Low-loss Shielded Through-Silicon Vias Filled With Multi-Walled Carbon Nanotube Bundle

Jinrong Su, Runbo Ma, Xinwei Chen, Liping Han, Rongcao Yang, and Wenmei Zhang^{*}
College of Physics and Electronics, Shanxi University, Shanxi, 030006, People's Republic of China
(e-mail: zhangwm@sxu.edu.cn).

Abstract—In this paper, the multi-walled carbon **nanotube** bundle (MWCNTB) based shielded through-silicon via (S-TSV) is proposed and the compact expression for the equivalent conductivity of MWCNTB (σ_{MWCNTB}) is deduced to calculate the resistance of MWCNTB based S-TSV (MS-TSV). Then, the electrical characteristics including the S parameters, attenuation constant and time delay are investigated. The results indicate that $|S_{21}|$ of MS-TSV increases with the increase of the outermost diameter of MWCNT and decrease of the thickness of the shielding layer. Compared with the copper filled S-TSV (CuS-TSV), the MS-TSV has a larger $|S_{21}|$, smaller attenuation and shorter time delay. Finally, the impact of the geometrical parameters on the conductivity of MS-TSV is analyzed. Also, the minimum packing density of MWCNTB satisfying $\sigma_{\text{MWCNTB}} \geq \sigma_{\text{Cu}}$ has been deduced. The results show that the outermost diameter of MWCNT has the most significant impact on the conductivity of MS-TSV, and thicker MWCNT is helpful to increase the conductivity of MS-TSV, decrease the packing density of MWCNTB and reduce manufacturing difficulty.

Index terms—Forward transmission coefficient, multi-walled carbon **nanotube** (MWCNT), propagation constant, through-silicon via (TSV), time delay

1. Introduction

Through-silicon vias (TSVs) providing a vertical connection between chips is the primary technology for three-dimensional (3-D) integrated circuits (ICs) to realize high-performance, high-functionality, and high-density. However, the silicon substrate noise will degrade the performance of the system when a high frequency signal is transmitted vertically through the TSV. To improve the performance, the coaxial through-silicon via (C-TSV) has been proposed [1]. Much research on the electrical model and characterization of C-TSV has been conducted. For example, in [2], the closed-form formulas for the per-unit-length resistance and inductance of C-TSVs are derived from the theory of quasi-magnetostatic fields. In [3], frequency- and temperature-dependent model and characteristic of circular and square C-TSVs are investigated. In [4], the C-TSV is fabricated and its S parameters are examined and compared with signal-ground paired TSVs. These studies indicate that C-TSV can serve as a low-noise and low-crosstalk structure.

Note that the conductor materials of C-TSV in the above reports are the copper, tungsten and

aluminum. The skin effect and electromigration of these metals will degrade the performance and reliability of ICs for high- frequency, high-temperature applications [5]. Fortunately, the emerging carbon [nanotube](#) (CNT) have a long mean free path (MFP), high thermal conductivity, and high current-carrying capability such that it is the most promising material to replace copper for very large scale integration interconnects in the future [6]-[8]. Also, lots of researches on the CNT based TSV have been done. For example, in [9], a submicron single-walled CNT (SWCNT) based TSV was characterized and the energy delay product of the SWCNT based TSV was investigated. In [10], the accurate impedance model of SWCNT and multi-walled CNT (MWCNT) based TSV was proposed. Literatures [11] and [12] presented the wideband model of SWCNT/MWCNT based differential TSV and mixed CNT based differential TSV, respectively. The results indicate that CNT based TSVs can provide superior performance than copper TSV. However, there is no report on CNT based C-TSV.

In this paper, the MWCNT bundle is used as the conductor material of shielded TSV (S-TSV, since the MWCNT is also coaxial, "shielded" is used to avoid confusion). The expression of the MFP is simplified using nonlinear curve-fitting method. Based on it a compact expression for the conductivity of MWCNTB (σ_{MWCNTB}) is deduced and is used to calculate the resistance of MWCNTB based S-TSV (MS-TSV). Then, the electrical characteristics of MS-TSV are calculated and compared with that of CuS-TSV (copper based S-TSV). Finally, parametric study on the conductivity of MWCNTB is discussed. Also, the minimum packing density of MWCNTB satisfying $\sigma_{\text{MWCNTB}} \geq \sigma_{\text{Cu}}$ is deduced.

