# Coupling Capacitance Extraction in Through-Silicon Via (TSV) Arrays

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***Abstract*—In this paper, we discuss a well known modeling approach that is used to extract the coupling capacitance between any two neighboring through silicon-vias (TSVs) in three dimensional integrated circuits (3D-ICs). This model has been used by many publications due to its modularity, easiness and quick turnaround time. However, the model is based on a homogeneous surrounding medium assumption. Our work shows that the homogeneous medium assumption is inaccurate due to the fact that each TSV is actually surrounded by a non homogeneous medium (silicon and silicon dioxide materials). The theory behind this claim is provided and validated using quasi static field solver simulations (ANSYS Q3D). The percentage error in coupling capacitance between Q3D extraction results and the homogeneous medium model results can reach 70%. We suggest alternative modeling approaches that can provide better accuracy with emphasizing the pros and cons of each approach.**

***Index Terms*—TSV, 3D-IC, 2.5D-IC, SiP.**

## I. Introduction

Three dimensional integrated circuits (3D-ICs) has been an important topic of research for several years now. 3D integration is an emerging packaging technology which considered by many as the natural evolution of Moore's law (More than Moore). As scaling down the transistor size becomes more difficult and costly due to the need for advanced lithography techniques, the integration of multiple dies in one package can achieve better performance and an enhanced form factor. Placing two dies side by side on an interposer (2.5D stacking) is already in production by FPGA manufacturers. Also stacking several dies vertically (3D stacking) is already planned to be in production by memory manufacturers and image sensors manufacturers.

For stacking two dies (or more) vertically, Through Silicon Vias (TSVs) are needed to connect I/Os between different dies. As digital circuits design becomes more interconnect-driven, TSVs can promise enhanced delay performance than bond wires in traditional packaging technologies. Each single TSV is simply a cylinder of metal (mostly copper or tungsten) coated with a thin layer of silicon dioxide (called oxide liner) in order to enable some kind of electrical isolation (reduce coupling to/from TSV). As a TSV goes all the way from die to die, it is surrounded by silicon material. A cross section of TSV structure is shown in Fig. 1

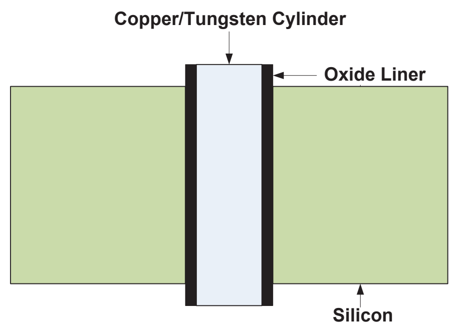


Fig. 1. Cross section of TSV structure

To enable parasitic extraction of 3D-ICs interconnects, an accurate electrical modeling of TSV arrays is required. A special attention is given to capacitance matrix extraction due to its effect on delay performance of digital circuits.

[1], [2] and [3] suggest using the relation between the inductance matrix and the capacitance matrix (per unit length) in a homogeneous medium in order to estimate the capacitance matrix of a TSV array:

$$[L][C] = \mu\epsilon_{\text{si}} \quad (1)$$

Where [L] is the inductance matrix per unit length, [C] is the capacitance matrix per unit length, $\mu$ is the permeability of free space and $\epsilon_{\text{si}}$ is the permittivity of silicon ($11.9\epsilon_{\text{o}}$). Mutual and self inductance of TSVs can be found easily by the well known formulas in [4]:

$$L_{mutual} = \frac{\mu_o h}{2\pi}\left[\ln(\frac{h}{p} + \sqrt{1+\frac{h^2}{p^2}}) - \sqrt{1+\frac{h^2}{p^2}} + \frac{p}{h}\right] \quad (2)$$

$$L_{self} = \frac{\mu_o h}{2\pi}\left[\ln(\frac{h}{r} + \sqrt{1+\frac{h^2}{r^2}}) - \sqrt{1+\frac{h^2}{r^2}} + \frac{r}{h}\right] + \frac{\mu_o h}{8\pi} \quad (3)$$

