Closed-form Formula For Frequency Dependent Bonding Pad Characterization

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Abstract **— It is well known that on-die bonding pad capacitance and conductance is quite frequency-dependent due to the existence of lossy substrate. This paper describes a very simple yet accurate method to determine them. The pad capacitance is divided into two parts, the parallel plate capacitance and the fringing capacitance. By taking the bonding pad as a transmission line four times, we can determine the fringing capacitances along the four edges. Closed-form formulas for all the capacitances are available. The conductance can then be determined from the capacitance. The results show good agreement with the full wave simulation results, which justifies the validity of our modeling.**

I. INTRODUCTION

Bonding pads, as shown in Fig.1, are used extensively in modern integrated circuits designs and also for measurement purposes. In ICs designs, bonding pads are placed around the edges on the die top surface for input and output interconnections purposes. The chip area occupied by the bond pads is sizable and thus its large parasitic capacitance makes the operating speed of integrated circuits degraded. The large input capacitance from the bonding pad also limits the frequency performance of I/O signals in high-speed integrated circuits. In measurement, traces should be widened into pads in order to allow the contact of the testing probes. Parasitic effect caused by the pad cannot be ignored and are found to be the dominant measurement error in wafer scale integration measurements[1]-[2]. The existence of the lossy substrate makes the pad's parasitic effect even more complicated. Experiments have shown that the parasitic pad capacitance and conductance, as shown in Fig.2 (a), are frequency dependent [1]-[2]. Papers have not paid enough attentions to the parasitic pad capacitance and conductance. In [3], stable Green function is developed for this purpose. However, it is usually a hard work to implement the Green function. In [4], a network analog method is adopted to determine the EM characterization of the pads. A network decomposition and pole extraction should then be used in the method [4]. It can be found that complicated mathematical computations are needed in the above two modeling ways.

In this paper, we developed an easier way to model a single pad on lossy silicon substrate, which needs only simple mathematical computations. Since the method does not need much mathematical computation, it is very useful for the designers in their initial designs. Our modeling approach is based on closed-form formulas for transmission lines, which has been well developed. Basically, the pad capacitance is divided into two parts, the parallel plate capacitance and the fringing capacitances along the four edges. To determine the fringing capacitance, the bonding pad is treated as a transmission line four times. The pad's fringing capacitances along the horizontal edges are determined in the first and second transmission line treatments, and the fringing capacitances along the vertical edges are in the third and fourth transmission line treatments of the pad. The whole capacitance is the summation of the fringing capacitances and the parallel plate capacitance. The conductance is then determined from the capacitance since there is a constant ratio between the conductance and the capacitance.

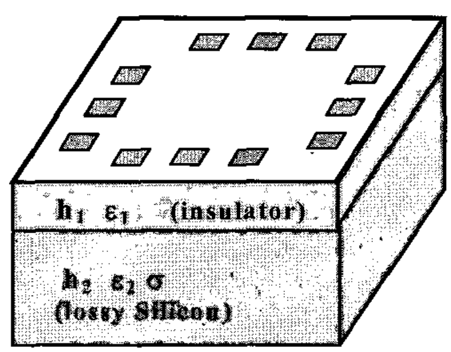

Fig. 1 3-D structure for On-Die bonding Pads

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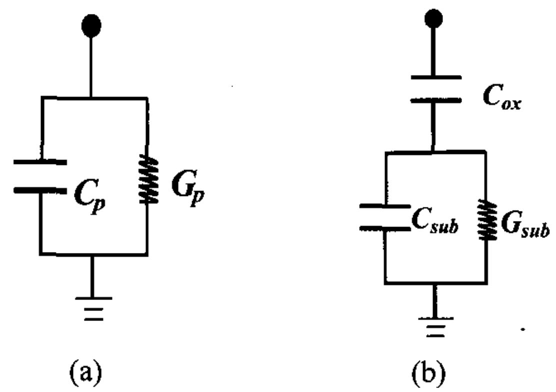

Fig. 2 Equivalent circuit Model for Single Pad
(a) Frequency-dependent parameters
(b) Frequency-independent parameters

