2D imaging technique for quantitative and qualitative characterisation of high-resistivity GaN semiconductor wafers for light and power electronics

Marzena Olszewska-Placha
QWED Sp. z o.o.
Warsaw, Poland
molszewska@qwed.eu

Ewelina Mozdzynska
Department of Graphene and Materials for Electronics, Lukasiewicz Research Network -IMiP, Warsaw Poland
ewelina.rozbiegala@imif.lukasiewicz.gov.pl

Janusz Rudnicki
QWED Sp. z o.o.
Warsaw, Poland
jrudnicki@qwed.eu

Malgorzata Celuch
QWED Sp. z o.o.
Warsaw, Poland
mceluch@qwed.eu

***Abstract* — In this work an automatic SPDR scanner is applied to 2D surface imaging of electrical parameters of GaN semiconductor wafer. The homogeneity of electrical parameters of GaN template is crucial for light and power electronics allowing for enhancing packaging efficiency and obtaining high quality and repeatability of resulting devices. For the first time, the new 10GHz SPDR scanner is applied to obtain 2D resistivity map of GaN template delivering both, quantitative and qualitative measure of inhomogeneities of the semiconductor structure.**

***Keywords* — material measurement, dielectric resonator, non-destructive testing, 2D imaging, GaN, semiconductor wafer, resistivity.**

I. Introduction

Dielectric resonator techniques have been proven with their high accuracy for non-destructive material measurements at microwave frequencies. The split-post dielectric resonator (SPDR) [1] and single-post dielectric resonator (SiPDR) [2] methods cover characterisation of a wide spectrum of materials. The SPDR method is an acknowledged standard [3] for characterising low-loss laminar dielectrics and high resistivity semiconductors, whereas the SiPDR configuration has been developed for the measurements of the surface impedance of resistive films as well as for the contactless measurements of low-resistivity semiconductor wafers. In both methods, material parameters are explicitly calculated from the measured resonant frequencies and Q-factors, extracted for a device without and with material sample inserted.

Standard dielectric resonator devices are dedicated to point-wise measurements, which deliver a complete information when dealing with samples that are assumed to be homogeneous across their surface. However, continuous advances in development of novel materials and their manufacturing techniques, such as printing techniques for carbon-based polymer composites [4-5] used in battery cells or organic semiconductors [6] gaining interest for photovoltaic cells, and even more importantly, a growing importance of improving device packaging efficiency, rises a need for surface mapping, allowing for detection of inhomogeneities in material parameters.

Electrical homogeneity across the whole structure is a crucial aspect of GaN-based technology, especially light-emitting and power electronics. For those applications, the fundamental aspect of GaN-based devices is to obtain homogeneously resistive GaN templates (HR-GaN) to grow the device structure that provides a cut-off state and high breakdown voltage [7]. Research in this area has shown that for efficient work of GaN-based LEDs, lower resistivity values (>10^3 Ω·cm) are sufficient, whereas for HEMT transistors, the resistivity of HR-GaN in the range of 10^5-10^{11} Ω·cm is required [8].

Current technological advances of GaN structures are mainly based on heteroepitaxial growth on foreign few-inch substrates, such as Al_2O_3, SiC, and Si. Despite the predominance of lower costs and scalability, heteroepitaxy suffers from the risk of lattice mismatch, leading to lower structural and therefore, electrical quality of the device. This rises a necessity to effectively control the quality of grown structure across the whole few-inch wafer. Most of the works carried out on electrical properties of GaN use the Hall effect [9], which is a single-point measurement with a limited range for resistive structures (typically up to 10^7 Ω·cm), lacking practical studies on extending the electrical measurements to surface imaging for detection of variability of properties across the wafer. Therefore, for increasing packaging efficiency and assuring high quality, repeatability, and reproducibility of operation parameters of final devices, it is necessary to find effective and accurate methods to control the electrical homogeneity of LEDs and HEMT structures.

