Geometry Effect with Respect to ESD and Radiative Charged Particles in SoC

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ABSTRACT

Thermal grown silicon dioxide (SiO_2) used as gate oxide are found commonly in a SoC (system-on-chip) design for the CMOS technology of 40nm and above, which is vulnerable under ESD (electrostatic discharge) stress typically known as CDM (charged device model) events. Reliability in SoC designs towards ESD protection and RadHard (radiation hardening) against single event effects (SEE) displays a key measure and desired feature in high-end applications such as automotive and aeronautical electronic systems. Using the calculated values of linear energy transfer *LET* and *Range* of radiative Alpha particles in SiO_2, in relation to the geometrical sizes in an SoC design, we continue analyze the potential ionizing radiation damage to transistor gate of CMOS in analogous to ESD damage described by CDM and TLP (transmission-line pulse) method. In this paper we present TLP testing structures with various rise times up to 10 ns on the thermal grown oxide from 70nm to 400nm with focus on the PMOS device, which is more likely damaged in the event of CDM stress due to its hot carrier penetrations to the gate oxide from the source area. Comparative results of Alpha particles are also presented and discussed as in a previous work using radiative particles of protons.

Keywords: silicon dioxide (SiO_2), electrostatic discharge (ESD), charged device model (CDM), ionizing radiation, radiation hardening (RadHard), single event effects (SEE), transmission-line pulse (TLP).

INTRODUCTION

There are increased concerns on safety and reliability in modern system-on-chip (SoC) designs adopted in advanced applications such as automotive and aeronautical electronic systems. It has qualitatively described that electro-static discharge (ESD) and single event effects (SEE), induced by ionizing radiation particles coming from solar or galactic cosmic rays, display similar damage phenomenon by causing voltage pulses or glitches that propagate the circuit. Some recent studies focus on single event upset (SEU) of SEE in SoC in relation to damage described by the charged device model (CDM) of ESD due to similar behavior in physics [1-4].

In the ESD prevention, analysis and testing, CDM has been considered playing a critical role, especially due to its peak current of up to >10A within a short rise time of <0.5 ns, even a few pF electric charges and up to kV voltage CDM can be observed [5], see *Table 1*. This phenomenon has lead to study of finding the corresponding types of SEE, see the study summary in *Table 2* [6]. While SEL can be prevented with epitaxial substrates, such as silicon on insulator (SOI) or silicon in sapphire (SOS) technology, both SEB and SEGR types can cause permanent damages by large dose of ionizing radiation, thus we limit the discussion below on SEU and SET.

Table 1: Measured ESD Parameters

Models	Measured ESD Parameters		
	$Time_{rise}$ (ns)	$Time_{decay}$ (ns)	V_{peak} (V)
HBM	<10	150±20	± 2000～15000
MM	6～7.5	66～90	± 100～400
CDM	<0.2～0.4	0.4～2.0	± 250～2000
IEC	0.7～1.0	～80	± 2000～15000

Table 2: Summary of SEE types and their behavior

SEE Type	Description	Degree of Severity	Notes
SEU	single event upset	non-destructive	may cause wrong logic turnover
SEFI	*SE function interrupt*	*non-destructive*	*derivative of SEU*
SET	single event transient	transient	may cause a transient logic
SEL	single event latchup	destructive	preventable with epitaxial
SEB	single event burnout	permanent damage	at huge radiation dose
SEGR	single event gate rupture	permanent damage	at huge radiation dose

The primary ionizing radiation particles are protons and electrons in the Van-Allen belts; and protons, Alphas and other heavy (HZE) ions in the Solar and Galactic cosmic rays (*Table 3*). Thus in the literatures, the SEE together with the total ionizing dose (TID, its SI unit is Gy, 1 Gy=1 J/kg) effect by protons are widely studied for IC or SoC designs. For example, it has shown that protons of 60 MeV energy can lose or transfer a few keV energy in a micrometer (μm) distance in a transistor gate of SiO_2 media [6].

