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Doping investigation of structured GaN devices by highly lateral resolved TOF-SIMS

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ABSTRACT

The measurement of doping concentrations is a fundamental need for the development and processing of power electronic devices like normally-off semi-vertical GaN trench MOSFETs. We employed highly laterally resolved TOF-SIMS to evaluate the doping levels of the *n*- and *p*- doped layers close to the gate trench. A lateral resolution of approx. 100 nm was achieved sufficient to resolve the gate trench geometry. Furthermore, the analysis and the visualization of the 3D data was optimized by implementing the correction of the topography and image distortions. No change of the Mg and Si doping of the *n*- and *p*- layers close to gate trench sidewall was observed.

Introduction

Vertical GaN devices are promising candidates for power applications, especially for high power applications like e.g. power supplies, electric vehicles and renewable energy systems (Mukherjee et al., 2021; Geens et al., 2024; Langpoklakpam et al., 2023). In addition to the advantages of GaN on Si devices like improved transport and breakdown properties compared to Si devices, the breakdown voltage of vertical GaN devices is not linked to the device area as for lateral devices. Therefore normally-off semi-vertical GaN-on-Si trench metal oxide semiconductor field-effect transistor MOSFET are extensively investigated to realize high performance vertical devices. Especially, the Mg-concentration of the p-GaN layer is of interest and influences the main device parameters (Mukherjee et al., 2021; Gonçalez Filho et al., 2024). Hence, the metrology of doping levels is a crucial point for process development and monitoring for GaN power electronic devices. As an analysis technique dynamic secondary ion mass spectrometry (DSIMS) is an established technique to determine and control doping concentrations requiring specific large area samples (Wilson & Zavada, 2012; Kumar et al., 2023). However, dimensions of several micrometers cannot be resolved by DSIMS, which is required to gain detailed information on doping concentrations at device level. Measuring the device with already etched trenches is required to investigate the impact of e.g. the trench process, the activation anneal or following process steps like deposition of dielectrics on the doping of the *n*- and p-doped layers. Time-of-flight (TOF)-SIMS offers lateral resolution and hence gives access to the three-dimensional chemical distribution (Kubicek et al., 2014; Senoner & Unger, 2012).

The aim of this study was to explore the high lateral resolution of TOF-SIMS for the measurement of structured samples. We present a detailed TOF-SIMS analysis of the gate trench and its surrounding area to look for changes in the doping level induced by processing steps.

Sample and TOF-SIMS experiment

Highly lateral resolved TOF-SIMS measurements are performed on doped GaN layers with processed trench structures to determine the impact of the gate trench process and dielectric deposition on the doping profile of the p-doped layers in close proximity to the gate trench sidewall and its surrounding area. Trench test structures were processed, which consist of arrays of trenches with a width of 2 μm, a length of 1 mm and a distance of 12 μm between each other. The geometry of the trenches and the structure of the *epi* layers can be seen in Fig. 1. Three kinds of test structures were processed, which differs in the dielectric layer (see Fig. 2). Sample A has a bare surface, sample B has 2.5 nm thick Al_2O_3 and sample C has a 50 nm thick SiO_2 layer at the top. The Al_2O_3 deposition is performed using atomic layer deposition (ALD) at 300 °C, while the SiO_2 is deposited using plasma-enhanced chemical vapor deposition (PECVD) at a deposition temperature of 400 °C. The TOF-SIMS measurements were performed on a TOF-SIMS M6 instrument

