Wideband Characterization of Mutual Coupling Between High Density Bonding Wires

Hai-Young Lee, *Member, IEEE*

***Abstract*— Mutual coupling between grounded bonding wires for high density IC packaging has been characterized over a wide frequency range using the Method of Moments in consideration of the ohmic and radiation losses. At high frequencies, the mutual inductance greatly increases due to the radiation-enhanced mutual coupling effect. For 500-μm-long bonding wires, a minimum 200- μm separation is required to maintain a 20-dB crosstalk level at low frequencies. This wideband analysis will be useful for designing packages and interconnection layouts of high frequency IC's with increased packaging density and operating frequency.**

I. Introduction

Recent advances in integration technology and performance of integrated circuits require greater density of packaging and interconnections demanding close arrangement of bonding wires. Especially in MMIC's and OEIC's operating at high frequencies, the bonding wire becomes dominant parasitic and limits their frequency performance and packaging density [1], [2]. Theoretical characterization of a single bonding wire has been treated using static and full-wave analyses [3], [4]. The full-wave analysis shows significant radiation of the bonding wire enhanced by the slow-wave effect of ohmic loss at high frequencies. The radiation enhances mutual coupling between high density bonding wires at high frequencies. Since the mutual coupling increases crosstalk as well as the parasitic effect between bonding wires, it should be accurately characterized in consideration of the radiation in order to increase packaging density and operating frequencies. Only a simple representation of static mutual inductance is available for infinitely long wires near a ground plane [5]. The radiation effect and the fringing effect at wire edges are not considered in the static approximation. Direct measurement of the mutual coupling has difficulties of precise calibration and error modeling due to the tiny geometry and the radiation problems.

In this letter, two grounded bonding wires coupled with a separation have been characterized over a wide range of frequencies using the Method of Moments (MoM). The mutual inductance and the radiation resistance are calculated by varying the separation between bonding wires. For 500-μm-long bonding wires separated by 200 μm, the mutual inductance is about 10% of the self inductance (0.28 nH) and the corresponding crosstalk level is 20 dB. High mutual coupling enhanced by the radiation has been observed at high frequencies. This wideband characterization of the mutual coupling is expected to be helpful for design and packaging of high frequency integrated circuits with increased packaging density and operating frequency.

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The author is with the Department of Electronics Engineering, Ajou University, Suwon 441-749, Korea.
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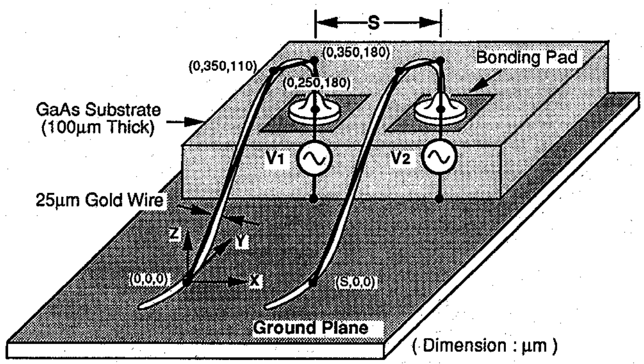

Fig. 1. Two grounded ball-bonding wires of a 25 μm diameter and a 500 μm length separated by S on a 100-μm-thick GaAs substrate.

II. Analysis

Two identical ball-bonding wires shown in Fig. 1 are considered to model the mutual coupling and to see the behavior for mutual separation (S) between the bonding wires. Two voltage sources (V_1, V_2) are respectively applied to two bonding pads on a 100-μm-thick semi-insulating GaAs substrate with a ground plane. Current distributions and input impedances of the bonding wires are calculated by the MoM with incorporation of conductor loss using the Phenomenological Loss Equivalence Method (PEM) [6]. In the MoM calculation, each bonding wire of total length 500 μm is approximately linearized as shown in Fig. 1, and then the linearized bonding wire is appropriately segmented by 12 total pulses using pulse-basis and pulse-testing functions. Distributed internal impedance of the gold bonding wire is calculated over a wide frequency range using the PEM, and it is appropriately distributed on the pulse segments using the lumped impedance loading method for the MoM calculation. The perfect ground plane is substituted by the image of the bonding wires. The dielectric effect of the semi-insulating substrate is neglected for the low-impedance wires, and electric coupling between two bonding pads is not considered but can be simply calculated using the conformal mapping method.

