Modeling of charge effects in dielectric films of radiation MOS sensors

D V Andreev¹, G G Bondarenko², V V Andreev¹ and A A Stolyarov¹

¹ Bauman Moscow Technical University, the Kaluga branch, 2, Bazhenov st., 248000 Kaluga, Russia
² National Research University Higher School of Economics, 20, Myasnitskaya Ulitsa, 101000 Moscow, Russia

E-mail: dmitrii_andreev@bmstu.ru

Abstract. We have modeled the charge effects in radiation metal-oxide-semiconductor (MOS) sensors functioning in a wide range of electric fields including high-field injection of electrons into the dielectric film. In order to study the charge effects taking place in MOS sensors, we use the extended model suggested by us previously. The extended model, besides the accumulation of positive charge in the dielectric and the generation of the surface states at the interface, takes into consideration the accumulation of negative charge in the bulk of dielectric film caused by the electron capturing on traps. We demonstrate that the accumulation of the negative and positive charges in the bulk of the gate dielectric under high fields can significantly influence on the redistribution of electric fields inside the dielectric and, as a sequence, on change of the charge state of MOS structure which describes the sensor characteristics. We have ascertained that in order to properly utilize MOS sensors under high-field injection of electrons it has been necessary to take into consideration the possible capturing of electrons in the bulk of gate dielectric and adjust results of measurements with the model suggested.

1. Introduction

A subject of great interest to design and utilize metal-oxide-semiconductor (MOS) radiation sensors is a study of charge processes taking place in MOS structures and devices, based on these, under the concurrent influence of the ionizing radiation and high-field Fowler-Nordheim tunnel injection of electrons into the gate dielectric [1-4]. Mainly these sensors are used to monitor absorbed dose and radiation and these are manufactured on the basis of radiation-sensitive MOSFETs (RADFET) [1-8]. One of the approaches to increase sensitivity of the sensors is an applying of positive voltage to the transistor gate what causes an electric field in the dielectric which stimulates separation of charges generated as a result of the ionizing radiation and accelerates transport of these in the dielectric film [2,5-8]. However, when utilizing RADFET sensors, one commonly uses relatively low fields which are significantly lower than fields under which high-field injection of charge into the gate dielectric is observed [5-8]. Use of RADFET sensors under high fields could increase sensitivity and highly extend function capabilities of these, e.g. utilize the sensors to monitor intensity of radiation [2,9-11]. When manufacturing RADFET sensors one commonly tries to use gate dielectric for which negative charge can be neglected [5-8]. However, high-field tunnel injection could cause the activation or formation of new electron traps in the oxide [12-16]. In some cases, electron traps are purposely formed in gate…
dielectric to lower local currents flowing in the defect spots and, by this, increase oxide stability to stresses [16]. Thus, it can be a subject of great practical interest to take into consideration the accumulation of negative charge in gate dielectric under high fields and radiation. In this paper using modeling we have studied charge effects which are observed in radiation MOS sensors based on thermal SiO$_2$ films under concurrent influence of ionizing radiation and high-field tunnel injection of electrons into the gate dielectric. In particular, we have studied an influence of redistribution of electric fields in the bulk of gate dielectric on the charge effects which is a consequence of accumulation in the dielectric of positive and negative charges.

2. Model of charge effects in MOS sensor
Main charge processes which are observed in radiation MOS sensors based on thermal SiO$_2$ film under concurrent influence of ionizing radiation and high-field tunnel injections of electrons are discussed in detail in [2,9-11] and are demonstrated in the band diagram in Fig. 1.

![Figure 1. Band diagram of MOS structure demonstrating main charge processes taking place under concurrent influence of radiation and high-field injection of electrons by Fowler-Nordheim: 1 – creation of electron-hole pairs by radiation; 2 – transport of holes; 3 – trapping of holes by traps located in SiO$_2$ near the interface with silicon; 4 – hydrogen realization; 5 – hydrogen transport; 6 – interaction of hydrogen with defects what causes creation of surface states; 7 – high-field tunnel injection of electrons by Fowler-Nordheim; 8 – annihilation of a fraction of trapped holes at interaction with injected electrons; 9 – generation of surface states as a result of annihilation of holes; 10 – transport and heating of injected electrons in conduction band of SiO$_2$; 11 – thermalization of hot electrons with subsequent creation of holes; 12 – capture of injected electrons on electron traps in the bulk of gate dielectric.](image-url)