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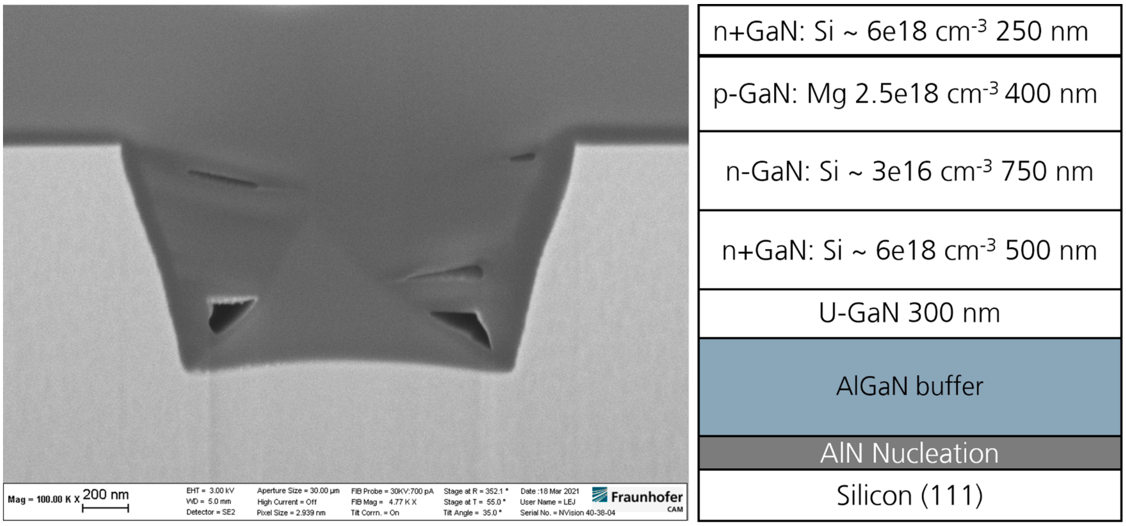

Fig. 1. Left: SEM image showing the cross section of the gate trench. Right: Scheme of the *epi* stack.

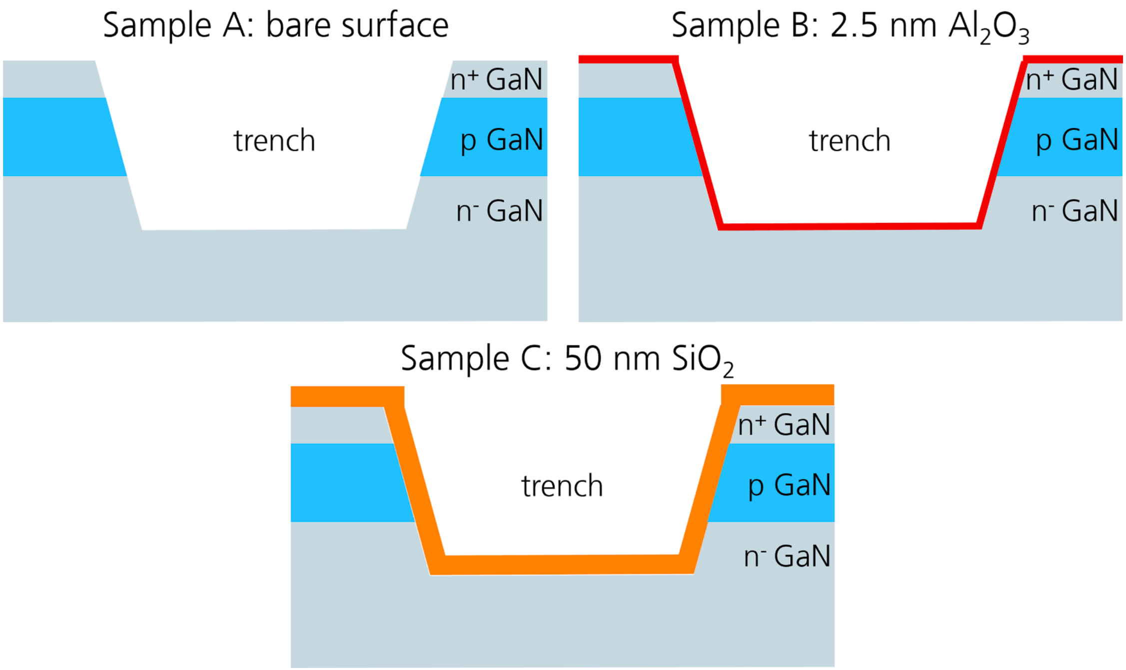

Fig. 2. Cross sectional scheme of the sample A, B and C including the dielectric and the epitaxial layers.

(Iontof GmbH, Münster, Germany) in positive polarity. The primary ion species used was Bi^+ at 30 keV with analysis current of 3.7 pA. Low energy flood gun for charge compensation and the imaging mode was used. As sputter species O_2^+ at 2 keV with sputter current of 550 nA and a sputter crater region of 200 µm by 200 µm is used. A region of 25 µm by 25 µm with a raster size of 256 × 256 pixels was measured.

