Coupled electro-magnetic field & Lorentz force effects in silicon and metal for ESD investigation in transient and harmonic regimes

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A R T I C L E   I N F O

Article history:
Received 29 May 2015
Received in revised form 15 June 2015
Accepted 15 June 2015
Available online xxxx

Keywords:
Electro-magnetic field
ESD
Lorentz force

A B S T R A C T

The purpose of this paper is to present a fully-coupled electro-magnetic field formulation including Lorentz force corrections with the purpose of investigating ESD events in great detail in silicon (FEOL) and the metal stack (BEOL). This study is focused on ESD events in advanced CMOS technology. For specific ESD events, responses, design and topology it is important to take into account all electromagnetic phenomena in the structure. To perform such an accurate study, the first step is to build a powerful tool for the harmonic and transient regime coupling all electric and magnetic fields. Typical ESD structures are simulated to ultimately know the impact of the electro-magnetic field and Lorentz force. The harmonic regime is used for parasitic capacitance extraction and the transient regime for the ESD behaviour. We demonstrate that the simulation tool has a wide range of applicability by giving additional applications.

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1. Introduction

Electro-Static Discharge (ESD) events are a major challenge due to the down-scaling that leads to the intrinsic device-robustness decrease as is well known [1–4]. Down-scaling leads to a continuous narrowing of the ESD window. For ESD experts, there are two major concerns: First, the intrinsic ESD robustness under very aggressive events typically 1 A up to 30 A in 1 ns up to 100 ns range time, and second is the ESD device impact on design functionality: the parasitic capacitance is a key parameter for the evaluation of analogue and RF design (see Fig. 1). In this framework, knowledge about the impact of electro-magnetic field (EMF) with Lorentz force (LF) corrections during the ESD event is a useful information. To assess the intrinsic robustness the transient regime is considered and the EMLF impact is evaluated in the silicon and in the metal stack layers. To perform the ESD parasitic capacitance extraction the harmonic regime is used. In the next sections of this paper, we will present the physical model and its coding in the numerical tool for both regimes. Different examples will be provided in transient and harmonic behaviours. (See Table 1.)

2. Physics equations and numerical solver

The aim of these 2 sub-paragraphs is to give a summary of the equations and of the solver.

2.1. The physics and the equations

This section introduces the equations used for underlying ESD analysis. Obviously, they can be used for other purposes involving these kinds of physical considerations. Typically, high current/voltage power switches, RF switches or magnetic sensors are the scope. First of all, the Maxwell equations are: \( \partial_t F = -4nJ \) and \( \partial_t \mu F = 0 \). The Faraday tensor is defined by \( F(t) = \partial_t A(t) \) and \( \partial_t (J(t) \times B(t)) \). Moreover, the Lorentz gauge condition \( \partial_t A(t) = 0 \) is used. The total force acting on the electron and hole carriers that takes into account the Lorentz force is \( F(t) = qE(t) + q\mu(t) \times B(t) \). In this case, the electric and magnetic fields are given by: \( E = -\nabla \phi - \partial_t A = \nabla \times A + B_{\text{ext}} \). Here, the magnetic field consists of 2 contributions of which one is the self-induced field and the other the external magnetic field \( B_{\text{ext}} \). For the silicon regions, the current densities for \( e^- \) and \( e^+ \) in the classical drift-diffusion modelling without thermal gradient effect but with the Lorentz force are:

\[
\begin{align*}
J_e &= q\mu_e n(E + v_n B) + kT\mu_e \nabla n \\
J_p &= q\mu_p p(E + v_p B) - kT\mu_p \nabla p
\end{align*}
\]

The current-continuity equation is one more condition for the description of the drift-diffusion model: \( \nabla \cdot J = -\partial_t n + U \). The charge density is \( \rho(V, \phi_n, \phi_p) \) in the local thermodynamic equilibrium and the carrier (\( e^- \) and \( e^+ \)) distributions are related to the inter levels \( \phi_n \) and \( \phi_p \) according to: \( n = n_i \exp[\frac{q(V - \phi_n)}{kT}] \) and \( p = n_i \exp[\frac{q(V - \phi_p)}{kT}] \). Moreover, to take into account the non-equilibrium, the recombination/generation rate in silicon material is basically: \( U = \)
R = G and the SRH model. Inside metallic wires the skin effect is induced due to the fast time-varying magnetic fields. An additional modification is triggered by the Lorentz force. Using the approximation \( |\mu_B| \approx 1 \), the current density in metallic regions takes the form:

\[
J = \sigma \cdot E + \mu_B \cdot \dot{\phi} \times B.
\]

### 2.2. Numerical solver overview

The key approach for the solver is the discretization step and the matrix form. Thus the device mesh and all decompositions are done on polyhedron [5] (Fig. 2).

