Simulation of proton irradiation of charge trapping flash memory cells

Katarina Karadžić

Abstract — **Proton irradiation of charge trapping flash memory cells was simulated using Monte Carlo method. Simulated memory cells included SONOS, SANOS, TANOS and three modifications of TANOS memory cell with different control gate material (TiN, WN and W). Proton energies were in ranges from 50 keV to 125 keV and 5 MeV to 50 MeV. Results are given in form of absorbed dose to memory cell and active layer, cross section for single event effects and threshold voltage shift.**

Index Terms — **Monte Carlo simulation, proton irradiation, charge trapping memory cells, radiation effects**

I. Introduction

THE MAIN characteristic of nonvolatile memory is the ability to recover stored information even after having been turned off and back on. One representative of nonvolatile memory is flash memory, a close relative to the E2PROM with difference that it can only erase one block at a time. The integration of flash memory into CMOS processes has helped advance the state of non-volatile as a low-power memory for portable device applications [1]. There are a number of physical phenomena which can be used to store information in a nonvolatile memory with charge storage being the simplest one [2]. Whether there is or isn`t net charge, what is the sign of stored charge or various amounts of charge can be used as a digital information. In order to accomplish this, a potential well need to be created where charge can be stored. Also suitable ways to inject, remove and sense the charge in a potential well are required. Floating Gate (FG), Charge Trap (CT) and Nano crystal (nXTL) memories operate in this manner.

There are two main drawbacks of floating gate cells. The first is that it has become more difficult to downsize them because of the thickness of the tunnel oxide which cannot be reduced any more without generating stress induced leakage current thus compromising retention (cell's ability to store charge over prolonged time) capability of the cell. The second one is due to conductive nature of the floating gate as the storage element because single leakage path originating from any point in tunnel oxide can discharge the whole floating gate. One of the major solutions for these problems is replacing conductive floating gate with a dielectric layer with high density of traps - charge trapping memory (Figure 1)

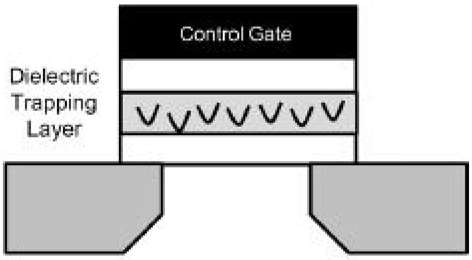

Fig. 1. Charge trapping memory cell [2]

Nitride layer (Si_3N_4) acts as the storage element in charge trapping memories, with difference in which materials they use as electrode and blocking (barrier) oxide, and also in manner they are being programmed. There are two mechanisms in which charge can be injected into the nitride, Fowler - Nordheim tunneling or by hot-carrier-injection (HCI, holes or electrons). After the charge is stored in nitride, it acts as to modify the device's threshold voltage. When using HCI mechanism, by choosing which n+ junction is grounded and on which voltage is applied (Figure 2), two bits can be stored in one cell and they can be operated independently (hot electron injection for programming and reading (in reverse) and hot holes injection for erasing). This makes charge trapping memory very desirable due to a decreased required area per bit. More recently, TANOS (Figure 2) and other charge trapping devices have replaced blocking oxide between control gate and storage layer with Alumina [1, 3]. The high-k blocking oxide (Al_2O_3), due to higher dielectric constant, allows the gate better control over the channel by lowering gate injection of carriers leading to lower erase saturation levels, reducing the electric field which reduces tunneling effect, and improving retention. The use of a high-work function metal (TaN) as the control gate reduces the injection of carriers through the blocking oxide [3].