In this work, we report a novel study on application of the recently developed automatic 2D SPDR scanner [10] for evaluation of homogeneity of GaN templates for power electronics. The novelty of the proposed solution is with delivering joint qualitative and quantitative measures of semiconductor characterisation. In this case, microwave measurement of resonant frequency and Q-factor, further converted to dielectric constant, loss tangent, or resistivity, is performed over a grid of points across the entire surface of sample under test (SUT) resulting in a 2D map of material

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properties. With this work we respond to practical needs of semiconductor industry and research, presently lacking an accurate and efficient method for non-destructive, electrical quality testing of GaN template wafers.

II. Materials and Methods

A. *Highly-resistive GaN structure*

The epitaxial structure of HR-GaN consisted of 750 nm AlN layer and 1.5 µm GaN layer on the top. The growth was performed using an AIX 200/4 RF-S metal-organic vapour phase epitaxy low-pressure reactor (LP MOVPE) on 2-inch single side polished (0001)-oriented sapphire (Al_2O_3) substrate. The growth process included three types of precursors: trimethylaluminium (TMAl), trimethylgallium (TMGa), and ammonia (NH_3), and for the carrier gas a hydrogen (H_2) was used. The epitaxial growth was performed at temperature of about 1000 ºC and 200 mbar pressure. During the growth process, thickness and quality of particular layers were in situ controlled by emissivity corrected pyrometry using a Laytec Epi-Curve TT system. The resultant HR-GaN template sample is shown in Fig. 1.

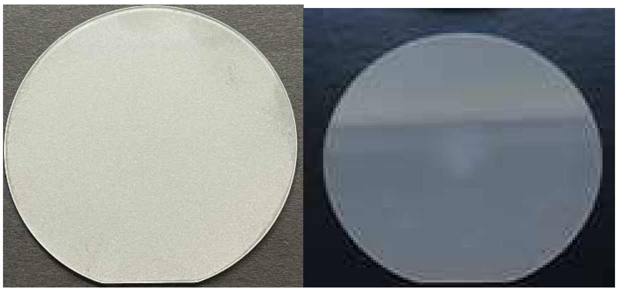
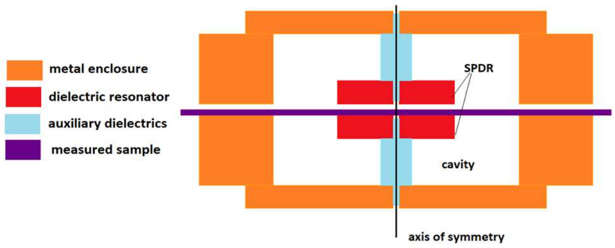


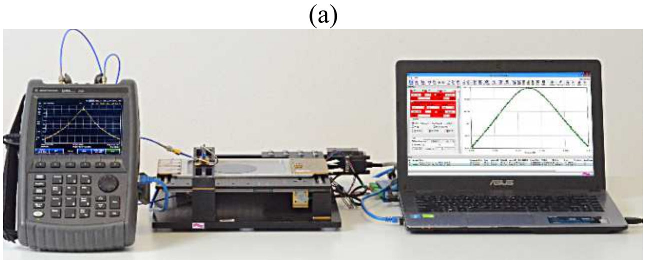
Fig. 1. Sapphire substrate and HR-GaN samples under test.

B. *2D SPDR scanner*

The 2D scanner for material imaging (Fig. 2) incorporates 10GHz SPDR mounted upon XY-motorized table. The motion of the table is performed with the use of Standa [11] and Nanotec [12] motors, with practical operational resolution of 1 mm (step resolution as low as 5µm is available). The table is equipped with a thin teflon foil serving as a SUT holder. The gap for sample insertion is 0.8 mm, which defines the upper bound for the SUT thickness. The admissible maximum lateral size, limited by mechanical design, is 80 x 100 mm^2 and the minimum, determined by raw lateral resolution related to a size of a probing head of 10GHz SPDR device, 16 x 16 mm^2. The measurement procedure is fully automated and controlled with a dedicated computer application (Master Unit Control Application), invoking table movement and precise SPDR positioning over the SUT and further, initiating microwave measurement of transmission coefficient with the use of Vector Network Analyser (VNA), or dedicated handheld Q-Meter devices [10], through LAN or USB protocols, respectively. In each spatial step, a measurement and readout of transmission coefficient curve is performed through linear frequency sweep and in-house algorithm is applied to accurately extract resonant frequency and loaded Q-factor values, which are essential for material parameters evaluation with SPDR method. The obtained parameters values are further aggregated into 2D maps of relative permittivity, loss tangent,



