{(\mu_{me}(E))_{air}} \dot{D}_e \left[\frac{Gy}{s}\right], \tag{5}$$

where $\dot{D}_e$ is the *exposed dose rate* that is usually measured by an ionization chamber. $\mu_{me}(E)$ and $(\mu_{me}(E))_{air}$ are the mass energy-absorption coefficients in a material and in air, respectively.

In the case of RADFETs, a silicon (Si) is usually used as a referent material. For silicon and air (the source is ${}^{60}_{27}Co$): $(\mu_{me}(1.25\,MeV))_{Si} = 2.65 \cdot 10^{-2}$ cm$^2/g$ and $(\mu_{me}(1.25\,MeV))_{air} = 2.67 \cdot 10^{-2}$ cm$^2/g$, meaning $(\mu_{me}(1.25\,MeV))_{Si} \approx (\mu_{me}(1.25\,MeV))_{air}$. Figure 3 displays μ_{me} versus photon energies for air, water (H_2O), and silicon (Si).

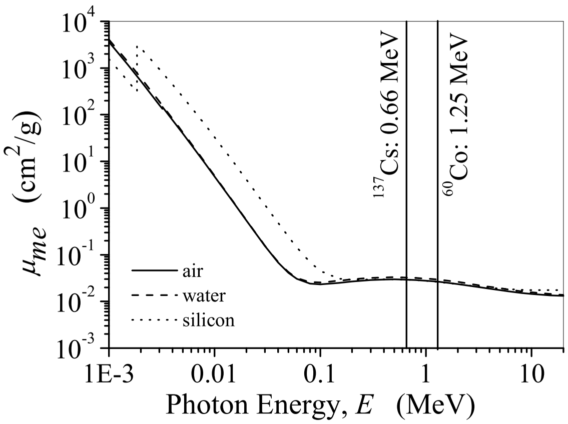

Fig. 3. The mass energy-absorption coefficients, $\mu_{me}(E)$, for air, water (H_2O), and silicon (Si) [17].

The absorbed dose rate for water, i.e., for the human tissue could be calculated by eq. (5) using $(\mu_{me}(1.25\,MeV))_{H_2O} = 1.112(\mu_{me}(1.25\,MeV))_{air}$:

$$\dot{D}(H_2O) = 37.646\,\dot{D}_e, \tag{6}$$

The exposed dose D_e (often called *exposure*, X) is defined as the total charge of one sign q produced in dry air when all electrons liberated by photons in a mass of air m are completely stopped in air:

$$D_e = \frac{q}{m}\ \left[\frac{C}{kg}\right]. \tag{7}$$

D_e is always defined relating to air. SI unit is C/kg, but the old unit, the roentgen $1\,\mathrm{R} = 2.58{\cdot}10^{-4}$ C/kg is still often used.

The exposed dose rate $\dot{D}_e$ is the time rate of the exposed dose change:

$$\dot{D}_e = \frac{D_e}{t}\ \left[\frac{C}{kg \cdot s}\right]. \tag{8}$$

For the polyenergetic beam, $\dot{D}_e$ is usually measured by an ionization chamber.

For the monoenergetic beam of energy E and point radiation source (e.g. ^{60}Co and ^{137}Cs) $\dot{D}_e$ can be calculated by

$$\dot{D}_e = 3.76 \cdot 10^{-17}\frac{E \cdot (\mu_{me}(E))_{air} A}{r^2}\left[\frac{C}{kg \cdot s}\right], \tag{9}$$

where $A = A_o \exp(-\lambda t)$ is the radiation source activity, A_o is the activity at the $t = 0$, λ is the radioactive constant, and r is the distance from the point source to the point of interest (along r the radiation absorbtion is neglected). A is in unit of *Becquerel* (Bq), E in MeV, r in m. Bq is the SI unit, but the old unit *Curie* (Ci): 1 Ci = $3.7{\cdot}10^{10}$ Bq is still in the use.

How to calculate the absorbed dose D in practice? Firstly, the $\dot{D}$ using both the eq. (5) and $\dot{D}_e$ measured by ionization chamber, then D using eq. (4) should be calculated, respectively.

IV. The RADFETs characterisations

A. *The threshold voltage*

A.1 The calculation of V_T in one point

The threshold voltage V_T, as a basic dosimetric parameter, is in the dosimetric read out system measured in one point. In that way, V_T represents gate voltage V_G for a given drain current I_D (usually, $I_D = 10\mu A$ in the case of pMOS dosimetric transistors). Source and bulk are shorted and represent one terminal, while drain and gate are also shorted and represent another terminal. This configuration is known as a reader circuit (RC) configuration [18] and is shown in Fig. 4.

