Temperature properties of the parasitic resistance of through-silicon vias (TSVs) in high-frequency 3-D ICs

Yintang Yang, Xiaoxian Liu, Zhangming Zhu, and Ruixue Ding

School of Microelectronics, Xidian University, Xi’an 710071, P. R. China

Abstract: The electrical performances of high-speed three-dimensional integrated circuits (3-D ICs) are affected by temperature due to large integration densities, which may seriously affect the modeling and limit the reliability of circuits. In this letter, the parasitic resistance of through-silicon via (TSV) including temperature effect is studied. With the consideration of skin effect, Temperature Coefficient of Resistance (TCR) is introduced to evaluate the sensitivity of TSV resistance to temperature changes. It can be found that the sensitivity of TSV resistance to temperature changes significantly both with the frequency and radius of TSV. The expression of TCR can be simplified to the one obtained by neglecting the skin effect, which shows better applicability.

Keywords: high speed three-dimensional integrated circuits (3-D ICs), through-silicon via (TSV), temperature coefficient of resistance (TCR)

Classification: Integrated circuits

References

[1] X. Liu, Z. Zhu, Y. Yang, F. Wang and R. Ding: IEICE Electron. Express 10 (2013) 20130449. DOI:10.1587/elex.10.20130449
[2] J. Kim, J. S. Park, J. Cho, E. Song, J. H. Cho, H. Kim, T. Song, J. Lee, H. Lee, K. Park, S. Yang, M. S. Suh, K. Y. Byun and J. H. Kim: IEEE Trans. Components Packag. Manuf. Technol. 1 (2011) 181.
[3] G. Katti, M. Stucchi, K. D. Meyer and W. Dehaene: IEEE Trans. Electron. Dev. 57 (2010) 256. DOI:10.1109/TED.2009.2034508
[4] T. Y. Cheng, C. D. Wang, Y. P. Chiou and T. L. Wu: IEEE Microw. Wirel. Compon. Lett. 22 (2012) 303. DOI:10.1109/LMWC.2012.2195776
[5] E. X. Liu, E. P. Li, W. B. Ewe, H. M. Lee, T. G. Lim and S. Gao: IEEE Trans. Microw. Theory Tech. 59 (2011) 1454. DOI:10.1109/TMTT.2011.2116039
[6] J. Kim, J. Cho, J. Lee, H. Lee, K. Park and J. H. Kim: CPMT Symposium Papers (2010) 1.
[7] W. Steinhog, G. Schindler, G. Steinlesberger, M. Traving and M. Engelhardt: J. Appl. Phys. 97 (2005) 023706. DOI:10.1063/1.1834982
[8] A. G. Chiariello, G. Miano and A. Maffucci: EPEPS Papers (2010) 97. DOI:10.1109/EPEPS.2010.5642555
1 Introduction

Three-dimensional integrated circuits (3D ICs) have become a promising solution for continued scaling of high-performance systems by providing interconnections along the vertical dimension. Through-Silicon Vias (TSVs) are the key technologies to achieve 3-D integration [1, 2, 3, 4, 5, 6]. Since the resistance of TSV represents a parasitic contribution to the signal delay in integrated circuits, it is compulsory to abstract the metal resistance when assess the IC performance. There are already many models presented in literatures to describe the electrical resistance of TSV [2, 3, 4, 5]. However, all these proposed models refer to ideal conditions with fixed temperature. Since the stacking of giga-scale 3-D ICs together with low thermal conductivity material used between stacked dies may elevate temperatures and lead to inefficiency in performance, it is not accurate to model the resistance of TSV copper under ideal conditions in state-of-the-art TSV technologies. Therefore, it is necessary to take the temperature effect into account quantitatively during the research of parasitic effects of TSVs.

2 Temperature coefficient of resistance

The cross-sectional view and top view structures of a single TSV with structural parameters are shown in Fig. 1. The diameter $d_{TSV}$ and height $h_{TSV}$ of the TSV is 10 µm and 90 µm, respectively. The general structure of a TSV is typically a conductive cylinder surrounded by a dielectric layer (usually SiO$_2$). The bottom layer and inter-metal dielectric (IMD) layer are both made usually by SiO$_2$. The equivalent resistance model is developed based on the geometric and material information up to gigascale.