Table 3: Ionizing radiation particles in/from the Space

Environment	Composition	Energy	Flux, $1/(cm^2 \cdot s)$
Inner Van Allen belt Alt. (1,000-6,000) km	protons (99%) electrons (1%)	10-50 MeV ≥100 keV	$(1-2)\times10^5$ (≥50MeV) 3×10^6 (≥1 MeV)
Outer Van Allen belt Alt. (13,000-60,000) km	protons (1%) electrons (99%)	1 MeV (0.1-10) MeV	2×10^6
Solar/Galactic cosmics At Earth's surface	protons (90%) alphas (9%) HZE ions (1%) photons (x-, g-)	1×10^9 (1 GeV) 1×10^{12} (1 TeV) 1×10^{16} (10 PeV) 1×10^{20} (100 EeV)	1×10^4 1×10^0 1×10^{-7} [a] 1×10^{-9} [b]

[a] a few times a year; [b] once a century

To continue investigate and compare the short pulse of CDM in ESD study (*Table 1*) and using SET in SEE, a transmission-line pulse (TLP) test for ESD measurement is proposed. Based on previous work on linear energy transfer (LET) and Range (R_{CSDA}) for protons and electrons, we continue to do the calculation for Alpha particles, such that a comparison can be performed.

METHODOLOGY

TLP Experiment and Layout Scheme

We firstly propose ESD design structures for future TLP testing. *Figs. 1 & 2* (Cases A-D) illustrate the four layout examples of a PMOSCAP (in pF) of a gate oxide of 70Å (Angstrom) with area of 1600μm2 (0.25~10.0pF) in the 0.35 μm HV process technology. To analyze the CDM damage to the gate oxide and its potential dependence of the layout geometry, we have chosen a PMOSCAP with area to perimeter A/P as the variable.

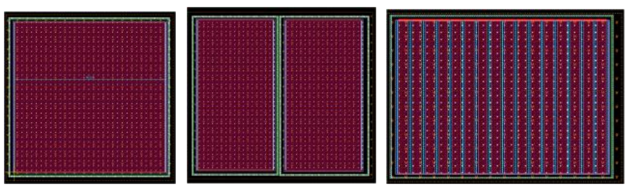

Figure 1: Case A (Left) with W=40, L=40, the total area A is 40x40 μm^2; the perimeter P=160, PMOSCAP becomes A/P=10. Case B (Middle) using multiple fingers M=2 with W=40, L=20, the total P=240, PMOSCAP becomes A/P=2 x 40 x 20/240=6.67. Case C (Right) using multiple fingers M=16 with W=40, L=2.5, the total P=1360, PMOSCAP becomes A/P=1.17

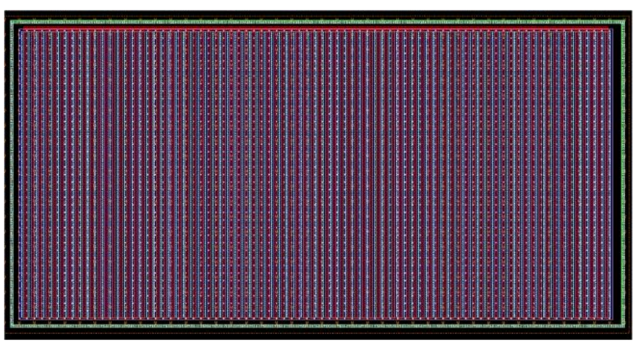

Figure 2: (Case D) Using multiple fingers M=80 with W=40, L=0.5, the total P=6480, PMOSCAP becomes A/P=0.25

Calculation of LET and Range

As discussed previously [6], the ionizing radiation of charged particles (protons, Alphas, heavy ions), when passing through matter, can be described with the *linear* stopping power *S(E)*; when solid media are studied, the *mass* stopping power S_m or simply S ($MeV\text{-}cm^2/g$) can be obtained from $S=S(E)/\rho$, where ρ is the density of the stopping material. The classic Bethe formula with corrections is used to calculate the S,

$$S = k_1 \frac{Zz^2}{M_a \beta^2}[\ln \frac{2\mu\beta^2\Delta}{I^2(1-\beta^2)} - \frac{(1-\beta^2)\Delta}{2\mu} - \beta^2 - 2\frac{C}{Z} - \delta] \quad (1)$$

