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SEGR in SiO_2–Si_3N_4 stacks

Arto Javanainen, *Member, IEEE,* Veronique Ferlet-Cavrois, *Fellow, IEEE,* Alexandre Bosser, Jukka Jaatinen, Heikki Kettunen, Michele Muschitiello, Francesco Pintacuda, Mikko Rossi, James R. Schwank, *Fellow, IEEE,* Marty R. Shaneyfelt, *Fellow, IEEE,* Ari Virtanen, *Member, IEEE*

***Abstract*—This work presents experimental SEGR data for MOS-devices, where the gate dielectrics are are made of stacked SiO_2–Si_3N_4 structures. Also a semi-empirical model for predicting the critical gate voltage in these structures under heavy-ion exposure is proposed. Then statistical interrelationship between SEGR cross-section data and simulated energy deposition probabilities in thin dielectric layers is discussed.**

***Index Terms*—SEGR, semi-empirical, MOS, SiO_2, Si_3N_4, modeling**

I. Introduction

SINGLE Event Gate Rupture (SEGR) is a desctructive event in Metal-Insulator-Semiconductor (MIS) devices induced by energetic heavy ions. Typically the phenomenon has been studied in MOSFETs with SiO_2 as the dielectric layer. Recently it has been shown that SiO_2–Si_3N_4 stack structures exhibit good resilience to Total Ionizing Dose (TID) [1]. Whereas for the SiO_2-structures a lot of research has been done concerning SEGR, the Si_3N_4-structures have remained relatively unexplored. In Ref. [2] observations on SEGR, induced by various heavy ions in SiO_2 and Si_3N_4 MIS-structures, has been reported. That study demonstrates a difference in the breakdown fields depending on the material. In Ref. [3] the dependence of SEGR on the ion energy has been studied. In that study a difference in the onset of breakdown voltages and the SEGR cross-sections has been observed in devices, irradiated with the same ion (Z_1) at the same LET, but at different energy (i.e. different sides of the Bragg peak). This is called the *energy effect*.

The work reported here presents experimental SEGR data for MOS-devices with SiO_2–Si_3N_4 stacks. Dielectrics with various thickness ratios have been studied. The devices have been irradiated with Xe-ions at 1217 MeV. Experimental breakdown voltages are shown to follow the model proposed in Ref. [4], when the intrinsic breakdown fields and the thicknesses of the corresponding dielectrics in the stack are introduced in the equations.

Possible physical mechanisms behind the SEGR are discussed in this work by comparing GEANT4-simulations to experimental SEGR cross-section data. Only qualitative picture is given as the physical models used in the simulations (GEANT4) are known to have discrepancies with experimental data. Nevertheless, relative comparison of simulation results, for different structure-ion combinations, to experimental data can still give a valuable insight what might be behind the SEGR. The qualitative model proposed here is in conjunction with the model proposed in Ref. [4]. Also similarities can be observed between simulation results and the data presented in Ref. [3].

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A. Javanainen, A. Bosser, J. Jaatinen, H. Kettunen, M. Rossi and A. Virtanen are with the Department of Physics, University of Jyväskylä, P.O. Box 35 (YFL), FI-40014 Jyväskylä, Finland (email: arto.javanainen@jyu.fi)

V. Ferlet-Cavrois and M. Muschitiello are with the European Space Agency, ESTEC, 2200 AG Noordwijk, The Netherlands

F. Pintacuda is with the STMicroelectronics Srl, Catania, Italy

J. R. Schwank and M. R. Shaneyfelt are with Sandia National Laboratories, Albuquerque, USA

TABLE I
Information on the structures under test used in this work. All devices are manufactured by STMicroelectronics, Catania, Italy.