This paper is organized as follows. In Section II, the expression for the conductivity of MWCNT is deduced and the resistance is calculated. Then, the S parameters, attenuation constant and time delay of MS-TSV are calculated in Section III. Impact of parameters on conductivity of MWCNTB, and the minimum packing density of MWCNTB are analyzed in Section IV. Finally, a conclusion is drawn in Section V.

2. Equivalent electrical model of MS-TSV

Fig. 1(a) shows the schematic of MS-TSV. It is composed of the inner via, insulation layer and outer shielding layer. [For simplicity, the substrate and the silicon dioxide layer between the shielding layer and the substrate are omitted.](#) The inner via and the outer shielding layer are filled with MWCNT bundle and the insulation layer is filled with benzocyclobutene (BCB). r_1 , r_2 and r_3 are the radii of the inner via, insulation layer and shielding layer, respectively. t_{ins} and t_s are the thickness of the insulation layer and shielding layer, respectively. H_{tsv} is the height of the MS-TSV and D_{out} is the outermost

diameter of the MWCNT.

Fig. 1 (a) Schematic (b) equivalent circuit and (c) equivalent transmission line model of MS-TSV

Fig. 1(b) is the equivalent circuit model of the MS-TSV in Fig. 1(a). In this figure, the subscripts in and out represent the inner via and outer shielding layer, respectively. L_k and C_q are the kinetic inductance and quantum capacitance of MWCNTB. $C_{q,in}$, $C_{q,out}$, $L_{k,in}$ and $L_{k,out}$ can be calculated by (10) - (14) given in [13]. Here, the electrostatic capacitance C_E between neighboring shells is ignored because it is seven orders of magnitude larger than C_q . The tunneling conductance of MWCNT can also be ignored according to the measured result in [14]. L_{ex} , C_{ins} and G_{ins} are the external inductance, capacitance and conductance of the insulation layer, and can be calculated using the formulas for the coaxial transmission line given in [15]. C_{ox} is the capacitance between the shielding layer and the substrate, and it has no impact on the performance of S-TSV. R_{in} and R_{out} are the per-unit-length resistance of the inner via and outer shielding layer, respectively, and can be calculated by

$$R_{in}(T) = \frac{1}{\pi r_1^2 \sigma_{MWCNTB}(T)} \quad (1)$$

$$R_{out}(T) = \frac{1}{\pi(r_3^2 - r_2^2) \sigma_{MWCNTB}(T)} \quad (2)$$

where $\sigma_{MWCNTB}(T)$ is the temperature-related effective conductivity of MWCNT bundle, and can be

expressed as

$$\sigma_{\text{MWCNTB}}(T) = H_{\text{tsv}} \cdot \frac{2}{\sqrt{3}} (D_{\text{out}} + s)^{-2} \sum_{\text{shell}} R_{\text{M},i}^{-1}(T) \quad (3)$$

where D_{out} is the diameter of the outermost shell of a MWCNT. For densely packing MWCNT bundle, $s \approx 0.34$ nm is the van der Waals gap between the neighboring CNTs. $R_{\text{M},i}(T)$ is the self impedance of the i^{th} shell (from the outer to the inner) of an individual MWCNT and can be expressed as [13]

$$R_{\text{M},i}(T) = \frac{h}{2q^2 N_i(T)} \left(1 + \frac{H_{\text{tsv}}}{\lambda_i(T)} \right) \quad (4)$$

where h is Planck's constant and q is the quantity of electric charge. $N_i(T)$ is the number of conducting channels of the i^{th} shell,

$$N_i(T) = \begin{cases} aTD_i + b, & D_i > d_T / T \\ 2/3, & D_i < d_T / T \end{cases} \quad (5)$$

where $a = 3.87 \times 10^{-4} \text{ nm}^{-1} \text{K}^{-1}$, $b = 0.2$ and $d_T = 1300 \text{ nmK}$ [16]. $D_i = D_{\text{out}} - 2s(i-1)$, is the diameter of the i^{th} shell and $\lambda_i(T)$ is the temperature-dependent electron MFP of the i^{th} shell. Using nonlinear curve-fitting method, we simplify the formulas (10)-(17) for MFP in [17] as

$$\lambda_i(T) = \left(\frac{k_1}{D_i} + \frac{1}{k_2 H_{\text{tsv}}} \right)^{-1} \quad (6)$$

where $k_1 = 10^{-5}(0.4T-43)$, $k_2 = 6.7 \times U$ and U is the bias voltage of MS-TSV.

