Buffer development for GaN power electronic applications using extrinsic carbon doping for a super-lattice structure

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Abstract

We report on a super-lattice (SL) buffer development for GaN-on-Si, enabling a high vertical breakdown. By increasing the SL buffer growth temperature, an improvement in material properties is observed. The desired carbon level at high temperature is adjusted by using a hydrocarbon source. Vertical breakdown measurements demonstrate the potential of this approach.

Introduction

GaN-on-Si power devices are gaining more and more attention for applications utilizing an operation voltage of 650V. For this voltage range, a buffer breakdown exceeding 650V together with low buffer dispersion is required. Comparing a step-graded AlGaN buffer with a super-lattice (SL) approach, the latter shows in general a better breakdown and especially a better dynamic behavior for same buffer thickness [1]. In literature, GaN/AlN SL structures as well as AlGaN/AlN SL are discussed. To obtain a buffer layer with a high average Al content AlGaN/AlN seems to be favorable to achieve a high breakdown voltage with reasonable buffer thickness, as the electrical breakdown field for AlN is higher than GaN.

For GaN-on-Si buffer design, strain engineering needs to be employed to compensate different lattice constants and the difference in thermal expansion coefficient between group III nitrides and Si. This is essential in order to avoid cracking of the epitaxial layers and ensure a flat wafer bow at room temperature. These requirements may conflict, especially on 200 mm wafers with a standard thickness of 725 µm. In addition, productivity aspects as cost driver such as growth duration need to be taken into account.

During metal-organic chemical vapor deposition (MOCVD), C-doping typically results from incorporation of C atoms supplied by the methyl or ethyl groups of the metal-organic precursor. To achieve a doping level in the range of $1 \cdot 10^{18}\,cm^{-3}$ to $1 \cdot 10^{19}\,cm^{-3}$, growth conditions such as low temperature, low pressure and low V/III ratio need to be applied [2] for this intrinsic doping approach.

To overcome the resulting process window limitation, we will report on an extrinsic doping approach, by using a hydrocarbon source. The carbon incorporation can easily be controlled by adjusting the hydrocarbon flow, allowing to widen the process window for a SL buffer growth.

Experimental

All deposition experiments were carried out in an AIXTRON G5+ Planetary MOCVD Reactor® in a 5x200 mm configuration [3,4] on 725 µm thick Si(111) substrates. The system is equipped with a fully automated cassette-to-cassette handling system, enabling wafer transfer at 600°C. Further, between each deposition experiment, the reactor chamber is cleaned by a Cl_2 bake procedure.

X-ray diffraction (XRD) was performed with a Phillips X'Pert PRO four-circle diffractometer. XRD full width at half maximum (FWHM) values for the (0002) and (10-12) GaN reflections were measured with an open detector configuration. FWHM for (0004) and (-2024) reflections of the SL main peak were extracted from reciprocal space mappings (RSM). Secondary ion mass spectrometry (SIMS) was carried out at EAG laboratories.

For electrical characterization, the stack shown in fig. 1 was used. On an AlN nucleation layer, a ~3µm thick AlGaN/AlN super-lattice (SL) was deposited, followed by GaN layers, partially c-doped. The carbon doping in the SL and GaN:C was achieved by using a hydrocarbon source [5]. The active area consists of a GaN channel and an AlGaN barrier layer with an Al content of 24%.

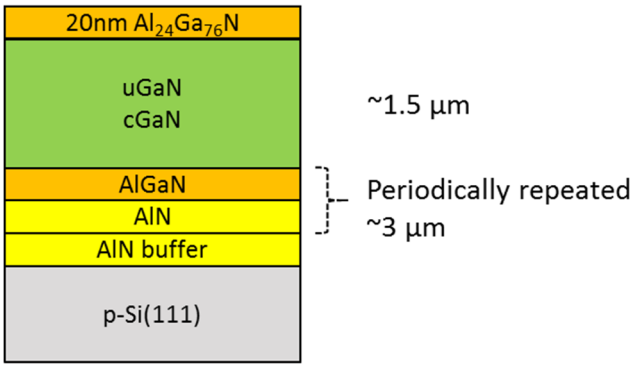

Figure 1: Investigated super-lattice buffer stack on p-Si (111) substrates

For vertical breakdown measurements, a mesa was etched in the AlGaN barrier and ~30 nm from the GaN channel.

Large Schottky contacts were deposited (no anneal) with a diameter of 3.6 mm and an area of A = 0.1018 cm².

