Multiport Investigation of the Coupling of High-Impedance Probes

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***Abstract*—We used an on-wafer measurement technique that combines two- and three-port frequency-domain mismatch corrections in order to characterize the influence of a high-impedance probe on a device under test. The procedure quantifies the probe's load of the circuit, and the coupling between the probe and the device.**

***Index Terms*—High-impedance probes (HIPs), invasiveness, three-port measurements.**

I. Introduction

The increased integration and operational speed of electronic circuits require a new approach to on-wafer metrology. Measurements at internal nodes of the integrated circuits or imaging of the circuit voltage/current maps with active and passive probes are becoming an important part of this new approach. We have recently developed a calibration technique for passive high-impedance probe (HIP) characterization [1], [2].

Here, we try to address one of the most complicated problems of probing metrology, namely the characterization of the influence of the probe coupling on the measured device under test (DUT) including the perturbation of the measured circuit performance due to the physical presence of the probe and the coupling to the neighboring active structures. To our knowledge, this investigation was never attempted before. We chose a simple geometry with the HIP introduced in different locations of the device. We used a combination of the previously developed two-port and multiport procedures [3], [4] together with the HIP characterization described in [1].

II. Test Structure

Fig. 1 shows an illustration of the experimental setup used in this study. The devices under test consisted of microstrip access lines with ground pads connected to the ground plane through via holes and a set of coupled lines terminated by different types of resistive and reactive loads. They were built on an alumina substrate of 127-μm thickness, using gold for the conductive parts. The length of the access lines was 250 μm, and the position of the on-wafer calibration reference planes for the device characterization coincided with the dashed line in Fig. 1. The position of the HIP with respect to the DUT is also depicted in

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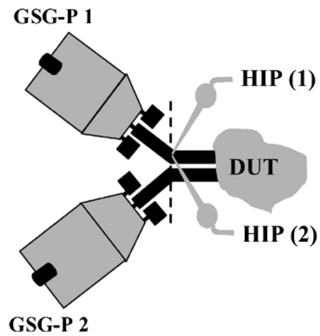

Fig. 1. Sketch of the microstrip line artifacts used as devices in the experiment. The dashed line shows the position of the final on-wafer calibration reference plane. GSG-P1 and GSG-P2 are the ground-signal-ground (GSG) probes. HIP (1) and HIP (2) represent the position of the HIP in the two illustrated positions.

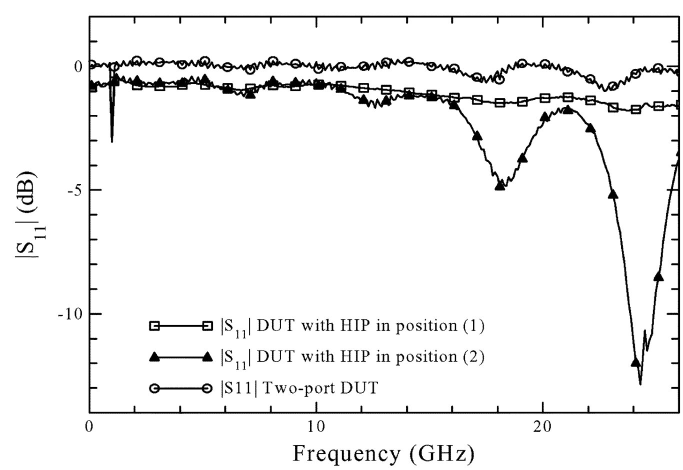

Fig. 2. Magnitude of S_{11} for the open-ended coupled lines without the HIP (open circles) and with the HIP in position (1) (open squares), and position (2) (solid triangles).

Fig. 1. In position (1), the HIP is off to the side of the circuit and the influence is expected to be less intrusive. In position (2), the HIP crosses the device lines and we expect stronger influence on the DUT. Since we used a commercial HIP with a built-in 950-Ω resistor at the probe tip, the HIP dimensions were not exactly known. The angle of the probe over the test lines was approximately 45° and the length of the tip was about 1 mm with another 2-mm length of the tip support.

Fig. 2 shows a measurement of $|S_{11}|$ as a function of frequency for an open-ended coupled line DUT with the HIP in positions (1) (open square symbols) and (2) (solid triangles). Fig. 2 also compares these measurements to $|S_{11}|$ in the absence of the HIP (open circles). The open-ended coupled lines were 100-μm wide, 500-μm long, and separated by a gap of 100 μm. The $|S_{11}|$ data in Fig. 2 are calibrated at the on-wafer reference planes. The data in Fig. 2 indicate a significant effect on the scattering parameters due to the HIP connected in position (2).

