Monte-Carlo Simulation for the Effects of Composite Materials on Single Event Effects of Sub-100 nm Semi-conductor Devices

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A Monte-Carlo simulation code SEALER was developed for neutron-induced single event upset of semiconductor devices at the ground level, in which composite material effects are fully simulated.
Any size and structures of 8 composite material such as Si, SiO_2, Si_3N_4, Ta_2O_5, WSi_2, Cu, Al, TiN can be included for analyses of nuclear spallation reactions and charge collection to storage nodes. Some preliminary implications of composite material effects are demonstrated including an apparent contribution of elastic scattering to single event upset in lower energy region as low as 2 MeV or even lower.

1. Introduction

Electron devices/components/systems are exposed to environmental radiation to cause single event upsets (SEU) which may further cause data corruption or even system crash at the ground level. Alpha ray from radioactive materials has been regarded as main source of such environmental radiation from late 1970s to 1990s [1,2]. Terrestrial neutrons which are produced by nuclear spallation reaction of high-energy cosmic ray with nuclei of atmospheric air in the inner space, are emerging as much more crucial radiation source as the minimum feature size of semiconductor device nose-dives toward sub-quarter microns [3,4].

A program package CORIMS (Cosmic Ray Impact Simulator) with Monte-Carlo (MC) simulation techniques for nuclear spallation reaction model (Intra-Nuclear Cascade (INC) and statistical evaporation models)[5] and charge collection models in 3D structure of major components including source, drain, isolation oxide, single/triple wells of infinite-matrix memory cells has been applied for analyses of single event effects (SEEs) of semi-conductor devices [6,7]. Experimental approaches by medium-energy (1-800 MeV) neutron irradiation experiments are also applied for commercial devices [8-10]. The simulation technique is particularly important under design phase to predict and minimize the susceptibility of semiconductor devices before mass production to the market. The simulation techniques appeared fairly satisfactory as a prediction tool for SEUs, but not so effective for SEU minimization or design tool so far.

Recently, Gasiot [11] indicated that SEU rate got higher by a factor of two when 14MeV neutron is irradiated from SiO_2 side than from Si substrate side. The simulation model in our precedent program package CORIMS is very limited in this viewpoint: It simulates only nuclear spallation reaction of Si nucleus and analyze secondary ion tracks and energy deposition in Si substrate.

In order to overcome such deficiency, we have made a new Monte-Carlo simulation code SEALER (Single Event Adverse and Local Effects Reliever) by which such composite material effects are fully simulated on Windows^{TM} PCs and material/layout design of device components can be made. It is shown that extremely large database is required for this purpose. Some preliminary implications of such composite material effects are also demonstrated in this paper.

2. Model description

2.1 Nuclear spallation reaction model

In general, 8 composite materials such as Si, SiO_2(commonly used for isolation oxide), Si_3N_4(gate side wall, etc), Ta_2O_5(DRAM capacitor material), WSi_2(contact), Cu (metal line), Al (metal line), TiN (buffer, etc) are used in Si-base semi-conductor devices. Therefore, 8 nuclei (Si-natural, ^{14}N, ^{16}O, ^{181}Ta, Ti-natural, ^{27}Al, Cu-natural, ^{184}W) are treated as target nuclei. Total and non-elastic-reaction cross section data from JENDL3.3 [12]/ JANIS2.0 [13]/ LA150 [14] are approximated as a polynomial function of neutron energy as shown in Fig. 1. Total scattering cross section of each component is calculated first for given neutron energy, and the component where neutron interaction takes place is determined by MC manner. Then type of reaction (elastic or non-elastic) and target nucleus are determined sequentially.

For elastic scattering, classic relativistic binary collision model is applied. For non-elastic nuclear reaction analyses, models similar to Tang's approach [5] is applied: Intra-nuclear cascade (INC) model in which many-body collision process is regarded as a sequential relativistic binary collisions with rexicographic processing of trees (a particle of interest is chased to the end) is applied for prompt nucleon-nucleon collision process in the target nucleus. Nucleons with energies high enough over the Fermi levels of each nucleus at the surface of the nucleus are released from the nucleus. After reaching the condition that all collided nucleons do not have such high energy, Weisskopf-Ewing type model is applied for light particle evaporation. Inverse reaction cross section is used to determine the reaction channel and is calculated based on Generalized Evaporation Model (GEM)[15]. The calculated inverse reaction cross section are fairly consistent with literature data[16] as shown in Fig.2.