II. Modeling Method

Usually, full wave electromagnetic simulation should be performed to determine the frequency-dependent pad capacitance and conductance. However, to perform the full wave analysis is usually time-consuming, and complicated when lossy silicon is involved. In addition, it is not easy to extract some characteristic features with a strong physical meaning that can guide the practical design. Compared with the few attentions to the pad properties on lossy silicon substrate, extensive analyses, including full wave simulations[5], quasi-static EM approaches [6] and equivalent circuit models [7], have been done for lossy transmission line on MIS structures. Physical explanations have also been given to help understand the frequency dependent per unit length capacitance of the transmission line [8][9]. Although these analyses are almost all devoted to determine the characteristic impedance and propagation constant for interconnection purposes, they are still very helpful to give us some useful guidance for pad modeling. Fig. 2 (b) depicts a good equivalent circuit model with strong physical meaning. As we know, models with frequency dependent parameters are difficult to handle in time domain simulations, therefore, equivalent circuit model with frequency independent parameters are especially applicable for CAD.

In 1971, Hasegawa etc [8] proposed an equivalent circuit to determine the per unit length capacitance and conductance for MIS transmission line. With more and more interests in this aspect, researchers have recently further developed this model. In this paper, the capacitances C_{ox} and C_{sub} as shown in Fig.2 (b) are divided into parallel plate part and fringing effect part. The invaluable results for MIS transmission line are then used to determine the fringing part capacitance of the pad. In this model, we will treat the pad as a short transmission line four times to determine the pad fringing capacitance. Details are shown below.

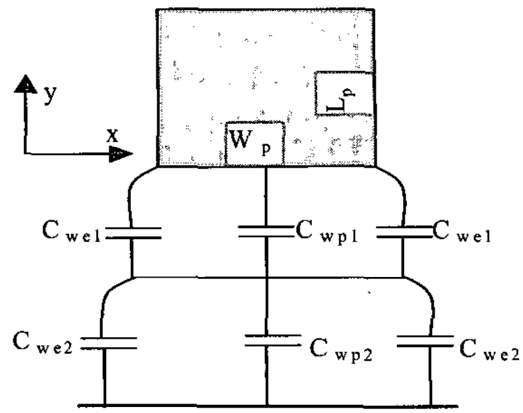

Fig. 3 Edge and Parallel plate contributions to the p.u.l capacitance for a microwave transmission line with trace width equal to W_p.

Fig. 3 depicts the way to determine the fringing capacitance from the pad's edges in x-axis direction, where C_{wp1} and C_{wp2} are the per unit length parallel plate capacitances and C_{we1} and C_{we2} are the per unit length fringing capacitances.

Let

$$C_{t1}=2\ C_{we1} + C_{wp1} \tag{1}$$

and

$$C_{t2}=2\ C_{we2}+ C_{wp2} \tag{2}$$

By treating the pad as a microstrip transmission line with width equal to W_p, the per unit length capacitance C_{t1} can be determined using close-form expressions [10]. Here the lossy silicon substrate is set to be perfect ground. Then treat the pad as another microstrip transmission line with width equal to W_p, but this time it is a lossless two-layer microstrip line. Following the idea of [7], we can get the per unit length capacitance C_∞ of this microstrip. With the same step in [7], we can get

$$C_{t2} = \frac{C_\infty C_{t1}}{C_{t1} - C_\infty} \tag{3}$$

The per unit length parallel plate capacitances C_{wp1} and C_{wp2} can be easily determined explicitly. Therefore the per unit length edge capacitances C_{we1} and C_{we2} can be obtained from the expressions (1)-(3).

So far, we have determined the per unit length capacitances attributed to the edge effect in the x direction. Following the similar procedure by treating the pad as a short microstrip transmission line twice but with trace width equal to L_p instead, we can get the per unit length capacitances C_{Le1} and C_{Le2}, attributed to the edge effect in the y direction. And the total oxide layer capacitance C_{ox} and substrate capacitance C_{sub} can be obtained by adding the parallel plate part and the fringing part together, as following,

$$C_{ox} = 2C_{we1}L_p + 2C_{Le1}W_p + C_{wp1}L_p \quad (4)$$

And

$$C_{sub} = 2C_{we2}L_p + 2C_{Le2}W_p + C_{wp2}L_p \quad (5)$$

And the conductance can be determined from the capacitance since there is a constant ratio between them [4][7]

$$G_{sub} = C_{sub}\frac{\delta}{\varepsilon_0\varepsilon_{r2}} \quad (6)$$

Apparently, this method contains the edge effect from the four edges of the pad and should be a very good approximation to the actual one. In the next section, we will compare the results from this model with full wave simulation results.