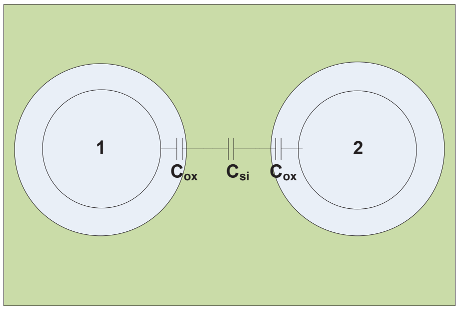


Fig. 2. homogeneous medium model for coupling capacitance extraction

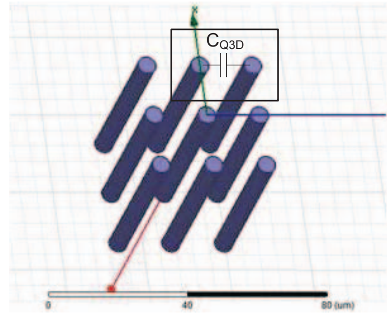


Fig. 3. 3x3 TSV array in Q3D

Where $\mu_o$ is the permeability of free space. $h$, $r$ are TSV length and TSV radius respectively. $p$ is TSVs pitch (center to center separation between TSVs).

(2) and (3) can be used to fill in the inductance matrix [L]. Thus, the capacitance matrix [C] will be the only unknown in (1).

In this paper, we show that using (1) to extract the coupling capacitance matrix of a TSV array is mostly inaccurate due to the fact that the surrounding medium of a TSV is actually non homogeneous. The physical reasoning behind this claim is presented and the results are validated using ANSYS Q3D, a quasi static electromagnetic (EM) field solver. Then, other modeling techniques that can be used to provide more accurate results of the coupling capacitance are presented.

## II. Problem Statement

[1], [2] and [3] propose the following model to extract the coupling capacitance of two TSVs as shown in Fig. 2

$$C_{ox} = \frac{\pi \epsilon_o \epsilon_{ox} h}{\ln\left(\frac{r+t_{ox}}{r}\right)} \quad (4)$$

$$[C_{si}] = \mu \epsilon_o \epsilon_{si} [L]^{-1} h^2 \quad (5)$$

Then the total coupling capacitance between the two TSVs is:

$$C_{tot} = \frac{0.5 C_{ox} C_{si}}{0.5 C_{ox} + C_{si}} \quad (6)$$

(4) is simply the modeling of the oxide liner capacitance as cylindrical wire capacitance. Usually, the value of this capacitance is relatively huge (tens of $fF$s) and its effect on the series combination (total capacitance) is insignificant. (5) is derived from (1). The value of $C_{si}$ is small and it has the most significant effect on $C_{tot}$ in (6).

According to [5], (5) assumes transverse electromagnetic field propagation (TEM). TEM means that electric field and magnetic field are assumed to be in the transverse plane and completely orthogonal (decoupled). This assumption is valid only if the following conditions are met:

1) Homogeneous Surrounding Medium: a medium is said to be homogeneous if the medium permittivity is constant at any given position in the medium (independent of space coordinates). This causes the EM wave to travel in the medium with a constant propagation velocity:

$$v = \frac{1}{\sqrt{\mu \epsilon}} \quad (7)$$

Where $\mu$ and $\epsilon$ are the permeability and permittivity of the medium respectively.

2) Lossless Surrounding Medium: Although (5) derivation in [5] is based on lossless medium ($\sigma$ = 0) assumption, introducing losses in the medium doesn't invalidate TEM assumption as long as the medium is homogeneous.

3) The dimensions of the structure of interest are much smaller than the EM wave length ($\lambda$) at the frequency of interest (i.e: electrically small structures).

Applying the previous conditions on TSV array case, we find that conditions (1) and (2) don't apply. Which makes (5) not applicable due to the fact that the surrounding medium is non homogeneous. Electric field lines will be partly in silicon dioxide and partly in silicon. EM wave travels in the same direction of the conductor (TSV) with two different propagation velocities:

$$v_{si} = \frac{1}{\sqrt{\mu \epsilon_{si}}} \quad (8)$$

$$v_{ox} = \frac{1}{\sqrt{\mu \epsilon_{ox}}} \quad (9)$$

## III. Coupling Capacitance Error

In this section, the methodology that will be used to validate the theoretical assumption in section (II) is presented. We assume a 3x3 TSV array example as shown in Fig. 3

According to section (II), we expect an error between the homogeneous medium model results and an EM field solver (Q3D) results. To characterize the error in this example, the below steps are followed:

1) Find the coupling capacitance using Q3D simulations. This is the reference value ($C_{Q3D}$).

