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Reduction of signal reflection in high-frequency three-dimensional (3D) integration circuits

Xiaoxian Liu[a), Zhangming Zhu, Yintang Yang, Fengjuan Wang, and Ruixue Ding
School of Microelectronics, Xidian University, Xi'an 710071, P.R. China
a) *liudou132@163.com*

Abstract: The through silicon via (TSV) technology provides a promising option to realize three dimensional (3D) gigscale systems with high performance. As the fundamental elements in this system, Redistribution Layers (RDLs), TSVs, and bumps, which constitute a TSV channel together, transmit high speed signals. Consequently the impedance mismatch among these elements causes signal reflection along the channel that need to be investigated. Chebyshev Multi-section Matching Transformers are proposed to reduce the signal reflection of the TSV channel when operating frequency up to 20 GHz, by utilizing of which S_{11} and S_{21} has been improved of 150% and 73.3%, respectively.

Keywords: three-dimensional (3D) integrated circuit (IC), through silicon via (TSV), TSV channel, signal reflection, S-parameters
Classification: Integrated circuits

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1 Introduction

Three-dimensional (3D) integration is a promising alternative solution to overcome technology and cost limitations of the component miniaturization dictated by the traditional Moore's law. Through-Silicon-Via (TSV) is the core technology to achieve 3D interconnection, which electrically connects chips vertically and provides shorter channel paths as compared to conventional 2D-ICs. For practical 3D ICs, the TSV channel includes not only the TSVs, but also the bumps and redistribution layers (RDLs). Signal reflection caused by impedance mismatch among these elements becomes

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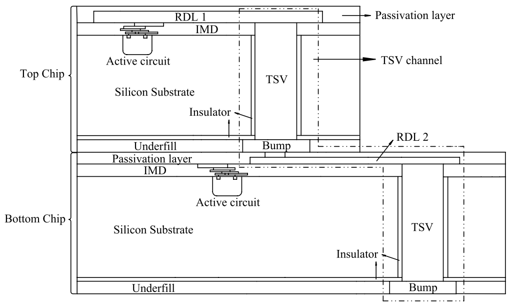
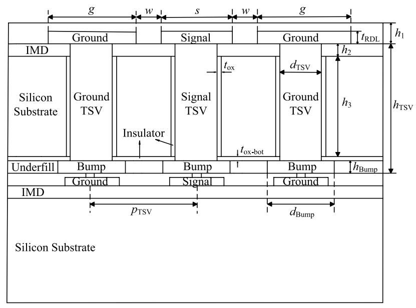
striking when operating frequency up to gigahertz range, which degrades performances of the 3D circuits like time delay and power dissipation. The detrimental effect of signal reflection in TSV channel has not attracted much attention so far. We proposed Chebyshev Multisection Matching Transformers to weaken the signal reflection up to 20 GHz.

2 Characteristic impedances of RDLs and TSVs

Face-to-Back (F2B) 3D technology is chosen in our paper, as shown in Fig. 1a. The TSV channel includes RDLs on top chip, TSVs, bumps and RDLs on Bottom Chip. Compared with micro-strip line (MSL), coplanar waveguide (CPW) with finite width (FW-CPW) is almost with the lowest transmission loss up to ~200 GHz [1]. We choose FW-CPW as RDLs to provide horizontal interconnections between stacked dies, structure of which is shown in Fig. 1b. Intra dielectric layer (IMD) and Passivation Layer are made of silicon dioxide and FR-4, respectively. Correspondingly, the high-speed single-ended ground-signal-ground (GSG) type TSVs are needed. As shown in Fig. 1b, two ground TSVs assist as the returning current path. TSVs are surrounded by a thin layer of insulator (SiO_2 in this paper) which serves as the isolation layer between the silicon (Si) substrate and TSVs. TSVs, RDLs, and bumps are all made of copper in this paper.





(a) Cross-sectional view (b) Vertical-section view

Fig. 1. Structures of vertical interconnect through the stacked dies.

