

Analysis of Multiple Vias Coupling in Silicon Interposer by using Cylindrical Mode Expansion Method

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Abstract

This paper presented a cylindrical mode expansion method for the analysis of the coupling between multiple through silicon vias (TSV) in silicon interposer. The scattering and multi reflection effects between the vertical cylindrical vias are considered by expanding the electromagnetic fields surrounding the vias by cylindrical waves. As the method fully captured the physical mechanism of the wave interaction between multiple vias, it can give a high accuracy and fast solution. Based on this method, the effect of the grounded TSVs for the reduction of electromagnetic interference is efficiently analyzed.

1. Introduction

Driven by the high performance of modern electronic products, there is a general tendency that three-dimensional (3D) integrated circuits gradually replace the traditional two-dimensional (2D) technology. Through silicon vias (TSVs) as a 3D integration technology which allows for heterogeneous integration, high-density, and high-speed packaging is promising to extend Moore's Law. The structure of though silicon vias and the silicon interposer are shown in Fig.1. As the silicon substrate where TSVs embedded is semi-conductive and lossy, it can cause strong electromagnetic coupling inside the dense TSV array and signal attenuation, which then results in serious electromagnetic compatibility (EMC) issues and signal integrity (SI) issues. The modelling of the signal propagation among large numbers of TSVs is attracting more and more attentions [1]. The efficient and accurate simulation technology to obtain the electrical performance of complex and dense TSV array based 3D packaging is very important for the 3D integration design, and it is also a challenge for available solvers.

So far, a few methods have been proposed to simulate the signal integrity and electromagnetic compatibility issues of TSV based 3D integrated circuit. In [2], a lumped circuit model with high efficiency is presented. However, this method is only valid with small numbers of TSVs, such as GS and GSG structures. For large number of TSVs, the lumped circuit model can not consider the full-wave coupling between every TSVs pair. On the other hand, the frequency domain integral-equation method [3] and the time domain differential-equation method [4] can accurately solve the problems, with the drawback of requiring large memory and long computational time. In this paper, the modal decomposition methodology which has been used in our previous work [5][6]is presented to exploit the salient features of multiple vias. The approach is accurate, memory and computational time saving compared to the aforementioned methods.

The paper is organized as follows: a detailed description of the modal expansion method is provided in the second section for the modeling of multiple TSVs. In section III, based on the proposed method, the electromagnetic coupling inside TSVs array is simulated, and the effect of grounded TSVs for the reduction of electromagnetic interference (EMI) inside TSV array is efficiently analyzed.

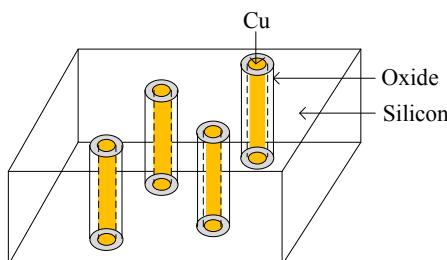


Fig.1. The structure of though silicon vias in silicon interposer.

2. Multiple Vias Modeling

Through silicon vias in electronic packaging are with the shape of circular cylinders, therefore the electromagnetic field in the silicon substrate can be expressed as the addition of cylindrical wave. The theory of multiple scattering is used to model large numbers of parallel conducting vias. Under the cylindrical coordinates, two independent solutions of Maxwell's equations are considered, namely, TM^z mode and TE^z mode. We can use the modal expansion method to express electric field E_z and magnetic field H_z as

$$E_z(\rho, \phi) = \sum_{n=-\infty}^{\infty} [a_n^E J_n(k\rho) + b_n^E H_n^{(2)}(k\rho)] e^{jn\phi} \quad \text{for TM}^z \text{ mode, and} \quad (1)$$

$$H_z(\rho, \phi) = \sum_{n=-\infty}^{\infty} [a_n^H J_n(k\rho) + b_n^H H_n^{(2)}(k\rho)] e^{jn\phi} \quad \text{for TE}^z \text{ mode,} \quad (2)$$

where a_n^E , a_n^H , b_n^E , b_n^H , are the expansion coefficients of the incoming TM^z wave, incoming TE^z wave, outgoing TM^z wave, and outgoing TE^z wave respectively. The symbol k is the wavenumber with the value of $\omega/\sqrt{\mu\epsilon}$, where ω is the angular frequency, and μ and ϵ are the permeability and permittivity of the silicon substrate respectively. $J_n(k\rho)$ and $H_n^{(2)}(k\rho)$ are the Bessel function with the order of n and the second kind Hankel function with the order of n respectively. The time dependence factor $\exp(j\omega t)$ is assumed throughout the paper. After that, the mode expansion of E and H field tangent to the propagation direction of $\hat{\rho}$ for TM and TE cases can be expressed as

$$\mathbf{E}_t(\rho, \phi) = \sum_{n=-\infty}^{\infty} [\hat{a}_n^E J_n(k\rho) + \hat{b}_n^E H_n^{(2)}(k\rho)] \hat{z} + j\eta [\hat{a}_n^H J'_n(k\rho) + \hat{b}_n^H H_n'^{(2)}(k\rho)] \hat{\phi} e^{jn\phi}, \quad (3)$$

$$\mathbf{H}_t(\rho, \phi) = \sum_{n=-\infty}^{\infty} [\hat{a}_n^H J_n(k\rho) + \hat{b}_n^H H_n^{(2)}(k\rho)] \hat{z} - j/\eta [\hat{a}_n^E J'_n(k\rho) + \hat{b}_n^E H_n'^{(2)}(k\rho)] \hat{\phi} e^{jn\phi} \quad (4)$$

As a result, the total electric and magnetic fields in the silicon interposer can be expressed as the summation of the incident and scattering modes, expanded in cylindrical waves.

