Uranium and Thorium Contribution to Soft Error Rate in Advanced Technologies

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***Abstract*—^{238}U and ^{232}Th and their relative daughters are impurity sources responsible for soft errors induced by alpha particles. In this paper, the contribution of each decay chain to the alpha emission rate is evaluated by assuming that secular equilibrium is reached. We show that for the same concentration of uranium and thorium in secular equilibrium, uranium decay chain has an alpha emission rate (AER) two times higher than the thorium decay chain. Furthermore, the contribution of these two decay chains to the Soft Error Rate (SER) and Multiple Cell Upset (MCU) is calculated for a 90 nm and a 65 nm CMOS technology by Monte Carlo simulations by considering a concentration of thorium 1.33 higher than uranium in secular equilibrium condition, which is representative to measurements found in literature. We show in these conditions that uranium has a contribution to the SER and MCU higher than that of thorium.**

***Index Terms*—Alpha particle, secular equilibrium, soft errors, thorium, uranium.**

I. Introduction

SOFT errors are becoming more problematic for newer technology nodes due to constant reduction of operating voltage. They are spontaneous changes of memory bits from one state to another and they may be produced by sensitivity to natural radiation. There are two major sources of radiation that produce soft errors at ground level [1], [2] . They are atmospheric neutrons and alpha particles. The neutrons at ground level result from interaction of the atmosphere and cosmic rays. Neutrons do not ionize the medium they travel. However, they produce secondary ions that generate electron-hole pairs and create soft errors. The alpha particles lose their energies directly by ionization, thus triggering directly soft errors. For instance, an alpha particle having energy of 3.6 MeV will generate 1 million of electron-holes pairs in Si. If the charge created this way in a sensitive volume is greater than the minimum charge (critical charge) a soft error is produced. Alpha particles result from the natural decay of isotopes called alpha emitters. Previous work established a list of alpha emitters and compared their probabilities to emit an alpha particle with the probabilities for atmospheric neutrons to induce a nuclear reaction [3]. Alpha emitters can be found in electronic devices either in impurity form or as natural isotopes of an element used to manufacture electronic devices (e.g., hafnium in gate oxides) [4], [5] In this paper, we examine radioactive impurities. The common radioactive impurities are ^{238}U and ^{232}Th. These radioactive nuclei are contained naturally in different raw materials (e.g., Si, Cu, acid solutions) used in the manufacturing technology. In our previous work [6], we calculated the Soft Error Rate (SER) of different technologies based on the Alpha particle Emission Rate (AER) of the Si bulk in secular equilibrium condition by assuming that the AER results only from the ^{238}U decay chain. This assumption was made because the contributions of the ^{238}U and ^{232}Th decay chains to the AER were not known. In this paper, we compare the contribution of ^{238}U and ^{232}Th decay chains to the AER, SER and MCU by assuming that secular equilibrium is reached for both decay chains.

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II. Uranium and Thorium Decay Chain

A. Uranium Decay Chain and Thorium Decay Chain

^{238}U (99.3% natural abundance) and ^{232}Th (100%) are one of the main primary sources of soft errors at ground level, present in most materials used in the semiconductor industry as impurities. These radioactive nuclei give several alpha emitting isotopes from their decay chains. The decay chains are shown in Table I for ^{238}U and Table II for ^{232}Th. The grey lines of Tables I and II are isotopes undergoing beta type disintegration. The non colored lines of Tables I and II represent the alpha emitters with their different characteristics.

Among its fourteen radioactive isotopes, the uranium decay chain has eight alpha emitter daughters. They disintegrate and emit alpha particles having energies varying from 4.18 MeV to 7.68 MeV. When the disintegration rate or activity of daughter nuclei in a chain is equal to that of the parent nuclei, a condition called secular equilibrium is reached. For instance, the uranium decay chain needs 3 million years so that secular equilibrium is reached. Table I shows the relative abundance of nuclei required to achieve a secular equilibrium condition. For example for 1 ppt (part per trillion: equivalent to 10^{-12}) of ^{238}U, 8.51×10^{-11} ppt of ^{210}Po is present when secular equilibrium is reached. For the thorium decay chain, ^{232}Th has six alpha emitters with two possible pathways (see Table II).