A three-dimensional data set is created by the TOF-SIMS measurement, which can be visualized in various ways. We have mainly chosen the option of accumulated maps from the side view along the gate trenches. Taking advantage of the 2-D trench geometry, the signal can be summed up along the trench to increase intensity, since no substantial differences were assumed in this direction. Fig. 3 shows a highly lateral resolved TOF-SIMS measurement of Mg. An intensity line profile of the Mg-map was extracted orthogonal to gate trench with a width of 250 pixels. Since no p-GaN and hence no Mg is present inside the trench, the line profile of the Mg-signal orthogonal to the trench is suitable to resolve the lateral resolution. The gate trench can successfully be resolved and a lateral resolution of approximately 100 nm was achieved by applying the 16–84% criterion (Xu et al., 2021; Noël, Busby & Mine, 2019). Fig. 4 exemplarily shows the standard visualization of TOF-SIMS results by accumulated maps of Mg and Al from top and side view for sample B. The gate trench can clearly be seen in the top view accumulated map. As expected no Mg was measured inside the trench and Al is present there. In contrast, the accumulated maps from side view show no real representation of the sample structure including the gate trench geometry, which was retrieved from the SEM cross section investigation (see Fig. 1) However, a precise and realistic visualization of the gate trench geometry of the TOF-SIMS data is required for a detailed analysis of the surrounding area close to the trench sidewall and to investigate the impact of the gate trench processing and the dielectric deposition.

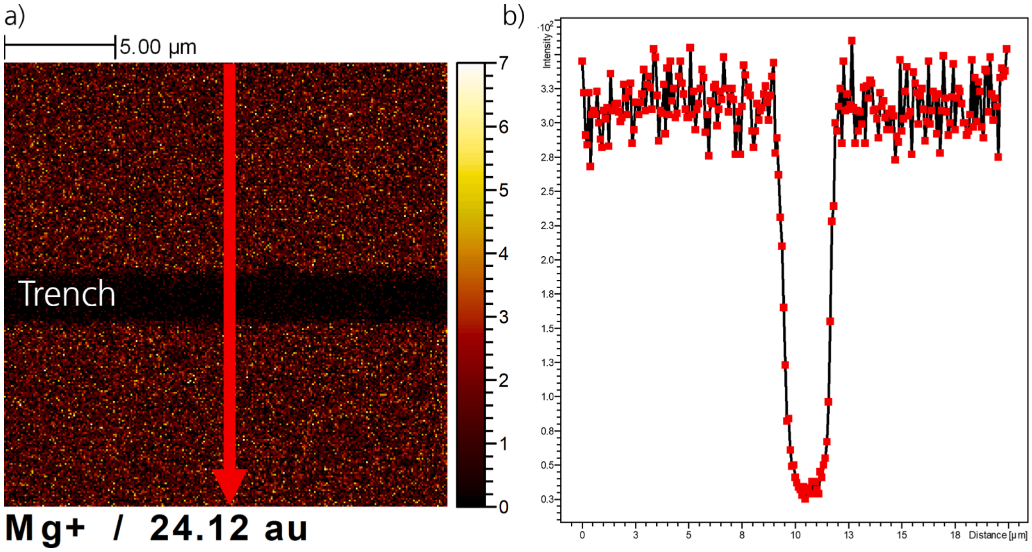

Fig. 3. Highly lateral resolved TOF-SIMS measurement of sample A. a) accumulated Mg-map from top view. b) line scan of Mg-signal orthogonal to the gate trench as indicated by the red arrow in a).

