Spice-compatible modeling of high injection and propagation of minority carriers in the substrate of Smart Power ICs
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Abstract
Classical substrate noise analysis considers the silicon resistivity of an integrated circuit only as doping dependent besides neglecting diffusion currents as well. In power circuits minority carriers are injected into the substrate and propagate by drift–diffusion. In this case the conductivity of the substrate is spatially modulated and this effect is particularly important in high injection regime. In this work a description of the coupling between majority and minority drift–diffusion currents is presented. A distributed model of the substrate is then proposed to take into account the conductivity modulation and its feedback on diffusion processes. The model is expressed in terms of equivalent circuits in order to be fully compatible with circuit simulators. The simulation results are then discussed for diodes and bipolar transistors and compared to the ones obtained from physical device simulations and measurements.

1. Introduction
Power integrated circuits (IC) are affected by substrate noise due to the transient forward biasing of PN junctions during the circuit operating conditions [1,2]. In this case minority or majority carriers are injected into the substrate where they propagate by drift–diffusion reaching sensitive circuit and compromising their functionality. Parasitic bipolar junction transistor (BJT) paths are then activated by diffusion currents and if also drift currents are significant, a local potential shift of the substrate is registered [3]. In Smart Power ICs where high-voltage and low-voltages stages co-exist, the reliability of the entire system can be seriously compromised by these substrate couplings [4].

The simulation of these effects is challenging because the bipolar couplings are strongly geometry dependent and compact models for parasitic BJTs cannot be developed for a general IC layout before circuit fabrication and characterization. To overcome this problem, a distributed modeling methodology of the substrate has been proposed [5] in order to simulate the diffusion currents and detect lateral parasitic BJTs between devices [6]. This model can be efficiently encapsulated in circuit simulators because it solves the spatial dependent diffusion equation of minority carriers together with majority carriers drift currents. This avoids finite element simulations of the circuits by technological computer aided design (TCAD) software that are memory and time demanding [7].

However, if the diffusion currents are correctly modeled, the drift currents computation is assumed to be solely dependent on majority carriers. This is the typical case of mixed-signal substrate noise analysis where the resistivity of the substrate is modeled only as function of the doping profile [8,9]. Nevertheless, the previous assumption is valid only in low injection regime. When a huge amount of minority carriers are injected into the substrate, they locally modify the resistivity of silicon and their drift currents cannot be neglected. This means that considering only diffusion of minority carriers is not enough for high injection regimes that typically occur in Smart Power ICs when N-wells are transiently biased below ground condition [10]. Simulations for these voltage ranges lead to big errors because of the lack of a proper modeling of high injection effects.

As a consequence, this work focuses on the extension of the distributed substrate modeling methodology [11] for high injection regimes where drift currents of minority carriers are important. In this way the resistive behavior of parasitic BJTs can be correctly simulated with standard spice-like software and substrate currents can be predicted for all ranges of possible applied voltages.

For this purpose, in Section 2 the distributed modeling methodology for the substrate is described and the physical coupling mechanisms between drift and diffusion currents of majority and
minority carriers are recalled. The main modeling issues for high injection regimes are then explained. The proposed models for substrate conductivity modulation and minority carriers drift–diffusion are presented respectively in Sections 3 and 4 in terms of voltages and currents for a piece of substrate. To simulate in circuit tools the overall couplings, an equivalent circuit of junctions is also required and reported in Section 5. Finally, the results of the implemented model is presented in Section 6 compared with TCAD simulations for diodes and parasitic BJT and with measurements of simple structures in Smart Power ICs. Conclusion is reported in Section 7.

2. Minority carriers modeling

Power transistors can be simulated by compact models. However, parasitic vertical and lateral BJTs always exist between the different N and P doped wells of the circuit. The corresponding junctions are normally reverse biased without compromising the reliability of the chip but during power stages switching they undergo to forward bias activating latch-up current paths. As a result, there is the need of adding to the transistor models a network of parasitic components related to the IC substrate (see Fig. 1). The overall substrate equivalent network can be then interfaced to the compact models of transistors. If on one side vertical BJTs can be characterized, all attempts to model parasitic lateral BJTs failed because they are dependent on the circuit layout (e.g. on the distance of various transistors).

