Single-event Latchup sensitivity: Temperature effects and the role of collected charge

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Abstract - Single-Event Latchup (SEL) concerns CMOS technology as a major reliability issue and it is influenced by different parameters. In this work, the effect of the temperature variation on SEL has been investigated and its effect has been analyzed combining the variation of three parameters related to the geometry and to the design of the component: doping profile, anode to cathode spacing (A-C spacing) and substrate and well taps placement. Moreover, charge collected has been analyzed. The goal was to verify if the concept of critical charge can be used also for SEL. 2D TCAD simulations have been performed, using an NPNP structure based on 65nm CMOS inverter. From these simulations, we have analyzed threshold LET and SEL rate. Results show that temperature impact is stronger when the component is less sensitive to SEL. Moreover, charge collected can be used for SEL, but more investigations need to be performed.

Index Terms – Single-Event Latchup, TCAD simulations, Cross section.

I. INTRODUCTION

SINGLE-Event Latchup (SEL) is a serious reliability concern for CMOS devices. It arises from parasitic bipolar transistors that are structurally intrinsic to this technology [1]–[4]. Temperature is one of the most important parameters that influences SEL sensitivity. Literature results showed that it has an impact on Single-Event Latchup cross section, which is dependent on the range of temperature considered [5]–[7]. Nonetheless, SEL sensitivity is influenced by a combination of numerous factors. In fact, component design must be considered to determine the probability of Single-Event Latchup in a device. Different studies have been performed in which other factors are considered. For instance, doping profile, substrate and well taps placement and anode to cathode spacing have been investigated in the literature, revealing that SEL sensitivity depends on them [8]–[16].

However, it is also interesting to analyze the behavior of cross section when these factors are combined. In our work, TCAD simulations have been performed to assess their impact. Firstly, we have analyzed the effect of the variation of the design parameters (doping profile, substrate and well taps placement and anode to cathode spacing) on SEL sensitivity. Then, we have investigated, considering a specific range of temperatures, what is the role of temperature on SEL sensitivity

when other parameters are modified. In order to achieve our goal, we have calculated SEL cross sections, following a 2D approach. As a result, more detailed information on the device SEL sensitivity are available. In fact, those curves have been crucial to estimate the in-orbit SEL rate for Geostationary Earth Orbit (GEO).

Furthermore, TCAD simulators allow to calculate the quantity of charge released in the device and the charge that is collected in the sensitive nodes of the structures. As for others Single Event Effects (for instance, Single Event Upset, Single Event Transient), the charge collected in specific nodes can be an indicator of SEE sensitivity. Generally, the collected charge at the node level may lead to errors in the [17]. Even for SEL, if the charge collected is enough to change the state of the structure, a SEL can occur [18]. This aspect has been investigated in the second part of this paper, by using the results from the previous simulations.

The structure of the paper is the following: in Section II we explain the methodology used and in Section III how we performed TCAD simulations, how we calculated SEL cross section curves and how we calculated the charge collected. In Section IV results are presented and discussed, and finally Section V includes our conclusions.

II. METHODOLOGY

As aforementioned, we have considered three parameters: the doping profile of the whole structure, well and substrate taps placement and anode to cathode spacing (A-C spacing). Each parameter has been evaluated for a set of values and for a range of temperatures. Then, cross section has been calculated for every case. In order to achieve our goal, we have performed 2D TCAD simulations. Despite the three-dimensional nature of the SEL mechanism, it has been demonstrated that 3D simulations follow the same trend as in 2D simulations [9], [19].

Thus, considering that we are interested in the trend of cross section, we have chosen to perform 2D simulations using Sentaurus Synopsys tool. TCAD simulations have been extensively used in the literature and thanks to them, it is possible to investigate mechanism of SEL by providing an insight view of the device. Due to the well-developed physical models available in TCAD tools, it is also possible to retrieve data that are useful to calculate parameters that are strictly related to radiation sensitivity, like cross section.

