Modeling and Analysis of TSV Arrays with Different Ground and Signal Distributions in 2.5D/3D Integration Systems

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Abstract. Signal and power incomplete are the main problems of integrated circuits (IC) due to the loss between through-silicon vias (TSVs) in TSV arrays. The finite element method is employed to simulate the transmission performance and crosstalk of TSV arrays in four shapes, and each shape is divided into two ground-signal (GS) distributions. Pentagon-pattern with the signal-in-center TSV obtains the best return characteristics and the crosstalk between two TSVs in square-pattern is minimal. The crosstalk loss is the smallest when signal TSVs are located in the four vertices of square-pattern. This paper may provide useful information in 2.5D/3D integration systems to improve the transmission performance and reduce the crosstalk.

1. Introduction
As the rapid development of the semiconductor technology, the characteristic sizes of chips are decreasing and the demand for small-sized electronic devices with multiple functions is increasing. To meet the industry demand, it is necessary to encapsulate multiple functional chips in a single module. Packaging technology has developed 2.5D and 3D integration which act as extensions of Moore’s law[1]. 2.5D integration has a silicon interposer separating the package substrate from the dies. One die is connected to the substrate through vertical interconnects, TSVs, that penetrate the silicon interposer[2]. And multiple functional chips are stacked vertically in 3D integration. The memory dies are stacked vertically inside the package and connected to the substrate by TSVs[3, 4].

However, there can be a high parasitic capacitance between the silicon substrate and the insulation layer wrapping outside the TSV metal conductor. Therefore, the signal TSV in TSV arrays is able to crosstalk into the surrounding silicon substrate or adjacent components, which affects the integrity of IC signals severely[5]. Studies of Cheng Pang[6] show that signal and ground distributions can obviously affect the distribution of electromagnetic field. And the simulation made by Kaushal Kannan[7] indicates that specific analytical model can be used as a first cut design approximation. However, further electromagnetic simulation is required to be performed for critical nets to improve shielding from electromagnetic interference and crosstalk.

This paper presents studies on a highly integrated silicon interposer with TSVs focused on integrating performance. The electromagnetic design and the modeling of TSV arrays in silicon are simulated under four shapes of the TSV arrays with different ground and signal distributions in order to get electrical characterization and the crosstalk analysis of TSV arrays. We have demonstrated several novel types of array distributions to reduce parasitic capacitance. These array distributions are able to match the signal and power integrity in a low cost and high density way.
2. MODELING AND SIMULATION PROCEDURE
The simulation model was built in the ANSYS HFSS software. Because TSV arrays are one of the key components parts of the 2.5D/3D Si interposer, it is necessary to decrease the transmission loss of TSV arrays. The arrays are divided into ground-TSVs and signal-TSVs according to the signal transmitted path. And the transmission loss varies with different ground and signal distributions.

In theory, the magnetic field during the high frequency generates the skin effect resulting in the transmission loss. Besides, the distributions of TSVs and distance between TSVs are two key elements to effect the magnetic field[6, 8, 9]. We have built several models in different distributions at the same distance between two TSVs. The results demonstrated that the loss saturates when the number of polygons is higher than six. Therefore, we discuss four basic shapes(circle, square, pentagon and hexagon) to simulate the different transmission performance in various patterns. Each shape is divided into two different ground-signal(GS) distributions. The distance between ground TSVs and signal TSVs in the eight patterns are the same.

The structure of the TSV is shown in Figure 1. According to the researches before, the thinner substrate, the thicker insulation and the smaller diameter of the TSV are required to reduce the loss of TSV arrays[10]. The four specific geometrical parameters of the TSV are shown in Table 1.

![Cross-section view of the TSV structure](image)

Figure 1. The coplanar waveguide structure we studied. The vias are filled with copper and wrapped by the insulating layer (silicon dioxide). All parts are built in the silicon substrate.

| Specimen                | Typical value |
|-------------------------|---------------|
| TSV Height(hTSV)        | 200μm         |
| TSV Diameter(dTSV)      | 25μm          |
| Substrate Thickness(tSi)| 190μm         |
| Insulator(SiO2) Thickness(tSiO2) | 5μm          |
As mentioned above, the distributions of TSV arrays are divided into four shapes: circle, square, pentagon and hexagon. Taking the distributions of “ground TSV” and “signal TSV” into account, there are two patterns for each shape. Due to the symmetry of graphics, we built the signal TSV at random as shown in Figure 2((a1)(b1)(c1)(d1)) and signal TSV in center in Figure 2((a2)(b2)(c2)(d2)).

