TSV Modeling Considering Signal Integrity Issues

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Abstract

Since a TSV has a metal-insulator-semiconductor structure, it supports three fundamental modes namely, skin-effect, slow-wave and dielectric quasi-TEM mode. In this contribution, we predict the frequency range of these modes, considering TSVs for interposer applications as an example. Furthermore, the impact of Si-resistivity on signal integrity is quantified and coaxial TSV configurations are proposed to minimize this impact.

Keywords: Slow-wave mode, dielectric quasi-TEM mode, skin-effect mode, TSV, signal integrity

1. Introduction

Due to the myriad of system-integration advantages offered by Through-Silicon Vias (TSVs), they are considered as one the key technologies needed for the development of future miniaturized and high-performance electronic products. However, the semi-conducting nature of silicon (Si) may cause signal integrity problems such as cross-talk, high insertion loss and electromagnetic interference, which may degrade the system performance. To prevent/minimize these problems, the impact of the conductivity of Si must be thoroughly investigated.

So far, extensive research work has been carried to develop accurate models which can be used to quantify the RF performance of TSVs (e.g., [1] – [4]. However, in all these works, TSVs are studied under the assumption that only the dielectric quasi-TEM mode is present. But, since a TSV has a metal-insulator-semiconductor (MIS) structure, it also allows the existence of two other modes, namely the skin-effect and slow-wave modes.

In this work, we predict the frequency range of each of these modes, considering TSVs for interposer applications as an example. The impact of the modes on the signal integrity is studied and coaxial TSV configurations are proposed to minimize this impact.

A cross-sectional view of the two-conductor TSV studied in this work is shown in Fig. 1. Each TSV has a diameter of 75 µm, pitch of 150 µm and height of 300 µm. The thickness of silicon dioxide (SiO_2) layer is 1 µm. The resistivities studied are as follows: 500 Ω cm is considered as high resistivity silicon (HRS), 10 Ω cm as medium resistivity silicon (MRS) and 1 Ω cm as low resistivity silicon (LRS).

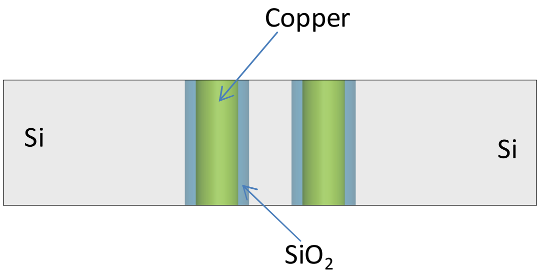

Figure 1: Cross-sectional view of two-conductor TSV configuration.

2. Slow-Wave, Dielectric Quasi-TEM and Skin-effect Modes

For the prediction of the frequency range of these modes, the frequency-resistivity domain chart, originally proposed in [5], was used. It has been extensively applied in previous research to predict the frequency ranges of the skin-effect, slow-wave and dielectric quasi-TEM modes on planar transmission lines. In this section, we derive this chart for interposer TSVs, based entirely on their geometrical dimensions and silicon resistivity. For this derivation equations (1)-(4) [5] [6] are used. In these equations, ρ_{si} represents Si-resistivity, ε_{si} is the relative permittivity of Si (11.9), ε_0 is the permittivity of vacuum ($8.854 * 10^{-12}$F/m), μ_0 is the permeability of vacuum ($4\pi * 10^{-7}$ H/m), t_{si} and t_{sio_2} are the thickness of Si and SiO_2, respectively.

- Dielectric relaxation frequency of Si between the TSVs, f_{rsi},

$$f_{rsi} = \frac{1}{2\pi} \frac{1}{\rho_{si}\, \varepsilon_0\, \varepsilon_{si}} \qquad (1)$$

- Relaxation frequency of the interfacial polarization, f_{ri},

$$f_{ri} = \frac{1}{2\pi} \frac{1}{\rho_{si}\, \varepsilon_0\, \varepsilon_{si}} \frac{t_{sio_2}}{t_{si}} \qquad (2)$$

- Characteristic frequency for skin-effect in Si, f_{ssi},

$$f_{ssi} = \frac{\rho_{si}}{\pi\, \mu_0\, (t_{si})^2} \qquad (3)$$

- Characteristic frequency of slow-wave mode, f_{sw},

$$f_{sw} = \frac{1}{\left(\frac{1}{f_{ri}} + \frac{2}{3f_{ssi}}\right)} \qquad (4)$$

