Characterization, simulation and modeling of PLL under irradiation using HDL-A

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Abstract

The PLL response to heavy ions radiation is investigated. Firstly, the radiation currents in transistors are introduced at the schematic level thanks to sources modeled in HDL-A. Secondly, the radiated block is simulated at the transistor level while the other blocks are replaced by a behavioral model in HDL-A. This allows to simulate the whole PLL in order to examine the effects of radiation at its output. The objective is to obtain a complete HDL-A behavioral model of PLL, including heavy ions effects.

***Keywords**: PLL, HDL-A, SEU, radiation effects, behavioral model.*

1. Introduction

In radiation environments, such as nuclear reactors, nuclear weapons, large accelerators and clearly satellites or space shuttles, a large variety of high-energy particles can be found with energies from keV to GeV. When these particles penetrate into silicon, they create along their path, a great number of free electron-hole pairs. These charges are separated by the electrical fields within the silicon and generate a parasitic photocurrent in the drain and source of transistor that can change the state of logic nodes and cause false information to be stored or propagated. The interest for using complex circuits – analog, digital or mixed-signal circuits- in radiation environments motivates the study of propagation of these altered signals towards the rest of the system.

The case of digital parts is well known in the literature as is showed in [1,2,3]. The number of bit errors produced by the radiation (Single Event Upsets or SEU) is represented in function of Linear Energy Transfer (LET) of incident particle (the energy transferred from the particle on silicon). Then, with the characteristics of the incident particles, it is possible to find the number of bit errors and, consequently, to increase the resistance of more sensible parts. In contrast, the study of analog and mixed signal parts were only started a few years ago [4,5] and are still not clear.

The problem is that the continuous nature of analog signals makes difficult the definition of what an error is. In function of where the circuit is, the radiation current can be propagated to the rest of the system or not. Subsequently, radiation effects in analog parts must be evaluated from a system level perspective.

In this article we propose a new approach to study the propagation of spurious signals dues to radiation in analog parts using the HDL-A language [6]. The circuit selected to probe this way of evaluation is a phase locked loop (PLL) owning to its mixed-signal nature.

A complete PLL HDL-A model has been presented in [7] and will be briefly reviewed here (section II). The induced transient currents in transistors are studied first by device simulation and modeled in HDL-A to allow the introduction in electrical simulations, as discussed in section III. This makes the simulation of all the system faster than by the traditional process coupling the circuit simulator –SPICE type– with the device simulator –MEDICI or ATLAS type. A VCO has been radiated with heavy ions and its response has been analyzed with the help of the transient currents introduced with HDL-A (section IV).

Finally, the PLL is simulated with the VCO block at transistor level with the radiation sources and the other blocks replaced by HDL-A models in order to reduce the simulation time (section V).

2. PLL block diagram

The PLL block diagram of a charge-pump based PLL [7] is shown in Figure 1. It consists in a phase-frequency detector (PFD), a charge-pump (CP), a loop filter (LF), a voltage-controlled oscillator (VCO) and a frequency divider (FD). The output frequency is given by

$$f_{out} = N.f_{ref} \tag{1}$$

where N is the division factor of the FD and f_{ref} is the input reference frequency.

The PFD detects phase and frequency differences between the reference clock and the divided output. The

CP injects current into the filter in function of this difference, so the control voltage of VCO is changed and the frequency at the output is readjusted. The objective of this work is to observe how the PLL system reacts to a spurious signal induced by radiation in the VCO.

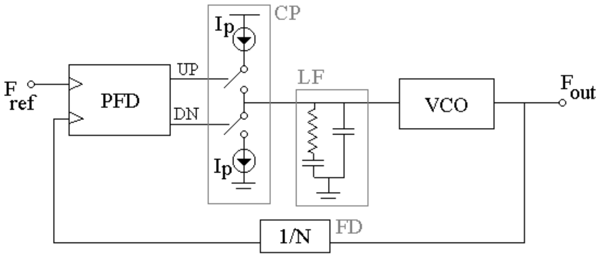

Figure 1. Charge-pump PLL

3. Evaluation of generated current and modeling in HDL-A

Device simulators, such as MEDICI or ATLAS [8,9], allow to calculate the transient current in a transistor caused by the pass of ionizing particles. In this kind of simulators, the output current of semiconductor devices is obtained by numerical resolution of the physical equations governing the transport mechanisms. The generated current depends on the particle (type and direction) and in transistor (topology and polarization) (Figure 2).