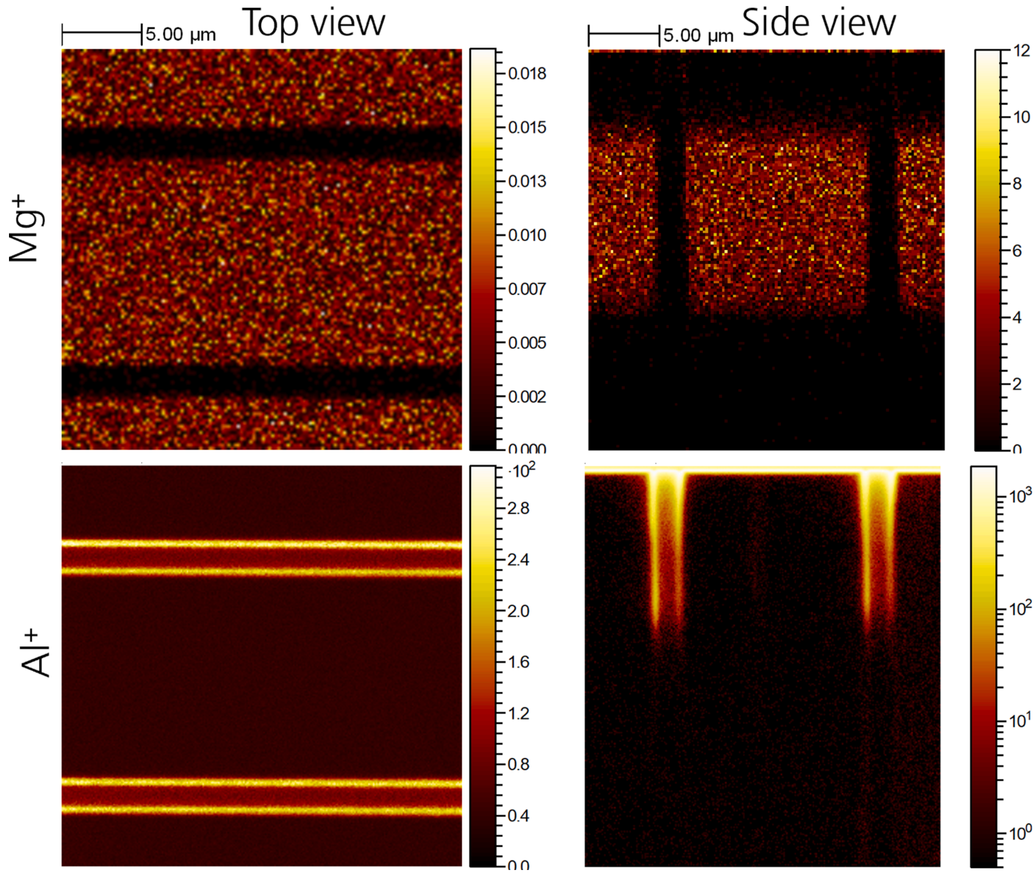

Fig. 4. Accumulated elemental maps for Mg and Al of sample B from two orthogonal perspectives.

Visualization of 3D TOF-SIMS data including topography and distortion correction

The shown standard visualization by accumulated maps in cross section has two important limitations. First, the topography of the structured sample is not considered, and the surface is assumed to be flat. Therefore, any features inside the gate trench are not correctly displayed. Second, the lateral resolution of 100 nm differs from the depth resolution of approximately 1 nm. The TOF-SIMS software typically assumes that the pixel size is the same in both directions, causing the resultant accumulated map to be distorted (see the right images of Fig. 4 and the left image of Fig. 5). To address these challenges, a python-based program was developed. The underlying concept is to use the SEM image of the cross section from Fig. 1 to extract the actual surface geometry as a 2D array, which encodes how far the trench surface deviates from an idealized flat plane. Additionally, the positions of