The key parameter of the MOS sensor characterizing absorbed dose of ionizing radiation, is the shift of the threshold voltage of the RADFET or shift of the midgap voltage of the MOS capacitor, caused by accumulation of the radiation-induced positive charge in the gate dielectric and by increasing density of surface states [5-11]. The effects caused by ionizing radiation (1-6), shown in Fig. 1, are described in detail in reviews [17-19] and discusses by us in [2,9-11]. When under high fields, besides charge effects depicted as 1-6, it is necessary to take into consideration high-field Fowler-Nordheim injection of electrons into the dielectric film (depicted as 7 in Fig. 1) [9-11]. Injected electrons can interact with trapped holes what results in annihilation of a fraction of the positive charge (depicted as 8 in Fig. 1). In its turn, when the annihilation of the positive charge is observed, an additional formation of surface states can take place (depicted as 9 in Fig. 1). Main fraction of injected electrons, when transporting in the conduction band of SiO$_2$, moves to the gate. For
thickness of the dielectric film of more than 50 nm, which are commonly used for RADFET sensors [2,9,12,13], a fraction of the electrons is heated up to energies higher than a width of the bandgap of SiO$_2$ (depicted as 10 in Fig. 1) and at thermalization of these electrons the band-to-band impact ionization with subsequent generation of holes can be observed (depicted as 11 in Fig. 1). These holes also transport to the cathode and can be partially captured on traps located near Si/SiO$_2$ interface in addition to the holes generated by the radiation. In that case, as we have demonstrated earlier in [2,9], in order to ascertain the density of holes accumulated in the gate dielectric under concurrent influence of radiation and high-field injection of electrons, it is necessary to solve the following equation:

$$ n_t = N_t \left[ 1 - \exp \left( -\frac{\sigma_p \cdot Q_{\text{inj}}}{q} \right) \right], \quad (2) $$

in order to calculate density of electrons accumulated in the bulk of the gate dielectric (depicted as 12 in Fig. 1), the following equation has been used [12,13]:

$$ J_{\text{rad}} = q \cdot Y(E) \cdot K_q \cdot d_{\text{ox}} \cdot I_{\text{rad}}, \quad (3) $$
in order to calculate a value of the cathode field we utilize Fowler-Nordheim equation [9,12,13]:

$$ E_{\text{inj}} = AE_c^{-2} \exp \left( -\frac{B}{E_c} \right), \quad (4) $$

value of the median field $E_{\text{m}}$ (Fig. 1) is given by:

$$ E_{\text{m}} = E_c - \frac{q}{\varepsilon \varepsilon_0} \cdot p \left( 1 - \frac{x_p}{d_{\text{ox}}} \right), \quad (5) $$

the anode field $E_a$ is calculated from:

$$ E_a = E_m + \frac{q}{\varepsilon \varepsilon_0} \cdot n \left( 1 - \frac{x_n}{d_{\text{ox}}} \right), \quad (6) $$
equation to evaluate a shift of the threshold voltage of RADFET or shift of midgap voltage of MOS capacitor being under electron injection from silicon when constant current flows through the capacitor:

$$ \Delta V_{\text{th}} \approx \Delta V_{\text{mg}} = \frac{q}{\varepsilon \varepsilon_0} \left[ p \left( d_{\text{ox}} - x_p \right) + n_t d_{\text{ox}} - n_t \left( d_{\text{ox}} - x_n \right) \right], \quad (7) $$

where $\alpha$ – ionization coefficient for SiO$_2$ film when it is under high-field injection; $\sigma_p$ – cross-section of hole traps; $N_p$ – density of hole traps; $\sigma_{\text{en}}$ – cross-section for injected electrons of filled hole traps (when annihilation of a fraction of positive charge) which is field dependent $\sigma_{\text{en}} = b_0 E^{3}$, where $b_0$ – model parameter; $N_t$ и $\sigma_t$ – density and cross-section of electron traps in the bulk of dielectric film; $q$ – electron charge; $Y(E)$ – charge yield when the sample is under irradiation (fraction of holes avoided recombination); $K_q$ – amount of electron-hole pairs per dose unit and unit of SiO$_2$ bulk (8·10$^{12}$ cm$^{-3}$rad$^{-1}$ (SiO$_2$) pairs); $d_{\text{ox}}$ – oxide thickness; $I_{\text{rad}}$ – radiation intensity (rad/s); $A=1.54\cdot10^{-6}$ m$^{-2}$V$^{-1}$ [AV$^2$] и $B=6.83\cdot10^7$ m$^3$/m$^2$·V$^{3/2}$ [V/cm] – constants of tunnel Fowler-Nordheim injection; $m_0$ and $m^*$ – electron mass in vacuum and its effective mass in the dielectric; $\varphi_0$ – height of potential barrier at injection interface; $\varepsilon \varepsilon_0$ – dielectric permittivity; $x_p$ и $x_n$ – locations of centroids (with respect to Si/SiO$_2$ interface) of positive charge, which are holes trapped in the SiO$_2$ and trapped electrons, accordingly. Equation set (1–7) has been solved at the following initial conditions: $p(0)=0; n_t(0)=0; n_t(0)=0$. In order to evaluate ionization coefficient ($\alpha$) we have utilized equations suggested in [12].
3. Modeling results and discussion
We have modeled MOS sensors, design and technological process of which have been described in detail by us in [2], and, besides, we have taken into consideration our previously acquired data when modeling [2,9-11]. MOS structures of these sensors were manufactured on the basis of n-type silicon with the gate dielectric of 100 nm thickness. From experimental data acquired previously [2,9-11] the following parameters of the model were acquired: \( N_p = 1 \times 10^{13} \text{ cm}^{-2}; \sigma_p = 5 \times 10^{-14} \text{ cm}^2; b_o = 3 \times 10^{-13} \text{ MV}^3/\text{cm}; N_t = (0.2-1.2) \times 10^{13} \text{ cm}^{-2}; \sigma_t = 1.4 \times 10^{-15} \text{ cm}^2; x_p = 6 \text{ nm}; x_n = 90 \text{ nm}.