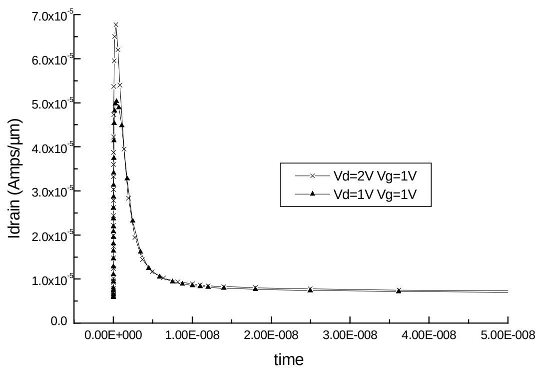

Figure 2. Transient currents for 2 different transistor biases in a FD SOI NMOSFET transistor with 2µm length. The particle is a $^{132}Xe^{26+}$ and the impact is perpendicular to the channel.

To obtain the circuits response to these effects, it is possible to introduce limited SPICE netlists – from 100 nodes in ATLAS to 500 in MEDICI- in device simulators and to make mixed-mode simulation. Due to the long time necessary to carry out these simulations, only blocks with low number of transistors are usually studied [10] in this way (usually memory cells). For more complex systems, like mixed circuits, others approaches have been studied: the introduction of different current sources [11] or the transistor substitution by other models with radiation effects included [12,13] (Figure 3).

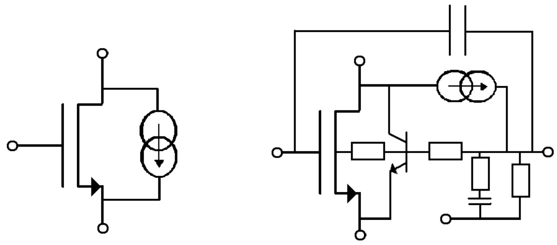

Figure 3. The left model represents the approach proposed in [11] . The right model is presented in [12].

In the first approach, it is necessary to know what is the polarization of the transistor at the impact and this is not possible always.

In the second approach, there are some problems to adjust the model with radiation effects included.

The solution we propose is the use of HDL-A as an easy way to introduce any electrical curve desired. First of all, the simulation with MEDICI device simulator for a transistor with different biases is performed. Then, a HDL-A current source model is implemented. This source, with the help of the HDL-A/C interface, models the best-fitted curve in function of transistor bias in the impact moment. With this methodology, the great burden of MEDICI simulations is only spent once at the beginning of the analysis. Then, every time that the transistor is changed, or the polarization conditions are changed, it is not necessary to repeat the device simulator step.

4. Evaluation of VCO under irradiation

In order to study the effects of radiation in the overall PLL's, we have started with the study of the VCO response to irradiation. A first experiment was made in the Cyclotron of Louvain-la-Neuve. Then, some simulations have been carried out to obtain the phase changes in the VCO output.

4.1 VCO Characterization under irradiation.

The VCO circuit presents a CCO-based schematic (Figure 4)[7]. The circuit has been implemented in the 2µm-SOI Fully Depleted technology from the UCL Microelectronics laboratory.

The circuit biased to oscillate with a constant frequency about 145.9 MHz. In this case, the VCO functions like a ring oscillator with a nominal frequency given by the current in the oscillator.

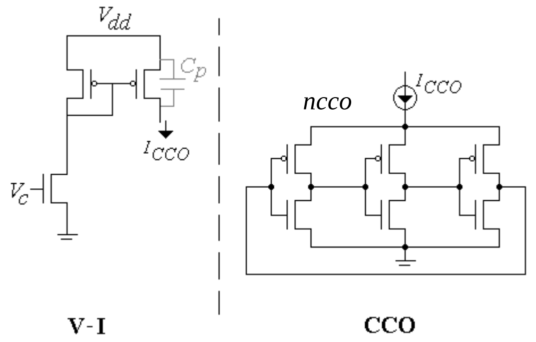

Figure 4. VCO schematic with output buffer

In absence of radiations, the output signal spectrum has dispersion over the nominal frequency that depends on the spectrum analyzer filter choused (Figure 6 top). Under irradiation, the spectrum presented new peaks different to the nominal frequency (Figure 5).

