Introduction

Because of the growing complexity and the reduced turn-around time of modern designs, IP based strategies are becoming more and more popular. Usually, IPs are characterized as stand alone units, neglecting their mutual interaction. Unfortunately, this oversimplification is not always realistic. As a result, the overall operation of the circuit may be considerably affected. In fact, with the shrinking of the devices, the proximity of high frequencies noise sources and sensitive devices causes the substrate to carry spurious signals. In particular, in mixed designs, the presence of slow analog signals and fast switching digital waveforms may lead to unwanted interaction that might corrupt the circuit operation. To overcome this issue, heavy over-designs are often adopted, thus giving up part of the potential of the new technologies. Due to these complications, substrate modeling has become an issue among the RF and mixed-signal designer community.

During the operation of larger digital circuits, a considerable number of gates can switch in a clock cycle. Each transition usually involves the injection of part of the current directly into the substrate by means of mechanisms which will be discussed later on. This current is perceived as noise by the surrounding sensitive devices and it is referred to as switching noise.

Due to the high complexity of the designs, their unpredictable time behavior (because of the possibly huge dimension of the input space) and the number of different physical phenomena involved, an exact modeling is almost impossible. To date, most of the published works are on the propagation of the noise through the substrate, and some lumped linear models have been developed[2][3][4]. Contradictory results are found in the literature: in [5] the models are shown to be valid up to 40 GHz, while in [6] good approximation is found only up to 5 GHz. Some work has also been devoted to efficient techniques to numerically simulate the substrate coupling [2], but with the exception of SUBWAVE, no work has been devoted to circuit level substrate current injection.

A Methodology to Characterize Substrate Noise Currents Injected by Digital IP Cores

Stefano Zanella

SUBWAVE[1] is a methodology for generating compact models of substrate injection on complex logic networks. For a given library, the injection patterns associated with a gate and input transition scheme are accurately evaluated using circuit level simulation. The cumulative switching noise is then evaluated using event driven simulation. The resulting injected signal is then sampled and translated into an energy spectrum. In this project an extension of SUBWAVE to address process variations issues is presented. Moreover, an explicit formula to approximate the spectrum of the injected current is derived, providing the designers with a useful information for evaluating its impact on the (possibly) sensitive neighboring blocks. A new gate level characterization strategy is also presented.
Models for switching noise injected in the substrate are becoming more and more important in order to evaluate its impact on the operation of large circuits. They can be employed during the floorplan phase to let propagate only the components of the spectrum to which the analog part is not sensitive (if possible) and abate the remaining portion during its travel in the substrate (which behaves as a filter). The spectrum is also useful to design analog components that are insensitive to the dominant frequencies (in my opinion this is the best way to achieve good results).

The only available methodology for circuit level characterization of injected substrate current is SUBWAVE. There, all the possible input transitions that can cause substrate injection are precharacterized (the injected current, called noise signature, Fig. 1, as function of the time is provided), by a device level transient analysis. An event driven simulation is run on the circuit in order to record all the times at which the inputs of the gates switch (thus causing an injection). In this way, the overall noise signature can be computed by just summing up all the individual signatures resulting from the simulation. Finally, the spectrum is evaluated by F-transforming the time-domain signature into its frequency domain signature.

While this method is very effective, it requires the explicit storage of the signatures and its output is a set of samples of the noise spectrum, so that no functional approximation is provided to the user. Having a closed formula approximation would be very useful to the designer in order to apply optimization techniques. Moreover, in modern DSM technologies, statistical effects during the process steps may cause a substantial alteration to the circuit operation and a considerable yield loss[7]. Thus, neglecting these variations may lead to an optimistic estimation of the impact of the substrate injection.

In this project, the extension of SUBWAVE to the aforementioned issues is addressed. The preliminary results are presented as well.

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**Background**

In this section the necessary background is presented.

**Principles of Substrate Injection**

![Substrate Injection Diagram](image)

**FIGURE 1.** Substrate injection mechanisms and noise signature of a cell.

In a modern CMOS technology, several physical phenomena contribute to substrate current injection (Fig. 1). Among them, the most important are:

a) Hot electrons injection;
b) Parasitic capacitances coupling;

c) Gate Induced Drain Leakage (GIDL);

d) Photon Induced Current (PIC);

e) Diode Leakage Current.

