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Model for forecasting the reliability of nanosized field-effect transistors considering possible influence of cosmic rays

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Abstract. Purpose. *Within the framework of this work the following purposes were set: study of physical mechanisms of degradation of performance of nanosized field-effect transistors caused by interruptions of Si-H; study of possible influence of cosmic rays on the reliability of nanosized field-effect transistors; development of a model to forecast the reliability of nanosized field-effect transistors considering possible influence of cosmic rays. To achieve the above listed purposes it was necessary to analyze: modern models used to forecast the reliability of nanosized field-effect transistors; data of the scope and intensity of cosmic-ray flux depending on energy.* **Results and Conclusion.** *According to the results of work, the most relevant physical model used to forecast reliability is the Bravais model which considers the following mechanisms of degradation of performance of nanosized field-effect transistors: - single Vibration Excitation – SVE, when the interruption of Si-H is initiated by one carrier with enough energy; – electron – Electron Scattering – EES, when the interruption is initiated by the carrier which received some energy from another carrier as the result of collision ionization, and thereafter having enough energy to interrupt the connection; – multi Vibration Excitation – MVE, when the Si-H interruption is initiated by a sequential bombing of connection by the carriers having energy not enough to interrupt the connection. It has been shown that cosmic-ray protons having high initial energy can penetrate through the structure of a field-effect transistor, losing a part of their initial energy by ionization losses, and achieve a Si/SiO2 boundary. When achieving the boundary protons may have energy sufficient for the initiation of dissociation of Si-H connections by two mechanisms: single Vibration Excitation of Si-H affected by a proton – SVEp is when a single proton having enough energy for interruption runs into a hydrogen atom, and initiates the Si-H dissociation; collision ionization by analogy with the electron – electron scattering described in the Bravais model, in this case there may be the Proton-Electron Scattering – PES. The Bravais model served as the basis for the development of the model to forecast the reliability of nanosized field-effect transistors that considers possible influence of cosmic rays, and helps to give a more accurate forecast of reliability of electronic devices based on nanosized field-effect transistors. This work reflects modern ideas of forecasting the reliability of nanosized field-effect transistors, describing main physical mechanisms of degradation of performance of nanosized field-effect transistors. This article shows that the reliability forecasting models developed for field-effect transistors with a long channel are not suited to modern nanosized devices due to differences in degradation mechanisms. Within the frameworks of this work it was shown that there is a probability of cosmic rays influence on degradation. As the result a model was developed to forecast the reliability of nanosized filed-effect transistors that shall consider such influence.*

Keywords: *reliability, degradation of performance, physical mechanisms of degradation, nanosized field-effect transistors, cosmic rays, model to forecast the reliability of nanosized field-effect transistors.*

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Introduction

Modern technologies that facilitate the reduction of physical sizes and improve performance of field-effect transistors have lead to the creation of nanosized electronic devices. This hopping from the micron size devices that had been the subject of studies for several decades, to nanosized devices, caused the need for new studies in the field of physical mechanisms of degradation and failures of modern electronic devices based on nanosized field-effect transistors. Models used to forecast reliability and degradation of performance, developed and successfully applied in micron sized electronic devices, can not estimate the reliability of modern nanosized devices in a full scope due to the fact that the latter have different physical mechanisms of degradation which is the reason for a parametric failure and loss in reliability.

Application of modern nanosized field-effect transistors in the space related equipment requires considering possible influence of cosmic rays when forecasting the reliability, as this influence becomes more significant in electronic devices based on field-effect transistors.

Up to date the current physical models which describe the mechanisms of degradation of performance of nanosized field-effect transistors and which are used to forecast the reliability, do not consider possible cosmic ray influence on the degradation of performance, and cannot estimate the reliability of space related electronic devices in a full scope. Thus, the development of the model that will be used to forecast the reliability and degradation of performance of nanosized field-effect transistors considering possible influence of cosmic rays is a relevant objective.