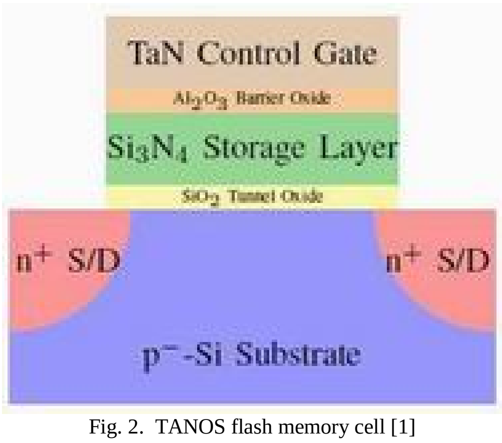

Fig. 2. TANOS flash memory cell [1]

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Nonvolatile memory cells are usually given the task of a secondary storage unit and their need for future space applications and nuclear technologies is on the rise leading to their operations in extreme environments [4]. Device properties like storage mechanism, size and array architecture influence radiation sensitivity for both total ionizing dose and single event effects. Possible SEE that can occur in nonvolatile memories are single event upset and multiple bit upsets. Alongside performance degradation, TID causes cells to lose functionality or information. Charge-based storage is usually more sensitive for a given cell dimensions with respect to other mechanisms (phase change, magnetic RAM, ferroelectric memory), because the main effect of ionizing radiation is generation of electron-hole pairs, which can get trapped in dielectric layers and generate interface states (TID) or give rise to transient currents (SEE).

Since it is complicated to reconstruct actual extreme environment in laboratory, it is suitable to have methods which will simulate these conditions in order to have indication of environment effects on memory devices. Simulation of SEE in electronic devices consists of interaction of radiation with the device and movement of charge as a result of interaction leading to changes in currents and voltages of device nodes. A Monte Carlo radiation simulation focuses on each individual quantum of primary radiation. This quantum is tracked as propagates through the semiconductor device. In Monte Carlo calculation, all of the various mechanisms by which radiation interacts with matter are sampled, and probabilities are used to determine whether a process will be associated with a given step. Secondary radiation quanta are recorded and each is followed until all quanta have been consumed in interactions, have left the volume of interest or have lost all of their kinetic energy and come to rest. Physics-based Monte Carlo simulators have gained popularity with the advancement of accurate, calibrated physical models for radiation transport and energy deposition [5, 6, 7, 8].

II. The Method

For the simulation of proton irradiation, we used MCNP and SRIM program packages. The particle radiation transport code MCNP (Monte Carlo N Particle) is a general purpose three dimensional simulation tool that transports 37 different particle types over broad range of energies. Its application includes criticality calculations, shielding, dosimetry, detector response and many others. MCNP contains numerous tallies: surface current and flux (track length), point or ring detectors, particle heating, pulse height tally for energy or charge deposition, mesh tallies and radiography tallies. In this paper we used MCNPX 2.7.0 version [9]. TRIM (Transport of Ions in Matter) is also a Monte Carlo based program that calculates the interaction of energetic ions with amorphous targets. It is part of SRIM program package. TRIM uses binary collision approximation in which randomly selects impact parameter of colliding particle. The result is stopping and range of incident ions into matter [10].

Simulations were performed for three configurations of charge trap flash memory cells: SANOS, SONOS and TANOS, with three additional modifications of TANOS control gate, in which TaN control gate, was replaced with TiN, WN and W [11]. Dimensions of different layers of memory cell were given in [1].

Simulations in TRIM were performed for proton energies from 50 keV to 100 keV (with increment of 10 keV) and 125 keV, while energy range in MCNP simulations was 5 and 10 to 50 MeV (with 10 MeV increment). Number of simulated protons was 1000 and 10^7 in TRIM and MCNP, respectively. TRIM output files provide results in form of energy loss of ions to the target electrons (eV/angstrom/ion), energy loss to the target that leads to creation of vacancies (vacancies/angstrom/ion), ion`s energy loss to the target phonons (eV/angstrom/ion) and ion range distribution ((atoms/cm^3)/(atoms/cm^2)). In MCNP simulations, we used F6 tally which provides us with energy deposition averaged over a cell (MeV/g).

$$D_{cell} = \frac{e}{1000} a \sum_{i=1}^{5} \frac{1}{\rho_i} \sum_j f_j R_j (I_j + P_j + V_j) \qquad (1)$$

where e is elementary electric charge, a is layer depth, ρ_i is density of each layer, f_j is the ion fluence in segment j, R_j is the ion distribution in segment j and I_j, P_j and V_j are energy loses due to ionization, phonons and vacancy production, respectively.