Instead of characterizing each bipolar combination between different wells, a multi-junction approach is preferred. As described in [12], the substrate can be divided in blocks creating a three dimensional equivalent parasitic network. When a PN junction is detected a diode is added to simulate injection or collection of minority carriers otherwise a diffusion resistor is placed. An example is reported in Fig. 1 assuming for simplicity rectangular shaping of diffusion wells. A part from the two terminals carrying physical voltages and currents as in substrate noise models [8], the introduced components have additional terminals to generate and propagate minority carriers.

On these new terminals equivalent voltages \( V_{eq} \) are proportional to the minority carriers excess concentration and equivalent currents \( I_{eq} \) are proportional to their gradient. Solving the Kirchhoff’s voltage law (KVL) and current law (KCL) to the added nodes, the complete distribution of minority carriers is simulated and bipolar paths can be detected [5]. Similar modeling approach for power diodes has been proposed in [13].

The minority carriers propagation is implemented in each component by analytic solution of 1D diffusion equation. However, in high injection conditions (i.e. injected minority carriers concentration comparable with doping) coupling mechanisms with majority carriers are significant. As reported in Fig. 2, if on one side the excess concentration of injected carriers modulates the conductivity and then the substrate voltage drop, on the other side non negligible electric field appears adding a drift component to the diffusion of minority carriers.

These coupling mechanisms are not included in the state-of-the-art modeling of the substrate and only TCAD based approaches are then available to simulate such effects. The objective of this work is then to provide a solution to the following three main modeling issues arising in high injection condition:

(i) Substrate conductivity modulation: if there is high injection of minority carriers the conductivity of silicon is spatially modulated depending on the injected concentration of electrons or holes. Because of the increase of minority carriers drift currents, the local potential drops are also affected by minority carriers and classical substrate tools do not predict the potential shift of the substrate;

(ii) Minority carriers propagation: in high injection spatial dependent electric field appears and closed form solution of the drift–diffusion equations does not exist because of the high coupling between minority and majority carriers. The proposed approach in this case is to avoid analytical formulas and to use instead a finite difference scheme to discretize continuity equations for minority carriers. The goal is to properly model the coupling between electrons and holes maintaining the same propagation approach with KCL and KVL;

(iii) Modeling of junctions: abrupt changes of carriers concentrations and electric fields appears at junctions. These phenomena strongly affects the propagation of electrons and holes due to the presence of energy barriers. This is not only the case of PN junctions but also of homojunctions PP+, NN+ situated at the contacts [14] where boundary conditions are applied. In these regions a compact model including minority carriers is then required. As a result, a spatial distributed model is used for the propagation of carrier in the whole substrate and only at PN junctions and contacts a compact model is applied.

In the following sections the proposed solutions for the modeling of these issues will be detailed.

3. Substrate conductivity modulation

To develop the substrate model, one dimensional drift–diffusion model is assumed for electrons and holes. For simplicity a
P-doped piece of substrate with doping concentration $N_d$ is considered hereafter, but same considerations can be applied for N-doped silicon.

In order to simplify the problem the quasi-neutral assumption is considered, i.e. the excess of holes (majority carriers) is equal to the difference between the electric field and the electric field $E(x)$ is assumed constant in the considered volume of cross section $A$ and length $\Delta x$.

This quasi-neutrality hypothesis can be assumed valid both in low injection and in high injection. In the first case $E(x) \cong 0$ and no significant voltage drop appears, while in high injection conditions where the electric field is significant, $E(x) - \bar{n}(x)$ is much less than injected minority carriers $\bar{n}(x)$ and can be neglected.

Under these conditions the total constant current density flowing in the semiconductor can be written as:

$$ J \cong q \left[ \mu_p (N_a + \bar{n}) + \mu_n (n_0 + \bar{n}) \right] E + q (D_n - D_p) \frac{\partial \bar{n}}{\partial x} $$

(1)

where $\mu_{np}$ are the carriers mobilities assumed constant, $D_{np}$ the diffusivity coefficients where Einstein’s relations can be used and $n_0$ the equilibrium concentration of electrons.

