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ABSTRACT
This work describes electrical characteristics and the correlation to material properties of high electron mobility transistor structures with a C-doped GaN current blocking layer, grown either by an extrinsic or auto-doping process with different doping levels. Increasing degradation of crystalline quality in terms of threading dislocation density for increasing C-doping levels was observed for all samples. Different growth conditions used for the auto-doped samples played no role for overall degradation, but a higher fraction of threading screw dislocations was observed. Independent of the doping process, 90% of all TSDs were noted to act as strong leakage current paths through the AlGaN barrier. This was found statistically and was directly verified by conductive atomic force microscopy in direct correlation with defect selective etching. Vertical breakdown was observed to increase with increasing C-concentration and saturated for C-concentrations above around $10^{19}$ cm$^{-3}$. This was attributed to an increasing compensation of free charge carriers until self-compensation takes place. A progressive influence of TDs for high C-concentrations might also play a role but could not be explicitly revealed for our material.

I. INTRODUCTION
Wide bandgap semiconductor materials such as silicon carbide, gallium nitride (GaN), aluminum nitride, or diamond are gaining fast growing interest for the power and optoelectronic device market. GaN grown heteroepitaxially on silicon (GaN/Si) and the application of AlGaN/GaN high electron mobility transistors (HEMTs) are cost-effective solutions for fast switching devices and devices with a high electrical breakdown. However, GaN grown by Metal Organic Chemical Vapor Deposition (MOCVD) always shows n-type behavior due to the incorporation of background impurities such as O and Si and due to intrinsic point defects acting as shallow donors. Free charge carrier compensation is necessary for ensuring best electrical blocking capability as needed for AlGaN/GaN HEMTs. For power devices, this compensation is usually achieved by doping with C. In n-type GaN, C predominantly incorporates as the deep acceptor C$_{N}$. For high C-concentrations or positions of the Fermi level near the middle of the bandgap, self-compensation takes place as formation of C$_{N}$ and C$_{Ga}$ becomes equally favored under N-rich growth conditions. C-doping of GaN can be realized either by auto-doping or by extrinsic doping. Auto-doping means doping by adjusting growth conditions such as temperature, pressure, or V/III-ratio in order to promote incorporation of C from background C-impurities. Such a doping process
II. EXPERIMENTAL DETAILS

All samples were grown by MOCVD on 200 mm p-type Si(111) and exhibit identical layer structures. The layer stack is depicted in the inset of Fig. 1(a) and consists of an AlN nucleation layer, step-graded AlGaN strain relief layers of 1.7 μm, a 2 μm thick C-doped GaN-layer, an unintentionally doped GaN channel layer with a thickness of 300 nm, an AlGaN$_{0.26}$N barrier (x = 0.26) of 21 nm, and a few nm thick GaN-cap on top. Samples E$_1$, E$_2$, and E$_3$ with a C-doped GaN-layer grown at a temperature of 1050 °C are extrinsically doped with ethene (10% C$_2$H$_4$ in H$_2$) as the C-source. The ethene-flux was the only varied growth parameter between these three samples and was generally negligible in its amount compared to the total gas flux. Resulting C-concentrations are 5.7 × 10$^{17}$ cm$^{-3}$ (sample E$_1$), 4.0 × 10$^{18}$ cm$^{-3}$ (sample E$_2$), and 1.0 × 10$^{19}$ cm$^{-3}$ (sample E$_3$) as measured by Secondary Ion Mass Spectrometry (SIMS). Sample A$_0$ is an auto-doped sample, grown under identical conditions as samples E$_1$ to E$_3$, but without additional supply of ethene. The C-concentration is 1.5 × 10$^{17}$ cm$^{-3}$. Sample A$_1$ is also auto-doped, but the C-doped GaN-layer was grown at a temperature of 965 °C and a slightly lower pressure, leading to a C-concentration of 8.5 × 10$^{16}$ cm$^{-3}$. For electrical measurements, Ti/Al/Ni/Au ohmic contacts of 100 × 100 μm$^2$, annealed at 830 °C for 60 s under N-atmosphere and BCl$_3$-based mesa-etching, were deposited on all samples. X-Ray Diffraction (XRD) was carried out with a Phillips X’Pert PRO four-circle diffractometer. Rocking curve full width half maximum (FWHM) values for the (002) and (102) reflections were measured with an open detector configuration. Cathodoluminescence (CL) was measured at room temperature with a Gatan MonoCL3 spectrometer attached to a Jeol JSM-7500F Scanning Electron Microscope (SEM). Selective Etching (DSE) was carried out in eutectic melt of KOH and NaOH at 450 °C for 4 min and the etch pits were observed by SEM. A Bruker Dimension Icon doped Si-tips with B-doped diamond coating were used for Conductive Atomic Force Microscopy (C-AFM) investigations performed on as-grown samples.