Under high-field injection of electrons into the dielectric in the constant current mode the cathode field is constant and its value is defined by density of injection current and using the equation (4).

Fig. 2 shows calculated on the basis of the suggested model time dependencies of the change of the median and anode fields in the gate dielectric of MOS structure when the accumulation of holes and electrons in it is observed which is a result of the influence by the ionizing radiation and high-field injection of electrons.

**Figure 2.** Time dependencies of the change of the median and anode fields in the gate dielectric of MOS structure when the accumulation of holes and electrons in it is observed which is a result of the influence by the ionizing radiation and high-field injection of electrons for different densities of hole traps: 1.4,5 – 10^{13} \text{ cm}^{-2}; 2 – 1.5x10^{13} \text{ cm}^{-2}; 3 – 2x10^{13} \text{ cm}^{-2} and electron traps 1,2,3 – 0 \text{ cm}^{-2}; 4 – 2x10^{12} \text{ cm}^{-2}; 5 – 1.2x10^{13} \text{ cm}^{-2}.

Curves 1, 2, and 3 in Fig. 2 correspond to the gate dielectric (thermal SiO\(_2\) film [2,9]) in which we can neglect the accumulation of negative charge and, as a consequence, the median field is equal to the anode field. As a result, these curves demonstrate the lowering of the median and anode fields in the dielectric what is caused by the accumulation of hole positive charge. Curve 1 corresponds to density of hole traps in the dielectric (10^{13} \text{ cm}^{-2}) which was calculated on the basis of experimental data [2,9,10]. Curves 2 and 3 in Fig. 2 characterize the field change \( E_m = E_a \) at a higher density of hole traps in the dielectric film. The lowering of electric field, shown in Fig. 2, can significantly decrease such parameters as the ionization coefficient for SiO\(_2\) film when it is under high-field injection (\( \alpha \)), the cross-section for injected electrons of filled hole traps (\( \sigma_{\alpha} \)), and the density of current caused by the ionizing radiation (\( J_{rad} \)). Curves 4 and 5 in Fig. 2 are obtained for MOS structures based on the SiO\(_2\) film doped with phosphorus. The phosphorus doping results in formation of electron traps in bulk of the gate dielectric. Fig. 2 (curves 4 and 5) shows that the formation of electron traps could cause a significant increase of the anode field what is necessary to take into consideration when analyzing charge effects observed in MOS structure under concurrent influence by radiation and high-field ionization.

Fig. 3 demonstrates experimental results characterizing shifts of voltage across MOS structure when it is under concurrent influence by injection of electrons from the silicon being in the mode of constant current with density of 10^{-7} \text{ A/cm}^2 and the radiation by \( \alpha \)-particles (curve 1).
Experimental results shown in Fig. 3 were acquired with MOS sensors based in the thermal SiO$_2$ film which almost does not have electron traps. Symbols 3 in Fig. 3 characterize shift of voltage across MOS structure which is irradiated by $\alpha$-particles when no positive voltage is applied to the gate. The difference in voltage shifts can be explained by field dependence of the hole yield parameter and is in a good agreement with other studies [5-8]. Symbols 2 in Fig. 3 characterize positive charge accumulating in the SiO$_2$ film because of high-field generation of holes at thermalization of hot injected electrons [9,12,13]. With the suggested model (equations 1-7) we calculated theoretical curves 1’, 1”, 2’, 2”, 2’’ shown in Fig. 3. Curves 1’ and 2’ are obtained for the case when electron traps are not presented in the gate dielectric. Curves 2” and 2”’ in Fig. 3 characterize time dependence of the voltage shift ($\Delta V_{th}$) for MOS structures with electron traps of different cross-sections: $2'' = 2 \times 10^{12}$ cm$^{-2}$; $2''' = 1.2 \times 10^{13}$ cm$^{-2}$. Fig. 3 shows that the negative charge accumulated in the bulk of the gate dielectric lowers the voltage shift ($\Delta V_{th}$) because of compensation of a fraction of positive charge (curve 2”) or results in opposite change of voltage shift (curve 2”’) because of a higher density of trapped negative charge in comparison with positive charge. Thus, when trapping of the negative charge in the bulk of the gate dielectric, the negative charge influence on the voltage shift ($\Delta V_{th}$) can be taken into consideration by determining its density and spots of its localization with additional measurements [16,20]. Then we can correct results of measurements by calculations based on the equation (1-7).