Within the framework of this work we set a task to develop the model to forecast the reliability and degradation of performance of nanosized field-effect transistors considering possible influence of cosmic rays.

Physical models to forecast reliability

Up to date there are many empirical and semi-empirical models to forecast the reliability of metal semiconductor oxide transistors (MSOT), describing the degradation of performance caused by the Si-H interruption at the Si/SiO_2 boundary [1, 2]. Most of these models are based on the concept of “lucky electron model”. This concept describes the mechanism of Si-H interruption in the transistors with long channel and electronic devices based on them. These devices are defined by high power supply voltage and, as a consequence, by high value of density of lateral electric field in the channel. This electric field is capable of boosting the electrons in the channel making them “hot”, i.e. making them having enough energy to initiate the dissociation of Si-H connection. Most electrons boosted by electric field in the channel of a field-effect transistor continue the movement towards the electron sink, but some of them (“lucky”) diverge form the movement trajectory and reach the surface of Si/SiO_2 boundary where they initiate the Si-H interruption, or penetrate into the oxide forming surface or three-dimensional traps. This very mechanism formed the basis of the concept of “lucky” electrons and, therefore of the models to forecast the reliability, based on this concept.

In modern nanosized field-effect transistors having lower power supply voltage and, as a consequence, lower value of density of lateral electric field in the channel, based on the concept of “lucky” electrons, the degradation of performance caused by Si-H interruption, should be minimized or there should be no degradation at all. However, despite the fact that this type of degradation is still observed in modern nanosized field-effect transistors and respective electronic devices, being even a more pressing problem in comparison to micron sized devices, which indicates the availability of different physical mechanisms in nanosized field-effect transistors, causing the Si-H interruption and therefore, the degradation of performance [3].

Thus, the concept of “lucky” electrons and the respective reliability forecasting model are not suited to forecast the reliability and describe the degradation of performance of modern nanosized field-effect transistors and the respective electronic devices. Therefore, we need new models that will consider the special aspects of nanosized field-effect transistors and physical processes behind the degradation of performance caused by Si-H interruption.

In paper [3] the author gives the review of modern physical models used to forecast the reliability and degradation of performance caused by Si-H interruption, for nanosized field-effect transistors. These models describe those new physical mechanisms peculiar for nanosized field-effect transistors that were present in the concept of “lucky” electrons:

– connection may be interrupted under the influence of a single carrier with high energy;

– dissociation of the connection may occur as the result of sequential bombing of the connection by several carriers with less energy;

– in nanosized field-effect transistors the electron – electron scattering is dominant in the process of Si-H interruption;

– in nanosized field-effect transistors, starting from a topology rate of 180 nm and lower, a steering force of degradation is the energy contribution by carriers in the channel, not the electric field.

The most successful physical model is the Bravais model, it does not require solving Boltzmann kinetic equation to define the function of energy distribution of electrons, besides, it combines the approaches developed in other models, and means that the degradation caused by Si-H interruption, may develop by three independent mechanisms:

– Single Vibration Excitation – SVE, when the interruption of Si-H is initiated by one carrier with enough energy. This mechanism is described well by the model of “lucky” electrons;

– Electron – Electron Scattering – EES, when the interruption is initiated by the carrier which received some energy from another carrier as the result of collision ionization, and thereafter having enough energy to interrupt the connection. This mechanism is described well within the energy controlled paradigm [3];

– Multi Vibration Excitation – MVE, when the Si-H interruption is initiated by a sequential bombing of connection by the carriers having energy not enough to interrupt the connection. This mechanism was proposed and described well by the Hess model based on a simplified model of harmonic oscillator [3].