![Fig. 1. Cross-sectional view and top view of a TSV with structural parameters.](image)

As frequency goes up, the skin effect emerges and current flows close to the surface of the TSV conductor, as shown in Fig. 1. The skin depth $\delta$ of copper is about 0.47 µm when frequency is 20 GHz, which is much less than the diameter of TSV plug. Therefore, the resistance of TSV, $R_{TSV}$, is given by [1]:

$$R_{TSV} = \sqrt{R_{TSV,dc}^2 + R_{TSV,ac}^2}$$

(1)

where $R_{TSV,dc}$ and $R_{TSV,ac}$ are the dc resistance and ac resistance of TSV calculated by:
\[ R_{\text{TSV,ac}} = \frac{h_{\text{TSV}} \mu_{\text{TSV}}}{\pi r_{\text{TSV}}^2} \]

\[ R_{\text{TSV,dc}} = \frac{h_{\text{TSV}} \rho_{\text{TSV}}}{2\pi r_{\text{TSV}} \delta} \]

\[ \delta = \sqrt{\frac{\rho_{\text{TSV}}}{\pi \mu_0 \mu_{\text{TSV}}}} \]

where \( r_{\text{TSV}} \), \( \mu_{\text{TSV}} \) and \( \rho_{\text{TSV}} \) is the radius, relative permeability, and resistivity of Cu plug, respectively; \( \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \) is the permeability of free space. However, this model is presented to describe the electrical resistance of TSV referring to fixed temperature. The resistivity of Cu is strongly affected by temperature. The resistivity \( \rho_{\text{TSV}} \) of Cu can be divided into a part depending on temperature and a temperature-independent part [7, 8]:

\[ \rho_{\text{TSV}}(T) = \rho_0[1 + \alpha_0(T - T_0)] \]

where \( T_0 = 293.15 \text{K} \) (20 °C), \( \rho_0 = 1.72 \times 10^{-8} \text{Ω m} \), and \( \alpha_0 = 0.004 \) for bulk Cu [8]. Eqs. (1)–(2) indicate that the resistance of TSV changes not only with operating frequency, but also temperatures.

Concept of the Temperature Coefficient of Resistance (TCR) is exploited to model the sensitivity of TSV resistance to temperature, defined as [8]:

\[ TCR(T^*) = \frac{\partial R/R}{\partial T} \bigg|_{T=T^*} \]

The width of copper traces in [7, 8] is in dozens of nanoscale, and the skin depth far outweighs \( r_{\text{TSV}} \), so TCR of the wire is calculated without considering the skin-effect, given by:

\[ TCR(T) = \frac{\partial R/R}{\partial T} = \frac{\alpha_0}{1 + \alpha_0(T - T_0)} \]

We revise TCR of TSV by taking skin effect into account in our letter. For a copper TSV described by (1)–(2), \( TCR_{\text{TSV}} \) is given by:

\[ TCR_{\text{TSV}}(T) = \frac{\partial R_{\text{TSV}}/R_{\text{TSV}}}{\partial T} = \frac{\rho_0 \alpha_0}{2} \frac{2\rho(T) + af_{\text{TSV}}^2}{\rho(T)^2 + af_{\text{TSV}}^2 \rho(T)} \]

\[ = \frac{\alpha_0}{2} \frac{2\rho_0[1 + \alpha_0(T - T_0)] + af_{\text{TSV}}^2}{\rho_0[1 + \alpha_0(T - T_0)]^2 + af_{\text{TSV}}^2 \rho_0[1 + \alpha_0(T - T_0)]} \]

where \( a = \pi \mu_0 \mu_{\text{TSV}}/4 \). It is obvious that \( TCR_{\text{TSV}} \) is the function of operating temperature, frequency, and radius of TSV.

### 3 Frequency affections on TCR

Submitting \( r_{\text{TSV}} = 5 \mu\text{m} \) into Eq. (5), values of \( TCR_{\text{TSV}} \) as a function of the temperature with different frequencies are shown in Fig. 2. Note that \( TCR_{\text{TSV}} \) decreases as the increase of frequency. The reduction is 48.7% when \( T = 300 \text{K} \), and the reduction achieves 50% at 400 K when frequency increases from zero to 100 GHz. What is more, reduction of \( TCR_{\text{TSV}} \) as the increasing of frequency is very weak and can be neglected when frequency up to dozens of gigascale. This phenomenon can be explained by the following analysis.

