Reliability concerns of Ge-based nanoelectronics subjected to terrestrial atmospheric neutrons

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Abstract

Germanium is potentially candidate to replace silicon in ultra-scaled transistors. This work analyses the radiation response of germanium in thin layer subjected to atmospheric neutrons and quantifies the underlying mechanisms potentially responsible of single event effects in Ge-based advanced CMOS technologies. Reliability assessments for Ge-based nanoelectronics are reported for technological nodes ranging from 180 nm to 14 nm.

1. Introduction

Germanium was the semiconductor material of first-generation transistors in the late 1940s and early 1950s before it was replaced by silicon for large scale-area microelectronics. However, using germanium instead of silicon as transistor material would enable more performant transistors and faster chips because of its higher mobility values for electrons and holes than those of silicon. In the last years, significant progress in passivation of the interface between Ge material and high-k gate dielectrics has revived the interest of Ge for ultra-scaled devices as a potential candidate for high-mobility channel material, in particular for nanosheet transistors, the next and maybe ultimate device architecture in Moore's Law for device integration. From a radiation reliability point-of-view, Ge is therefore characterized by a lower energy of electron-hole pair creation than Si, that questions its susceptibility to radiation in general, and to natural radiation at atmospheric level for this study.

Following a robust methodology previously used for the study of neutron interactions with silicon [1] and III-V materials [2], this work also extends our study presented at ESREF 2019 concerning a first estimation of stability of Ge-based SRAMs subjected to single event effects (SEE) [3]. The present contribution precisely examines the susceptibility to atmospheric neutrons of a thin film of natural Ge, mimicking the active semiconductor top layer of a typical integrated circuit. In the following, we report a complete analysis of neutron-Ge interactions in terms of number/types of reactions and number/nature of secondary products produced in Ge and Si targets. We also discuss the impact of a low energy threshold for secondaries with respect to the critical charge of SRAM cells for CMOS technological nodes from 180 nm to 14 nm, demonstrating the increasing importance of low energy products in the SEE occurrence probability when pushing the integration.

2. Simulation details

We used a recent version of Geant4 (10.06.p01 with G4NDL4.6 neutron library and QGSP_BIC_HP physics list [4]) to numerically simulate the impact of high energy (E>1 MeV) atmospheric neutrons on a thin film (1cm^2 × 20 µm) of natural Ge (and of natural Si for comparison), following the methodology detailed in Ref. [2]. This simple geometry is representative of the typical "active volume" of a microelectronic circuit. In the present case, we considered the natural isotopic composition of natural Ge, which is a mixture of five isotopes: ^{70}Ge (20.52%), ^{72}Ge (27.45%), ^{73}Ge (7.76%), ^{74}Ge (36.52%) and ^{76}Ge (7.75%). A total of 5×10^8 of incident neutrons (arriving perpendicularly to the target largest surface) has been randomly generated; it corresponds to a theoretical duration of 25×10^6 hours of natural irradiation at sea-level.

The simulation output file contains all the information related to the neutron interaction events in the target material. For each event, this information includes the nature and the coordinates of the vertex of the interaction, the energy of the incident neutron, the exhaustive list of secondary particles produced during the interaction (excluding n, γ, π^0, e^+, e^- and η particles that are not able to detectable SEE), the energy and the emission direction vector for each of

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these emitted particles. Contrary to our previous works conducted on other materials [1-2], we did not impose any minimum energy threshold for the secondaries recorded in the output file; in other words, this raw file contains all particles produced by the Geant4 code during the simulation run. As we will see in Section 3, fixing a minimum energy threshold mechanically decreased the number of less energetic events and potentially eliminates secondary products that may induce SEEs in the most integrated technologies.

2. Simulation results

Table 1 summarizes the number of nuclear interactions induced by high energy atmospheric neutrons at sea level during 25×10^6 h in a layer of material of 1 $cm^2 \times 20$ μm. We recall here that interactions of neutrons with atomic nuclei can be divided in two major mechanisms: scattering (elastic, inelastic) and capture (or nonelastic) [5]. In the elastic scattering, the nature of the interacting particles is not modified; the recoil nucleus is then the same as the target nuclei. The inelastic scattering is similar to the elastic scattering except that the impacted target nucleus undergoes an internal rearrangement into an excited state from which it eventually releases radiation. Instead of being scattered, an incident neutron may be absorbed or captured by a target material nucleus. Many reactions are possible and a large variety of particles can be emitted. This type of interaction is also called nonelastic interaction.