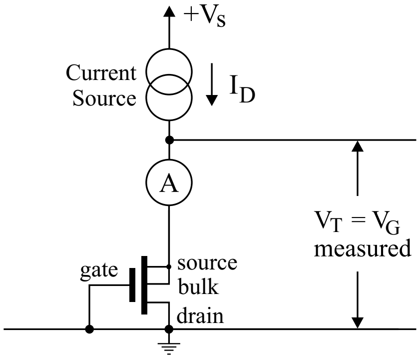

Fig. 4. Set-up for a measurement of V_T in one point (a reader circuit configuration).

A.2 The calculation of V_T by transfer characteristics

The V_T could be determined [14] by the transfer characteristics in saturation, as the intersection between V_G-axis and the extrapolated linear regions of the $(I_D)^{1/2} - V_G$ curves that are modelled by the following equation [19]:

$$I_D = \frac{\mu W C_{ox}}{2L_{eff}}(V_G - V_T)^2. \tag{10}$$

B. *The separation techniques*

B.1 The midgap-subthreshold technique

The midgap-subthreshold (MG) technique [20] is using for determination of the densities of fixed traps (FT) and switching traps (ST). The FT are the traps in the gate oxide, and ST are the traps near and at oxide/supstrate (SiO_2/Si) interface. The ST created in the oxide, near SiO_2/Si interface are called the slow switching traps (SST), but the ST created at this interface are called the fast switching traps (FST). FT represent traps in the gate oxide that do not capture the carriers from the channel, but the SST and FST, making the ST, represent the traps that do capture (communicate with) the carriers from the channel within the time frames of electrical MG measurements [14]. FT and SST are known as the oxide trapped charge, but FST as the interface traps (Fig. 2).

The contribution of FT (ΔV_{ft}) and ST (ΔV_{st}) to the net threshold voltage shift ΔV_T is:

$$\Delta V_T = \Delta V_{ft} + \Delta V_{st}. \tag{11}$$

The FT decreases, but ST increases ΔV_T in nMOS transistors, compensating the effects of each others, but both the FT and ST increase the absolute values of ΔV_T in the pMOS transistors.

The areal density of fixed traps, $\Delta N_{ft}\,[cm^{-2}]$, and the areal density of switching traps, $\Delta N_{st}\,[cm^{-2}]$, after irradiation/annealing could be determined as

$$\Delta N_{ft} = \pm\frac{C_{ox}}{q}\Delta V_{ft},\ \ \Delta N_{st} = \frac{C_{ox}}{q}\Delta V_{st}, \tag{12}$$

where C_{ox} oxide capacitance per unit area, and q absolute value of electron charge. The signs "+" and "-" are for p-channel and n-channel MOSFETs, respectively.

B.2 The charge pumping technique

The charge pumping (CP) technique [21]–[22] is using for determination of the density of FST. MG and CP techniques have great difference in their effective frequencies (a few Hz for MG compared with a few MHz for CP technique). The average substrate (charge pumping) current, I_{cp}, is measured while the surface is being continuously pulsed from inversion to accumulation, which results from applying repeated pulses on the gate.

The absolute switching trap density determined by CP technique, N_{st}, can be calculate by:

$$N_{st} = \frac{I_{cp,max}}{fqA_G}. \tag{13}$$

where $I_{cp,max}$ is the maximum value of charge pumping current, f is the frequency, and A_G is the area under the gate active in charge pumping ($A_G = L \cdot W$). The change in the areal density of switching traps is: $\Delta N_{st}(CP) = N_{st}(t) - N_{st0}$, where $N_{st}(t)$ is the absolute switching trap density during irradiation/annealing, and N_{st0} is the absolute switching trap density before irradiation.

The density $\Delta N_{st}(CP)$ found by the CP technique is, in fact, the density of fast switching traps (true interface trap), i.e. $\Delta N_{st}(CP) \approx \Delta N_{fst}$. Namely, as a much faster technique, CP technique can sense only the FST and eventually just the fastest among SST. The simultaneous using of both (MG and CP) techniques have a great advantage. For instance, if ΔN_{st}(MG) has been changed, but ΔN_{st}(CP) has not, it means that ΔN_{sst}, i.e., the density of SST has been changed, since $\Delta N_{st}(MG) = \Delta N_{sst} + \Delta N_{fst}$ and $\Delta N_{st}(CP) = \Delta N_{fst}$ [23].

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