The interval between two adjacent shells is the van der Waals gap $s \approx 0.34$ nm. Note that s is small such that the difference of $R_{\text{M},i}(T)$ between two adjacent shells is small too. Therefore, the summation in (3) can be approximated by an integral. Assuming $D_{\text{out}} = 2D_{\text{in}}$ (similar to the experimental measurements in [18]), we have

$$\sigma_{\text{MWCNTB}}(T) \approx \begin{cases} Den_d H_{\text{tsv}} (1 + \eta) \times \left[\frac{2q^2 a T}{h} \left(\frac{3D_{\text{out}}^2}{8(1+k_2)} - \frac{k_1 H_{\text{tsv}} D_{\text{out}}}{2(1+k_2)^2} \right) + \frac{q^2 b D_{\text{out}}}{h(1+k_2)} \right. \\ \left. + \frac{2q^2 k_1 H_{\text{tsv}}}{h(1+k_2)^2} \left(\frac{a T k_1 H_{\text{tsv}}}{(1+k_2)} - b \right) \ln \frac{2(1+k_2)D_{\text{out}} + 2k_1 H_{\text{tsv}}}{(1+k_2)D_{\text{out}} + 2k_1 H_{\text{tsv}}} \right], & D_{\text{out}} > 1300 / T \\ Den_d H_{\text{tsv}} (1 + \eta) \times \left[\frac{4q^2}{3h} \left(\frac{D_{\text{out}}}{2(1+k_2)} - \frac{k_1 H_{\text{tsv}}}{(1+k_2)^2} \right) \ln \frac{2(1+k_2)D_{\text{out}} + 2k_1 H_{\text{tsv}}}{(1+k_2)D_{\text{out}} + 2k_1 H_{\text{tsv}}} \right], & D_{\text{out}} < 1300 / T \end{cases} \quad (7)$$

where $\eta = 0.55 + 0.2e^{-0.06H_{\text{tsv}}}$ is correction factor, and Den_d is the total number of CNTs per unit area, and can be expressed as

$$Den_d \approx \frac{2}{\sqrt{3}(D_{\text{out}} + s)^2} \quad (8)$$

Note that Den_d can also be defined as the density of densely packing bundle.

In order to verify the accuracy of (7), the calculated results using (3) and (7) are compared as shown in Fig. 2. It depicts that the two results agree well. The average (maximum) percentage error is 2.96% (5.53%), 0.94% (3.82%) and 0.95% (3.28%) when H_{tsv} is 30 μm , 50 μm and 80 μm , respectively. Hence, (7) can be used to analyze $\sigma_{MWCNTB}(T)$.

Fig. 2 σ_{MWCNTB} calculated using (3) and (7)

The equivalent circuit in Fig. 1(b) can be further reduced to the transmission line model shown in Fig. 1(c). The per-unit-length admittance and impedance are,

$$Y = G + j\omega C = [(G_{ins} + j\omega C_{ins})^{-1} + 1/j\omega C_{q,in} + 1/j\omega C_{q,out}]^{-1} \quad (9)$$

$$Z = R + j\omega L = R_{in} + R_{out} + j\omega(L_{k,in} + L_{k,out} + L_{ex}) \quad (10)$$

3. The electrical characteristics of MS-TSV

The propagation constant γ and the characteristic impedance in the transmission line model of MS-TSV can be expressed as,

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (11)$$

$$Z_c = \sqrt{(R + j\omega L)/(G + j\omega C)} \quad (12)$$

The ABCD matrix and S parameters can be calculated by [15]

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh(\gamma H_{tsv}) & Z_c \sinh(\gamma H_{tsv}) \\ \sinh(\gamma H_{tsv})/Z_c & \cosh(\gamma H_{tsv}) \end{bmatrix} \quad (13)$$

$$\begin{cases} S_{11} = \frac{A + B/Z_0 - CZ_0 - D}{A + B/Z_0 + CZ_0 + D} \\ S_{21} = \frac{2}{A + B/Z_0 + CZ_0 + D} \end{cases} \quad (14)$$

where $Z_0 = 50 \Omega$. Using the formulas for R , L , G and C addressed in Section II, the S parameters and α can be calculated and the results are shown in Figs. 3-4. For comparison, some results of CuS-TSV are also provided. The baseline dimensions of S-TSV are $D_{out} = 20 \text{ nm}$, $H_{tsv} = 30 \mu\text{m}$, $t_{ins} = 2 \mu\text{m}$, $r_1 = 5 \mu\text{m}$, $r_2 = 7 \mu\text{m}$, $r_3 = 8 \mu\text{m}$ and $U = 0.2 \text{ V}$. The conductivity of Cu at temperature T is

$5.8 \times 10^7 \times [1 + 0.00385(T - 300)]$ S/m and the complex permittivity of BCB filled in the insulation layer is $2.6\epsilon_0(1 - j0.0008)$.

