Behavioural Model Based Simulation of the ESD-Soft-Failure-Robustness of Microcontroller Inputs

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Abstract—**Failures in digital devices can be caused by ESD-pulses coupled directly or indirectly to input pins. Weak pulses will not destroy a device but can be interpreted as logical signals (ESD soft failure). In this paper, a modelling and characterization methodology for a microcontroller input is proposed. With this model the ESD soft failure behaviour can be simulated. First a measurement setup for characterization of input behaviour was developed and applied to a commonly used microcontroller. For the digital input an RC model approximation is used and related parameters are extracted. SPICE simulations have been performed and results have been compared with the measurements. It could be shown that the RC model can predict quite well the ESD soft failure behaviour.**

Keywords— Integrated circuit, EMC modeling, soft failure, black-box modeling, microcontroller EMC, SPICE simulations

I. INTRODUCTION

In today's world, a remarkable rates of electronic products include microcontrollers. Microcontrollers are very sensitive and easy to affect by electro static discharges (ESD). The system-level ESD failures can be separated into two main groups: ESD hard failures and ESD soft failures [1]. Mostly, the root causes of the ESD hard failures are easier to analyse than those of the ESD soft failures since it is possible to follow back their causes by finding the locations of the defects by using the IC decapsulation techniques [2]. On the other hand, it is not such easy to find the origin causes of the ESD soft failures because they intermittent and the system recovers to its normal state after reboot. Reset, power-off, abnormal display status and freezing of the system are typical and common examples of the ESD soft failures [2].

Several studies are already presented in the literature related to ESD soft failures on various electronic elements and devices e.g. [2-3]. A systematic analysis methodology for mobile phone's ESD soft failures is presented by Kim and Kim [2]. A hybrid method to model ESD LCD (Liquid Crystal Display) upset in a portable product is developed and presented by Xiao et al [3].

In this study, we introduce a methodology to define system level ESD soft failures of a microcontroller and present a an RC model approximation. SPICE simulations were compared with measurements and the validity of the approach could be proved.

The paper is organized as follows: After this Introduction, in Section II, behavior models for soft failures in digital inputs have been briefly introduced. In Section III, measurement flow is explained and results are provided. Then, in Section IV RC model approximation is introduced and parameters are obtained after extraction steps. In Section V simulations have been performed and their predictions have been compared with the measurements. Finally in Section VI the paper is concluded.

II. BEHAVIOR MODELS FOR SOFT FAILURES IN DIGITAL INPUTS

In today's world, electronic device and system complexity is increasing at the system, board, IC and die level. That's why, EMC design issues and precautions are much more important than past. Particularly, integrated circuits (ICs) are one of the main sensitive of the disturbance signals. Therefore, EMC (Electromagnetic Compatibility) models of ICs are becoming unavoidable for appropriate EMC simulations.

Many studies have been presented in the literature dealing with the immunity modeling of ICs [4-7]. In [4], some new models have been developed considering a noise pulse on either circuit inputs or the clock input. They specify the circuit noise immunity in terms of amplitude and the noise pulse duration. SPICE simulations are performed to check validity of these models. One another SPICE based model of a microcontroller has been developed to investigate its immunity to electrical fast transients (EFTs) [5]. A new technique based on the direct power injection (DPI) for immunity modeling of integrated circuits especially compliant with industrial requirements have been introduced [6]. A model has been introduced to predict the changes in propagation delay in a logic inverter caused by low-level radio frequency [7]. Predictions of the model obtained by Spice simulations have been checked with experimental results

III. MEASUREMENT OF MODEL PARAMETERS

For validation and parameter measurements a simple Arduino UNO based test setup has been chosen. A single Arduino pin has been programmed as input and was observed with respect to trapezoidal pulse signal with very narrow pulse width values.

The Arduino Uno is a microcontroller board based on the Atmel ATmega328 CPU. This board both can be powered and programmed from the USB connector. Arduino UNO has a 16 MHz ceramic resonator and it operates at 5V.

Main concept of this step is to define the failure limits with respect to pulse width and signal amplitude. The status of the input pin is observed when a pulse signal with various pulse width and amplitude is applied. Detection of status change by the µC is defined as "soft failure". Detection of the "soft failure" is observed on PC by using Arduino serial monitor. For this purpose, a counter was programmed that each pulse causes an increment. Block schematic of the test setup is shown in Fig. 1.