TABLE I
COUPLING CAPACITANCE ERROR FOR DIFFERENT MEDIUM PROPERTIES

| Medium Properties | $t_{ox}$ ($\mu m$) | $C_{model}$ ($fF$) | $C_{Q3D}$ ($fF$) | $Error$ (%) |
|---|---|---|---|---|
| Homogeneous + Lossless | 0 | 4.28 | 4.42 | $-3.2$ |
| Homogeneous + Lossy | 0 | 4.28 | 4.44 | $-3.6$ |
| Non Homogeneous + Lossless | 0.3 | 3.94 | 3.69 | 6.8 |
| Non Homogeneous + Lossy | 0.3 | 3.94 | 12.78 | $-69.2$ |

TABLE II
COUPLING CAPACITANCE ERROR FOR NON HOMOGENEOUS, LOSSY MEDIUM AT DIFFERENT FREQUENCIES

| Frequency ($GHz$) | $C_{model}$ ($fF$) | $C_{Q3D}$ ($fF$) | $Error$ (%) |
|---|---|---|---|
| 1 | 3.94 | 12.78 | $-69.2$ |
| 10 | 3.94 | 5.07 | $-22.3$ |
| 20 | 3.94 | 4.06 | $-3$ |

2) Find the coupling capacitance using the homogeneous medium model ($C_{model}$) in (5).

3) Calculate the percentage error between $C_{Q3D}$ and $C_{model}$ with using $C_{Q3D}$ as the reference value:

$$Error = \frac{C_{model} - C_{Q3D}}{C_{Q3D}} \times 100 \qquad (10)$$

*A. Characterization of coupling capacitance error vs. surrounding medium properties*

In this section, we calculate the coupling capacitance error defined in (10) by comparing Q3D results with the homogeneous medium model results. The comparison is done for different surrounding medium properties. TSV array parameters are $h$ (TSV height) = $50\mu m$, $r$ (TSV radius) = $2.5\mu m$ and $p$ (TSVs pitch) = $16\mu m$. The operating frequency is $1GHz$. Silicon substrate conductivity is $\sigma_{si}$ and oxide liner thickness is $t_{ox}$. We consider the following cases:

1) Homogeneous, Lossless Surrounding Medium: in this case, $t_{ox}$ = 0 and $\sigma_{si}$ = 0.

2) Homogeneous, Lossy Surrounding Medium: in this case, $t_{ox}$ = 0 and $\sigma_{si}$ = $10S/m$.

3) Non Homogeneous, Lossless Surrounding Medium: in this case, $t_{ox}$ = $0.3\mu m$ and $\sigma_{si}$ = 0.

4) Non Homogeneous, Lossy Surrounding Medium: in this case, $t_{ox}$ = $0.3\mu m$ and $\sigma_{si}$ = $10S/m$.

For simplicity, we will just observe the coupling capacitance between two neighboring TSVs in the array as shown in Fig. 3. The results of this investigation are shown in Table I.

In Table I, As long as the surrounding medium is homogeneous (only silicon material with no oxide liner) - whether the medium is lossy or not - the homogeneous medium model results agree with Q3D results with a small percentage error (3%-4%). When the non homogeneous medium effect is introduced (oxide liner around TSV is present) with lossless condition, the error increases (6.8%). When introducing both non homogeneous medium effect and losses effects, the error increases dramatically (69.2%).

The previous results align with the physical theory presented in section (II). In case of non homogeneous medium, $\epsilon$ is not constant in the interface region between silicon and silicon dioxide which makes (5) not accurate. Losses effect will be discussed in the next section.

*B. Characterization of coupling capacitance error vs. frequency*

Historically, many publications have been dedicated to predict the silicon substrate behavior vs. frequency. This has been related to TSVs in [6] and [7]. Silicon substrate is electrically modeled to have two natures: a "conductor" nature and a "dielectric" nature. Based on the operating frequency, one nature may dominate the behavior. The "conductor" nature is represented by a substrate conductance ($G$) and the "dielectric" nature is represented by a substrate capacitance ($C$).

1) At low frequency ($\omega C < G$): the "conductor" nature dominates the substrate electrical behavior. Silicon substrate acts as a lossy conductor.
2) At high frequency ($\omega C > G$): the "dielectric" nature dominates the behavior. The electrical behavior of the substrate becomes mainly capacitive.