If the operating frequency is zero or in the low frequency range, curve of \( TCR_{\text{TSV}} \) accords with the one described by (3), by which the skin effect is neglected and explained as:
\[
\lim_{f \to 0} TCR_{TSV}(T) = \lim_{f \to 0} \frac{\rho_0 \alpha_0}{2} \frac{2 \rho(T) + a f_{TSV}^2}{\rho(T)^2 + a f_{TSV}^2 \rho(T)}
\]

\[
= \frac{\alpha_0}{2} \frac{2 \rho_0 [1 + \alpha_0(T - T_0)]}{\rho_0 [1 + \alpha_0(T - T_0)]^2} = \frac{\alpha_0}{1 + \alpha_0(T - T_0)}
\]

(6)

If \( T = T_0 \), \( TCR_{TSV} \) achieves the maximum value of \( \alpha_0 \), and drops inversely with the increase of temperature. If the frequency up to dozens of gigahertz, values of \( TCR \) of the TSV are much smaller than that in the range of dc and low frequencies. And the reduction of \( TCR \) as the increase of frequency is not significant anymore. This may be explained by:

\[
\lim_{f \to \infty} TCR_{TSV}(T) = \lim_{f \to \infty} \frac{\rho_0 \alpha_0}{2} \frac{2 \rho(T) + a f_{TSV}^2}{\rho(T)^2 + a f_{TSV}^2 \rho(T)}
\]

\[
= \frac{\rho_0 \alpha_0}{2} \frac{1}{\rho_0 [1 + \alpha_0(T - T_0)]} = \frac{\alpha_0}{1 + \alpha_0(T - T_0)}
\]

(7)

If \( T = T_0 \), \( TCR_{TSV} \) achieves the maximum value of \( \alpha_0/2 \), and drops inversely with temperature increase. Also note that \( TCR_{TSV} \) is not associated with frequency finally when the frequency becomes large enough, and changes inversely with the temperature increase. The sensitivity of resistance of TSV to temperature changes with considering the skin effect becomes less sensitive with the increase of frequency.

![Fig. 2. Values of \( TCR_{TSV}(T_0) \) as a function of frequency.](image)

**4 Affections of TSV radius to \( TCR_{TSV} \)**

Eq. (5) also indicates that the transverse characteristic dimensions have effect on the calculation of \( TCR_{TSV} \). In order to research the effect of radius of TSV to the values of \( TCR_{TSV}(T_0) \), we fix the temperature \( T = T_0 \) and the operating frequency \( f = 20 \) GHz, then (5) can be rewritten as:

\[
TCR_{TSV}(T_0) = \frac{\alpha_0}{2} \left( 1 + \frac{\rho_0}{\rho_0 + a r_{TSV}^2} \right)
\]

(8)

Values of \( TCR_{TSV}(T_0) \) with different radii of TSV are shown in Fig. 3. As the radii of TSVs increase, \( TCR_{TSV}(T_0) \) decrease rapidly, and finally tends towards stability when the radius is large enough. The steady value of
$TCR_{TSV}(T_0)$ is $\alpha_0/2$. When $r_{TSV}$ is in the range of dozens of nanometer, $TCR_{TSV}(T_0)$ is calculated as:

$$\lim_{r_{TSV} \to 0} TCR_{TSV}(T_0) = \lim_{r_{TSV} \to 0} \frac{\alpha_0}{2} \frac{2\rho_0 + ar_{TSV}^2}{\rho_0 + ar_{TSV}^2} = \alpha_0$$

(9)

which accords to the value in [7, 8]. Therefore, calculation of $TCR_{TSV}$ including skin effect of high-speed circuits in this letter has better applicability than the one neglected skin effect.

![Fig. 3. Values of $TCR_{TSV}(T_0)$ as a function of radius of TSV.](image)

5 Conclusion

In this letter, the temperature effect on the resistance of TSV metal in high-speed 3-D ICs is studied by exploiting the concept of temperature coefficient of resistance ($TCR$), which is compulsory in state-of-the-art high performance 3D circuits with large integration and packing density. Since the skin depth is far less than the radius of TSV plug with frequency up to gigscale in this letter, skin effect has to be taken into account. The $TCR$ of TSV is a function of temperature, frequency, and radius of TSV metal, which decrease as these parameters increase. What is more, the expression of $TCR$ can be simplified to the one of dc and low frequency range that the skin effect is neglected. Therefore, $TCR$ with the consideration of skin effect in this letter has better universality.

Acknowledgments

This work was supported by the National Natural Science Foundation of China under grants 61322405, 61204044, 61376039, 61334003, and National Key Basic Research Program of China under grant 2014CB339900.