Results and Discussion

First, the impact of SL growth temperature on carbon incorporation was investigated. A test structure was deposited for which the growth temperature for the SL buffer was varied between 930°C and 1040°C and measured by SIMS. C concentration of ~$1 \cdot 10^{19}$ cm^{-3} at 930°C decreases by almost two orders of magnitude to ~$3 \cdot 10^{17}$ cm^{-3} at a growth temperature of 1040°C (see fig.2). This exponential decrease in carbon concentration with increasing deposition temperature shows a similar trend as observed for GaN:C [2].

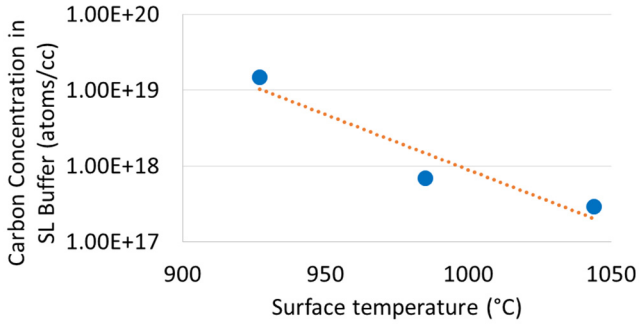

Figure 2: Carbon level in SL buffer as function of buffer growth temperature

For decreasing carbon concentration, XRD FWHM for SL main peak and GaN respectively are also found to be reduced. In fig. 3 the XRD FWHM as a function of SL growth temperature is shown. The FWHM of the symmetric as well as the asymmetric reflex for GaN and SL decrease with increasing growth temperature.

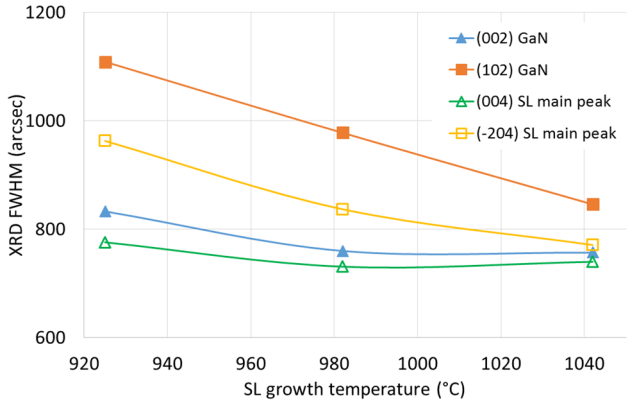

Figure 3: XRD FWHM for GaN and SL main peak as function of temperature

This indicates that a SL buffer grown at higher temperature exhibits a reduced defect density. A reduced defect density in the SL then translates in a reduced defect density in subsequently deposited GaN layers. This improvement is in contrast to the need for a certain carbon level in the SL buffer to achieve a high vertical breakdown voltage [5].

To distinguish between impact of growth temperature and carbon level on the XRD FWHM, and to explore the possibility to compensate the reduction of carbon concentration by a hydrocarbon source, another series was grown and investigated.

For this series a SL buffer was deposited at 1042°C and different hydrocarbon flows during SL buffer were applied. In fig. 4 the carbon concentration in the SL buffer as function of dopant flow is measured by SIMS is displayed. In the investigated flow regime the carbon concentration introduced by the hydrocarbon source is more than a magnitude higher than the intrinsic carbon background.

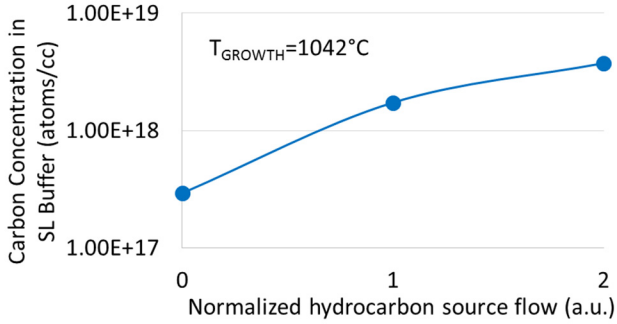

Figure 4: Carbon level as function of dopant flow at a growth temperature of 1042°C

The impact of carbon level on XRD FWHM is monitored and shown in fig. 5. By modulating the carbon level in SL buffer with the hydrocarbon source flow, only a minor increase with increasing carbon concentration – for both SL main peak and GaN – of XRD FWHM is observed. We attribute the reduced defect density - observed in fig.3 - to the increase of growth temperature and not a reduced carbon concentration.