3.1 S parameters

Fig. 3 plots the $|S_{21}|$ of MS-TSV for different t_{ins} . In Fig. 3(a), $|S_{21}|$ of MS-TSV increases with t_{ins} . At 100GHz, as t_{ins} increases from 1 μm to 3 μm , $|S_{21}|$ increases from -0.068 dB to -0.025dB and the fractional increment is 63.2%. Fig. 3(b) illustrates the $|S_{21}|$ of CuS-TSV for different t_{ins} . The R , L , G and C of CuS-TSV are calculated according to the formulas for the coaxial transmission line in [15]. The varying of $|S_{21}|$ with t_{ins} is similar to that of MS-TSV. However, the fractional increment of $|S_{21}|$ for Cu-TSV is 85.7%, which is larger than that of MS-TSV. This implies that t_{ins} has greater impact on $|S_{21}|$ of CuS-TSV than that of MS-TSV. This is because $|S_{21}|$ increases with the decrease of C . For CuS-TSV, C is equal to C_{ins} and decreases with the increase of t_{ins} . However, for MS-TSV, C equals the total capacitance of $C_{\text{q,in}}$, $C_{\text{q,out}}$ and C_{ins} in series. As t_{ins} increases, $C_{\text{q,out}}$ increases and C_{ins} decreases. The two opposite effects partially counteract that the impact of t_{ins} on C is weakened. Moreover, the $|S_{21}|$ of MS-TSV is larger than that of CuS-TSV because C and G of MS-TSV are less than that of CuS-TSV.

Fig. 3 $|S_{21}|$ varying with frequency for different t_{ins} : (a) MS-TSV, (b) CuS-TSV

Fig. 4 displays the effect of other parameters. Fig. 4(a) depicts $|S_{21}|$ for different t_s . For comparison, the results of CuS-TSV are also provided. For MS-TSV, $|S_{21}|$ decreases with t_s . This is because the total number of individual tubes in a MWCNT bundle (N_{tot}) increases with t_s . Then, $C_{\text{q,out}}$ increases simultaneously. As a result, the signal leakage through the shielding layer increases. However, for CuS-TSV, t_s doesn't affect the impedance of the shielding layer due to the skin effect. Also, C and G of CuS-TSV don't vary with t_s . Thus, $|S_{21}|$ doesn't vary with t_s . This implies that for CuS-TSV, one can adjust t_s according to the manufacturing difficulty and cost, and don't have to worry about the transmission performance. However, for MS-TSV the shielding layer should be as thinner as possible to decrease loss.

Fig. 4 $|S_{21}|$ varying with frequency for different (a) t_s , (b) D_{out} , and (c) T

Fig. 4(b) plots $|S_{21}|$ of MS-TSV for different D_{out} . One can see that $|S_{21}|$ increases with D_{out} . This is because the resistance of MWCNTB decreases with the increase of D_{out} . Then, the conductor loss is reduced simultaneously. In addition, it can be observed that the impact of D_{out} on $|S_{21}|$ weakens as D_{out} increases. For example, when D_{out} varies from 10 nm to 50 nm and 100 nm, $|S_{21}|$ at 20 GHz increases from -0.0067 dB to -0.0048 dB and -0.0044 dB, and the increments are 0.0019 dB and 0.0004 dB, respectively. This is because a larger D_{out} will produce more conducting channels for every individual MWCNT. However, N_{tot} will decrease simultaneously. For example, N_{tot} of the bundle with a radius of 5 μm are about 8.5×10^5 and 9×10^3 for $D_{out} = 10$ nm and $D_{out} = 100$ nm, respectively.

Fig. 4(c) illustrates $|S_{21}|$ of MS-TSV for different T . It states that $|S_{21}|$ decreases slightly as T rises. This is because as T increases, $\lambda_i(T)$ decreases and $N_i(T)$ increases. Then, R_{in} and R_{out} increase with the decrease of $\lambda_i(T)$, and C_q increases with the increase of $N_i(T)$. As a result, the conductor loss and the loss cause by leakage increase.

