Through-Silicon-Via Characterization and Modeling Using a Novel One-Port De-Embedding Technique

An-Sam PENG\(^{\text{a)}\},\) Ming-Hsiang CHO\(^{\text{b)},\) Nonmembers, Yueh-Hua WANG\(^{\text{c)},\) Member, Meng-Fang WANG\(^{\text{\dag\dag)}\},\) David CHEN\(^{\text{\dag\dag)}\},\) and Lin-Kun WU\(^{\text{\dag\dag)}\},\) Nonmembers

SUMMARY In this paper, a novel and simple one-port de-embedding technique has been applied to through-silicon-via (TSV) characterization and modeling. This method utilizes pad, via, and line structures to extract the equivalent circuit model of TSV. The main advantage of this de-embedding method is that it can reduce the chip area to fabricate test element groups (TEGs) for measurements while keeping S-parameter measurement accuracies. We also analyzed the electrical characteristics of substrate coupling and TSV equivalent impedance. Our results show good agreements between measurement data and the equivalent circuit model up to 20 GHz.

key words: 3D IC, TSV, de-embedding, TEGs, microwave, RF modeling

1. Introduction

To keep up with Moore’s law, conventional CMOS scaling is facing increasing and risky capital investments. Therefore, industries have started to develop a relatively economical and simple solution that is through-silicon via (TSV) technology. 3D-IC packaging based on TSV is a promising technology that can overcome the challenges of Moore’s law by directly using through-silicon substrates to connect the topside metal with the backside metal via through-wafer interconnects. The TSV technique has been utilized with CMOS sensors, microelectromechanical systems, and memory application. Furthermore, TSV has also been successfully implemented in 28 nm CMOS technology \cite{1}. However, there are still many challenges for 3D-IC packages \cite{2}, difficulties related to mass production, and manufacturing reliability issues \cite{3}. Therefore, the TSV silicon interposer (2.5D-IC), which is a low-cost, simple, and preliminary solution, has been developed and realized. This 2.5D-IC technology can integrate various function chips with different processes into stacked chip packages \cite{4}. TSV takes advantage of vertical interconnects and die stacks to shorten the interconnect length. This efficient method can reduce signal loss and parasitic effects, and can increase the transmission speed to meet the increasing demands for smaller size, lower signal propagation delay, lower power consumption, and high frequency performance \cite{5}. Consequently, analog and RF circuits are expected to adapt this technique in the near future. Therefore, it is necessary to accurately analyze and model the TSV RF behavior. Previous papers have focused on a TSV RF model over the past years. The inter-TSV coupling model was proposed in \cite{6}. The TSV impedance also has been extracted in \cite{7}. The RF analytical modeling of TSV and RF lines with different lengths on the back-side has also been demonstrated \cite{8}. In this paper, we propose a novel and simple de-embedding technique to model the TSV behavior using one-port layout testkeys. In contrast to conventional two-port technique, this method can preclude the effects of direct coupling and insertion loss between two opposing ports. Therefore, we can improve the measurement accuracy to enhance the modeling accuracy. As shown in Fig. 1, these testkeys require at least two TSV (a) pad and (b) via structures with different pitch lengths to extract model parameters of substrate coupling effects. Here, the filled pillars of TSV via structures with copper are placed below a probing pad to mitigate the vertical substrate coupling. Similarly, we also need a couple of TSV (c) line structures with the same line width, but with varying line numbers.

2. Experiments

TSV testkeys were fabricated using the via-middle approach in a 1P7M 28 nm CMOS process with backside metal adhesion. An interface SiN layer was used to isolate the backside metal and substrate. We used Cascade Microtech’s ground-
signal-ground Infinity probes with 50-, 75-, and 100-μm pitch lengths to probe the contact pad on the backside metal. One-port S-parameter measurements were performed for the frequency range 100 MHz to 20 GHz using an HP8510C network analyzer, and we used the short-open-load calibration procedure with a ceramic impedance standard substrate.

3. Model Description

Figure 2 shows cross-sectional views of the proposed TSV de-embedding testkeys. Figure 2(a) illustrates the equivalent circuit model of TSV pad structures, where $Co$ represents the insulator capacitance between the backside metal and the silicon substrate via SiN layer. Here, the topmost layer is the backside metal used for probing. Because the coupling effect of the silicon substrate is frequency dependent [9], the $Rs$ and $Co-Rss$ branches are connected in parallel in order to model this characteristic. Figure 2(b) shows the equivalent circuit model of a TSV via structure, accounting for the substrate coupling effect between the signal and ground pads. In this case, $Cox$ depicts the insulating capacitance composed of circular silicon dioxide between the TSV and substrate. The TSV is encircled by this insulating dielectric layer to provide DC isolation between the TSV and silicon substrate. The dielectric layer also results in the substrate model of via structures being different from the pad structure; hence, we use the new elements, denoted as $Rsi$, $Cs$, and $Rssi$, to model the silicon substrate coupling. Figure 2(c) shows the equivalent circuit of the TSV line structure model. These TSV pillars are filled with copper metal, and its model is similar to a metal line. $L_{TSV}$ represents the effective inductance, $R_{TSV}$ specifies the effective resistance, and $Lp$ and $Rp$ are used to model the skin effect. In addition, $L_{a}$ and $R_{a}$ are used to model the equivalent impedance of the frontside metal lines.