Device type	t_{SiO_2} [nm]	$t_{Si_3N_4}$ [nm]	Lot	wafer
NMOS capacitor	20	100	3 219 371	15
	47	70	3 219 371	20
	57.5	30	3 219 371	25
	110	0	5 238 004	5
	61	50	5 302 642	1 and 9
	31	110	5 302 642	18
N-type powerMOS	20	30	3 250 989	5 and 10
	20	100	3 250 965	3
	35	100	3 250 966	2 and 12
	47	70	3 250 965	17
	62	30	3 213 349	8
	62	70	3 250 966	20
	85	0	3 213 349	12

II. Experimental setup

Experiments were carried out at RADEF [5] in the University of Jyväskylä, Finland. Xenon-ions from the standard 9.3 MeV/u heavy-ion cocktail of RADEF were used. All the irradiations were made in vacuum.

There were two types of NMOS devices studied in this work, (1) capacitors and (2) powerMOS transistors. All the devices under study were manufactured by STMicroelectronics in Catania, Italy. The detailed information on the studied devices is presented in Table I. For three of the studied device lots there are two different wafers. The difference between these wafers are in the configuration of the stuctures, e.g. the order of the layers, existence of the epilayers or spacer layers. The different configurations exhibited the same behaviour, i.e. only the dielectric thicknesses seemed to play a role in the observed SEGR.

III. Semi-empirical model

In a stacked SiO_2–Si_3N_4 structure the voltage drops accross the corresponfing dielectric layers can be derived from the total voltage drop accross the stack, by using the thicknesses and the relative permittivities of the materials as follows

$$V_{SiO_2} \approx \frac{V_{tot}}{\left(1+\frac{\varepsilon_{SiO_2}}{\varepsilon_{Si_3N_4}}\cdot\frac{t_{Si_3N_4}}{t_{SiO_2}}\right)},$$
$$V_{Si_3N_4} \approx \frac{V_{tot}}{\left(1+\frac{\varepsilon_{Si_3N_4}}{\varepsilon_{SiO_2}}\cdot\frac{t_{SiO_2}}{t_{Si_3N_4}}\right)}, \quad (1)$$

where $\varepsilon_{SiO_2} = 3.9$ and $\varepsilon_{Si_3N_4} = 7.5$ are the typical [6] relative permittivities of the corresponding materials. The relative permittivity of dielectrics in MOS devices is process dependent. Nevertheless, these typical values can be assumed to be accurate enough.

A model for predicting SEGR in SiO_2-based MOS-devices was proposed in Ref. [4]. By using this model we can write the estimation for the dielectric breakdown voltage as a function of dielectric thickness as follows

$$V_{crit}(\chi, t_{dielec}) = \frac{E_{int}\cdot t_{dielec}}{1+a\cdot(\chi)^b}, \quad (2)$$

where $a = 0.1648\ \mathrm{MeV}^{-b}$ and $b = 0.25$ are the semi-empirical parameters and E_{int} is the intrinsic breakdown field for a given material. For SiO_2 $E_{int}(SiO_2) \approx 10$ MV/cm (value taken from Ref. [4]) and for Si_3N_4 $E_{int}(Si_3N_4) \approx 4.5$ MV/cm, taken from Ref. [7]. The variable, χ, in this model is defined as

$$\chi = LET\cdot Z_1^2\cdot t_{dielec}[MeV], \quad (3)$$

where LET is the linear energy transfer, Z_1 is the atomic number of the impinging ion and t_{dielec} is the thickness of the dielectric material where the ion deposits its energy. Here, one should note the units of χ are in MeV. Thus, if LET is given in MeV/(mg/cm^2), the units for the dielectric thickness should be given in mg/cm^2.

