Investigation on impact of substrate on low-pass filter based on coaxial TSV

Fengjuan Wang\textsuperscript{1a)}, He Li\textsuperscript{2}, and Ningmei Yu\textsuperscript{1}

\textsuperscript{1} School of Automation and Information Engineering, Xi’an University of Technology, Xi’an, Shanxi 710048, China
\textsuperscript{2} The Second Institute of China Aerospace Science & Industry Corp, Beijing 100854, China

\textsuperscript{a)} wfjxiao4@163.com

Abstract: An ultra-compact Butterworth low-pass filter (LPF) has been proposed based on through-silicon-via (TSV) technology without investigation the substrate impact. The conductivity of substrate generally leads to noise interference on the passive devices. This letter analyzes the substrate impact on the components, i.e. the inductor and capacitor, and on the whole LPF, by establishing and studying the equivalent circuit model. It is concluded that this type of LPF based on coaxial TSV can be widely used for any-resistivity substrate.

Keywords: through-silicon-via (TSV), low-pass filter (LPF), substrate impact

Classification: Electron devices, circuits and modules

References

[1] E. Musonda and I. C. Hunter: “Exact design of a new class of generalized chebyshev low-pass filters using coupled line/stub sections,” IEEE Trans. Microw. Theory Techn. 63 (2015) 4355 (DOI: 10.1109/TMTT.2015.2492969).
[2] F. Cervera and J. Hong: “High rejection, self-packaged low-pass filter using multilayer liquid crystal polymer technology,” IEEE Trans. Microw. Theory Techn. 63 (2015) 3920 (DOI: 10.1109/TMTT.2015.2496219).
[3] C. X. Zhou, et al.: “Lowpass filter with sharp roll-off and wide stopband using LTCC technology,” IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (2015) 1 (DOI: 10.1109/IMWS-AMP.2015.7325054).
[4] L. Qian, et al.: “Electrical modeling and analysis of a mixed carbon nanotube based differential through silicon via in 3D integration,” IEEE Trans. Nanotechnol. 15 (2016) 155 (DOI: 10.1109/TNANO.2015.2509019).
[5] X. Yin, et al.: “Effectiveness of p+ layer in mitigating substrate noise induced by through-silicon via for microwave applications,” IEEE Microw. Wireless Compon. Lett. 26 (2016) 687 (DOI: 10.1109/LMWC.2016.2597218).
[6] L. Qian, et al.: “Study of crosstalk effect on the propagation characteristics of coupled MLGNR interconnects,” IEEE Trans. Nanotechnol. 15 (2016) 810 (DOI: 10.1109/TNANO.2016.2586920).
[7] X. Yin, et al.: “Thermo-mechanical characterization of single-walled carbon nanotube (SWCNT)-based through-silicon via (TSV) in (100) Silicon,” Nanosci. Nanotechnol. Lett. 7 (2015) 481 (DOI: 10.1166/nnl.2015.1991).
1 Introduction

Eliminating undesired signals, microwave low-pass filters (LPFs) are widely required in modern wireless communication systems. In common, they are realized based on transmission line technology [1], or some novel technologies, such as low-temperature cofired ceramic and liquid crystal polymer processes [2, 3]. However, these LPFs suffer from the disadvantages of big size and non-integration. On the other hand, by stacking semiconductor layers on top of each other, three-dimensional integrated circuits (3D ICs) offer the most promising platform to implement “more than Moore” technologies and attract tremendous attentions of researchers [4, 5, 6, 7]. By employing through-silicon-vias (TSVs), which can provide vertical interconnections among stacked layers, 3D ICs have advantages of short delay, high speed, low power, and small form factor [8, 9, 10].

Taking both the aspects mentioned above, we could give a solution to LPF by employing TSV technology. Therefore, an ultra-compact LPF is proposed in our previous work [11], which is composed by coaxial TSV capacitors and spiral inductors, as shown in Fig. 1. However, the impact of substrate on the characteristics of LPF is not investigated, which is of great importance for the application range of LPF. For the most common case, the resistivity of substrate is 10 Ω·cm. The conductivity of substrate leads to noise interference on the passive devices [12]. Therefore, it is necessary to make clear this issue and ensure the electrical reliability. This paper investigate the impact of substrate on the characteristics of LPF in detail.

2 Impact of substrate on spiral inductor and capacitor

Before analyzing the impact of substrate on the whole LPF, we firstly study that on the components, i.e. the inductor and capacitor.
As shown in Fig. 2, the LPF includes five layers from top to bottom, in order, inductor layer, oxide layer, substrate layer, oxide layer, and inductor layer. The coupling current from top inductor to bottom one has to flow through three impedances, i.e. the impedance of top oxide layer ($Z_{OX}$), that of substrate layer ($Z_{SUB}$), and that of bottom oxide layer ($Z_{OX}$), as shown in Fig. 2(a). The corresponding parasitic circuit model is given in Fig. 2(b), where $C_p$ is the parasitic capacitance between inductor and substrate. The substrate is modeled as parallel conductance ($G_{sub}$) and capacitance ($C_{sub}$) [13]. Also, there are parasitic capacitances ($C_{ox-TSV}$) between substrate and TSVs, which is shown in Fig. 3 in detail. Here, $\pi$-type model is selected.