In Fig. 2, the frequency-resistivity domain chart for the interposer TSVs is shown. Considering MRS as an example, the slow-wave modes starts from lower frequencies and extends to 200 MHz. This mode is characterized by very slow propagation velocity of the signal that travels though the TSVs. This slow propagation occurs because electromagnetic fields only partially penetrate through the Si-substrate [6]. Due to the strong interfacial polarization (Maxwell-Wagner mechanism), a thin space-charge layer is formed at the SiO_2-Si interface [5],[7]. These charges act as a lossy ground plane, allowing magnetic fields to penetrate through Si to the return-current TSV (see Fig. 1), since δ is much larger than the TSV pitch at these frequencies. Thus, the inductance is large. However, because the intrinsic impedance, η (see (5)) of Si is very low, it acts as a shield to electric fields [7], [8], causing them to be concentrated in the SiO_2 layer.

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}} \qquad (5)$$

Since the thickness of the SiO_2 layers is only 1 µm, a large capacitance occurs. The combination of this capacitance and the large inductance results in a very slow velocity of the signal propagating through the TSV, in fact, much slower that the phase velocity of the TSV when either Si or SiO_2 is considered as the dielectric. As frequency increases, η also increases, thereby allowing the penetration of electric fields into Si. As long as the frequency is smaller than f_{ssi}, the magnetic fields also penetrate through the Si to the return-current TSV and δ is still larger than the pitch. This signifies the transition from the slow-wave to the dielectric quasi-TEM mode. This transition extends from 200 MHz to 21 GHz.

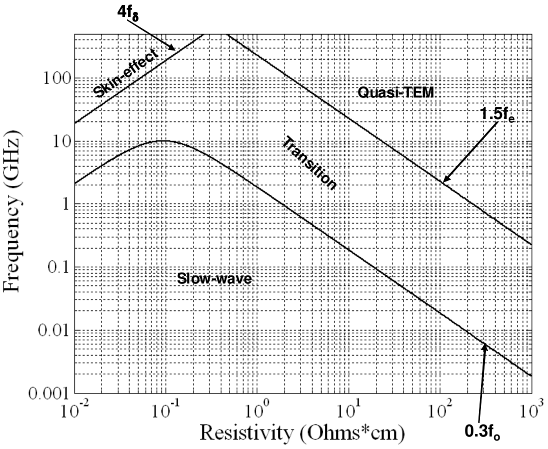

Figure 2: Frequency-resistivity chart for interposer TSVs.

The dielectric quasi-TEM mode occurs at frequencies higher than f_{rsi}, and smaller than f_{ssi}, and Si behaves like a dielectric, allowing complete penetration of electric and magnetic fields. This occurs at 21 GHz and the phase velocity of the signal propagating through the TSV becomes approximately equal to the phase velocity when only Si is considered as the dielectric.

The skin-effect mode occurs when the product of Si conductivity and frequency is very high to yield a small skin depth of penetration into Si. Si then behaves like a lossy conductor wall and must therefore be modeled as an imperfect conductor (floating ground). However, as can be seen in Fig. 2, the skin-effect mode doesn't occur up to 1 THz, considering the Si-resitivities studied in this work.

3. Quantification of the Impact of Slow-wave and Dielectric Quasi-TEM Mode on Signal Integrity

Ensuring signal integrity entails keeping the timing and quality of a signal within acceptable limits. The slow-wave mode causes signal delays at lower and higher frequencies, depending on the resistivity, thus degrading the timing. The dielectric quasi-TEM mode results in significant power lost at higher frequencies, thus degrading the quality. Hence, as signals propagate through TSVs, their integrity is degraded both at lower and higher frequencies [6]. In the following paragraphs, we quantify signal integrity degradation (using the insertion loss and time delay) caused by the slow-wave and dielectric quasi-TEM modes.

1) Insertion Loss

To study the impact of Si-resitivity on interposer TSVs, the TSVs were modeled and simulated as a two-conductor TSV using ANSYS HFSS. In Fig. 3, the impact of LRS, MRS and HRS on the insertion loss of the TSV is given. For example, if MRS is considered, then more than 10% power is lost already at 2.4 GHz. If LRS is used, approximately 20% is lost at 5 GHz and more than 80% at 60 GHz.

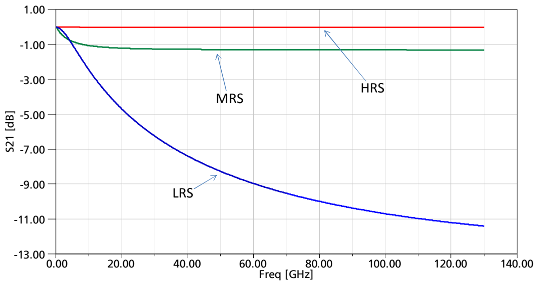

Figure 3: Impact of Si-resistivity on insertion loss of TSVs for interposer application, considered as an example.