IV. Experimental SEGR critical voltages

Fig. 1 presents the experimental breakdown voltages across the dielectrics, divided by the corresponding dielectric thicknesses. Voltages in different layers of the stack are estimated by using Eq. (1). In the graph there are also the estimations derived from Eq. (2). One for plain SiO_2 and another for plain Si_3N_4. From this graph it is obvious that in case of Xe-ions the SEGR is dominated by the nitride layer. However, it is not possible to directly estimate the critical voltage for these structures by using the nitride thickness in Eq. (2) as there are structures with the same nitride thickness but different oxide thickness, and they exhibit different breakdown voltages. However, it was found that the observed data can be reproduced with average accuracy of 3.1% by using simply

$$V_{tot,crit} = V_{crit}(SiO_2) + V_{crit}(Si_3N_4), \quad (4)$$

Thus, no other parameters are needed than those a and b in Eq. (2). The data and the estimates from Eq. (4) are presented in $t_{SiO2} - t_{Si_3N_4}$ coordinates in Fig. 2. Here the experimental data are in presented as dots with the corresponding breakdown voltage value in the box next to them. The box contains also the relative difference to the estimated value. The estimations are depicted with contours for which the estimated breakdown voltages are marked correspondingly. These results show that the model proposed in Ref. [4] can be used to predict SEGR quite accurately, not only in plain SiO_2 MOS-devices, but also devices consisting stacked SiO_2–Si_3N_4 structures. One only needs to take into account the difference in the intrinsic breakdown electric field for given dielectrics.

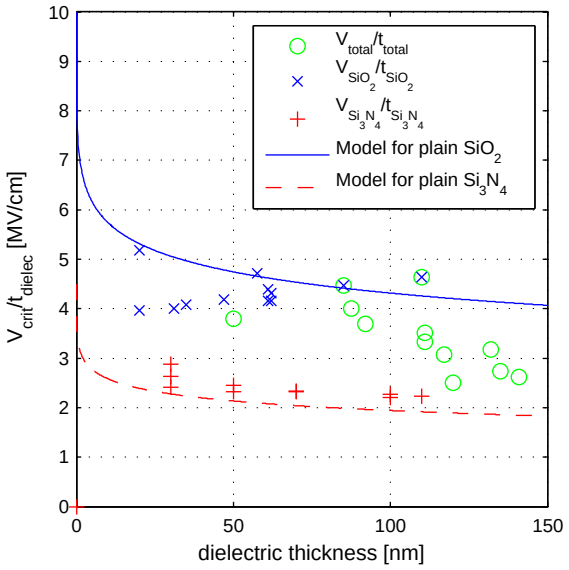


Fig. 1. The breakdown voltages across the dielectrics divided by the corresponding material thickness for Xe-ion exposure. The solid blue and dashed red lines correspond to the estimations derived from Eq. (2) for plain SiO_2 and Si_3N_4, respectively.

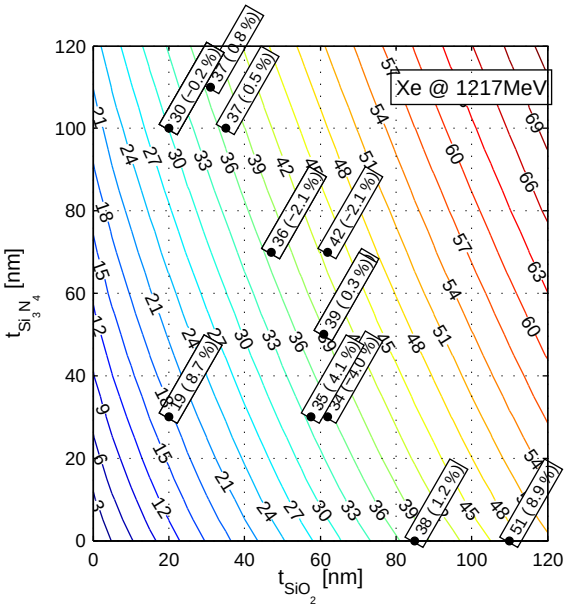


Fig. 2. 2-D contour graph of experimental (dots) and estimated (contour lines) breakdown voltages for SiO_2–Si_3N_4 stacks as a functions of material thicknesses. Abscissa and ordinate are the thicknesses for SiO_2 and Si_3N_4, respectively.