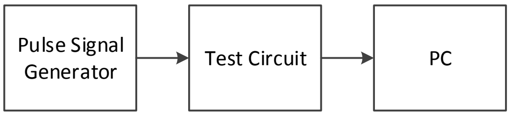

Fig. 1. Block schematic of the test setıp

In order to get most sensitive detection process, interrupt function is used. For this purpose Pin 2 of the Arduino UNO is configured as interrupt input. Circuit schematic of the pulse signal generator and the test circuit is shown in Fig. 2.

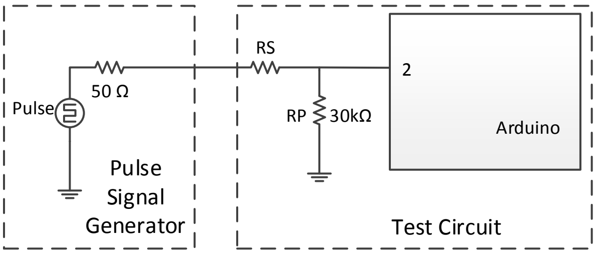

Fig. 2. Circuit schematic of the pulse signal generator and the test circuit

R_P is used as the pull-down resistor for signal stabilization on interrupt pin input as shown in Fig 2. The series resistor R_S is used to obtain RC model values to define minimum "detectable" amplitude level for three different R_S for each particular PW values characterization.

Photograph of the test setup is shown in Fig. 3.

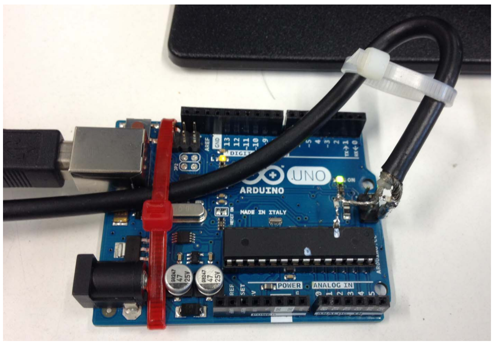

Fig. 3. Photograph of Ardıino UNO based measurement setup

Flowchart of the measurement steps, for soft failure detection, is shown in Fig. 4. A certain time stable operation by itself on the first conditional block is defined as the decision criterion. In this process N (No) for conditional bock is the decision criterion that the pulse is not detected by the Arduino during 20 seconds.

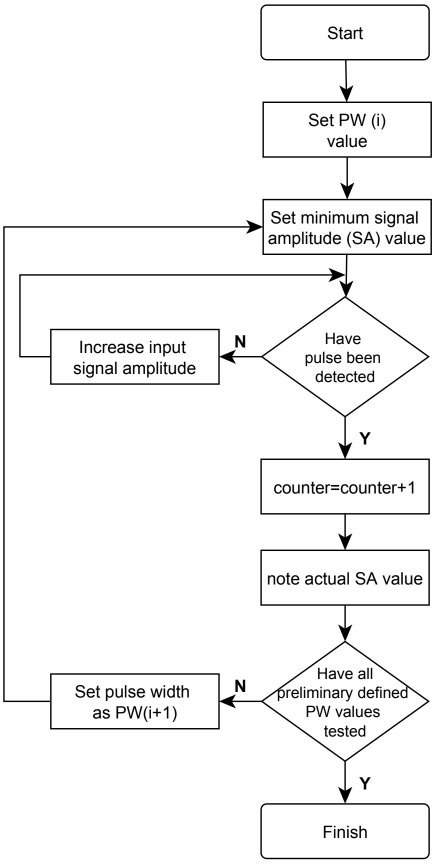

Fig. 4. Flowchart of the measurement methodology

Measurement equipment is listed in Table I. For longer pulse widths (4 – 100 ns) a Tektronix AWG is used. For the shortest PW value (0.8 ns) the Schwarzbeck IGUF 2910-S signal generator is used. It gives a pulse shape with constant amplitude and pulse width. Measured pulse width is 0.8ns for this device with 250Hz repetition frequency. To adjust the output amplitude a Weinschel Engineering Model 2808 variable attenuator is used.

TABLE I. MEASUREMENT EQUIPMENT

Device	Description
Arbitrary Signal Generator (SG1)	Schwarzbeck IGUF 2910-S
Arbitrary Signal Generator (SG2)	Tektronix AFG3252
Oscilloscope	LeCroy 760ZI 6 GHz Oscilloscope
Adjustable Attenuator	Weinschel Engineering Model:2808
Test Board	Arduino UNO

Measurements are done for 18 pules width (PW) values from 0.8 ns to 100 ns. R_S values are 0 Ω, 50 Ω and 470 Ω, respectively. Results obtained have been provided in Table II. and graphically demonstrated in Fig. 5.

