Radiation Physics and Chemistry 95 (2014) 44–46

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Experimental evidence and modeling of non-monotonic responses in MOS dosimeters

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HIGHLIGHTS

- Switched bias evolution of MOS dosimeters were tracked.
- Non-monotonical behavior was observed.
- A simple one-trap model cannot explain the experimental data.
- A two-traps model is proposed to predict threshold voltage evolution.

ARTICLE INFO

Article history:
Received 15 October 2012
Accepted 23 April 2013
Available online 3 May 2013

Keywords:
MOS devices
Dosimetry
Gamma rays

ABSTRACT

The evolution of the threshold voltage of MOS dosimeters during irradiation under switched bias is investigated with the aim of using the sensors with a new biasing technique. The devices response to a bias change does not only depend on the instant threshold voltage and bias, and may lead to non-monotonical behavior under fixed bias following the switch. This work shows experimental evidence for this effect and presents a simple model based on oxide charge buildup and neutralization. The proposed model reproduces the experimental data assuming the existence of two types of hole traps in the oxide. Physical interpretations of the results are discussed.

1. Introduction

When p-channel Metal Oxide Semiconductor (MOS) transistors are irradiated, positive charge buildups in the gate oxide, and the threshold voltage (V_T) of the devices shifts (Oldham, 1999; Hughes and Benedetto, 2003). The negative shift in V_T can be used to quantify the ionizing radiation absorbed dose, turning the devices into sensors in radiation dosimeters (Holmes-Siedle, 1974).

Recently, a new biasing technique has been proposed to extend the measurement range of MOS dosimeters (Faigon et al., 2008) taking advantage of the effect known as Radiation Induced Charge Neutralization (RICN) (Fleetwood, 1990). This effect is observed when, after irradiating a MOS transistor with a positive gate bias, the gate bias is switched to a less positive, zero or negative value. Under these conditions, the net oxide charge can decrease and V_T rebounds. The new biasing technique named BCCM for Bias Controlled Cycled Measurement consists of alternating stages in which the dosimeter is used in the standard way – i.e. irradiated under positive gate bias – with stages of negative gate bias, in which the positive shift in V_T is also used to quantify the absorbed dose. The technique allows the continuous use of the sensor to a very high dose, maintaining V_T in a convenient range which prevents the sensor to enter into low sensitivity regions due to V_T shifts saturation. The BCCM technique has also been used on commercial RADFETs, proving its applicability to thick gate oxides (Lipovetzky et al., in press).

Measuring radiation dose using alternate negative and positive V_T shifts in MOS dosimeters requires a precise knowledge of the sensor response when the gate bias is switched. In fact, the same requirement occurs in case a sensor is mistakenly unbiased as was studied in Ref. (Benson et al., 2006), or in electrically erasable dosimeters (Lipovetzky et al., 2007); in general in any case the external conditions determining charge trapping kinetics are suddenly changed.

This work presents measurement results of switched bias irradiations. In some cases it is observed a non-monotonical behavior after the bias switch which motivated the development of a physical model to explain this phenomenon.

The following section presents experimental results. A physical model for the MOS sensors is proposed in Section 3 which is

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http://dx.doi.org/10.1016/j.radphyschem.2013.04.029

contrasted with the processed measurements in Section 4, followed by a summary and brief conclusions.

2. Measurements

The threshold voltage, V_T, of p channel MOS transistors used as sensors in a radiation dosimeter was measured each 10 s during much longer gamma irradiations from a ^{60}Co source at a dose rate of 26.7 kGy [SiO_2]/hr. Outside the 70 ms interval of V_T measurements the gate was biased with all other terminals grounded. The repeated switching from bias to measurement does not affect the V_T evolution for intervals between measurements longer than 3 s. This measurement system allowed to track three devices simultaneously in each irradiation.

The evolution of the threshold voltages under constant dose rate irradiations including a bias switch are plotted in Figs. 1 and 2. The main observed results are as follows.

