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Carbon doping of non-polar cubic GaN by CBr_4

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ABSTRACT

Non-polar carbon-doped cubic GaN (c-GaN:C) films were grown by the plasma-assisted molecular beam epitaxy (MBE) using carbon tetra-bromide (CBr_4) as a carbon source. The growth was in-situ monitored by the reflection high-energy electron diffraction (RHEED) and for the atomic carbon detection quadrupole mass spectrometry (QMS) was applied. Time-of-flight secondary ion mass spectroscopy (ToF-SIMS) was used to quantify the carbon incorporation behavior. The structural, morphological and optical properties of the epilayers were studied by high-resolution X-ray diffraction (HRXRD), atomic force microscopy (AFM) and photoluminescence (PL) measurements at room temperature and at 4 K. The electrical properties of c-GaN:C samples were determined by measuring the current–voltage (*I*–*V*) characteristics at room temperature.

1. Introduction

Due to the absence of polarization fields in non-polar cubic group III-nitrides phase pure cubic GaN/AlGaN heterostructures may offer the realization of normally-on and normally-off operation of hetero field-effect transistors (HFETs) with the large technological allowance and the same flexible device design ability as the GaAs/AlGaAs HFET technology [1]. For such devices a highly insulating GaN buffer layer has a pivotal role in HFET fabrication since it provides a good electrical isolation from the substrate interface for accurate determination of electrical properties and considerably improves the rf-performance of the devices by suppressing the parasitic capacitance. In polar hexagonal nitrides carbon [2], beryllium [3] and iron [4] have been used to achieve high-quality semi-insulating GaN buffer layers. In this contribution we show that C-doping by carbon tetra-bromide (CBr_4) is suitable to produce highly resistive non-polar cubic GaN (c-GaN) epilayers.

2. Experiment

c-GaN epilayers were grown by rf-plasma-assisted molecular beam epitaxy (MBE) on conducting free-standing 3C-SiC (0 0 1) substrates [5]. Carbon doping via CBr_4 is investigated as a means to produce semi-insulating GaN buffer layers for device applications [6]. The growth was in situ monitored by reflection high-energy electron diffraction (RHEED) [7] and quadrupole mass spectrometry (QMS) was applied to detect the atomic carbon. Time-of-flight secondary ion mass spectrometry (ToF-SIMS) was used to quantify the C incorporation behavior. The C-concentration was calibrated via reference samples, in which a defined amount of C was built in by the ion implantation. The electrical and optical properties were investigated by low-temperature photoluminescence (PL) and current–voltage (*I*–*V*) characteristics, respectively.

3. Results and discussion

For ToF-SIMS measurements a 500-nm-thick GaN sample containing three different amounts of C-concentrations was prepared on free-standing 3C-SiC substrate. In Fig. 1 the measured depth profiles of C, Br and GaN is depicted. Whereas the GaN concentration is constant all over the c-GaN epilayer thickness, three clear regions with different C-concentrations can be identified in the C-profile. In the inset of Fig. 1 the incorporated C-concentration is plotted vs. the CBr_4 flux. This measurement shows that the amount of incorporated C is linearly related to the incident CBr_4 flux and varies between 2×10^{19} and $6\times10^{19}\,cm^{-3}$. The Br concentration is at the SIMS detection limit ($\sim10^{15}\,cm^{-3}$) and indicates that no Br is built in. This behavior is similar to that observed in hexagonal GaN [2].

The reciprocal space map of the (0 0 2) reflection of a c-GaN epilayer homogeneously doped with a C-concentration of $\sim4\times10^{19}\,cm^{-3}$ is shown in Fig. 2. Besides the 3C-SiC and the c-GaN reflection at ($0\,Å^{-1}$, $2.83\,Å^{-1}$) and ($0\,Å^{-1}$, $2.785\,Å^{-1}$),

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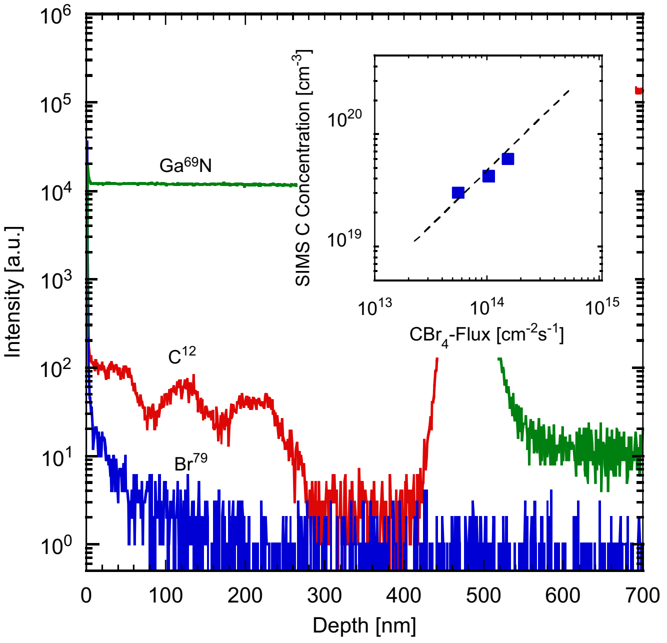

Fig. 1. SIMS depth profiles of GaN, C and Br of a C-doped cubic GaN epilayer which contains three different C-doping levels. The inset shows the incorporated C-concentration measured by SIMS vs. CBr$_4$ flux.