III. Multiport Measurements

We used the four-port system described in [4]. The system consists of a conventional two-port vector network analyzer (VNA), and six computer-controlled broadband coaxial switches that connect the ports of the VNA to different probes. The switches are arranged so that the probes not connected to the ports of the VNA are terminated in nominally 50-Ω loads.

We began with a conventional first-tier four-port network-analyzer calibration at a set of coaxial reference planes, using the method described in [4]. This calibration accounts for imperfections in the measurement hardware, including its imperfect terminations. Next, we used this four-port calibration at the coaxial reference planes to characterize the three-port consisting of the GSG probes, the on-wafer DUT, and the HIP shown in Fig. 1.

However, our goal was not to characterize the GSG/DUT/HIP combination at the coaxial reference planes, but rather to characterize the DUT and the HIP separately at the on-wafer reference planes shown by dashed lines in Fig. 1. To accomplish this, we determined the scattering parameters of the two GSG probes and the HIP in a separate two-tier calibration experiment. The first-tier LRM calibration was at a coaxial reference plane and a second-tier calibration was done at an on-wafer reference plane in the microstrip lines. We established the on-wafer reference planes with a multiline thru-reflect-line (TRL) calibration [5] and reference impedance correction [6] and [7]. The calibration artifacts were fabricated on the same alumina substrate as the DUTs. The structures include microstrip transmission lines 20.195-, 7.065-, 3.7-, and 2.635-mm long, a 0.5-mm-long microstrip thru line, and a symmetric microstrip line reflect. From this two-tier calibration experiment, we determined the two "error-boxes" corresponding to the S-parameters of our two GSG probes.

We proceeded with measuring the 0.5 mm long microstrip line with a GSG probe at one port and the HIP on the other port. We then used the method described in [1] to deembed the characteristics of the first GSG probe and the 0.5-mm microstrip line from the measurement. This procedure determines the S-parameters of the HIP including the contributions from the 25-μm portion of the open-ended microstrip line, the parasitic capacitance of the open-ended microstrip line, and the HIP itself.

Finally, we measured the DUT as a two-port device at the on-wafer reference planes. The first measurement was performed without the HIP whereas the following measurements include the HIP in positions (1) and (2) as a three-port device.

IV. Coupling and Invasiveness of the High-Impedance Probe

The above measurements provide the complete set of experimental data necessary to determine the influence of HIP. We proceed with comparing the three-port measurements with the combination of the two two-port HIP and DUT scattering parameters. Any differences between the compared sets of data are due to the interaction between HIP and DUT. We introduced a simple, first-order circuit model shown in Fig. 3 in order to quantify this interaction. The notation of the matrices is defined in the figure caption. The additional three-port circuit labeled "CPL" represents the coupling of the HIP. We determined the "CPL" circuit from our three-port measurement of the DUT and high-impedance-probe combination. To do this, we subtracted the two-port scattering parameters of the DUT and the HIP from the measured three-port scattering parameters of the entire circuit by converting the measured S-parameter matrices to admittance parameters and converting the result, after the subtraction, back to S-parameter matrix format.

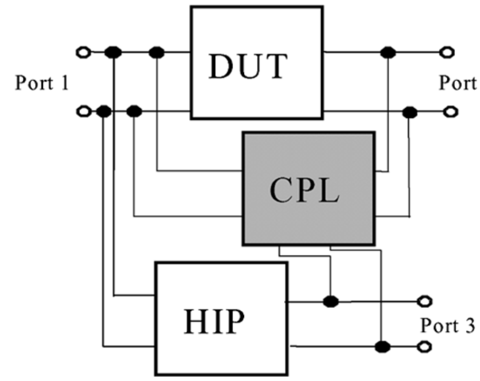

Fig. 3. Circuit model for the characterization of the HIP probe's influence on the measured DUT. The CPL three-port characterizes the additional influence of the probe, as described in the text.

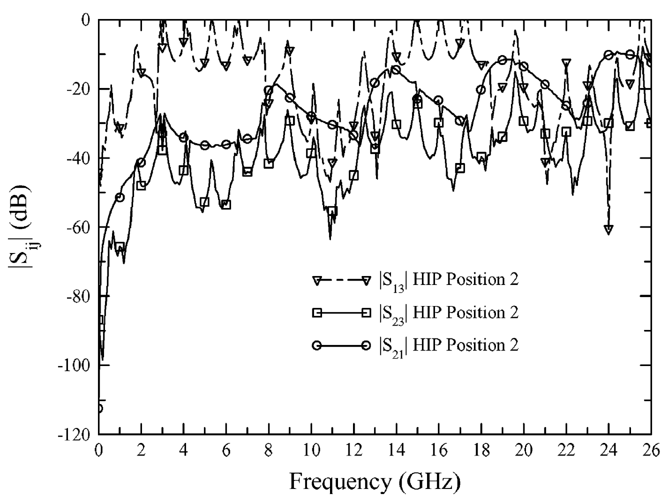

Fig. 4. Magnitude of S_{12}, S_{13}, and S_{23} of the "CPL" coupling matrix elements in the presence of the HIP, which is in position (2).

