Impact of Substrate Parameters on Sheet Resistance Measurements using iSiPDR at 10 GHz

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***Abstract*—This manuscript investigates the impact of substrate properties on sheet resistance measurements using a 10 GHz scanner employing an inverted Single Post Dielectric Resonator. Our study focuses on carbon coatings deposited on quartz wafers, utilizing retro-modelling to predict the effects of variations in permittivity and thickness of the substrate. Through experimental analysis and predictive modeling, we elucidate the substrate's influence on sheet resistance, providing practical guidelines for thin film measurements on different substrates.**

***Keywords*—materials measurement, surface properties, iSiPDR, carbon coating, substrates**

I. INTRODUCTION

Microwave measurements employing resonance techniques offer exceptional precision in material characterization. They also provide scientific knowledge about novel materials - also such materials that are not typically used at microwaves, for example, battery materials. This stimulates the increasing interest of material scientists in the use of microwave characterization techniques for materials. However, for many users who are not microwave engineers by education, the intricate interplay between a sample and the microwave measurement process remains a non-trivial aspect to comprehend. It becomes even more challenging in the case of multi-layer samples, such as thin film battery materials deposited on a substrate.

This study focuses on a specialized variant of the Single-Post Dielectric Resonator (SiPDR) [1] known as the 2D inverted Single-Post Dielectric Resonator (iSiPDR) [2]. The iSiPDR is uniquely configured for contactless scanning over resistive films through an inverted resonator head. As part of the I4Bags project [3], test samples featuring carbon coatings deposited on quartz wafers are fabricated. The principal objective is to investigate the intricate influence of the quartz substrate (and the user's knowledge of the substrate parameters, or the lack of such knowledge) on the extraction of sheet resistance R_s of the carbon coatings. A practical question is, to what extent the 10 GHz iSiPDR can serve to explore the electrical properties of the carbon coatings, if isolated substrate (without the coating) is not available for a reference measurement and has not been previously characterized.

Section II will give insight into the measurement methodology itself, pointing out the differences between the 10 GHz iSiPDR in the scanner and the commrcial stand-alone SiPDR [4]. In Section III, we will describe the measurement results and the modeling procedure for manipulating the substrate parameters. Finally, we will conclude in Section IV.

II. METHODOLOGY

A. 10 GHz iSiPDR and SiPDR

The measurement methodology employed in this study primarily focuses on the electrical characterization of materials using a 2D iSiPDR. This resonator is a variant of the Single-Post Dielectric Resonator (SiPDR), originally proposed for the characterization of semiconductor wafers [1][4], and later adapted for use with various materials [5][6]. The SiPDR construction serves as a foundation for the iSiPDR and enables the direct measurement of thin films. SiPDR design is particularly advantageous as it allows for the isolation of the thin film from the substrate, facilitating accurate characterization by minimizing the influence of the substrate on the measurement. In the SiPDR configuration, the sample rests on the metal cavity walls, with its thin layer closing the cavity as at Fig. 1a. To expand the capability of the SiPDR for assessing material parameters across a sample, an inverted resonance head configuration has been implemented (Fig. 1b).

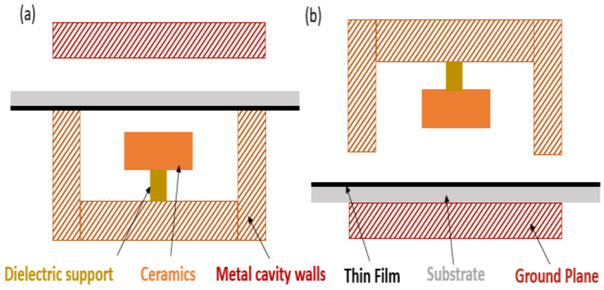

Fig. 1. Schematic diagram of (a) SiPDR and (b) iSiPDR operating at 10 GHz

This adaptation allows for scanning measurements, enabling the characterization of how material parameters change across the sample. The incorporation of the inverted design facilitates the subsequent incorporation of the resonator into a 2D scanning stage. Both the SiPDR and iSiPDR share a common constructional framework. They both feature ceramics are connected to metal cavity walls through dielectric support. This configuration allows for the precise positioning of ceramics within the cavity. While in SiPDR, the sample lies on the metal cavity walls with its thin layer closing the cavity (Fig. 1a), the iSiPDR arrangement involves the sample resting on the ground plane with its substrate (Fig. 1b). The inverted design of the iSiPDR has facilitated its integration into a 2D scanning stage. This advancement allows for surface imaging of samples as large as 100mm x 100mm.