The current-conservation equation becomes with finite integration:

\[
\sum_j d_j J_{ji}^\text{EM} (t) + \sum_j d_j J_{ni}^\text{ff} + s R_i (t) \Delta V_i + s \partial_i c_i (t) \Delta V_i = 0.
\]

The associated matrix of the Newton-Raphson solving procedure is

\[
\begin{bmatrix}
\frac{\partial}{\partial \phi} & \frac{\partial}{\partial \phi} & \frac{\partial}{\partial \phi} & \frac{\partial}{\partial \phi} & \frac{\partial}{\partial \phi} \\
\frac{\partial}{\partial \phi^\text{EM}} & \frac{\partial}{\partial \phi^\text{EM}} & \frac{\partial}{\partial \phi^\text{EM}} & \frac{\partial}{\partial \phi^\text{EM}} & \frac{\partial}{\partial \phi^\text{EM}} \\
\frac{\partial}{\partial \phi^\text{ff}} & \frac{\partial}{\partial \phi^\text{ff}} & \frac{\partial}{\partial \phi^\text{ff}} & \frac{\partial}{\partial \phi^\text{ff}} & \frac{\partial}{\partial \phi^\text{ff}} \\
\frac{\partial}{\partial \phi^\text{MM}} & \frac{\partial}{\partial \phi^\text{MM}} & \frac{\partial}{\partial \phi^\text{MM}} & \frac{\partial}{\partial \phi^\text{MM}} & \frac{\partial}{\partial \phi^\text{MM}} \\
\frac{\partial}{\partial \phi^\text{Q}} & \frac{\partial}{\partial \phi^\text{Q}} & \frac{\partial}{\partial \phi^\text{Q}} & \frac{\partial}{\partial \phi^\text{Q}} & \frac{\partial}{\partial \phi^\text{Q}} \\
\frac{\partial}{\partial \phi^\text{A}} & \frac{\partial}{\partial \phi^\text{A}} & \frac{\partial}{\partial \phi^\text{A}} & \frac{\partial}{\partial \phi^\text{A}} & \frac{\partial}{\partial \phi^\text{A}}
\end{bmatrix}
\begin{bmatrix}
\Delta V \\
\Delta \phi^\text{EM} \\
\Delta \phi^\text{ff} \\
\Delta \phi^\text{MM} \\
\Delta \phi^\text{Q}
\end{bmatrix}
= -
\begin{bmatrix}
P \\
J^\text{EM} \\
J^\text{ff} \\
J^\text{MM} \\
J^\text{Q}
\end{bmatrix}.
\]

Moreover, the boundary conditions are Neumann and Dirichlet for all field equations. The time consumption is around 10 h with the computing farm for a full 3D structure under surge stress. This is acceptable for the fast time-varying magnetic fields. An additional modification is triggered by the Lorentz force. Using the approximation \( |\mu_B| \approx 1 \), the current density in metallic regions takes the form:

\[
J = \sigma \cdot E + \mu_B \cdot \dot{\phi} \times B.
\]

Each node carries variables \( V, \phi_x, \phi_y \). Each link carries variables \( A, \Pi \).

### 3. Example of ESD local protection

This section is focused on ESD transient behaviour. The stress could be as usual HBM, MM, CDM or Gun. What is interesting is to evaluate the limit or extreme event in standalone protection. The harmonic regime will be also discussed.

#### 3.1. Extreme ESD transient response

As the first example (Fig. 3), a local protection with Silicon Controlled Rectifier (SCR) is investigated in extreme stress with the impact of electro-magnetic field with Lorentz force in fast transient event. Fig. 3 shows the full ESD protection (top view, design and 3D topology FEOL + BEOL) under study for this example.

An example of the \( V(t) \) response is shown in Fig. 4 with a zoom in of the over-voltage spike at the beginning of this stress. The over-voltage can be easily tackled by a properly-adjusted value of \( R \).

Due to this response, several steps are identified with their electromagnetic field distributions. Fig. 5 reports the magnetic field for these different time steps.

Mainly, for low current and with high time slope, the magnetic field increases into whole perimeter structure (silicon and metal stack). This is the same trend for high current and with low time slope. The first behaviour is for the threshold region and the second one is for the quasi-static regime. It is clearly shown that the distribution \( B(t) \) is not homogeneous and that the current density is impacted by the induced magnetic field even if the structure is symmetrical. Fig. 6 shows the current density in silicon with associated \( B(t) \) distribution extraction at 0.107 ns.

Thanks to this study and physical extractions in extreme behaviour it is possible to catch some possible sensitive area. For example, Fig. 7 reports the current density distributions in the structure (cross section) without and with B and LF. A difference induced by 56 mT of B field is observed. Obviously, in other case where the magnetic field B could be

<table>
<thead>
<tr>
<th>ESD device + associated trigger</th>
<th>HBM meas.</th>
<th>LU meas.</th>
<th>3D TCAD simulation (this study)</th>
<th>3D TCAD classical</th>
<th>RF measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP + DN (diodes)</td>
<td>2 kV</td>
<td>100 mA injection</td>
<td>190 IF (FE + BE)</td>
<td>120 IF (FE + BE)</td>
<td>175 IF (FE + BE)</td>
</tr>
<tr>
<td>SCR + DN</td>
<td>2 kV</td>
<td>100 mA injection</td>
<td>80 IF (FE + BE)</td>
<td>70 IF (FE + BE)</td>
<td>85 IF (FE + BE)</td>
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Please cite this article as: P. Galy, W. Schoenmaker, Coupled electro-magnetic field & Lorentz force effects in silicon and metal for ESD investigation in transient and harmonic regimes, Microelectronics Reliability (2015), http://dx.doi.org/10.1016/j.microrel.2015.06.091
with high magnitude, the final response would be strongly impacted. Thus, a magnetic sensor is a good candidate to illustrate this concern.

