The Role of Energy Deposition in the Epitaxial Layer in Triggering SEGR in Power MOSFETs†

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Abstract- In these SEGR experiments, three identical-oxide MOSFET types were irradiated with six ions of significantly different ranges. Results show the prime importance of the total energy deposited in the epitaxial layer.

Introduction- Titus, Wheatley, and co-workers have, for many years, studied SEGR experimentally and reported several semi-empirical expressions describing their results [1-4]. The semi-empirical expression for critical SEGR voltages has been expressed in the following form: $V_{GS} = F \cdot V_{DS} + G$, where both F and G are functions of LET (incident) or (as of 1998) of Z. In the 1996 paper [3], using one MOSFET (FSL234), they focused on incident ions of Z= 35 and 36 with a wide range of energies and concluded: "These data suggest that the (SEGR) mechanism is a function of the total energy transferred to the epitaxial layer..." [p.2942]. However, no semi-empirical equation based on epi-deposited energy has been published. The present experiments investigate whether that conclusion can be extended to a select set of test ions with different Z's. Three test devices with identical oxides were chosen with different epitaxial characteristics (doping and depth) for this study. The results show strong support for the 1996 conclusion given a particular epi (and oxide); the energy deposited throughout the epi (even far from the oxide) contributes directly to oxide stress and rupture.

Background- The adopted methodology was to select test devices with as identical oxides as possible, but different doping profiles and epitaxial depth. The test devices were subjected to ions with several energies and widely varying ranges. The selected ions with intermediate ranges were Br^{79} (276MeV), I^{127} (350MeV) from Brookhaven National Laboratory. The long range ions were Nb^{93} (907 and 1030MeV) and Xe^{129} (1961MeV) from Texas A&M, and the short-range ions used were produced from fission fragments spontaneously emitted from a Californium (Cf^{252}) source. Molybdenum (Mo^{106} 104MeV) is a representative of those fragments because it is the most abundant of the lighter and more energetic half of the distribution of fission fragments, which are presumed to be more effective at causing SEGR. The test devices used were the IR2N6782 (100V), IR2N6790 (200V), and IR2N6786 (400V), which have identical geometric structure with the exception of the epitaxial depth and doping levels. The oxide thickness for all three devices is 75 ± 5nm. Doping levels and epitaxial depth is as follows: 3×10^{15} ions/cc and 15μm, 1×10^{15} ions/cc and 26μm, and 4×10^{14} ions/cc and 40μm for the 100V, 200V and 400V devices, respectively.

Experimental Results- The results in figures 1 and 2 shows the effect of ion species and energy on two of the test device types. SEGR for the contour lines in the figures indicate the minimum V_{DS}, V_{GS} bias conditions under which SEGR occurred for an irradiation of 1×10^{5} ions/cm^{2} for the selected ion and energies. Over 60 devices were electrically stressed (without ions), in order to determine silicon (Si) and oxide breakdown points. Due to the high doping level in the 100V device, its measured breakdown voltage is lower than the 200V, 126 volts and 245, respectively. In the 200V device, the oxide breakdown voltage is consistent at –85 volts, where as in the 100V, its value was –86 volts. A large variation in oxide and Si breakdown values for the 100V devices were observed, approximately ± 15%. No variations (down to ~1.3%) were detected for the 200V device. We suspect that the difference between these two oxides to be an issue of quality control and that they are not fundamentally distinct.

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In table 1, we have ranked the ions on SEGR efficiency based on the experimental observations from figures 1 and 2. Based on the energy-range tables from SRIM/TRIM for each ion, table 1 shows the expected energy deposited in the epi, assuming a 5μm silicon-equivalent dead layer above the oxide. Note the correlation between SEGR data and energy deposited in the epi. We define the SEGR efficiency of rank 1 as the ion (of the test ions) most capable of causing SEGR, i.e., lowest V_{DS},V_{GS} pair. From table 1, it is clear that neither incident LET or Z correlate well SEGR efficiency as epi-deposited energy does. Highlighted are the more glaring inconsistencies. This table will be expanded with data to be obtained soon (February 23).

Table 1. SEGR efficiency based on figures 1 and 2.