Consequently, the methodology enables the creation of spatial 2D maps of material properties, providing a comprehensive understanding of the electrical characteristics across the sample.

B. Measurement Setup of 10 GHz iSiPDR

The 10 GHz iSiPDR measurement setup is a pivotal component in advancing materials characterization, offering non-destructive and contactless assessment of electrical properties. The measurement procedure comprises crucial steps: initially measuring the iSiPDR with inserted quartz to establish a reference curve for thin film measurements and after that measure sample with carbon coating. Spot measurements are conducted using a Q-Meter [5], generating a family of resonant curves used to extract sheet resistance R_s. The measuring station, illustrated in Fig. 2, comprises a 2D iSiPDR scanner, a dedicated Q-Meter, and a laptop with specialized software for movement operations and material parameter extraction. involves initially determining the substrate thickness, such as in this case quartz with its 0.5 mm thickness. In additional, the range of motion and step size for the resonator head should be specified.

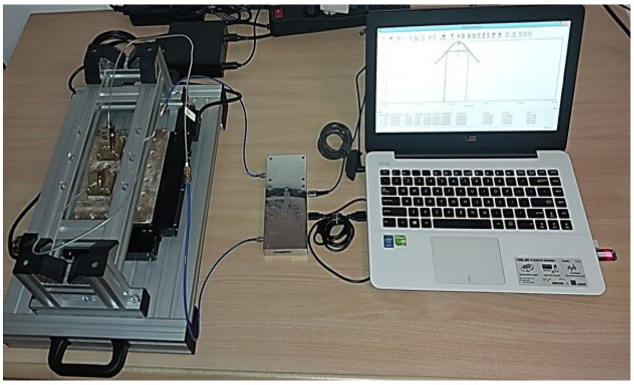

Fig. 2. A measuring station consisting of 10 GHz iSiPDR scanner, Q – meter and laptop with dedicated software

III. RESULTS

To gain insights into the substrate influence on carbon coating sheet resistance (Rs), a series of measurements were conducted using the setup illustrated in Fig. 2. Three distinct measurements were performed: the resonator without a sample, with a quartz wafer (hs = 0.5 mm) serving as a reference substrate, and a carbon coating deposited on the same quartz wafer. The measured values, including the calculated sheet resistance Rs, are presented in Table 1 for air, quartz, and the carbon-coated substrate. Recognizing the challenge of achieving identical carbon coatings with variations in material parameters, a complementary approach utilizing retro-modeling [6] with the QuickWave [7] simulator was employed. A model of the 10 GHz iSiPDR, along with a model object representing a quartz wafer and carbon coating, was prepared. Material parameters for quartz, obtained from 10 GHz Split Post Dielectric Resonator (SPDR) [1][8] measurements, yielded a relative permittivity ε of 4.44 and a loss tangent $tan\delta$ of 1.8E-05.

TABLE I. MEASUREMENTS AND SHEET RESISTANCE EXTRACTED WITH AND WITHOUT REFERENCE SAMPLE

Case	Freq. [GHz]	Q – factor	Sheet resistance R_s
Carbon coatings on Quartz substrate	10.1629	13059.49	—
Ref.: Empty iSiPDR	10.1636	14006.27	33833.5
Ref.: iSiPDR with Quartz	10.1632	14003.81	33915.9

The central focus of the study was to predict the model's response to changes in material parameters, specifically the permittivity of quartz. By introducing a ±10% variation in ε_s, the resulting frequency shifts and q-factor changes were compared with the actual measured values. The findings, detailed in Tab. 2, indicate minimal impact on frequency and q-factor. Consequently, the recalculated R_s for the carbon coating showed only a marginal difference of approximately 0.005%.