**Hot Electrons Injection.** When a MOSFET device is operating in saturation regime, a high electric field develops in the depleted channel. While traveling in proximity of the drain, some electrons can gain a considerable amount of energy[8] (that’s why they are called hot). When they scatter in the lattice, some energy may be lost through a generation of an electron-hole pair, in a process called impact ionization. In a N-MOSFET device, electrons reach the drain terminal and holes are swept into the substrate, where they are collected at the bulk terminal. The impact ionization current, is usually proportional to the drain current by a coefficient that shows exponential dependency with the electric field applied to the channel.

**Parasitic Capacitances Coupling.** The drain (source) region of a MOSFET and the substrate form a pn junction. Therefore, they are directly coupled by means of the parasitic capacitances of the junction. Thus, if voltage fluctuations at the contact occur, the substrate behavior is directly affected. Moreover, a coupling can also take place between the gate and the bulk via the gate-channel and channel-substrate junctions.

**Gate Induced Drain Leakage.** When a high voltage drop between gate and drain occur, band to band tunneling can take place, resulting in a hole injection into the drain region. These carriers are then swept into the substrate and originating a current. Usually, this phenomenon is not very relevant, but it may become important under certain bias conditions. To date, it is not yet included in the transistor models for circuit simulation.

**Photon Induced Current.** Sometimes, hot electrons can release their energy by emitting a photon. Such a particle has a much greater average traveling distance than an electron (hole) and can propagate even in substrates that would normally block direct currents. When the photons are absorbed by the lattice, an electron/hole pair may be created. It is important to note that the locally generated minority carriers can be efficiently collected into sensitive, high-impedance nodes that would normally be capacitively isolated. This current shows the same dependence to device biasing and geometry of the impact ionization. This phenomenon has not yet been included in the transistor models for circuit simulation.

**Diode Leakage Current.** The source and drain junctions, as well as the substrate-well junction, are usually reverse biased. Some electron/hole pairs can thus be generated in the depletion region, leading to an additional current flow. This contribution is not usually significant, but under particular operating conditions, these junction may become forward-biased and a considerable amount of current can flow. This condition should be avoided by a careful design approach.

Usually, impact ionization and capacitive coupling are the dominant mechanisms of the substrate current. The other ones are normally neglected in circuit simulators. Nonetheless, they may play a significant role in the future technologies or even today under particular conditions. At cell level, all the devices injections sum up and result in the overall injection under a particular input transition. The injected current is also called cell signature (Fig. 1).
Process Variations Effects

With the steady decrease of the minimum feature size of deep submicron processes, the unavoidable inherent variability may considerably change the performances of a circuit with respect to its nominal behavior. The injected current may also change as result of phenomena that are not under complete control of the designers and/or process engineers. The process variations can be divided into two major categories:

a) Random variations;

b) Systematic variations.

Random Variations. In every process some steps are affected by the inherent stochastic effects. The main sources of randomness are:

a) Temporal and spatial non-homogeneity (diffusion, implantation, oxide growth, etc.);

b) Time-variance due to slightly different processing conditions (temperature, speed, pressure, etc.)

c) Materials imperfections (radial distribution of the resistivity along the wafer radius, for instance).

All these phenomena result in a randomness that is not predictable, and the operation of each device (even in the same die) is affected in a slightly different and unpredictable way.

Systematic Variations. In some process steps, deviations from the ideal set-up of the equipment (mask misalignments, optical aberrations, etc.) and/or material imperfections (different average resistivity of the wafers, composition of the gases, etc.) are usually unavoidable. The effect of these sources of variability is usually deterministic within one or more lots (all the devices in a certain die have the same effective length, for instance), and can sometimes be corrected[9]. Still, when the wafer is diced the information about die position is lost, thus it can be modeled as a random process[10].

