Account for Radiation Effects in Signal Integrity Analysis of PCB Digital Systems

K.O. Petrosjanc, I.A. Kharitonov
Moscow Institute of Electronics and Mathematics of National Research University “Higher School of Economics”, Moscow, Russia
eande@miem.edu.ru

Abstract - A method of account for radiation effects (total dose and particle fluence) in signal integrity analysis of digital system by using IBIS model is presented. It is shown that account for these effects in IBIS models can be performed by correction the input impedances of protection circuits (GND Clamp and POWER Clamp), output MOSFETs (PULL_UP, PULL_DOWN) characteristics and RAMP parameters in accordance with the known physical relations. Examples of digital IC output and crosstalk signals simulation with HyperLynx software using the created IBIS model is presented.

Keywords – signal integrity, IBIS model, radiation effects, diode parameters, MOSFET parameters.

I - INTRODUCTION

It is well known that the design of high-speed digital systems on printed circuit boards (PCBs) is getting tougher and more complicated due to higher integration densities and clock frequencies. PCB physical effects like crosstalk, ground bounce and reflection need to be simulated to provide correct system performance [1]. The variables which can affect signal integrity in digital systems are [3]: signal path design, ICs impedances and loading, transmission line effects (see Figure 1).

Digital systems for aerospace, nuclear, energetics, military and other special electronics work under the combined influence of temperature and radiation (total dose) factors. For all of these applications the radiation environment and its influence on electronic components must be taken into account.

IBIS (I/O Buffer Information Specification) models of digital components are used in signal integrity analysis tools [2]. IBIS model describes IC package parasitics and defines the behavior of each input (GND Clamp and Power Clamp characteristics) and output buffer (PULL Down, PULL UP and Ramp characteristics) of the IC (Figure 2). As it is known the static and dynamic parameter of IC elements degrade after irradiation: MOSFET threshold voltage and mobility degrades, output voltage slew rate decreases, ohmic resistances increase [4]. IBIS models take into account the thermal and supply voltage deviation effects by the “minimum” and “maximum” characteristics. As a result these models allow to perform signal integrity analysis accounting for components and ambient deviations. By the same way IBIS model could account for IC parameters degradation after irradiation in signal integrity analysis. Methods for IBIS models creation with account for temperature and supply voltage deviations using measured or SPICE simulated digital ICs characteristics are well known [3, 5].

II IBIS MODEL CREATION WITH ACCOUNT FOR RADIATION EFFECTS.

However the aspects of the account for radiation effects in IBIS models for the purpose of signal integrity analysis of special digital systems are not described enough.

Figure 1. Signal waveforms correlation with trace and driver/receiver parameters [3].

Figure 2. IBIS model structure (a) and conceptual diagram of model keyword structure (b) [4].

As it is seen from Figure 2 IBIS model includes three groups of characteristics which can depend on radiation factors:
1- GND Clamp and POWER Clamp I-V-characteristics;
2- PULL Down and PULL Up I-V-characteristics;
3- RAMP $dV/dT$ characteristics.

Account for radiation effects in GND Clamp and POWER Clamp I-V-characteristics
These characteristics are measured [3] for applied voltage varying in the range $-V_{cc}$ to $2^*V_{cc}$, so they are defined by:
- protection diodes ohmic resistances (see Figure 2) when diodes are in forward mode (left down corner of I-V-graph) for GND Clamp and left upper corner of I-V-graph for POWER Clamp)
- diodes leakage currents (right upper corner of I-V-graph in Figure 5 (c) for GND Clamp and right down corner of I-V-graph for POWER Clamp) [3].

As it is known the diode resistance and recombination currents increase after irradiation (see Figure 5 (b)).

Diode resistance dependence on radiation fluence $F$ [1/sm²] can be described by [5]:

$$R_{d_{_{\text{load}}}}(F)= R_{d_{_{\text{load}}0}}(1 + K_R F),$$

where $R_{d_{_{\text{load}}0}}$ - diode resistance before irradiation, $K_R$ - fitting coefficient.