TABLE II. EFFECT OF VARIATION PERMITTIVITY VARIATION OF SUBSTRATE ON SHEET RESISTANCE OF MEASURED CARBON COATING

Substrate	Freq. [GHz]	Q – factor	Sheet resistance R_s
$\varepsilon_s = 4.88994$	10.1631	14003.75	33918
$\varepsilon_s = 4.00086$	10.1633	14003.87	33913.9

In contrast, when considering variations in the thickness of the substrate, particularly a ±10% deviation from the 0.5 mm value, a significant difference in the recalculated *Rs* of carbon coatings emerged. This difference amounted to approximately 19.4%, underscoring the substantial impact of substrate thickness on the observed variations in carbon coating sheet resistance. These results underscore the importance of substrate properties, especially thickness, in influencing the electrical characteristics of deposited carbon coatings.

TABLE III. EFFECT OF THICKNESS VARIATION OF SUBSTRATE ON SHEET RESISTANCE OF MEASURED CARBON COATING

Substrate	Freq. [GHz]	Q – factor	Sheet resistance R_s
$h_s = 0.55\ mm$	10.1636	14004.37	41106.3
$h_s = 0.45\ mm$	10.1636	14000.15	27912.5

IV. CONCLUSIONS

In conclusion, our study has revealed that for the considered thin-film battery materials, the choice of the substrate (and accurate knowledge of the substrate’s permittivity) has a minimal impact on the measurement of sheet resistance using iSiPDR at 10 GHz. However, it is crucial to emphasize the significance of accurately determining the substrate thickness during measurements, as it determines the distance between the measured film and the dielectric resonator head, so that even slight variations can lead to a substantial impact on the calculated surface resistance values.

Looking ahead, we aim to further advance this research by exploring the effects of different substrates, while keeping the thin film measurement results consistent. In particular, possibilities of characterizing films deposited on cheaper and easily available substrates, such as glass, will be studied. We shall also extend our work to films of lower sheet resistance, where not only the Q-factor, but also the resonant frequency is influenced by the substrate parameters. By broadening the scope of our investigations, we anticipate uncovering additional nuances that will contribute to the continual improvement of sheet resistance measurement techniques and their broader use in various scientific fields.

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REFERENCES

[1] SiPDR broshure: https://qwed.eu/resonators_sipdr.html

[2] M. Olszewska-Placha, A. Masouras, A. Wieckowski, N. Chotza, and M. Celuch, "Contactless Device for 2D Imaging and Precise Characterisation of Electrical Parameters of Anode Materials for Battery Cells", MIKON 202212-14 Septemeber 2022, Gdansk, Poland

[3] I4Bags project website: https://qwed.eu/i4bags.html

[4] J. Krupka and J. Mazierska “Contactless Measurements of Resistivity of Semiconductor Wafers Employing Single-Post and Split-Post Dielectric-Resonator Techniques” IEEE Transaction on Instrumentation and Measurement, October 2007 doi:10.1109/TIM.2007.903647

[5] M. Celuch, O. Douheret, P. Korpas, R. Michnowski, M. Olszewska-Placha, and J. Rudnicki, "Portable low-cost measurement setup for 2D imaging of organic semiconductors", accepted for IEEE MTT-S IMS 2020, Los Angeles, 21-26 June 2020

[6] L. Nowicki, K. Filak, M. Celuch, M. Zdrojek, M. Olszewska–Placha, and J. Rudnicki, "A Fast Modelling-Based Technique for the Characterization of Graphene-Based Polymer Composites", IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization (NEMO'2023), 29 June 2023

[7] QuickWave Software: https://qwed.eu/quickwave.html

[8] O. Stec, M. Olszewska-Placha, J. Rudnicki, and M.Celuch, "Fast and accurate extraction of complex permittivity from surface imagining with SPDR scanner and hand-held VNAs", 23rd Intl. Conference on Microwaves, Radar and Wireless Communications MIKON-2020, Warsaw, 5-8 October 2020