Two contributions to the total current can be recognized: the ohmic part $J_{\text{ohm}}$ proportional to the applied voltage drop assuming a constant electric field $E = \Delta V / \Delta x$, and a correction term $J_{\text{bulk}}$ taking into account the difference between majority and minority diffusion currents. Due to the quasi-neutrality hypothesis $J_{\text{bulk}}$ is solely proportional to the gradient of injected minority carriers. The conductivity of the semiconductor piece is then modulated by the spatial dependent excess of minority carriers as:

$$ \sigma(x) = q \left[ \mu_p (N_a + \bar{n}(x)) + \mu_n (n_0 + \bar{n}(x)) \right] $$

(2)

Two limit cases can be analyzed:

- Low injection $\bar{n} \ll N_d$: in this case the conductivity is not spatially dependent and it is mainly determined by the doping. This is the case considered in all previous models of substrate [8].

$$ \sigma_0 = q \left[ \mu_p N_a + \mu_n n_0 \right] \approx q \mu_p N_a $$

(3)

- Very high injection $\bar{n} \gg N_d$: in this case the conductivity is strongly spatial dependent and it is determined only by minority carriers excess concentration.

$$ \sigma_{\text{hi}}(x) \approx q \left[ \mu_p + \mu_n \right] \bar{n}(x) $$

(4)

In medium or high injection conditions the general Eq. (2) should be used. Notice that in the case of P-type substrate in high injection, the $J_{\text{ohm}}$ is mainly dominated by electrons (minority carriers) drift current that is bigger than holes (majority carriers) current due to the mobility ratio.

The equivalent substrate circuit corresponding to Eq. (2) for the total current propagation is reported in Fig. 3 where $A$ represents the cross section area of the considered substrate volume. The inspection of the circuit shows the standard resistive element of substrate noise analysis (conductance $G_0$), plus a term that is proportional to the minority carriers injection level (conductance $G_{\text{min}}$). The physical current $I_{\text{tot}}$ includes the contributions of drift and diffusion of both majority and minority carriers.

The $J_{\text{bulk}}$ correction term (proportional to $(D_n - D_p)$) is usually smaller than the rest but it can have a non negligible effect [15] thus it should be added for completeness.

4. Minority carriers propagation via drift–diffusion mechanism

For a complete description of the drift–diffusion processes inside a silicon volume, minority carriers concentration $\bar{n}$ and gradient $\partial \bar{n} / \partial x$ should be known (cf. Eq. (1)). Minority carriers propagates by drift–diffusion mechanism and it is assumed that they fully recombine at ohmic contacts.

In high injection conditions, the solution of the stationary drift–diffusion differential equations cannot be written in closed form. To model the propagation of minority carriers a different approach should be used. The quasi-neutrality assumption strongly simplifies our analysis because only minority carriers continuity equation is considered.

In case of a P-doped silicon, the one-dimensional continuity equation to solve can be written in the stationary case as:

$$ \frac{d}{dx} \left( q \mu_n \bar{n}(x) E(x) + q D_n \frac{d \bar{n}(x)}{dx} \right) = q \frac{\bar{n}(x)}{\tau_n} $$

(5)

where $\tau_n$ is the lifetime of electrons and a simple recombination model proportional to the excess of minority carriers is considered.

Applying a central difference finite-difference scheme this equation can be linearized in a length $\Delta x$ of the space. This corresponds to the discretization of the substrate volume proposed in the modeling methodology. The linearized equation can be expressed in terms of an equivalent $R$-circuit as the one presented in Fig. 4.

The equivalent voltage is proportional to the excess concentration of electrons $V_{eq} = q \bar{n}$, where the elementary charge $q$ is added for scaling purposes. The equivalent current flowing in the circuit is instead proportional to the minority carriers current and corresponds to a diffusion current $I_{eq} = q D_n \partial \bar{n} / \partial x$. Knowing $V_{eq}$, $I_{eq}$ allows to correctly modify $G_0$ and $J_{\text{bulk}}$ terms of Fig. 3 introducing couplings between the two circuits. For low injection condition ($E = 0$) the proposed circuits are decoupled and the resulting network is equivalent to the substrate modeling methodology presented in [11].