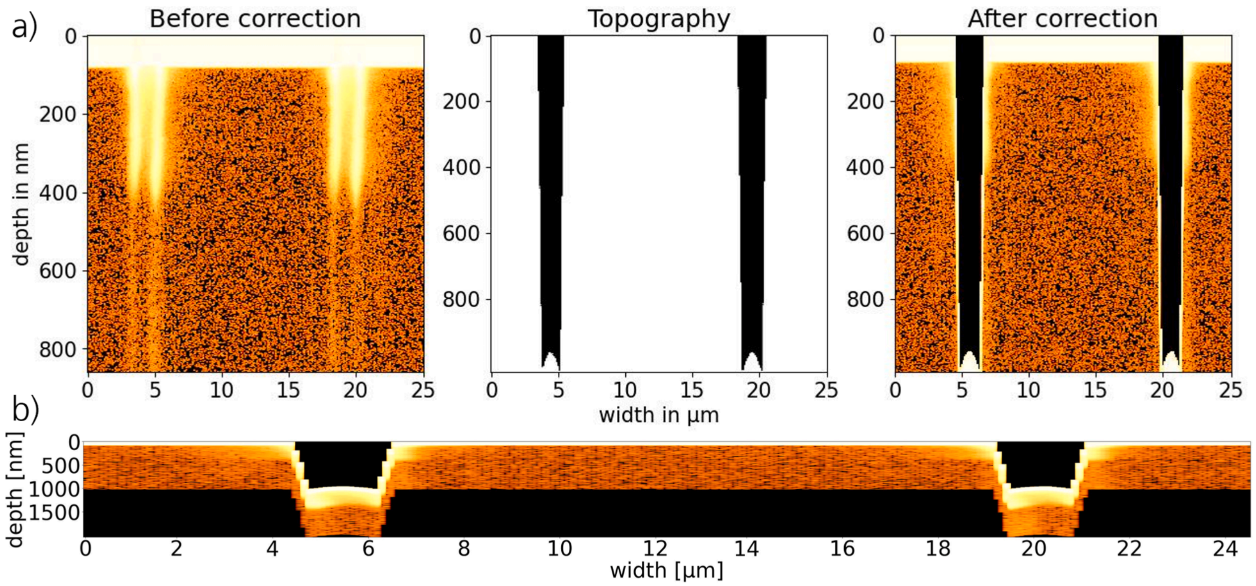

Fig. 5. A) Correction of topography and b) rescaling of a three-dimensional TOF-SIMS data set exemplarily shown for sample C.

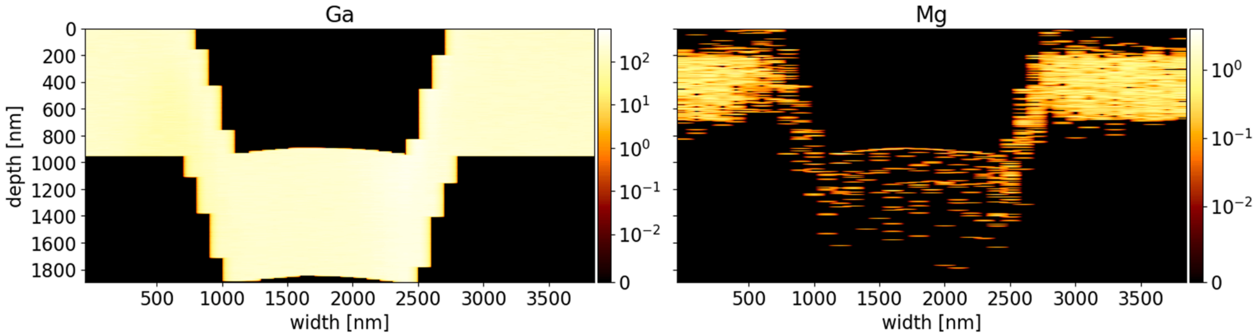

Fig. 6. Zoom of accumulated elemental maps after topography and distortion correction for Ga and Mg sample A showing the trench and its surrounding.

the trenches are extracted from the TOF-SIMS data. The first step involves a mapping of each pixel in the SEM image to a height value and an extrapolation of the 2D array to match the size of the TOF-SIMS data, as illustrated in the centre image of Fig. 5a. Once the 2D topography map has been obtained, the 3D TOF-SIMS data array containing the two lateral information and depth dimension is corrected line by line. For each lateral position in the TOF-SIMS dataset, the corresponding local offset derived from the 2D topography map is used to shift the recorded intensities in the depth direction so that the information is correctly aligned with the real physical surface of the sample. Fig. 5a provides a representation of this process. A final rescaling step then accounts for the difference between the lateral and depth resolution. Because the lateral resolution is on the order of 100 nm while the depth resolution is close to 1 nm, the raw dataset appears to be stretched in the depth dimension if its voxel size is kept uniform. To avoid this distortion, the program adjusts the voxel size to match the ratio between lateral and depth resolution. As shown in Fig. 5b, the combined effect of topography correction and rescaling leads to a realistic representation of the gate trench region.