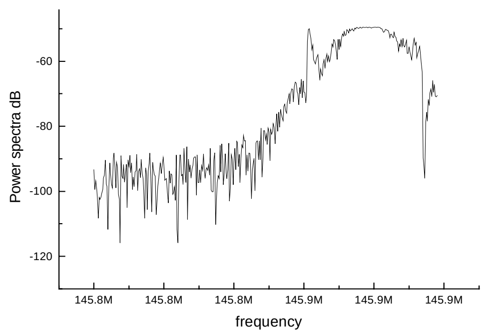

Figure 5. Output frequency spectrum under low flux radiation

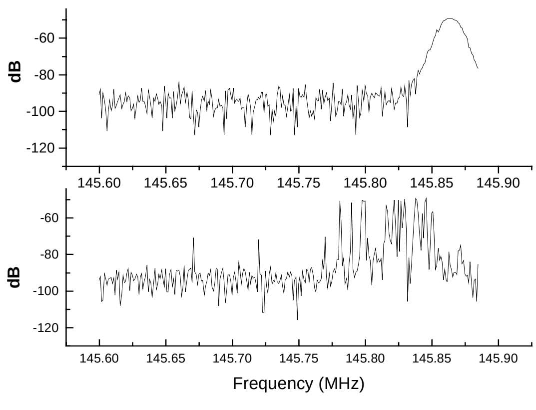

Figure 6. Frequency Spectrum of ring oscillator without radiation (top) and under large flux (bottom).

If the flux of particles is increased, the number of peaks increases and is not possible to recognize where the nominal frequency is (Figure 6).

4.2 VCO simulation with irradiation sources

With the HDL-A current sources presented in section 3 it is possible to simulate the VCO block with ELDO and to obtain its response to the same radiation than in the experience (Figure 7). Simulation shows that radiation currents in the ring oscillator inverters change instantaneously the phase in the output of oscillator. This change depends on the particle characteristic, the transistor position and the moment of the impact.

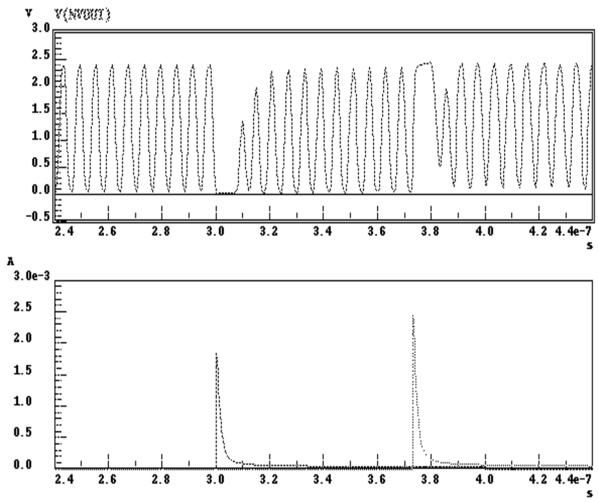

Figure 7.Example of VCO simulation with 2 impacts in the transistors of the second ring oscillator inverter. The first corresponds to the nmos impact and the second one to the pmos.

It is also possible to compare the spectrum under irradiation with the spectrum without radiation in order to explain the experiment observation. Figure 8 presents the spectrum of a ring oscillator without irradiation and the spectrum of the output signal modified by one ion impact. The more important aspect is the peaks apparition in perturbed signal and the nominal frequency shift (maximal peak).

To understand the experiment results it must be considered that the analyzer spends some time to find the signal power for every frequency required. So, when the total spectrum is showed, many impacts have happened and the final result is the superposed effect of all these single events.

5. Simulation and characterization of PLL

To finish with the circuit analysis, the behavior of PLL under irradiation must be characterized.

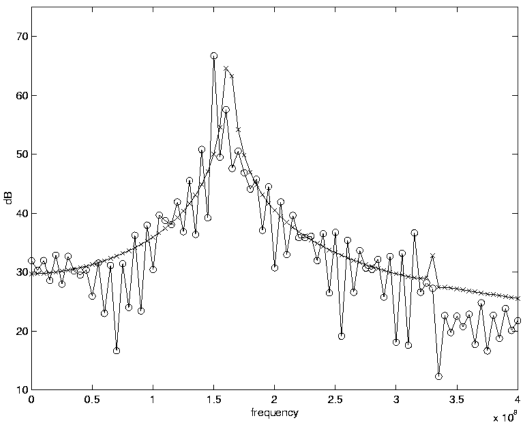

Figure 8. Fequency Spectrum for simulation of VCO under normal conditions (-x-) and under irradiation (-o-).

The objective is to observe the response of the overall system to perturbations in the VCO. In the future, the others blocks will be characterized following the same procedure. It will permit to find the more sensible blocks, the worst case in phase and frequency changes, and a behavioral model of PLL under radiation. This overall model of irradiated PLL will be useful to study the propagation of single events in PLL to systems more complexes where the PLL will be integrated. In order to reduce simulation time, behavioral models for the non-irradiated blocks (FD, PFD, CP) have been used.

