Doping of MBE grown cubic GaN on 3C-SiC (001) by CBr_4

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Abstract. We report on carbon doping of cubic GaN by CBr_4 using plasma-assisted molecular beam epitaxy on 3C-SiC (001) substrates. The samples consist of a 70 nm thick GaN buffer followed by a 550 nm thick GaN:C layer. Carbon doping is realized with a home-made carbon tetrabromide sublimation source. The CBr_4 beam equivalent pressure was established by a needle valve and was varied between $2x10^{-9}$ mbar and $6x10^{-6}$ mbar. The growth was controlled by in-situ reflection high energy electron diffraction. The incorporated carbon concentration is obtained from secondary ion mass spectroscopy. Capacitance voltage characteristics were measured using metal-insulator-semiconductor structures. Capacitance voltage measurements on nominally undoped cubic GaN showed n-type conductivity with N_D-N_A=$1x10^{17}$ cm^{-3}. With increasing CBr_4 flux the conductivity type changes to p-type and for the highest CBr_4 flux N_A-N_D=$4.5x10^{18}$ cm^{-3} was obtained.

Keywords: cubic GaN, MBE, C-doping
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1. INTRODUCTION

Controlled p-type doping is crucial for advanced electronic and optoelectronic devices based on group-III nitrides, like heterojunction bipolar transistors (HBTs), light emitting diodes (LEDs), or laser diodes (LDs) [1,2]. In heterojunction field effect transistors (HFETs), carbon doping can be used to reduce the conductivity of the GaN bulk layer, which typically shows n-type character.

In this paper we report on doping experiments of GaN with cubic crystal structure. Compared to other dopants in cubic (Al)GaN materials, such as magnesium, carbon has a very low diffusion coefficient [3]. It is also known from p-doping in (Al)GaAs that carbon doping is less sensitive on the composition of ternary compounds [4]. Thus it is well suited for the fabrication of p-doped distributed Bragg reflector (DBR) structures for vertical-cavity surface-emitting laser (VCSEL) application. Carbon tetrabromide (CBr_4) has become widely used as carbon source in molecular beam epitaxy (MBE) since high doping concentrations can be reached using CBr_4. Further no carrier gas is needed to transport the CBr_4 molecules to the sample surface and a CBr_4 doping system can be easily incorporated into the MBE without modifying the existing pumping system.

2. EXPERIMENTAL

Carbon doped cubic GaN layers were grown by plasma assisted MBE at 720 °C on free standing, highly conductive 3C-SiC (001) substrates under one monolayer of excess Ga [5]. A 70 nm thick cubic GaN buffer layer was first deposited to adjust the growth conditions, followed by a 550 nm thick GaN:C layer. The morphology and the structural properties were analyzed by atomic force microscopy and high resolution x-ray diffraction. These measurements show that carbon doping has no influence on the structural properties. The carbon source is a self-made CBr_4 sublimation source connected directly to the MBE chamber. The cylinder with solid CBr_4 powder is kept at constant temperature by a heating jacket with a temperature controller; a gas line connects the source to the MBE system. To avoid sublimation in the gas line it is permanently heated to 65 °C. The CBr_4 beam equivalent pressure (BEP) was established by a needle valve and was varied between $2x10^{-9}$ mbar and $6x10^{-6}$ mbar. For BEP calibration the temperature of the CBr_4 source was 20 °C, and the BEP was measured at the sample position. By varying the setting of the needle valve the BEP was varied.
The incorporation of carbon in our c-GaN layers was measured by secondary ion mass spectroscopy (SIMS). Cubic GaN layers with a given dose of implanted C^+ ions were used as reference samples. A carbon concentration of $1x10^{17}$ cm^{-3} was found in a nominally undoped sample. We assume that this background carbon concentration is due

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to residual C-compounds in the MBE chamber. A maximum carbon incorporation of $7.5 x 10^{19}$ cm^{-3} was reached with our doping system.

The electrical characterization of the carbon doped GaN layers was performed by capacitance-voltage (CV) measurements on metal-insulator-semiconductor (MIS) structures. Because of the high conductivity of the 3C-SiC substrates the doping concentration in our samples can not be obtained from Hall measurements. The isolation layers of the MIS structures were 100 nm thick Si_3N_4 which was deposited by plasma enhanced chemical vapour deposition. Using standard lithography, round contact structures with a diameter of 100 µm were placed on top of the isolation layer. Metal gate contacts consisting of 15 nm Ni and 50 nm Au were thermally evaporated. The Ohmic contacts were realized by soldering a Cu plate with In onto the SiC substrate. The capacity was measured with an Agilent E4980A universal-LCR-Meter.