Alternatively, the linear energy transfer (LET or L) is used, we can define the unrestricted LET, conventionally expressed as $S(E)=-dE/dx=L$, where the minus sign means energy loss. The unit L (keV/μm) is the energy loss per unit length, it is the product of S (in general) or S_{tot} (electronic and nuclear fractions) and the density ρ,

$$L = S_{tot} \bullet \rho \quad (2)$$

Charged particles having initial energy E_0 lose energy through many ionizing interactions in passing through the matter, due to the straggling, in a continuous slowing down approximation (CSDA), until their energy is about zero, the total distance travelled which may not be in a straight line path, the CSDA Range, R_{CSDA} (g/cm^2), or simply Δx is

$$\Delta x = \int_0^{E_0} [1/S(E)]dE \quad (3)$$

RESULTS AND DISCUSSION

From the computing programs available at National Institute of Standards and Technology (NIST) of USA [7], we have performed several calculation works, the results are presented below [*Figs. 3 & 4*, *Table 4*].

Results

The total stopping power (electronic and nuclear) in SiO_2 using Eq. (1) is shown in *Fig. 3*, for Alphas energies E(a) between 1 keV and 1 GeV. Similarly, the CSDA Range (maximum Range versus projected Range) in SiO_2 using Eq. (3) are calculated and shown in *Fig. 4*.

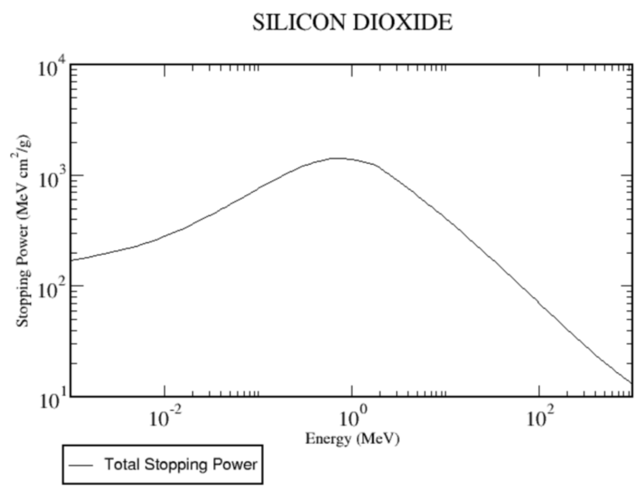

Figure 3: Total Stopping Power of Radiation Particles in Silicon Dioxide, for Alphas at 1keV-1GeV

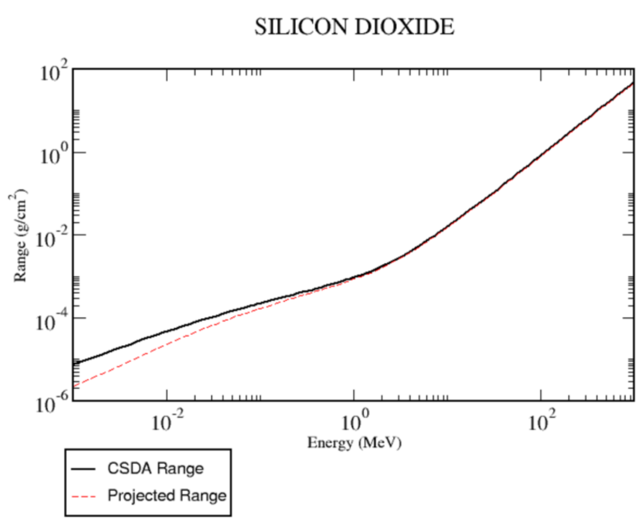

Figure 4: CSDA Range (Δx) in Silicon Dioxide, for Alphas at1keV-1GeV

The stopping power *S* using Eq. (1), linear energy transfer *L* using Eq. (2), and Ranges (R_{CSDA}, R_{CSDA}/ρ) from Eq. (3) are derived for Alphas at various energy E(a); as a comparison, protons of E(p) is also listed (Table 4). Only selected values are listed for the discussion and analysis purpose.