In the minority carriers circuit of Fig. 4 three components similar to the Linvill’s circuit ones [16] can be recognized:

1. The diffusance $G_0$ is a conductance dependent on the diffusivity and regulates the diffusion current $I_{eq}$:
2. The combination $G_c$ is a conductance dependent on the lifetime and regulates the portion of minority carriers that recombines in the considered volume:

$$G_c = \frac{\Delta x}{2\tau_n}$$

(7)

3. The driftance $g_{\text{drift}}$ is a transconductance that weights the contribution of the electric field (drift term) and it is dependent on the average minority carriers concentration:

$$g_{\text{drift}} = \frac{V_{eq,1} + V_{eq,2}}{2}$$

(8)

Although similarities, the derivation of this circuit is different from the Linvill's one. As a result, in our proposed modeling methodology only minority carriers and constant total current are considered without the need of majority carriers diffusion modeling nor Poisson’s equation inclusion. The simplification of three semiconductor equations into one has been possible with the quasi-neutrality hypothesis. This is the main advantage compared to standard numerical modeling or more complete approaches like the Sah's circuit [17] where quasi-fermi levels are considered as variables instead of carriers concentrations.

Furthermore, the presented circuit for minority carriers is equivalent to the one used in transmission-line modeling (TLM) [18]. With respect to TLM, our approach differs by 2 major contributions:

- the model of the electric field effect (drift) on minority carriers propagation (diffusion) is more detailed since spatial dependent field is included;
- minority carriers circuit is coupled back to the total current circuit where majority carriers are taken into account.

To solve this coupled system, boundary conditions are applied from the contacts. They can be current (Neumann’s condition) or voltages (Dirichlet’s conditions) for the total current circuit and total recombination $V_{eq} = 0$ (Dirichlet’s condition) for minority carriers. Using then KVL and KCL to the different blocks interconnected together, the overall distribution of currents, voltages and minority carriers is obtained with standard circuit simulators.

5. Equivalent circuits of junctions

Apart from propagation, also injection of minority carriers must be taken into account. This injection occurs at PN junctions which can be viewed as source regions of electrons and holes. For a correct current estimation, a modeling is required also in high injection since the injected carriers concentration slowly saturates for high applied forward bias voltages.

Hereafter equivalent abrupt profile junctions will be considered. However, in real circuits the doping profile is spatial dependent and there are regions where PP+ or NN+ junctions appears. This large discontinuity of doping is the typical case of contacts. At these interfaces the minority carriers boundary condition changes thus they cannot be neglected. In the following subsections the modeling of homo- and hetero-junctions with equivalent circuits will be presented.

5.1. Homojunction circuit

Two differently P-doped (or N-doped) regions of the substrate constitute a high-low doped homojunction. Neglecting for simplicity the presence of a space charge zone, it is interesting to investigate the effects of these homojunctions on minority carriers propagation. From the point of view of total current a PP+, NN+ junction can be seen as a resistance discontinuity where the voltage drop abruptly changes. In this case connecting together two total current circuits with different doping will be enough. This is evident in the general homojunction equivalent circuit reported in Fig. 5, where for the total current two silicon resistive elements are simply interconnected together.

On the contrary, for minority carriers excess concentration a jump is registered to fulfill Boltzmann’s statistics. Assuming quasi-neutrality out of the equilibrium, the mass action law imposes a relation between the injected minority carriers $\tilde{n}_1$ on the P side and $\tilde{n}_2$ on the P+ side (Eq. (9)).

$$\tilde{n}_1 (N_{e1} + \tilde{n}_1) = \tilde{n}_2 (N_{e2} + \tilde{n}_2)$$

(9)

This condition can be modeled as discontinuity of minority carriers concentration and then as a drop of equivalent voltages $\Delta V_{eq} = q(\tilde{n}_2 - \tilde{n}_1)$. The introduced voltage discontinuity can be viewed as a reflection of minority carriers at the PP+ interface which changes the recombination boundary condition. This leads to “minority carriers mirrors” effects as detailed in [14].

5.2. Heterojunction circuit

In a PN junction there is an exchange of minority–majority carriers. At the border of the depletion region between the metallurgical junction, minority carriers excess concentration is regulated by junction laws that fulfill the Boltzmann statistics. If in low injection Shockley boundary conditions can be used with an exponential injection of carriers, in high injection more general Misawa boundary conditions apply [19]:

$$\tilde{\rho}_n \simeq \frac{N_a}{2} \sqrt{\frac{4\eta_n^2 \left( \frac{v}{v_t} \right)^n}{1 + \frac{v}{v_t} - 1}}$$

(10)

$$\tilde{\rho}_p \simeq \frac{N_p}{2} \sqrt{\frac{4\eta_p^2 \left( \frac{v}{v_t} \right)^p}{1 + \frac{v}{v_t} - 1}}$$

(11)

where $\eta_i$ is the intrinsic concentration of carriers in silicon, $v_i$ is the thermal voltage, $v_t$ a voltage correction term, $N_a$ the doping of P-side and $N_p$ the doping of N-side assuming abrupt junction. In low injection case the $\approx v^{n/2n}$ dependency is obtained while in high injection $\approx v^{p/2p}$ is expected. As shown in Fig. 6, Eqs. (10) and (11) are equivalent to voltage sources of minority carriers concentration controlled by the voltage drop across the junction $V_j$ (namely $V_{eq,n} = \tilde{\rho}_n$ and $V_{eq,p} = \tilde{\rho}_p$).