The CPL S-parameter matrix encompasses the contributions from both the coupling and the invasiveness (load) of the probe. We discuss both aspects separately below.

A. Coupling

Fig. 4 shows, as an example, the calculated magnitudes of the coupling terms S_{21}, S_{13}, and S_{32} of the "CPL" scattering matrix for the HIP inserted in position (2). The coupling between ports 1 and 2, and ports 2 and 3 is negligible (on the order of -20 dB over the whole frequency range).

This is not the case for the magnitude of the S_{13} parameter. The frequency response of $|S_{13}|$ shows a strong interaction between ports 1 and 3. Intuitively, we would expect with the HIP

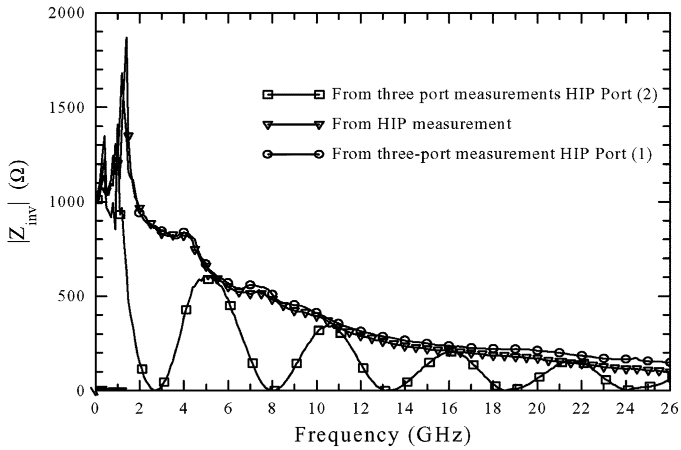

Fig. 5. Magnitude of the load impedance. The line with open circle symbols represent the data obtained from three-port measurement for HIP in position (1), with square symbols from the three-port measurements for HIP in position (2), and with triangles represent data obtained from the high-impedance-probe characterization procedure.

in position (2), an increased coupling between ports 1 and 2. Instead, there is a strong additional signal at the output of the HIP produced by the crosstalk between the tip of the probe and the crossed line of the measured device.

A similar calculation for the high impedance probe in position (1) (not shown here) indicates that the coupling between ports 1 and 3 is negligible. Here, the combination of the two-port scattering matrices of the DUT and the HIP is sufficient to fully characterize the system, without invoking the CPL circuit.

Therefore, this simple analysis already allows revealing the coupling channels.

B. Load Impedance

In this section, we examine the impedance the circuit is loaded with by the presence of the HIP. This load impedance can change the performance of the circuit and therefore plays an important role in practical applications.

There are several approaches for measuring the load (invasiveness) introduced by the probe to the device. Recently, we developed a procedure to quantify the invasiveness of the HIPs with the aid of two-port measurements [8]. We also investigated, in detail, the repeatability and the relation of the load impedance to the measured parameters of the HIP.

Here, we use the three-port measurements to estimate the invasiveness in the presence of the coupling. The load impedance $Z_{\rm inv}$ is obtained from the reflection coefficient measured at one of the DUT ports with and without the HIP present. Fig. 5 shows the magnitude of the impedance $Z_{\rm inv}$ as measured on the device consisting of open coupled-lines at port 1. There is an excellent agreement between the three-port measurements and the independent technique introduced in [8] for the HIP in position (1). In order to account for different microwave device structures, the impedance was corrected for the estimated fringe capacitance $C_{\rm fr} = 25$ fF at the end of the microstrip line.

In [8], we showed that the load impedance of the HIP is closely related to the measured probe's scattering matrix parameters. Based on our three-port measurements we can further conclude that when the coupling is small [HIP in position (1)], the probe's characterization provides a good general estimate of the load impedance in the required frequency range. However, as shown in Fig. 5 (square symbols), when the coupling is stronger [HIP in position (2)], the estimate of the load impedance in such an environment is significantly compromised, and gives nonphysical results.

V. Conclusion

We presented a study with intent to address the important problem of the influence of a probe on the properties of the measured device. We showed that simultaneous two- and three-port measurements provide reasonable information about the coupling. We demonstrated this on a commercially available HIP. We showed that the full two-port characterization of the HIP gives the required information about the probe's behavior. This information can prove to be useful in the development of coupling and invasiveness models for contact and noncontact high-frequency nanoscale metrology probes.

Acknowledgment

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