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Efficient Modeling of Multi-Stage Integrated Circuit Passive Isolation Structures

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Abstract—In this paper, an efficient electromagnetic modeling methodology is proposed for multi-stage integrated passive isolation structures. The methodology is based on a modal expansion of interference field components. With it, we are able to accurately characterize a great variety of structures approximately 300 times faster than with full-wave simulations. Calculated results have been compared to both simulations and measurements, obtaining good agreement. The proposed model is intended to be a tool for fast prediction purposes at early stages of the design flow.

Index Terms—Electromagnetic interference, integrated circuits, signal integrity, substrate coupling.

I. INTRODUCTION

IN the past years, integration levels in electronic systems have been continuously increasing so as to enable the development of high-performance products and applications [1]. This implies that different electronic functional blocks (e.g. ADC's, RF modules, etc) are implemented in the same substrate and, therefore, share a common path for potentially unwanted coupling between them. In this context, to characterize and provide insight on electromagnetic interference propagation mechanisms in multilayered substrates is a key point to enable a disturbance-aware design environment and, consequently, to avoid expensive design iterations.

The continuous increase of operating frequencies pushes the validity limit of static or quasi-static approximations. An investigation of their validity in the context of integrated circuits (IC) substrate modeling can be found in [2]. In addition, it also pushes the bandwidth of validity of behavioral equivalent RC networks, which are based on single-mode representations, as they neglect the effects derived from multimodal propagation [3]. Consequently, there is a need for models able to account for electromagnetic effects [4], in an efficient way.

In order to prevent two sections of the same IC from interfering each other, highly resistive and/or charge-free sections are commonly embedded in order to increase isolation between them [5]. Their role is to discontinue the substrate top layer (active layer), where circuits are implemented, and thus interrupt the normal flow of currents that support interference propagation. Consequently, this type of structures can be considered as discontinuities transverse to the direction of interference propagation. Therefore, they can cause effects

such as mode conversion and mode enhancement, which can modify interference propagation patterns, as described in [6].

In the present paper, a novel modeling methodology is proposed to characterize interference propagation in multilayered substrates in the presence of multi-stage discontinuities. This methodology builds up on previous work [6], where a single stage discontinuity model was proposed that was able to efficiently characterize the effect of SiO₂ trenches on interference propagation, providing insight on the isolation effectiveness of such structures. In the present work, the concept is applied to multi-stage discontinuities, in order to model complex passive isolation structures of different kinds (e.g. triple wells or filled trenches) or multiple cascaded structures. The developed methodology efficiently deals with multiple sections that are not bounded by conductive layers, which is the common case for ICs [3]. The proposed model is intended to be a tool for fast interference prediction purposes, that provides insight on the effect of technological boundaries in interference propagation and effectiveness of isolation structures.

II. DESCRIPTION OF THE STRUCTURES UNDER STUDY

IC substrates can be modeled as a multilayered stack, where the cross section doping profile is decomposed in m layers in the vertical direction and can be considered practically homogeneous in the radial direction. We consider that layer $m+1$ is a semi-infinite non-conductive region and that layer 1 is bounded by a perfect electric conductor (PEC) at the bottom. If this is not the case, the ground plane of the printed circuit board can be used as a reference by adding additional layers. Other boundary conditions can be considered by modifying the expressions of fields induced inside the stack [3].

The physical properties of the layer stack determine the propagation modes that the substrate is able to support. As the structure is semi-open, both discrete and continuous modes can propagate. Discrete modes correspond to surface waves, while continuous modes can be either propagative, which account for radiation into the open-space, or evanescent, which account for energy storage close to the source [7].

Considering the standard IC substrates [3], despite the fact that these structures are open, there is usually an intermediate and/or top layer (active layer) with a relatively high conductivity (typical values are between 100 and 2000 S/m). In the presence of these layers, surface waves are dominant among the continuous spectrum close to the source. In [3], a study can be found on the distance range in which propagation can be characterized only with discrete modes, for different standard IC substrates, and for different conductivities and frequencies.

In this context, implemented isolation structures feature one or multiple sections with different doping profiles, embedded

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in the original multilayered substrate. Each of those sections is able to support a different set of modes. Due to the fact that the primary function of these structures is to interrupt the active layer, at least one or several stages do not include intermediate or top conductive layers. Even though they are still able to support propagation of surface waves, the dominant propagation modes close to the source belong to the continuous spectrum for such stages.

Therefore, as shown in Fig. 1, the structures under study will consist of N consecutive sections with different doping profiles. Each section is then characterized by its number of layers m and, subsequently, each layer by its conductivity σ_n , permittivity ϵ_n and height h_n . The source of interference will be a certain current density distribution located in section 1, sections 2 to $N - 1$ have isolation purposes and section N is where a potential victim is located.

Fig. 1. General diagram of the structures under study.

As interference propagates radially from the source [3], for the sake of simplicity we will consider that the structure described in Fig. 1 is radially symmetric, and thus the different sections have the shape of concentric rings. In this type of structures, interference propagates mainly by means of Transverse Magnetic modes (TM^z), with field components E_z , E_r and H_ϕ . Sections will be characterized by their absolute radius (r_1 to r_N).