Results and discussion

Fig. 6 shows the trench and its surrounding area for sample A after topography and distortion correction. For a better visualization, only the gate trench and its close surrounding is displayed although the correction was applied to the complete three-dimensional data set. The lateral resolution of 100 nm results in a relatively coarse visualization of the gate trench geometry especially the gate trench sidewall, which has a width of 300 nm and a depth of 1 µm (see Ga accumulated map of Fig 6). In the current approach the pixel size of the TOF-SIMS measurement is used and the smaller pixel size of the SEM measurement is converted. Converting the pixel size of the TOF-SIMS measurement into the pixel size of the SEM measurement, might lead to a better visualization. On the other hand the representation would be misleading since the actual lateral resolution has not been improved. For a better and more accurate visualization of the gate trench sidewall, the resolution of the TOF-SIMS measurement should further be improved. A Mg-signal underneath the gate trench is visible, although no p-GaN layer is present. The Mg-signal is two orders of magnitude lower compared to the Mg-Signal of the p-GaN layer. A source for the Mg-signal underneath the gate trench could be contamination on the surface, which will be transported into deeper regions by the sputtering process during the TOF-SIMS measurement. Additionally, close to the upper trench edge some minor measurement artefacts due to the topography were observed, which also depend on the scan direction.

Fig. 7 shows the corrected accumulated maps at one gate trench for sample B. The Ga- and Mg-maps are similar to the one of sample A. For the accumulated map of Al a linear instead of a logarithmic scale is selected due to the high signal intensity and since Al is not a dopant. The Al_2O_3 layer inside the gate trench is homogenous. Comparing the corrected accumulated maps of sample B with the uncorrected accumulated maps (see Fig. 4), the requirement of the correction is evident for a