TABLE II. MINIMUM AMPLITUDE VALUES CAUSING "SOFT FAILURE" FOR EACH PARTICULAR PW VALUES.

#	PW (ns)	V_{R0} (V) for R_S=0Ω	V_{R1} (V) for R_S=50Ω	V_{R2} (V) for R_S=470Ω
1	0.8	8.75	10.02	17.8
2	4	3,002	3,322	4,86
3	5	2,864	3,054	4,19
4	6	2,812	2,91	3,756
5	7	2,756	2,814	3,456
6	8	2,692	2,744	3,244
7	10	2,65	2,674	2,976
8	12	2,616	2,63	2,82
9	15	2,592	2,608	2,756
10	20	2,592	2,608	2,756
11	25	2,592	2,608	2,704
12	30	2,592	2,608	2,644
13	40	2,592	2,608	2,636
14	50	2,592	2,608	2,628
15	60	2,592	2,608	2,626
16	70	2,592	2,608	2,626
17	80	2,592	2,608	2,626
18	100	2,592	2,608	2,624

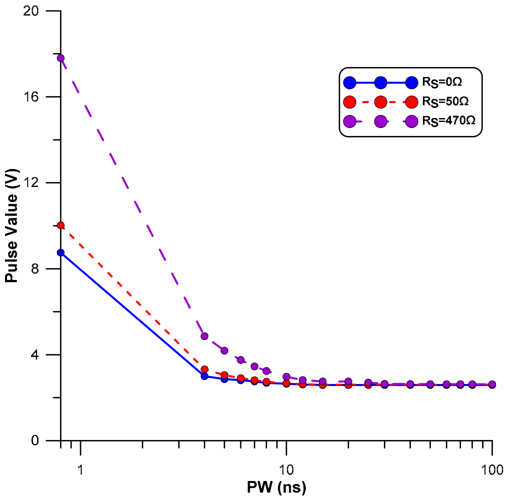

Fig. 5. Detected minimum amplitude vs. PW for "soft failure"

IV. RC MODEL APPROXIMATION

From the measured data the RC behavioural model can be parametrized. This process is presented now. The circuit schematic with the RC model representing the Arduino pin is shown in Fig. 6.

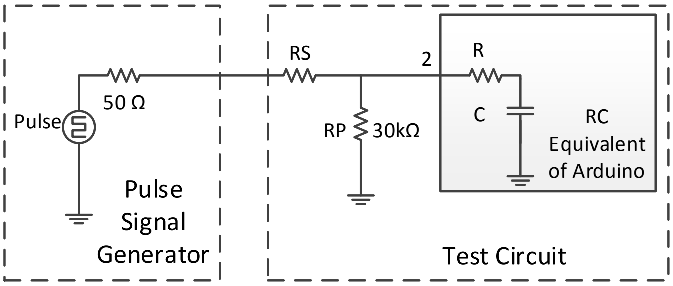

Fig. 6. Circuit schematic of the pulse signal generator and the test circuit with RC equivalent

To obtain R and C values, MATLAB curve fitting tool is applied to the measurement results. Fitted curves based on the basic exponential RC equivalent as expressed in (1) for R_{S1}=0Ω, R_{S2}=50Ω and R_{S3}=470Ω are shown in Fig. 7, 8 and 9, respectively.

$$v_I = v_C\left(1-e^{\frac{-t}{\tau}}\right) \quad (1)$$

Where v_I is the amplitude of the pulse signal, v_C is the capacitor voltage and τ is the time constant of the RC block.