4. Conclusion
We have demonstrated that the accumulation of negative and positive charges in the bulk of gate dielectric could greatly influence on the redistribution of electric fields in the dielectric and, as a consequence, on the charge state of MOS structure which has specified the main characteristics of the sensors. We suggest the model characterizing charge effects in the MOS sensor which is under concurrent influence of ionizing radiation and high-field tunnel injection of electrons. The model takes into consideration the following charge effects: accumulation of positive charge in the bulk of gate dielectric which is a result of the generation of holes by the radiation and high-field ionization; annihilation of a fraction of the trapped holes caused by interaction with injected electrons; the redistribution of local electric fields in the bulk of dielectric which is a result of the accumulation...
in the dielectric of positive and negative charges; an ability of electrons to be accumulated in the dielectric film. We have shown that when utilizing the MOS sensors under high fields, especially under injection fields, the use of the suggested model has allowed to separate a contribution of radiation in the change of charge state of the MOS structure and to increase metrological characteristics of the sensors.

Acknowledgements
The study has been financially supported by Ministry of Science and Higher Education of the Russian Federation as a part of the project “Fundamental research of methods of digital transformation of the component base of micro-and nanosystems” No. 0705-2020-0041.

References
[1] Lipovetzky J, Holmes – Siedle A, Inza M G, Carbonetto S, Redin E, Faigon A 2012 IEEE Trans. Nucl. Sci. 59 3133-40
[2] Andreev D V, Bondarenko G G, Andreev V V, Stolyarov A A 2020 Sensors 20 2382(1-11)
[3] Ilić S, Jevtić A, Stanković S, Ristić G 2020 Sensors 20 3329(1-26).
[4] Zhang C, Hasan S M R 2019 IEEE Trans. Nucl. Sci. 66 1906-15
[5] Holmes-Siedle A, Adams L 1986 Radiat. Phys. Chem. 28 235-44
[6] Ristic G S, Vasovic N D, Kovacevic M, Jaksic A B 2011 Nucl. Instrum. Methods Phys. Res. B 269 2703–8
[7] Siebel O F, Pereira J G, Souza R S, Ramirez-Fernandez F J, Schneider M C, Galup-Montoro C 2015 Radiation Measurements 75 53-63
[8] Kulhar M, Dhoot K, Pandya A 2019 IEEE Trans. Nucl. Sci. 66 2220-28
[9] Andreev V V, Maslovsky V M, Andreev D V, Stolyarov A A 2019 Proc. SPIE, International Conference on Micro- and Nano-Electronics 2018 11022 1102207(1-7)
[10] Andreev V V, Bondarenko G G, Andreev D V, Stolyarov A A 2020 Journal of Contemporary Physics (Armenian Academy of Sciences) 55 144–150
[11] Andreev D V, Bondarenko G G, Andreev V V, Maslovsky V M, Stolyarov A A 2020 Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques 14 260–63
[12] Arnold D, Cartier E and DiMaria D J 1994 Phys. Rev. B. 49 10278-97
[13] Strong A W, Wu E Y, Vollertsen R, Sune J, Rosa G L, Rauch S E and Sullivan T D 2009 Reliability wearout mechanisms in advanced CMOS technologies (Wiley-IEEE press) p 624
[14] Palumbo F, Wen C, Lombardo S, Pazos S, Aguirre F, Eizenberg M, Hui F, Lanza M 2019 Adv. Funct. Mater. 29 1900657(1-26)
[15] Wu E Y 2019 IEEE Trans. Electron Devices 66, 4523-34
[16] Andreev D V, Bondarenko G G, Andreev V V, Maslovsky V M, Stolyarov A A 2019 Acta Phys. Pol. A. 136 263-66
[17] Schwank J R, Shaneyfelt M R, Fleetwood D M, Felix J A, Dodd P E, Paillet P, Ferlet-Cavrois V 2008 IEEE Trans. Nucl. Sci. 55 1833-53
[18] Oldham T R, McLean F B 3003 IEEE Trans. Nucl. Sci. 50 483-99
[19] Fleetwood D M 2018 IEEE Trans. Nucl. Sci. 65 1465-81
[20] Andreev V V, Bondarenko G G, Maslovsky V M, Stolyarov A A and Andreev D V 2015 Phys. Status Solidi C. 12 299–303