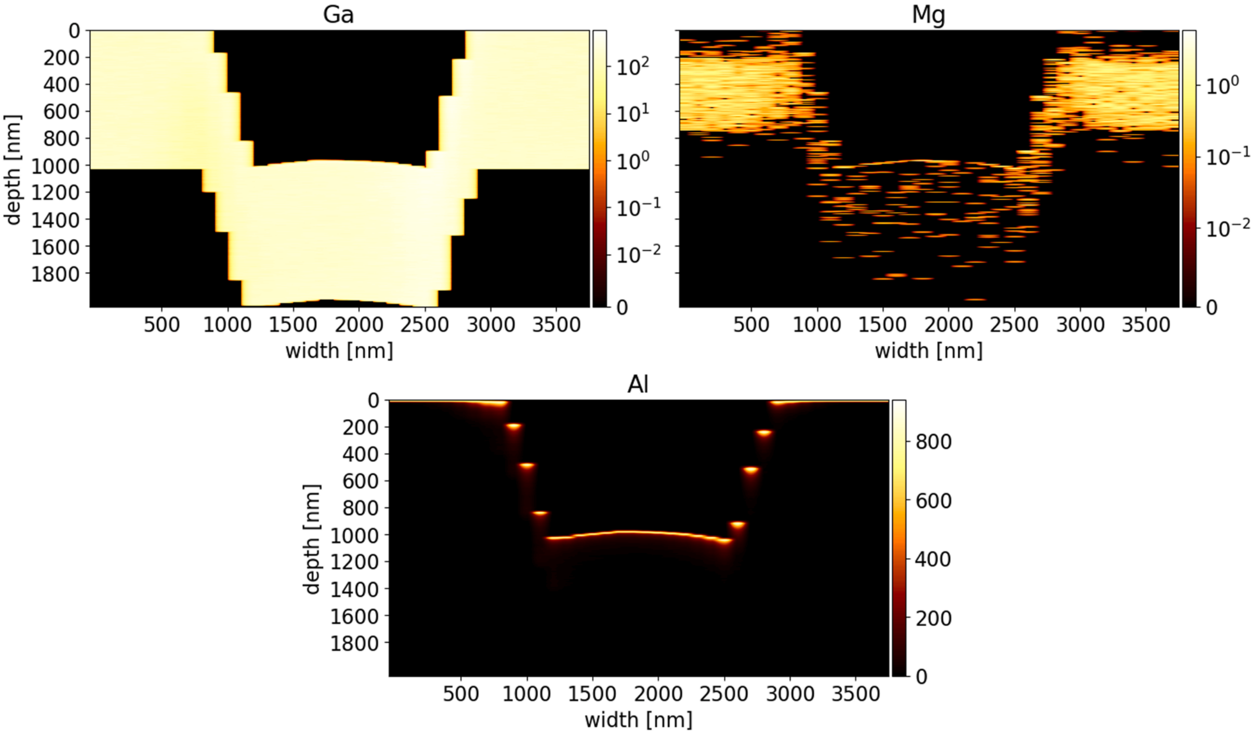

Fig. 7. Zoom of accumulated elemental maps after topography and distortion correction for Ga, Mg and Al of sample B showing the trench and its surrounding.

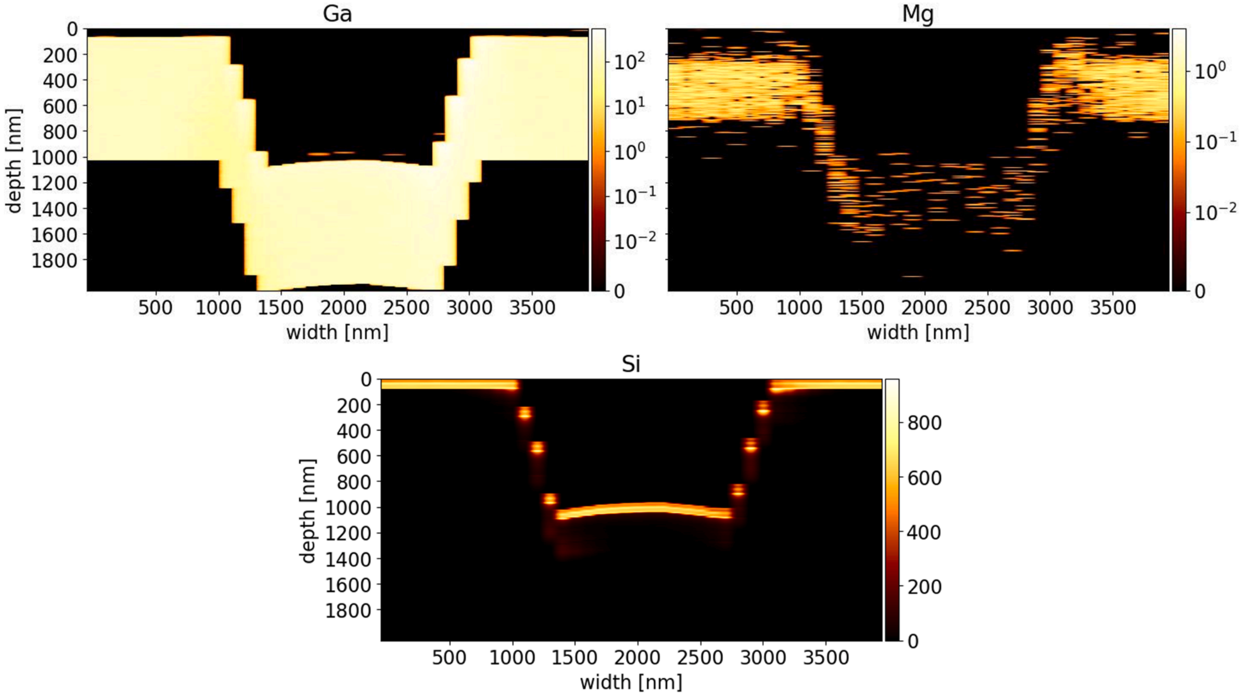

Fig. 8. Zoom of accumulated elemental maps after topography and distortion correction for Ga, Mg and Si of sample C showing the trench and its surrounding.

detailed investigation of the gate trench.

The corrected accumulated maps of sample C are displayed in Fig. 8. The thickness of the SiO_2 layer inside the gate trench is comparable to the layer outside of it. This also shows that the topography and distortion correction was successful.