The combination of these two sources of device characteristics variability is a random deviation of the performance of the circuits from their nominal behavior. Sometimes, it results in an unacceptable performance spread that can cause a considerable yield loss. Therefore, the impact of process variations should be taken into account in order to increase the yield and, thus, the revenue.

SUBWAVE

![SUBWAVE flow](image)

FIGURE 2. SUBWAVE flow.
To the extent of my knowledge, a considerable effort has been spent in modeling the substrate, but the only methodology available for the circuit level characterization is SUBWAVE. This technique is composed by four different steps[1]:

a) Signature characterization;

b) Event driven simulation;

c) Evaluation of the injected current (as function on time);

d) Spectrum computation (FFT);

Initially all the cells in a library are characterized. Every input transition of each cell is simulated and its signature is stored. All the input events are recorded even if they don’t produce any output transition. In fact, the internal stages of the cells may switch. Moreover, changing an input may cause a different voltage distribution in one or more devices in the cell.

It is important to notice that the characterization is a preliminary phase that is run once per process and is circuit-independent.

Given a sequence of input vectors, an event driven simulation is run in order to determine all the input transition of the cells in the circuit. This information, called switching activity, is then used to evaluate the overall injected current. If the substrate can be considered equipotential, all the cell signatures just sum up to give the circuit signature. The FFT is then computed yielding the power spectrum of the injected noise.

This methodology allows a designer to quickly evaluate the power spectrum in a fairly accurate way. Its major drawback is the fact that the power spectrum is computed numerically and is actually the one resulting in the nominal (best/worst) case conditions. Usually, these conditions are calculated with reference to the power/timing performances and not to the substrate injection. Thus, they may not represent the behavior of the circuit under process variations. Moreover, the substrate is considered to be completely equipotential.

**Legendre Polynomials**

In this section a quick overview of the properties of the Legendre polynomials is presented. Only those relevant to the problems herein addressed are illustrated. For further details the reader is referred to [11].

**DEFINITION 1** Let $f$ be a function defined on a set $G$. If the integral

$$m_n(f) = \int_G x^n f(x) dx, \quad n \geq 0, \quad n \in \mathbb{R}$$

exist, it is called the $n$-th moment of the function $f$.

Let us suppose from now on that the function $f$ assume non-zero value only on an interval $[a, b]$. Let us also suppose without loss of generality that $[a, b] = [-1, 1]$. If this were not the case, the affine transform:

$$Y = 2 \frac{X - a}{b - a} - 1, \quad X \in [a, b]$$

could be applied.

**DEFINITION 2** The polynomial:
Library Characterization

\[ L_n(x) = \sum_{k=0}^{\infty} d_{n,k} x^k, n, k \in \mathbb{R}, k \leq n \]  

(3)

is called the Legendre Polynomial of order \( n \) if:

\[ (n + 1)d_{n+1,k} = (2n + 1)d_{n,k} - nd_{n-1,k} \]

(4)

\[ d_{0,0} = 1 \quad d_{0,k} = 0, k > 0 \]

\[ d_{1,1} = 1 \quad d_{1,k} = 0, k = 0, k > 1. \]

THEOREM 1 The Legendre polynomials are mutually orthogonal, i.e. \( \int_{-1}^{1} L_n(x)L_m(x)dx = 0 \) if and only if \( m \neq n \).

THEOREM 2 Every function \( f \), square integrable in \([-1, 1]\) can be expanded as:

\[ f(x) = \sum_{n=0}^{\infty} c_n L_n(x) \]

(5)

and the coefficients \( c_n \) are given by:

\[ c_n = \frac{1}{h_n} \int_{-1}^{1} f(x)L_n(x)dx, n \in \mathbb{R} \]

(6)

where:

\[ h_n = \int_{-1}^{1} L_n^2(x)dx = \frac{2}{2n-1}, n \in \mathbb{R} \]

(7)

THEOREM 3 The coefficients \( c_n \) of the series expansion are given by:

\[ c_n = \frac{1}{h_n} \sum_{k=0}^{\infty} d_{n,k} m_k. \]

(8)

Proof: \[ c_n = \frac{1}{h_n} \int_{-1}^{1} f(x)L_n(x)dx = \frac{1}{h_n} \sum_{k=0}^{\infty} d_{n,k} \int_{-1}^{1} f(x)x^k dx = \frac{1}{h_n} \sum_{k=0}^{\infty} d_{n,k} m_k. \]

Using the theory of the orthogonal polynomials, it is thus possible to directly relate the moments of a function to the coefficients of the series expansion in a simple and elegant way.

