Effect of Carbon Doping on the Voltage-Blocking Properties of AlN/AlGaN/GaN Heterostructures

Martin Huber[1, 2, *], Ingo Daumiller[1], Andrei Andreev[1], Marco Silvestri[1], Lauri Knuuttila[1], Michael Wahl[3], Michael Kopnarski[3], Alberta Bonanni[2] and Anders Lundskog[1]

[1]Infineon Technologies Austria AG, Siemensstraße 2, A-9500 Villach, Austria
[2]Johannes Kepler University, Institute of Semiconductor and Solid State Physics, Altenbergerstrasse 69, A-4040 Linz, Austria
[3]IFOS Institut für Oberflächen- und Schichtanalytik GmbH, Trippstadter Strasse 120, D-67663 Kaiserslautern
*e-mail: martin.huberVIH@infineon.com Phone: +43 676 8205 1850

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5b

Abstract

Saturation effect of C doping on the vertical leakage current of AlN/AlGaN/GaN heterostructures is investigated. Material properties, studied using secondary ion mass spectrometry (SIMS) and atom probe tomography (APT), have been used to understand vertical leakage current behavior. For the purpose of this study, vertical blocking voltage is defined as the voltage that gives a specific current density (10 µA/mm^2). At low C-densities, the thickness normalized blocking voltage increases linearly with increasing C-concentration, with saturation occurring for high C-concentrations above ~10^{19} cm^{-3}. Interestingly, APT results show that the voltage saturation does not coincide with the onset of C-clustering.

INTRODUCTION

The AlGaN/GaN HEMT grown on Si-substrate is of high interest for high-power switch applications. One of the key requirements of such applications is a low leakage current [1]. Since as-grown unintentionally doped GaN is lightly n-type, compensation using C or Fe deep acceptors is needed. One effective way to achieve this is to introduce acceptor-like impurities like Fe or C [2 and 3]. At the moment there are various models in place for the compensation with C: (i) substitutional C on the N site (C_N) is a shallow acceptor [4], which provides auto compensation of C_N-C_{Ga} states [5] and (ii) a dominant C_N acceptor level [6]. (iii) Finally some theoretical studies had also reported deep levels arising from interstitial carbon [7] with very high formation energy during the epitaxial growth. Irrespective of which described compensation mechanism is in place, a quite high C concentration is required to get an acceptable amount of donor compensation centers.

In this work, we report on the impact of C concentration on the vertical leakage current in AlN/AlGaN/GaN heterostructures. We utilize a combination of complementary characterization techniques in order to understand the relationship between vertical leakage current, C concentrations and a possible limiting role of the C-clustering in the GaN layers. A special focus in this study is 3D APT which offers unique capabilities for clustering investigations combining 3D compositional mapping, atomic lateral resolution and high detection sensitivity up to 10 ppm [8].

EXPERIMENT

A set of AlN/AlGaN/GaN structures have been grown on Si(111) substrates by metal organic vapor phase epitaxy (MOVPE) in a multi-wafer AIXTRON planetary reactor. The epitaxial stack is shown in Fig.1(a). It consists of two parts, namely a multilayer AlN/AlGaN structure grown on the Si substrate and a subsequent C doped GaN:C layer. The thickness of the layers is 500 nm and 4500 nm and 7000 nm, respectively. In this study, only the growth conditions of the GaN:C layer systematically have been varied in order to achieve different C concentrations [9]. Supply of C atoms during the growth has also been established using a hydrocarbon gas source similar to [10]. An overview of the samples and characterizations is shown in Table 1.

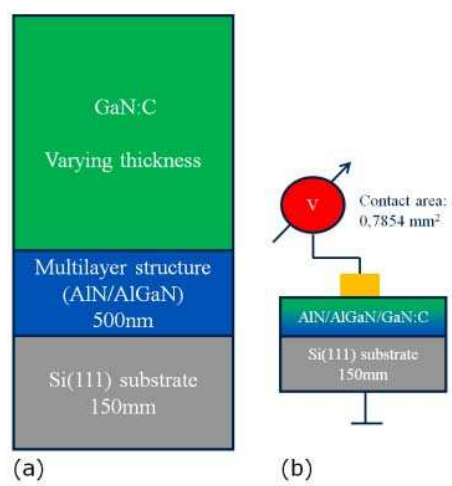

Fig.1: (a) Sketch of the studied AlGaN/GaN structure. (b) Sketch of the measurement setup for vertical leakage measurements.