Results of Table 1 show that atmospheric neutrons induce much more interactions in germanium than in silicon: 121 versus 86 kilo-events (+39%) for the considered target geometry and neutron flux. Such an increase with respect to silicon is not uniform: it corresponds to only +10% of elastic events but more than 3 times of inelastic events and about +60% of nonelastic events. For this last category, the nature and the distribution of the most numerous nonelastic reactions are also different:

Table 1
Number of nuclear interactions induced by high energy (>1 MeV) atmospheric neutrons at sea level during 25×10^6 h in a layer of material of 1 $cm^2 \times 20$ μm. Results are deduced from Geant4 numerical simulations.

Interactions	Natural Ge	Natural Si
Elastic	66,823 (55.4%)	60,576 (70.6%)
Inelastic	26,604 (22.1%)	8,302 (9.7%)
Nonelastic	27,184 (22.5%)	16,884 (19.7%)
Total	120,611	85,742

Table 2
Details of secondaries produced in natural silicon and germanium targets (1cm^2 × 20 μm, 25×10^8 n) by atmospheric neutrons estimated from Geant4 simulations.

Natural Ge		Natural Si	
Ge recoils	102,492	Si recoils	69,871
p + d + t	24,118	p + d + t	21,292
$\alpha + {}^3He + {}^6He$	3,772	$\alpha + {}^3He + {}^6He$	3,495
Other ions (2 < Z < 14)	16,169	Other ions (2 < Z < 32)	15,799
TOTAL	146,551		110,457

- For silicon, only 6 reactions producing Al and Mg ions in secondaries represent more than the half of the total number of nonelastic reactions.
- For germanium, the 10 first nonelastic reactions in numbers only represent one third of the total number of events; all these reactions give a germanium nuclei with a lighter mass with respect to the initial impacted nucleus.

These results will be detailed in the final paper. The difference in atomic number Z between Si (14) and Ge (32) can explain such quantitative results, in so far as the number of nuclear reactions increases monotonically with Z, in particular inelastic and nonelastic interactions [5].

Concerning now the total number of secondaries produced, Table 2 gives the distributions for the two material targets. We distinguished four categories of secondaries: recoil nuclei, protons + deuterons + tritons, helium nuclei ($\alpha + {}^3He + {}^6He$) and finally a last category regrouping all the other ions produced. Logically with respect to results of Table 1, Ge exhibits much more secondaries than Si, about +33%. In details now, a roughly similar number of protons, alpha particles and heavy ions are obtained in both materials, the main difference comes from the amount of recoils which is much more larger (+46%) in the case of Ge with respect to Si. This result is important in the perspective of device integration, since heavy recoil nuclei are characterized by low kinetic energies and low ranges in target materials. This aspect is illustrated by the distribution histograms of secondaries in energy and range, shown in Figures 1 and 2. Below typically 0.1 MeV in energy and 10 nm in range, distributions are dominated by such recoil nuclei. The consequence is that they are only susceptible to induce weak amounts of electrical charge in the semiconductor material, not enough to induce SEEs in submicron technologies but possibly enough in nanometer ones, as discussed in the following.

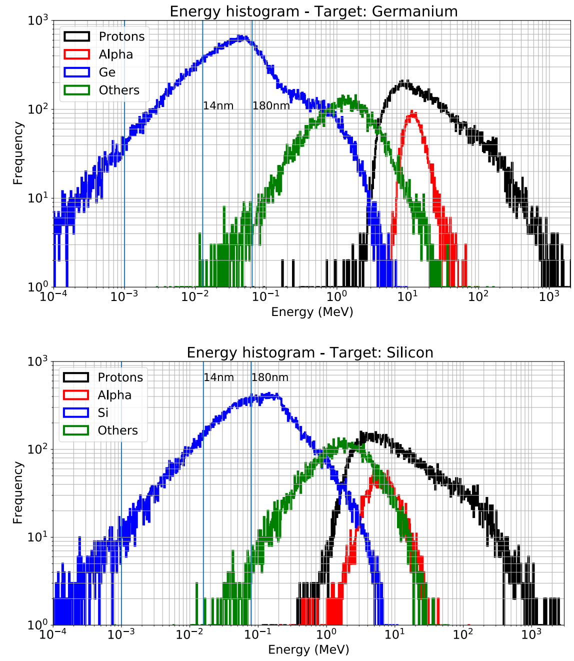

Figure 1. Energy histograms (1000 bins) of protons, alphas, target nucleus recoils and other ions produced by atmospheric neutron interactions in natural germanium and silicon bulk targets (1cm^2 × 20 µm, 25×10^8 n).