3. RESULTS AND DISCUSSION

3.1 CV-measurements

We used MIS structures for CV measurements. Former experiments have shown that Si_3N_4 is appropriate for the applied dc voltage region. In Fig. 1 a) and b) the measured capacitance is shown as a function of the applied DC voltage. Fig. 1 a) shows CV-characteristics from nominally undoped and low carbon doped samples. From the slope of the CV curve we find that in these layers the concentration of donors N_D exceeds that of acceptors N_A. The CV characteristic of a highly doped sample is shown in Fig. 1 b). This GaN:C layer was grown with a CBr_4 BEP of $6 x 10^7$ mbar. The diagram shows the characteristic of a p-n-junction resulting from the interface between n-type 3C-SiC and the carbon doped c-GaN layer.

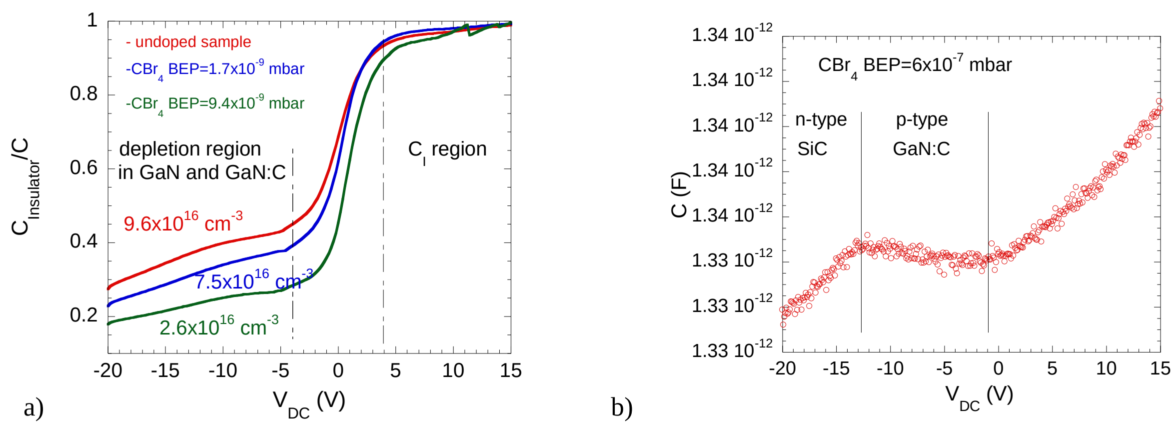

FIGURE 1. Capacitance as a function of the applied DC voltage of a) an undoped and two samples with a low level of carbon doping, b) GaN:C grown with a CBr_4 BEP of $6 x 10^{-7}$ mbar.

The net donor or acceptor concentration was obtained from the slope of the CV curve by equ.1:

$$N_A - N_D = \frac{2}{e\varepsilon_0\varepsilon_r \frac{d(1/C^2)}{dV}} \qquad (1)$$

Calculations for N_D-N_A in the SiC region reveal donor concentrations of about $(3\text{-}5) x 10^{18}$ cm^{-3}. These values are typical for our 3C-SiC substrates and are comparable to Hall-measurement results (n = $(1\text{-}5) x 10^{18}$ cm^{-3}) in former experiments.

The slope of the CV curve in the GaN:C region is positive for samples with a low doping level (Fig 1a) while it is negative for high carbon concentrations in the c-GaN layers, which indicates a surplus of acceptors (Fig.1b). The CV measurements show that at low carbon doping levels compensation of native donors in cubic GaN takes place. The nature of these donors is not fully identified yet, supposably they are oxygen atoms contained in the nitrogen gas.

Fig. 2 shows $|N_A\text{-}N_D|$ concentration as a function of the CBr_4 BEP. The diagram is divided into two regions, the donor dominated region for lower BEP of CBr_4 and the acceptor dominated region at higher CBr_4 flux. The excess donor concentration in GaN changes to an excess acceptor concentration at a CBr_4 BEP of $3.8\text{x}10^{-8}$ mbar.

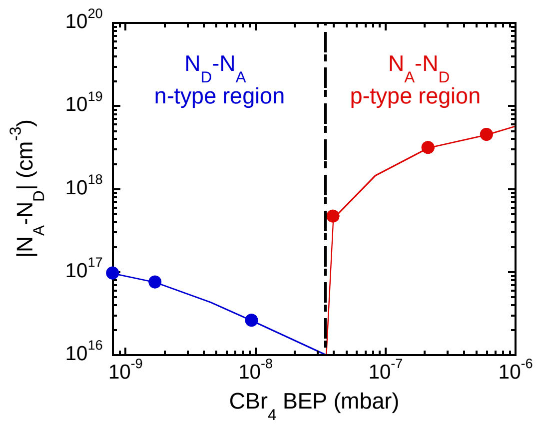

FIGURE 2. $|N_A\text{-}N_D|$ as a function of the CBr_4 BEP. The full lines are guides for the eye.