Table 1: Overview of measurement, C concentration and vertical max. normalized blocking voltage for samples A-D, respectively.

Sample	**Characterization**	**C [10^{18} cm^{-3}]**	**Max. normalized vertical BV/µm**
A	SIMS, BV, APT	8	~0.8
B	SIMS, BV, APT	100	1
C	SIMS, BV, I-V plot	2.8	~0.6
D	SIMS, BV, I-V plot	35	1
rest	SIMS, BV	0.25 - 100	0.1 - 1

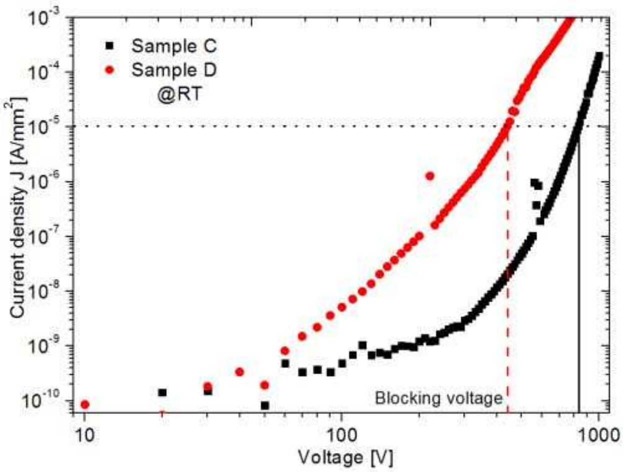

Fig.2: I-V plots for samples C and D with a C concentration of $2.8*10^{18}$cm^{-3} and $3.5*10^{19}$cm^{-3}.

In order to measure vertical leakage current, a circular contact structure of 1 mm diameter was deposited using shadow-mask patterning and e-beam evaporation of a Ti/Pt/Au metal stack. During measurement, the substrate was placed on a grounded chuck of a semi-automatic probe station equipped with a with a Keithley high voltage source (Fig.1(b)). In order to compare the different investigated heterostructures, the blocking voltage at leakage current criteria of 10 µA/mm^2 is divided by the total stack thickness:

$$\frac{BV}{\mu} = \frac{Voltage@10\mu A/mm^2}{thickness_{total}} \quad (1)$$

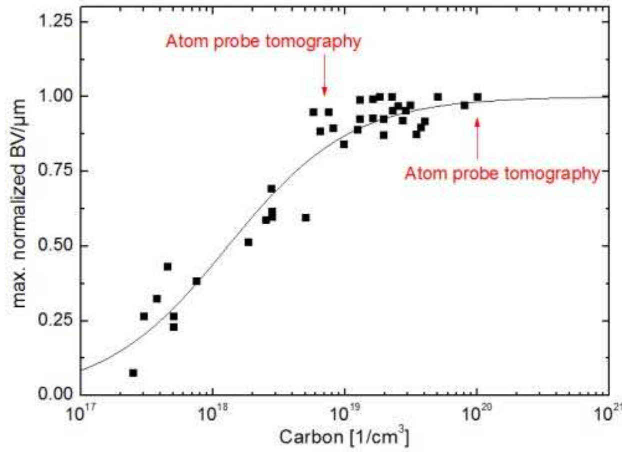

Fig.3: Maximum normalized blocking voltage per µm (BV/µm). Concentrations at which APT measurements has been carried out, are indicated.

The SIMS analysis has been performed in a Phi-Evans quadrupole secondary ion mass spectrometry system equipped with Cs primary ion source [11]. Note that with SIMS measurements only the overall concentration of C in the UID-GaN layer is obtained, while neither information on the electrically active C, nor actual incorporation site of C in the lattice can be obtained.

The APT analysis has been carried out using a LEAP 4000X HR instrument, equipped with a reflectron-type time-of-flight mass spectrometer, combined with a double multichannel plate and a triple delay line detector. The preparation of the APT tips has been done applying the cut-and-lift-out method [12], using an ALTURA 875 dual-beam focused ion beam instrument with an in situ Kleindiek micromanipulator.