With research of signal reflection of TSV channel, a thorough understanding of channel elements properties is vitally important. A 3D fullwave EM simulator (Ansoft's HFSS) is employed, by which S-parameters are obtained and converted to ABCD matric. The ABCD matrix for a lossy transmission line is

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} \cosh(\gamma L) & Z_0 \sinh(\gamma L) \\ \sinh(\gamma L)/Z_0 & \cosh(\gamma L) \end{pmatrix}, \tag{1}$$

where L is the length of transmission line. Z_0 and γ are the characteristic impedance and propagation constant of the line, which can be acquired from the ABCD matrix by

$$Z_0 = \sqrt{B/C}, \qquad \gamma = \cosh^{-1}(A)/L. \tag{2}$$

In the fast-switching circuits produced by deep-submicrometer technologies today, the GSG-type TSV pair had better to be treated as a lossy transmission line [2]. So the characteristic impedance of TSV could be

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Table I. Design parameters of RDLs.

Parameter	Symbol	RDL 1	RDL 2
Signal RDL width	s/μm	15	5
Ground RDL width	g/μm	20	15
Space between RDL	w/μm	10	17.5
RDL thickness	t_{RDL}/μm	3	2
Passivation layer thickness	h_1/μm	5	4
IMD thickness	h_2/μm	3	2
Silicon substrate thickness	h_3/μm	25	30
Length of RDLs	L/μm	200	

Table II. Design parameters of TSVs.

Parameter	Symbol	Value	Parameter	Symbol	Value
TSV diameter	d_{TSV}/μm	5	TSV height	h_{TSV}/μm	25
TSV-to-TSV pitch	p_{TSV}/μm	27.5	Underfill height	$h_{Underfill}$/μm	3
Bump diameter	d_{Bump}/μm	10	Bump height	h_{Bump}/μm	3
Bottom SiO_2 thickness	t_{ox_bottom}/μm	0.5	Insulator thickness	t_{ox}	0.5

deduced by theories above.

3 Chebyshev Multisection Matching Transformers

In order to reduce the signal reflection of TSV channel, Chebyshev Multisection Matching Transformers are employed, which are generally referred to as the theory of small reflections. Consider a multisection transformer, which consists of N equal-length sections of transmission lines, the total reflection coefficient Γ can be written in the form of a finite Fourier cosine series in frequency (θ) domain [3]:

$$\Gamma(\theta)=2e^{-jN\theta}[\Gamma_0\cos N\theta+\Gamma_1\cos(N-2)\theta+\cdots+\Gamma_n\cos(N-2n)\theta+\cdots]. \quad (3)$$

Chebyshev Multisection Matching Transformer is designed by equating the reflection coefficient $\Gamma(\theta)$ to a Chebyshev polynomial that has the optimum characteristics needed for this type of transformer. The nth-order Chebyshev polynomial is a polynomial of degree n, denoted by $T_n(x)$. The first three Chebyshev polynomials are:

$$T_1(x)=x; \quad T_2(x)=2x^2-1; \quad T_3(x)=4x^3-3x. \quad (4)$$

For the first three Chebyshev polynomials, $|T_{\mathrm{n}}(x)|\leq 1$ when $-1\leq x\leq 1$. In this range the Chebyshev polynomials oscillate between ± 1. This is the equal-ripple property, and this region will be mapped to the passband of the matching transformer. Now let x=cosθ for $|x|$<1. Then it can be shown that the Chebyshev polynomials can be expressed as

$$T_n(\cos\theta)=\cos n\theta. \quad (5)$$

We desire equal ripple for the passband response of the transformer, so it is necessary to map θ_m to x=1 and $\pi-\theta_m$ to x=-1, where θ_m and $\pi-\theta_m$ are the lower and upper edges of the passband, respectively. This can be accomplished by replacing cosθ in Eq. (5) with cosθ/cosθ_m:

$$T_{\mathrm{n}}\left(\frac{\cos\theta}{\cos\theta_m}\right)=T_n(\sec\theta_m\cos\theta)=\cos n\left[\cos^{-1}\left(\frac{\cos\theta}{\cos\theta_m}\right)\right]. \quad (6)$$

Then $|\sec\theta_m\cos\theta|\leq 1$ for $\theta_m<\theta<\pi-\theta_m$, so $|T_n(\sec\theta_{\mathrm{m}}\cos\theta)|\leq 1$ over this