^{212}Bi undergoes either beta or alpha type decays. The energy of alpha particles emitted from this decay chain is between 4.00 MeV and 8.78 MeV. At this energy an alpha particle can travel about 60 μm in Si. The thorium decay chain has a large range of possible alpha particle energies.

TABLE I
URANIUM DECAY CHAIN.

Isotope	Half life (s)	Mean Energy (MeV)	Relative abundance (secular equilibrium)
^{238}U	1.41E+17	4.18	1,00E+00
^{234}Th	2.08E+06		1,48E-11
^{234}Pa	2.41E+04		1,71E-13
^{234}U	7.73E+12	4.76	5,48E-05
^{230}Th	2.38E+12	4.67	1,69E-05
^{226}Ra	5.05E+10	4.77	3,58E-07
^{222}Rn	3.30E+05	5.49	2,34E-12
^{218}Po	1.83E+02	6.00	1,30E-15
^{214}Pb	1.61E+03		1,14E-14
^{214}Bi	1.18E+03		8,37E-15
^{214}Po	1.64E-04	7.68	1,16E-21
^{210}Pb	7.04E+08		4,99E-09
^{210}Bi	4.33E+05		3,07E-12
^{210}Po	1,20E+07	5.30	8,51E-11

TABLE II
THORIUM DECAY CHAIN.

Isotope	Half life (s)	Mean Energy (MeV)	Relative abundance (secular equilibrium)
^{232}Th	4.39E+17	4.00	1
^{228}Ra			
^{228}Ac			
^{228}Th	6.00E+07	5.40	1.37E-10
^{224}Ra	3.11E+05	5.67	7.08E-13
^{220}Rn	5.45E+01	6.29	1.24E-16
^{216}Po	1.80E-01	6.78	4.10E-19
^{212}Pb	9.69E+03		2.21E-24
		Two CASES	
^{212}Bi	5.63E+03		1.28E-14
^{212}Po	3.00E-07	8.78	6.83E-25
		OR	
^{212}Bi	9.84E+03	6.32	2.24E-14
^{208}Ti	1.01E+04		2.30E-14

B. Secular Equilibrium Discussion

Any microelectronic material cannot be on secular equilibrium since it undergoes many modifications in order to obtain a semiconductor grade material from raw materials. Raw materials experience extensive industrial processes (e.g., melting, vaporization) which modify the concentration of different isotopes of a given decay chain leading to disequilibrium. Consequently, these processes may increase the disintegration rate of materials leading to AER raise.

However, work [7] showed that for moderate, low and ultra low alpha materials refining has a minimal effect on secular equilibrium existing prior to refining. Though, this work showed that secular equilibrium is not affected after purification, it explains that due to the uncertainty in AER measurement for low activity materials, the alpha emissivity could be the result of decays of one or more alpha emitting species.

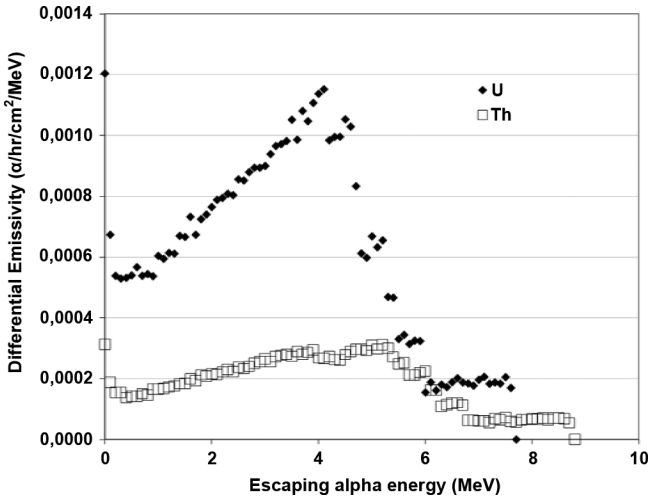

Fig. 1. Simulated emissivity spectrum of a silicon volume contaminated by the 1 ppb of uranium and 1 ppb thorium decay chain in secular equilibrium.

By assuming that secular equilibrium is not disturbed by refining and the AER is due to overall alpha emitting species in decay chains in equilibrium, we discuss about the contribution of the two decay chains to AER and SER in secular equilibrium condition.