3. RESULTS AND DISCUSSION

3.1. Effect of GS distribution on transmission performance

We used the three-dimensional full-wave electromagnetic software HFSS to simulate the TSV arrays to obtain the electrical characteristics. When sweep frequency varies from 0.1GHz to 40GHz and the solve frequency is 5GHz, the scattering parameters (S-parameters) of different “signal TSVs” are shown in Figure 3.
As we can see in Figure 3, the electrical characteristics of the “signal TSVs” vary with their positions relative to the ground TSVs. Most signal-in-center TSV arrays obtain better transmission performance than the signal-at-random ones since they received the lower transmission loss which is related with the distance between TSVs. According to the Figure 3(a), the insertion loss increases fast at the solution frequency 5GHz and increases slowly in a negative slope from 5GHz to 40GHz. As the frequency increases, the effective resistance of TSVs increases due to the skin effect. The reason why insertion loss during high frequency increases in a negative slope is that thicker oxide liner thickness results in a smaller oxide capacitance compared to the case of thinner oxide during low frequency. Besides, the signal-in-center TSV array obtains a wider return path than the random one. As we can see in Figure 3(b), the curves of return loss have sharp slopes during low frequency. All curves show the positive ramps with the frequency increases. And pentagon-pattern with the signal TSV in center obtains the best return characteristics.

Both the curves S21(a) and S11(b) demonstrate the same electrical behavior of transmission performance exactly. All the curves of insertion loss increase by no more than 0.1dB. However, only the four signal-in-center TSV arrays obtain the better return loss than the signal-at-random ones.

Meanwhile, comparing the transmission loss of eight distributions in four shapes, all the curves of signal TSVs are below -70dB with the sweep frequency varying from 0.1GHz to 40GHz. The curves of return loss in the shape of square, pentagon and hexagon for signal-in-center TSV arrays hold almost the same maximum and minimum value, which means these three shapes obtain the better transmission performance than the circle.

3.2. Effect of GS distribution on crosstalk
The simulation models for crosstalk analysis of TSV arrays are almost same as the ones shown in Figure 2. Considering the GS distributions and the symmetry of TSV arrays, two different test models are built and simulated: (a) two signal TSVs and one of them chose from the ground TSVs at random; (b) two signal TSVs with no ground TSVs.

In model(a), we extracted the S-parameters between two “signal TSVs” in the eight patterns. And the distance between each pair of “signal TSVs” are the same. As we can see in Figure 4, all the curves demonstrate positive slopes from 0.1GHz to 40GHz indicating that the crosstalk of TSV arrays increase with frequency. The signal-in-center TSV array in the square shape gets the best result while the signal-at-random TSV array in the circle shape obtained the worst since the crosstalk between two “signal TSVs” in square-pattern (Figure 2(b2)) is below -120dB up to 40GHz.

Referring to the simulation results in model(a), the signal-in-center TSV array in the square shape was extracted to analyze the crosstalk between different TSVs in model(b). Considering the symmetry of square, we chose three kinds of TSVs located in different adjacent positions(center-TSV, midpoint-TSV and vertex-TSV) as signal TSVs. And then three pairs of TSVs were taken to simulate the crosstalk: the center-TSV and midpoint-TSV, the center-TSV and vertex-TSV, the vertex TSV and
midpoint-TSV. As we can see in Figure 5, all of the curves show positive slopes and there are clear growth points between 0.1GHz and 5GHz. It means that the crosstalk between two TSVs increases with frequency. Besides, the TSVs located in the four vertices of square get better electrical performance than the midpoints ones on the four sides of square. We speculate that both the distance between TSVs and the conductive and capacitance nature of silicon substrate lead to the results above.

4. Conclusion
This paper presents the comparison study on the electrical performance for TSV array with different ground-signal patterns under high frequency and demonstrates the effect of distributions in four shapes on the crosstalk between two kinds of TSVs. Using the finite element method, the simulation results show that the signal-in-center TSV in pentagon-pattern obtains the best return characteristics while the crosstalk between two TSVs in square-pattern is minimal. Besides, the four vertex-TSVs in square-pattern suffer the minimal crosstalk than the others. Taking the above cases into account, this work may guide the design of 2.5D/3D integration systems using TSV arrays to improve the transmission performance.

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