By combining these three mechanisms of Si-H interruption, the Bravais model to forecast the reliability and degradation of performance is described by the following equation:

$$R_{it}=\frac{1}{\tau}=C_1\cdot\left(\frac{I_{ds}}{W}\right)^{a_1}\cdot\left(\frac{I_{bs}}{I_{ds}}\right)^{m}+C_2\cdot\left(\frac{I_{ds}}{W}\right)^{a_2}\cdot\left(\frac{I_{bs}}{I_{ds}}\right)^{m}+ +C_3\cdot V_{ds}^{a_3/2}\cdot\left(\frac{I_{ds}}{W}\right)\cdot\exp\left(\frac{-E_{emi}}{k_BT}\right) \quad (1)$$

where, R_{it} if the rate of occurrence of surface states as the result of Si-H interruption; τ is a lifetime (time to a parametric or critical failure); C_1 (SVE), C_2 (EES) C_3 (MVE), a_1, a_2, a_3, m are empirical parameters obtained from the results of accelerated tests; E_{emi} = 0.26 eV is the energy of hydrogen emission from the last binding energy level (defined in the Bravais model [3]); k_B is the Boltzmann's constant; T is temperature; I_{ds} is a drain current; I_{bs} a base current; V_{ds} is a voltage on drain; W is a width of channel;

Despite the fact that this model is good in describing the mechanisms of occurrence of surface states from the physical point of view, and though it has a great advantage over the obsolete model of "lucky" electrons which is still applied as an industrial one, the Bravais model can be applied to describe the degradation of performance not only in the devices not exposed to external influence, that may affect the occurrence of surface states at the boundary of Si/SiO_2. This external influence may be ionizing radiation of cosmic rays that may affect the reliability and degradation of performance of modern nanosized field-effect transistors used in the space related equipment.

Modelling of cosmic ray influence on the reliability of MSOT

According to papers [4, 5] cosmic rays consist of nuclei of high-energy protons (10^8 – 10^{20} eV) for more than 80 %, and the intensity of cosmic-ray flux, depending on the energy of particles, is described by formula:

$$I_N(E)\approx 1.8\times 10^4\,(E/1\,GeV)^{-\alpha} \quad (2)$$

where $\alpha\,(\equiv\gamma+1)=2,7$; E is the energy of particles.

We can assume that the protons of cosmic rays, which have high initial energy, can penetrate through the structure of a field-effect transistor, losing a part of their initial energy by ionization losses, and achieve a Si/SiO2 boundary. When achieving the boundary protons may have energy sufficient for the initiation of dissociation of Si-H connections by two mechanisms:

– Single Vibration Excitation of Si-H affected by a proton – SVEp is when a single proton having enough energy for interruption runs into a hydrogen atom, and initiates the Si-H dissociation;

– collision ionization by analogy with the electron – electron scattering described in the Braviax (Bravais) model, in this case there may be the Proton-Electron Scattering – PES. The proton having not enough energy to interrupt Si-H connection, pass the necessary amount of energy to the electron of the channel, which will be able to initiate the process of Si-H dissociation.

According to works [3, 6] the rate of occurrence of surface states R_{it}, as the inverse function from the time to the occurrence of a parametric failure $R_{it}=\frac{1}{\tau}$, which is the basis of the Bravais model, is proportional to the integral of product of two functions:

$$R_{it}\propto\int f(E)\cdot S(E)dE \quad (3)$$

where, $f(E)$ is the energy distribution function, $S(E)$ is the reaction cross section.

Thus, in case of calculation of the rate of occurrence of surface states due to the influence of cosmic-ray protons, it is necessary to define the function of energy distribution of protons and cross section of the reaction of interaction of cosmic-ray protons with hydrogen atoms in oxide and with electrons of the channel.

The intensity of cosmic-ray flux, or a differential flux, nothing else but the function of distribution of cosmic-ray protons by energy, described by equation (2). Thus, it is necessary to define the reaction cross section.

According to [7] the reaction cross section can be defined as follows:

$$S(E)=\frac{dn}{jN} \quad (4)$$

where, dn is the number of predefined reactions, j is the density of flux of particles bumping into the target, N is the number of target particles.

According to [8] the intensity of cosmic rays is defined as follows:

$$I=D\cdot E \quad (5)$$

where, I is the intensity of flux, D is the density of flux, E is the energy.