III. URANIUM AND THORIUM DECAY CHAIN CONTRIBUTION TO AER

The aim of this section is to compare the effect of 1 ppb of ^{238}U and 1 ppb ^{232}Th in secular equilibrium with their respective daughters. For that, a Monte Carlo based tool named MC-ORACLE [8] is used. In order to compare these two decay chains, a silicon cube with side length of $100\ \mu$m is studied. In this volume, all radioactive nuclei of the two decay chains are uniformly distributed. The concentrations of radioactive nuclei incorporated in the cube, are taken from Tables I and II indicating the relative abundance in secular equilibrium. Subsequently, the number of alpha particles escaping from the silicon volume is counted as a function of their energies. According to Fig. 1, alpha particles escape the layer with energies up to ~ 8 MeV for the uranium decay chain and ~ 9 MeV for the thorium decay chain. The emissivity due to uranium is seen to be higher than that for thorium. At approximately 4 MeV, the emissivity of the uranium chain is about four times higher than that of thorium chain in secular equilibrium condition for the same concentration. The two decay chains have their own peak in terms of the number of alpha particles escaping the Si volume. For the uranium chain, the peak is localized at the 4 MeV. Moreover, for the thorium decay chain, two peaks are situated at approximately 4 MeV and 5 MeV. Alpha particles escaping the Si volume with these energies are more frequent. Moreover, Fig. 2 displays the cumulative emissivities seen in Fig. 1. According to Fig. 2, by considering a threshold energy of 2 MeV for the detection, the contribution of the uranium decay chain is two

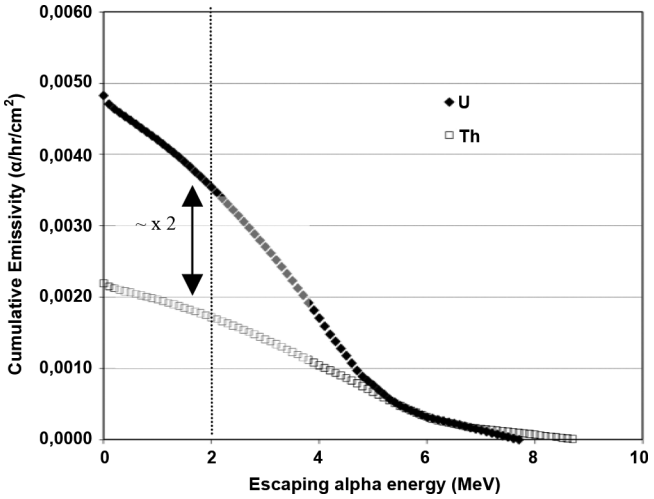

Fig. 2. Simulated cumulative emissivity spectrum of a silicon layer contaminated by the 1 ppb of uranium and 1 ppb thorium decay chain in secular equilibrium.

times higher than that of the thorium in secular equilibrium condition. At approximately 4 MeV, the emissivity of the uranium chain is about four times higher than that of thorium chain in secular equilibrium condition for the same concentration. The two decay chains have their own peak in terms of the number of alpha particles escaping the Si volume. For the uranium chain, the peak is localized at the 4 MeV. Moreover, for the thorium decay chain, two peaks are situated at approximately 4 MeV and 5 MeV. Alpha particles escaping the Si volume with these energies are more frequent. Moreover, Fig. 2 displays the cumulative emissivities seen in Fig. 1. According to Fig. 2, by considering a threshold energy of 2 MeV for the detection, the contribution of the uranium decay chain is two times higher than that of the thorium in secular equilibrium condition.

Thus, for a given concentration of impurities, uranium has a higher emissivity than that of thorium in secular equilibrium, which gives a first crucial result: considering that alpha particles are only due to uranium represents a worst case which can be used to have an order of magnitude of the Soft Error Rate in secular equilibrium condition. However, in some cases, it is possible to have information on the abundances of uranium and thorium in microelectronic materials. In the next section we will provide data on the ratio of ^{232}Th to ^{238}U in different microelectronic materials.