Here, we focused our analysis on the effects of temperature for A-C spacing, doping profiles variation and substrate and well taps placement. The aim is to verify to what extent SEL sensitivity dependence on each parameter is influenced by the

Fig. 1. Simplified NPN structure used in our work. A-C spacing is depicted and substrate and well taps distance is depicted.

temperature variation. Additionally, we have calculated cross-section curves from 2D simulations and from them we have estimated SEL rate. In this way, we have analyzed the sensitivity of the device for the whole linear energy transfer (LET) range and not only in term of threshold LET. Hence, when specific parameters are selected for a design, these results can indicate if temperature variation will strongly modify the behavior of SEL sensitivity.

III. TCAD SIMULATIONS

A. Device structure and simulation setup

The first step was to design a CMOS inverter using design data for a commercially available bulk 65nm technology with Cadence Virtuoso. Based on the physical layout of the minimum-sized inverter, an NPNP structure (Fig. 1) has been retrieved. This structure is formed by the PMOS and the NMOS source and it was chosen because it is the basic structure required to investigate SEL mechanisms [1].

Firstly, we have chosen the range of temperature to use in the simulations. Temperatures of 350 K, 375 K, 400 K and 425 K have been chosen. As we have mentioned before, SEL is more likely at higher temperature, so we have chosen a set of temperature in which it was more likely to obtain Single-Event Latchup. Secondly, we have chosen five values for each parameter to explore a broad range of possibilities. Thus, for substrate and well taps placement we considered their distance and we have chosen 1.05, 1.25, 1.55, 1.85 and 2.15 μm by moving taps symmetrically further from the center, where 1.25 is the nominal value. Doping profile of the whole structure has been modified by multiplying a reference value, based on a commercial bulk 65nm process, times 0.75, 0.85, 1.15 and 1.25. Its value was changed across the whole structure. Eventually, these five values have been chosen for A-C spacing: 0.25, 0.27, 0.32, 0.37 and 0.40 μm , where 0.32 is the nominal value.

In order to perform simulations on Sentaurus Synopsys we needed to choose physical models. We have chosen proper models for a 65 nm technology and they have been based on previous literature [7], [20], [21]. The hydrodynamic model has been chosen along with Fermi statistics as carrier transport model. The mobility was modelled with the built-in model by Arora [22], which is a doping and temperature dependent model. For recombination, the doping dependent Shockley-

Fig. 2. P+ diffusion currents for sustained latchup current (red) and non-sustaining current for different LET values.

Read-Hall, Auger recombination and avalanche generation have been chosen. Finally, bandgap narrowing for high doped region has been selected.

Ion track has been generated through the built-in tool on Sentaurus Synopsys. A range of 2.3 μm in order to cover the entire structure with a constant linear energy transfer has been selected. The radial distribution has been set with a Gaussian profile with a 50 nm radius, after works [10], [21].

B. Cross section calculation

In order to calculate cross section, we followed the approach as reported in [23]. To perform this step, it is necessary to find the threshold LET for different positions along the device. It means that the LET value at which a steady current is obtained at the P+ diffusion has to be found (that we call it “minimum LET”). As an example, in Fig. 2, P+ diffusion currents are shown when SEL is triggered and when it is not. Then, the desired LET value is registered and after all these values are collected, a chart is created, as the one in Fig. 3. From this chart, it is then possible to calculate for any LET value, in a range between 2 and 250 $\text{MeV cm}^2/\text{mg}$, which portion (that we call “sensitive zone”) of the device is sensitive to Single-Event Latchup for that value of LET.

By multiplying the sensitive zone by the width of the component, the cross section is calculated. The width is in the order of magnitude of μm . An example of SEL cross section curve is shown in Fig. 4. In this figure, it is shown the SEL cross section for four different temperature versus the LET.