III. MULTI-STAGE DISCONTINUITY MODELING

When a certain mode, excited in a particular waveguide section, meets a discontinuity, part of the energy is transferred to the subsequent section and part of the energy is reflected. The energy is transferred to all the modes that the new section is able to support and, in the same way, it is reflected to all the modes that the first section is able to support. Using the expressions of the tangential field components at the discontinuity interface together with the orthogonality property of the set of modes in each section, one can write equations to relate the different modal parameters at both sides of the discontinuity. A detailed explanation of the procedure for a 2-stage discontinuity in closed waveguides can be found in [8].

In the case of having an upper open boundary, the discontinuity interface should be extended to infinity. In addition, the modal expansion of tangential fields should be modified to include the contribution of the continuous spectrum. Thus the general expressions for electric and magnetic field components in a certain section excited with mode 1 will be

$$\mathbf{E} = a_1 \mathbf{e}_1 + \sum_{i=1}^{\infty} a_i \rho_{i-1} \mathbf{e}_i + \int_{\mathcal{D}} a_1 \rho_1(k_r) \mathbf{e}(k_r) dk_r, \quad (1)$$

$$\mathbf{H} = a_1 \mathbf{h}_1 + \sum_{i=1}^{\infty} a_i \rho_{i-1} \mathbf{h}_i + \int_{\mathcal{D}} a_1 \rho_1(k_r) \mathbf{h}(k_r) dk_r, \quad (2)$$

where a_i are the modal amplitude coefficients, ρ_{i-1} is the reflection coefficient of mode i when the discontinuity is excited with mode 1 and $\mathcal{D}$ is the integration domain in the complex plane.

Given a certain discontinuity (1|2) in a multi-stage scenario, where Section 1 is characterized by p modes and Section 2 is characterized by t modes, the inputs of its system of equations will be the amplitude coefficient of the excitation mode (e.g. a_{11}), and the $t \times t$ reflection coefficients at the subsequent section (ρ_{21_21} to ρ_{2t_2t}). The corresponding unknowns to be obtained are the t amplitude coefficients at the subsequent section for the given excitation (a_{21_11} to a_{2t_11}) and the p reflection coefficients at the prior section (ρ_{11_11} to ρ_{1p_11}). Finally, this system of equations has to be solved p times, for all possible excitations (a_{11} to a_{1p}). Consequently, in order to be able to solve the complete structure, the system of equations that corresponds to the discontinuity located further away from the source ($N-1|N$) has to be solved first [8]. Figure 2 shows the solution flow of the complete set of systems of equations.

Fig. 2. Solution flow of the complete multi-stage structure, where each box represents a discontinuity interface.

Taking into account the field modal expansion expressions (1)-(2), if a discretization of the continuous spectrum is performed and after obtaining all the intermediate parameters, the amplitude coefficients of interference propagation modes in section N can be obtained as follows

$$a_{Ni} = \sum_{q_1=1}^{\infty} a_{1q_1} \sum_{q_2=1}^{\infty} a_{2q_2_1q_1} \dots \sum_{q_{N-1}=1}^{\infty} a_{Ni_ (N-1)q_{N-1}} \cdot (3)$$

It is obvious that a truncation of the number of modes considered in each section is needed to be able to solve the problem. In addition, even with a finite number of systems of equations, the complete problem can still be very complex and computationally expensive. For this reason, a simplification is required to be able to characterize propagation through a multi-stage discontinuity in an efficient way.

At this point, we will characterize each section with the few most significant modes, i.e. those with a greater contribution to energy transfer between sections. This means that instead of focusing on accurately describing the fields in the intermediate

Fig. 3. Optimization strategies considered: (a) known source and (b) arbitrary source.

sections, we prioritize an accurate description of fields at the first and last sections. Taking into account the main application of the structures under study, this will allow us to obtain an accurate transfer function and therefore apply this methodology for isolation effectiveness studies.

The criteria for choosing the most significant modes is described below. Those sections with top or intermediate relatively highly conductive layers (as described in Sec. II), will be characterized only by the propagating discrete modes. These are obtained by means of a transcendental equation that can be derived when fields are forced to be evanescent in layer $m + 1$ [3]. For all other sections, we will consider the discrete propagating modes plus the spectral components that maximize the energy transfer or, in other words, the spectral components that are better matched with the modes exciting the discontinuity interface. In order to optimize the selection of these modes and avoid iterations, instead of taking into account the complete structure, we will just consider the discontinuity to be optimized. The prior section will be fully characterized with all relevant excitation modes and in the following section we will consider only the spectral component to be optimized. At this point, two different strategies can be followed. If the interference source current distribution is known and located in the section before the discontinuity, the amplitude coefficients of each excitation mode are known. Therefore all excitation modes can be considered simultaneously and the spectral component that maximizes the overall transmission can be selected. On the other hand, if the weighted contribution of each excitation mode is not known, an arbitrary source will be used and the matching with each excitation mode will be optimized separately. Figure 3 shows a diagram of both strategies.