Library Characterization

The signature of every cell in the library is characterized. The behavior of each cell may be represented as a function of input slope, output load, supply voltage, temperature and statistical process parameters (such as \( V_{th}, T_{ox}, \Delta L \), etc.).
Signature Approximation

The signature could be explicitly approximated by a function of the time of which coefficients are related to the parameters mentioned above. Unfortunately, each cell is characterized by its own set of signatures which can be very different. Thus a considerable number of different functions would be required. Moreover, these functions would have to be manually determined during the library characterization. Therefore, an unacceptable effort would be necessary.

According to the theory of orthogonal polynomials, each function defined in a finite interval \([t_1, t_2]\) can be expanded in series of Legendre polynomials. In order to determine the coefficients of the series, the moments must be calculated. If no statistical variations are taken into account, the moments are constants, otherwise they are functions of characterized process variations. In the former case, a circuit level simulation is sufficient to calculate the moments up to any order. In the latter case, each moment could be approximated with a polynomial function of both the deterministic and random parameters. Fitting such a model requires a set of circuit level simulations. In order to minimize their number, a Design of Experiments[12] can be applied, and the Response Surface Method[13] can be used. These two techniques provide a fairly accurate macromodel of the interested performance while minimizing the need characterization effort. An example is shown in experimental results.

The moments can also be used to directly approximate the Laplace transform of the signature, without actually applying it. In fact, as shown in [14], the n-th moment of a function \( h(t) \) and the n-th coefficient of the Mac-Laurin series expansion of its Laplace transform \( H(f) \) (called n-th circuit moment, \( m_n \)) are linked by a simple relation(10):

\[
H(f) = \sum_{n=0}^{\infty} \tilde{m}_n s^n \quad \text{(9)}
\]

\[
\tilde{m}_n = (-1)^n m_n \quad \text{(10)}
\]

Therefore, if the moments are available, an explicit approximation of the spectrum of the signature can be determined. This technique is known as moment matching.

Convergence of the series

An import issue in function approximation, is to determine under which conditions the series converges and how it does it (uniform convergency is very important in error bounding). Mathematically we must carefully state the problem in order to check the hypotheses rigorously.

Since we are representing a current, we will suppose the function \( h(t) \) be \( 0 \) for all \( t < 0 \) and for all \( t > t_0 \), where \( t_0 \) is the minimum time after which the cell doesn’t inject current anymore. Therefore \( h(0) = 0 \) and \( h(t_0) = 0 \). Moreover, \( h \) can be considered continuous and of bounded variation. Only pathological functions, usually, are not of bounded variation. It can be shown that under these hypotheses, the series converges uniformly (Hobson’s theorem[11], pag. 236).

If we have an approximation of the signature, the mean square error is the same in both frequency \( E(f) \) and time \( e(t) \) domain (Parseval Theorem):

\[
\int |E(f)|^2 df = \int |e(t)|^2 dt . \quad \text{(11)}
\]

Experimental Results

Some of the noise signatures corresponding to a subset of cell of the available library have been approximated with a Legendre series. In particular, the signature corresponding to the rising edge at...
an input (with the other one set to \( V_{DD} \)) of AND2 gate is shown in Fig. 3. The signature has been derived by a circuit level simulation, and the moments computed by MATLAB\cite{16}. This information has been fed into some function that calculate the coefficients of the series expansion. The reported approximation is calculated by using 15 moments. This is still a relevant number, but probably a better convergence can be achieved by properly scaling the function. In this way, the relative importance of the moments changes. If a proper scaling factor is selected, it is possible to increase the low order moments weight.