2) Time Delay

To quantify the impact of the slow-wave mode on signal integrity, we modeled the same 2 conductor TSV-configuration for interposer applications using ceramic, glass and FR4 substrates. The time-delay (TD) considering these four substrate technologies is given in ps/µm in Fig. 4. At 100 MHz, the TD for TSVs in LRS and MRS is approximately 5 times greater than that in ceramic and more than 6 times greater than that when glass or FR4 are considered. TD falls rapidly with frequency when MRS is considered than when LRS is considered. For example, at 2.4 GHz, TD considering TSVs in MRS is only approximately 2 times greater than TD when the same via configuration in ceramic is considered but still more than 4 times greater when LRS is considered. At higher frequencies, the impact of the slow-wave on the time delay falls considerably. This occurs from 5 GHz and 50 GHz respectively, when MRS and LRS are considered.

In the next section, the coaxial configuration is presented to overcome the impact of the slow-wave and skin-effect modes on signal integrity.

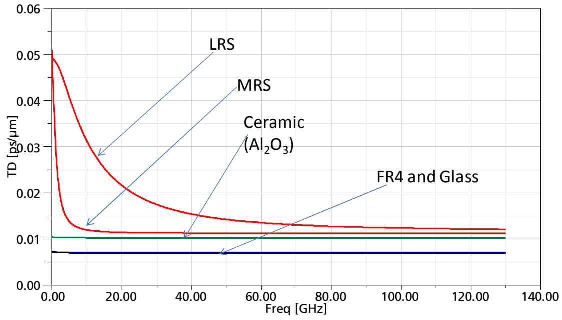

Figure 4: Comparison of TD for a two-conductor TSV with delay that occurs through same via configuration in glass, ceramic and organic (FR4) substrates.

4. Coaxial TSV Configurations for Minimizing Signal Integrity Problems

In [9] and [10], a coaxial TSV configuration was proposed. In [11], we proposed two new configurations. In this section, these coaxial TSV configurations are characterized up to 130 GHz, comparing their insertion loss and TD to two-conductor TSV configurations. The aim of these configurations is to overcome the signal integrity problems caused by slow-wave and the dielectric quasi-TEM modes, discussed in the previous section. The advantages of these coaxial TSV configurations will be illustrated using the worst-case example, i.e., when LRS is considered for interposer TSVs. Since LRS is much cheaper than MRS or HRS, overcoming the signal integrity problems which occur when LRS is used will significantly reduce the cost of development of Si-based system modules [11].

Schematic top views of the three coaxial TSV configurations are shown in Fig. 5. 4 µm and 75 µm were chosen as the inner and outer conductor diameters of these coaxial TSVs. Consequently, they have the same size as one of the TSVs in the two-conductor TSV configuration studied in the previous sections. Both have a height of 300 µm.

We call the configuration on the top LHS in Fig. 5, Si-filled coaxial TSV (SF Coax TSV). The aim of this structure is to control the inductance/capacitance of the TSV and hence, prevent any fluctuation in the characteristics impedance of the signal path or impedance profile of the power distribution network. Furthermore, since the outer ring is much thicker than the skin depth at RF/microwave frequencies, there is no leakage of power. Hence, cross talk and EMI are also eliminated. However, because Si is the medium of propagation, there is still power lost. Hence, the insertion loss and TD are high. The advantages of SF coax-TSV over the two-conductor TSV are shown in Fig. 6 and Fig. 7. For example at 60 GHz, approximately 65% of power is lost as signal propagates through SF Coax-TSV. This is approximately 20% less, when compared to a 2 conductor TSV. Furthermore, TD of a SF coax-TSV is approximately half that of the two-conductor TSV. By replacing part of the Si between the inner and outer conductor with a low-loss dielectric, such as BCB, the insertion loss and TD can be greatly minimized. We call the coaxial TSV configuration used for this purpose, the mixed-dielectric-filled coaxial TSV (MDF Coax-TSV). This configuration is shown on the top RHS in Fig. 5.