IV. Concentration Ratio of ^{232}Th and ^{238}U in Materials Used for Electronic Devices

Based on previous works [7], [9]–[13] we evaluated the concentration ratios of ^{232}Th to ^{238}U for different materials used in the microelectronic industry. The ratios are presented in Table III. According to this table, the evaluated ratios are not always constant for these materials. This is due to the fact that the raw materials used to get semiconductor grade materials may come from different places of the world. Uranium and thorium concentrations in raw materials vary from place to place in the world. This means that the contamination level of electronic materials is different from vendor to vendor and

TABLE III
Uranium and Thorium Ratio in Some Common Materials.

Material	Ratio (^{232}Th/^{238}U) concentration	Work
Al (6N) 17 years old	0,30	[13]
Al (5N) sample 12	0,50	[13]
Al (5N) sample 10	0,10	[13]
Evaporated Al film sample J3	2,00	[13]
Evaporated Al film sample F	1,00	[13]
Wafers	1,33	[13]
Al_2O_3	0,53	[11]
Al_2O_3	0,24	[12]
Al_2O_3	0,04	[14]
AlN	0,13	[11]
Al (5N)	1,15	[12]
Purified Al (5N)	1.5	[10]
High Purity Silica	0.02	[9]
High Purity Alumina	2	[9]

from manufacturer to manufacturer. In this paper, we focus only on these concentration ratios which have been done so far. In Section III, we showed that, for the same level of contamination, the contribution to AER is approximately two times higher for ^{238}U than for ^{232}Th above 2 MeV (in secular equilibrium). According to Table III, the literature reports concentration ratio of ^{232}Th to ^{238}U lower than two, with a maximum of two which is the worst case. In this case, the contribution of each decay chain to AER is equal in secular equilibrium. According to Table III, ^{238}U is more abundant in the materials used in electronic devices. Because of its abundance in electronic materials, ^{238}U (and its daughters) is the dominant source of alpha particles and alpha particle-induced soft errors in secular equilibrium condition. However, we have to note this statement is based on the measurement published so far.

V. Evaluation of ^{238}U and ^{232}Th Contamination Level in a Wafer

In our previous work [15], we have determined the equivalent ^{238}U concentration, in the secular equilibrium condition, of a wafer having an emissivity of 4×10^{-4} $\alpha/(\mathrm{cm}^2 - \mathrm{hr})$. Assuming that only alpha particles with energy higher than 2 MeV are detected, the evaluation showed that 90 ppt of ^{238}U is required to give an emissivity of 4×10^{-4} $\alpha/(\mathrm{cm}^2 - \mathrm{hr})$. Based on recent MC-ORACLE simulations this value is actually updated

to 110 ppt, which is quite comparable. However, the work considered only the uranium decay chain. In this section, we considered both decay chains in order to determine the equivalent concentration of ^{238}U and ^{232}Th in a wafer having an emissivity of 4×10^{-4} $\alpha/(\text{cm}^2 - \text{hr})$ in secular equilibrium. For that, we took into account the concentration ratio of ^{232}Th to ^{238}U which is about 1.33 in a wafer (see Table III) and compared the emissivity spectrum of 1 ppb of ^{238}U and 1.33 ppb of ^{232}Th. Based on MC-Oracle simulations, the silicon wafer emissivity due to 1 ppb of ^{238}U and its decay chain (at secular equilibrium) is 3.54×10^{-3} $\alpha/(\text{cm}^2 - \text{hr})$. For 1.33 ppb of ^{232}Th and its decay chain, the emissivity is 1.29×10^{-3} $\alpha/(\text{cm}^2 - \text{hr})$.

Consequently, we found out, at secular equilibrium 76 ppt of ^{238}U and 101 ppt of ^{232}Th are responsible for an AER of 4×10^{-4} $\alpha/(\text{cm}^2 - \text{hr})$ in a Si wafer. As the contamination level varies depending on the source of the raw material, this evaluation of the contamination level of both uranium and thorium is not constant. It can be assumed as an evaluation for one vendor or manufacturer. It may vary from vendor of materials or manufacturer depending on the geographical localization of raw materials.

