A Fast 3D Modeling Approach to Parasitics Extraction of Bonding Wires for RF Circuits

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Abstract

An approach to fast 3D modeling of the geometry for bonding wires in RF circuits and packages is demonstrated. The geometry can readily be used to extract electrical parameters such as inductance and capacitance. An equivalent circuit is presented to model the frequency response of bonding wires. To verify simulation accuracy, test structures have been designed and measured. Excellent agreement between simulated and measured data is demonstrated up to 10 GHz.

Introduction

Because of the high frequency design concerns, consideration of parasitic effects for the bonding wires in IC packaging of RF and deep submicron high speed VLSI circuits is essential. Moreover, bonding wires are used as high quality-factor on-chip inductors in RF circuits. Hence, it is necessary that the inductance, resistance and capacitance of the bond wires in the IC package be modeled accurately. Typically, adjustment of the bonding wires is done through empirical effort, with little or no help from simulation tools, since accurate modeling depends on 3D geometry extraction. To model packaging parasitics, previous methods have compared simulation of intrinsic device and measured S-parameters from the packaged circuit [1]. This method relies on the modeling accuracy of the intrinsic device and requires measurement for individual devices. Moreover, bonding wire models need to be improved. For complex 3D geometries, a better method of extraction and modeling should ideally be linked to the geometry itself. A fast 3D modeling approach is presented which captures the geometry from SEM photos and the electrical parameters are extracted based on the geometry 3D representation. A carefully designed test structure has been fabricated and measured. Simulation results are in good agreement with the measured data.

A New Geometry Extraction Method

Physical simulation of interconnects is possible only when detailed knowledge of the 3D geometry is available. In many cases the structures can be defined from planes parallel to the coordinate planes. Solid modeling tools have become popular in defining geometries for RF applications. The most common way of capturing is based on projections of the object in 2 or 3 of the three coordinate planes (xy, yz and zx). Even though shape can be controlled by the bonding machines with high accuracy (and reproducibility), it is impossible to predict the shape of bonding wires in advance. To obtain the geometry of the wires, a new extraction method is developed. SEM photos have a large depth of focus and are used to capture the shape of the wires. Complete 3D information can be obtained from several photos with known viewing location and angle. In practice, however, it is found sufficient to use only one properly positioned photo and to make the extraction unique by adding limited assumptions about the geometry.

A Java program has been written that can display the SEM photo and let users define the reference coordinate system. A simplified drawing is superimposed on the photo interactively, moving the cursor on the screen and assigning depth information to emulate 3D movements. The 3D space and objects are described in a world coordinate system, a reference coordinate system and a device coordinate system. The relations among the systems are described using transformation matrices. The tool can be run across the network or internet using a Virtual Java Machine (JVM) available in Netscape and Internet Explorer on most computer systems. The Java program automatically creates input files for the 3D electromagnetic simulators such as FASTHENRY [2] and FASTCAP [3] to extract the electrical parameters for the structure. Fig. 1 shows the user interface of the software used to capture 3D geometry, and the extracted drawing is shown in Fig. 2.

Design of Test Structure and Model Parameter Extraction

A. Test Structures and Measurement

In order to verify the accuracy of the modeling approach, test structures have been designed and made so that the S-parameters of the bonding wires can be measured with high precision. Two SEM photos of three test structures are shown in Figs. 3-4, which are referenced as stra21 (two straight wires each of

1mm long) and curv31 (three curved wires each of approximately 1mm long). The other is curv22 (two curved wires each of approximately 2mm long). The bonding wires are made of 99.99% gold with a diameter of 0.7mil. Two-port S parameters were measured using an HP 8720B Network Analyzer and Cascade Microtech coplanar ground-signal-ground probe. Since the aluminum (Al) interconnect is much more resistive than the gold wire, the bonding wire's resistance may be totally masked by the ground return path if made in Al. In our structure, the return path is provided by the same bonding wires so that the parasitics caused by the return interconnect to the ground pad is completely avoided. During these measurements, the backside of the silicon substrate was grounded through the testing chuck. Further, the parasitics of the probe pads were de-embedded using open dummy structures.