III. RESULTS AND DISCUSSION

A. Structural quality

In Fig. 1(a), the GaN(002) and GaN(102) rocking curve FWHMs and (b) TD- and TSD-densities obtained by DSE vs C-concentration of GaN by extrinsic (E$_1$, E$_2$, E$_3$) and auto-doping (A$_0$, A$_1$). (c) Relation between FWHM values from (a) and TD-TSD-densities from (b). Solid lines represent logarithmic or linear fits, respectively, and dashed lines are extrapolations.
of the corresponding C-doped GaN-layers. The error bars indicate the total range of C-concentration measured within these layers. FWHM values of the GaN(002) peak monotonically increase from 322 arcsec for sample A0 to 434 arcsec for sample A1. The GaN(002) signal behaves correspondingly. Material degradation in terms of larger FWHM values of samples A0 over E1 to E3 and corresponding C-concentrations are apparently directly related to ethene-flux during growth. Thus, a direct correlation between observed FWHMs and C-concentrations exists for these four samples, and logarithmic fitting was performed. Extrapolation of the GaN(002) values toward sample A1 gives good agreement despite its different growth temperature and pressure. In contrast, the extrapolated FWHM value of GaN(002) of sample A0 is significantly lower than the experimentally measured value. It is well known that the (002) FWHM is sensitive to all types of TDs, i.e., TSDs, threading edge (TEDs), and threading mixed (TMDs) dislocations, but the FWHM is sensitive to TDs at the near-surface AlGaN/GaN interface. Therefore, a higher fraction of TDs with screw component is expected for sample A1.

Densities and types of TDs were analyzed by DSE,15,16 which is sensitive to TDs at the near-surface AlGaN/GaN interface.17 This was achieved by counting all etch-pits on an area of $20 \times 20 \, \mu\text{m}^2$ and analyzing their diameter by observation in an SEM, where large etch pits have been identified with TSDs. The relation between TD-/TSD-densities determined by DSE and corresponding C-concentrations is shown in Fig. 1(c). TD-/TSD-densities increase from $6.7 \times 10^8 \, \text{cm}^{-2}/2.7 \times 10^7 \, \text{cm}^{-2}$ for sample A0 to $1.7 \times 10^9 \, \text{cm}^{-2}/8.8 \times 10^7 \, \text{cm}^{-2}$ for sample A1 with an assumed error of 10%. The obtained values are typical for GaN/Si and are around three orders of magnitude higher as compared to free-standing GaN grown by Hydride Vapor Phase Epitaxy (HVPE).17,18 Logarithmic fitting was performed equivalent to that of FWHM values. Extrapolation of the TD-density toward sample A1 shows good agreement with the experimentally measured value, which was expected from the results in terms of GaN(002) FWHMs. This means that extrinsic and auto-doped samples show an identical dependence of material degradation due to TDs as a function of C-concentration in our case. Thus, the TD-density seems to be dominantly affected by C-incorporation itself and not by potentially non-ideal growth conditions used for auto-doping. Other studies also observed an increase in TD-density with an increase in C-concentration.9,12 However, the extrapolated TSD-density of sample A1 underestimates the experimental value. Thus, growth conditions used for auto-doping lead to a higher fraction of TSDs in our case. Concerning results for the GaN(002) FWHMs, a higher fraction of TDs with screw component was expected. As direct investigation of TMD-density by DSE is challenging for GaN/Si, the relation between GaN(002) FWHMs and TSD-density was investigated in Fig. 1(c). Linear fitting of samples A0, E1, E2, and E3 was performed and extrapolation toward sample A1 gives very good agreement. As TMD-densities are usually around one order of magnitude higher than TSD-densities in GaN/Si, this is indicative for a constant fraction of TMDs in all samples and therefore for a higher TSD-fraction.