3. Two traps dynamic balance model

The curves in Fig. 1(b) (no similar results were reported to our knowledge) show unequivocally that the knowledge of V_T is not enough information to predict the response of the sensor under irradiation at a given bias: the turn-around implies that same instant values of V_T (before and after the maximum) are followed by opposite evolutions. Thus, the internal state of the device must be described by at least two internal variables. Capacitance–voltage and sub-V_T slope in current voltage measurements (Antognetti et al., 1982) show there is not significant contribution from surface states to the changes being described. The quasi-steady V_T value corresponding to a given bias, suffers from a very long-term drift toward lower voltages but is quite stable during the time scales involved in our experiences. Thus, trap creation is disregarded, and the two internal chosen variables are the population fractions of two kinds of traps. The described behavior is consistent with a dynamic balance model (DBM) in which the occupation of each one of the two classes of trap centers reaches a dynamical equilibrium between charge trapping and de-trapping. Two or more types of trap centers or trapped charge were often proposed in the literature in order to explain different phenomena (Freitag et al., 1994; Pershenkov et al., 1996).

A simple such description for a single trap is found in (Boesch et al., 1986):

$$\frac{\partial p_t}{\partial t} = \sigma_p J_p (N_t - p_t) - \sigma_n J_n p_t \tag{1}$$

where p_t is the density of trapped holes, $J_{p,n}$ current density, $\sigma_{p,n}$ capture cross section for a hole in a trap and for an electron in a trapped hole, and N_t the hole traps density. Eq. (1) solves to

$$p_t = (p_{ti} - p_{tf}) \exp[-(\sigma_p J_p + \sigma_n J_n) t] + p_{tf} \tag{2.a}$$

where p_{ti} and p_{tf} are the initial and steady densities of trapped holes, being

$$p_{tf} = N_t \frac{\sigma_p J_p}{\sigma_p J_p + \sigma_n J_n}. \tag{2.b}$$

Assuming that the traps centers do not extend all over the insulator, but only in a region close to the Si-SiO_2 interface, a sheet of traps at distance x_0 from it, is taken as the traps spatial distribution centroid (Boesch). Thus if a model with two different

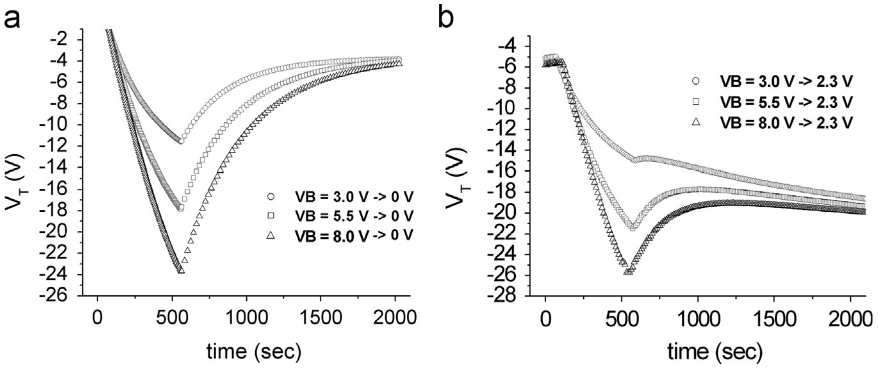

Fig. 1. (a) monotonic and (b) non-monotonic behavior toward quasi-steady-state after a bias change. While the former could be represented by a single kind of traps, the second shows that at least two kinds of trap centers are involved.

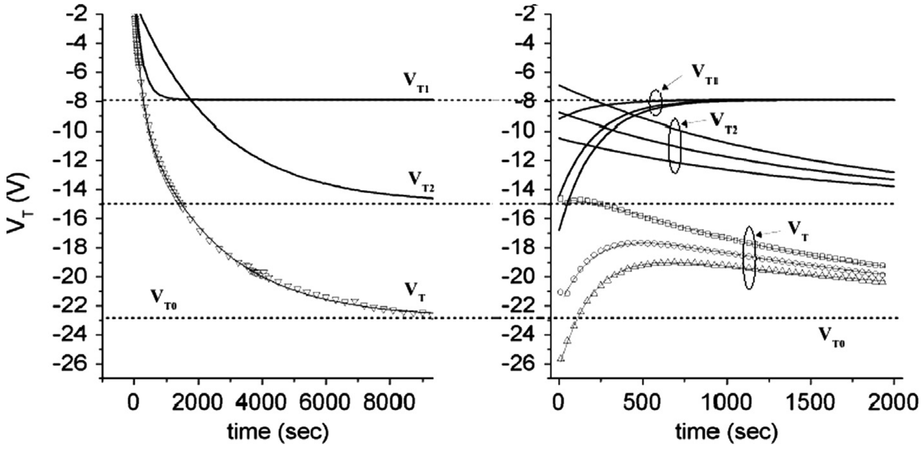

Fig. 2. Decomposition of different evolutions corresponding to the same bias (2.3V) and different initial states into two exponentials having the same asymptotic values.