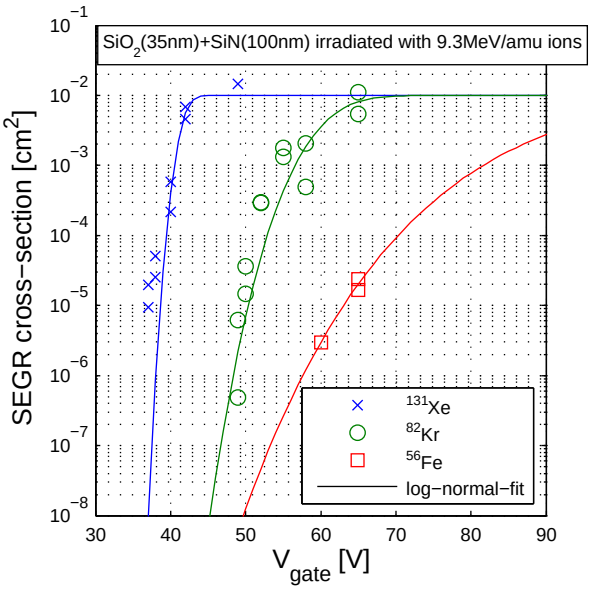


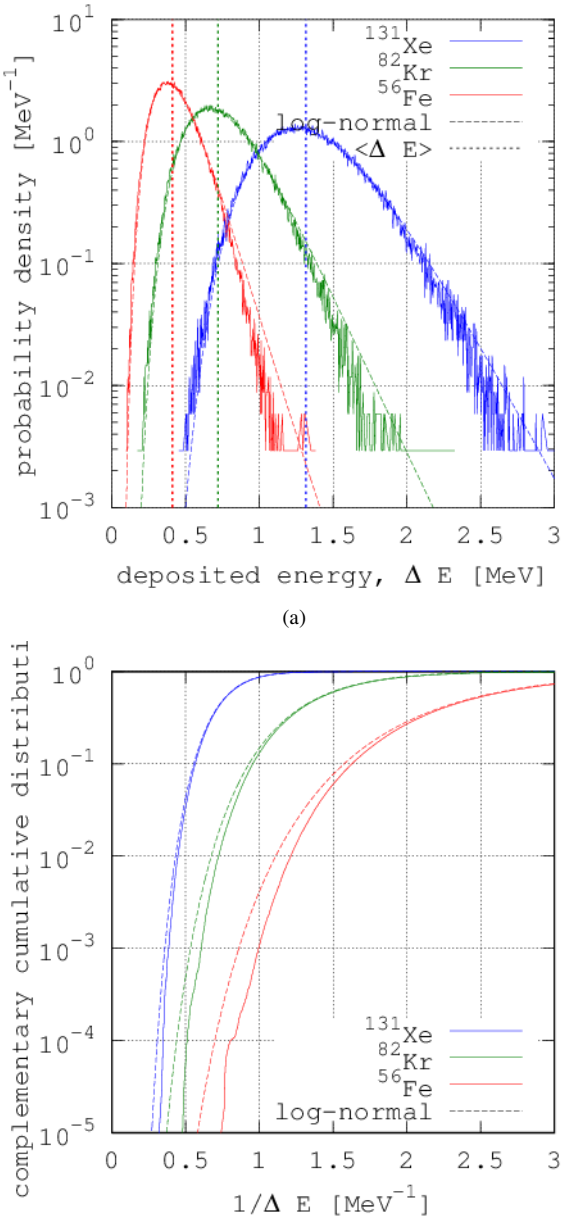
Fig. 3. SEGR cross-section data for SiO_2(35nm)-Si_3N_4(100nm) stack from Xe, Kr and Fe-irradiations as a function of gate voltage. The solid lines correspond to cumulative log-normal-fit with Eq. (6) where the distribution is scaled with σ_{sat}.