### B. Devices: Vertical leakage and breakdown

Electrical performance in terms of vertical leakage and breakdown was characterized by two terminal measurements. Figure 2(a) shows the current–voltage characteristics recorded between an Ohmic contact on top and the Si substrate. The leakage current decreases from sample A0 to A1 over the entire investigated voltage range. Vertical breakdown was defined as the voltage corresponding to a leakage current density of 10 mA/cm² and alternatively to 1 $\mu\text{A/mm}^2$. Different vertical leakage behavior and/or breakdown voltages of GaN/Si structures with identical layer stacks can have their origin in different carrier concentrations, TD-densities, TD-clustering, or densities of extended defects.20–23 Clustering of TDs at the AlGaN/GaN interface was analyzed by panchromatic CL mappings with a beam energy of 3 keV.24 Figure 3 exemplarily shows the results for samples A0 and A1. No significant correlation between the density of local TD-clusters and C-concentration could

![FIG. 2](image-url) (a) Vertical IVs with dashed lines indicating the two used definitions of vertical breakdown. (b) Mean of vertical breakdown voltages calculated from (a) for both definitions in dependence of corresponding C-concentration and TD-density. (c) Density of leakage paths through the AlGaN-barrier observed by C-AFM vs TSD-density determined by DSE. Both the solid and dashed line are lines through the origin with the solid one being a fit.
be observed. Therefore, we assume that TD-clustering plays no role in our case. Extended defects such as V-pits are unlikely as well. Their formation is very sensitive to the growth conditions of the AlN nucleation layer, which were identical for all samples. Carrier concentrations in each layer can be affected by corresponding growth conditions as they can strongly influence the incorporation of native and impurity related point defects. The concentration of native point defects is unknown in our samples, but we assume them to be similar at least for samples A₀, E₁, E₂, and E₃ due to the same growth conditions. O-concentrations were measured by SIMS to be 6.0×10¹⁵ cm⁻³ (sample A₀), 4.1×10¹⁵ cm⁻³ (sample E₁), 3.7×10¹⁵ cm⁻³ (sample E₂), 3.6×10¹⁵ cm⁻³ (sample E₃), and 3.2×10¹⁵ cm⁻³ (sample A₁) and are very similar for all samples. The relation between vertical breakdown and C-concentration and TD-density is depicted in Fig. 2(b). An increase of breakdown voltage with an increase in C-concentration is observed. Above a C-concentration of around 10¹⁹ cm⁻³, breakdown saturates at around 400 V for 1 μA/mm² and 650–700 V for 10 mA/cm². We assume that this saturation is predominantly due to the self-compensation of the C-doped GaN-layer. As shown in Fig. 1(b), the TD-density increases with the increase in C-concentration. Consequently, vertical breakdown is an increasing function of the TD-density in our case. Under the assumption that TDs have either a negative or no effect on vertical breakdown, this allows the following conclusions: (i) below the point of saturation, the effect of free carrier compensation with the increase in C-concentration dominates over that of an increasing TD-density and explicitly also over that of TDs with screw component as they exhibit a constant fraction for samples A₀, E₁, E₂, and E₃. (ii) The observed saturation of the breakdown voltage with the increase in C-concentration might be supported by a progressive influence of TDs. (iii) The absolute value of the breakdown voltage corresponding to the point of saturation might shift to lower/higher values for material with significantly higher/lower TD-density as compared to our investigated samples. (iv) In our experimental results, no negative influence of TDs on vertical breakdown could be resolved. The standard deviations of observed breakdown voltages are 0.5%–3.0% of the samples’ mean breakdown values and thus indicative for a mechanism related to a material characteristic that is continuously and homogeneously distributed over the wafer and/or to defects that are frequently present in the material underneath the Ohmic contacts. Both fit well to the assumption of dominating compensation-related effects. Therefore, we explain the current–voltage characteristics in Fig. 2(a) as follows: the first strong increase in leakage current with the voltage is directly related to the electrical conductivity of the C-doped GaN-layer or to its compensation level, respectively. With the increase in voltage, the influence of other layers than the C-doped GaN-layer become dominant, and the total current conduction mechanism changes, e.g., to a space-charge-limited mechanism. The second steep increase appears due to the formation of an inversion layer at the interface between Si and the AlN nucleation layer. This takes place earlier for low C-concentrations as the voltage drop across the C-doped GaN-layer is lower and that across the AlN/Si interface is higher, respectively. Formation of this inversion layer goes along with electron injection from Si into AlN and a steep increase of leakage current.
C. Microstructure: Vertical leakage