C. Charge collection calculation

Charge collection is calculated at the source terminal. We have chosen the source terminal, as it is used in SPICE simulations, in order to obtain SEL in a circuit [21]. As aforementioned, the threshold LET has been calculated for each chosen position. In order to calculate the threshold LET, we have performed simulations, for each position, by increasing the LET by a 1 $\text{MeV cm}^2/\text{mg}$ step. Once the SEL occurs, we have retrieved the current at source terminal at the threshold LET and at the previous LET value in which SEL does not occur (that we called “NO SEL”).

Eventually, the charge collected is calculated by integrating the current over time. The time interval has been chosen with two

Fig. 3. Minimum LET value to trigger SEL versus position along the component.

different criteria. To explain the first criterion, we have to look at Fig. 5. In this figure, it is shown the source current for increasing LET. When SEL is not achieved, after the ion strike, source current increases, it reaches a peak, and then it drops to zero. As the LET increases, more charge is deposited in the device, then the peak will increase. When SEL occurs, current will follow the same trend until a certain timestep, when the current will increase and will reach a saturation value. Then, we can assume that the time at which is reached the peak, it is the time in which the parasitic transistors are turning off and so, the time in which SEL is no longer sustained in the device. In conclusion, the time interval is taken from the moment the ion impacts with the structure (1×10^{-9} s) until it reaches the peak for the no-SEL case. The same interval is used when SEL occurs (Fig. 5).

Instead, the second criterion takes into account the time at which the current (for no-SEL) reaches zero. At this timestep, we can assume that the parasitic transistors are definitively off. This timestep is used also for the case in which SEL occurs. So, the time interval would be between the impact of the ion and the moment in which the current drops to zero (Fig. 5).

For both criteria, aside the charge collected, we have also calculated another parameter. This parameter is calculated as the charge collected divided by the time interval in which the charge is collected. In this way, we are able to consider if the time in which charge is collected plays a role in Single-Event Latchup.

Eventually, the two time intervals used are depicted in Fig. 5.

IV. RESULTS AND DISCUSSION

A. Threshold LET

First, in Fig. 6, the threshold LET trend for doping profiles is shown. More specifically, it is shown the trend for the range of temperature considered. As expected, threshold LET decreases as the temperature increases and increases as the doping profile increases [8]. Moreover, it is interesting to focus on the trend. If we consider the condition in which the device design is more favorable to induce Single-Event Latchup, as the worst-case

Fig. 4. Example of SEL cross section curve calculated by 2D approach. It shows the variation of cross section (σ) for different temperatures.

Fig. 5. Representation in the current versus time chart of the two different time intervals used as criterion in this work.

scenario (lowest threshold LET, i.e. lower doping level) and the best-case scenario as the opposite, we can observe that the threshold LET difference for each single doping case, increases as the conditions become less favorable to SEL. In fact, in the worst-case scenario, the difference between threshold LET at 425 K and at 350 K is 50%, meanwhile in the best-case scenario a difference of 60% is reached between 425 K and 375 K. Moreover, at 350 K, no SEL is observed for $x1.15$ and $x1.25$ case, which are thus the best condition for immunity.

In Fig. 7, threshold LET curves for substrate and well taps placement are shown. Thresholds decrease as the temperature increases and it is higher as taps are placed closer to the center of the device, which is confirmed by literature. Furthermore, temperature influence can be also seen in this case. In the worst-case scenario, the difference between 350 K and 425 K is 50% and as we have seen previously, in the best-case scenario the difference becomes higher. Indeed, threshold LET is increased by 75% just between 425 K and 375 K and at 350 K SEL is not even achieved.

Eventually, in Fig. 8 threshold LET curves for anode to cathode spacing are shown. The trend that has been observed for the previous parameters is also confirmed for the A-C

Fig. 6. Threshold LET vs doping profile for four different temperatures (350 K, 375 K, 400 K and 425 K).

spacing. Regarding this condition, in the worst case, threshold LET between the lower and the higher temperature increases by 58%, meanwhile in the best-case scenario threshold increases by 53% between 425 K and 375 K and SEL is not reached for 350 K. In this case, the difference is smaller with respect to previous examples. The reason may be that the effects of anode to cathode spacing variation is lower with respect to the other parameters.