Next, the extraction of $B(t)$ is done at the same time and at different levels of the metal to investigate the magnetic distribution and impact within the metal stack. Fig. 8 gives the $B(t)$ distribution on 3 metal levels at the same time stress showing an inhomogeneous magnetic map.

TLP 100 ns experimental measurements for different $R$ (see Fig. 3: $R_{\text{Ngate of SCR}}$) values give a $V_{t1}$ range $[2 \text{ V} - 13.7 \text{ V}]$ compared to $[2.4 \text{ V} - 16.5 \text{ V}]$ provided by simulations. The difference observed for high $R$ value is attributed to parasitic elements on test chip (extra PAD connection). These results are very encouraging. For more details, see [6].

3.2. Extreme RF harmonic response

The next step on this example is to provide an evaluation of the ESD protection in extreme range as 100 GHz RF behaviour in dipole condition. In this case, the parasitic capacitance of the protection is studied. Typically, the physical extractions in small-signal or harmonic analysis are performed and depicted in Fig. 9 and show a different distribution compared to the transient regime. In the harmonic regime the symmetry of physical parameters is conserved. It is interesting that, even if the SCR and diode are blocked an induced current by the displacement current in the capacitors is mainly observed in the middle of the device which leads to a local $B(j\omega)$. The electric field $E(j\omega)$ is located at the perimeter. It should be reminded that the silicon is with doping regions according to the SCR and the diode device.

To extract the $S$ parameters, test structures are an "open", an "short" and "embedded" device. Measurements lead to 85 fF parasitic capacitance and the numerical result gives 80 fF. These values match well. Moreover, this approach was also used to characterize ESD RF diodes with FEOL and BEOL. The measured parasitic capacitance (175 fF) and the extracted from $S$ parameters in the simulation (190 fF) lead to the same values compared, whereas if both are compared to 120 fF obtained by the classical separated method a mismatch occurs which demonstrates the need for the new TCAD [7]. Moreover, depending of the silicon structure complexity, this mismatch can be enhanced as shown in SCR and diode topology.

4. Example of coplanar structure behaviour

In this second example we consider coplanar metal wires used for RF applications. This coplanar transmission line is adapted to 50 Ω and no extraction effort is done in the harmonic here. Nevertheless, the question is to know: what is the ESD transient regime as in previous case?
To give an overview of the structure's behaviour, the same approach is followed: a high current pulse (Dirac like) is injected on the input and all physical parameters are extracted and analyzed. Fig. 10 gives the shape of stress (1 A square pulse), the 3D mesh of the structure and a potential extraction.

As expected during the fast transient, the electromagnetic field is into the whole environment, e.g. in the Front End Of Line (FEOL) and the Back End Of Line (BEOL). Fig. 11 gives a cross section with the electric field and the magnetic one within the FE + BE topology. It is clearly shown, that a field is induced in the silicon below the metal strip and leads to an induced current.

Thanks to this preliminary investigation it is possible to go ahead by putting a distributed ESD protection inside the transmission line. An example of a transmission line with an embedded ESD protection is depicted in Fig. 12 with physical extractions done at 110 GHz and located on ESD local protection. The induced current density has a penetration into silicon centred on ESD protection. The electromagnetic field is also extracted and its distribution follows the structure topology with a localized spread.

An in-depth ESD study with silicon results for this purpose is proposed with full details in [8,9].

5. Conclusion

This paper introduces a way to investigate in detail ESD events, especially in transient and in harmonic regimes. In these particular conditions, the E and B electromagnetic field and Lorenz force could be a contributor on the final response. Thanks to the numerical solver, it is demonstrated that the electromagnetic field plays a role during the physical event. The Lorentz force has only a marginal effect on the final TLP IV curve (see Section 3.1) at this B magnitude (56 mT). Due to topologies and silicon regions, distributions of physical variables are inhomogeneous within the structure. It was shown in two examples that these distributions are with different magnitudes and lead to different impacts. Thus, to investigate the limit in extreme regimes, the knowledge of all physical variables such as E, B, V, and I is useful and helps the expert to improve the ESD robustness of the initial solution. In this framework, two examples illustrate these concerns. Moreover, this investigation is done in the field of ESD and can be extended to high power devices, magnetic sensors and other regions that involve electromagnetic phenomena. (3D die/interconnect structure with TSV).

Acknowledgement

The authors would like to thank all colleagues/teams for their help and measurements. Part of this work was funded by the EU projects ICESTARS (GA 2214911) and nanoCOPS (GA 619166).
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