Since with high injection the maximum voltage drop across the junction saturates to the built-in potential $V_{bi}$, the carriers injection is expected to saturate. Despite this, the injected carriers level is

![Fig. 5. Homojunction (PP+) equivalent circuit.](image-url)
dependent on the quasi-fermi potentials (called imref) splitting that in high injection is not corresponding to the voltage drop anymore. From the definition of imref, the correction term \( V_{\text{r}} \) dependent on the minority carriers gradient is added and defined as:

\[
V_{\text{r}} = V_{\text{r}} \ln \left( \frac{N_{p0} + \bar{N}_{p}}{N_{p0} + \bar{N}_{n}} \right) + V_{\text{r}} \ln \left( \frac{N_{p0} + \bar{N}_{n}}{N_{p0} + \bar{N}_{p}} \right)
\]  

(12)

In Eq. (12) \( n_{p0} \) are the excess carriers concentrations at the boundaries \( x_{p} \), \( x_{n} \) of the depletion region and \( n_{1}, p_{1} \) the concentrations at \( W_{p} \) and \( W_{n} \) geometrical boundaries respectively (see Fig. 6). As a consequence the injected concentration of minority carriers could continue to increase also in high injection and does not completely saturates.

Finally, to ensure that the total current \( I_{\text{tot}} \) flowing inside the system is conserved (solenoidal current), the current \( I_{\text{tot}} \) in the total current circuit is imposed by minority carriers currents of electrons at P-side boundary \( x_{p} \) and of holes at N-side boundary \( x_{n} \). In low injection these are diffusion currents, in high injection they become mainly drift currents also for minority carriers while generally Eq. (13) applies. Taking into account all these aspects, the equivalent circuit of a PN heterojunction is reported in Fig. 6 where Thvenin’s theorem is applied to simplify unnecessary components (see shaded elements).

\[
I_{\text{tot}} = I_{\text{e}, \text{diff}}(x_{p}) + I_{\text{p}, \text{diff}}(x_{p}) + I_{\text{p}, \text{diff}}(x_{n}) + I_{\text{e}, \text{diff}}(x_{n})
\]

(13)

6. Model validation

The presented models for diffusion resistance, homojunction and heterojunction have been implemented in VerilogA code and simulated in Spectre circuit simulator. The validation of the results is done by comparison with TCAD simulations in one dimensional structures. Synopsys Sentaurus Device simulator has been used for this purpose. The required parameters of the VerilogA model are the doping concentrations, the lifetime of carriers and the geometrical dimensions. These parameters are equals to the one set in TCAD simulations and follows the same doping and temperature dependencies. In particular, Arora’s mobility model [20] has been used to evaluate the silicon resistivity and Scharfetter relation is used for lifetime [21]. An additional recombination lifetime trapping parameter is added in the VerilogA code to take into account the generation–recombination processes for reverse bias and low forward bias region [22]. In each simulation the parameter values are set by the geometry and dopant densities and no additional fitting parameters are added (e.g. no series resistance parameter is present).

Since the proposed modeling methodology is junction based, first the behavior of diodes in high injection is investigated and then the typical configuration of parasitic BJT between two wells in a Smart Power ICs is studied. Finally, a lateral parasitic BJT in high-voltage technology has been also measured and compared with model results.

6.1. Resistivity of PN junctions

To study the resistivity of a PN junction, a diode with N-side doping concentration of \( N_{d} = 10^{17} \text{ cm}^{-3} \) and with a low doped P-side with \( N_{p} = 7 \times 10^{14} \text{ cm}^{-3} \) has been considered as case-study. Two P+ and N+ end contacts of 200 nm thickness and \( 2 \times 10^{19} \text{ cm}^{-3} \) dopant concentration have been added. The geometrical dimensions and the equivalent circuit modeling is presented in Fig. 7.