Diode leakage current $I_{d_{_{\text{leak}}}}$ dependence on radiation fluence $F$ can be described as [5]:

$$I_{d_{_{\text{leak}}}}(F)= I_{d_{_{\text{leak0}}}}(1+K_I F),$$

where $I_{d_{_{\text{leak0}}}}$ - diode leakage current before irradiation. $K_I$ - fitting coefficient.

The fitting coefficients depend on the kind of radiation influence and resistance value [5].

Account for radiation effects in PULL Down and PULL Up I-V-characteristics.
PULL DOWN characteristics describe buffer output current capabilities (see Figure 2). They are measured for voltage varying in the range $-V_{cc}$ to $V_{cc}$, so they are defined by:
- NMOSFET output I-V-characteristics for positive voltage [3] (right upper corner of I-V-graph in Figure 6 (c)) and drain-substrate diode (see Figure 6 (b)) I-V-characteristic in forward mode for negative voltage (left down corner of I-V-graph in Figure 6 (c)) [3].

PULL UP characteristics are measured for applied voltage varying in the range $0$ to $2^*V_{cc}$, so they are defined by:
- PMOSFET output I-V-characteristics for voltage values less than $V_{cc}$ (right down corner of I-V-graph) and drain-substrate diode I-V-characteristic in forward mode for voltage values more than $V_{cc}$ (left upper corner of I-V-graph) [3].

As it was shown in [4] output current capabilities of irradiated IC decrease because of MOSFET mobility degradation after irradiation. Figure 3 from [4] presents MOSFET mobility degradation as a function of total dose and post-irradiation biased anneal for different oxides.
To account for radiation effects in MOSFET I-V-curves it necessary to modify output MOSFETs threshold voltage and to reduce MOSFET mobility [4]. The more important effect in modern CMOS ICs is mobility reduction because the threshold voltage shift is small and can be neglected. The corrected characteristics can be then inserted into IBIS model.

\[
\mu(D) = \frac{\mu_0}{1 + D \cdot K_\mu},
\]

where $\mu_0$ – mobility in unirradiated MOSFET,
$K_\mu$ – mobility degradation coefficient.

To account for radiation effects in PULL Down and PULL Up I-V-characteristics, the drain-substrate diode I-V-characteristics in forward mode can be corrected by the same manner as GND and POWER clamp characteristics (see (1) and (2)).

Account for radiation effects in RAMP $dV/dT$ values.
RAMP values describe rising and falling slew rates of buffer for resistive load.

As it was shown in already mentioned paper [4] IC timing decrease after irradiation because of output MOSFET mobility degradation. Figure 4 from [4] presents change in integrated circuit timing as a function of total dose.

Slew rate degradation can be accounted in RAMP values by the mean similar to mobility dependence on dose or fluence [4].

Figure 3. MOSFET Mobility degradation as a function of total dose and post-irradiation biased anneal for groups with different oxides [4].

MOSFET mobility degradation after irradiation (dose D or particle fluence F) can be approximated by the known equation [4]:

\[
\mu(D) = \frac{\mu_0}{1 + D \cdot K_\mu},
\]

Figure 4. Change in integrated circuit timing as a function of total dose and post-irradiation biased anneal [4].
Analyzing radiation effects together with temperature and voltage supply variations it is possible to conclude that the maximum values for PULL_UP, PULL_DOWN and RAMP characteristics will correspond to low temperature, high supply voltage and unirradiated conditions. The minimum values will correspond to high temperature, low supply voltage and maximum radiation influence.

“Maximum” GND_Clamp and POWER_Clamp characteristics will correspond to high temperature, high supply voltage and no irradiation. Minimum characteristics will correspond to low temperature, low supply voltage and maximum total dose.

There are two traditional methods to get the necessary characteristics for IBIS models creation [2, 3, 6]. The first method is SPICE simulation of digital integrated circuit and generation all of the necessary characteristics for IBIS model [6]. The second one is obtaining the I-V curves and rise/fall times for output or I/O buffers by direct measurement.

We use both of these methods in our works on IC radiation hardness modeling. Some examples of SPICE MOSFETs and IC modeling with account for radiation effects are described in [7,8]. Our results confirm that IC output voltage slew rate degradation depend on MOSFETs parameters degradation.