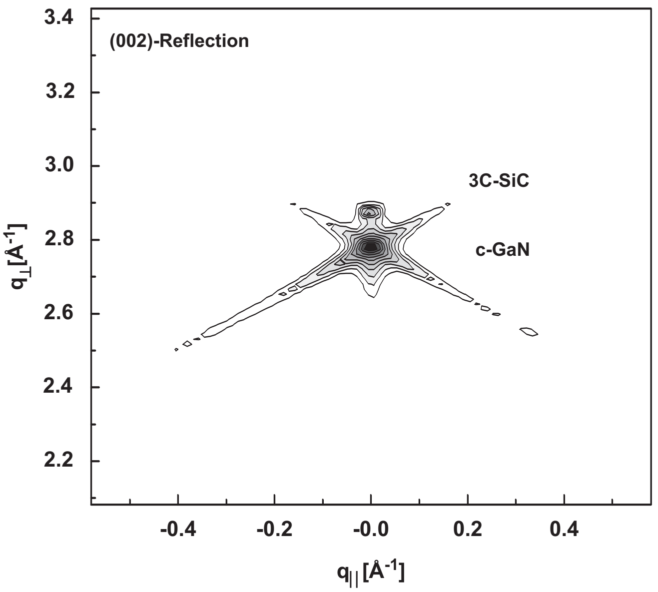

Fig. 2. Reciprocal space map of the (0 0 2) reflection of C-doped cubic GaN/3C-SiC epilayer ([C]~4×10^{19} cm^{-3}).

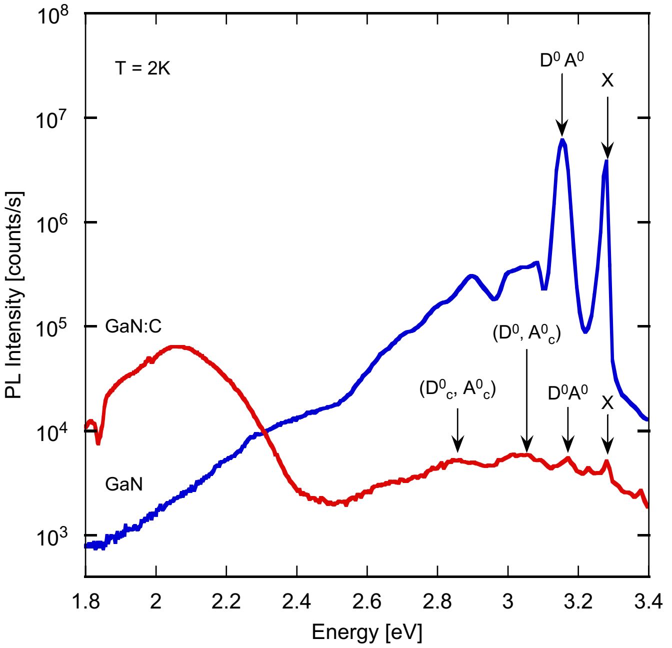

Fig. 3. Low-temperature photoluminescence spectra of undoped (blue) and C-doped (red, [C]~4×10^{19} cm^{-3}) cubic GaN/3C-SiC epilayers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

respectively, no additional (0 0 0 2) or (1 0 $\bar{1}$ 1) reflections of the hexagonal GaN is detectable at (0 Å^{-1}, 2.4 Å^{-1}) or (−0.4 Å^{-1}, 2.5 Å^{-1}). Therefore, no degradation of the phase purity and structural properties of the c-GaN epilayers is observed up to a C-concentration of ~10^{20} cm^{-3}. Atomic force microscopic (AFM) measurements further show that also the surface roughness is not deteriorated due to C-doping and a typical rms roughness (5×5 μm^2) of about 5 nm is measured for both undoped and C-doped samples.

