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Natural radioactivity consideration for high- κ dielectrics and metal gates choice in nanoelectronic devices

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Abstract. In order to face downscaling, new chemical elements are used and suggested for the semiconductor industry. However, some of these elements have natural radioactive isotopes, which may cause reliability issues in nanoelectronic devices by triggering soft errors. In this paper, we focus on high- κ dielectric materials and metal gates. We show that beside physical, chemical and mechanical properties of high- κ dielectrics and metal gates, natural radioactivity is also a crucial property to be considered in order to select suitable materials. Using samarium in gate oxides and platinum in electrodes turns out to be a crucial issue for ground level applications.

Alpha emitting nuclei, Soft Errors, High- κ dielectrics, Metal gates

1. Introduction

Alpha particles are the major reliability issues in electronic devices causing soft errors at ground level [1]. They are emitted from natural disintegrations of radioactive nuclei called alpha-emitters. Once emitted, alpha particles lose their energy by ionizing atoms of the medium in which they travel, resulting in charges generation, which are then collected by sensitive nodes. The collected charge may induce a soft error by changing a bit from the state "1" to the state "0" or vice versa [2]. Sources of soft errors induced by alpha particles are classified into two categories. The first source corresponds to common impurities (^{238}U , ^{232}Th and their relative daughters) that are naturally present in refined materials or incorporated in devices during their processing (e.g. residual left behind etching with acid solutions). On the other hand, the second source corresponds to elements used in devices, naturally containing an amount of isotopes emitting alpha particles. These elements are introduced in the semiconductor industry in order to face the scaling of electronic devices ignoring sometimes their ability to emit alpha particles (e.g. HfO_2 as high- κ dielectric containing ^{174}Hf , which is a natural alpha emitting isotope (see Table 1). This paper focuses on materials used and suggested for present and future nodes, containing alpha emitting isotopes. We evaluated the materials contribution to Soft Error Rate (SER) in order to evaluate their risk.

Table 1. List of radioactive isotopes contained in new elements used or suggested for the semiconductor industry [3].

Alpha emitter isotopes	Half life (years)	Natural abundance(%)
^{174}Hf	2.0×10^{15}	0.162
^{152}Gd	1.08×10^{14}	0.20
^{144}Nd	2.29×10^{15}	23.8
^{148}Sm	7.0×10^{15}	11.3
^{147}Sm	1.06×10^{11}	15.0
^{190}Pt	6.5×10^{11}	0.01

2. New chemical elements for gates oxides and metal electrodes

Scaling of gate oxides made that recent technologies nodes have an oxide thickness around 10 Å. At this range, quantum tunneling leads to unacceptable leakage current and unexpected values of key parameters affecting device operations. Thus, it appears likely that dielectrics other than SiO_2 are required for new CMOS technologies. Solutions to this problem suggest employing high- κ materials for gate oxides [4]. High- κ insulators are materials with higher permittivity, which means they are sufficiently thicker preventing quantum tunneling. For example, hafnium based oxides has attracted much attention for the last decade. As a result, Intel integrated these oxides in its 45 nm MOS devices [5]. Even though the approval, hafnium based gate oxides

represents disadvantages in terms of thermodynamically stability [6, 7, 8]. Hence, investigations on attractive high- κ dielectrics, suggested rare earth based oxides as future gate dielectrics [9-19]. Among these potential rare earth based gate dielectrics, Gd_2O_3 [12, 13, 14], GdScO_3 [15, 16, 17], SmScO_3 [18], and Nd_2O_3 [19] have been suggested as favorite candidates for future MOS technologies. Moreover, traditional poly-silicon gate electrodes do not satisfy the desired requirements because of the poly-silicon depletion effect (boron penetration in Si) [4]. To overcome this problem, fully silicided (FUSI) and fully germinide (FUGE) metal electrodes have been developed due to their CMOS compatibility [20]. An alloy of nickel and platinum (Ni/Pt) [20, 22], PtSi [23], and Pt_3Ge_2 [24] are proposed as gate electrodes for P-MOSFETs. On the other hand, by alloying nickel and gadolinium, Ni(70)Gd(30) has been proposed as metal electrode for N-MOSFETs [25]. These propositions for both gate oxides and metal electrodes rely only on physical, chemical properties and process compatibility, but the radioactivity aspect of the new chemical elements have not been touched on.