The input impedance for in-phase excitation (Z_+) and that for out-of-phase excitation (Z_-) have been respectively calculated for an in-phase and an out-of-phase excitation of two voltage sources (i.e., $V_1, V_2 = 1$ V and $V_1 = 1$ V, $V_2 = -1$ V).

The input impedance of the bonding wires is obtained from the applied source voltage divided by the calculated source current at bonding pad. Using lumped element modeling, the coupled bonding wires can be equivalently represented by coupled inductors with series resistances associated with the ohmic and radiation losses at a given frequency. Then, the self inductance (L) and the mutual inductance (M) can be calculated, respectively, by

$$L = \mathrm{Im}(Z_+ + Z_-)/2\omega \quad (1)$$

$$M = \mathrm{Im}(Z_+ - Z_-)/2\omega \quad (2)$$

The series wire resistance associated with the ohmic loss and the radiation loss is obtained from the real part of the input impedance. The pure radiation resistance is obtained from the input resistance calculated by assuming an ideal conducting wire.

III. Numerical Results

In Fig. 2(a), shown are the self inductance and the mutual inductance of the coupled bonding wires calculated by the MoM over a wide frequency range for different bonding wire separations (S). They are compared with the static results calculated by simple static formulas [5] commonly used in CAD software. In the static calculations, the curved bonding wires are approximated by two coupled straight wires of 500 μm total length and 100 μm average height from a ground plane. Their self inductances are in very good agreement at low frequencies below 20 GHz. As shown in Fig. 3, it is observed that the current disbribution, calculated by the MoM with the incorporation of the ohmic resistance using lumped loading method, is highly uniform along the bonding wires and the static approximation is valid at low frequencies. For a very close separation of 20 μm, the static mutual inductance is underestimated compared to the MoM result due to the static approximation of straight wires and the fringing effect of the real bonding wires.

At high frequencies above 20 GHz, the self and mutual inductances greatly increase due to the radiation effect and the radiation-enhanced mutual coupling effect, respectively. In order to see the radiation effect clearly, the total resistance and the radiation resistance are shown in Fig. 2(b) for a typical 100-μm separation since the input resistance is almost independent of the wire separation. The total resistance is dominated by the ohmic resistance and the radiation resistance at low and high frequencies, respectively. The increasing radiation resistance implies the significant radiation and consequent high mutual coupling at high frequencies. The nonuniform current distribution at high frequencies shown in Fig. 3 is due to the radiation effect as well. The current disbribution increasing from the bonding pad at high frequencies is related to the radiation-enhanced magnetic coupling between the real bonding wire and its image wire. Higher magnetic coupling around the ground point effectively increases vertical current component of the real bonding wire, whereas horizontal current around the top of the bonding wire is decreased by the opposite image current. Since the mutual inductance is increasingly more rapidly to the increasing frequency than the self inductance because of the radiation-enhanced mutual coupling, high density bonding wires for high frequency integrated circuits should be accurately characterized in consideration of the radiation.