In order to calculate cross section σ as a function of collected charge in active region following method was used. Deposited energy (from MCNP simulations) was converted into collected charge, and every event in which net collected charge was greater than critical charge was noted. Finally cross section values were calculated as [14]:

$$\sigma = A \frac{\sum_{Q>Q_{crit}} N_{SEE,i}}{\sum N_i} \qquad (2)$$

where $N_{SEE,i}$ is the number of single event effects that were observed out of total number of events N_i and A is active region surface.

Sensitive volumes represent regions of sensitivity within semiconductor material. Weighted sensitive volume model [15, 16] can be used to describe intercellular variation in charge collection (Figure 3). Collected charge from deposited energy in sensitive volumes is given by [15]:

$$Q_{coll} = k_{conv} \sum \alpha_i E_{dep,i} \qquad (3)$$

where k_{conv} which equals to 1/22.5 pC/MeV is conversion coefficient that assumes that 3.6 eV, on average, is required to produce one electron-hole pair in silicon, α_i is charge collection efficiency for each sensitive volume and $E_{dep,i}$ is deposited energy in each sensitive volume.

Critical charge was determined with [17]:

$$Q_{crit} = c_{conv} A \qquad (4)$$

where c_{conv} is conversion factor of 0.023 pC/μm^2 that assumes that 3.6 eV, on average, is required to produce one electron-hole pair in silicon and A is the active region surface.

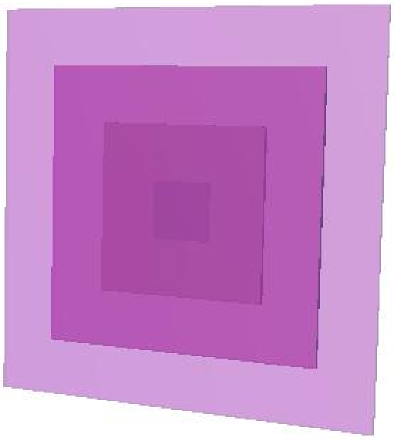

Fig. 3. Sensitive volumes of Si_3N_4 for calculation of collected charge

Finally, threshold voltage shift is calculated using formula [18]:

$$\Delta V_{th} = -q\left(\frac{t_{Al2O3}}{\varepsilon_{Al2O3}} + \frac{t_x}{\varepsilon_{Si3N4}}\right) \qquad (5)$$

where –q is the lost charge, t_{Al2O3} is the thickness of high-k oxide layer, t_x is the distance of the charge in trapping layer and ε_{Al2O3} and ε_{Si3N4} are dielectric constants of high-k oxide and nitride layers, respectively. In these calculations, t_x equaled half of t_{Si3N4}.

III. RESULTS AND DISCUSSION

The results of calculations are shown in Figures 4 – 7. From figures 4 and 5 we can observe drop in absorbed dose as the proton energy increases both in keV and MeV range calculated form simulations results using Equation 1. We can see that all memory cell configurations follow similar trend, which also reported in other published data [12, 13, 19, 20]. Maximum dose in keV range is 155 Gy absorbed in (WN)ANOS cell layout, while SONOS layout absorbed maximum of 117 MGy in MeV range.

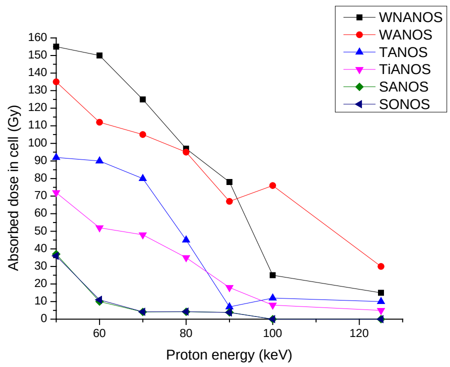

Fig. 4. Absorbed dose in different memory cell structures for proton energies in keV range