VI. Contribution of Uranium and Thorium Decay Chains to SER and MCU

Previous sections showed that the most dominant source of AER is ^{238}U and that the contribution of this isotope (and its relative daughters) in secular equilibrium to AER is two times higher than ^{232}Th for energies of alpha particle above 2 MeV. Since uranium's emissivity is higher than the thorium's for the same concentration in secular equilibrium, we expect a higher SER for uranium than for thorium in secular equilibrium and for the same concentration. However, the alpha energies are different for the two decay families (see Fig. 1). In order to quantify their associated SER, we performed Monte Carlo simulations.

The simulations compare the SER and the MCU due to 1 ppb of ^{238}U and 1 ppb ^{232}Th in secular equilibrium with their respective daughter nuclei in 90 nm and 65 nm technology node.

A. Simulated Structures

The simulation structures are generated by MC-ORACLE [8] and represented in Fig. 3. We considered a Si bulk of 60 μm since this value represents the maximum distance that an alpha particle having energy of 9 MeV can travel in Si [16]. In the upper region of Si 100×100 sensitive volumes of a 65 nm and 90 nm technology nodes are found (see Fig. 3). The characteristics of the sensitive volumes are reported in Table IV. By assuming that silicon dioxide (SiO_2) represents the metallization and dielectric layers of the technologies nodes studied, we considered a SiO_2 film having a thickness of 8 μm on the Si layer (see Fig. 3). The dots in Fig. 3 represent the origin of alpha particles striking sensitive zones.

1) Assumptions and Simulations Parameters: The simulations realized are placed in a secular equilibrium case. This means that daughter nuclei concentrations (concentration equivalent to one ppb of ^{238}U and to one ppb ^{232}Th) corresponding to secular equilibrium are incorporated in the Si and SiO_2 volumes (see Tables I and II). The radioactive elements are uniformly distributed in these volumes. In order to evaluate the SER and the MCU, we used simulations parameters for a 65 nm and 90 nm technology node indicated in Table IV.

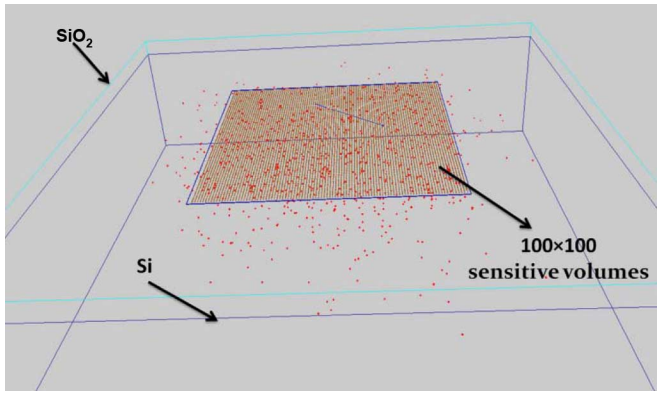

Fig. 3. Simulated structures for a 90 nm and 65 nm.

TABLE IV
Parameters Used for Simulations [17].

Gate length (nm)	Sensitive volume (μm^3)	Critical charge (fC)
90	0.0100	1.2
65	0.0035	0.8

The Rectangular Parallelepided (RPP) criterion [18] has been used to evaluate the alpha SER and the MCU of a 90 nm and 65 nm technology.

B. Results and Discussion for SER

By incorporating 1 ppb of ^{238}U and ^{232}Th in the structures (Si and SiO_2) and by simulating a great number of disintegrations in the structures, the SER is calculated for each decay chain as a function of the critical charge of a technology. After the disintegrations, the emitted alpha particles lose their energy by ionization and generate charge. If the charge generated is more than the critical charge, an SEU (Single Event Upset) is triggered. The volume of the sensitive volumes is taken from Table IV. Figs. 4 and 5 show, respectively for 90 nm and 6 -nm technology nodes, the SER due to the uranium and thorium decay chains as functions of the critical charge in secular equilibrium and for the same concentration. According to Figs. 4 and 5, 1 ppb of ^{238}U produces more soft errors than 1 ppb of ^{232}Th in the secular equilibrium condition for both technologies. Results show, for any critical charge variations of a technology, the contribution ratio of each decay chain to SER is quite constant. The distance separating the two curves representing the contribution of each decay chain is the same for any critical charge.

