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Improved Probing Reliability in Antenna-on-Chip Measurements

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Abstract—Antenna-on-chip (AoC) measurements are mostly performed with on-wafer probes. The connection between the probe tips and antenna under test (AUT) plays a crucial role in influencing the measurement reliability. A tilted probe or a non-planarly packaged AoC can result in floating pin(s) during the landing process of the probe. We have measured the behavior of the input reflection coefficient when a ground-signal-ground (GSG) probe touches a SHORT calibration standard and the possible contact states are modelled, simulated, and compared with measurements. The analysis demonstrates that the probe will radiate as an antenna, which will make it almost impossible to determine the real AoC characteristics. To improve the probing reliability, it is necessary to determine a reference force to be applied to the AUT. We recommend adding an on-chip SHORT to be integrated with the AoC, which can be aligned with the test pads.

Index Terms—Antenna-on-Chip (AoC), calibration accuracy, probe radiation, millimeter-wave antenna measurements, millimeter-wave IC measurements.

I. INTRODUCTION

The increasing requirements for high-speed data wireless communication, automotive radar, and imaging applications motivate the spectrum shift towards millimeter-wave (mm-wave) frequencies. (Bi-)CMOS technologies supply a platform to implement these applications owing to their low cost and high transistor density. Moreover, mm-wave antennas can be integrated with (Bi-)CMOS and achieve competitive performances, see, e.g. [1]–[6].

However, on-chip antennas cannot be characterized in the usual manner, i.e., by a connectorized measurement in an anechoic chamber [7], [8]. Instead, the antenna needs to be connected using on-wafer probes, which are widely used to determine the performance of integrated circuits (ICs). The probe-based antenna measurement setup was first proposed in [9] and this concept is now more commonly used to determine the characteristics of mm-wave antenna-in-package (AiP) and antenna-on-chip (AoC) configurations [10]–[12]. Subsequently, 3D radiation pattern and robotically-controlled measurement setups have been introduced in [13]–[16]. In addition, near-field mm-wave measurement setups have been proposed in [17]–[19].

An in-house designed millimeter wave anechoic chamber provides an automated probe station [20]. In this setup, systematic errors, cable and the probe itself can be de-embedded using a planar calibration substrate [21]. However, as shown in [22], not all probe parasitics can be calibrated out. Moreover, the calibration process is critical where several steps have to be taken to complete the sequence. One of the important steps is to make sure that all probe pins are correctly landed on the device-under-test (DUT). However, for a somewhat tilted probe or packaged on-chip antenna, problems can arise to correctly land the probe as not all pins may touch simultaneously, see Fig. 1. As a result, the probe will radiate like an antenna due to the coupling between the probe tip and the substrate. This reduces the accuracy and reliability of the calibration and AUT measurements due to the imperceptible floating pin(s). More force could solve this problem, but too much force will damage the probe. To determine the reference force to be applied to the AUT, we propose to use a low-cost solution with an on-chip SHORT to be integrated with the AoC. This solution does not add cost, is easy to integrate, and can be commonly used for different probe types, like GSG, SGS, GSSG, and GSGSG. In this paper, we will investigate the effectiveness of such a solution.

Fig. 1. Possible reasons for causing non-planarity. (a) Tilted probe tip. (b) AoC packaging using non-planar adhesive.

This paper is organized as follows: Section II describes the measurement problem statement when probing a SHORT calibration standard. Section III presents the simulation results with floating pin(s) and analyzes the possible process. An on-chip SHORT is proposed for improving the probing reliability in Section IV.

II. MEASUREMENT PROBLEM STATEMENT

A. Test on-wafer probe

The cross-section of a typical GSG probe (Picobprobe RVP type: 67A-GSG-200-RVP [23]) and its probe tips are shown in Fig. 2 (a). The signal propagates through a sub-miniature coaxial cable of the probe through the RF connector interface. At the end of coaxial cable, a co-planar waveguide (CPW) is
attached. The tapered CPW line is adjusted to fit the pitch of the contact pads on a chip. When the probe is not connected (Air OPEN), we will observe a capacitive behavior, whereas a probe that is landed on a SHORT standard will show an inductive behavior, as illustrated in Fig. 2 (b).