Device Type	Doping (ions/cc)	Epi_{depth} (μm)	Ranking of Ions	Ion (MeV) Species	Energy(MeV) deposited	LET_{ini}	Z
IR2N6782 (100V)	3.0×10^{15}	15	1	I^{127} (350)	203.7	61.9	53
			2	Xe^{129}(1961)	169.1	47.5	54
			3	Mo^{106} (104)	55.1	44.5	42
IR2N6790 (200V)	1.0×10^{15}	26	1	Xe^{129} (1961)	297.2	47.5	54
			2	I^{127} (350)	272.9	61.9	53
			3	Nb^{93} (907)	235.3	36.7	41
			4	Nb^{93} (1030)	224.8	35.3	41
			5	Br^{79} (276)	218.5	38.1	35
			6	Mo^{106} (104)	55.1	44.5	42
IR2N6786 (400V)	4.0×10^{14}	40	1	Xe^{129} (1961)	465.6	47.5	54

From table 1, notice that for the three ions used in the 100V device, incident LET works well as an indication of SEGR efficiency, but Z does not. For the 200V device, incident LET can not serve as an indicator of SEGR efficiency since there is no correlation between incident LET and SEGR. On the other hand, energy deposition is an unambiguous indicator of SEGR efficiency which works well for all device types, see column 6 and compare it with figures 1 and 2.

Particularly interesting is the ranking switch between I^{127} and Xe^{129} for the 100V and 200V devices. The profile of energy deposited in the oxide and the first 15μm of epi. is identical for both devices. In the last 11μm of epi for the 200V device, the Xe^{129} deposits so much energy that it surpasses the total deposited by I^{127} and becomes more effective at causing SEGR. Thus, even energy deposited deep in the epi is contributing significantly to SEGR.

Figure 3 shows the effect of doping levels and epitaxial depth on SEGR for the case of Xe^{129}. Notice the shift down of each contour line as a function of increasing doping. In all three device types the energy deposited in the oxide is the same, ~910 keV. Clearly, in the case of Xe^{129} at normal incidence, the epitaxial doping parameter affects SEGR directly. This makes sense because the epi-deposited energy must couple to the oxide to rupture it.

Numerical Results- Computer simulations results, like thus of reference 5, give insight into how the energy deposited in the epi develops a short duration large electric field on the gate oxide. The effects of a 40μm ion track incident on a virtual Power MOSFET were studied with computer simulations using PISCES. The baseline case is an ion with a constant LET of 40 $MeV \cdot cm^2 \cdot mg^{-1}$ with a gaussian radial distribution having a 0.5μm characteristic radius. The energy was assumed to have been deposited instantaneously prior to the commencement of the simulation. The baseline case was a Power MOSFET structure with an oxide thickness of 46nm and an epi depth of 19μm with a doping level of 1×10^{16} ion/cc, and biased with $V_{GS} = 0$ volts. Four cases were studied using a single variation on the baseline case, thus a total of 5 cases were studied. First, the doping level was lowered in the epi to 1×10^{15} ions/cc. Second, the oxide depth was increased to 75nm. Third, gate bias was set to V_{GS} = -10 volts. Four, the ion track was shorten and allow to terminate in the epi at 8μm below the oxide/epi interface. Table 2 summarizes the peak value and time for each case study.

Table 2. Peak electric fields strength per case study based on PISCES

Case studies 1 through 5	Electric Field (MV/cm)	Time (picoseconds)
Baseline	13.6	3.92
Lower doping	11.2	5.00
Oxide increased	10.7	5.00
V_{GS} = -10 Volts	14.5	4.01
Short ion track	12.1	2.88

Traversal time for each ion were calculated and are shown in table 3. Traversal times are based on average ion velocities at various regions of interest.

Table 3. Ion Traversal time (picoseconds) based on SRIM/TRIM

Ion (MeV) Species	5μm Si dead layers	Oxide (75nm)	Epitaxial 100V 15μm	200V 26μm	400V 40μm
Xe^{129} (1961)	0.92	1.5×10^{-3}	0.28	0.50	0.79
Nb^{93} (1030)	0.11	1.7×10^{-3}	0.34	0.60	0.97
Nb^{93} (907)	0.12	1.9×10^{-3}	0.36	0.65	1.06
I^{127} (350)	0.24	4.0×10^{-3}	0.96	2.78	4.12*
Br^{79} (276)	0.21	3.6×10^{-3}	0.81	2.17*	3.61*
Mo^{106} (104)	0.49	8.1×10^{-3}	2.84*	2.84*	2.84*

* = stops within the epitaxial layer

Note that the passage of the ion through the entire power MOSFET epi can take almost 4 picoseconds. PISCES calculations indicate significant movement of deposited charge on this time scale. Thus, ion passage should not be treated as essentially instantaneous, as was done in the simulations of table 2 and ref. 5.

