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An Active Interferometric Method for Extreme Impedance On-Wafer Device Measurements

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***Abstract*—Nano-scale devices and high-power transistors present extreme impedances, which are far removed from the 50-Ω reference impedance of conventional test equipment, resulting in a reduction in the measurement sensitivity as compared with impedances close to the reference impedance. This letter describes a novel method based on active interferometry to increase the measurement sensitivity of a vector network analyzer for measuring such extreme impedances, using only a single coupler. The theory of the method is explained with supporting simulation. An interferometry-based method is demonstrated for the first time with on-wafer measurements, resulting in an improved measurement sensitivity for extreme impedance device characterization of up to 9%.**

***Index Terms*—Calibration, extreme impedance measurement, interferometry, vector network analyzer (VNA).**

I. INTRODUCTION

THE demand for characterizing extreme impedance devices in numerous applications has been rapidly growing. Examples of these devices are nanowires, carbon nanotubes, and graphene materials, which have impedances on the order of the quantum resistance (≈13 kΩ) [1], [2]. These impedances are "extremely high" as compared with the 50-Ω reference impedance of a vector network analyzer (VNA). When measuring the S-parameters of these devices, a large portion of the electromagnetic (EM) waves are reflected back to the test ports. Conventional VNAs have poor sensitivity for extreme impedance device characterization, due to inadequate measurement resolution of high reflection coefficients [3].

To date, several interferometry-based methods have been introduced addressing this issue. The interferometry principle uses the superposition of the reflected wave from an extreme impedance device under test (DUT) and a wave generated from a controlled source or reflected from a known reference impedance, called the cancelation wave. The aim is for the two waves to combine destructively and cancel the reflected wave (b_1) transmitted toward the VNA's receiver. These results in a measurement close to 50 Ω, where the equipment has optimum measurement sensitivity.

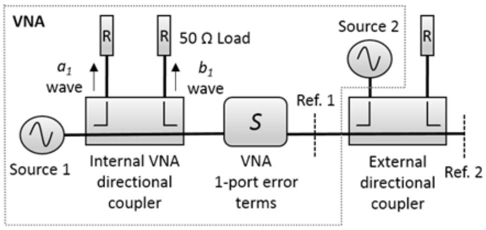

Fig. 1. Schematic of the simulation test setup. Sources 1 and 2 provide the excitation and cancelation waves for the DUT, respectively.

Randus and Hoffmann [4] introduced a passive interferometric method using a VNA, which used the reflection of known reference impedance as the cancelation wave. Other research groups [5], [6] presented different setups based on the same principle but using a set of reference impedances or an impedance tuner as a reference impedance. In [7], an active interferometric method was introduced that uses an injected signal, controlled by an I/Q mixer connected to a low-noise amplifier, for the cancelation of the reflection signal. In [8], an evaluation of the measurement resolution of a VNA, based on the setup of [7], was presented but only results for impedances up to 500 Ω were demonstrated. Both the passive and active methods introduced, require complicated measurement setups, potentially increasing the measurement uncertainty. Moreover, the components used in the setups often limit the frequency range capability of the methods within their bandwidths.

In this letter, a new approach that is based on a direct microwave active interferometric method is presented. This method requires only the use of a single coupler and can significantly improve the measurement sensitivity of a VNA for extreme impedance devices in the mΩ or kΩ range. The principal idea of the proposed method is to generate the cancelation wave, for the DUT's reflection wave, using the second source of the VNA. In this letter, the method is demonstrated using simulation and measurement data for high-impedance devices.

II. METHODOLOGY

The schematic used for the development and simulation of this technique is shown in Fig. 1. The internal VNA directional coupler is used for the separation of the excitation (a) and reflected (b) waves within the VNA and the external directional coupler is used to inject a signal to the DUT's reflected wave. To describe approximately the behavior of a conventional VNA, the one-port error

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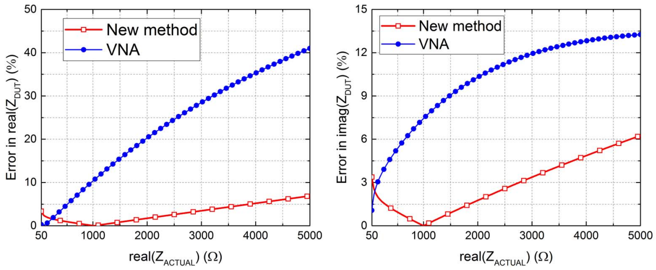

Fig. 2. Simulation of the calculated load resistance and reactance of an ideal resistor, varying between 50 Ω to 5 kΩ, using the proposed method, labeled "New method," and a conventional VNA, labeled "VNA."

