

# DEFECT STATES IN SiC/GaN- AND SiC/AlGaN/GaN- HETEROSTRUCTURES CHARACTERIZED BY ADMITTANCE AND PHOTOCURRENT SPECTROSCOPY

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## ABSTRACT

Deep defect levels in n-type GaN/AlN/6H-SiC- and GaN/AlGaN/6H-SiC- heterostructures grown by Metallorganic Vapor Phase Epitaxy were analyzed by Thermal and Optical Admittance and Photocurrent Spectroscopy. The various thermal and optical transitions in the spectra originating from both the Schottky contact as well as the GaN/SiC- and AlGaN/GaN-heterojunctions were separated. This was achieved by variation of the modulation frequency, the use of different contact arrangements and by comparison with reference spectra from GaN/Sapphir samples and SiC substrates. In the GaN/AlGaN/SiC structures a bias voltage dependent peak shift was found which is correlated to an interface related defect distribution. In additionally to, SiC related defects, defect-band-transitions involving defects with transition energies at 2.2eV, 1.85eV,  $E_G$ -(470±40) meV and  $E_G$ -(65-95) meV were found for the GaN layer.

## INTRODUCTION

Besides their optoelectronic potential, GaN and their related compounds are very important for high-frequency, high-power and high- temperature electronic devices /1/. Especially, heterostructures based on GaN and AlGaN on SiC- substrate are main parts of some novel devices such as MESFET's, MODFET's, bipolar transistors /1/, UV-detectors /2/, LED's and laser diodes /1/. Defects states in the layers and in the interface regions influence both optical /3/ and electrical /4/ properties. For example, in GaN / p-type SiC -structures the photoluminescence and electroluminescence spectra show defect related transitions /3/ which cause tunneling-assisted currents described in /4/. Furthermore, in GaN / p-type SiC heterojunctions, indications on interface defect states were found by C-V-characteristics /5/ and by admittance spectroscopy /6/.

In GaN/AlGaN pin-structures on SiC-substrates, Mg-related recombination centers were found with temperature dependent dark current measurements and with current-DLTS having activation energies of 0.191eV and 0.207eV, respectively /7/.

The aim of this paper is to present evidences for defects and localize these traps in the layers and interfaces using Thermal and Optical Admittance Spectroscopy. We show, that defect spectra of heterostructures can be led back to those of the corresponding single layers on sapphire. We were able to separate the different heterojunctions by variation of the modulation frequency and the contact arrangement of the samples.

These investigations provide the for the determination of the capacitance and conduction values of the individual parts of the heterostructure. Only with these knowledge an calculation of the

concentrations of the different traps would be possible. The quantitative analysis will be the aim of future work.

## **EXPERIMENTAL**

The first group of samples consist of a n-type 6H-SiC- substrate (carrier concentration of about  $1.5 \cdot 10^{18} \text{ cm}^{-3}$ ), a 17nm thick AlN nucleation layer followed by a 1 $\mu\text{m}$  thick, nominally undoped, n-type GaN layer. The second kind of heterostructures is based on the same SiC substrate followed by a 500nm thick AlGaN buffer layer ( [Al] 43-47%). The undoped GaN top layer is 500nm thick. All layers were grown by Metallorganic Vapor Phase Epitaxy (MOVPE) at a growth temperature of 1000°C. For reference measurements we investigated various undoped GaN layers deposited with the same MOVPE equipment on sapphire substrates as well as the SiC substrate itself.

The samples were cleaned with organic solutions and etched in HF (SiC) and ammonium hydroxyd (GaN) solution. Ohmic contacts were formed by sputtering of Ni on SiC- substrate and by evaporation of Al- layer on GaN followed by an annealing process at 700°C for 10 min. in an inert gas atmosphere. The Schottky contacts were realized by sputtering of a 100nm thick Pt-layer having a diameter of 1mm. Sandwich arrangement with the ohmic contact on the SiC substrate and the Schottky contact on the GaN side as well as coplanar arrangement consisting of both contacts on the GaN layer were used. All GaN on sapphire samples are contacted in coplanar arrangement. For further reference measurements, contacts on the SiC sample were deposited in sandwich arrangement using a Pt Schottky contact. All Schottky contacts show rectifying behavior up to a frequency range of about 100kHz - 500kHz.

Thermal Admittance Spectroscopy (TAS) measurements were carried out in the temperature region between 78K and 450K using a high precision LCR-meter (HP 4284A) at modulation frequencies between 20Hz and 1MHz under zero bias conditions. The experimental set up and the evaluation method is described in detail in /8/. For the Optical Admittance Spectroscopy (OAS) an optical-electrical cryostat was used for measurements at temperatures between 78 and 295K. A monochromator illumination system yielded monochromatic light with wave length between 300nm and 3000nm (see also /9/).

## **RESULTS AND DISCUSSION**

In TAS spectra of all heterostructures with sandwich contacts a peak is observed at a temperature of about  $T_{\text{max}}=85\text{K}$  at 1MHz. A peak with identical  $T_{\text{max}}$  is also found in the reference spectrum of the n-type SiC sample (thermal activation energy  $(61 \pm 5)\text{meV}$ , see Table 1). Thus, we conclude that these peaks are caused by the same defect level. The origin of this electron trap is probably the N-donor in 6H-SiC /10/. This behavior corresponds very well with TAS investigations of n-type GaN layers grown by LPCVD on n-type 6H-SiC- substrates described in /6/.