V. SEGR PROBABILITY

In this work also the statistical aspect of the SEGR was studied by using different heavy ions. Fig. 3 presents the cross-section data obtained for one of the sandwich structures used in this work (lot: 3 250 966, wafers: 2 and 12). The difference in these wafers is in the order of the dielectric (nitride–oxide) layers, which was not found to exhibit differences in the voltage threshold of the breakdown. In this part of the tests the devices were biased above the critical voltages and the fluence-to-breakdown was recorded. Several different voltage values were tested. The reciprocal of the breakdown fluence value gives the SEGR cross-section for the device at corresponding conditions (bias and radiation stress). At high voltages the saturation cross-sections were achieved for Xe- and Kr-exposures. For Fe-ions the saturation was not reached due to the time limitations during the tests. The obtained saturation cross-section value $\sigma_{sat} \approx 10^{-2}$ cm^2 is well in conjunction with the information about the device's gate area. From the graph in Fig. 3, one can see that in case of lighter ions higher voltages are required for SEGR to occur. This is naturally expected, due to the lower LET. The unexpected feature in the data is the slope in the transition region from the threshold to the saturation. For Xe-ions the transisition is steeper than for Kr-ions. Also the data for Fe-ions seems to exhibit even more gradual transisition, although there is only few data points for Fe-ions and no definite conclusion can be made. The data was fitted by using cumulative log-normal distribution, Eq. (6), and the corresponding curves from these fitting are presented also in the graph with the data. Also from the fit-curves it can be seen that more data are required for Fe-ions in order to validate the use of log-normal distribution functions.

According to SRIM-code [8], the LET values in SiO_2 and Si_3N_4 for heavy ions used in this work are within few percent. Thus for simplicity only SiO_2 was used in the simulated target geometries. The energy deposition spectra were simulated by using GEANT4. The simulation results are presented in Fig. 4. Here are the simulated energy deposition spectra in 135 nm thick quartz-slab for Xe-, Kr- and Fe-ions at initial ion energy of 9.3 MeV/u.

From graphs of Fig. 4 it can be observed that the energy deposition follows quite accurately the log-normal distribution. There is some deviation at high energy depositions, which



(a)

(b)

Fig. 4. Geant4-simulation results. Top graph presents the energy deposition spectra in 135 nm thick SiO_2 target for Xe-, Kr- and Fe-ions at 9.3 MeV/u energies. The dotted lines correspond to the average energy deposition determined from the spectra (c.f. $LET \cdot t_{ox}$). In the bottom graph the same data is presented as a complementary cumulative distribution as a function of reciprocal energy deposition.

can be attributed to escape of high energy delta-electron (c.f. spatially restricted LET). The probability density function (PDF) for log-normal, $f_{logn}(x)$, is defined as

$$f_{logn}(x) = \frac{1}{x \cdot \sigma\sqrt{2\pi}} \cdot e^{-\frac{(\ln(x)-\mu)^2}{2\sigma^2}}, \quad (5)$$

where μ is the logarithm of mean and σ is the standard deviation of the distribution. The cumulative distribution function (CDF) for log-normal distribution is defined as

$$F_{logn}(x) = \int_0^x f_{logn}(t)dt = \frac{1}{2} + \frac{1}{2} \cdot \text{erf}\left(\frac{\ln(x)-\mu}{\sqrt{2\sigma^2}}\right), \quad (6)$$

where $\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2}$ the error function.

Now the energy deposition spectra can be presented differently by using so called complementary (or inverse) cumulative distribution function (ICDF)

$$\overline{F_{logn}(x)} = 1 - F_{logn}(x). \quad (7)$$

ICDF gives the probability that the random variable takes on a value above x. The ICDF for the simulated data is presented as a function of reciprocal energy deposition, $\frac{1}{\Delta E}$ in Fig. 4(b). Higher value for $\frac{1}{\Delta E}$ corresponds to lower deposited energy. Qualitatively looking back to Fig. 3 this lower energy deposition would mean higher voltage required in order to induce SEGR, which is actually what is observed. This would mean that there could be a way to link the energy deposition to the SEGR by comparing the spectra of energy deposition in the dielectric layer of the studied MOS-device and the SEGR cross-sections.