3.2 The attenuation constant

The attenuation constant α is the real part of γ and can be calculated using (11). Fig. 5 plots α of MS-TSV and CuS-TSV. One can observe that the attenuation when $t_{ins} = 1$ μm is larger than that of 2 μm for both MS- and CuS-TSV. This is because C_{ins} increases with the decrease of t_{ins} . Additionally, one can see that α of MS-TSV is dramatically less than that of CuS-TSV. To investigate the reason for that, we derive the expression of α from (11) as

$$\alpha = \frac{\sqrt{2\omega C}}{2} (\sqrt{\omega^2 L^2 + R^2} - \omega L)^{1/2} \quad (15)$$

Note that G is ignored since it is far smaller than $j\omega C$. In (15), L of MS- and CuS-TSV are mainly determined by L_{ex} , and they are close. While, MS-TSV has a less C (as addressed previously) and R (because MWCNT can suppress the skin effect significantly) than that of CuS-TSV. As a result, α of MS-TSV is less than that of CuS-TSV.

Fig. 5 α of MS- and CuS-TSV

3.3 Time delay

The time delay of S-TSV t_d can be calculated by [19]

$$t_d = \sqrt{RC} / \omega \quad (16)$$

Fig. 6 illustrates t_d of MS-TSV for different t_{ins} . It reveals that t_d of 1 μm t_{ins} is longer than that of 2 μm since C increases as t_{ins} decreases. Additionally, the results of CuS-TSV are also plotted here for comparison. One can observe that t_d of MS-TSV is a little smaller than that of CuS-TSV. The reason for this is similar as that for α .

Fig. 6 t_d of MS-TSV and CuS-TSV

4. Parametric study on the conductivity and packing density of MWCNTB

4.1 Parametric study on $\sigma_{MWCNTB}(T)$

To investigate the impact of the variables affecting σ_{MWCNTB} in (7), we define the sensitivity coefficient σ_x as

$$\sigma_x = \frac{\partial \sigma_{MWCNTB}}{\partial x} \quad (17)$$

where x represents the variables H_{tsv} , D_{out} , T and U . Table I lists σ_x when $D_{out} = 20$ nm, $H_{tsv} = 30$ μm , $T=300K$ and $U = 0.2$ V. It states that D_{out} has the largest impact and T has the weakest one on σ_{MWCNTB} . Increasing D_{out} is an effective method to increase σ_{MWCNTB} . In addition, $\sigma_U < 0$ indicates that σ_{MWCNTB} decreases with the increase of U .

Table I SENSITIVITY COEFFICIENTS OF $\sigma_{MWCNTB}(T)$

Variables	H_{tsv}	D_{out}	T	U
σ_x	1.14 (S/ μm^2)	784 (S/ μm^2)	0.047 (S/ $\mu m \cdot K$)	-69.1 (S/ $\mu m \cdot V$)

4.2 The packing density of MWCNTB

The packing density affects $\sigma_{\text{MWCNTB}}(T)$ directly, and will affect the loss and attenuation of MS-TSV consequently. In the previous analysis, the MWCNTB is assumed to be densely packed. However, densely packing is difficult in the actual process [20]. Therefore, it is necessary to explore an appropriate packing density satisfying $\sigma_{\text{MWCNTB}} \geq \sigma_{\text{Cu}}$. To simplify the expression of σ_{MWCNTB} , we substitute the expression in the square brackets of (7) with $R_{\text{M,int}}(T)$, and get,

$$\text{Den} H_{\text{tsv}} (1 + \eta) R_{\text{M,int}}(T) \geq \sigma_{\text{Cu}}(T) \quad (18)$$

Then, Den can be derived from (18) as

$$\text{Den} \geq \frac{\sigma_{\text{Cu}}(T)}{H_{\text{tsv}} R_{\text{M,int}}(T) (1 + \eta)} \quad (19)$$

Denoting the minimum Den satisfying (19) as $\text{Den}_{\min}$, we define the sparseness degree D_{spa} as

$$D_{\text{spa}} = \frac{\text{Den}_{\min}}{\text{Den}_d} = \frac{\text{Den}_{\min} \sqrt{3} (D_{\text{out}} + s)^2}{2} \quad (20)$$

where Den_d is the density of densely packing. If Den_d is 100%, D_{spa} means the minimum percentage satisfying $\sigma_{\text{MWCNTB}} \geq \sigma_{\text{Cu}}$.