It is important to note that, anyway, with such a number of moments the result shown is absolutely on the average. And a very accurate approximation is usually achieved.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Approximation of a signature of a2 inputs AND gate.}
\end{figure}

\textbf{Signature Evaluation}

In order to trace the switching activity of a circuit, an event driven simulation is run. The output is a list of times and transitions. Each time in the list corresponds to an input transition of a gate and a signature is associated with it. The circuit signature is just the sum of all the signatures in the list.

In order to determine the circuit signature, the substrate will be considered equipotential everywhere. This hypothesis is not strictly necessary, but it simplifies the calculation of the injected noise. In fact, if the substrate weren’t equipotential, the injected current would be different from the one received by the sensitive IP because of its propagation in the substrate. If the substrate is linear, it could be modeled as a filter. In this case, the received spectrum would be simply the product between the injected current and the filter impulse response. Moreover, if the equipotentiality doesn’t hold in the injecting IP area, the overall spectrum would be the sum of all the signatures, each multiplied by its individual transfer function between the injecting and the receiving point. Thus, if we have \( N \) events in the list and at the \( k \)-th event a time \( t_k \) and a signature \( s_k(t) \) are associated, the circuit signature is:

\begin{equation}
I_B(t) = \sum_{k=1}^{N} s_k(t-t_k).
\end{equation}
Possibly, \( s_i(t) = s_j(t), i \neq j \), i.e. the same transition takes place more than once in different moments and/or places in the circuit (example: 2 inverters driving the same cell and connected to the same input).

In Fig. 4, the switching activity of a cell is reported. In this particular case, the cell undergoes 3 different input transitions that lead to 3 different signatures.

Formally, the circuit signature is evaluated by means of the moments. Its \( n \)-th moment is:

\[
m_n(I_B) = \int t \left( \sum_k s_k(t - t_k) \right)^n dt = \sum_k \left( \int (t + t_n s_k(t)) dt \right)^n = \sum_k \sum_j \int (n_j t_k t^{n-j} s_k(t)) = \sum_k \sum_j \int (t_k m_{n-j}(s_k), \quad (13)
\]

thus, it is linear combination of the first \( n \) moments of the signatures.

The same techniques used for the cell modeling are applicable here. In addition, the spectrum can be computed by just adding up the individual contributions. This approach is probably better when considering a substrate which is non-equipotential in the injection area, because the individual “filter” multiplication is easily performed in the frequency domain. Suppose \( H_k(s) \) is the transfer function between the gate injecting the \( k \)-th signature and the receiving IP. Then, the overall received spectrum is:

\[
I_B(s) = \sum_k H_k(s) S_k(s) e^{-st_k}, \quad (14)
\]

where \( S_k(s) \) is the Laplace transform of \( s_k(t) \).

Ongoing and Future Work

The characterization of a small counter (whose size is approximately 50 gates) in a 350 nm technology is being performed. Since the tool needed for the automatic characterization (Circuit Surfer[15]) is not yet available the the gates have been manually by simulation. All the signatures have been derived from a transient circuit analysis. No statistical variations are yet taken into account, but they will be as soon as Circuit Surfer is available. Due to the lack of the standard cell models, the event driven simulation has also been run manually, by inspecting the result of a circuit level simulation. The necessary mathematical routines to perform the Legendre series approximation have been implemented in MATLAB[16], and the signatures can be approximated with a very good accuracy.
In the future, the issue of bounding the error of the approximation is vital in order to be able to run the methodology automatically with the least possible manual effort. After the preliminary example of the counter is run, a relevant number of (possibly) standard benchmarks will be analyzed, in order to thoroughly test the methodology. Some measurements against an actual silicon test case should also be performed.

Conclusions

The SUBWAVE methodology is being extended in order to derive the spectra of the substrate current injected by an IP and received by a neighboring sensitive (possibly analog) circuit. The process variation effects are also taken into account and a mathematical approximation of the spectra is given. This capability might be very useful when designing a circuit and/or optimizing its yield. No explicit storage of the signature is required. A library characterization strategy accounting for process statistical variations is also being developed. In case of no process variation, the proposed characterization strategy is shown to be very effective. Many issues are still open and must be investigated in order to assess the methodology completely, but the theoretical results achieved so far seem to be very interesting.

REFERENCES