Figures 5, 6 present schematics for characteristics measurement (a) and the measured characteristics (c) for CMOS IC KR1561IE21 with account for power supply, temperature and Co^{60} total dose D0 for GND clamp, POWER clamp, PULUp, PULLdown. This IC is designed for special applications and has the main parameters: maximum output current 25 mA, maximum working frequency 20 MHz. D0 corresponds to total dose requirement for radiation tolerant (RT) electronics for nuclear reactor environment, satellites and some other application [5].

![Figure 5](image1.png)

![Figure 6](image2.png)

**Figure 5.** Schematic for GND clamp characteristic measurement (a), typical I-V characteristics of diode before and after irradiation (b) and the measured GND clamp characteristics (c): 1 - -60°C, max $V_{dc}$ ("maximum"), 2 – +27°C ("typical"), 3 - +27°C and dose D0, 4 - +120°C, dose D0 and min $V_{dc}$ ("minimum").

**Figure 6.** Schematic for Pulldown characteristic measurement (a), cross section of NMOS FET with drain-substrate diode (b) and the measured Pulldown characteristics (c): 1 - -60°C, max $V_{dc}$ ("maximum"), 2 – +27°C ("typical"), 3 - +27°C and dose D0, 4 - +120°C, dose D0 and min $V_{dc}$ ("minimum").

Developed IBIS model for IC KR1561IE21 has been inserted into HyperLynx software from Mentor Graphics using HyperLynx IBIS Editor. Figure 7 presents simulated rising/falling waveforms for the created IBIS model with 500 Ohm load. It is seen that irradiation decreases slew rate.

![Figure 7](image3.png)

**Figure 7.** Rising/falling waveforms for the created IBIS model with 500 Ohm load: 1 - “maximum”, 2 - “typical”, 3 - “minimum” (with irradiation).

**III EXAMPLE OF DIGITAL IC OUTPUT AND CROSSTALK VOLTAGE SIMULATION WITH ACCOUNT FOR RADIATION EFFECTS**

IBIS model of CMOS IC KR1561IE21 was used for signal integrity analysis with account for radiation effects. Such ICs were used as a driver, as a receiver and as a ‘victim’.

Test board parameters were as the following:
- 4 layers, FR4,
- thickness of each layer - 0.09 mm,
- trace width - 0.3 mm,
- trace spacing - 0.3 mm,
- trace length - 130 mm.

HyperLynx software from Mentor Graphics was used for simulation.

Figure 8 (a) presents simulated voltage waveforms of the KR15611E21 driver output with account for PCB parameters and radiation effect. As it is seen the created model showed degraded slew rate after irradiation.

Then this IC was used as an “aggressor” and parallel trace “victim” crosstalk voltage (Figure 8 (b)) was simulated with the created IBIS model. The results showed that degraded “aggressor” slew rate resulted to smaller crosstalk voltage.

![Voltage waveform](image)

**Figure 8.** Voltage waveforms of the driver output (“aggressor”) (a) and “victim” crosstalk voltage (b) simulated with the created IBIS model: 1- “maximum”, 2- “typical”, 3- “minimum” (with total dose D0).

**IV CONCLUSION**

It has been shown that account for radiation effects in signal integrity analysis of PCB digital systems can be realized by IBIS models parameters and characteristics correction in according with irradiation levels.

Effects of radiation influence on IBIS model parameters and characteristics has been correlated with MOSFETs and diodes degradation.

IC input impedance, described by GND clamp and POWER clamp characteristics in IBIS model, has been correlated with the input diodes resistance increase and diodes leakage current increase with radiation influence.

IC output current capability, described by PULL UP and PULL DOWN characteristics, has been described. IC

IBIS model of digital IC KR15611E21 has been created with account for radiation effects.

Example of digital IC KR15611E21 output and crosstalk voltages simulation with account for radiation effects was presented and analyzed.

The study was implemented in the framework of the Basic Research Program at the National Research University Higher School of Economics (HSE) in 2013 (project TZ-108) and Russian Foundation for Basic Research (grant 12-07-00506).

**REFERENCES**