Besides device leakage and breakdown, the distribution of microstructurally related leakage paths was directly investigated by C-AFM. TDs with screw component are widely suspected to act as current leakage paths and are therefore potential candidates for device reliability degradation.\textsuperscript{7,27} A bias of $\pm 5$ V was applied to the Si substrate with the AFM tip being grounded. Figure 3 shows the result for sample $A_0$ and $A_1$, recorded on the same region as the CL-mappings. The density of strong leakage spots with an estimated error of 10\% was analyzed on a scale of $20 \times 20 \mu m^2$ for all samples and increased from sample $A_0$ over $E_1$, $E_2$, $E_3$ to $A_1$. The relation between leakage spot density and TD-density was investigated by additionally performing DSE on a different region of $20 \times 20 \mu m^2$. The result is shown in Fig. 2(c). A common distinct linear relation with a slope of 0.9 was found. Verification of this result was performed exemplarily for samples $A_0$ and $A_1$ by direct correlation of C-AFM and DSE on the same place. Results are illustrated in Fig. 3 for sample $A_0$ and $A_1$. Beside very few artifacts, Fig. 3 shows that all observed prominent leakage spots indeed consistently correspond to TDs (red circles). However, a fraction of around 10\% of TDs does not show a leakage spot (blue circles). This result is in good agreement to findings in Fig. 2(c). It was already shown in previous studies that electrical properties of a TD are not clearly defined by its type only.\textsuperscript{17,28,29} A correlation of observed device leakage behavior and breakdown values to leakage spot densities is not justified as the samples differ by C-concentration additionally. Low C-concentrations result in higher leakage due to low compensation, but lower leakage due to TDs. High C-concentrations result in lower leakage due to higher compensation, but higher leakage due to TDs. Thus, both effects act against each other with the compensation being dominant at high voltages as discussed above. Consequently, the observed vertical breakdown is an increasing function of the leakage spot density. Additionally, one has to note that a leakage spot observed in Fig. 3 needs not to be necessarily representative for a vertical leakage path through the whole layer stack, but through the AlGaN barrier.\textsuperscript{1} The reason for this is the two dimensional electron gas at the AlGaN/GaN-interface, which is able to shunt the buffer. Therefore, the C-AFM current mappings recorded at low voltages show variations in current flow through the AlGaN-barrier only and no direct conclusions about buffer leakage can be drawn. However, leakage at high voltages and vertical breakdown are determined by buffer properties. On the other hand, the observed trend to a higher density of leakage paths through the AlGaN-barrier with the increase in C-concentration is indicative for a potentially degrading GaN HEMT reliability, especially when grown in an auto-doped process exhibiting a higher TD-fraction.\textsuperscript{30,31}

IV. CONCLUSION

In conclusion, extrinsic and auto-doping exhibit an identical relation between increasing material degradation and the increasing C-doping level. It was found that this degradation is caused by TDs, which dominantly form due to C-incorporation itself and not due to growth conditions used in auto-doping processes. In general, lowest TD-densities in GaN were achieved when aiming for lowest possible C-incorporation. However, vertical leakage/breakdown were observed to be highest/lowest in such a case and to saturate for C-concentrations above $10^{19}$ cm$^{-3}$. This shows that TDs only had a minor influence on breakdown in the investigated voltage regime up to around 700 V, but the grade of buffer compensation was crucial. In our samples, 90\% of all TDs act as microstructural leakage current paths through the AlGaN-barrier. Thus, for a constant fraction of TDs, a higher density of such leakage paths was observed for higher TD-densities or higher C-doping levels in the buffer, respectively. Consequently, there is no straightforward correlation between barrier leakage paths and vertical leakage at high biases or vertical breakdown. However, as growth conditions used for auto-doping favored the formation of a higher fraction of TDs, a superior device reliability is expected for extrinsically doped samples as compared to auto-doped samples with the same C-doping level.

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