B. An Equivalent Circuit for the Bonding Wires

The input to FASTHENRY is generated for the geometry structures discussed above. Inductances, mutual inductances and resistances of the bonding wires are then extracted. To accurately model the skin effect, the resistance is calculated considering frequency dependency; a similar dependence is used for the inductance. If bonding wires are used in higher frequency (6 ~ 10 GHz) application, the capacitance of the bonding wires to the substrate and the mutual capacitances of bonding wires must be considered in the modeling process. Input to FASTCAP can also be generated as needed.

In addition, in order to compare the simulation results and measurement data, contact impedance of the test probe and the bonding wire's solder ball, which is frequency dependent, should be included since it is extremely difficult to mask or decouple the contact resistance in the measurements. The resistance of a straight bonding wire can be estimated as follows [4].

$$R \approx \frac{l}{2\pi r \delta \sigma} \tag{1}$$

where δ is the skin depth and σ is the conductivity. r is the radius of a wire. R is thus frequency dependent for δ depends on the frequency. The frequency dependent contact resistance can be deduced from the measured data by subtracting the resistance as expressed in (1). Regression data fitting is used to find the analytical expression for the contact resistance.

The equivalent circuit for the entire test setup including bonding wires is shown in Fig. 5. Input and output ports are added for completeness.

Simulation Results and Comparisons

The S parameters of the generated models were computed and compared to the measurement using MDS or HSPICE. In order to compare not only magnitudes of S parameters, but also their phases, real and imaginary parts are plotted and compared. Figs. 6-7 show the comparison between the simulation and measurement of S_{11} of two different structures when inductance and resistance are extracted. The agreement is very good up to 5 ~ 6 GHz. Figs. 8 - 13 show S_{11} and S_{12} comparisons of all the three structures with the bonding wires capacitances included in the model. The agreement is then extended to 10 GHz, indicating that the parasitic capacitance plays an important role in high frequency range. Table 1 shows the inductance from the simulation and measurement at 1.1 GHz. The simulation errors are rather small. Measured S-parameters were converted to Y-parameters to extract the inductance. Result from analytical calculation in [4] for straight lines of bonding wires is also included for comparison.

Conclusions

A 3D modeling approach for characterization (and design optimization) of bonding wires is presented. Simulated electrical parameters show good agreement with measured data up to 10 GHz. The tool can be used for RF device modeling and circuit simulations, e.g. to combine 3D solid modeling of package/bonding wire with compact model of RF power devices (BJT, LDMOS) to provide a macro model for circuit simulation (SPICE, MDS). It is well suited for the design and analysis of circuits for cellular phone communication (up to 2 GHz) and future wireless communication (about 5 GHz).

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References

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[4] Thomas H. Lee, *The Design of CMOS Radio-Frequency Integrated Circuits*, Cambridge University Press, 1998.

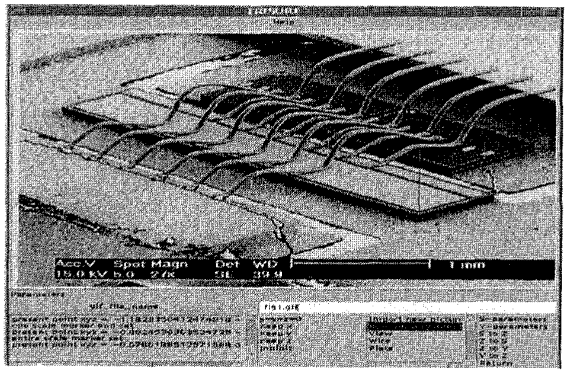

Fig.1 A Java program is developed to capture the 3D bonding wire geometry and to generate input files for L/C extraction programs.