3.2 Discussion

To obtain the fraction of incorporated carbon acting as an acceptor we calculate the carbon concentration in our samples making the following assumptions: The donor concentration is constant in all measured samples. Its value is $1\text{x}10^{17}$ cm^{-3}.

The incorporated carbon concentration is proportional to the CBr_4 BEP. A layer doped with a CBr_4 BEP of $6\text{x}10^{-7}$ mbar and an undoped c-GaN layer were used for calibration. SIMS revealed a carbon concentration of $7.5\text{x}10^{19}$ cm^{-3} in the highly doped layer and $1\text{x}10^{17}$ cm^{-3} for the nominally undoped c-GaN. These values are marked as circles in Fig. 3. The full line indicates the carbon concentration using that the concentration of the incorporated carbon is proportional to the BEP of the CBr_4 source. We used the SIMS data (circles) as calibration points.

In order to explain the experimental results we further assume that about 10 % of the incorporated carbon atoms act as acceptors whereas about 90 % form self-compensated defects.

Thus the net acceptor concentration N_D-N_A in our samples may be calculated by equation (2):

$$N_A - N_D = [C]\cdot 0.1 - N_D(const.) \qquad (2)$$

where *[C]* is the total carbon concentration in the GaN layer and $N_D = 1\text{x}10^{17}$ cm^{-3} the residual donor concentration. Results are shown in Tab. (1) together with experimental data of N_D-N_A.

TABLE (1). Comparison of the via CV measured N_A-N_D and the calculated N_A-N_D concentration depending on the carbon concentration

Carbon concentration (cm^{-3})	measured N_A-N_D (cm^{-3})	calculated N_A-N_D (cm^{-3})
$1.00\text{x}10^{17}$	$-1.00\text{x}10^{17}$	$-9.00\text{x}10^{16}$
$2.12\text{x}10^{17}$	$-7.50\text{x}10^{16}$	$-7.88\text{x}10^{16}$
$1.17\text{x}10^{18}$	$-2.60\text{x}10^{16}$	$-1.70\text{x}10^{16}$
$4.95\text{x}10^{18}$	$+4.70\text{x}10^{17}$	$+3.95\text{x}10^{17}$
$2.66\text{x}10^{19}$	$+3.13\text{x}10^{18}$	$+2.56\text{x}10^{18}$
$7.50\text{x}10^{19}$	$+4.50\text{x}10^{18}$	$+7.40\text{x}10^{18}$

In Fig. 3 $|N_A-N_D|$ and the carbon concentration are plotted as functions of the CBr_4 BEP. The experimental results are the full circles and the calculated the full squares. The full line indicates the carbon concentration. We find an excellent agreement between experimental and calculated data which supports the assumptions made in our model to explain the CV results.

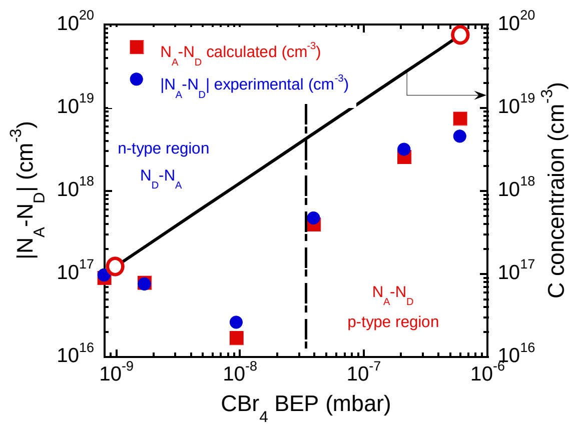

FIGURE 3. Measured (full circles) and calculated (full squares) values of $|N_A-N_D|$. The total carbon concentration used in our model calculation is plotted as full line. The circles represent the carbon concentration in a highly doped and an undoped c-GaN layer measured by SIMS.

CONCLUSIONS

Carbon doped cubic GaN was grown by plasma assisted MBE. Electrical characterization was done by CV measurements. Weak compensation of the native donor concentration was observed at low carbon doping levels. At higher doping levels, we observe a transition to an acceptor surplus in highly doped c-GaN:C samples. A net acceptor concentration of 4.5×10^{18} cm^{-3} was reached. Modeling our experimental data reveals that only 10 % of the incorporated carbon atoms are uncompensated acceptors, 90 % form self compensated defects.

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