In contrary, three electron traps with activation energies between 130 meV and 320meV were found in the reference samples consisting of GaN/AlN/Sapphire layers using TAS (see also Table I). These defects are well known from the literature, for example in /6/,/13/ and /14/ detected by DLTS and TAS in MOVPE and MBE grown material. The discrepancy between the detection of defects in the heterostructures and the reference samples shows, that the high doping concentration in the SiC substrate dominates the TAS signals of the heterostructures strongly.

In GaN/AlGaN/SiC-heterostructures a bias voltage dependent shifting peak at frequencies between 0.5 and  $2.5 \cdot 10^5$  1/s is observed by AS in reverse direction, as shown in Fig.1. The peak height remains constant at about (2-3) nF. Because of the conductance of the SiC-substrate we

used the Kramers-Kronig transformation of the admittance data to eliminate the series resistance/11/. A bias dependent shift of an AS peak position is well known from Si/SiO<sub>2</sub>- interface defect distributions ( for example see /12/). We conclude, that this peak is caused either by an intermediate layer in one of the heterojunctions, gradients of defect states in the interface regions, or interface defect state distributions. A similar behavior is also observed in n-type GaN (LPCVD grown) /p-type SiC heterostructures (for more details see /6/).

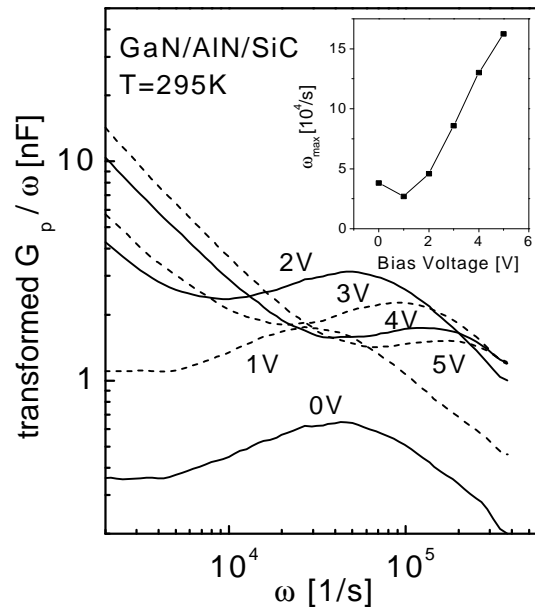


Fig. 1 : Transformed Conductance /11/ as a function of frequency of the GaN/AlGa<sub>N</sub>/SiC heterostructure for different reverse bias voltages. The insert shows the shift of the peak maximum with increasing bias voltage.

The TAS and AS results clearly show, that all components of the heterostructures, i.e. the SiC substrate, the AlGa<sub>N</sub> and GaN layers, the corresponding heterojunctions as well as the Schottky contact on the GaN top layers contribute to the measured signals.

In order to separate these different parts of the heterostructures we compare OAS spectrum of the GaN/AlN/SiC structure with OAS spectra of the SiC-substrate and of GaN layers on sapphire (Fig. 2). The spectrum of the heterostructures in coplanar contact arrangement shows the same structure as the spectra of GaN on sapphire. However, in sandwich arrangement the heterostructures show the SiC-spectrum, leading to the conclusion that the GaN/SiC-spectrum with sandwich contacts is influenced by the SiC-side of the heterojunction and the coplanar arrangement is dominated by the Schottky contact on the GaN layer, respectively. All defect-band transitions in the OAS spectra are summarized in Table 1 together with TAS results.

Another method to separate the various parts of the structures is based on the variation of the modulation frequency, visualized in Fig. 3. In the GaN/AlGa<sub>N</sub>/SiC heterostructures the near band gap region (NBG) of AlGa<sub>N</sub> and GaN below 3.4eV occurs. With increasing frequency the Schottky contact on the GaN layer breaks down, the NBG peaks vanish and the SiC-side of the heterojunction (peak at 2.65eV) dominates the OAS spectrum.

Using coplanar contact arrangement and low frequencies OAS spectra of the heterostructures which dominated by defects of the GaN layer were measured. The defect-to-band transitions found are shown in Table I.

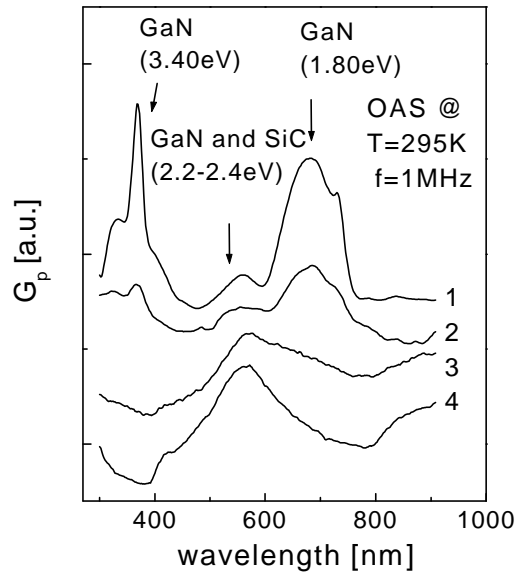


Fig. 2 : Optical Admittance Spectra of different GaN structures. 1- GaN on sapphire; 2- GaN/AlN/SiC with coplanar contacts; 3- GaN/AlN/SiC with sandwich contacts; 4- 6H-SiC.