For a cross section area of 2.5 \( \mu \text{m}^2 \) the classical equivalent dopant dependent series resistance of this low-doped silicon volume is about 780 k\( \Omega \). It is expected that when high injection is reached the current flowing in the semiconductor will be limited by this huge resistivity. However, simulations show that several hundred of milliampere can flow in this diode when forward bias is greater than 1 V. Simulation results of forward bias up to 2 V characteristics are reported in Fig. 8 for TCAD and VerilogA coded model at different temperatures. The temperature dependency follows the same empirical formulas for the silicon bandgap, the intrinsic carriers concentration, the mobility and the lifetime in the VerilogA code and in TCAD. In these simulations mobility degradation due to electric field is disabled because the values of electric field in the P and N side do not change remarkably the mobility value even in high injection. Moreover, the ohmic contact is assumed to have zero-resistance in order to check the model of the intrinsic conductivity modulation of the device. In reality the presence of a contact resistance can limit the current flowing in the device as shown in the measurements reported in Section 6.3.

The model results are in good agreement with physical device results in high injection regime only when conductivity modulation is taken into account. If the coupling mechanisms of Fig. 2 are disabled in the model, the classical doping dependent resistivity is instead simulated. This simulation clearly shows that if the overestimation of the diode resistance due to standard doping-dependent conductivity model is applied, it results in orders of magnitude error in the current.

The effect of conductivity modulation to the average series resistances of P and N sides is reported in Fig. 9. It is clear that P-side undergoes high injection before N-side as expected by doping difference inspection. The resistance is much lower for high applied voltages than the one of a pure silicon piece doped \( N_{d} \) or \( N_{p} \). In the first case few ohm series resistances as expected for diodes are obtained, while in low injection several k\( \Omega \) as expected for integrated diffusion resistors are simulated. The same behavior is present in the base resistance degradation of BJTs [23].

As previously described, the conductivity is also spatially modulated in the P and N region by carriers injection. Repeating the simulation with 10 subdivisions of the P-side at 1.2 V forward bias,
the space modulation is clearly visible as reported in Fig. 10. In particular, the resistance is lower near the PN junction and is higher near the PP+ junction. This means that electrons are more concentrated at the homojunction PP+ than at the heterojunction PN. This counterintuitive effect is due to the PP+ interface that accumulates electrons. If the P+ is removed the simulation shows indeed the opposite behavior where more electrons are injected at the PN junction while total recombination is imposed at the metallization. The reported simulation is then a proof of the importance of homojunctions in minority carriers modeling.

Moreover, if there are more electrons at PP+ interface, this means that in high injection the gradient of minority carriers reverses and the diffusion current is negative. This effect is confirmed in Fig. 11 around 0.7 V, where it can be noticed also the increasing importance of minority carriers drift current when large forward bias voltages are applied. As expected in high injection the drift current of electrons is the dominant one for the P-side of the diode (e.g. at 1.5 V the electron current is 19 mA while the hole current is 8 mA).

6.2. Parasitic lateral BJT simulations

Since the proposed model is able to propagate minority carriers, bipolar transistors can be simulated just interconnecting the different devices together.

Let’s consider typical aggressor–victim configuration in Smart Power ICs between 2 equal N-wells with average donor doping concentration \( N_d = 10^{17} \text{ cm}^{-3} \). One of the two wells is supposed to undergo below ground condition injecting electrons in the substrate (emitter \( N_1 \)) and the other is reverse biased at the supply voltage of 50 V collecting the current (collector \( N_2 \)). The low-doped P substrate with an equivalent doping of \( N_d = 4 \times 10^{15} \text{ cm}^{-3} \) is biased at 0 V and it acts as the base of the parasitic lateral BJT. This configuration can be simulated with an equivalent NPN bipolar transistor whose parameters and the equivalent circuit model are reported in Fig. 12. P+ and N+ contacts implantations doped \( 10^{19} \text{ cm}^{-3} \) are also included for completeness.