Fig. 7 (a) $\text{Den}_{\min}$ and (b) D_{spa} varying with H_{tsv} at different T .

To find the MS-TSV satisfying $\sigma_{\text{MWCNTB}} \geq \sigma_{\text{Cu}}$, $\text{Den}_{\min}$ and D_{spa} varying with D_{out} and H_{tsv} at different temperatures are studied and the results are shown in Fig. 7. In Fig. 7(a), the two dash lines are $\text{Den}_d = 2.75 \times 10^{11} \text{ cm}^{-2}$ and $7.09 \times 10^{10} \text{ cm}^{-2}$ for $D_{\text{out}} = 20 \text{ nm}$ and 40 nm , respectively. The MWCNTB can't be realized if $\text{Den}_{\min} > \text{Den}_d$. In addition, one can see that $\text{Den}_{\min}$ declines with the increase of D_{out} , H_{tsv} and T . For example, when $H_{\text{tsv}} = 40 \mu\text{m}$ and $D_{\text{out}} = 20 \text{ nm}$, as T rises from 300 K to 400 K, $\text{Den}_{\min}$ decreases from $2.72 \times 10^{11} \text{ cm}^{-2}$ to $1.91 \times 10^{11} \text{ cm}^{-2}$. Besides, when $D_{\text{out}} = 20 \text{ nm}$ at 300K, as H_{tsv} increases from 40 μm to 60 μm , $\text{Den}_{\min}$ decreases from $2.72 \times 10^{11} \text{ cm}^{-2}$ to $2.24 \times 10^{11} \text{ cm}^{-2}$. Fig. 7(b) reveals that D_{spa} declines as H_{tsv} increases. For example, when $T = 300 \text{ K}$, $D_{\text{out}} = 20 \text{ nm}$, D_{spa} are 97.31% and 66.3% for $H_{\text{tsv}} = 40 \mu\text{m}$, and 100 μm , respectively. In addition, D_{spa} decreases with the increase of D_{out} . For

example, when $T = 300\text{K}$, $H_{\text{tsv}} = 100 \mu\text{m}$, D_{spa} are 66.38% and 45.81% for $D_{\text{out}} = 20\text{nm}$ and 40nm , respectively. Besides, both Den_{min} and D_{spa} decrease as T rises because σ_{Cu} decreases with T .

Above all, thicker MWCNT should be used for shorter vias to satisfy $\sigma_{\text{MWCNTB}} \geq \sigma_{\text{Cu}}$ easily, and the manufacturing difficulty can be reduced simultaneously.

5. Potential fabrication method

A potential fabrication process for MS-TSV is suggested in Fig. 8. It start with the deep reactive ion etching (DRIE) an annular trench in substrate 1 [21]. Then, a layer of SiO_2 is sputtered inside the trench for insulation. Next, MWCNT forests are grown by thermal chemical vapor deposition (CVD) to fill the trench. Again, DRIE is utilized to remove the silicon post inside the annular trench. At the same time, MWCNT forests are grown on substrate 2 and then transferred to the via in substrate 1. Furthermore, the BCB layer is then spin coated to fill the gap between the MWCNT and the sidewall of the via [22]. Finally, the chemical-mechanical polish is used to remove the excess surface materials.

Fig. 8 Illustration of the fabrication process of TSVs.

6. Conclusions

High-performance shielded TSV filled with MWCNTB has been proposed in this paper. A compact expression for the conductivity of MWCNTB has been deduced and the resistance of MS-TSV is calculated. Then, together with formulas of L , G and C , the S parameters, the attenuation constant and time delay have been calculated. For comparison, the results of CuS-TSV have also been provided. It indicates that MS-TSV has larger $|S_{21}|$, smaller attenuation and shorter time delay than CuS-TSV. In addition, $|S_{21}|$ of MS-TSV increases with the increase of D_{out} and decrease of t_s . Also, the parametric study on σ_{MWCNTB} has been done. The results show that D_{out} has the largest impact on σ_{MWCNTB} . Finally, the minimum packing density satisfying $\sigma_{\text{MWCNTB}} \geq \sigma_{\text{Cu}}$ has been derived. It reveals that thicker MWCNT is helpful to increase the conductivity of MS-TSV and reduce manufacturing difficulty.

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