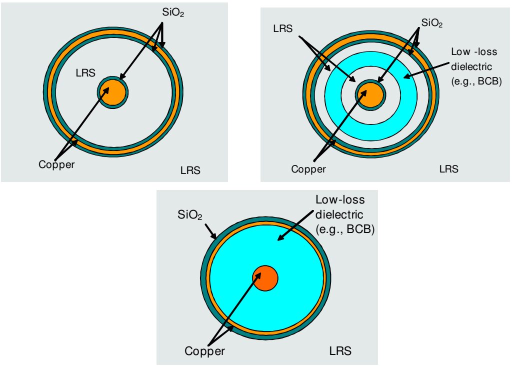

Figure 5: Coaxial TSV configurations for RF performance enhancement using LRS. SF Coax-TSV – Top LHS; MDF Coax-TSV – Top RHS; LLDF Coax-TSV – bottom.

However, as can be seen in Fig. 6 and Fig. 7, the improvement achieved depends on the ratio of Si to BCB used. For example, consider a MDF Coax-TSV with the following Si to BCB distribution: 10 µm (Si) – 11 µm (BCB) – 10 µm (Si), and a SiO$_2$ thickness of 2 µm (i.e., 1 µm between the inner conductor and silicon and 1 µm between the outer conductor and silicon). For this configuration, approximately 17 % of the power is lost at 60 GHz, compared to 65% lost when SF Coax-TSV is considered. This power lost reduces to approximately 7%, when 21 µm thick BCB is used and the thickness of Si is reduced by 1/2. By further increasing the thickness of BCB to 26 µm and reducing the Si thickness by half the previous value, the amount of power lost reduces to approximately 4% at 60 GHz. For all the three configurations of MDF Coax-TSV, less than 2% power is lost at 5 GHz. With regards to TD, MDF Coax-TSV exhibits an approximately constant TD from 100 MHz to 130 GHz, especially when the ratio of Si-to-BCB is small. With an approximate 2:1 Si-BCB ratio (i.e., when Si has a thickness of 10 µm), the TD of MDF is 5 times less than that of a two-conductor TSV and approximately equal to that of two-conductor via in ceramic substrates. The smaller the Si-BCB ratio, the smaller the TD, as can be seen in Fig. 7.

The third configuration of coaxial TSV shown on the bottom in Figure 5 is called low-loss dielectric-filled TSV (LLDF Coax-TSV). Using BCB as the dielectric in this case leads to only approximately 2% power loss at 60 GHz and 3% at 120 GHz. The TD is about 10 times smaller than that of a two-conductor TSV. Hence LLDF leads to negligible insertion loss and TD from 100 MHz to 130 GHz.

Since LRS is still used as the substrate technology in these TSV configurations, only the portion of Si between the inner and outer conductors is partly or completely replaced, the use of coax-TSVs may lead to considerable cost reduction, while still ensuring excellent signal integrity [6]. Furthermore, the integration density can be increased because one coaxial TSV can replace 2 TSVs (signal and reference) in a two-conductor configuration.

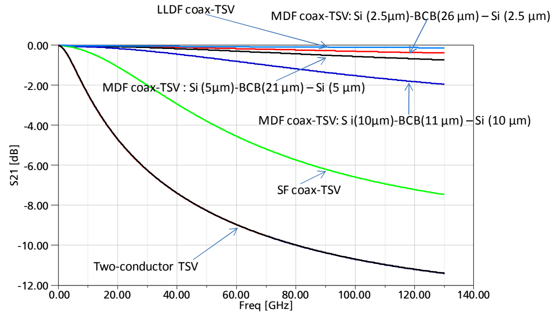

Figure 6: Comparison of insertion loss of three coaxial and two-conductor TSV configurations for interposer applications.

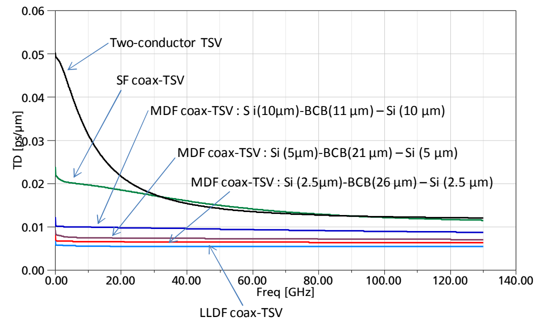

Figure 7: Comparison of time delay of three coaxial and two-conductor TSV configurations for interposer applications.

5. Summary

In this work, the frequency-range of skin-effect, dielectric quasi-TEM and slow-wave modes are predicted for interposer TSVs using the frequency-resistivity domain chart. The impact of Si-resistivity on the quality and timing of signals propagating through these TSVs are quantified and coaxial TSV configurations are proposed to overcome some of these limitations.

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