The coarse lateral resolution and the low signal intensity hamper a sufficient analysis of the region directly at the trench sidewall. However, the region close to the trench sidewall was analyzed by comparative depth profiles analysis. Fig. 9 exemplarily shows a depth profile analysis for sample C. Due to the low signal intensity a width of the line profile of 10 pixels was selected. One line profile was extracted close to the gate trench sidewall and one line profile was extracted between the gate trenches as reference. Both line profiles have a similar shape although both curves suffer from noise. Nevertheless, no change of the Mg-signal close to the gate trench is detected. The comparative line profile analysis of sample A and B (not shown) deliver similar results. Comparing the

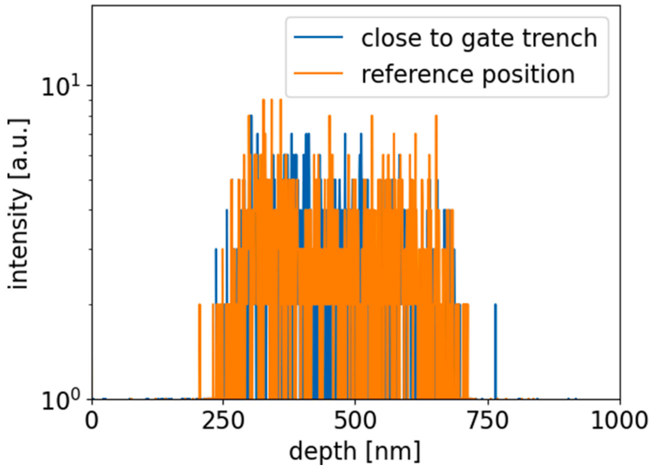

Fig. 9. Mg-line profile of sample C close to the gate trench and at a reference position.

Mg-maps shown in Fig. 7 and 8 with the Mg-map of the reference sample A in combination with the depth profiles analysis results, no substantial change of the Mg doping level outside the gate trench was detected for sample A, B and C. Hence, no influence of the dielectric deposition or the gate trenching on the Mg doping was observed.

Conclusion and outlook

A TOF-SIMS method to enable high lateral resolution and 3D representation of µm scaled gate trenches of semi-vertical GaN-on-Si MOSFETs was established and successfully tested. The gate trench structure within the Mg and Si doped GaN-layers including isolation layer could be characterized. A lateral resolution of approx. 100 nm for the TOF-SIMS elemental mapping was achieved. It was demonstrated that the conventional visualization by accumulated maps is not sufficient for the investigation of 3D structured samples. Therefore, a python-based topography and distortion correction was implemented to optimize the visualization of the TOF-SIMS data around the gate trenches. The presented results demonstrate that structured samples can successfully be measured by TOF-SIMS and that the gate trench structure can be sufficiently visualized for process characterization. Due to the high sensitivity and the sufficient lateral resolution, TOF-SIMS is a convincing way of evaluating doping levels on µm-structured samples. Furthermore, no impact of the gate trench processing and the dielectric deposition on the Mg-signal inside the pGaN layer was observed. The method can be further improved by increasing the signal intensity to enhance the signal to noise ratio. This could be achieved by increasing the emitter current by increasing the impuls width or increasing the number of measurement scans per depth profile step (a ratio of 1:1 is used). Furthermore, the accelerating voltage of the flood gun could be increased to 300 V instead of 21 V to compensate charging effects and to compensate for time increase of previous approaches. Additionally, the lateral resolution of the measurement can be further improved. One way would be to increase the raster size to 512 by 512 pixels and thereby the pixel size of the TOF-SIMS measurement, which also increases the measurement time by a factor of four. However, we expect that the achieved later resolution of 100 nm is already close to the maximum. A good tradeoff between signal intensity and high lateral resolution has to be found and therefore several experiments would be required to identify the best strategy to further improve the measurement.

CRediT authorship contribution statement

Patrick Diehle: Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Stephan Gierth:** Writing – review & editing, Investigation. **Mickael Lejoyeux:** Investigation. **Karen Geens:** Writing – review & editing, Resources, Conceptualization. **Matteo Borga:** Writing – review & editing, Resources, Conceptualization. **Frank Altmann:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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