4. Model Extraction

We start to extract the TSV pad structures at first. Because the TSV pad structures are bilateral symmetrical, the electrical impedance of TSV pad structures, denoted $Z_{pad}$, can be written as

$$2Z_{pad} = \frac{2}{j\omega C_o} + Rs / \left( Rss + \frac{1}{j\omega Cs} \right)$$  \hspace{1cm} (1)

Where $\omega$ represent the angular frequency and symbol $//$ indicate a parallel connection. At low frequencies, the impedance of $Rs$ is so small compared with $Rss-Cs$ branch that it can be neglected. Therefore, we can also extract the initial value of $Rs$ and $Co$ as follows:

$$Rs = Re(2Z_{pad})$$ \hspace{1cm} (2)

$$Co = \frac{1}{-\omega Im(Z_{pad})}$$ \hspace{1cm} (3)

At high frequencies where the current flows mostly through the branch of $Rss-Cs$ relative to $Rs$, Therefore, we can calculate total capacitance in series at high frequencies as follows:

$$\frac{2}{Co} + \frac{1}{Cs} = -\omega Im(2Z_{pad})$$ \hspace{1cm} (4)

Then, we can obtain the $Cs$ by using the Eq.(4) and the extracted $Co$ from Eq.(3). In addition, $Rss$ is mainly used for fitting the slope of $S_{11}$ from 5 GHz to 20 GHz. Figure 3 shows the $(-\omega Im(2Z_{pad}))^{-1}$ as function of frequency. The extraction results are listed in Table 1. As the pitch lengths increase, $Rss$ and $Rs$ are seen to increase linearly while $Cs$ decreases inversely. In addition, $Co$ is independent of the different pitch lengths. This means that the model of TSV via structures are scalable. Figure 4 compares the measured (symbols) and simulated (lines) reflection $S_{11}$ of TSV.
pad structures to estimate for the impact of substrate noise coupling, which is an important issue in RF/Mixed-signal IC. The noise of digital circuits injected through the substrate will degrade the performances of sensitive RF circuits. The higher $S_{11}$, the less signals run through the substrate to ground pad, has better noise isolation. Therefore, this physical based, scalable TSV pad model can be used to predict the influence of substrate noise coupling with different pitch lengths and pad size for RF circuit designers.

Because the TSV pad and via structures are similar, we can extract the model parameters of TSV via structures as well as pad structures. Figure 5 and Fig. 6 show the $(-\omega\text{Im}(2Z_{\text{via}}))^{-1}$ and reflection $S_{11}$ of TSV via structures as function of frequency. Where $Z_{\text{via}}$ represents the electrical impedance of TSV via structures. The extraction results are listed in Table 2. Because TSV via structures have extra cu pillar, the effective substrate lengths are shorter than TSV pad structures. This explains why TSV pad structures have lower substrate resistances and higher substrate capacitances.

To extract the model parameters, TSV line structures are de-embedded from the substrate coupling effect using...
Fig. 7  Equivalent circuits for TSV line structures with single and double line numbers.

YLine - YVia. Here, YLine and YVia are the admittance matrices of the TSV line and via structures. Because the TSV line structures are symmetrical along a centrally vertical axis, the model after de-embedding can be simplified as in Fig. 7.

The series impedance of TSV line structures with single and double line numbers, simply written as \( Z_1 \) and \( Z_2 \), can be calculated as shown below.

\[
Z_1 = \frac{3}{2} \left[ \frac{j\omega L_{TSV}}{R_{TSV} + R_P + j\omega L_P} \right] + \frac{j\omega L_T}{2} + \frac{R_L}{2} \quad (5)
\]

\[
Z_2 = \frac{3}{2} \left[ \frac{j\omega L_{TSV}}{R_{TSV} + R_P + j\omega L_P} \right] + \frac{j\omega L_T}{4} + \frac{R_L}{4} \quad (6)
\]

Thus,

\[
2Z_2 - Z_1 = \frac{3}{2} \left[ j\omega L_{TSV} + \frac{R_{TSV}(R_P + j\omega L_P)}{R_{TSV} + R_P + j\omega L_P} \right] \quad (7)
\]

Therefore, the impedance of a single TSV pillar

\[
Z_{TSV} = \frac{3}{2} \left[ j\omega L_{TSV} + \frac{R_{TSV}(R_P + j\omega L_P)}{R_{TSV} + R_P + j\omega L_P} \right] \quad (8)
\]

can be expressed as

\[
Z_{TSV} = \frac{2}{3} [2Z_2 - Z_1] \quad (9)
\]

