New coaxial through silicon via (TSV) applied for three dimensional integrated circuits (3D ICs)

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Abstract: Coaxial through silicon via (TSV) is a promising technology in three dimensional integrated circuits (3D ICs). Conventional coaxial TSV offers shield around part of the TSV in silicon substrate leave the two ends of TSV and the whole pad without any shield. This paper reports a new coaxial TSV, which offers more shields around TSV and pad with gaps for inter-connection. Furthermore, the new structure is more feasible by using double dielectrics with considering deformation and process error. The full-wave extraction simulation result shows that the new structure offers less coupling with adjacent TSVs than conventional coaxial TSV structure does. The losses of new structure is lager but can be reduced by increasing the thickness of gap.

Keywords: three-dimensional integrated circuits (3D ICs), coaxial through silicon via (TSV), electrical coupling

Classification: Integrated circuits

References

1 Introduction

Coaxial through silicon via (TSV) has proven to be the key three-dimensional integrated circuits (3D ICs) technology today, which vertically connects different layers with less coupling than other TSV structures. Signal attenuation is eliminated and coupling is avoided by confining signal propagation within the coaxial TSV shield [1]. Keep-out-zone (KOZ) induced by coaxial TSV can be reduced by using coaxial-annular TSV, without decreasing the electrical performance of coaxial TSV [2]. And coaxial TSV is a good choice in power delivery design for 3D ICs due to its good behavior in reducing routing blockages [3].

It is essential to research electrical model of coaxial TSV in 3D ICs design. In the previous works, resistance, inductance, conductance and capacitance (RLGC) model and wideband impedance model have been proposed [4, 5, 6]. In other works, coaxial mixed dielectric TSV and modeling of airgap have been researched [7, 8] and 30 Gbps high-speed characterization of coaxial TSV has been proposed [9].

In this paper, we propose a new coaxial TSV which provides more shield than that in conventional structure. We use double dielectrics fulfill the space between TSV and shield to increase the reliability and reduce the capacitance. A 3-D electromagnetic solver (HFSS) is employed to compare the proposed new structure and conventional structure about coupling, losses and magnetic field distribution. The results show that the new structure offers less coupling and more losses than conventional structure, but the losses can be reduced by increasing the thickness of gap.

2 New structure of coaxial TSV

Coaxial TSV can reduce the coupling between TSVs in signal channel by confining electromagnetic wave propagation within the coaxial TSV shield. As shown in Fig. 1, the area of substrate has little electromagnetic wave due to signal attenuation in shield but the coupling is considerable in other areas. And in high density circuits, the coupling will decrease electromagnetic compatibility and signal integrity at high frequency.
In our new structure, more shields are provided around the whole TSV and pads with gaps for interconnection (RDL). What is more, the connection of shield

Fig. 1. Illustration of conventional coaxial TSV structure, (a) top view of the structure and (b) front view of the structure (cross-section).

Fig. 2. Illustration of new coaxial TSV structure, (a) top view of the structure and (b) front view of the structure (cross-section).

In our new structure, more shields are provided around the whole TSV and pads with gaps for interconnection (RDL). What is more, the connection of shield
located in far end of shield from RDL which can reduce the capacitance between RDL and connection by increasing the distance, as shown in Fig. 2.

In [10, 11], stress analysis and thermal analysis of air-gap have been researched. Single dielectric (air) may leads to short circuit due to deformation under the action of stress or thermal expansion. Double dielectric (BCB and air) in our new structure can increase reliability and reduce coaxial capacitance. The gap length between TSV and shield can be calculated by Eq. (1).

\[ L_{\text{gap}} = T_{\text{air}} + T_{\text{BCB}} \geq 120\% \times (L_1 + L_2 + L_3) \]  

where \( L_{\text{gap}} \) is the length of gap, \( T_{\text{air}} \) and \( T_{\text{BCB}} \) are thicknesses of air and BCB respectively, 120\% is safety factor with a margin amount 20\%, \( L_1 \) is displacement caused by stress, \( L_2 \) is displacement caused by thermal expansion and \( L_3 \) is length of process error.

Displacement of TSV caused by thermal stress can be calculated by generalized Hooke law, as shown in Eq. (2, 3, 4)

\[ \varepsilon_r^p = \frac{1}{E_p} [\sigma_r^p - u^p(\sigma_r^p + \sigma_z^p)] + \alpha^p T \]  
\[ \varepsilon_\theta^p = \frac{1}{E_p} [\sigma_\theta^p - u^p(\sigma_r^p + \sigma_z^p)] + \alpha^p T \]  
\[ \varepsilon_z^p = \frac{1}{E_p} [\sigma_z^p - u^p(\sigma_r^p + \sigma_\theta^p)] + \alpha^p T \]  

where \( \varepsilon_r^p, \varepsilon_\theta^p \) and \( \varepsilon_z^p \) are displacements in radial direction, ring direction and vertical direction respectively, \( \sigma_r^p, \sigma_\theta^p \) and \( \sigma_z^p \) are stress in radial direction, ring direction and vertical direction respectively, \( E_p, \alpha^p \) and \( u^p \) are Young modulus, coefficient of thermal expansion and Poisson ratio of copper respectively, and \( T \) is load temperature.