According to the analysis above, the parasitic circuit model of substrate between the top and bottom inductors of LPF are extracted as shown in Fig. 4(a) and (b), where $C_{sub}$ and $G_{sub}$ represent the capacitance and conductance of substrate, respectively; $C_{ox-TSV}$ represents the capacitance of the outer oxide liner
of coaxial TSV. Then, $C_{\text{sub}}$ of 2.6 fF, $G_{\text{sub}}$ of 1.0 mS, and $C_{\text{ox,TSV}}$ of 0.7 pF can be obtained according to [13].

The corresponding impedance model of Figs. 4(a) and (b) is shown in Fig. 4(c), where $Z_{\text{ox}}$ represents the impedance of the oxide layer between inductor and substrate, $Z_{\text{sub}}$ represents that of substrate layer, and $Z_{\text{ox,TSV}}$ represents that of the oxide liner of coaxial TSV. They can be calculated by Eqs. (1), (2), and (3), respectively.

$$Z_{\text{ox}} = \frac{2}{j\omega C_p}$$

$$Z_{\text{sub}} = \frac{1}{G_{\text{sub}} + j\omega C_{\text{sub}}}$$

$$Z_{\text{ox,TSV}} = \frac{1}{j\omega 4C_{\text{ox,TSV}}}$$

According to the values of $C_{\text{sub}}, G_{\text{sub}},$ and $C_{\text{ox,TSV}}$ calculated above and that of $C_p$ (28.9 fF), we can obtain the amplitude of $Z_{\text{ox}}, Z_{\text{sub}},$ and $Z_{\text{ox,TSV}}$, as shown in Fig. 5. It is shown that $Z_{\text{sub}}$ and $Z_{\text{ox,TSV}}$ are far smaller than $Z_{\text{ox}}$ at lower frequencies, thus ignorable. While $Z_{\text{ox,TSV}}$ is far smaller than $Z_{\text{ox}}$ and $Z_{\text{sub}}$ at higher frequencies, thus ignorable. Therefore, the simplified impedance model can be obtained as shown in Fig. 6(a). It is can be seen that, for the higher frequencies, both ends of the $Z_{\text{sub}}$ is connected to GND. Thus, the impedance from substrate to GND is zero, while that to inductor is $Z_{\text{ox}}$. And the current in substrate would chose the zero impedance path. Hence, there is no current path from substrate to inductor.
Please note that, it is clear that both two cases in Fig. 6(a) can be equal to Fig. 6(b). Therefore, the substrate has ignorable impact on the inductor.

![Equivalent impedance models between the top and bottom inductors of LPF.](image)

On the aspect of coaxial TSV capacitor, due to the protection of the grounded outer metal of coaxial TSV, the substrate has hardly any impact on the capacitor as well. This point can be observed in Fig. 3.

3 Impact of substrate on LPF

In this section, the impact of substrate on the whole LPF is investigated by adding the equivalent circuit model of substrate into that of the LPF as shown in Fig. 7. Table I lists the parameters of equivalent circuit model of LPF with consideration of substrate impact.

| Parameter      | Value  |
|----------------|--------|
| $R_{tsv}$      | 46.5 mΩ |
| $L_{tsv}$      | 20.9 pH |
| $C_{tsv}$      | 3.53 pF |
| $R_L$          | 0.96 Ω  |
| $L_L$          | 0.32 nH |
| $C_L$          | 9.8 fF  |
| $C_p$          | 28.9 fF |
| $C_{ox,TSV}$   | 0.7 pF  |
| $G_{sub}$      | 1.0 mS  |
| $C_{sub}$      | 2.6 fF  |

Based on the equivalent circuit model, we obtained the S-parameters of LPF with and without considering substrate by employing ADS. The S-PARAMETERS
module and linear frequency sweep are selected. The frequency is swept from 0.1 GHz to 20 GHz with step of 0.1 GHz. Two terminals with 50 Ω impedance are connected with the ends of “In” and “Out” respectively in the simulation. The results are shown in Fig. 8. It can be concluded that the substrate has hardly any impact on the LPF.

4 Conclusion

In this letter, the impact of substrate on the LPF based on TSV technology is investigated in detail by establishing and analyzing the equivalent circuit model of the LPF and its parasitic parameter. It is concluded that this type of LPF is appropriate for any-resistivity silicon substrates.

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