![Fig. 2. (a) Cross-sectional view of the test RVP probe and landing on a SHORT standard. (b) The equivalent capacitive and inductive behavior in case of an OPEN and SHORT.](image)

**B. Measurement setup and results**

The schematic measurement setup is illustrated in Fig. 3 (a), which shows the probe connected to Port 1 of the VNA (Agilent PNA E8361A) via a coaxial cable. The Picoprobe is mounted on an automated probe station to land on the SHORT on the CS-5 calibration substrate, which is shown in Fig. 3 (b). The probing process is controlled accurately with a minimum movement of 1 μm in each direction.

To investigate the intrinsic behavior of the probe and to remove the interference from the long cable, a TC-CK-185 calibration kit is used to move the reference plane to the connector of the on-wafer probe. Afterwards, the cable is screwed onto the probe connector while the probe tips are still in the air. Due to the insertion loss of the probe, the measured reflection coefficient drops from 0 dB to -2.5 dB, as shown in Fig. 4 for OPEN (black curve). Besides, the reflection coefficient shows a ± 1 dB ripple around an average value of -2.5 dB starting from 54 GHz. This is most likely caused by the bent shape of this type of probe, which is close to 90°.

The probe tips are moved to the top of the SHORT standard and lowered slowly with 1 μm steps. The lowering process can be divided into three stages between the OPEN and CS-5 SHORT, see Fig. 4. The first stage occurs when the probe tip just touches the surface of CS-5 SHORT, the entire curve of the amplitude drops around 4 dB to -6 dB with ripples. With more force to lower the probe, the second stage occurs, which shows that the reflection coefficient drops to the minimum value around -10 dB. This is not the characteristic of a SHORT, so more force is applied to lower the probe to the third stage, where the curve goes up to around -4 dB. In the final step, the reflection coefficient returns to -2.5 dB similar to the case of Air OPEN, but with the ripples in the opposite direction, which represents the expected SHORT behavior. However, the observed sequence of the entire transition, notably the decrease of the amplitude, cannot be explained by tuning the capacitance $C_{open}$ or the inductance $L_{short}$.

![Fig. 3. (a) Measurement setup in the millimeter-wave anechoic chamber. (b) Photo when probing the SHORT standard.](image)

![Fig. 4. Measured reflection coefficients with probing started from the air OPEN case and moving to the SHORT standard on the calibration substrate gradually.](image)

To further understand every stage of the probing process, the pertaining input impedance is also plotted in terms of the real and imaginary part. Taking the real part of the case Air OPEN as an example in Fig. 5 (a), the peak occurs at five different frequencies, i.e., at 50.34 GHz, 53.66 GHz, 57.01 GHz, 60.43 GHz, and 63.79 GHz. This periodic behavior is a result of the length of the probe of around 5 cm from the reference plane to the probe tip, taking into account the permittivity of Teflon ($\varepsilon_r = 2$ to 3), the dielectric used inside the probe’s coaxial cable. Observing the transition from Air OPEN to CS-5 SHORT, the input impedance shows a U-shaped transition. First, the magnitude is reduced towards 150 Ω at the same frequency. In the second and third stage, the peaks shift to the frequencies of the CS-5 SHORT case and start to increase towards the level obtained with the CS-5 SHORT.
III. PROBE RADIATION DUE TO FLOATING PIN(S)

Considering the probing process, it is very likely that one or two pins make contact at the beginning, the other pin(s) only make contact with the metal bar when further lowering the probe with more force. Based on this assumption, the probing process may follow a procedure where, first, there is no contact (Air OPEN), followed by one-pin contact, two pins contact and, finally, all the three pins contact (SHORT), as shown in Fig. 6. The one-pin contact can be subdivided into two cases, i.e., either a Ground or a Signal pin touching. Two pins contact also has two cases, i.e., Ground and Signal (G&S) and Ground and Ground (G&G) touching. Hence, there are three possible probing sequences, i.e.,

1: S → G & S → G & S & G;
2: G → G & G → G & S & G;
3: G → G & S → G & S & G.