In conclusion, for all the conditions investigated, temperature influence on SEL sensitivity is lower when conditions are more favorable to SEL and increases as parameters are modified to make the component less sensitive.

B. SEL rate

To further investigate this trend, we have calculated the SEL rate for a specific orbit, using OMERE, a free software dedicated to space environments [24]. Cross sections calculated with the 2D approach (Fig. 4) have been used to calculate the SEL rate. Regarding the doping profile, in Fig. 9, it can be seen that SEL rate follow the same trend observed for threshold LET. Considering that SEL rate takes into consideration the whole cross section, it means that the trend that has been seen for the threshold LET is present even for higher LET. Considering, 425 K as a reference, SEL rate increases from 30% to 40% for the worst case (x0.75), it increases from 40% to 80% when reference doping profile is analyzed, and increases from 70% to 97% for the best-case scenario (x1.25, which is not calculated at 350 K because SEL was not obtained). In Fig. 10, it is shown the SEL rate for substrate and well taps placement. Even in this case, the trend is confirmed. SEL rate increases from 35% to 40% for the best-case scenario and it increases from 65% to 88% in the worst-case scenario. Eventually, SEL rate for A-C spacing is presented (Fig. 11). SEL rate varies from 46% to 82% for the best case and from 37% to 54% in the worst case.

C. Charge collected

When an ion hits a component, electron-hole pairs are generated in the device and will diffuse inside it, due to diffusion and transport [25]. If the charge collected is enough to switch the parasitic transistor, a SEL will occur [18]. Then, we have investigated the charge collection for the different

Fig. 7. Threshold LET vs substrate and well taps distance for four different temperatures (350 K, 375 K, 400 K and 425 K).

Fig. 8. Threshold LET vs anode to cathode spacing for four different temperatures (350 K, 375 K, 400 K and 425 K).

cases. The goal was to analyze if the concept of the “critical charge”, as used for other Single Event Effects, can be used for SEL.

In order to calculate the collected charge, we have used the two methodologies shown in section III-C. In the next figures, we will show the charge collected for each temperature simulated. For each temperature, it is shown the charge collected when SEL is achieved (red dots) and when it is not achieved (blue dots) for all the simulations performed. In order to achieve our goal, we would expect a clear difference between the SEL collected charge and the “no-SEL” collected charge. The results for the four different temperatures (350 K, 375 K, 400 K, 425 K), using the first methodology showed that no clear distinction is achieved. From these results, it is not possible to define a threshold for the collected charge value that would trigger SEL. Furthermore, we have calculated the second parameter (charge collected divided by time), with the previous methodology and also in this case, results show no distinction. An example of the results is depicted in Fig. 12.

Despite a clearer difference, the goal is not reached also when the second criterion is applied. At all temperatures, the charge collected for SEL overlaps with no-SEL case. In Fig. 13, we

Fig. 9. SEL rate vs doping profile for four different temperatures (350 K, 375 K, 400 K and 425 K).

show an example for this case. Eventually, we have calculated the second parameter, for this methodology (Fig. 14). With this method, the difference between the charge collected for SEL and no-SEL is more distinct. Considering all the cases (which represents 420 simulations), only in 10 cases the results overlap. Also, at lower temperature the results are slightly worse with respect to higher temperatures.

D. Discussion

1) Threshold LET and SEL Rate

From the results it can be observed that temperature plays a different role depending on the condition of the device. When conditions of the device are favorable to SEL, temperature variation is affecting threshold LET and SEL rate less relevantly than in the case if which the device is more hardened. In order to explain that, SEL triggering conditions must be considered. As aforementioned, the structure of the CMOS creates two parasitic transistors inside it. The activation of these transistors is the initial step for Single-Event Latchup. Hence, a circuit is created inside the structure as depicted by [1]. Certainly, the characteristic of the circuit is related to the design of the device and then, a variation of a parameter leads to a variation of the response of the circuit and then to a variation on SEL sensitivity. Specifically, the doping profile influences the PNP bipolar current gain and the resistances inside the device [8]. Substrate and well taps placement variation causes a modification of the resistances present inside the device. A lower resistance will reduce SEL sensitivity, meanwhile a higher resistance will increase it. Concerning the A-C spacing, if it is increased, the bipolar current gain is decreased (as similarly observed for the doping profile). Eventually, temperature modification will cause a change on the resistances and it will modify the forward bias voltage of the base-emitter junction. A variation of this parameter means a variation of the potential barrier needed to trigger SEL [21].