3. Alpha Particle induced Soft Error Rate calculation

Gadolinium (Gd), samarium (Sm), neodymium (Nd), and platinum (Pt) have natural alpha emitter isotopes (see Table 1). If introduced in devices, they may induce soft errors. A 32 nm half-pitch gate stack of a high performance logic technology is here considered in order to evaluate the Soft Error Rate (SER) of these materials. It has a gate oxide that has an equivalent oxide thickness (EOT) of 9 Å EOT. The volume of the gate oxide is $18 \text{ nm} \times 90 \text{ nm} \times 9 \text{ Å}$ (EOT). The volume of the metal electrode is $18 \text{ nm} \times 90 \text{ nm} \times 26 \text{ nm}$. The dimensions of the volumes are taken from ITRS [26]. The main gate dielectrics studied in this paper are HfO_2 , GdScO_3 , Gd_2O_3 , SmScO_3 , Nd_2O_3 and the main metal electrodes studied are PtSi, Pt_3Ge_2 and the alloy of (nickel/gadolinium) Ni(70)Gd(30).

All these oxides have a dielectric constant between 10 and 25. In this paper, an average dielectric constant of 20 is taken in order to estimate the order of magnitude of the gate oxide thickness. Using equation (1), the thickness of the high- κ insulator required to form a gate oxide of 9 Å EOT is 46 Å.

$$t_{ox} = t_{eq} \times \frac{k_x}{k_{\text{SiO}_2}} [12]. \quad (1)$$

Where, t_{eq} , and t_{ox} are the thicknesses of the equivalent oxide and the high- κ dielectric respectively. k_x and k_{SiO_2} are dielectric constants of the high- κ dielectric, and SiO_2 , respectively. Hence, the volume of the gate dielectric is then $7,452 \text{ nm}^3$ and that of the metal electrode is $42,120 \text{ nm}^3$. By using the basic molar mass calculation, we developed equation 2 which determines the number of radioactive atoms N_0 present in these volumes.

$$N_0 = \frac{\rho V}{M} \times N_A \times \frac{a}{100} \times n. \quad (2)$$

Where ρ is the density of the compound, V and M are the volume and the molar mass, respectively, of the gate oxide or the metal electrode. N_A is the Avogadro number, a and n are the percentage of natural abundance and the number of radioactive atoms in the molecule, respectively. Using equation (2), a 32 nm half-pitch gate made by HfO_2 contains 334 atoms of ^{174}Hf , which are alpha emitters. A unit SRAM memory cell contains six MOSFETs (Metal Oxide Semiconductor Field Effect Transistor). In this paper, we take a 6T SRAM, thus the cell is made of six gate oxides. Assuming that the entire six transistors have the same size, a 1 MBit memory cell encloses 2.01×10^9 atoms of radioactive ^{174}Hf . The number of disintegrations involved by these radioactive atoms is obtained by using the exponential radioactive decay law (3).