The incorporation of C has a profound influence on the optical properties as studied by the low-temperature PL. In Fig. 3 the spectra of a nominally undoped c-GaN sample (blue curve) and a C-doped c-GaN sample (red curve, [C] ~4×10^{19} cm^{-3}) are depicted. In the undoped GaN sample the PL-spectrum is dominated by the exitonic transition X at 3.28 eV and the omnipresent donor acceptor (D^0A^0) transition at 3.15 eV [8]. The PL-spectrum of the C-doped sample is dominated by a deep-red luminescence band, which appeared at 2.1 eV. In addition, the integral PL-intensity is severely reduced indicating the compensation effects. The PL peaks assignment is based on previous publications [9–11], where temperature- and intensity-dependent PL measurements were performed on c-GaN epilayers deposited on GaAs substrates. In these c-GaN samples grown on GaAs substrates, where an e-beam evaporation source was used to incorporate C, a clear correlation between different PL transitions and the build in C was found [9–11]. It is well known that C can be incorporated at different lattice sites acting either as an acceptor, if it replaces nitrogen (C_N) or acting as a donor if it replaces gallium (C_{Ga}) [12]. Following the discussions in Refs. [10] and [13], we attribute the ($D^0_CA^0_C$) transition at 2.85 eV to the donor acceptor-transitions from C_{Ga} to C_N and the ($D^0A^0_C$) transition at 3.085 eV to a donor acceptor-transition form an omnipresent residual donor in GaN to C_N. Both transitions are indicated in Fig. 3 by arrows. Up to now, the chemical identity of the residual donor is unknown, however O may be a good candidate for it.

Among substitutional insertion of C into the GaN films carbon may also be incorporated on an interstitial site or form diverse complexes. Such complexes may act as non-radiative centers, which reduce the overall PL-intensity or form deep defects, which may compensate the free carriers resulting in semi-insulating epilayers. The appearance of the deep-red luminescence band at 2.1 eV at highly C-doped GaN epilayers ([C]$\geqslant 1\times10^{18}$ cm^{-3}) is a sign for such compensation effects.

Concomitant to the reduction in the integral PL-intensity a strong increase in resistivity of the GaN:C epilayer is observed. Unfortunately, due to the low specific resistivity of the free-standing 3C-SiC substrates (ρ ~6.6×10^{-3} Ω cm) Hall-effect measurements on the GaN epilayers itself could not be performed. Therefore, to get an idea of the influence of C-doping on the electrical properties of c-GaN *I–V* measurements on well-defined

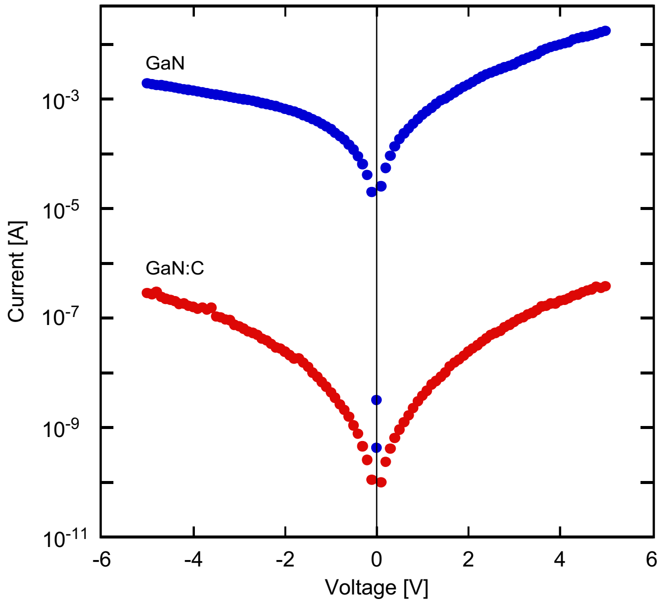

Fig. 4. Room temperature current–voltage characteristics (log scale) measured between two ohmic Ti/Al contacts of an undoped (blue, upper curve) and a C-doped (red, lower curve, $[C]\sim4\times10^{19}\,cm^{-3}$) cubic GaN epilayer. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Ti/Al contacts have been carried out. Two circular Ti/Al (30 nm/100 nm) ohmic contacts with a diameter of 300 μm and a center distance of 1.1 mm were produced by thermal evaporation. Fig. 4 shows the *I–V* characteristics of both the undoped and the C-doped samples in a semi-logarithmic scale. One clearly sees that the current flowing through the C-doped samples (red lower curve) is by more than four orders of magnitude lower than that for the undoped c-GaN layer (blue upper curve).

4. Conclusion

The growth of highly resistive non-polar c-GaN:C films via rf-plasma-assisted MBE under Ga-rich growth conditions is demonstrated. SIMS measurements showed that the amount of incorporated C is linearly related to the incident CBr_4 flux and that no Br is built in. No degradation of the phase purity and structural properties of the c-GaN epilayers is observed up to a C-concentration of $\sim10^{19}\,cm^{-3}$. At high C-doping levels the near band edge luminescence is strongly decreased and a deep-red emission band appeared. At the same time the resistivity of the GaN:C epilayer is increased by more than four orders of magnitude. These results demonstrate that C-doped GaN epilayers via CBr_4 can effectively be used to produce reliable and stable semi-insulating templates for future electronic devices.

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