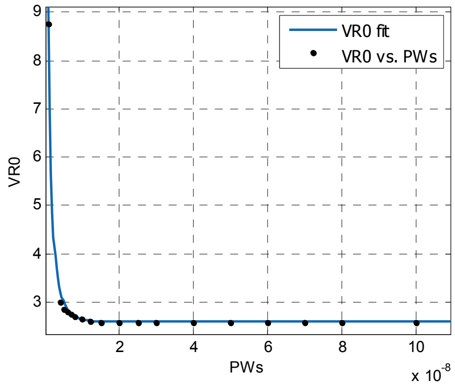

Fig. 7. Fitted curve for R_{S1}=0Ω

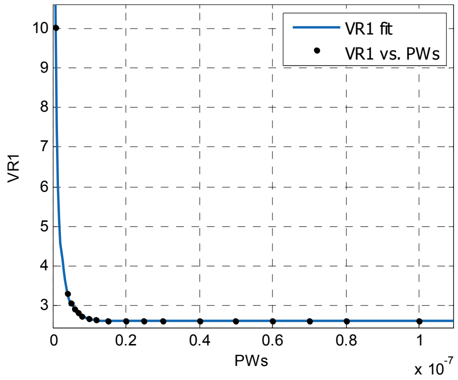

Fig. 8. Fitted curve for R_{S2}=50Ω

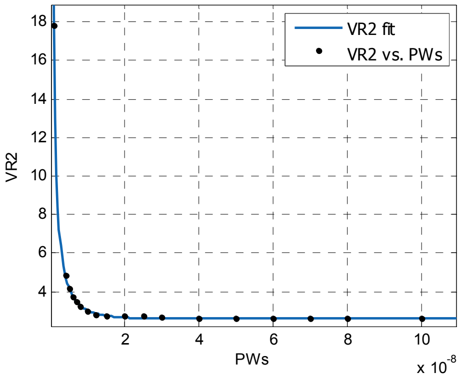

Fig. 9. Fitted curve for R_{S3}=470Ω

Then first order polynomial expression as stated in (2) is considered for RC equivalent.

$$\tau_i = \left(R_I + R_{Si} + R\right)C \qquad (2)$$

Where τ_i stands for the three fitted values from Fig. 7, 8 and 9. R_I=50Ω is input resistance of signal generator for 50Ω system. By applying curve fitting the unknowns R and C have been determined as R=330 Ω and C=6 pF.

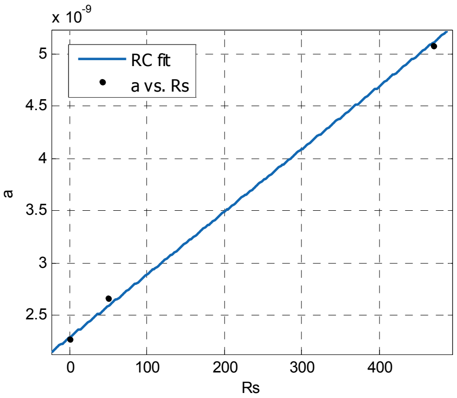

Fig. 10. Fitted curve for R & C extraction

V. SIMULATIONS AND COMPARISON OF THE RESULTS

In this section by using RC model equivalent and extracted R and C values for related pin of Arduino given in Fig. 6, PSPICE simulations have been performed.

For the simulations two type pulse shape such as rectangular and trapezoidal are considered in each step. Rectangular shape stands for basic capacitor charge equation, Trapezoidal one is for real shape from the signal generator.

Simulations have been performed for same set of R_S values such as 0Ω. 50Ω and 470Ω for each PW values listed in Table II. The circuit schematic used for SPICE simulations is shown in Fig. 11. Two different type pulse signal has been applied as shown in Fig. 12 (rectangular) and Fig. 13 (trapezoidal) respectively.

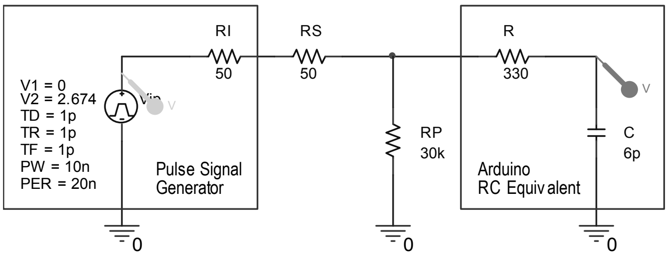

Fig. 11. PSPICE circuit schematic of the test circuit for simulations with rectengular pulse shape

Each theoretically calculated capacitor value which obtained by using Equation (1) has been compared simulated v_C value. Sample simulated characteristics for v_I=4.19V and PW=5ns are shown in Fig. 12 and 13.

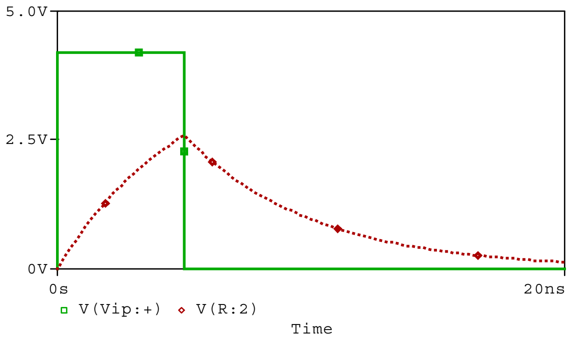

Fig. 12. PSPICE simulation characteristics of pulse and capacitor voltages for rectangular pulse shape with v_I=4.19V and PW=5ns values.