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same range. Because $\cos^n\theta$ can be expanded into a sum of terms of the form $\cos(n-2m)\theta$, the Chebyshev polynomials of Eq. (4) can be rewritten in the following useful form:

$$T_1(\sec\theta_m\cos\theta) = \sec\theta_m\cos\theta; \tag{7a}$$

$$T_3(\sec\theta_m\cos\theta) = \sec^3\theta_m(\cos 3\theta + 3\cos\theta) - 3\sec\theta_m\cos\theta; \tag{7b}$$

$$\begin{aligned} T_4(\sec\theta_m\cos\theta) = {} & \sec^4\theta_m(\cos 4\theta + 4\cos 2\theta + 3) \\ & - 4\sec^2\theta_m(\cos 2\theta + 1) + 1. \end{aligned} \tag{7c}$$

These results can be used to design matching transformers with up to three sections. We can now synthesize a Chebyshev equal-ripple passband by making Γ proportional to $T_N(\sec\theta_m\cos\theta)$, where N is the number of sections in the transformer. Thus, using Eq. (3), we have:

$$\begin{aligned} \Gamma(\theta) &= 2e^{-jN\theta}\begin{bmatrix} \Gamma_0\cos N\theta + \Gamma_1\cos(N-2)\theta \\ + \cdots + \Gamma_n\cos(N-2n)\theta + \cdots \end{bmatrix} \\ &= Ae^{-jN\theta}T_N(\sec\theta_m\cos\theta). \end{aligned} \tag{8}$$

where the last term in the series of Eq. (8) is $(1/2)\Gamma_{N/2}$ for N even and $\Gamma_{(N-1)/2\cos\theta}$ for N odd. We can find the constant A by letting θ=0, corresponding to zero frequency. Thus,

$$\Gamma(0) = \frac{Z_L - Z_0}{Z_L + Z_0} = AT_N(\sec\theta_m), \tag{9}$$

so we have

$$A = \frac{Z_L - Z_0}{Z_L + Z_0}\frac{1}{T_N(\sec\theta_m)}. \tag{10}$$

If the maximum allowable reflection coefficient magnitude in the passband is Γ_m, then from Eq. (10) Γ_m=|A| since the maximum value of T_n ($\sec\theta m\cos\theta$) in the passband is unity. Then Eq. (10) gives

$$T_N(\sec\theta_m) = \frac{1}{\Gamma_m}\left|\frac{Z_L - Z_0}{Z_L + Z_0}\right| \approx \frac{1}{\Gamma_m}\left|\ln\frac{Z_L}{Z_0}\right|. \tag{11}$$

In our paper, the TSV and RDL 2 on Bottom Chip, which are connected in series, are treated as load of RDL 1 on top chip. So the load impedance is Z_L=Z_{0TSV}+Z_{0RDL2}, where Z_{0TSV} and Z_{0RDL2} are the characteristic impedance of TSV and RDL 2. By the above theory, a three-section Chebyshev transformer is designed, the subject of which is to match Z_L to a line whose characteristic impedance is Z_{0RDL1}. The maximum reflection coefficient Γ_m is assumed to be 0.02 in this paper.

From Eq. (7c) with $N = 3$,

$$\Gamma(\theta) = 2e^{-j3\theta}(\Gamma_0\cos 3\theta + \Gamma_1\cos\theta) = Ae^{-j3\theta}T_3(\sec\theta_m\cos\theta). \tag{12}$$

Using Eq. (7c) for T_3 gives

$$\begin{aligned} 2(\Gamma_0\cos 3\theta + \Gamma_1\cos\theta) = {} & A\sec^3\theta_m(\cos 3\theta + 3\cos\theta) \\ & - 3A\sec\theta_m\cos\theta. \end{aligned} \tag{13}$$

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Equating similar terms in $\cos n\theta$ gives the following results:

$$\cos 3\theta : 2\Gamma_0 = A\sec^3\theta_m, \qquad \Gamma_0 = 0.0664$$

$$\cos\theta : 2\Gamma_1 = 3A\left(\sec^3\theta_m - \sec\theta_m\right), \quad \Gamma_1 = 0.1429$$

