Experimental Analysis of Via-hole-ground Effects in Microwave Integrated Circuits at X-band

Ghulam Mustafa Khan Junejo
Microwave Electronics Lab, University of Kassel, Kassel, Germany
gmjunejo@student.uni-kassel.de

Abstract. This research presents the influence of via-hole diameter, quantity of via-holes, position of via-hole and the aging effects in via-hole-grounds in the microwave integrated circuits at X-band frequency range.

Keywords
RF Grounding, Interconnect Technologies, Via-hole Technologies, Ribbon-bond

1. Introduction

Radio Frequency (RF) grounding is very important in microwave electronic circuits. Without good RF grounding high gain, low insertion loss, low noise figure (NF), high output power, high efficiency, etc cannot be achieved [1, 2]. An RF/microwave printed circuit board can experience problems in above mentioned parameters, when its grounding is insufficient. Due to several advantages (very low inductance, easy to realize in complex circuits, very good thermal conductivity) via-hole technology is very successful from low to higher frequencies (GHz range) [1]. The RF ground connection for both, active and passive devices in MICs (Microwave Integrated Circuits) and MMICs (Monolithic Microwave Integrated Circuits) are usually realized by via-holes. The flexibility of via-hole is significant in physical layout; they are very small in length \( h \) depends on the height of the substrate as shown in Fig. 1(c). Via-holes provide very low inductance as compared to other RF-grounding technologies (wrap-around, wire-bond, etc). In wrap-around, wire-bond, ribbon-bond technologies RF grounding usually positioned in close proximity to the boundary of the circuit. Hence, these grounding technologies require more space in the circuits and make the circuit larger.

In this research, two different high performance RF grounding technologies (ribbon-bond and via-hole) suitable for MICs have been investigated and realized on Rogers RO4003C low dielectric constant substrate with \( \varepsilon_r = 3.55 \), height of substrate \( h=0.813 \) mm and a metal thickness of \( t=17.5 \) μm [3]. Two different layouts (thru-line shorted in centre and shorted-stub circuits) were fabricated for analysis of RF grounding. The effects of variable via-hole diameter \( d_1=200 \) μm, \( d_2=400 \) μm, and \( d_3=800 \) μm), influence of the quantity of (single and double) via-holes and the position of via-holes, reliability of the via-hole applying accelerate aging technique according to Arrhenius model [4] were investigated by using state-of-the-art in-house fabrication and measurement techniques.

2. Model of microstrip via-hole ground

In the microstrip line, via-hole can be modeled by a series of inductance and resistance in parallel with the capacitance of the pad to obtain wideband short circuits.

Fig. 1. Microstrip via-hole ground (a) ideal circuit (b) equivalent circuit with losses (c) physical 3d view of microstrip via-hole ground
The equivalent circuit of via-hole is shown in Fig. 1(a) without losses, 1(b) including losses. According to [5] the inductance ($L_{\text{via}}$), resistance ($R_{\text{via}}$), of the microstrip via-hole can be calculated as below:

$$L_{\text{via}} = \frac{\mu_0}{2\pi} \left[ h \cdot \ln \left( \frac{h + \sqrt{r^2 + h^2}}{r} \right) + \frac{3}{2} \left( r - \sqrt{r^2 + h^2} \right) \right]$$ \hspace{1cm} (1)

The inductance is in picohenries ($pH$), $h =$ length of via (substrate height) in $\mu m$, $r =$ outer radius of via in $\mu m$, $\mu_0 =$ free space permeability which is equals to $1.2566 \times 10^{-6}$ H/m

$$R_{\text{via}} = R_{\text{dc}} \sqrt{1 + \frac{f}{f_\delta}}$$ \hspace{1cm} (2)

where;

$$R_{\text{dc}} = \frac{h}{\sigma \pi \left[ r^2 - (r - t)^2 \right]}$$

$$f_\delta = \frac{1}{\pi \mu_0 \sigma t^2}$$

$f = \text{operating frequency}$, $\sigma = \text{conductivity of the conducting material used for via}$, $t = \text{metal thickness}$, $f_\delta = \text{skin effect corner frequency}$

While the capacitance ($C_{\text{via}}$) which is the pad capacitance of the microstrip via-hole can be calculated as below [6]:

$$C_{\text{via}} = \frac{1.441 \epsilon_r \epsilon_0 d_1}{d_2 - d_1}$$ \hspace{1cm} (3)

$d_1 =$ via-pad diameter, $d_2 =$ anti-pad diameter, $t =$ thickness of dielectric material, $\epsilon_r =$ relative dielectric constant of the substrate

### 3. Realized test circuits

#### 3.1 Microstrip shorted-stub

Ribbon-bond grounds and via-hole grounds have very low inductance and very good RF performance over wire bond and wrap-around RF grounding techniques. Therefore, both of these RF grounding technologies have been realized as shown in Fig. 2 and Fig. 3.