Table 1
Physical model's parameters estimated from the experimental fitting.

Parameter	Trap 1	Trap 2
N_t (cm^{-2})	4.50×10^{12}	8.50×10^{12}
σ_p (cm^2)	1.11×10^{-13}	1.15×10^{-14}
σ_n (cm^2)	8.55×10^{-13}	1.00×10^{-13}

kind of trap centers is assumed, the following simple expression yields for the threshold voltage evolution

$$V_T = V_{Tf1} + V_{Tf2} + (V_{Ti1} - V_{Tf1})\exp[-t/\tau_1] + (V_{Ti2} - V_{Tf2})\exp[-t/\tau_2] \quad (3)$$

where the values V_{Ti1} and V_{Ti2} the contribution of each trap to the V_T value at the beginning of the transient, depend on the current population of each trap, being thus two history dependent parameters characterizing the state for predicting future evolution. V_{Tfj} is the asymptotic value of V given by:

$$V_{Tfj} = \frac{q}{C_{ox}}\left(\frac{t_{ox} - x_0}{t_{ox}}\right) N_{tj}. \quad (4.a)$$

where j indicates the trap type and can be 1 or 2, $f_j(E)$ is the steady fraction of occupied traps at field E; $t_{OX} = 70$ nm the oxide thickness; $x_0 = 5$ nm the distance between the interface and the traps centroid; C_{OX} is the gate capacitance per unit area; and

$$\tau_j = \frac{1}{\sigma_{pj} J_p + \sigma_{nj} J_n}. \quad (4.b)$$

The current densities are

$$J_p = g_0 D_r Y(E)(t_{ox} - x_0), \quad (5.a)$$

$$J_n = g_0 D_r Y(E) x_0. \quad (5.b)$$

Where $g_0 = 7.6 \times 10^{14}$ pairs cm^{-3} Gy^{-1} the nominal generation rate of pairs due to the incident radiation; $Y(E)$ is the net generation fraction, and $D_r = 26.7$ kGy/h is the dose rate.

4. Model application to experimental data

Considering the proposed two traps DBM model, the measurements were fitted with a two negative exponential equation.

$$V_T(t) = V_{To} + A_1 \exp[-t/T_1] + A_2 \exp[-t/T_2] \quad (6)$$

with the restriction that all the evolutions under the same applied voltage share the values of V_{To}, T_1 and T_2. Different curves at the same applied voltage result thus from their distinctive (A_1,A_2) pair expressing the initial population of both kinds of traps. A detailed decomposition is plotted in Fig. 2.

There is a direct relationship between the fitting parameters extracted from the measurements and those of the physical model. Comparing Eq. (6) with Eq. (3), the time constants τ_j of the traps are the T_j; and the contribution of each trap to the steady V_T value, V_{Tfj}, is given by the A_j obtained in virgin devices for which $V_{Tij} = 0$. The model parameters were obtained from the last fitting procedure and shown in Table 1.

The mean field dependence of these parameters was constructed using the accepted models (Krantz et al., 1987; Ning, 1976; Boesch et al., 1986; Dozier et al., 1987), fitting quite well results obtained at different fields between 0.1 and 1.2 MV/cm, will be shown in the full length paper.

5. Summary and conclusion

The simple knowledge of the instant value of V_T and the gate bias is not enough information to determine how the oxide charge is trapped, and thus it does not suffice to predict how V_T will shift except from a number of pre-calibrated states. A two exponential model, consistent with a two-trap dynamic balance model together with a track of the dosimeter history allows this prediction.

Acknowledgments

The authors are indebted with the technical staff of the PISI–CAE–CNEA, which gave us all the technical assistance needed in performing the irradiations. This work was supported by the ANPCyT (Agencia Nacional de Promoción de Ciencia y Tecnología) under Grant PICT Redes 2007 number 1907-03, by the UBACyT (Secretaria Ciencia y Tecnica Universidad de Buenos Aires) under Grants Y064 I096, by the CONICET under Grant PIP 01063. M. García Inza and S. Carbonetto hold a Peruilh Grant.

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