2.2 Device and charge collection models

Bird's eye 3D view of CMOS-SRAM (static random access memory) is illustrated in Fig. 3. A pMOSFET is placed in the center between nMOSFETs. When the storage node (diffusion layer) is hit by a secondary ion, a certain amount of electrons/holes produced along the ion track is collected to the nodes typically by the funneling mechanism. Some amount of electrons and holes are also collected by diffusion process. Such charge collection models (funneling and diffusion) are incorporated into the program packages CORIMS/SEALER and SEU takes place when charge collected to the node exceeds the critical charge Qc over which the data "1(high)" in the node change to "0(low)". As device scaling proceeds, charge collected due to alpha particle decreased because charge density along alpha particle path is only about 5-10 fC/μm while charge collected due to heavier secondary ions (C,N,O,…,Ta,W) is as high as 100-200fC/μm. This is why neutron SEU is getting dominant as device size is shrunk.

The nuclear reaction models are benchmarked with 65, 180, 380 MeV proton reaction data with ^{27}Al and a fairly good consistency close to those in Ref.[5] .

3D device model is constructed by using common CAD algorithms based on device design parameters. Ion track analysis of secondary ions in the multi-component device structure is also carried out by specially designed algorithm. Deposited energy of any secondary ions (from proton to ^{184}W) in any substrate material can be calculated by using polynomial approximation functions made from SRIM.

Simulated results from CORIMS are compared with test results in the field or accelerator neutron facilities (TSL, LANSCE, CYRIC, FNL, RCNP) and good agreements are obtained for all cases within 20-30 % error in average [7].

In order to evaluate the composite material effects preliminarily, a virtual (neither real nor to-scale) device model was used as shown in Fig. 4. Isolation oxides (SiO_2), copper metal lines, WSi_2 contacts over storage nodes, Si_3N_4 gate side walls are incorporated in the base Si substrate.

3. Preliminary implications from simulated results

3.1 Secondary ions from different materials

Figure 5 shows histograms of secondary ions from Si-base materials (Si, SiO_2, Si_3N_4) when 100 MeV neutrons are bombarded. As for Si target, heavy ions (Al, Mg) and light ions (p,α) are dominant secondary ions. Meanwhile, it is seen that medium weight ions (C,N) are produced from SiO_2 and Si_3N_4 substrates of the same order of Mg, Al from Si substrate.

Figure 6 shows energy spectra of secondary ions *produced in* the WSi_2 substrate. It is seen that W (though inelastic reaction) and Ta are produced from W target in WSi_2 with low energy but relatively high probability.

3.2 Results from virtual composite material device

Figure 7 shows energy spectra of secondary ions *reached at the sensitive region* (Si well). The followings are pointed out:

(1) Among heavy secondary ions, Na ion has the highest probability while Al has the highest probability of production from Si. This implies that the probability to reach at the sensitive region is determined from the rate and location (range) relative to the sensitive region.

(2) The probabilities of medium weight ions (C,N) are not so high. This is due to the assumption of the thickness of SiO2 (5μm) which is much thinner than Si substrate(50μm), so that the total amount of target nucleus in the device is another key parameter.

(3) The probabilities of Ta and W are negligibly small even though WSi_2 is contacted to the sensitive region. This may be due to very short range of these secondary ions, since the energy is very low as seen in Fig. 6.

Figure 8 shows calculated charge density at the inlet of the sensitive region (Well) for 2MeV neutron bombardment. Cumulative frequency over specific charge density is plotted for oxygen, silicon, elastic scattering, non-elastic scattering, and total scattering. Major findings are:

(1) Although slight charge deposition takes place by non-elastic (actually in-elastic n-n’) scattering for 2MeV neutron, charge density by elastic scattering is as high as 40fC/μm. This density can cause SEU depending on the device structure/size and critical charge and thus can be major mechanism of the low SEU threshold energy

below the threshold energy of nuclear reaction of Si nucleus [17].

(2) It is also noteworthy that oxygen nucleus recoiled from SiO_2 by elastic scattering has major contribution to deposition density in the range of 20-40 fC/μm.

(3) For low energy neutron irradiation as in Gasiot's paper (14 MeV), contribution of elastic scattering is relatively high so that dependency of SEU on neutron beam direction may be explained in future.