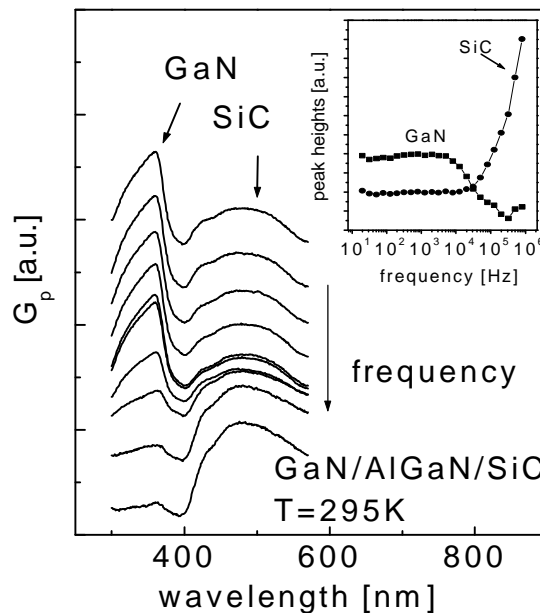


Fig. 3 : Optical Admittance Spectra of an GaN/Al<sub>0.43</sub>Ga<sub>0.57</sub>N/SiC heterostructure for different modulation frequencies. The peak heights of the both peaks at 3.4eV (GaN) and 2.56eV (SiC) are plotted as a function of the frequency in the insert.

In the OAS spectra of the GaN/Al/SiC we have to distinguish between the near band gap region involving defects-to-(opposite) band transitions, the blue band originating from transitions from deep defects to the opposite band, the yellow band which is comparable to the yellow luminescence band and the deep defect at 1.85eV. All, these defects were also found in MBE grown GaN (seen /6/ and /9/) as well as in MOVPE grown GaN layers on sapphire (see /13/ and /14/).

Differences between the OAS spectra of the GaN/AlN/Sapphire sample and the GaN/AlN/SiC heterostructures show up in the near band region. For the GaN/AlN/SiC-heterostructures shallower transitions ( $E_G$ -18meV) were observed in comparison of the GaN/AlN/Sapphire reference samples ( $E_G$ -(65-95)meV). One reason may be a dominance of shallower defects, for example the Si level, in the GaN layer on SiC.

The similarities in the OAS spectra between the GaN/AlN/SiC heterostructure and the reference samples on Sapphire show that the substrate material influences not the occurrence of these defects qualitative. Otherwise, the quantitative analysis of these defects will be made in the future.

Table I : Summary of observed thermal activation energies and peak maximum temperatures of GaN/AlN/Sapphire-layers and in heterostructures measured with TAS and with OAS detected defect-band-transition energies of various layer structures. A band gap energy of  $E_G= 3.44\text{eV}$  at 295K was used according to [15]. The meaning of the abbreviations is : NBG near band gap region; BB blue band region, YB yellow band region and SiC-peak ; DT deep defect-band transition.

method	GaN/AlN/Sapphire	GaN/AlN/SiC	GaN/AlGaN / SiC	n-type SiC
TAS	(130-170) meV (276±28) meV (320±24) meV	peak at 85K	peak at 85K	peak at 85K (61±5)meV
OAS /NBG	(65-95)meV below gap	18meV below gap	3.42eV	-
OAS / BB	290; 370 , 460 and 760meV below gap	(450-510) meV below gap	-	
OAS / YB+SiC	2.2eV	2.22-2.26 eV	-	2.25eV
OAS / DT	1.82eV	1.87eV	-	-

In the OAS spectra of the GaN/AlGaN/SiC structures only the near band gap (NBG) peak consisting of the GaN (360nm) and the AlGaN (290nm) layers occurs. Other defect-band transitions were not observed. A corresponding PC spectrum on the reference sample AlGaN/AlN/Sapphire shows only the near band gap peak similar to the spectra of the heterostructures. We assume this behavior in the OAS spectra is caused by the high resistivity of the AlGaN layer within the heterostructures.

In summary, n-type GaN/AlN/6H-SiC- and n-type GaN/AlGaN/6H-SiC-heterostructures were characterized for defect levels in the GaN-layers using thermal and optical admittance spectroscopy. Different contact arrangements, variation of modulation frequency and comparison with spectra of GaN/Sapphire and SiC samples enables us to assign the signals to the individual junctions. A defect distribution correlated with the interface between GaN and SiC is found by admittance spectroscopy. Using OAS some deep defect- band-transition in the GaN layer of the GaN/Al/SiC heterostructure were detected.

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