Conclusions- Our results on additional MOSFETs reinforce the results of ref. 2 that energy deposition in the epitaxial region correlates with SEGR. Our evidence contradicts the hypotheses that incident LET or Z is directly related to the ion's ability to cause SEGR. Experimental results produced a direct correlation between energy deposition in the epitaxial region and SEGR and showed that energy deposited many microns from the oxide contributes to rupturing. Epitaxial parameters like doping and depth have a direct impact on SEGR by influencing the maximum electric field imposed on the oxide. As far as single-event effects modeling is concerned, the assumption of an instantaneous ion traversal is incorrect. The time for an ion to exit the epitaxial region can be anywhere from ~1 to > 4 picoseconds. Additional simulations should shed light on how big an effects the epi-traversal time is.

References-

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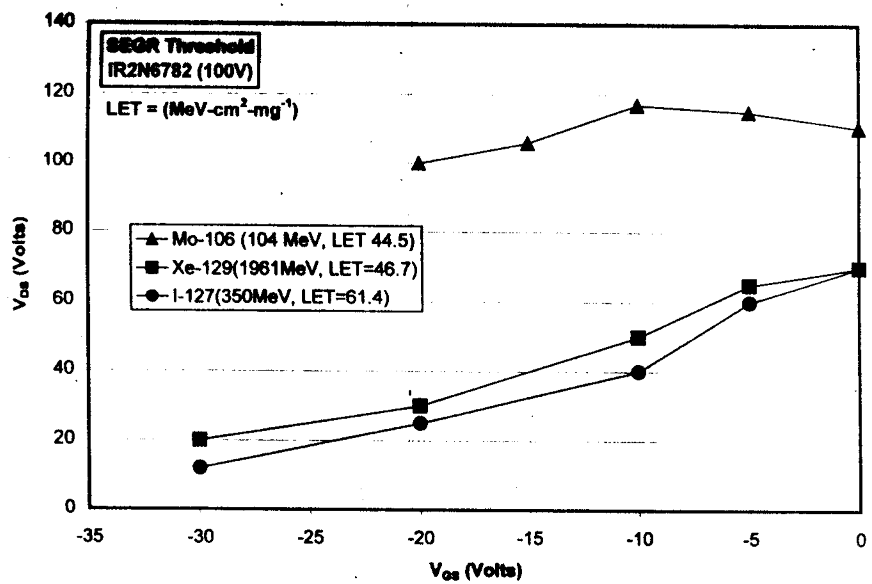

Figures 1, SEGR contour (IR2N6782)