Since a simple equivalent-circuit model is not sufficient to explain the entire transition from Air OPEN to SHORT, a probe model is developed and simulated with CST Microwave Studio [24]. Fig. 7 (a) shows the side view and front view of the probe model (compare to Fig. 3). The characteristic impedance of the coaxial cable is designed to be 50 Ω, with an inner diameter of 0.11 μm, an outer diameter of 0.4 μm, and a Teflon dielectric (εr = 2.2). The loss tangent of Teflon is set to 0.007 to add the necessary insertion loss such that the reflection coefficient of Air OPEN is around -2 dB with few ripples similar to the measurement in Fig. 4. The probe tip is modeled as a CPW line connected to the coaxial cable. The SHORT standard is located beneath the probe tip. It is modeled as a metal strip of 600 × 100 × 17 μm3. Two scenarios are considered here, one where the SHORT is positioned on a substrate and one where the substrate is omitted to approximate the ideal lumped-element SHORT with minimum influence from the environment. The one-pin contact for the latter case is shown as an example in Fig. 7 (a); other possible states also use this configuration. The simulated reflection coefficients for the six possible states between Air OPEN and SHORT are provided in Fig. 8 (a). The results for all the possible states only exhibit slight differences of less than 1 dB and do not match the measured results shown in Fig. 4. Hence, this model does not explain the measurements.

In the second scenario the SHORT is located on an alumina substrate (εr = 9.8, tan δ = 0.0004) shown in Fig. 7 (b), where the dimensions of the substrate model are 2000 × 2000 × 635 μm3. By adding the substrate, Fig. 8 (b), we observe a behavior that is quite similar to the measurements of Fig. 4. Especially the one Signal pin case, exhibiting a minimum reflection coefficient of around -9 dB, is now comparable to the measured values from Section II. The related input impedances of these six possible contacts are plotted in Fig. 9. From the simulation results, we observe that only probing sequence 3, i.e. G → G & S → G & S & G, satisfies the U-shaped character from Fig. 5, which has a similar amplitude and resonance-frequency behavior.
Fig. 9. The real (a) and imaginary part (b) of the input impedance of the six states after adding the alumina substrate.

From the differences, i.e., one Signal pin touching with and without substrate, as shown in Fig. 8, we can conclude that a key role is played by the coupling with the substrate which creates the U-shaped behavior in the input impedance. To further explain this effect, the electric field lines of the one Signal pin contact with and without the alumina substrate is shown in Fig. 10. In the left drawing without substrate, the metal becomes part of the signal line. However, the limited size of the metal restricts most of the electric field to the gap between the metal bar and Ground pins. Only a small fraction of the electric fields can radiate from the edge of the metal to the Ground pins. After adding the substrate, the electric field couples into the alumina. Hence, the energy is not only restricted to the gap, and more energy will radiate from the surface of the substrate into free space.

The simulated gain patterns of these two cases are shown in Fig. 11. Due to the mirror symmetry of the GSG probe, the x-z plane also indicates a symmetrical radiation pattern. The simulation with the substrate has a 15 dB higher gain than the one without substrate at broadside. In the y-z plane, the presence of the probe results in a multi-ripple radiation pattern and the maximum gain reaches 1.74 dBi when the substrate is presented. The radiation pattern without substrate has only around 4.5% radiation efficiency at 60 GHz in simulation, while the other one with the substrate can reach quite high efficiency, about 60%, a behavior similar to a radiating antenna.

The simulation gain patterns of the two cases at 60 GHz in Fig. 10. (a) x-z plane. (b) y-z plane.

V. CONCLUSION AND RECOMMENDATION

The tilt of the probe tip or non-planarly packaged AoCs may cause floating pins during the landing of a probe on the AUT. The radiation behavior due to floating pins will deteriorate the calibration accuracy and cause unexpected radiation behavior during an AoC measurement. To improve the probing reliability for mm-wave AoC characterization, we suggest using an on-chip SHORT, which is to be integrated with the AoC under test. The idea comes from an on-chip SHORT-OPEN-LOAD (SOL) in Fig. 12 (a), which are originally used for calibration structures. The authors test the on-chip SHORT to determine how much force is required to achieve a complete touch state before probing the AUT. This solution does not add further cost, it is easy to integrate on the top layer, and can be commonly used for any type of probe, like GSG, SGS, GSSG, and GSGSG. This on-chip SHORT could be aligned with the contact pads as a separate structure, see option 1 in Fig. 12 (b). Also, ground pads are necessary to connect with a real ground plane on the top layer, which can be reused as an on-chip SHORT by just adding two more contact pads with the same pitch, i.e., option 2. Compared to the visual inspection of a high-resolution micro-camera, the on-chip SHORT also provides a good electric reference using reflection analysis.

Fig. 10. The electric field lines when one signal pin touches the metal bar with (right) and without (left) substrate. (a) x-z plane. (b) y-z plane.

Fig. 11. (a) An AoC with integrated on-chip SOL calibration structure. (b) An on-chip SHORT is recommended with two optional alignments.
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