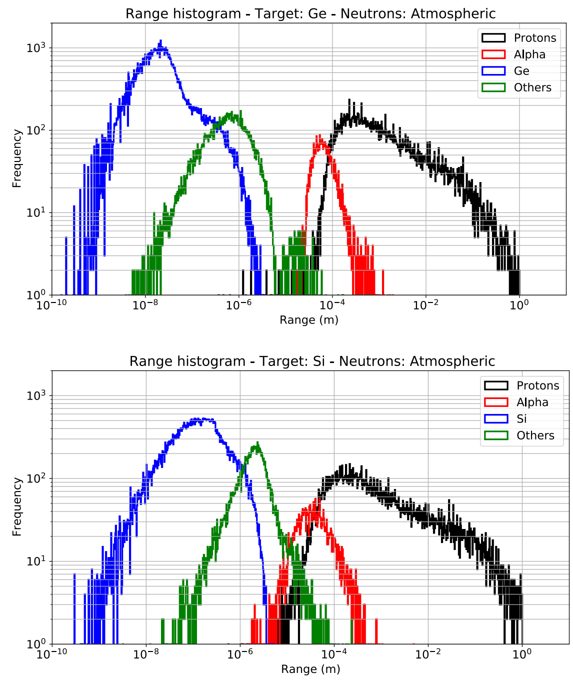

Figure 2. Range histograms (100 bins) of protons, alphas, target nucleus recoils and other ions produced by atmospheric neutron interactions in natural germanium and silicon bulk targets (1cm^2 × 20 µm, 25×10^8 n).

2. Reliability concerns for Ge-based electronics

To quantify the impact of atmospheric neutrons on Ge-based electronics and its sensitivity to low energy secondary products, we considered the case of a SRAM memory and the evolution of its critical charge on a large domain of technological nodes, from 180 to 14 nm as shown in Figure 3. The critical charge Q_{crit} is a first-order metric that has been introduced to evaluate the susceptibility for a static memory to be upset from a logical state to the other. It corresponds to the minimum amount of electrical charge that can flip the data bit stored in a memory cell. To deposit such an amount of electrical charge in a given semiconductor material, a secondary product must have a minimum energy $E_{min} = (Q_{crit}/q)\times E_{eh}$ where q is the electron elementary charge and E_{eh} is the average energy for creation of an electron- hole pair (eV). E_{eh} = 3.6 eV in bulk silicon and E_{eh} = 2.9 eV in bulk germanium. Each value of Q_{crit} in Figure 3 can thus be converted into a minimum energy threshold for both Si-based or Ge-based circuits. For a given product of energy E, a "necessary but not sufficient condition" to upset a memory bit is to verify $E > E_{min}$. On this basis, we can evaluate the exact number of interactions capable of producing at least one secondary product satisfying this condition, by post-processing Geant4 datafiles with such a "filter". Results are shown in Figure 4 for both Si and Ge. For the 180 nm technological node characterized by the highest Q_{crit} value, the number of interactions verifying the previous condition is minimal: 53,566 for Si and 50,439 for Ge. On the contrary, for the most advanced node (14 nm), these numbers are much more important, due to the contribution of additional interactions: 76,990 for Si (+43%) and 96,465 for Ge (+91%). These additional interactions produce low energetic secondaries that have been identified to be exclusively recoil nuclei corresponding to elastic and inelastic interactions.

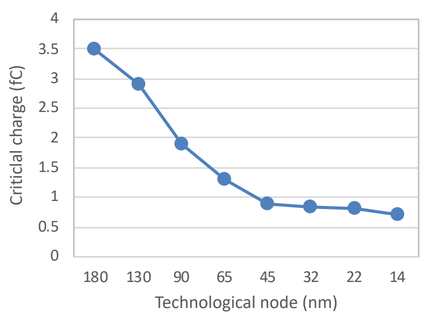

Figure 3. Critical charge versus CMOS technological nodes. After Seiffert [6] and Ni [7].