Once all the structure parameters are known, we can use different metrics to characterize its isolation. We obtain the transfer function by calculating the ratio of the voltage induced across the stack at the source and victim positions (equivalent to a S_{21}) and its isolation effectiveness as the ratio of the fundamental mode amplitude coefficient at the victim section, with and without isolation structure. A discussion of those metrics and the effects that they take into account can be found in [6].

IV. EXPERIMENTAL VALIDATION

In order to assess the validity of the proposed modeling methodology, it will be applied to characterize two types of structures: a triple well and a filled trench. The first one consists of two wells of different doping type (one inside the other) so that, together with the substrate, two consecutive reverse-biased junctions are formed, as sketched in Fig.4-a. The second one consists of a multi-layer stack formed by a p-well, a p-epitaxial layer, a buried oxide and a n-substrate, where a SiO_2 trench is embedded and filled with doped polysilicon, so it contacts the substrate, as sketched in Fig.4-b.

Fig. 4. Structure of the study cases considered: (a) triple well and (b) filled trench.

The triple well is simulated with the 3D full-wave tool CST Microwave Studio, [9] in order to obtain the fields induced inside the substrate stack. The current density used as a source is a vertically oriented one, flowing across the whole stack height $\mathbf{J} = I\delta(r)\hat{z}$. The structure is modeled with 5 sections of absolute radius $r_1 = 50 \mu\text{m}$, $r_2 = 50.5 \mu\text{m}$, $r_3 = 51 \mu\text{m}$ and $r_4 = 51.5 \mu\text{m}$. The parallel charge-free regions are $1 \mu\text{m}$ and $0.5 \mu\text{m}$ thick respectively. The substrate considered is highly resistive ($\sigma = 10 \text{ S/m}$) and $250 \mu\text{m}$ thick. The active layer has a conductivity of 1000 S/m and a thickness of $1.5 \mu\text{m}$. The conductivity of the wells is 1000 S/m for the n case and 1500 S/m for the p case. Section 4 is the only one without intermediate or top conductive layers, so in this case an optimization is carried out with an arbitrary source. Propagation coefficients are obtained in each section, in the range from 1 MHz to 10 GHz [3]. According to the criteria described in Sec. III, either two or three modes are used to characterize each section. Subsequently, the procedure described in Fig. 2 is applied to obtain all coefficients. The structure has been simulated using a frequency domain solver and was excited with a current port. The total computation time was 12 minutes for 100 frequency points, while simulation time in the same computer was three hours for five frequency points (300 times faster for each frequency point).

There is good agreement between the simulated and the calculated results (see Fig. 5). After the transverse discontinuities location, one can observe a transitory decrease of the field magnitude. This is due to the fact that the high-order modes that are excited interact destructively with the fundamental propagation mode in section 5. However, they attenuate faster and after a certain distance this effect is not present anymore. The simulated and calculated transitory magnitude drops do not coincide. However, this phenomena can be more accurately

Fig. 5. Magnitude of the E_z component induced in layer 1 in the triple well structure at $z = 240 \mu\text{m}$, where the effect of mode interaction is higher.

Fig. 6. Characterization of the triple well structure: (a) voltage ratio and (b) isolation effectiveness.

characterized if additional evanescent modes are included in this section, at the obvious expense of increasing complexity. In Fig. 6 we show the calculated transfer function and isolation effectiveness.

In order to characterize the filled trench case, we have implemented a test structure in a $0.13 \mu\text{m}$ SOI technology that consists of two squared p-well tubs of $200 \times 200 \mu\text{m}$ separated by deep trench isolation (DTI) (see Fig. 4b). In order to obtain the transfer function, it has been embedded in a coplanar ground-signal-ground structure. The layout is shown in Fig. 7. The measured S_{21} is compared to a calculated transfer function obtained from a radially symmetric version of the structure. Results are shown in Fig. 8.

As it can be seen, there is quite good agreement between the measured and calculated results, except from the range between 100 kHz and 1 MHz, where measured results reached

Fig. 7. Layout of the implemented test structure.

Fig. 8. Comparison of the measured and calculated DTI transfer function.

noise floor. Even though the shape of the test structure is not radially symmetric, the results obtained with the proposed model show that the behavior can be extrapolated, providing a reasonable accurate transfer function. In this case, computation time was eight minutes for 100 frequency points.

V. CONCLUSION

This paper presents a modeling methodology for efficient electromagnetic characterization of multi-stage passive isolation structures embedded in IC substrates. We have shown that with a smart selection of the most representative modes, the proposed model is able to accurately represent structures formed by multiple sections of different doping profiles in an efficient way. We have compared the calculated results for triple wells and filled trenches to full-wave simulations and measurements, respectively, obtaining very good agreement. The proposed formulation has been developed assuming radially symmetric structures. The comparison to measurements has shown that, even if the structure characterized experimentally was not radially symmetric, the calculated results can still be extrapolated to other topologies.

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