![Fig. 2. Microstrip ribbon-bond shorted-stub (a) geometry (b) mounted circuit on aluminum fixture and SMA connectors for measurement](image)

![Fig. 3. Microstrip shorted-stub with via-hole (a) geometry (b) mounted circuit on aluminum fixture and SMA connectors for measurement](image)

#### 3.2 Microstrip thru-line shorted with via-hole

The geometry and fabricated circuit of 50 $\Omega$ (calculated by line calculator, an ADS tool) microstrip transmission line with a via-hole placed in the centre of the line to provide RF grounding as shown in Fig. 4.
4. Experimental results

4.1 Comparison between ribbon and via-hole grounding

Fig. 5 shows measurement results for the comparison of via-hole and ribbon-bond, as expected both of the circuits are good short (ground returns) at lower frequencies. It has been observed that both, via-hole and ribbon have almost similar response over the entire frequency range from 300 MHz to 18 GHz. The short circuited response of the circuits can be seen at DC, $\lambda/2$ (at 4.9 GHz), $\lambda$ (at 9.7 GHz), etc. The via-hole shorted stub can be tuned to the desired frequency by varying the length of the shorted-stub.

4.2 Comparison between simulation and measurement results of via-hole

A 50 $\Omega$ microstrip shorted-stub has been shorted at the end of the stub with 400 $\mu$m diameter via-hole as shown in Fig. 8(b). The geometry of the fabricated circuit is shown in Fig. 3. A microscopic top view of the fabricated circuit shows that when the via-holes are drilled at the edge of circuit, there may be some damage of via-pads. Fig. 6 shows simulated (Using standard via-hole model in ADS) and measured return loss and insertion loss of microstrip shorted-stub with 400 $\mu$m diameter via hole in frequency range 300 MHz to 18 GHz (The measurements are started from 300 MHz due to the limitations of the vector network analyzer (Agilent’s VNA model E5071C). The measurement shows good agreement of the insertion loss and return loss over the entire frequency range between simulated and measured results. It has been observed that the transmission parameters show good ground returns at DC, $\lambda/2$ (at 4.9 GHz), $\lambda$ (at 9.7 GHz), etc. The via-hole shorted-stub can be tuned to the desired frequency by varying the length of the shorted-stub.
4.3 Thru-line shorted with 200µm diameter via-hole

A via-hole grounded microstrip line shorted at the center of the circuit. The s-parameters show a close agreement between simulated and measured data up to the X-band (10 GHz). It is clearly observed that as expected the via-hole behaves as a good short at lower frequencies and the short circuited effect decreases gradually as the frequency increases. It is also observed that there are some small resonances, which are possibly caused by the parasitic effects and from SMA connectors and measurement cables limitations.

![Simulation and Measurement](image)

Fig. 7. Simulation (redstar) and measurement (bluecircle) magnitude of return losses and insertion losses of the circuits shorted with 200µm via-hole diameter

4.4 Shorted-stub with 200µm, 400µm, 800µm diameter via-hole

Several structures of Fig. 3 which includes pad at the end of the stub with different diameters of the via-hole, single and double vias, and different offset length of vias have been realized to investigate the behavior of vias in the MIC circuits. The microscopic image of the via-holes is shown in the Fig. 8.

![Microscopic View](image)

Fig. 8. Microscopic view of via with metalized wall (a) 200µm via-hole diameter (b) 400µm via-hole diameter without pad (c) 400µm via-hole diameter with pad (d) 800µm via-hole diameter

4.4.1 Via-hole diameter effects

It has been observed that the stub which is shorted with via-holes of 400 µm and 800 µm diameter are identical over the whole frequency range 1 GHz to 18 GHz.

![Simulation and Measurement](image)

Fig. 9. Measured magnitude of return losses and insertion losses: 200µm via-hole diameter (redstar), 400µm via-hole diameter (bluecircle), 800µm via-hole diameter (greensquare)

While the stub shorted with 200 µm has 3dB more losses at
14.5 GHz as compared to 400 µm and 800 µm via-hole diameter and has some disagreement with the others at higher frequencies as shown in Fig. 9. This is due to higher inductance of the 200 µm via-hole. The inductance of the via-hole has been calculated from equation (1). A 200 µm diameter via-hole has an inductance which is approximately 238 pH. 400 µm diameter via-hole has an inductance of 152 pH, and 800 µm diameter via-hole has an inductance of 85 pH.