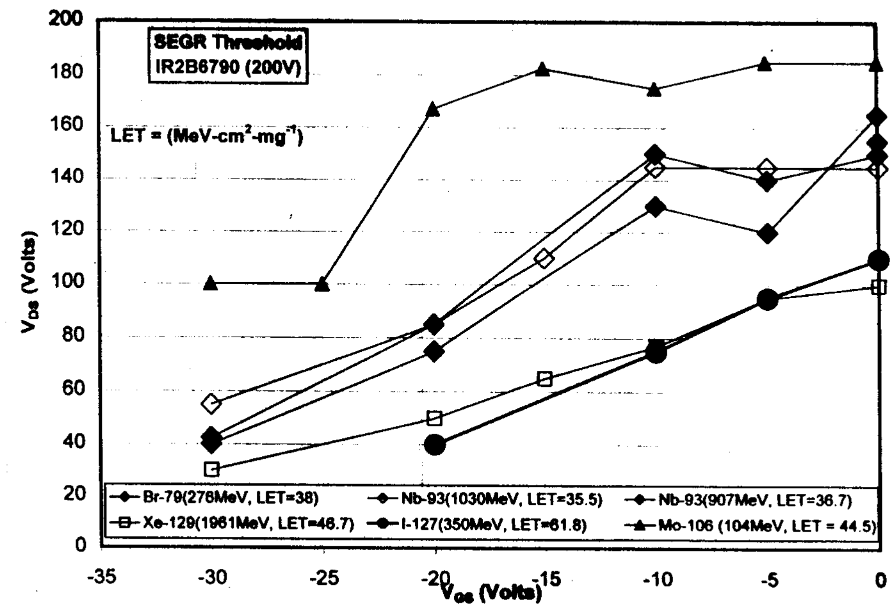

Figure 2, SEGR contour IR2N6790

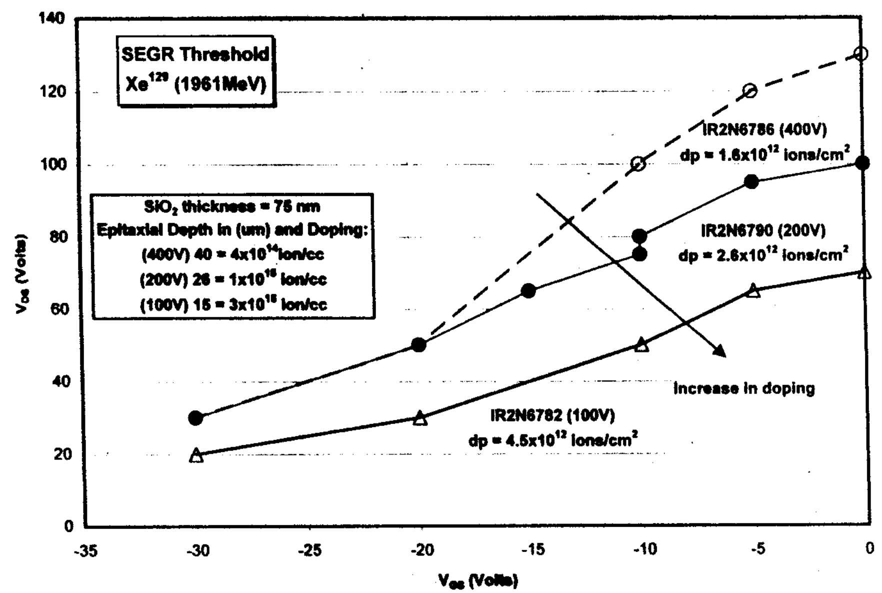

Figure 3, Doping effects on SEGR

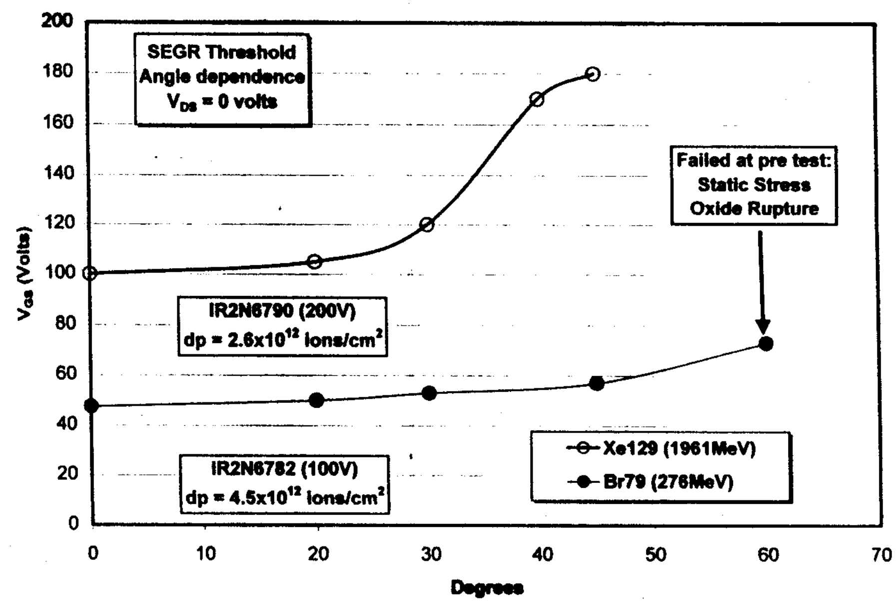

Figure 4, Angular dependence on SEGR