4. Conclusion

(1) MONTE-CARLO simulator SEALER was developed to deal with neutron induced soft-error in all possible materials in semiconductor devices. (2) The effects of secondary ions like C,N from SiO_2, Si_3N_4 on soft-error may be underestimated by Si-only model.

(3) The amount of secondary ions passing through sensitive node depend on positions of various components with different materials; does not necessary correspond to the amount of secondary ions produced.

(4) Heavier secondary ions (from Cu, W, Ta) may have only local (spatially limited) effects.(5) Oxygen and Si nuclei recoiled by elastic scattering from Si/SiO_2 causes SEU when neutron energy is as low as 2MeV or even lower.

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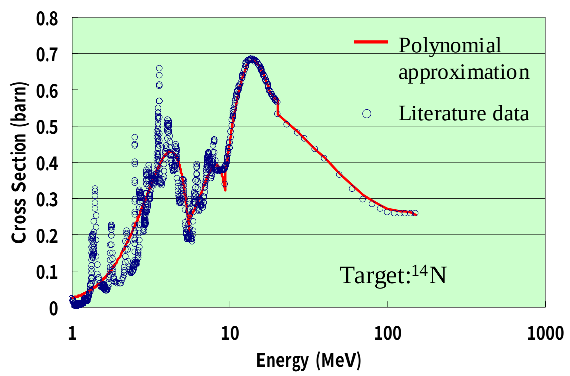

Fig.1 Literature data of non-elastic reaction cross-section and calculated results from polynomial approximation (^{14}N)

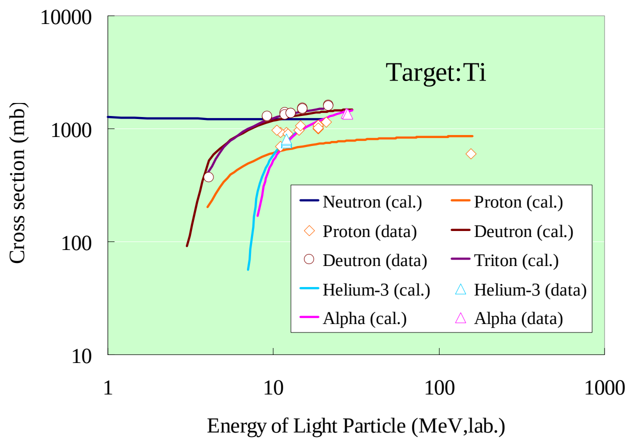

Fig.2 Literature data of inverse reaction cross-section and calculated results from GEM

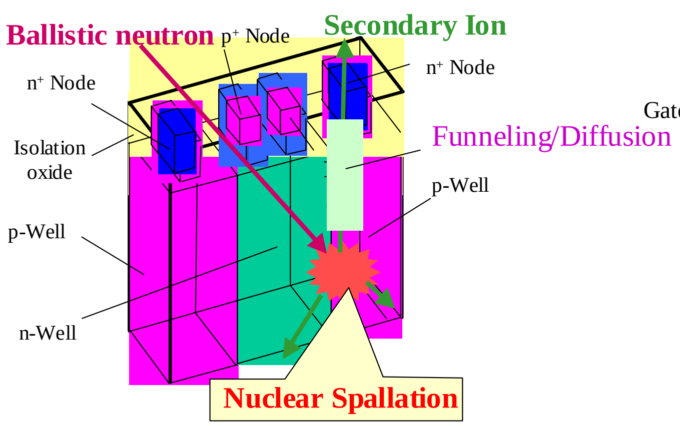

Fig.3 Bird's eye view of CMOS-SRAM device and microscopic mechanism of single event upset

