ELECTROMAGNETIC INTERFACING OF SEMICONDUCTOR DEVICES AND CIRCUITS

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Abstract: This paper discusses the interactions between semiconductor devices and electromagnetic waves and the possible ways to interface modern devices and circuits in the mm-wave range. This topic is very important for advancing current MMIC designs and for developing futuristic devices and applications. The electromagnetic wave propagation through semiconductor devices is modeled by coupling a physical electron-transport model, or a circuit approach, with Maxwell's equations. The solution is developed in time-domain using Finite-Difference Time-Domain (FDTD) technique. Examples of device and circuit simulations will be presented.

Introduction:

To meet the increasing demand for processing and transmitting more information at a faster rate, analog and digital electronic systems must operate at higher frequencies or higher clock speeds. On the other hand, there is a continuous pressure towards lower-cost products. On the circuit level, this leads to highly integrated circuits such as MMICs. The highly packed circuits consist of closely spaced active and passive devices, with many levels of transmission lines and discontinuities. The circuit performance may be adversely affected by the high density, due to unwanted effects such as crosstalk, caused by coupling, surface waves, and unintended radiation, to name just a few. Evidently, careful circuit designs must be developed based on advanced design tools that take the electromagnetic wave effects into consideration [1-2]. This creates a need for comprehensive analysis and design tools that consider all the circuit elements simultaneously, including the active devices, the passive components, the radiation elements, and the package.

The development of the above mentioned design tools is much easier said than done. The drastic diversity in physical dimensions, physics and electromagnetic basics, the numerical stability and accuracy requirements for modeling the various circuit components makes it extremely difficult to achieve the desired global modeling approach. This paper reviews some of the conditions for modeling the different circuit elements and components. The possibility of achieving this global circuit modeling will be demonstrated using two examples for using the electromagnetic wave approach to interface transistors with passive circuits [2-3].

The Classical Approach to Circuit Design:

The modern circuits and devices still have to perform basic operations such as generation, amplification, modulation and switching of electrical signals. In the microwave and mm-wave frequency ranges, these operations can be viewed as interactions between electromagnetic waves and electrons moving inside the semiconductor device. The electrons act as the catalyst that gains energy from a DC source and converts it into a high frequency signal, the electromagnetic wave. At low frequencies, this interaction is normally analyzed using the equivalent circuit approach. For obvious historical reasons, this approach was extended to the microwave and mm-wave ranges. For example, an amplifier problem is classically analyzed as follows. First, the DC bias problem is solved quasi-statically. In this step, the physical characteristics of the solid-state device controlling the electrons are introduced. An AC equivalent circuit is then developed based on the DC solution. Second, amplifier gain characteristics are developed based on the equivalent circuit, and an amplifier gain model is developed. The amplifier model is incorporated with high frequency models of the other system elements. The details of the actual steps may look different, but the methodology is basically the same. This approach obviously separates the electron beam physics from the wave propagation phenomena. Thus, the gain-producing mecha-

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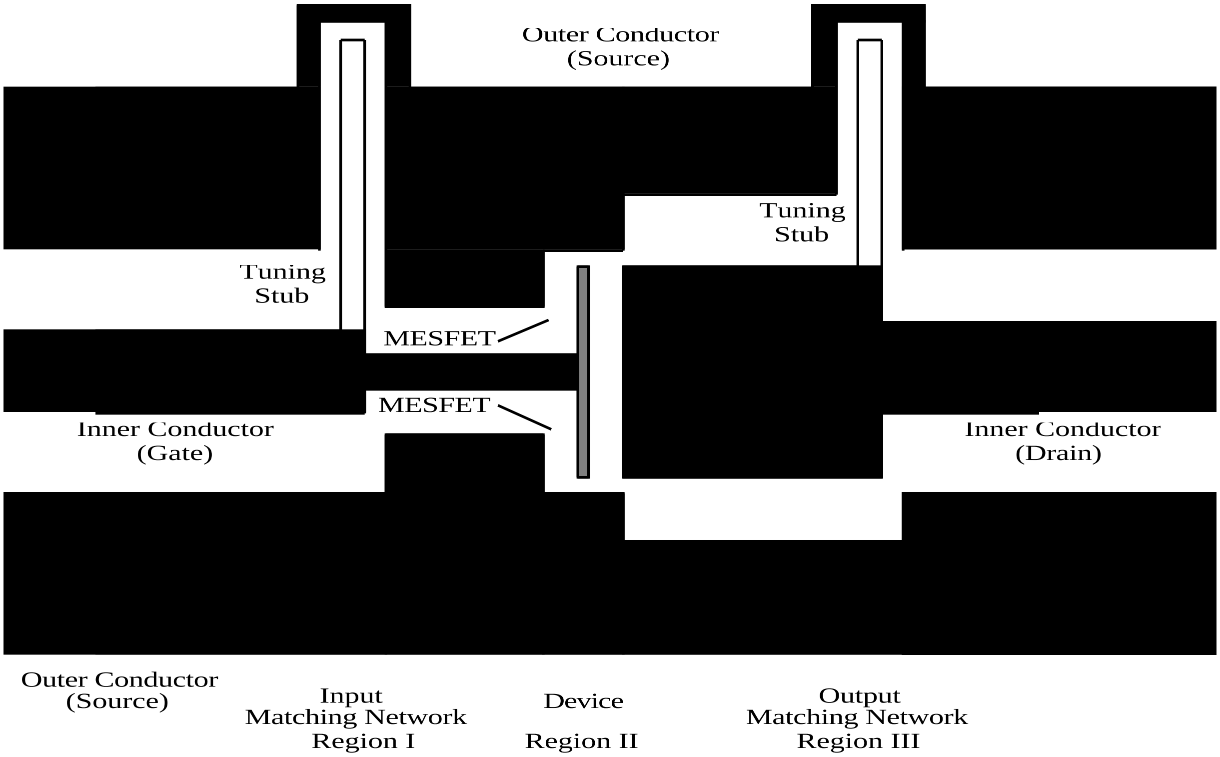