Thus, the density of the flux of cosmic-ray protons required for the calculation of cross section, can be defined by dividing equation (2), that describes the intensity of the cosmic-ray flux, by the energy:

$$j=I_N(E)/E\approx\frac{1,8\cdot 10^4\,(E)^{-2,7}}{E}\approx 1,8\cdot 10^4\,(E)^{-3,7} \quad (6)$$

Denoting the cross section of the reaction of interaction of cosmic-ray protons with hydrogen atoms in oxide by function $S_{SVEp}(E)$, accepting that the number of hydrogen atoms in oxide is found as, n is the concentration of hydrogen atoms in oxide (in m^{-3}), L, W, T_{ox} are the length of the channel, width of the channel, thickness of oxide, respectively, and the number of predetermined reactions dn is defined as the number of occurred surface states $dN_{it}(E)$, we shall obtain the following formula to calculate the cross section of the reaction of interaction of cosmic-ray protons with hydrogen atoms in oxide:

$$S_{SVEp}(E)=\frac{dN_{it}(E)}{1,8\cdot 10^4\cdot(E)^{-3,7}\cdot n\cdot L\cdot W\cdot T_{ox}} \quad (7)$$

By combining equation (2), that describes the function of energy distribution of protons, with equation (7), that describes the function of dependence of the cross section on the energy, we shall obtain the expression for the rate of occurrence of surface states in case of SVEp of Si-H dissociation:

$$R_{itSVEp} \propto \int 1,8\times10^4 (E)^{-2,7} \cdot \frac{dN_{it}(E)}{1,8\cdot10^4\cdot(E)^{-3,7}\cdot n\cdot L\cdot W\cdot T_{ox}} dE. \quad (8)$$

taking the constants off the integral sign, substituting all known variables and solving the integral, we shall obtain:

$$R_{itSVEp} = C_4 \cdot \frac{dN_{it}(E)}{n\cdot L\cdot W\cdot T_{ox}} \cdot \frac{E^2}{2} \quad (9)$$

where, C_4 is a proportionality coefficient obtained empirically; $dN_{it}(E)$ is the number of surface states occurred after the interaction of protons with hydrogen atoms, which depends on the initial energy of protons and intensity of their flux; n is the concentration of hydrogen in oxide; L is the length of the channel; W is the width of the channel; T_{ox} is the thickness of oxyde; E is the energy of cosmic-ray protons.

For the case of proton – electron scattering, denoting the cross section of the reaction of interaction of cosmic-ray protons with electrons in the channel by function $S_{PES}(E)$, assuming that the speed of electrons in the channel is negligibly low in comparison to the speed of cosmic-ray protons, considering them to be equally distributed in the channel, with the concentration which is defined as $N = \frac{I_{sd}}{e}\cdot L\cdot W$, where I_{sd} is the current flowing through the channel from the source to the drain, e is an electron charge, L is the length of the channel; W is the width of the channel, we shall obtain the following formula to calculate the cross section of the reaction of interaction of cosmic-ray protons with electrons of the channel:

$$S_{PES}(E) = \frac{dN_{it}(E)}{1,8\cdot10^4\cdot(E)^{-3,7}\cdot\frac{I_{sd}}{e}\cdot L\cdot W}. \quad (10)$$

By analogy with the interaction of cosmic-ray protons with hydrogen atoms in oxide, we shall obtain the expression of the rate of surface states for proton – electron scattering:

$$R_{itPES} = C_5 \cdot \frac{dN_{it}(E)}{\frac{I_{sd}}{e}\cdot L\cdot W} \cdot \frac{E^2}{2}, \quad (11)$$

where, C_5 is a proportionality coefficient obtained empirically;