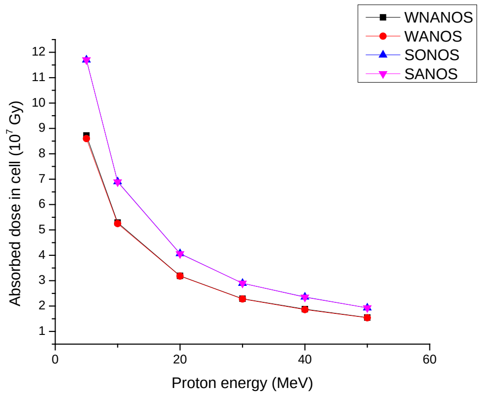

Fig. 5. Absorbed dose in different memory cell structures for proton energies in MeV range

Table 1 shows the ratio of absorbed dose in active region and absorbed dose in entire memory cell. Ratio varies from 30% to 41% and is in agreement with ratios previously found in similar studies [12, 13, 19, 20].

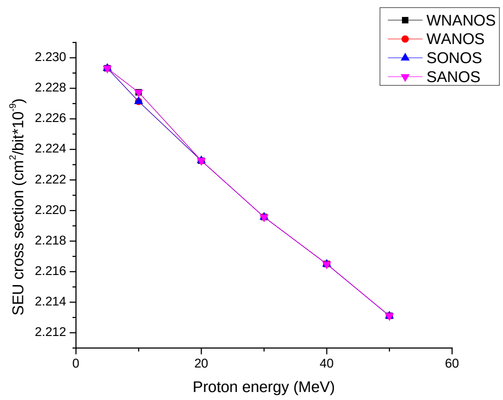

Fig. 6. Cross section for SEU as a function of proton energy

TABLE I
RELATIVE ABSORBED DOSE FOR DIFFERENT PROTON ENERGIES AND DIFFERENT MEMORY CELL STRUCTURES

		$D_{activelayer}/D_{cell}$ (%)			
Cell structure		(WN)ANOS	WANOS	SANOS	SONOS
Photon energy (MeV)	5	41	42	31	31
	10	40	40	31	31
	20	38	39	31	31
	30	39	39	31	31
	40	38	38	30	30
	50	38	38	30	30

Cross section for SEU as a function of proton energy is shown in Figure 6 using Equations 2 - 4. Values of cross section are almost equal which can be explained by fact that the amount of charge collected needed to induce an upset (Q_{crit}) is dependent of surface area of memory cell and not on type of particle nor its energy. As memory cells are scaled down in dimensions, Q_{crit} which will lead to easier upset generation than in larger devices.

One of the possible induced radiation effects is shift in threshold voltage. Figure 7 shows the change in the value of threshold voltage. The shift, from Equation 5, is negative which means that memory cells can be activated with lower voltage values than designed leading to irregular memory cell operation.

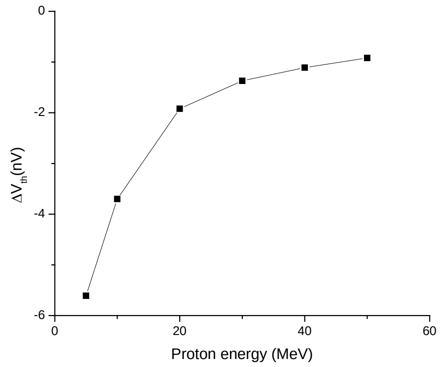

Fig. 7. Threshold voltage shift as a function of proton energy

IV. CONCLUSION

In this paper, we simulated effects induced by protons in charge trapping flash memory cells. Three types of memory cell structures were simulated with modifying one structure with different control gate materials. Proton energies were in keV and MeV range. Results were given in a form of absorbed dose in memory cell and active region, cross section for single event effects and threshold voltage shift.

Charge trapping memory is emerging type due to replace floating gate. Results shown in this work should serve as either addition to previously published data such as comparison of absorbed dose with different mechanism memory (phase change) or starting point for further research such as cross section for SEU and voltage threshold shift since those data are presently scarce in literature.

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