Taking into account of a set of randomly distributed cylindrical vias with different radius. The total electromagnetic field at an observation point p can be express as the summation of all the outgoing waves from each via, and given by

$$\phi(\bar{\rho}) = \sum_{q=1}^{N_{via}} \sum_{n=-N_q}^{N_q} f_{qn} H_n^{(2)}(k\rho_q) e^{jn\phi_q}, \quad (5)$$

where N_{via} is the number of the cylindrical vias, $2N_q+1$ is the truncated order of Hankel functions. f_{qn} is the coefficient of each wave mode and can be derived from the following equation:

$$f_q = \bar{T}_q \left(a_q + \sum_{p=1, p \neq q}^{N_{via}} \bar{\alpha}_{qp} f_p \right), \quad (6)$$

where \bar{T}_q is the transforming coefficient of outgoing wave from incoming wave of the q th via; a_q denotes the incident wave coefficients in terms of Bessel functions. The incident wave of the q th via caused by the scattered wave of the p th via can be represented by the translation matrix $\bar{\alpha}_{qp}$. By using addition theorem of cylindrical harmonics, $\bar{\alpha}_{qp}$ can be obtained as

$$\alpha_{qp}(m, n) = H_{m-n}^{(2)}(k\rho_{pq}) e^{-j(m-n)\phi_{pq}}. \quad (7)$$

Now we can apply the boundary condition on the TSV surface, and expression of the T matrix is obtained as followed

$$T_{mn} = \begin{bmatrix} -\frac{J_n(k\rho)}{H_n^{(2)}(k\rho)} & 0 \\ 0 & -\frac{J'_n(k\rho)}{H_n'^{(2)}(k\rho)} \end{bmatrix}. \quad (8)$$

Finally, submitting equations (8) and (7) into (6), we can solve for coefficient of each wave mode f_{qn} .

3. Numerical Examples

Firstly, the accuracy of the proposed method is verified by comparing its result with that of 3D full-wave finite element simulator. As shown in Fig.2, a current source with the amplitude of 1A is applied to the via in the z direction,

and only TM wave can be excited. Fig.2 shows the Ez field distribution around the TSV. As can be seen in Fig. 2, the Ez field distribution of the proposed modal expansion agrees well with that of the 3D full-wave simulator. The proposed method gives an isotropic distribution of Ez, while for the full-wave simulation result, the Ez distribution is not perfect isotropic due to the non-uniform meshing.

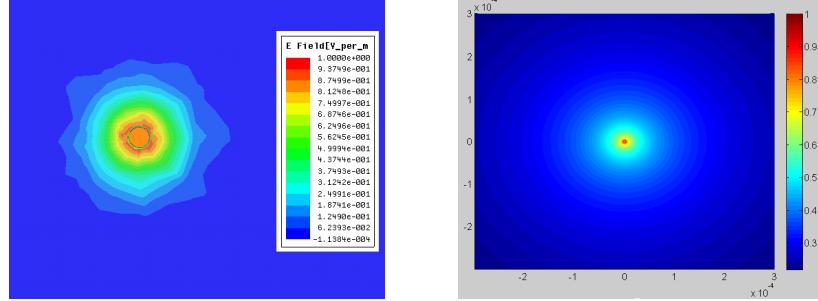


Fig.2.Comparison of the Ez field distribution at 20 GHz: our simulation results (left) versus 3D full-wave simulation results (right).

Next, a numerical example shown in Fig.3 is to demonstrate the electromagnetic interference of four through silicon vias, where the Ez distribution is plotted. The geometry size of the TSV array is 200um by 200um, with the operating frequency of 20GHz. To simulate the worst case, assume currents with the same directions flowing through these four TSVs at the same time. Under this condition, they will induce the stronger electromagnetic noise surrounding them. As it can be seen that when signal is applied to the TSV at the same time, the electromagnetic filed in the middle region of the array is very high. Such global coupling effects can cause serious simultaneous switching noise and electromagnetic interference problems.

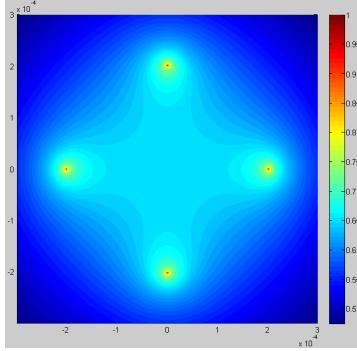


Fig.3. Coupling effects between four TSVs

To reduce the electromagnetic interference, grounded TSV array are inserted into two signal TSVs to improve the system performance. Grounded shield TSV is effective to help eliminating the noise coupling between two adjacent signal TSVs. As depicted in Fig.4, the electromagnetic coupling is greatly reduced with 3 grounded TSVs inserted between the two signal TSVs, and nearly eliminated when a 3x3 TSV array is used. The distance between grounded TSV is chosen according to the working frequency. Fig.4 also shows that the grounded TSVs not only reduce the electromagnetic field between the two signal TSV, they also reduce the electromagnetic field propagation away from the signal TSVs.