Therefore, the uranium decay chain plays a major role in determining the SER in secular equilibrium. The SER ratio of the uranium decay chain to the thorium decay chain is approximately 3.5 for a 65-nm technology with a critical charge of 0.8 fC and for a 90-nm technology with a critical charge of 1.2 in secular equilibrium condition.

C. Data Calibration for the 65 nm Technology Node

In this section, we assume that the SiO_2 (interconnect) layer has the same emissivity as the Si wafer (bulk). Since 4×10^{-4} $\alpha/(\text{cm}^2 - \text{hr})$ is due to 78 ppt of ^{238}U and 101

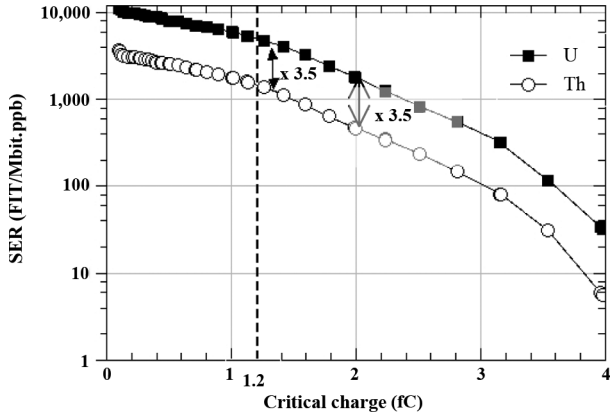

Fig. 4. SER for uranium and thorium decay chains as a function of critical charge for a 90 nm technology node.

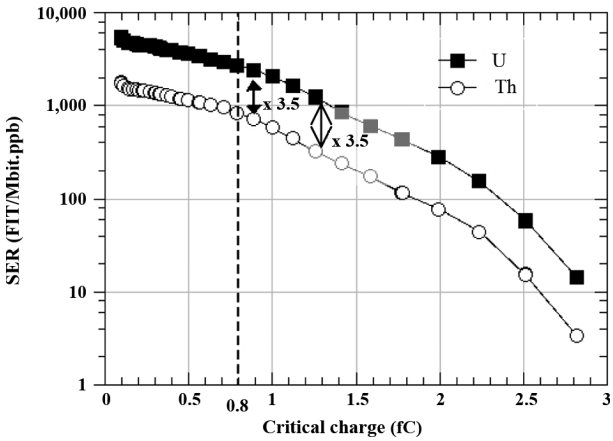

Fig. 5. SER for uranium and thorium decay chains as a function of critical charge for a 65 nm technology node.

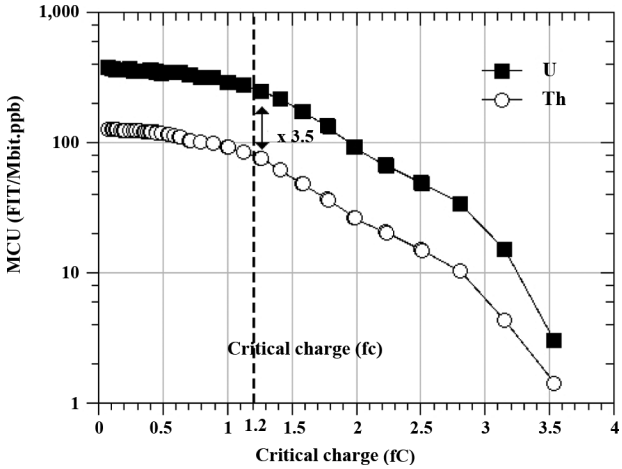

Fig. 6. MCU rate for uranium and thorium decay chains as a function of critical charge for a 90 nm technology node.