(a)



(b)

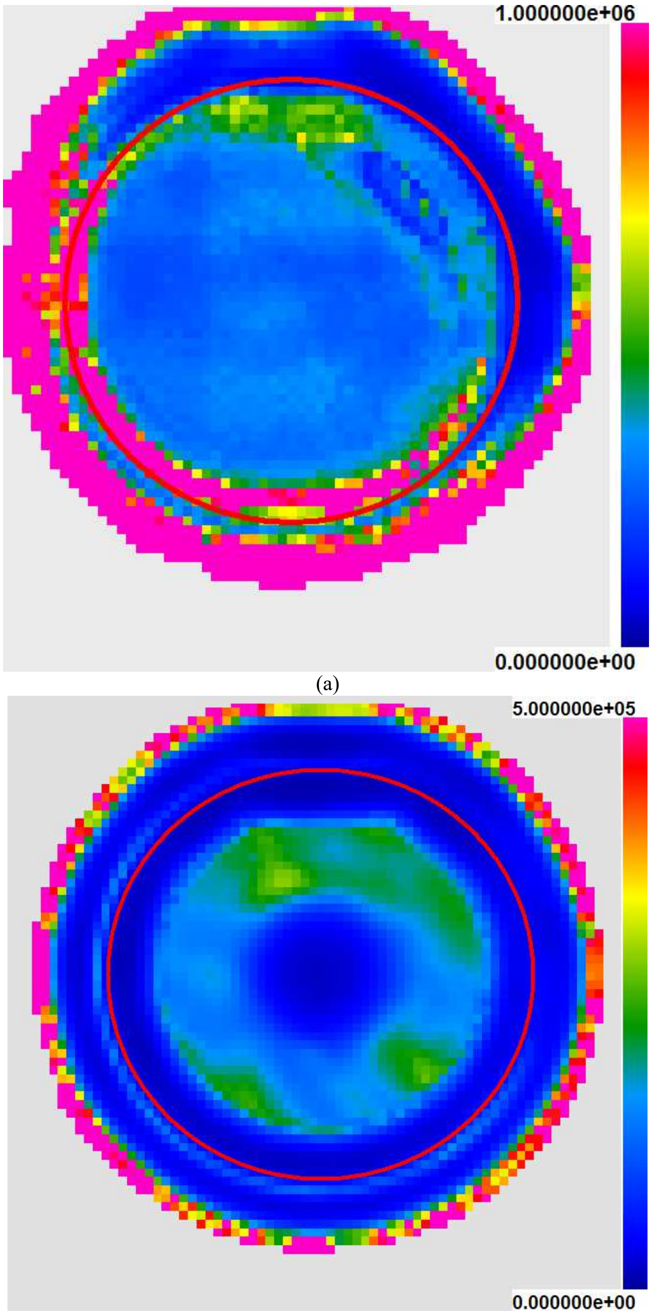
Fig. 2. Scheme of SPDR device (a) and measurement setup for 2D imaginig, incorporating 10GHz SPDR scanner, Keysight FieldFox VNA, and MUCA run on a laptop (b).

and resistivity of SUT. The 2D SPDR scanner has been previously successfully validated with respect to stand-alone SPDR device, with its point-wise measurements of reference samples, such as laminar dielectric and organic semiconductor material.

III. 2D Imaging of Semiconductor wafers

The 2D imaging of 2-inch samples of sapphire and HR-GaN (Fig. 1) has been performed over the area covering SUT with ca. 1 cm margin around the sample. Scanning resolution has been set to 1mm giving the total of 5112 measurement points. The obtained surface maps of resistivity are shown in Fig.3, with physical SUT size indicated with red circle. As reported in [13], a point-wise SPDR measurement delivers values of material parameters averaged over a surface corresponding to a size of the resonator head. While SUT scanning, the spatial points beyond the sample (over the handling Teflon foil), for which the resonator head is still partially covering the SUT, have a value of resistivity averaged from two materials. For SPDR positioning beyond SUT, a value related to reference Teflon background is obtained (for clarity purposes, this area is removed from the resistivity scaling and marked with light grey background).