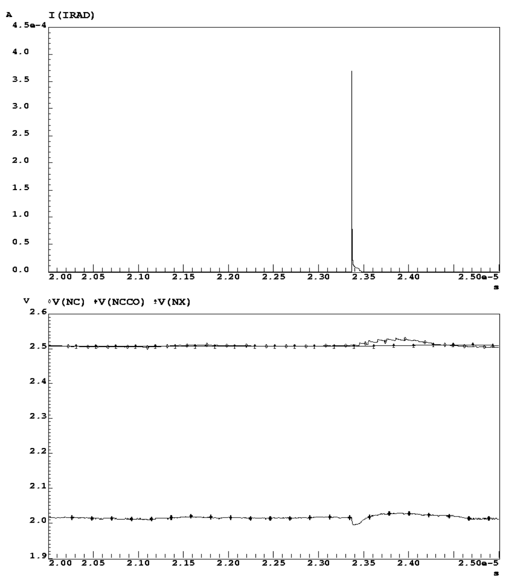

Figure 9. Irradiation current and voltages in the filter node (*nx*), VCO input (V*c*) and CCO input (*ncco*)

In figure 9, we can observe one of these simulations with one heavy ion impact in a VCO PMOS. The figure shows how the voltage at the control node of CCO changes (node *ncco*) and how the voltage at the input of the VCO (node *Vc*) rises to compensate this change. The *nx* corresponds to the node between the resistance and the capacitance in LF block.

Figure 10 shows the PLL output change after particle strikes for the same case than figure 9.

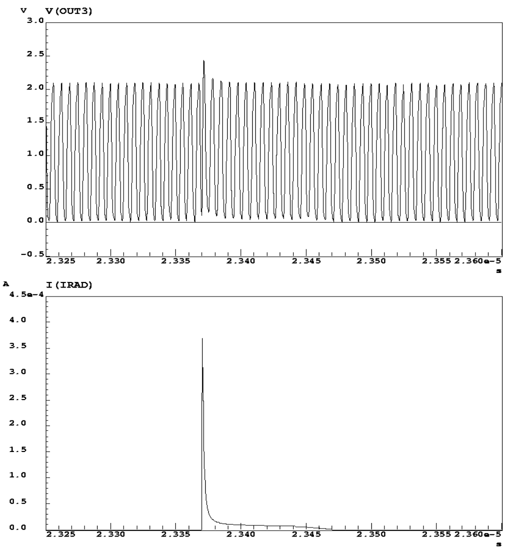

Figure 10. VCO Output for the same case than figure 9.

The changes in the phase and the lost of synchronization can be observed with the digital signals that enter in the PFD (Figure 11).

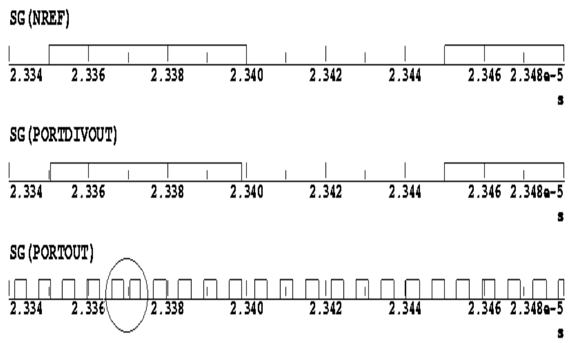

Figure 11. Digital inputs for PFD and VCO output after digitalization. The marked zone corresponds to Single Event in the output signal.

Figure 11 shows how the FD output (*portdivout*) are not synchronized with the input reference (*nref*) after the particle impact (marked zone)

As an example of the analysis utility, consider a microprocessor system connected to external circuits through a synchronized BUS. The internal clock is generated by the PLL as a multiple of the BUS clock frequency to facilitate the communication with the other parts of the system. If SEU occurs, bus data will be lost until the BUS clock and the internal clock will be resynchronized. The last analysis allows to find how many data can be lost by particle impacts.

6. Conclusions

A new approach to study the effects of ionizing particle passing through integrated circuit has been presented. In this new approach we use HDL-A as an easy way to introduce radiation effects in the circuits by transient currents addition simulated by device simulators. The block and the overall system simulation must be carried out in order to obtain the effects at the circuit output. As an example, the response of the PLL to a transient effect in the VCO has been shown.

In the future, we will characterize the radiation affects in the other blocks of the PLL. These effects will be included in a behavioral model of the PLL in order to allow a fast evaluation on systems using PLL.

Agreements

We would agree the collaboration of Guy Berger for his help to the realization of measurements in the Cyclotron of Louvain-la-Neuve (cyclone).

6. References

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