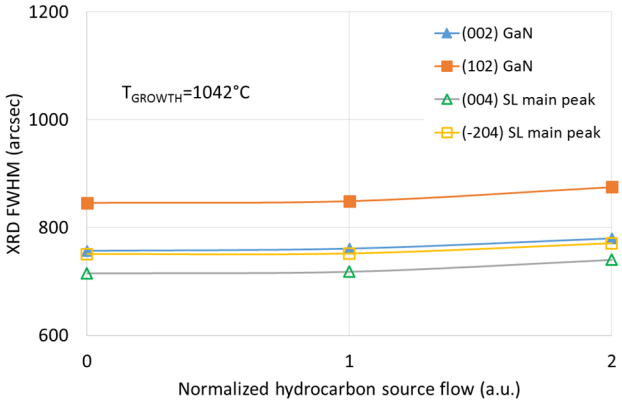

Figure 5: XRD FWHM for GaN and SL main peak as function of dopant flow

These results are in accordance with our findings on extrinsically doped GaN:C layers [5]. From fig. 4 it is obvious

that a high carbon level in the SL buffer, deposited at high temperature, can be realized by using a hydrocarbon source. Taking these findings, a SL buffer was grown at 1042°C with an optimized carbon flow for a target carbon concentration of $6 \cdot 10^{18}$ cm^{-3}. Hall measurements in a van-der-Pauw geometry show an excellent carrier mobility above 2100 cm²/Vs and a carrier concentration of $7.3 \cdot 10^{12}$ cm^{-2} with a uniform distribution. Fig. 6 shows the distribution of carrier mobility, carrier concentration and the resulting sheet resistance as box plot.

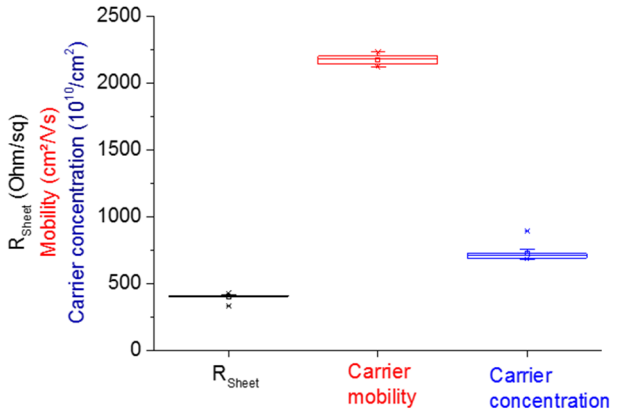

Figure 6: Box plot of R_{Sheet}, carrier mobility and carrier concentration

In fig. 7 the vertical leakage density as a function of the vertical applied voltage is shown. For voltages below 600 V a very low leakage current is observed. Above 600 V a diode-like behavior is noticed with a very uniform behavior across a 200 mm wafer. Using leakage criteria of 1 µA/mm² as soft breakdown, a breakdown voltage above 900 V is achieved.

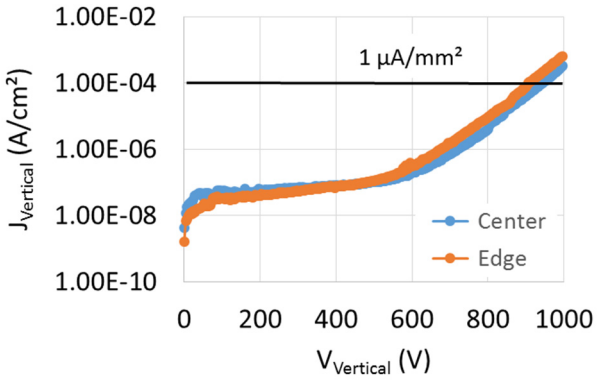

Figure 7: vertical breakdown measurements on an extrinsically doped SL buffer deposited at high temperature

Conclusion

We presented our findings for a SL buffer on Si. Deposition at elevated temperature shows an advantage to reduce the dislocation density in the SL buffer and the sub-sequentially grown GaN layers. For the first time carbon doping of a SL buffer at high temperature was presented. By using a dedicated carbon source, the carbon level can be easily adjusted to the desired concentration. This approach significantly increases the process window and the flexibility to optimize such an SL buffer.
The vertical breakdown measurements show the capability of this approach to achieve soft breakdown voltages above 900 V.

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Acronyms

FWHM: Full Width Half Maximum
MO: Metal-Organic
MOCVD: Metal-Organic Chemical Vapor Deposition
SIMS: Secondary ion mass spectrometry
XRD: X-Ray Diffraction