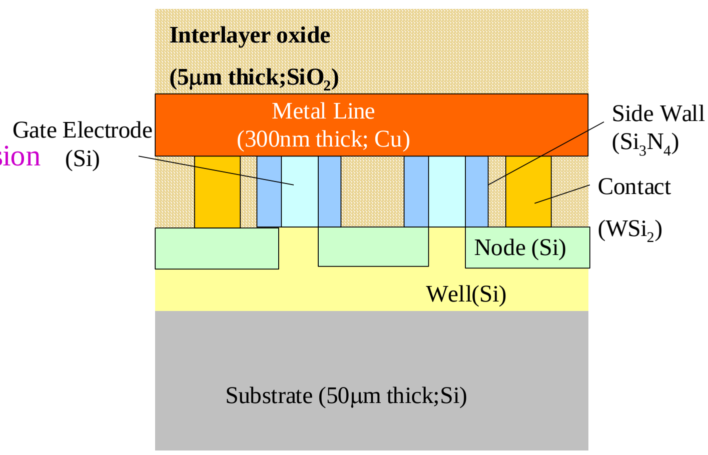

Fig.4 Cross-section of virtual composite material device model

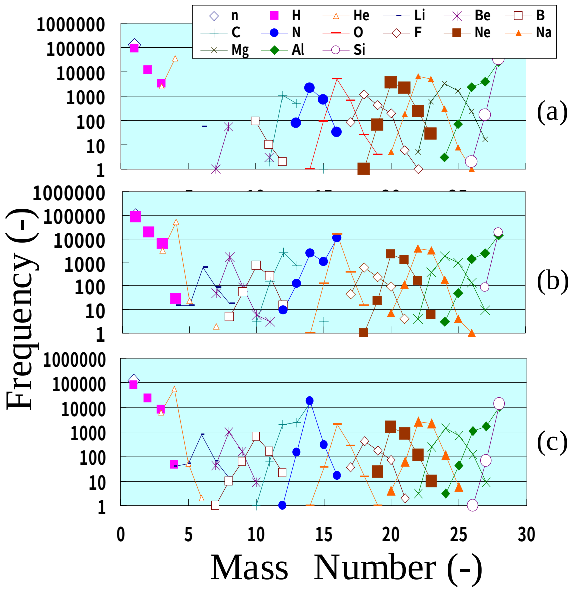

Fig.5 Histogram of secondary ion produced in Si-base material by 100 MeV neutron (a) Si, (b) SiO_2, (c) Si_3N_4

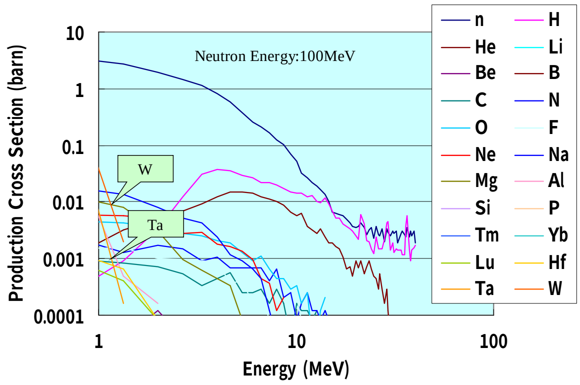

Fig. 6 Energy spectra of secondary ions produced in WSi_2 substrate by 100 MeV neutron

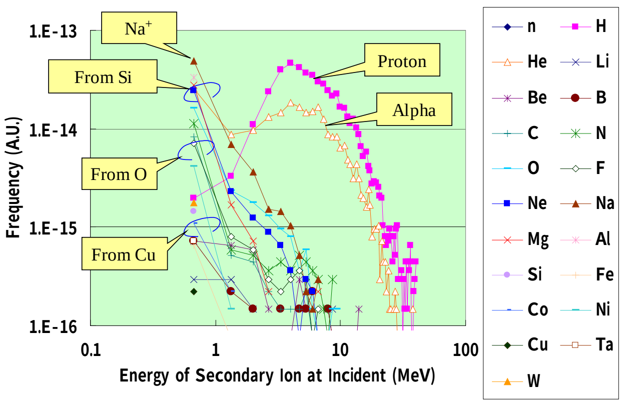

Fig. 7 Energy spectra of secondary ions at the inlet of sensitive region (Well) of the virtual SRAM device

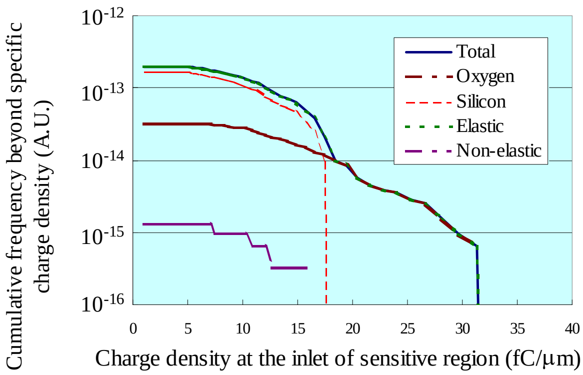

Fig.8 Charge density spectrum by secondary ions at the inlet of sensitive region