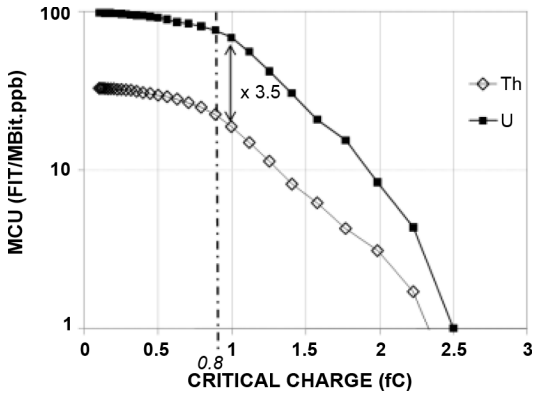

Fig. 7. MCU rate for uranium and thorium decay chains as a function of critical charge for a 65 nm technology node.

ppt of ^{232}Th (see Section V), we evaluated the SER level of a 65 nm technology node having a critical charge of 0.8 fC using Fig. 5. On Fig. 5, by drawing a line for the critical charge of interest, here 0.8 fC, we found two interception points for the uranium and thorium curves. Then with these points of uranium and thorium, we took the SER expressed in FIT/Mbit.ppb and evaluated these points' SER by using 78 ppt of ^{238}U and ^{232}Th ppt of thorium. The SER evaluated this way for these contamination levels is 290 FIT/Mbit in secular equilibrium. The SER induced by alpha particles of a 65 nm device from experimental measurements has been determined in [19] The technology studied has an emissivity of $(0.9 \pm 0.3) \times 10^{-3}\ \alpha/(\mathrm{cm}^2 - \mathrm{hr})$ and the same critical charge and sensitive volumes as shown in Table IV. The measured SER is 674 Fit/Mbit. This value compared to our evaluated SER of 290 FIT/Mbit indicates obtained discrepancy with a factor of around 2. The difference is partly due to the bad knowledge of the real concentration of impurities (for the considered device) and also to the fact that packaging materials are not taken into account in this paper. Moreover, for the same technology it has been shown that the bulk and the interconnect system contribute approximately 60% of the total SER induced by alpha particles in [6]. Furthermore in this same work, we evaluated the SER by Monte Carlo based simulations. We found out a SER of 326 FIT/Mbit for the Si and SiO_2. However, ^{238}U was only considered in the materials. Therefore, we can conclude that the SER evaluated in this paper is consistent with different values obtained in different works.

D. Results and Discussion for MCU

Figs. 6 and 7 show the MCU rate due to the uranium and thorium decay chains as a function of the critical charge and for 1 ppb of ^{238}U and for 1 ppb of ^{232}Th in secular equilibrium with their daughter's nuclei respectively for the 90 nm and 65 nm node.

Figs. 6 and 7 show that the ratio of contribution of the uranium and thorium decay chains to MCU is 3.5 as for the SER for a 65 nm and 90 nm technology node. Therefore, the uranium decay chain is the principal source of MCU in secular equilibrium.

VII. Conclusion

The main sources of alpha particles inducing soft errors are two decay chains: the uranium (^{238}U) and the thorium (^{232}Th) decay chains. In this paper, we studied the contribution of each decay chain to the AER, SER and MCU for two technologies in secular equilibrium condition. We have shown that 1 ppb of ^{238}U contributes 2 times higher than 1 ppb ^{232}Th in terms of alpha emissivity in secular equilibrium condition. This indicates

the importance of the uranium decay chain for the emission of alpha particle in secular equilibrium condition. Regarding [13] a typical ratio of contamination of a Si wafer $^{232}\mathrm{Th}/^{238}\mathrm{U}$ is 1.33. Therefore, the equivalent contamination of a wafer having a emissivity of $4 \times 10^{-4}\ \alpha/(\mathrm{cm}^2 - \mathrm{hr})$, in the secular equilibrium assumption, corresponds to concentrations of 76 ppt for $^{238}\mathrm{U}$ and 101 ppt for $^{232}\mathrm{Th}$. Monte Carlo simulations were performed in order to evaluate the SER and MCU for a 90 nm and 65 nm CMOS technology in secular equilibrium. Based on this condition, we showed that the SEU and MCU rates due to 1 ppb of $^{238}\mathrm{U}$ are 3.5 times greater than 1 ppb of $^{232}\mathrm{Th}$ in the secular equilibrium. However, secular equilibrium can be upset by refining raw materials. This can lead in some cases to alpha emitters enrichment in the uranium and thorium decay chains resulting in an increase of the AER and SER. In the future, we shall consider disequilibrium of the decay chain in order to evaluate which decay chain plays an important role in AER, SER and MCU in advanced technologies. However, information on this disequilibrium is extremely difficult to obtain and complementary measurements should probably be performed.

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