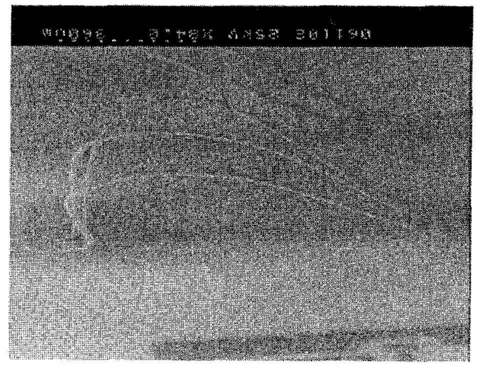

Fig.4 SEM photo for curv31 test structure.

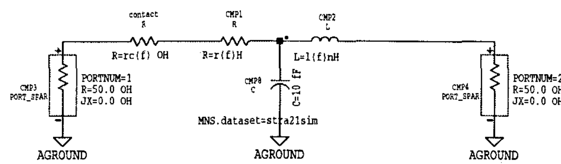

Fig. 5 An equivalent circuit for bonding wires.

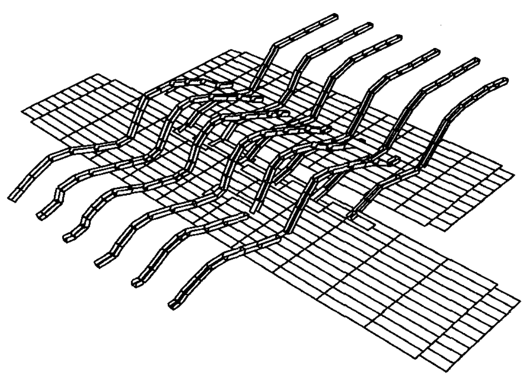

Fig.2 Extracted 3D geometry model for simulation from the Java program.

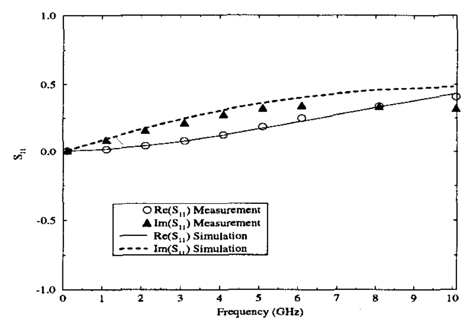

Fig. 6 S_{11} for the stra21 structure: data points are from measurement and lines from simulation without capacitance included.

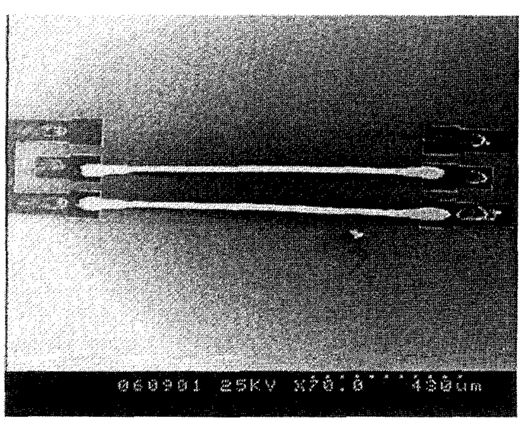

Fig.3 SEM photo for stra21 test structure.

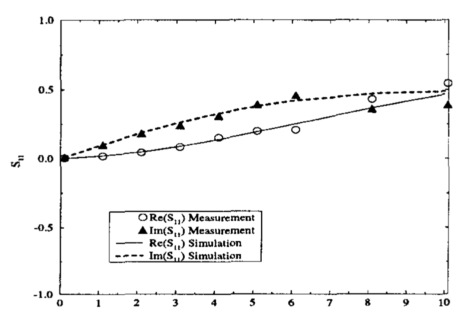

Fig. 7 S_{11} for the curv31 structure without capacitance included.