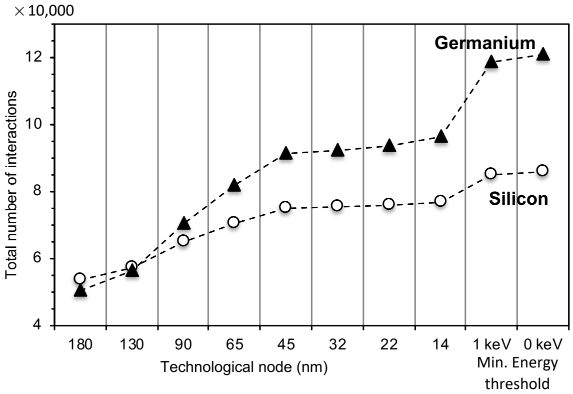

Figure 4. Total number of n-Si or n-Ge interactions that produce at least one secondary product satisfying the condition $E > E_{min}$ determined by Q_{crit} values of Figure 3 for technological nodes ranging from 180 to 14 nm. Two additional values are examined : E_{min} = 1 keV and 0 keV (no product filtering).

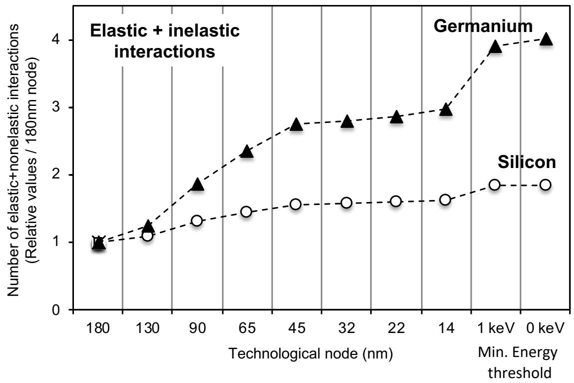

Figure 5. Relative evolution of the total number of elastic+inelastic interactions that produce a recoil nuclei satisfying the condition $E > E_{min}$. Values are normalized with respect to the ones corresponding to the 180 nm node.

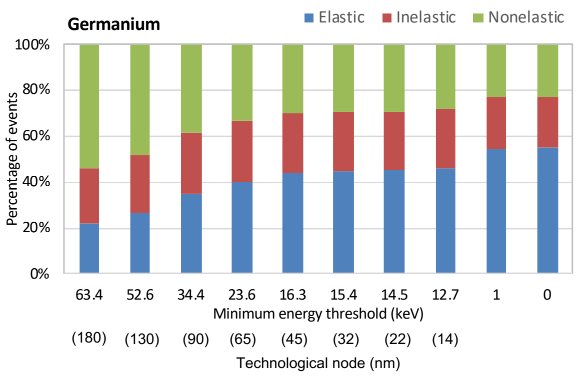

Figure 6. Proportions of elastic, inelastic and nonelastic events calculated for germanium on the basis of interactions that produce a recoil nuclei satisfying the condition $E > E_{min}$.

Figure 5 shows the relative evolution of this total number of elastic+inelastic interactions that produce a recoil nuclei satisfying the condition $E > E_{min}$. Values have been normalized with respect to the ones corresponding to the 180 nm node. These result show that, for Ge, three times more reactions should be counted for the 14 nm node compared to the 180 nm one. For Si, this factor is only 1.6. This additional number of interactions to be considered for the most advanced nodes profoundly modify the proportions of elastic, inelastic and nonelastic events, as illustrated in Figure 6. Elastic events count for only 20% of the total number of events at 180 nm while it represents 40% at 14 nm. Note that results of Figure 6 are in perfect agreement with our previous work in which we adopted a higher energy threshold (59 keV) [1].
In the final paper and in the direct continuation of our ESREF 2019 paper [3], numerical simulations performed on both Si-based and Ge-based generic SRAM cells will reported to quantitatively analyze the impact of such low energy products on the soft-error rate (SER) for these circuits.

In conclusion, the additional contribution of very low energy products induced by atmospheric neutrons when reducing Q_{crit} appears as a new source of particles that expands the variety and spectrum of particles to which a nanometer circuit is sensitive. For ultimate CMOS nodes and in addition to the possible contribution of atmospheric muons and protons [8], very low energy recoils induced by neutrons may have a more or less significant impact of the circuit SER, primarily depending on the nature of the considered semiconductor material. If such an increase is found relatively moderate for silicon (+40%), the impact may be much more important for Ge-based circuits for which our results evidence a possible ×2 increasing factor when considering a scaling reduction from 180 nm to 14 nm nodes. These new results at material level will be declined at circuit level in the final paper.

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