Table 4: S, L, and R of Alphas and Protons

E(a)	S	L	R_{CSDA}	R_{CSDA}/ρ
MeV	MeV-cm^2/g	keV/um	g/cm^2	um
0.001	170	39.03	7.31E-06	0.0318
0.01	282	64.79	4.66E-05	0.2025
0.1	759	174.6	2.20E-04	0.9565
1	1390	319.5	9.26E-04	4.027
6	583.3	134.2	6.91E-03	30.05
10	408.9	94.05	1.53E-02	66.35
60	105.3	24.22	0.3226	1403
100	70.3	16.17	0.7985	3472
600	18.02	4.145	19.2	8.35E+04
1000	13.01	2.992	45.91	2.00E+05

E(p)	S	L	R_{CSDA}	R_{CSDA}/ρ
MeV	MeV-cm^2/g	keV/um	g/cm^2	um
0.001	101.9	23.44	1.39E-05	0.06
0.01	276.2	63.53	6.14E-05	0.267
0.1	533.9	122.8	2.56E-04	1.114
1	189.8	43.65	3.49E-03	15.16
6	53.85	12.38	0.06489	282.1
10	36.38	8.367	0.1573	683.9
60	8.874	2.041	3.791	1.65E+04
100	6.036	1.388	9.391	4.08E+04
600	2.147	0.4938	185.2	8.05E+05
1000	1.859	0.4276	388.1	1.69E+06

Discussion

To prepare CDM for ESD test, the proposed transmission line pulse (TLP) layouts (*Figs. 1 & 2*, with common W=40, L=40, 20, 2.5 and 0.5µm and M=1, 2, 16 and 80 respectively) can be linked to energy depositions and traveling ranges of radiation particles in SiO_2. With the varying A/P values (10, 6.67, 1.17 and 0.25 pF), an RCL circuit can be applied to measure CDM behavior, such as rise times, pulse duration at high voltage tolerance, in TLP experiments in future. Primarily TLP test showed the damage to the oxide by very fast voltage/current purge is inversely proportional to the perimeter to area ratio. That also correlates well with the experimental findings that thick gate oxide is more susceptible to radiation damage than ultra thin gate oxide.

For the SEU or SET types of SEE study, the results of the stopping power *S*, linear energy transfer *L*, the Ranges (R_{CSDA} and R_{CSDA}/ρ) for Alpha particles in CMOS gate media SiO_2 are obtained, these data can be used as references for RadHard study such that energy deposition to be evaluated for either SEE or TID, as a comparison to visualize the TLP tests (*Figs. 1 & 2*) or physical tracks of Alphas in a CMOS device (see *Fig. 4*) at known energies.

For example, for Alphas of 60 MeV, the total stopping power S_{tot} is 105.3 MeV-cm^2/g, *L* is 0.32 keV/µm, the R_{CSDA} is only 1.4 mm. Compared with that of proton of 60 MeV, its S_{tot} is 8.874 MeV-cm2/g, *L* is 2.04 keV/µm, and R_{CSDA} is 16.5 mm. This shows us a 60 MeV proton can travel more than 10 times distance, or lose 1/3 energy per unit length, of that of Alphas in SiO_2. In comparative experiments for SEU or SET in accumulated TID studies, from Table 4, *L* and R_{CSDA} can provide geometrical guidance; as the Range is monotonic as a function of the particle energy, therefore it is more meaningful to use them to relate to physical application of CMOS gate.

For an SET which may propagate a pulse signal as in a coupling effect in a pair of parallel routing paths, to result in a signal integrity issue, if to result in an incorrect value being latched in a sequential logic unit, it is then considered an SEU. Thus understanding the differences between SET and SEU impose significant meaning in preventing them. Both SET and CDM may exhibit sudden short pulse rise in electric charges or current to cause a CMOS device failure. It is anticipated that the SET has a similar behavior as CDM. These glitches can cause a failure in a SoC design which can lead to life threatening accent if it is applied in an automotive electronic system, or aviation disaster such as in a civil air flight or advanced satellite [2, 3].

Conclusion

Primary study on geometries of TLP layouts and Ranges of Alpha particles present a linkage for the study between CDM of ESD and SEU and/or SET of SEE. Study of CMOS physical dimensions versus the energy depositions and Ranges of the protons and electrons [6] has been extended to Alpha particles in current work. The method of CMOS gate geometries relating to monotonic values of Range of charged particles is established for future work.

FFUTURE WORK

The calculation of Alpha particles may be extended to other heavy (HZE) ions and non-charged particles such as neutrons, results in SoC design for automobile applications for high reliability, including spacecraft and aviation. TLP measurement vs. SEU or SET to be determined in future tape-out chips.

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