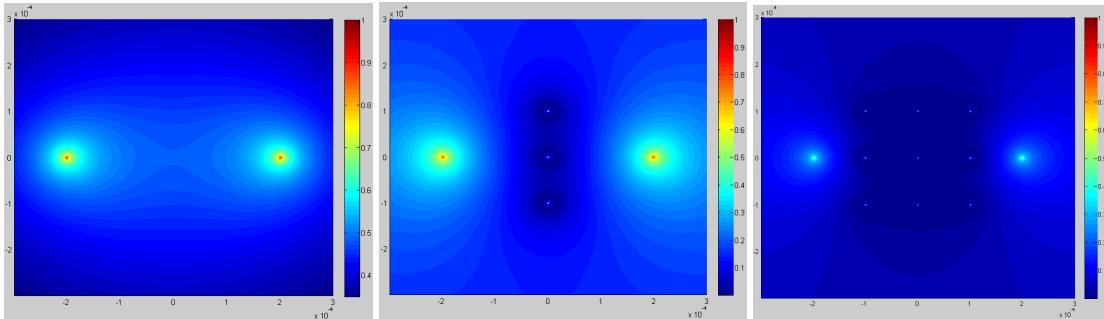


Fig.4. Grounded TSVs for reducing electromagnetic coupling: two signal TSVs without grounded TSV (left), two signal TSVs with 3 grounded TSVs (middle), two signal TSVs with 9 grounded TSVs (right)

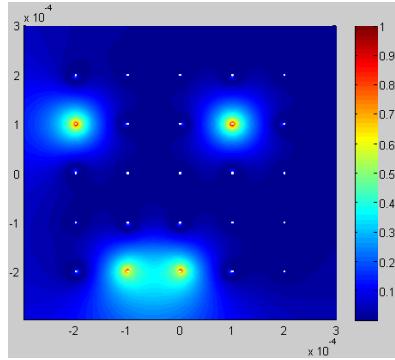


Fig.5. The Ez distribution in a 5x5 TSV array.

For a larger problem simulation with a 5x5 TSV array, the computational time of the proposed method is about 10 seconds compared to 31 minutes used by the full-wave finite element simulator. The simulation is conducted on a Intel desktop computer of 3.3GHz with 8G memory. As the result shown in Fig.5, adjacent signal TSVs have strong electromagnetic coupling, however, the electromagnetic interference is nearly eliminated by applying the aforementioned grounded TSVs.

4. Conclusion

The proposed modal expansion method which takes the multiple vias scattering into consideration is computationally efficient with a high accuracy. Based on the proposed method, grounded TSVs are presented to help eliminating electromagnetic coupling inside signal TSV array. Numerical examples show that this method is powerful for the analysis of signal integrity and electromagnetic interference issues related to TSV interposer.

5. Acknowledgement

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6. References

1. Z. H. Guo and G. W. Pan, "On Simplified Fast Modal Analysis for Through Silicon Vias in Layered Media Based Upon Full-Wave Solutions," *IEEE Tran. Adv. Packag.*, vol. 33, no. 2, pp. 517-523, May 2010.
2. J. Kim, J. S. Pak, J. Cho, E. Song, J. Cho, H. Kim, T. Song, J. Lee, H. Lee, K. Park, S. Yang, M. S. Suh, K.Y. Byun, and J. Kim, "High-frequency scalable electrical model and analysis of a through siliconvia (TSV)," *IEEE Trans. Comp. Packag. Manuf. Technol.*, vol. 1, no. 2, pp. 181-195, Feb. 2011.
3. S. G. Hsu and R. B. Wu, "Full-wave characterization of a through hole via in multi-layered packaging," *IEEE Trans. Microwave Theory & Tech.*, vol. 43, no. 5 (1995), pp.1073-1081, May 1995.
4. B. Archambeault, C. Brench, and M. Ramahi, EMI/EMC computational modeling handbook, Norwell, Kluwer Academic, MA, 1998.
5. E. X. Liu, X. C. Wei, Z. Z. Oo, E. P. Li, L. W. Li, "Modeling of Advanced Multilayered Packages with Multiple Vias and Finite Ground Planes , " Electrical Performance of Electronic Packaging, pp.275-278, 2007.
6. Z. Z. Oo, E. X. Liu, E. P. Li, X. C. Wei, Y. J. Zhang, M. Tan, L. W. Li, R. Vahldieck, "A Semi-Analytical Approach for System-Level Electrical Modeling of Electronic Packages With Large Number of Vias," *IEEE Tran. Adv. Packag.*, vol. 31, no. 2, pp. 267-274 ,May 2008.