For the variables \( L_1 \) and \( L_2 \) are much less than \( L_3 \) in our new structure, the gap length \( L_{\text{gap}} \) can be simplified as Eq. (5).

\[ L_{\text{gap}} = T_{\text{air}} + T_{\text{BCB}} \geq 2L_3 \]  

Signal attenuates exponentially with distance in the shield, thus the thickness of shield should be no less than the skin effect depth as shown in Eq. (6).

\[ T_{\text{shield}} \geq \delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \]  

where \( T_{\text{shield}} \) is the thickness of shield, \( \delta \) is skin effect depth at frequency \( f \), \( \mu \) and \( \sigma \) are permeability and conductivity of shield respectively.

The coaxial capacitance between TSV and shield can be expressed in Eq. (7).

\[ C_{\text{ox}} = \frac{2\pi u_{\text{dielectric}} H_{\text{shield}}}{\ln((R_{\text{TSV}} + L_{\text{gap}})/R_{\text{TSV}})} \]  

It is obviously that the capacitance of double dielectric (BCB and air) used in new structure is smaller than that of single dielectric BCB used in conventional structure. The influence of capacitance on losses will be discussed in the next section. Cross sections of the two structures are shown in Fig. 3.
The feasibility of coaxial TSV has been proved in [12]. The manufacture costs and difficulty of the two structures (conventional structure and the new structure) are nearly the same due to their similar physical structures and both the two structures can be processed by the same process. Design limitation in layout can be ignored because there are only pads and shields in the layer, the shield thickness and the distance between pad and shield are very flexible. There is little demerit in new structure process and the design parameters are shown in Table I.

### 3 New structure used in TSV array

In square matrix of TSVs, each signal TSV radiates electromagnetic wave and the whole field of the TSV array is complex. Our new structure can eliminates more coupling than that of conventional structures due to the shields. Magnetic field distributions (at 50 GHz) of $4 \times 4$ TSV array with conventional structure and new structure are shown in Fig. 4 (in next page).

As shown in Fig. 4(a), signal TSV radiates electromagnetic wave in all the directions and parts of the wave travel into the substrate through the gap in new structure. In Fig. 4(b), the wave arrives at the adjacent TSVs without any shield and then interfere the signal in conventional structure. The magnitudes of coupling between two adjacent TSVs are shown in Fig. 5 (in next page).

With full port impedance setting $50 \Omega$ in simulation, $S$-parameters of the TSV channel can be expressed as Eqs. (8, 9, 10).

$$S_{11} = 20 \log |Z/(Z + 100)|$$  \hspace{1cm} (8)

$$S_{21} = 20 \log |100/(Z + 100)|$$  \hspace{1cm} (9)

$$Z = (R_{TSV} + 2R_{pad} + j\omega(L_{TSV} + 2L_{pad})) \parallel (-j/\omega C_{ox})$$  \hspace{1cm} (10)

![Fig. 3. Illustration of two structures with different dielectrics, (a) BCB and (b) BCB and air.](image-url)
Fig. 4. Magnetic field distributions of 4 × 4 TSV array with (a) new structure and (b) conventional structure.

Fig. 5. Coupling between two adjacent TSVs.
The new structure offers an extra capacitance between pad and shield which will lead to extra losses in TSV channel. From Eqs. (7, 8, 9, 10), we can get a conclusion that increasing the thickness of dielectric can reduce the whole capacitance and compensate part of the loss. S-parameters of the two structures with different thicknesses are shown in Fig. 6.

As shown in Fig. 6, the losses of new structure are larger than that of conventional structure with the same gap length $L_{\text{gap}} = 2 \, \mu\text{m}$. The extra losses are inevitable due to the extra capacitance between pad and shield. As we discussed, increasing the thickness of dielectric $L_{\text{gap}}$ can reduce part of losses.

Insert loss reflects the ratio of energy transferred to the destination port, a less magnitude (dB) will be better. In Fig. 6(a), the insert loss ($S_{21}$) of new structure is nearly $-0.3$ dB at 100 GHz with a gap length $L_{\text{gap}} = 1 \, \mu\text{m}$. With the gap length $L_{\text{gap}} = 2 \, \mu\text{m}$, the magnitude of insert loss is much less than that of $L_{\text{gap}} = 1 \, \mu\text{m}$, about $-0.125$ dB at 100 GHz. When the gap length $L_{\text{gap}} = 3 \, \mu\text{m}$, the magnitude of insert loss in new structure (about $-0.06$ dB) is smaller than that of conventional structure (about $-0.07$ dB).

Different from insert loss, return loss reflects the ratio of energy reflected to the source port and a larger magnitude (dB) will be better. In Fig. 6(b), the magnitudes of all the return losses ($S_{11}$) of new structure with different gap length are smaller than that of conventional structure at the same frequency. As the insert loss, we can reduce the return loss by increasing the gap length. When $L_{\text{gap}} = 3 \, \mu\text{m}$, the maximum of return loss in new structure at 100 GHz is about $-20$ dB, which is a typical value in high frequency circuits design.

4 Conclusion

The new structure proposed this paper offers more shield than conventional structure and the gap length between TSV and shield was calculated considering deformation caused by stress and thermal expansion. The magnitudes of coupling between two adjacent TSVs are compared with those two structures. The return loss and the insertion loss were compared from the magnitudes of $S_{11}$ and $S_{21}$. With these comparisons, a conclusion was made that the new structure can effectively reduce the coupling between adjacent TSVs. The losses of new structure is larger
but can be reduced by increasing the thickness of dielectric within the allowable range of design requirements and process.

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