Fig. 1. GaAs transistor amplifier with CPW matching networks.

nism is developed without taking the electromagnetic wave into consideration. If such an approach is acceptable at low frequencies, it is not clear if it can safely be applied in the mm-wave range for many reasons including; 1) the electromagnetic-wave effects and discontinuities at the device input and output terminal are not directly incorporated; 2) the multi-mode propagation aspects of EM-waves are not properly accounted for; 3) the interference between the active device and other neighboring elements is not taken into consideration, at this stage. There are other effects pertaining to the semiconductor device itself, such as 1) device and circuit critical dimensions can be comparable to the wave length; 2) the electron transit time progressively approaches the wave period; 3) the relaxation times governing the electron transport phenomena may be comparable to the wave period; and 4) when the signal is large, the AC signal becomes a considerable fraction of the DC bias, which means that both the AC electric and magnetic fields interact with the electron beam physics and may alter them significantly from the quasi-static case. The latter reason is related to the effects of the electromagnetic wave on the non-linear aspects of the circuit materials. Therefore, more accurate approaches combining the DC fields and the electromagnetic waves, and simultaneously applying them to the semiconductor devices have to be developed.

Approaches to Global Modeling of Circuits:

As a demonstration of approaches towards global modeling of microwave and mm-wave circuits, this paper reviews two examples of interfacing semiconductor devices with electronic circuits. In the two examples, the electromagnetic wave propagation through the circuits is analyzed using the FDTD technique.

Case 1: From Device to Circuit

In this example [3], a full-wave analysis is performed to simulate the microwave amplifier with two tuned coplanar wave guide (CPW) sections as matching networks. This approach is based on coupling the hydrodynamic set of equations for the electron transport with Maxwell's equations. To demonstrate the

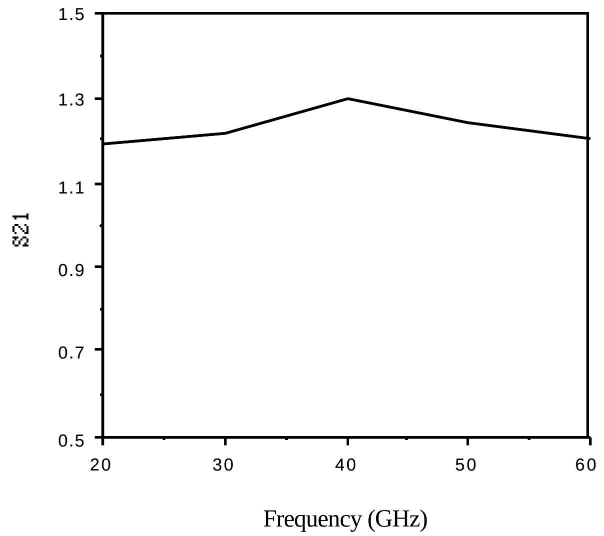

Fig. 2. The dependence of S_{21} on frequency.

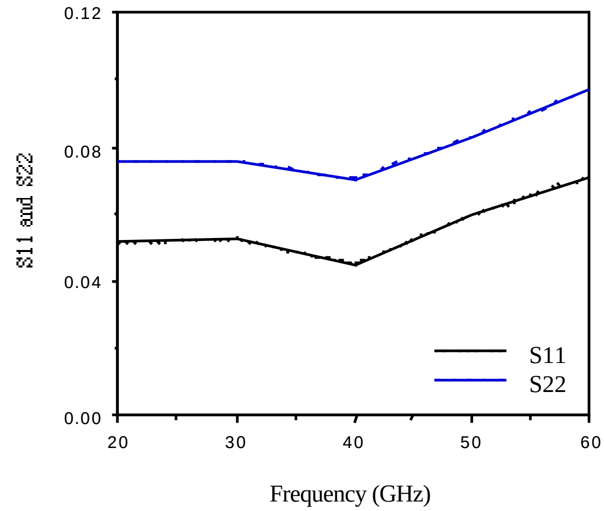

Fig. 3. The dependence of S_{11} and S_{22} on frequency.