However, SEL sensitivity is clearly dependent to a combination of all these effects. This work shows that for all the parameters (doping profile, substrate and well taps placement and A-C spacing) a more relevant variation of threshold LET and SEL rate is obtained for the best-case

Fig. 10. SEL rate vs substrate and well taps distance for four different temperatures (350 K, 375 K, 400 K and 425 K).

Fig. 11. SEL rate vs anode to cathode spacing for four different temperatures (350 K, 375 K, 400 K and 425 K).

scenario, with respect to the worst-case scenario. On first consideration, we can say that in the best-case scenario, conditions are already favorable to SEL immunity and then the decrease of temperature will help to increase SEL immunity of the device. Meanwhile, in the worst-case scenario, the device situation is already on SEL favor. Then, temperature will have a lower impact on SEL sensitivity. In general, it can be considered that temperature impact is not equal in all conditions and it is not independent from device design.

2) Charge collection

As aforementioned, the goal was to obtain a value of critical charge able to trigger SEL. Once obtained, this value could have been used in SPICE and Monte Carlo simulations to calculate SEL sensitivity of the devices.

Collected charge has been calculated following two different procedures for the time interval choice. Furthermore, a second parameter has been calculated, that is the collected charge divided by the time interval in which it is collected. In the following figures, each single dot represents a single simulation, with different parameters. The only common value is the temperature. In Fig. 12, we show an example of the

Fig. 12. Collected charge when no clear distinction is achieved.

Fig. 13. Collected charge for the second criterion.

results, where no critical charge value has been found for these cases. Indeed, it is not possible to find a threshold value for the collected charge or for the second parameter. More specifically, when the first criterion is used, SEL and NO SEL collected charge overlap continuously for all the temperature investigated. Meanwhile, when the second criterion is applied, they overlap less in comparison to the previous criterion. Furthermore, when the second criterion is applied and the second parameter is calculated, the results show a clearer distinction between SEL and NO SEL collected charge (Fig. 14).

From these data, it can be said that the first criterion is not useful for our purpose. Meanwhile, the second criterion seems more promising and specifically, it shows that the time in which the charge is collected can play a role in SEL triggering. This method can be refined by using a smaller maximum simulation timestep, which would help to refine the time interval used in the calculation.

V. CONCLUSION

In this work a comparison between the effect of temperature on four different parameters has been made. Cross-section curves for each parameter have been calculated using 2D TCAD simulations and then SEL rate has been estimated from these curves. For each parameter, we have modified its value and then for each single case we have investigated temperature

Fig. 14. Collected charge divided by time interval using the second criterion at (a) 350 K, (b) 375 K, (c) 400 K and (d) 425 K

effects, for a chosen temperature range. At first, threshold LET is investigated. We have observed, for every case, that when the component is less sensitive to SEL, temperature has a stronger impact on threshold LET, with respect to the opposite case. To further investigate this trend, we have calculated SEL rate for the GEO orbit. Indeed, the same trend has been observed for SEL rate. In the extended version of the paper, we will investigate this aspect.

Furthermore, we have investigated if the collected charge at the source terminal can be used to find a critical charge for SEL triggering. The results show that collected charge divided by the time interval in which it is collected is a promising methodology in order to reach the goal. More investigation would be necessary to refine the procedure.

ACKNOWLEDGEMENT

This work was realized within RADSAGA project. The RADSAGA Innovative Training Network project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie-Sklodowska-Curie grant agreement number 721624.

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