RESULTS AND DISCUSSION

Room-temperature vertical I-V measurements for samples C and D doped with C concentrations of $2.8*10^{18}$ cm^{-3} and $3.5*10^{19}$ cm^{-3} are shown in Fig.2. For the vertical leakage current or blocking voltage analysis an ohmic behavior of the contact scheme is not required. The voltage drop caused by the Schottky behavior of the chosen metal system is negligible compared to the breakdown capability of the investigated epi stacks. The C concentration is expectedly showing significant impact on the I-V behavior of the different samples [13]. This means that the SI behavior is increasing towards higher C concentrations. The I-V curves plotted in Fig.2 are very typical comparing to other GaN on Si results. At the moment the research is focusing on physical explanation of the observed curves [14 and 15].

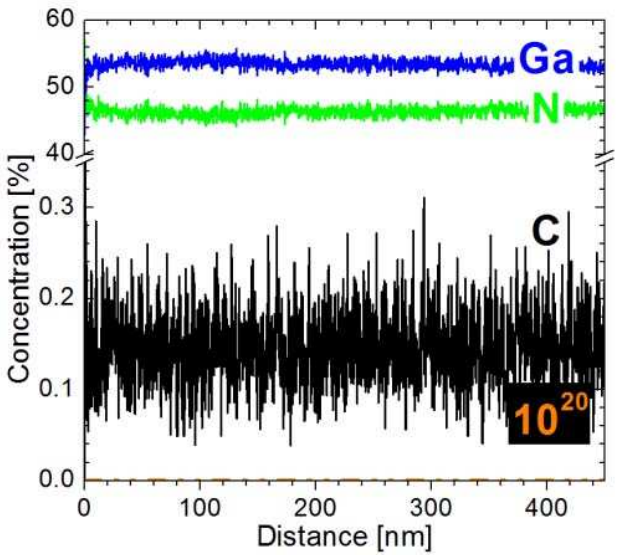

Fig.4: 1D linescan of GaN and C concentration for sample B measured with a laser power of 0.1 pJ.

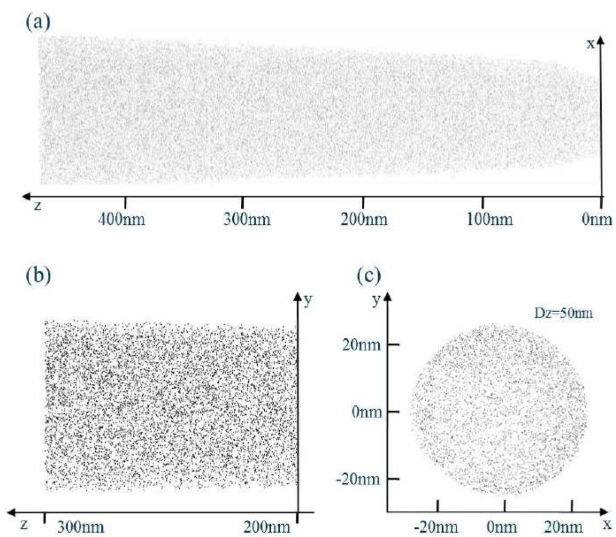

Fig.5: 3D reconstruction for sample B of all C-atoms in X-Z (a) and Y-X plane (c); zoomed 3D reconstruction in Y-Z plane (b).

The results of the SIMS and BV/µm measurements for all the samples of this study are summarized in Fig.3. If the C-concentration is low in the range of 10^{17} cm^{-3} to 10^{18} cm^{-3}, the buffer is very leaky due to intrinsic impurities arising from the MOVPE growth. In a medium range of C-doping (10^{18} cm^{-3} to 10^{19} cm^{-3}), a linear increase in the vertical blocking voltage was observed. Finally, above a C-concentration of ~10^{19} cm^{-3}, the normalized blocking voltage is found to saturate. In order to study the origin of this behavior, APT measurements have been performed to detect any possible occurrence of C-clustering. In Fig.4 one selected 1D concentration depth profile is displayed,