In order to illustrate the proposed qualitative relationship, data from Ref. [3] is presented in Fig. 5. These data are showing the SEGR cross-sections for MOS-capacitors as a function of applies voltage across a 60 nm thick oxides, for Au-ions at energies of 2000 MeV and 346 MeV. They have observed that at these energies the devices exhibit different response. At these energies, conventionally (i.e. from SRIM-code), the *average* energy deposition (LET) is the same. However, Geant4-simulations show that the energy deposition spectra look very different. The simulation results for 60 nm-thick oxide are presented in Fig. 6. Here one can see that not only the average energy deposition is actually slightly different but also the width of the distribution (i.e. straggling) is different. For higher energy ions the spectrum extends to higher energy deposition values, which would, in practice, mean lower SEGR threshold voltage, just like it is observed in Fig. 5. By looking at the energy deposition spectra and the SEGR data one can see the similarities to what was discussed above. In order to verify the proposed interrelationship between SEGR and the energy deposition, more experimental SEGR cross-section data would be needed and they should be carefully compared with similar simulations presented here, and/or theoretical considerations including energy loss straggling.

VI. Conclusions

This work shows that the model for predicting critical voltage for SEGR [4] works well for MIS devices with SiO_2–Si_3N_4 stacked structures. This confirms that the assumption

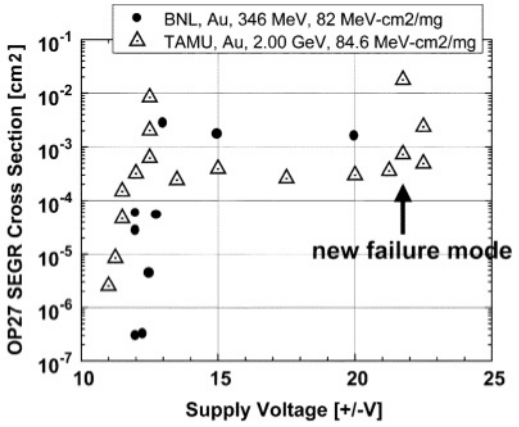


Fig. 5. SEGR cross-section data taken from Ref. [3].

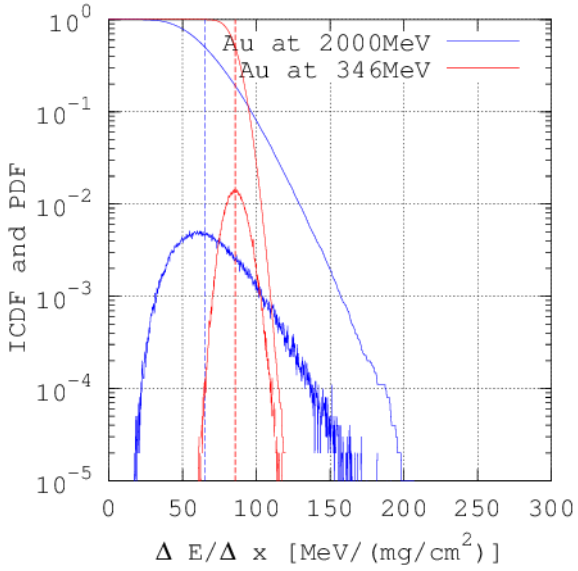


Fig. 6. Geant4-simulation for energy deposition probabilities in 60 nm thick SiO_2 for Au-ions at 2000 MeV (blue) and 346 MeV (red) as a function of energy deposition per target thickness.

that the statistical variations in the heavy-ion energy deposition (i.e. the *straggling*) play a role in the observed SEGR. Indeed more evidence is presented in this paper by showing similarities in the energy deposition spectra in thin oxides, simulated with Geant4, and experimental SEGR cross-section data.

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