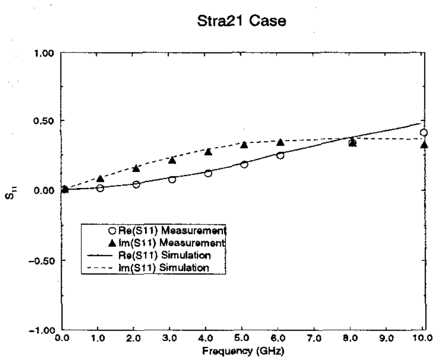

Fig.8 S_{11} for the stra21 structure: data points are from measurement and lines from simulation with capacitance included.

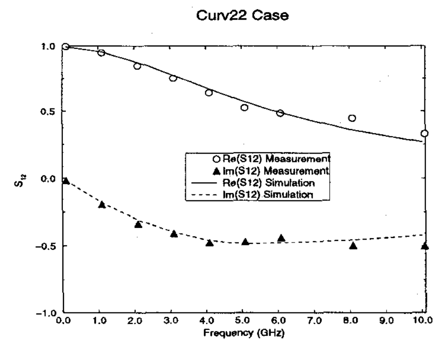

Fig. 11 S_{12} for the curv22 structure with capacitance included.

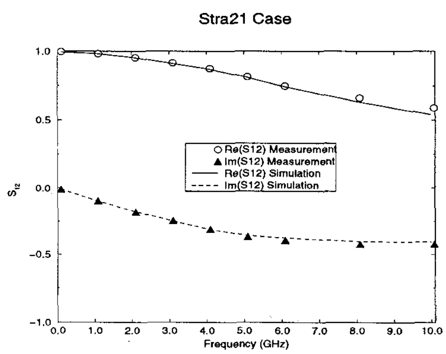

Fig. 9 S_{12} for the stra21 structure with capacitance included.

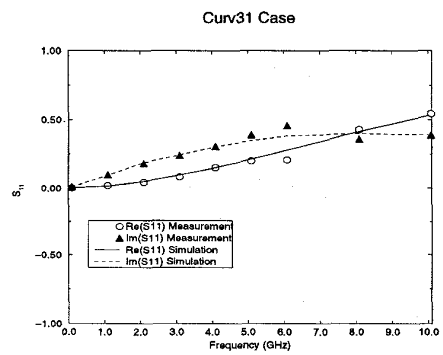

Fig. 12 S_{11} for the curv31 structure with capacitance included.

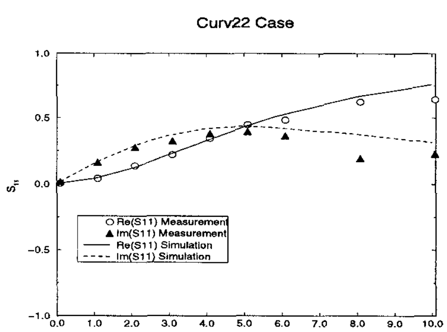

Fig. 10 S_{11} for the curv22 structure with capacitance included.

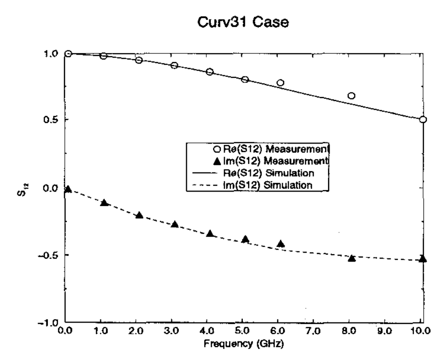

Fig. 13 S_{12} for the curv31 structure with capacitance included.

Table 1: Inductance comparison at 1.1GHz (nH)

stra21				curv22				curv31			
Simulation	Calculation	Measurement	Sim. Error	Simulation	Calculation	Measurement	Sim. Error	Simulation	Calculation	Measurement	Sim. Error
1.414	1.51	1.377	2.69%	2.694	N/A	2.802	3.85%	1.533	N/A	1.546	0.84%

11.5.4