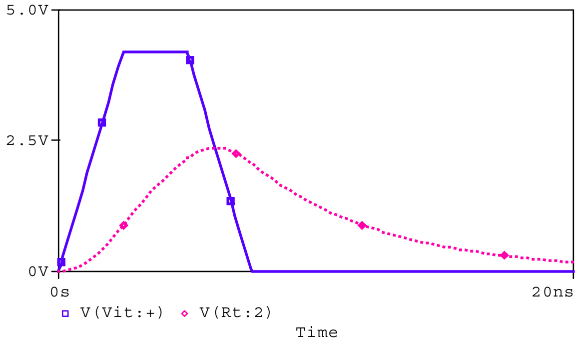

Fig. 13. PSPICE simulation charracteristics of pulse and capacitor voltages for trapezoidal pulse shape with v_I=4.19V and PW=5ns values.

Difference between calculated and simulated values are expressed as percentage error and results are shown in Fig. 14 for trapezoidal pulse shape. Average RMSE (Root Mean Squared Error) is calculated as below 2%.

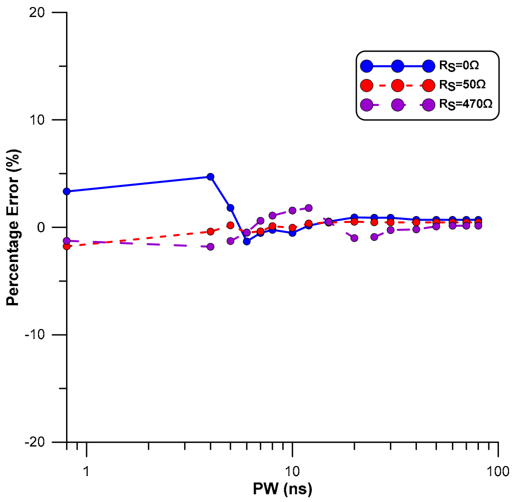

Fig. 14. Percentage error in capacitor voltage values with respect to frequency for rectangular pulse shape

Same procedure is applied for the other Arduino UNO interrupt pin and results are confirmed.

VI. CONCLUSIONS

Most commonly known definition is that soft failures do not destroy a device and by simple user interaction (reset, power interruption, or another simple operation) a device returns to normal operation. Soft failures can only appear during operation, but not during unpowered handling. Often systems are much more sensitive to soft failures and low disturbance levels might trigger them. Anyway it is difficult to generalize a difference between soft and hard failures regarding the disturbance level or the severity of a failure. Systems behaviour can be very complex.

For functional ESD soft failures a simple characterization method was applied to a microcontroller. It could be shown that with a set of simple to perform characterization measurements the switching behaviour of digital inputs can be analysed and a simple simulation model can be parametrized.

The method was applied to a 16 MHz Atmel microcontroller (Arduino) board; the interrupt mode was parametrized. A failure model was created and simulation results were compared to measurements. Results of simulation are in good agreement to measurements.

REFERENCES

[1] J. E. Vinson, J. C. Bernier, G. D. Croft, and J. J. Liou, ESD Design and Analysis Handbook. Boston, MA: Kluwer, 2003, p. 48.

[2] K. H. Kim and Y. Kim, “Systematic Analysis Methodology for Mobile Phone’s Electrostatic Discharge Soft Failures”, Electromagnetic Compatibility, IEEE Transactions on, 2011, Vol. 53, No:3..

[3] J. Xiao, D. Pommerenke, F. Zhou, J. L. Drewniak, H. Shumiya, T. Yamada, K. Araki, “Model for ESD LCD Upset of a Portable Product”.

[4] A. Kabbani, A.J. Al-Khalili, “A technique for dynamic CMOS noise immunity evaluation, Circuits and Systems I: Fundamental Theory and Applications”, IEEE Transactions on, Volume: 50 , Issue: 1, 2003 , pp. 74 – 88.

[5] J. Zhang, J. Koo, R. Moseley, S. Herrin, X. Li, D. Pommerenke, D.G. Beetner, “Modeling Injection of Electrical Fast Transients Into Power and IO Pins of ICs”, Electromagnetic Compatibility, IEEE Transactions on, 2014.

[6] F. Lafon, M. Ramdani, R. Perdriau, M. Drissi, F. Daran, “An Industry-Compliant Immunity Modeling Technique for Integrated Circuits”.

[7] J. Laurin, S.G. Zaky, K.G. Balmain, “EMI-induced Delays In Digital Circuits: Prediction”, IEEE International Symposium on Electromagnetic Compatibility, 1992.