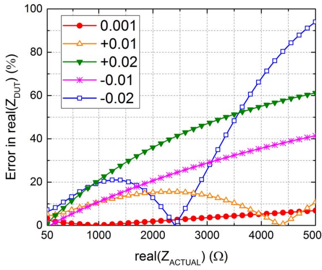

Fig. 3. Simulation of the calculated DUT resistance using the proposed method for different values obtained from $\Gamma_{50\Omega} - \Gamma_{EIS}$.

terms (directivity, source match, and tracking error terms) of a Keysight N5247A PNA-X microwave network analyzer were included in the simulation schematic, as the S-parameter block between the two couplers, as was done in [8]. The error terms were obtained from a short-open-load (SOL) calibration performed at one of the PNA-X's ports, labeled as Ref. 1 (reference plane 1) in Fig. 1. Ref. 2 (reference plane 2) indicates the DUT's position in the circuit and the reference plane of the proposed method.

An SOL calibration is performed with source 2 turned OFF. Then, an extreme impedance standard (EIS), which has a known high value of reflection coefficient magnitude, is measured with source 2 turned ON. The magnitude and phase of source 2 are adjusted to cancel the reflected wave of the EIS. For the impedance calculation of the DUT, the following equation is used:

$$\begin{gathered} Z_{\mathrm{DUT}} = \frac{Z_0[1+(\Gamma+\Gamma_{\mathrm{REF}})]}{[1-(\Gamma+\Gamma_{\mathrm{REF}})]} \\ \Gamma_{\mathrm{DUT}} = \Gamma + \Gamma_{\mathrm{REF}} \end{gathered} \tag{1}$$

where Z_{DUT} and Γ_{DUT} are the impedance and reflection coefficients of the extreme impedance DUT, respectively, Z_0 is the characteristic impedance of the measurement system, Γ is the measured reflection coefficient of the DUT with the cancelation wave present, and Γ_{REF} is the known reflection coefficient of the EIS.

A simulation using Keysight's ADS was performed at a single frequency (1.8 GHz), to compare the impedance characterization of a resistor using a VNA system only (at Ref. 1 in Fig. 1) and this method (at Ref. 2). An ideal resistor ($Z = R + j0$) of 1 kΩ was used as the EIS in the simulation. In addition, an ideal resistor varying between 50 Ω to 5 kΩ was used as the DUT. In order to define an error range in the calculated Z_{DUT} compared with its actual value (Z_{ACTUAL}), the relative variation of the impedance to the reflection coefficient variation was used [9]: $\partial Z_{\mathrm{DUT}}/Z_{\mathrm{DUT}} = [(Z_{\mathrm{DUT}} + Z_0)^2/2Z_{\mathrm{DUT}}Z_0]\partial\Gamma$, where $\partial\Gamma$ is the difference between the actual reflection coefficient of the DUT and Γ_{DUT}. Fig. 2 shows the calculated error in Z_{DUT}. Close to 50 Ω, the VNA introduces a smaller error compared with the proposed method due to its high measurement sensitivity in this range. However, moving toward the extreme impedance region the proposed method reduces significantly the error in the calculation of the Z_{DUT} with optimum sensitivity at 1 kΩ, which is the EIS's impedance.

To investigate the effect of an imperfect cancelation of the EIS's reflection on the proposed method, a simulation was performed to achieve different values for $\Gamma_{50\Omega} - \Gamma_{\mathrm{EIS}}$, where $\Gamma_{50\Omega}$ is the calibrated reflection coefficient of a 50-Ω load with source 2 turned OFF and Γ_{EIS} is the calibrated reflection coefficient of the EIS with source 2 present. Fig. 3 shows the calculated error in the obtained resistance of an ideal resistor using the proposed method varying between 50 Ω to 5 kΩ. The results indicate that, in order to achieve high accuracy, the difference between the two reflection coefficients should be as small as possible. Therefore, the following equations must be satisfied, with the value of 0.001 selected to ensure an error below 10% in the calculation of Z_{DUT} up to 5 kΩ:

$$\begin{gathered} \mathrm{real}(\Gamma_{50\Omega} - \Gamma_{\mathrm{EIS}}) \leq |0.001| \\ \mathrm{imag}(\Gamma_{50\Omega} - \Gamma_{\mathrm{EIS}}) \leq |0.001| \end{gathered} \tag{2}$$

Since the proposed method relies on knowing Γ_{REF}, it is critical that the EIS has a reflection coefficient that the VNA can characterize accurately. Therefore, it is recommended that $\Gamma_{\mathrm{REF}} \leq |0.5|$ where the VNA can characterize it within approximately an error range of 3%. However, the higher Γ_{REF} is, the better the cancelation of the DUT's reflection will be. This will result in a measurement closer to 50 Ω, where the VNA has higher measurement resolution.

III. EXPERIMENT AND RESULTS

Measurements of two extreme impedance devices were performed at 1.8 GHz using the proposed technique. For the S-parameter measurements, a Keysight N5247A PNA-X with option 088 was used. Option 088 enables the control of the relative phase and power between the two internal sources of the analyzer [10]. The devices measured were planar offset opens based on a coplanar waveguide design, with a conductor width of 100 μm, separated by 66 μm from the ground lines. The conductors consist of a 500-nm-thick gold (Au) layer and a 25-nm-thick titanium (Ti) layer, for adhesion purposes, placed on a 400-μm gallium arsenide (GaAs) dielectric substrate. For the measurement an MPI Corporation TS-2000 SE probe station and two MPI Titan 26 GHz ground-signal-ground (GSG) probes with a 150-μm pitch were used.