$$N = N_0(1 - e^{-\lambda T}). \quad (3)$$

Where N , N_0 , and λ are the number of emitted alpha particles, the above calculated radioactive atoms, and the decay constant respectively. T is defined as 10^9 hours so that results can be directly compared to Failure in Time (FIT), which represents the number of failures during 1 billion hours. Thus, a 1 MBit memory cell, made of HfO_2 gates, undergoes 0.08 disintegrations/MBit/ 10^9 hours. Supposing that, in the worst case, every emitted alpha particle gives rise to a soft error, a one MBit SRAM memory made by HfO_2 has a failure rate of 0.08 FIT/MBit. This evaluation is consistent according to [21]. Note that this failure rate only concerns failures caused by alpha particles emitted from the gate oxide. The value of 0.08 FIT/Mbit has to be compared with the acceptable SER. From the ITRS road map [22], the targeted SER is between 1000 and 2000 FIT/MBit for 32 nm based SRAM memories. Consequently, a one MBit SRAM memory cell has a very low SER induced by the HfO_2 gates. Therefore, Hf based gate oxides cannot be a concern for device failures induced by alpha particles. Using the same reasoning, table 2 summarizes the failure rate caused by each material containing alpha emitters. GdScO_3 , Gd_2O_3 and Nd_2O_3 as gate oxides in the worst case, lead respectively to only 3.3, 4.8, and 9.6 FIT/MBit respectively. In comparison to the targeted SER, we conclude that gate oxides made of gadolinium and neodymium based compounds should not be a problem (in terms of soft error induced by alpha particles), even though the latter are alpha emitters.

The case of samarium (used in SmScO_3) is different. Results show that a 1 MBit SRAM memory cell using Sm based gate dielectrics can have, in the worst case, a rate of 7.9×10^3 FIT/MBit. This high rate is explained by a high disintegration rate in comparison to ^{147}Sm , because it has a shorter half-life than ^{148}Sm . Hence, Sm based materials may lead to an unacceptable level of SER. However, this evaluation remains in the worst case. In fact, not all disintegrations result in soft errors. In order to estimate definitely the influence on SER, a Monte Carlo based simulations would have to be performed on the device of interest.

For metal electrodes, the SER is calculated by assuming that the 6T SRAM memory is composed of two N-MOSFETs and two P-MOSFETs to store data and two N-

Table 2. Summary of SER of different compounds studied

Compound	Used as	SER (FIT/MBit)
HfO ₂	Gate Oxide	0.08
GdScO ₃	Gate Oxide	3.3
Gd ₂ O ₃	Gate Oxide	4.8
Nd ₂ O ₃	Gate Oxide	9.6
SmScO ₃	Gate Oxide	7.9×10^3
PtSi	P-MOSFET metal electrode	34.2
Pt ₃ Ge ₂	P-MOSFET metal electrode	38.0
Ni ₇₀ Gd ₃₀	N-MOSFET metal electrode	6.5

MOSFETs access transistors. For metal electrodes composed of Ni(70)Gd(30), the SER is negligible (6.5 FIT/MBit). This type of electrode should not be a problem in SRAMs. Metal electrodes of P-MOSFETs, PtSi and Pt₃Ge₂, give 34.2 FIT/MBit and 38.0 FIT/MBit, respectively. These values may appear lower than the recommendations of ITRS but they are not negligible since metal electrodes are near sensitive zones. The contribution of P-MOSFETs to SER is higher than the N-MOSFETs, this is due to platinum high disintegration rate. Whereas, the N-MOSFET composed of gadolinium will result in a low alpha particle emission rate because gadolinium has a low disintegration rate. We have to note if platinum is used in N-MOSFETs, the SER level will increase.

4. Conclusion

To summarize, we have evaluated the SER in the worst-case approach. Gd, Hf, and Nd based materials do not play a major role in triggering soft errors. This is due to their high half-life resulting in a low disintegration rate. These elements may be used in gate oxides without taking account their contributions to soft errors. Conclusion must be, however revised, if the quantity of these atoms based materials introduced in devices is significantly increased. In literature, samarium is suggested to be used in gate oxide compound (SmScO₃)[18]. However, in the worst-case calculation, we show a very high contribution to SER. Hence, we do not recommend using this material in nano-electronic devices. However, if its introduction in devices is essential, its contribution to SER must be first evaluated precisely (e.g. Monte Carlo method). Otherwise, samarium isotopes especially ¹⁴⁷Sm must be purified from the samarium based material. Separating samarium isotopes can be achieved by chemical means either by crown ether [27] or by acetate/amalgam separation system [28]. Finally, as far as platinum is used, it is also a potential source of soft errors induced by alpha particle. Even if its activity is much lower than that of samarium, its contribution to soft errors must be taken into account because of its proximity with the sensitive zones.

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