III. Results And Discussion

In this section, a comparison between our modeling method and full wave simulation is given. In the example, the pad is placed on the top of the insulator with 1um thickness. Under the insulator is the lossy silicon substrate with 500um thickness. The dimensions of the pad are 100um by 100um. The lossy silicon substrate has a uniform conductivity, and three conductivities 10 s/m, 20 s/m and 50 s/m are chosen. Fig.4 and Fig.5 Shows the comparison of the results predicted using this model and the full wave simulation results by SONNET. The solid curves are the modeling results in this paper, and the dash curves are full wave simulation results. It is found that at low frequency, the pad capacitance is a constant equal to the oxidation layer pad capacitance, where the lossy silicon behaves like a perfect conductor. When the frequency goes up, the electromagnetic field will penetrate into the lossy silicon substrate, the capacitance begins to decrease. With the further increase of the frequency, the silicon behaviors more like an insulator, and the pad capacitance approaches to another constant. The larger the silicon conductivity, the larger is the transition frequency due to the larger the relaxation frequency of the lossy silicon. All these effects can be seen in our modeling results and the full wave simulation. The comparisons in Fig.4 and Fig.5 clearly show that this model can give a frequency dependent pad capacitance and conductance with enough accuracy, and can thus be used in the initial practical design.

IV. Conclusion

Equivalent lumped circuit model is used to determine the frequency dependent pad capacitance and conductance. Closed-form formula is used to determine the frequency independent parameters in this model by simply taking the pad as a transmission line four times. Good agreement between the results from this model and the full wave simulation results justifies the validity of this modeling method. The modeling method needs little simulation time and CPU memory and thus suitable for computer aided design.

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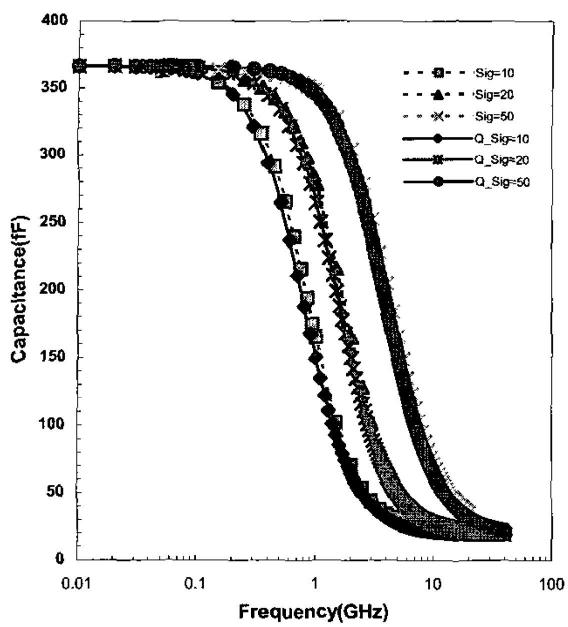

Fig. 4 Comparison of the pad capacitance between our modeling and full wave simulation with the substrate conductivity equal to 10, 20, and 50 s/m respectively. The solid curves are the modeling results in this paper, and the dash curves are full wave simulation results.

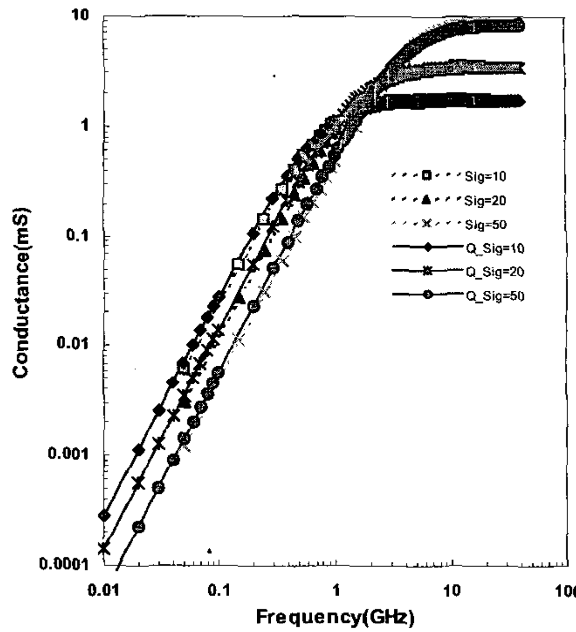

Fig. 5 Comparison of the pad conductance between our modeling and full wave simulation with the substrate conductivity equal to 10, 20, and 50 s/m respectively. The solid curves are the modeling results in this paper, and the dash curves are full wave simulation results.