In the frequency range of roughly 5 GHz to 20 GHz, the electrical impedance of \( R_{TSV} \) is so small compared with \( R_P \) and \( L_P \) branch that it can be neglected, Eq. (8) can be rewritten as

\[
Z_{TSV} = \frac{2}{3} [2Z_2 - Z_1] \approx j\omega L_{TSV} + R_{TSV} \quad (10)
\]

We can extract \( L_{TSV} \) and \( R_{TSV} \) at high frequencies as follows:

\[
R_{TSV} = \frac{\text{Re}(Z_{TSV})}{\omega} \quad (11)
\]

\[
L_{TSV} = \frac{\text{Im}(Z_{TSV})}{\omega} \quad (12)
\]

To prevent the contact resistance effect on parameter extraction, Cascade Microtech’s Infinity probes that have low contact resistance (typically < 0.05 \( \Omega \)) and automatic measurement technique [10] were employed in this study. The extraction results for the TSV line structures are summarized in Table 3. \( R_{TSV} \) and \( L_{TSV} \) are about 0.11 \( \Omega \) and 30.7 \( \Omega \), respectively. Figure 8 shows the measured and simulated \( \text{Re}(Z_{TSV}) \) and \( \text{Im}(Z_{TSV})/\omega \) as a function of frequency. As was expected, \( \text{Re}(Z_{TSV}) \) and \( \text{Im}(Z_{TSV})/\omega \) remain constant beyond 4 GHz. At low frequencies from 0.1 GHz to 4 GHz, the effective \( R_{TSV} \) increases and effective \( L_{TSV} \) decreases with increasing frequency are mainly due to skin effect. \( R_P \) and \( L_P \) have been used to successfully model the contributions of the skin effect. Furthermore, it’s noted that the effective \( R_{TSV} \) starts decreasing with increasing frequency when the frequencies go beyond the bounds of applicability range of equivalent circuits. The limitations of TSV model range are caused by the effect of distributed \( R_{TSV} \), \( L_{TSV} \), \( C_{ox} \) and \( C_{ssi} \).

5. Conclusions

This paper presents the one-port de-embedding technique for TSV characterization and modeling. We analyzed the coupling effects between TSVs and extracted the substrate coupling parameters using the TSV via structures with different pitch lengths. Then, the TSV line structures with single and double line numbers were used to extract the transfer impedance of TSV. The agreements between the measurement and simulation results show that this proposed approach is dependable and accurate up to 20 GHz.

References

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An-Sam Peng was born in Hsinchu, Taiwan, in 1976. He received a B.S. in electronics engineering from Feng Chia University, Taichung, Taiwan, in 1999, and an M.S. degree in electrical engineering from the National Chung Hsing University, Taichung, Taiwan, in 2001. He is currently pursuing the Ph.D. degree in communication engineering at the National Chiao Tung University, Hsinchu. His current research interests focus on RF De-embedding technique and device modeling.

Ming-Hsiang Cho was born in Kaohsiung, Taiwan, R.O.C., in 1976. He received the M.S. and Ph.D. degree in communication engineering from the National Chiao Tung University in 2001 and 2008, respectively. His research interests include the microwave de-embedding technique, electromagnetic simulation, high-speed interconnects, RF passive components and MOSFET characterization.

Yueh-Hua Wang was born in I-Lan, Taiwan, R.O.C., in 1971. He received the Electrical Engineering Diploma degree from the National Taipei Institute of Technology in 1991, and M.S. degree in communication engineering from the National Chiao Tung University in 1995, and is currently working toward the Ph.D. degree at NCTU. He is currently a Director in Wavesat Inc. His current research focuses on MIMO Antenna design.

Meng-Fang Wang was born in Taipei, Taiwan, in 1972. He received the B.S. degree in electrical engineering department from National Cheng Kung University, Tainan, Taiwan, in 1996, and M.S. and Ph.D. degrees in institute of electronics from the National Chiao Tung University, in 1997 and 2002, respectively. Since 2002, he has been with ATD Modeling Division, United Microelectronics Corporation (UMC), Hsinchu, as a Staff Engineer, working on CMOS devices modeling of nanometer technology and back-end-of-line (BEOL) modeling.

David Chen received the Ph.D. degree in electrical engineering from the University of Southern California, Los Angeles, in 1997. Since 1997, he has been with the ATD Modeling Division, United Microelectronics Corporation, Hsinchu, Taiwan. His current research interests include baseband and radio-frequency (RF) device modeling of nanometer technology, RF and mixed signal circuit design, and neural network application for communication systems.

Lin-Kun Wu was born in Hsinchu, Taiwan, in 1958. He received the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Kansas, Lawrence, in 1982 and 1985, respectively. From November 1985 to December 1987, he was a Postdoctoral Research Associate with the Center for Research Inc., University of Kansas, where he was involved with microwave remote sensing and computational electromagnetics. Since 1988, he has been with the Department of Communication Engineering, National Chiao Tung University, Hsinchu, where he is currently a Professor. His current research interests include computational electromagnetics, biological effects and medical applications of electromagnetic energy, and electromagnetic compatibility.