From symmetry we also have that

$$\Gamma_3 = \Gamma_0 = 0.0664, \qquad \Gamma_2 = \Gamma_1 = 0.1429.$$

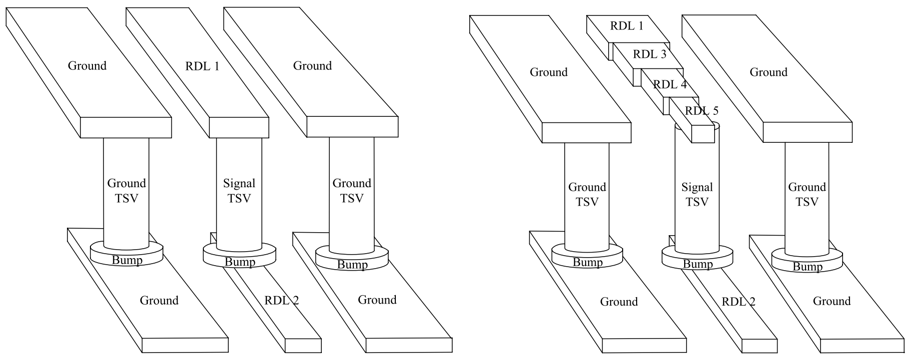
Then the characteristic impedances are:

$$n = 0 : \ln Z_1 = \ln Z_0 + 2\Gamma_0, \qquad Z_1 = 66.24\Omega;$$

$$n = 1 : \ln Z_2 = \ln Z_1 + 2\Gamma_1, \qquad Z_2 = 88.16\Omega;$$

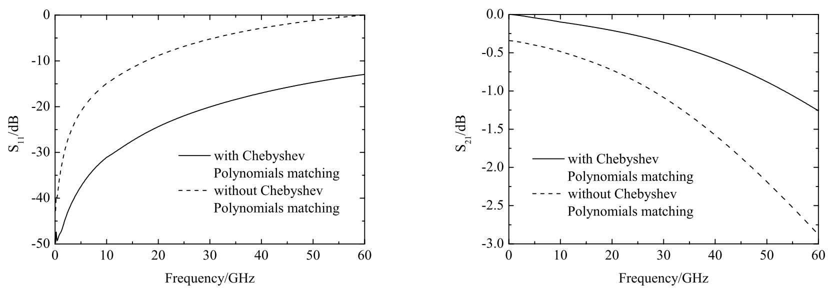
$$n = 2 : \ln Z_3 = \ln Z_2 + 2\Gamma_2, \qquad Z_3 = 117.33\Omega.$$

The characteristic impedances of needed Chebyshev sections, RDL 3, RDL 4, and RDL 5, are 66.24 Ω, 88.16 Ω, and 117.33 Ω, respectively. Structure of TSV channel without and with Chebyshev matching is shown in Fig. 2 (a) and (b), while simulated S-parameters of which are shown in Fig. 3 (a) and (b), respectively. It can be seen that the signal reflection (S_{11}) decreases from −10 dB to −25 dB, which shows 150% improvement. The transmission coefficient of the TSV channel (S_{21}) increases from −0.75 dB to −0.2 dB, which displays 73.3% improvement.



(a) TSV channel without matching (b) TSV channel with matching

Fig. 2. Structures of the TSV channel without and with Chebyshev Multisection Matching Transformers.



(a) S_{11} of the TSV channel (b) S_{21} of the TSV channel

Fig. 3. Simulation results of S-parameters of the TSV channel.

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4 Conclusions

At gigscale frequency range, especially above 10 GHz, signal reflection due to impedance mismatched becomes significant, which becomes a serious setback for the Si Interposer. Chebyshev Multisection Matching Transformers are presented to weaken the signal reflection in the TSV channel that includes RDLs, TSVs, and bumps when the operating frequency is 20 GHz. S_{11} of the TSV channel decrease form -10 dB to -25 dB, which shows a 150% improvement of the signal reflection by exploring the Chebyshev matching. It can be seen that the Chebyshev Multisection Matching Transformers is an effect way to lessen the signal integrity problems in high speed 3D ICs.

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