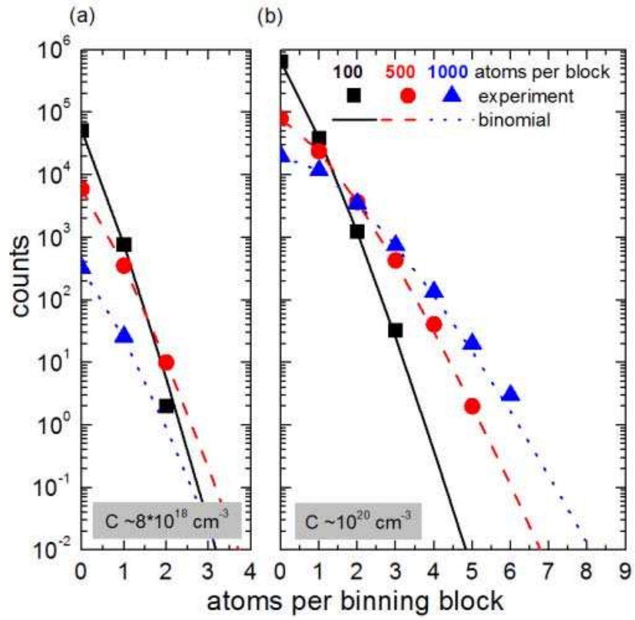

Fig.6: Frequency distribution of samples A and B with a C concentration of $8*10^{18}$ cm^{-3} (a) and 10^{20} cm^{-3} (b).

which has been measured with laser energy of 0.1 pJ. At energy this high, the obtained Ga/N ratio, which is dependent on that energy, is no longer stoichiometric. This causes the slight deviation from the expected value from the tip surface to 100 nm. A near- to-stoichiometric ratio (GaN50/50) has been achieved for laser energies of 0.03-0.06 pJ. The C concentration on the other hand is independent of the laser energy. Again there is no sign of systematical fluctuations in the C concentration as a function of the sample depth, which could be correlated with a possible clustering of the C-atoms. Different projections of the lateral distribution of all C atoms obtained from a sample with a nominal C concentration of 10^{20} cm^{-3} are shown in Fig.5. Carbon-maps seem to be homogeneous in all these views and especially no C-clusters can be found by visual inspection of the maps.

The main question regarding the APT results is if a random lateral distribution or a tendency for clustering of the C atoms in the analyzed volume exists. In order to answer this question, in addition to the simple visual inspection a statistical approach based on the frequency distribution [16] has been carried out. The data of the 3D reconstruction has been binned in 100, 500 and 1000 atom bins respectively, and the number of dopant atoms in each bin has been calculated. A regime of 100, 500 and 1000 atoms would have a spherical real space dimension of ~1, 1.5, and 2 nm in diameter. In Fig.6 the resulting plots of the frequency distribution of the C for samples A and B with C concentrations of $8*10^{18}$ cm^{-3} and 10^{20} cm^{-3} are plotted. The theoretical binomial distribution expected for the case of a random alloy is additionally plotted in Fig.6 as a solid line.

For both samples, a good agreement of the experimental data with the binomial distribution is obtained.

Conclusion

In conclusion, the influence of the C concentration on the vertical leakage current of AlN/AlGaN/GaN heterostructures has been investigated by means of vertical I-V measurements, SIMS and APT. An increasing trend of the vertical blocking voltage at a given current density from undoped conditions (~10^{17} cm^{-3}) up to a C concentration of ~10^{19} cm^{-3} is observed. For higher C concentrations than ~10^{19} cm^{-3} no further increase of the vertical blocking voltage can be obtained. The APT results are indicating that there is no clustering of C in the GaN lattice for a concentration range up to ~10^{20} cm^{-3}. Thus a clustering of C atoms can be excluded from the possible mechanisms for this vertical blocking voltage saturation.

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Acronyms

GaN:	Gallium nitride
AlN:	Aluminum nitride
AlGaN:	Aluminum gallium nitride
MOVPE:	Metal organic vapor phase epitaxy
HEMT:	High electron mobility transistor
2DEG:	Two dimensional electron gas
SI:	Semi-insulating
SIMS:	Secondary ion mass spectrometry
APT:	Atom probe tomography
IV:	Current-voltage
RT:	Room-temperature