According to [6], the frequency value that separates the "conductor" mode and the "dielectric" mode is:

$$f_{mode} = \frac{\sigma_{si}}{2\pi\epsilon_{si}} \qquad (11)$$

Relating this theory to our TSV coupling capacitance problem, we find that at high frequency (exceeding $f_{mode}$), the capacitive behavior of the silicon substrate dominates over the conductive behavior (the medium becomes more lossless). Consequently, we expect that the non homogeneous, lossy medium case will behave similar to the non homogeneous, lossless ($\sigma_{si} = 0$) medium case. This means that the homogeneous medium model can be applied on the non homogeneous, lossy medium with a small error at high frequency only. To validate this theoretical assumption, Q3D is used to find the coupling capacitance (as shown in Fig. 3) in the case of non homogeneous, lossy surrounding medium ($t_{ox} = 0.3\mu m$, $r = 2.5\mu m$, $p = 16\mu m$, $h = 50\mu m$ and $\sigma_{si} = 10S/m$) at different frequencies ($1GHz$, $10GHz$ and $20GHz$). The results are shown in Table II.

The results in Table II show that as the operating frequency increases, the coupling capacitance error decreases. In other words, as the frequency increases, the homogeneous medium model can provide more accurate results. At low frequency (lower than $f_{mode}$), the homogeneous medium model will result in a large coupling capacitance error. This aligns to the theoretical expectation.

## IV. Alternative Approaches

As shown in the previous sections, For the practical case of a TSV array (non homogeneous, lossy surrounding medium) at low frequency, the homogeneous medium model can not be used as is because it assumes constant permittivity ($\epsilon_{\text{si}}$) across the medium. It has to be modified to account for the variability of $\epsilon_{\text{si}}$ in the interface region between silicon and silicon dioxide. In the following subsections, we present some alternative modeling approaches with the pros and cons of each approach.

### *A. Numerical Electromagnetics*

In order to accurately model EM fields behavior for cases where there are no closed form expressions available, numerical techniques can be used. Some examples of these techniques are finite element method (FEM) and method of moments (MoM). [5] suggests that for the non homogeneous medium case, MoM can be used to accurately extract the capacitance matrix. MoM is used in [5] for the case of ribbon cables (similar to TSV arrays structure). [8] uses the same technique in [5] for TSV array case. Free and bound charges are modeled at each interface region (conductor-oxide and oxide-silicon) by expanding charge distribution into fourier series then applying boundary conditions at each interface region. For the case of widely separated conductors, approximations that assume uniform distribution of charges in the medium can be made. Using more fourier coefficients when expanding charge distributions can achieve higher accuracy. However, This increases the matrices sizes that need to be handled which causes the expected run time to be significantly slow.

### *B. Conformal Mapping*

In [7] and [9], the interface region between silicon and silicon dioxide in a TSV is modeled using conformal mapping technique. Two neighboring TSVs modeled as a parallel wire structure are transformed into a parallel plate structure using conformal mapping. As the potential of the interface between oxide layer and silicon substrate layer is assumed to be non uniform, the interface region is divided into sections and capacitance is estimated for each section individually. Using more sections is expected to result in better accuracy. The author in [7] and [9] applies this technique for two TSVs only. In case of large $nxm$ TSV array, this technique is expected to be more complicated and slow in run time.

### *C. Library Based Macro Modeling*

In [10], a library based algorithm is used in order to extract the capacitance matrix of any large, arbitrary $nxm$ TSV array. The idea of the algorithm is to divide the desired $nxm$ TSV array into smaller TSV arrays of fixed size (for example, $3x3$), use Q3D simulations to extract the capacitance matrix of the smaller TSV arrays (windows) and store the solutions in a library. The last step would be to combine the solutions of the smaller sub problems ($3x3$ TSV arrays) to generate the solution of the original problem (large $nxm$ TSV array). This approach is accurate and fast in run time. The only limitation is the stored library is dependent on TSV parameters. Also EM field solver simulations are involved in the flow.

## V. Conclusion

This paper shows that using the relation between the inductance matrix and the capacitance matrix to extract the coupling capacitance of a TSV array is inaccurate at low frequency. This is because it assumes a homogeneous surrounding medium while the surrounding medium of a TSV is non homogeneous. Based on Q3D extraction results as the reference, the homogeneous medium model can introduce an error that reaches 70%. We present other modeling approaches that provide higher accuracy. They are either library-based which affect the model modularity or numerical solutions which affect the extraction turnaround time. A better approach will be to enhance the homogeneous medium model to account for the space-dependent permittivity in the interface region between silicon and silicon dioxide in a TSV array.

## VI. Acknowledgment

This research was partially funded by Zewail City of Science and Technology, AUC, the STDF, Intel, Mentor Graphics, ITIDA, SRC, ASRT and MCIT.

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