2D resistivity maps of Fig. 3 deliver both, quantitative and qualitative information concerning homogeneity of tested samples. The 2D image obtained for reference sapphire substrate is recognised to be homogenous in terms of resistivity values, being in the rage of 2.5-3 $\cdot 10^5$ Ωcm. For HR-GaN template, next to edge ring inherent to so-called edge effect, clear inhomogeneities with lower quality are visible across the SUT's surface. Resistivity values vary from ca. $2 \cdot 10^4$ Ωcm right in the centre (dark blue), through ca. $5 \cdot 10^4$ Ωcm along the inner ring (light blue) up to 1.2 – 3 $\cdot 10^5$ Ωcm across outer SUT's area (blue-green). The centre located defect can be noticed already optically when looking at the HR-GaN SUT (Fig. 1, right) however, no quantitative or even qualitative conclusion can be raised from this. To validate and further confirm the advantages of 2D SPDR imaging technique for effective quality control of GaN semiconductor wafers, the optical microscope with Nomarski contrast has been applied to investigate SUT's surface quality and preliminary morphology (Fig. 4). The optical image of the HR-GaN was registered as a map using 5x, and as a single images with 5x and 100x magnifications. The morphology observed at 100x corresponds to Volmer-Weber (island) growth mode of GaN on sapphire substrate. A strong inhomogeneity of morphology can be clearly observed in the central area of the wafer. Such form of morphology can appear due to non-uniformity of the growth and is consistent with the defects visible on 2D surface map of resistivity.



(a)

(b)

Fig. 3. 2D surface maps of resistivity values (in Ωcm) of 2-inch sapphire substrate (a) and HR-GaN samples (b), with physical sample area marked with red circle (high-resistivity value areas (pink) are related with parameter values being beyond SPDR measurement range).

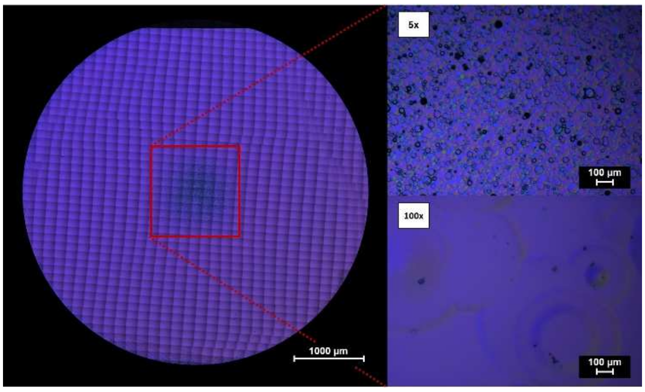


Fig. 4. Optical map and images of HR-GaN SUT (magnification 5x and 100x)

Looking at the morphology image obtained with optical microscopy, it can be presumed that only the central part of it cannot be used for the implementation of devices. However, the 2D resistivity scanning gives a deeper insight into SUT's properties and shows a heterogeneity of electrical properties in relation to the morphological quality of the sample. Therefore, with 2D SPDR imaging, it is possible to determine that the tested wafer will not ensure sufficient homogeneity of the electrical properties of all samples (devices) obtained from it and thus, does not meet the technological requirements. The proposed quick and relatively cheap testing performed with the new 2D SPDR scanner prevents investing further technological efforts into the costly manufacturing of light or power devices that would then fail the performance requirements.

IV. Conclusion

In this paper a 2D microwave resonator technique for surface mapping of electrical parameters of laminar dielectrics and high-resistivity materials has been for the first time applied to quality control of HR-GaN templates for light and power electronics. The measurement setup consists of 10GHz SPDR resonator incorporated into 2D scanner connected to VNA (or Q-Meter device), fully automated and controlled with a computer application responsible for SPDR positioning over the SUT and invoking microwave measurement, leading to extracting material parameters. The scanning setup is applied to 2D imaging of resistivity of reference sapphire substrate and HR-GaN template, for its electrical homogeneity evaluation. While the obtained image is in qualitative agreement with optical images, it additionally provides quantitative information, which is the novel aspect of this work, opening new perspectives for large surface material testing for light and power electronics.

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