The effect of varying diameter of the via-hole (200 µm, 400 µm) is clear in the thru-line shorted as shown in Fig. 10. As expected the via-hole behaves as a good short at lower frequencies and the short circuited effect decreases gradually as the frequency increases. There are some small peaks above 12 GHz, which are caused by the SMA connector transition effects and the cables limitations used in the measurement setup. The measurement comparison shows grounding effect of the via-hole is improved as the diameter increases in the entire frequency range. Because, when the diameter of via-hole increases, the inductance decreases unless substrate thickness remains constant. This low inductance increases the short circuit effect. It has also been observed some ripples after 5 GHz in the measurement of circuit with 400 µm diameter. These ripples may be due to bad contact of the via with the fixture.

### 4.4.2 Effect of single and double via-holes

Figs. 11 and 12 show comparison of the microwave shorted-stub with single via-hole and double via-holes. It has been observed that the return loss (S11) and insertion loss (S21) of the circuits shorted with 400 µm with single via-hole and double via-holes are identical as well as the circuits shorted with 800 µm with single via-hole and double via-holes are also identical. No effects of the quantity of the via-holes have been seen.
4.4.3 Via-hole position offset effect

The positions of the via-hole in microstrip-thru-line have been varied in the length of the stub and no effect due to changing in the position has been observed. Whereas, to investigate the effects on the position of the via-holes in the shorted-stub circuits; three circuits have been realized (a) shorted at the edge of the circuit (b) shorted with position offset of 3mm (c) shorted with position offset of 5mm. The 400µm diameter via-holes have been used to shorten the microstrip stub.

Fig. 13 shows measured comparison of the response of the circuits shorted and the position offset. The stub is shorted at the length of 14 mm; the first shorted response observed at 5.0 GHz frequency (see Tab. 1). The odd response of the stub which is due to the position offset of 3mm behaves as an open stub at 11.4 GHz frequency have been observed, the stub behaves like a narrow band stop filter is the frequency range between 11 GHz to 12 GHz. The results of the short circuited stub with position offset of 5mm shows some unusual behavior at around 7.5 GHz; it behaves like an open circuit around that frequency.

4.5 Aging effects

For the consideration of reliability over the time of the circuits with via-hole, accelerated aging technique has been used [4]. Three circuits with identical topology but different via-hole diameters size (d1=200µm, d2=400µm, d3=800µm) have been realized. The temperature has been used as an acceleration factor (AF), which has been determined from Arrhenius equation (eq. 4) at 150°C equals

$$AF = \exp \left[ \frac{E_a}{k} \left( \frac{1}{T_{use}} - \frac{1}{T_{stress}} \right) \right]$$  (4)

Where;
- $k = $ Boltzmann’s constant ($8.617 \times 10^{-5}$ in eV/K),
- $E_a$ = activation energy (0.5),
- $T_{use}$ = temperature at normal use condition (°K),
- $T_{stress}$ = temperature at stress (°K)

around 492 (AF). The fabricated circuits were kept in the hot-air oven at 150°C for 48 hours. That is around 32 months of age at normal room temperature (23°C).

The results [S11], [S21] shows that after the accelerated aging test the efficiency is slightly decreased in all the circuits. From the data it has been observed that after applying the aging tests the circuits with via-hole grounds are still stable and the circuit which has been shorted by 400 µm diameter via-hole is more stable as compare to others. A strong variation in return losses at lower frequencies (before aging and after aging) has been observed in case of 800 µm diameters shown in Fig. 14(c). This is due to the some
damage in the via-hole conductor, which was inspected and verified physically.

Fig. 14. Measured return loss $|S_{11}|$ and insertion loss $|S_{21}|$ of via-hole (before aging red-star) (after aging blue-circles) (a) 200µm diameter (b) 400µm diameter (c) 800µm diameter

Conclusion

The short circuit (RF grounding) effect of the via-hole is varied when the diameter of the via-hole is changed in the entire frequency range. No effect on the quantity of the via-holes was observed. In thru-line shorted no effect observed due to the change in position of the via-hole. In shorted-stub like design the position of the via-hole is very important, the shorted position and the position offset have a very strong effect on the behavior of the circuit. If the circuits are carefully designed and the through conduct is applied properly then for grounding one via-hole is also sufficient. However, multiple via-holes can be employed for RF grounding for a wider microstrip transmission line. Furthermore, from the experimental data of the accelerated aging test it was observed that the performance of the via-holes as RF grounds is very stable over a long period of time.

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