The measurement setup is shown in Fig. 4, including the PNA-X and a single directional coupler. Port 1 (source 1) and port 4 (source 2) of the PNA-X are used to provide the excitation and cancelation waves, respectively. In order

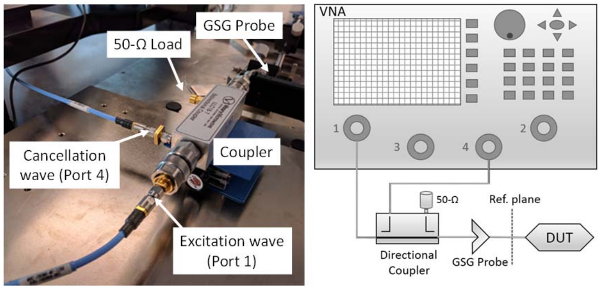

Fig. 4. Photograph and schematic of the measurement setup.

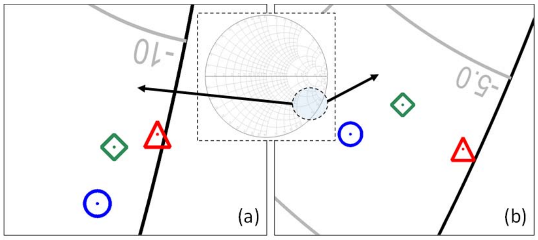

Fig. 5. Measured and simulated reflection coefficient of (a) 1.14 and (b) 2.14 mm offset opens. The circle, diamond, and triangle symbols represent the reflection coefficients measured using the PNA-X only, using the proposed method and the EM simulation of the devices, respectively.

for the cancelation wave to overcome the 30-dB coupling of the coupler used, within the power level range of the VNA sources (-30 to $+10$ dBm), the input power of port 1 was set to -30 dBm. This measurement setup provides phase coherence between the two internal sources of the PNA-X and eliminates the need for external equipment. A power calibration is performed at the end of the cable on port 4 and then a SOL-thru calibration is carried out at the probe tips of the GSG probes. After the calibration has been completed, the cable from port 4 is connected to the directional coupler (toward port 1), which was terminated with a 50-Ω load during the calibration.

An offset open with the length of 0.514 mm was used as the EIS, and an EM simulation was performed to obtain its reflection coefficient. The EM simulation of the EIS and the DUTs were implemented in *em* from Sonnet Software. Two offset opens were measured, with the lengths of 1.14 and 2.14 mm, as they are expected to generate a reflection wave with a phase close to the one of the EIS at this frequency. Hence, the cancelation wave would minimize the reflected waves of these devices appropriately, toward 50 Ω.

Two sets of measurements were performed on the two DUTs, to have a measurement comparison between the proposed method and a conventional measurement. The first measurement was performed with source 2 turned OFF to obtain a measurement using the PNA-X only, and the second measurement was performed with source 2 turned ON to utilize the proposed method. The measured and simulated reflection coefficients of the devices are shown on a close-up of a Smith chart in Fig. 5, and the impedance analysis is presented in Table I. Comparing with the simulation of the DUTs, the magnitude of the impedances obtained through the proposed method has 8.8% and 2.4% better agreement compared with the results obtained using the conventional measurement, for the 1.14 and 2.14 mm offset opens, respectively. In terms of the phase of the impedances obtained, there is no change in the agreement for the 1.14-mm device, whereas for the 2.14-mm device the proposed method resulted in an increased agreement by 2%. Overall, a higher increase in the agreement percentage is achieved for the 1.14-mm device as compared with the 2.14 mm, because the cancelation wave, optimized for the EIS, resulted in a measurement with a lower reflection coefficient. This is due to the 1.14-mm device introducing a reflection coefficient with phase closer to the one of the EIS at this frequency.

TABLE I
SIMULATED AND MEASURED IMPEDANCES OF THE DUTS

DUT (open-circuit lengths)	**1.14 mm**	**2.14 mm**
$\Gamma_{50\Omega} - \Gamma_{EIS}$	real = 0.0005, imag = 0.0003	
Z_{DUT} (Ω) from EM simulation	|430.5|, -89.4°	|229.8|, -89.2°
Z_{DUT} (Ω) from proposed method	|418.3|, -86.4°	|233.2|, -85°
Z_{DUT} (Ω) from PNA-X only	|384.3|, -86.4°	|221|, -83.3°

IV. CONCLUSION

This letter has presented a novel method for high-frequency extreme impedance device measurements based on using a PNA-X and a directional coupler only. Compared with conventional measurements, this method increases the measurement sensitivity of the VNA for the impedance characterization of highly reflective devices at microwave frequencies. Simulated results have been presented to validate the method, accompanied with on-wafer measured data of two devices. The agreement between simulated and measured values shows that the proposed technique has been successful.

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