By analogy with the Bravais model, in which all mechanisms of the degradation of performance, caused by Si-H interruption, are independent, considering the contributions to the degradation from the mechanisms described by equations (9) and (11) to be independent as well, let us combine the Bravais model equation (1) with equations (9), (11) and obtain the expression of the expanded Bravais model, physical model to forecast the reliability of nanosized field-effect transistors that considers possible influence of cosmic rays:

$$R_{it} = \frac{1}{\tau} = \left[\begin{array}{l} C_1\cdot\left(\frac{I_{ds}}{W}\right)^{a_1}\cdot\left(\frac{I_{bs}}{I_{ds}}\right)^{m} + C_2\cdot\left(\frac{I_{ds}}{W}\right)^{a_2}\cdot\left(\frac{I_{bs}}{I_{ds}}\right)^{m} + \\ + C_3\cdot V_{ds}^{a_3/2}\cdot\left(\frac{I_{ds}}{W}\right)^{a_3}\cdot\exp\left(\frac{-E_{emi}}{k_B T}\right) \end{array} \right] + \\ + \left\langle C_4\cdot\frac{dN_{it1}(E)}{n\cdot L\cdot W\cdot T_{ox}}\cdot\frac{E_1^2}{2} + C_5\cdot\frac{dN_{it2}(E)}{\frac{I_{sd}}{e}\cdot L\cdot W}\cdot\frac{E_2^2}{2} \right\rangle, \quad (12)$$

where, C_1, C_2, C_3, C_4, C_5 are proportionality coefficients obtained empirically for SVE, EES, MVE, SVE_p and PES mechanisms of the occurrence of surface states, respectively; a_1, a_2, a_3, m are empirical parameters obtained forn the results of accelerated tests (were defined within the Bravais model [3], but may require specification for different types of devices); E_{emi} = 0.26 eV is the energy of hydrogen emission from the last binding energy level (defined in the Bravais model [3]); k_B is the Boltzmann's constant; T is temperature; I_{ds} is a drain current; I_{sd} is the current flowing in the channel from the source to the drain; I_{bs} a base current; V_{ds} is a voltage on drain; L is the length of the channel; W is a width of channel; T_{ox} is the thickness of oxide; n is the concentration of hydrogen in oxide; e is an electron charge; $dN_{it1}(E)$ is the number of surface states occurred by SVE_p mechanism, which depends on the initial energy of protons and intensity of their flux, defined by the results of accelerated tests; dN_{it2} is the number of surface states occurred by PES mechanism, which depends on the initial energy of protons and intensity of their flux, defined by the results of accelerated tests; E_1 is the initial energy of cosmic-ray protons able to reach the $Si\text{-}SiO_2$ boundary with final energy sufficient to initiate the occurrence of surface states by SVE_p mechanism, defined by the structural features of devices; E_2 is the initial energy of cosmic-ray protons able to reach the $Si\text{-}SiO_2$ boundary with final energy sufficient to initiate the occurrence of surface states by PEE mechanism, defined by the structural features of devices.

The operand of equation (12), wrapped in square brackets, refers directly to the model developed by Bravais and co-authors [3], whereas the operand операнд, wrapped in triangular brackets, refers to the supplement to the Bravais model, developed within this work and allowing for the consideration of possible cosmic-ray influence on the degradation of performance caused by Si-H interruption.

Conclusion

Within the framework of this work it was shown that modern nanosized field-effect transistors and the respective electronic devices are still exposed to the degradation of performance caused by Si-H interruption, despite the reduction of power supply voltage and the value of lateral electric field in the channel.

Empirical and semi-empirical models to forecast the reliability and degradation, based on the obsolete model of "lucky" electrons which is still applied, can not estimate the reliability of modern nanosized field-effect transistors and the respective electronic devices in full scope.

Modern physical models, such as, for instance, the Bravais model helps to describe physical mechanisms of the degradation of performance caused by Si-H interruption, which are peculiar for modern nanosized field-effect transistors and able to give a more accurate forecast of reliability of electronic devices based on nanosized field-effect transistors.

The model developed in this article is based on the physical Bravais model. This model expands the Bravais model and considers possible influence of cosmic rays on the degradation of performance of nanosized field-effect transistors, and as the result it gives a more expanded forecast of the reliability of the respective electronic devices which are potentially suited to be applied in the space related equipment.

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