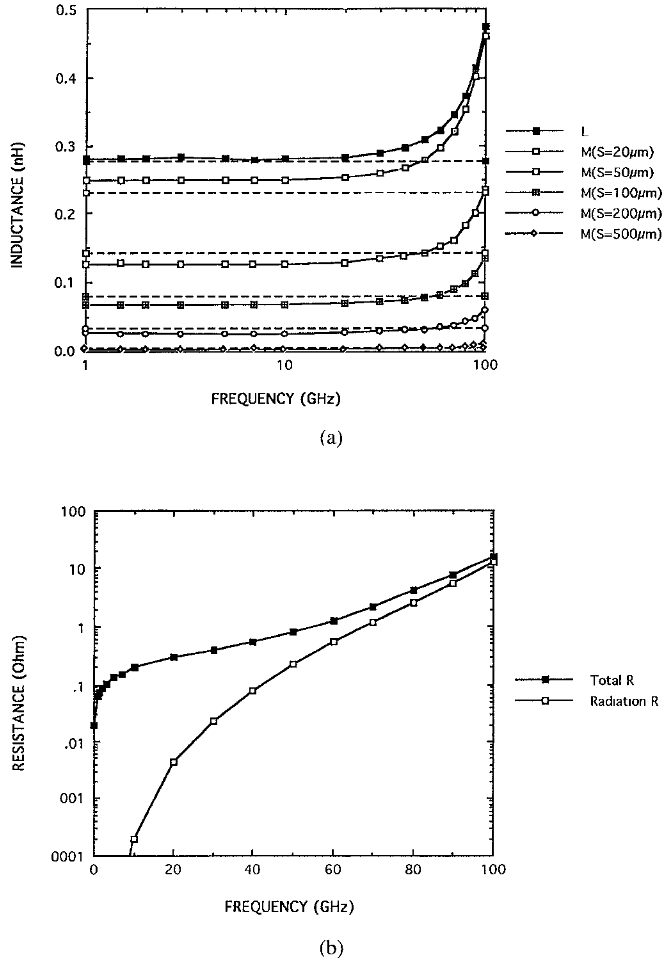

Fig. 2. (a) Self (L) and mutual (M) inductances of coupled bonding wires for different wire separations (S) calculated by the MoM (solid line) and static formulas (dashed line). (b) Total input resistance and pure radiation resistance calculated by the MoM for a 100-μm wire separation.

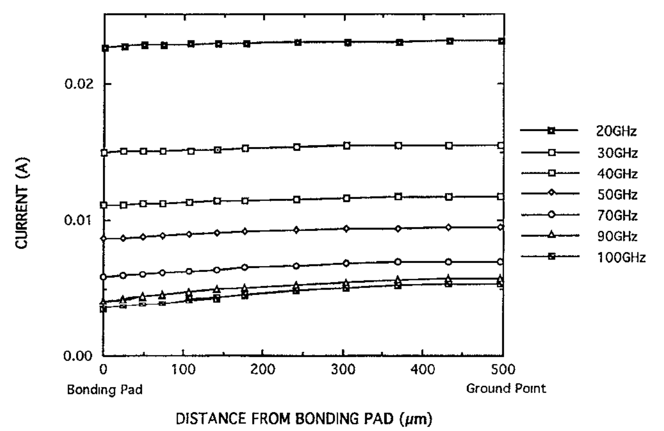

Fig. 3. Current distributions along the bonding wire axis for in-phase excitations (V_1, V_2 = 1 V) of different frequencies in the case of 100-μm separation.

From the variations of calculated self and mutual inductances to the separation in Fig. 2(a), we can note that the bonding wires should be separated by at least 200 μm in order to keep 20-dB crosstalk factor [7] corresponding to 10% mutual inductance to the self inductance. However, the minimum separation to maintain the low crosstalk level is increasing proportionally to both operating frequency and total wire length due to the radiation-enhanced mutual coupling effect.

IV. Conclusion

The method of moments with incorporation of ohmic loss is applied to two grounded bonding wires in order to characterize the mutual coupling for a wide variation of wire separations. The calculated results show high mutual coupling, enhanced by the radiation effect, greatly increases the equivalent mutual inductance at high frequencies. For 500-μm-long bonding wires, a minimum 200-μm separation is required to maintain a 20-dB crosstalk level at low frequencies. The minimum separation is increasing proportionally to the frequency as well as the wire length due to the radiation-enhanced mutual coupling. Simple static formulas are not accurate for close wire separations due to the straight wire approximation and the fringing effect at the wire ends. These wideband results are expected to be useful for designing packages and interconnection layouts of high frequency integrated circuits with increased packaging density and operating frequency.

References

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