potential of this approach, a mm-wave amplifier implemented in a CPW is analyzed. The amplifier along with the matching networks are shown in Fig. 1. The input and the output matching networks are designed based on the scattering parameters of the transistor. The transistor channel length and aspect ratio are selected to achieve the required transconductance and the cut-off frequency. The cut-off frequency of the transistor was estimated as 77 GHz. The operating frequency is chosen to be 40 GHz to illustrate the principle of the approach. The S-parameters are computed for the MESFET. The amplifier is divided into three regions. The simulation of the two matching networks is performed separately and properly coupled to the transistor stage. A sinusoidal wave is applied to the amplifier input. It should be noted that this is done to illustrate the concept; but, in general, any arbitrary wave form can be applied to the amplifier without any significant increase in the computational effort. The scattering parameters are obtained at different frequencies. In Fig. 2, S_{21} is shown as a function of frequency. The magnitude of S_{21} remains within a certain range for the frequency band of 20-60 GHz. The value of S_{21} for this amplifier is low because the transistor width is very small. Increasing the device width would increase the value of S_{21}. The corresponding variations of S_{11} and S_{22} are presented in Fig. 3. The return loss is less than 25 dB, at 40 GHz. It should be noted that no attempts were made to optimize the amplifier performance in this paper, since the aim is to report on the technique rather than on the amplifier itself.

Case 2: Effects of the packaging Structure

In this example [2], the device is represented with its lumped-circuit model, to avoid the long execution time of the semiconductor transport model. The dielectric constant in the device region is taken as that of air. Since the size of a device is typically much smaller than a wavelength, this method produces a reasonable approximation and still retains a high degree of accuracy in full-wave analysis. The key concept of this approach is to connect quantities of the electromagnetic fields with quantities of the circuit model. Direct implementation places the lumped circuit in the device region and matches internal modes of the lumped circuit with the FDTD grids as used in [4] . Each circuit element, placed on the edge of a FDTD cell as a two terminal element, is directly incorporated in the FDTD algorithm. Alternative implementation is to place effective electric currents, or current sources, in the device region [2]. The equivalent sources serve as dependent sources, which satisfy Maxwell's equations and the device circuit model. The simulation of the rest of the circuit is carried by full-wave analysis using the FDTD scheme.

This scheme is used to analyze an amplifier circuit including the packaging structure, as shown in Fig. 4. The analysis of the packaged structure is beyond the capabilities of typical circuit simulators. Physically, the packaging structure forms a partially dielectric-filled cavity. Excited by the circuit, the cavity stores energy due to the natural resonance phenomena. The stored energy is coupled back to the circuit. For a nonlinear active circuit, this feedback makes the stability circles drift, and could lead to oscillation. Fig. 5 shows the effect of the packaging structure on the s-parameters.

The two cases for interfacing semiconductor devices with circuits presented in this paper differ in their main emphasis, computational load and anticipated results. However, the two approaches should be combined together to enhance the global circuit modeling ability.

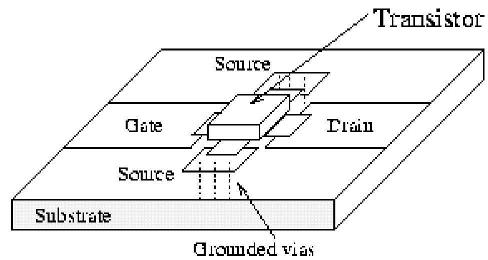

Fig. 4. A packaged transistor connected to the ground plane through via holes.

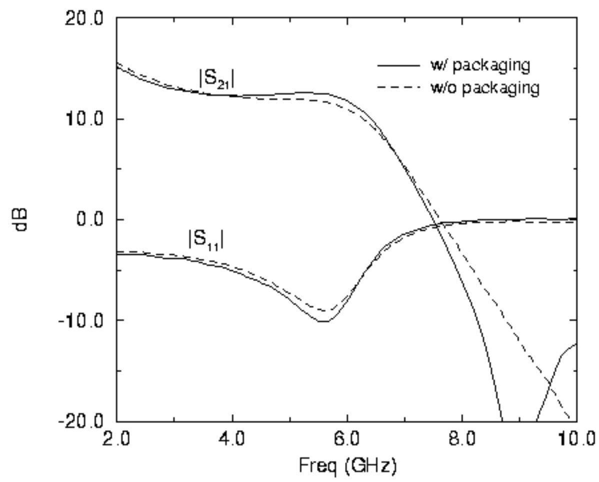

Fig. 5. Effect of package on the Transistor.

Conclusion:

The highly packed integrated microwave and mm-wave circuits create an immediate need for developing global analysis and design tools that combines all the circuit elements simultaneously. This requires electromagnetic interfacing of various elements such as semiconductor devices, passive components, radiation elements, and packages. Two examples for EM-wave and semiconductor device interfacing are presented.

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