The simulation results of base, emitter and collector currents are reported in the Gummel plot of Fig. 13 in the case where the two wells are separated by a distance \( d = 20 \mu \text{m} \) with the base contact in the middle. A good agreement of the circuit model with TCAD from low to high injection levels is present. In particular around 1.2 V the base current becomes larger than the collector current because at these voltage ranges drift mechanisms are dominant. This gain degradation can be also be viewed in the high injection roll-off of the \( \beta \) reported in Fig. 14. In the same graph is also reported the \( \beta \) of the same transistor where P+ contact is
removed and 0 V is applied directly to the low doped substrate. The huge difference is due to the presence of the homojunction which does not fully recombine the electrons letting them pass through the base towards the collector (minority carrier mirror). Once again the simulation and modeling of homojunctions is proved to be fundamental in minority carriers propagation modeling.

If now the distance between the two wells is doubled, the bipolar effect is weakened. To study the effect of wells-distance on their coupling, it is sufficient to add more diffusion resistors in the base equivalent circuit (assuming the base contact kept in the middle). From the new simulations at \( d = 40 \mu m \) (both model and TCAD, see Fig. 14) a 30% reduction of the gain of the parasitic BJT is obtained. The simulated base transport factor \( \alpha \) reported in Fig. 15 shows that in all low injection regime the new distance has practically no impact and the two wells are strongly coupled \( (\alpha \approx 1) \). However, in high injection the effect of increasing the base resistance

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**Fig. 12.** Simulated parasitic BJT (top) with equivalent circuit (bottom) including N+ and P+ contact resistances.

**Fig. 13.** Gummel plot simulation for a base length \( d = 20 \mu m \). Dots are from TCAD simulations and continuous lines from circuit model. The inset shows the detail of currents in high injection.

**Fig. 14.** Simulated gain \( \beta \) for different base lengths. Dots are from TCAD simulations and continuous lines from circuit model.

**Fig. 15.** Simulated base transport factor \( \alpha \) for two different base lengths. Dots are from TCAD simulations and continuous lines from circuit model.
(see $R_1$ and $R_2$ in Fig. 12) reduces the coupling. The good agreement of the results proves that the base resistance composed by the interconnection of $R_1$, $R_2$ and $R_3$ is well modeled.

The results match with TCAD predictions and the circuit simulations can be quickly repeated for several other geometrical configurations with a gain of around a factor 1000 in simulation time.

6.3. Parasitic lateral BJT measurements

In order to validate the proposed model, a dedicated test structure was designed in a Smart Power 0.35 μm technology to compare measurement with spice simulations. The test structure (see Fig. 16) consists of two aligned high voltage N wells distant $d = 71 \, \mu m$ with area equal to $\approx 15,000 \, \mu m^2$. Each well is surrounded by a 4.5 μm wide substrate P+ contact ring connected to ground. During the measurements done on probe station, the emitter voltage $VE$ was swept from 0 V to $-1.4 \, V$ while the collector was biased to a constant voltage $VC = 10 \, V$. Under these bias conditions, the parasitic lateral NPN was activated and characterized from low to high injection.

Due to the particular long well shape, the proposed structure can be simulated using a 2.5D substrate equivalent circuit model. The corresponding parasitic substrate network is derived from the layout cross sections and shown in Fig. 16. The final VerilogA model parameters match the technology average substrate and N-wells doping concentrations. In this case, a lumped element standard resistance was connected in series with the emitter, base and collector terminal to include the effects of parasitic metal resistances connections to the external IC pads.

The measured and simulated Gummel plot of the parasitic lateral NPN is reported in Fig. 17 together with the $x$ variation from low to high injection regime. Simulations and measurements are in agreement with an average error of 30%.

7. Conclusion

Substrate couplings in Smart Power ICs require the modeling of minority carriers in circuit simulators. In high injection condition drift currents are dominant and the substrate conductivity is strongly modulated by the injection of electrons and holes. Equivalent circuits for diffusion resistances, heterojunctions and homojunctions have been then proposed and implemented in VerilogA to extend the simulation of drift–diffusion currents in spice-like tools.

The proposed models allows fast substrate simulations of minority carriers from low to high injection voltage ranges. Results are in good agreement with TCAD device simulations with an improvement of simulation time around 1000. The spatial modulation of substrate resistance has been verified for diodes and bipolar transistors. Simulations showed that the model is able to detect points where drift current and resistive effects became dominant and their impact on the parasitic coupling between 2 wells.

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References


solid-state device research conference (ESSDERC); 2010. p. 194–97. doi:http://dx.doi.org/10.1109/ESSDERC.2010.5618395.


