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Carbon doped asymmetric cubic AlN/GaN multi quantum well structures for high electrical isolation to 3C-SiC substrates

A. Zado* **and D. J. As**

University of Paderborn, Faculty of Science, Department of Physics, Warburger Str. 100, 33098 Paderborn, Germany

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* Corresponding author: e-mail azado@mail.upb.de, Phone: +49 5251 60 5829, Fax: +49 5251 60 5843

In this work we present a novel method of the electrical separation of the substrate and the hetero junction field effect transistor device. For the epitaxial growth of our structures free standing 3C-SiC (001) substrates with a free carrier concentration of n=2.7x10^{18} cm^{-3} and a resistivity of ρ=34 mΩcm were used. On a 50 nm c-GaN buffer layer an asymmetric multi quantum well structure consisting of 5 periodes of two cubic GaN:C asymmetric QWs (1 nm and 2 nm) embedded between 3 nm thick c-AlN:C barriers. A 50 nm c-GaN cap layer completes the sample structure. A detailed conduction band profile and the quantized electron states within the asymmetric quantum well were calculated using a 1D Poisson-Schrödinger-solver. The structural properties were analyzed by atomic force microscopy and high resolution x-ray diffraction. Current-voltage measurements of these structures showed an increase of the serial resistivity by six orders of magnitude (from 5 mΩ to 8 kΩ) compared to an unstructured c-GaN reference sample.

1 Introduction Currently, state of the art hetero junction field effect transistors (HFET) are fabricated of the *c*-plane surface of wurtzite (hexagonal) AlGaN/GaN hetero structures. Their inherent spontaneous and piezoelectric polarization fields produce extraordinary large sheet carrier concentrations at the AlGaN/GaN hetero-interface. Therefore, all these devices are of the normally-on type. However, for switching devices and digital electronics field-effect transistors with normally-off characteristics are desirable.

A direct way to eliminate this polarization fields is the growth of non-polar cubic (c-)AlGaN/GaN. Recently, the first hetero junction field effect transistor with normally off characteristics based on cubic AlGaN/GaN heterostructure was realized [1]. The most suitable substrate for the growth of cubic AlGaN/GaN hetero-structures is free standing 3C-SiC (001) with an effective lattice mismatch of 3.5% to cubic GaN. However, the critical issue in the HFET operation on this substrate is its high conductivity, which increases the parallel conductance of the device resulting in a buffer leakage current. This is undesirable for high power and low noise applications and severely reduces the device performance. One way to electrically separate the active device from the substrate is the incorporation of a c-AlN barrier layer, due to a large conduction band discontinuity between c-GaN and c-AlN of 1.4 eV [2]. Another possibility is to compensate unintentionally doped c-GaN by carbon, which reduces the c-GaN conductance by two orders of magnitude at an appropriate carbon flux [3, 4-6].

In this work we present a combination of these two methods of device insulation. To avoid tunneling leakage current asymmetric c-GaN (1 nm/2 nm) multi quantum well (MQW) structure with 3 nm thick c-AlN barriers was grown. Due to large lattice mismatch between c-GaN and c-AlN (3.5 %) the thickness of 3 nm barrier is the maximum thickness of appropriate layer quality. Additionally the structure was doped by carbon to compensate the unintentionally incorporated donors during molecular beam epitaxy (MBE) growth.

2 Experimental The growth of the cubic phase of GaN and AlN takes place in a narrow parameter window. The optimum conditions for the growth of cubic GaN are mainly determined by two parameters, namely the surface

stoichiometry and the substrate temperature [7]. Both parameters are interrelated therefore an in-situ control of both is necessary. This is achieved by monitoring the growth process by reflection high energy electron diffraction (RHEED) [8]. Cubic GaN and c-AlN layers were grown at 720 °C on free standing, highly n-doped 3C-SiC (001) substrates, the average growth rate was 158 nm/h. In order to minimize hexagonal inclusions in our layers and to obtain an optimum interface roughness at one monolayer (ML) Ga coverage was established during growth [8]. The background pressure during growth was $7x10^{-6}$ mbar, the atomic fluxes of nitrogen, gallium and aluminum were $2x10^{14}$ $cm^{-2}s^{-1}$, $3.6x10^{14}$ $cm^{-2}s^{-1}$ and $3.5x10^{14}$ $cm^{-2}s^{-1}$, respectively. The carbon source was a CBr_4 sublimation source connected directly to the MBE chamber. No carrier gas was used and the CBr_4 flux was set by a high precision needle valve at constant source temperature of 20 °C.

In our experiments three samples were investigated. Sample A is a 150 nm thick c-GaN layer grown on the 3C-SiC substrate and is used as a reference. In sample B and C a 50 nm c-GaN buffer layer is followed by an asymmetric multi QW structure (Fig. 1). The asymmetric multi QW structures consist of five periods of alternating 1 nm and 2 nm thick c-GaN quantum wells embedded between 3 nm thick c-AlN barriers. In sample C the quantum wells and the barriers were additionally doped with carbon at a CBr_4 beam equivalent pressure (BEP) of $1.2x10^{-8}$ mbar. To ensure equivalent surface conditions for ohmic contacts in all three samples a 50 nm c-GaN cap layer was grown.

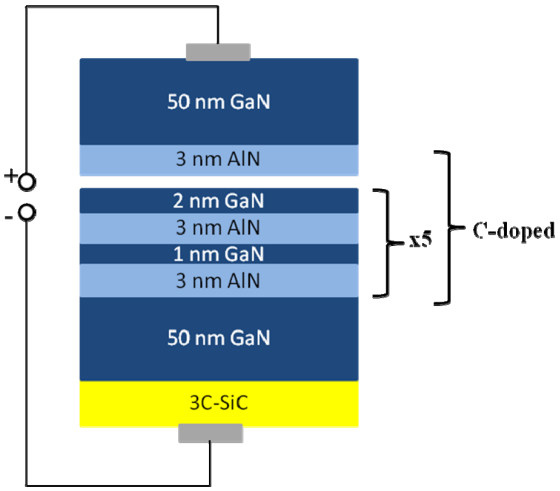

Figure 1 Schematic drawing of the IV-measurement arrangement. Samples B (undoped) and C (carbon doped) consist of a 50 nm c-GaN buffer followed by 5 asymmetric (1 nm/2 nm) c-GaN quantum wells with (3 nm) c-AlN barriers.

Using standard lithography circular contact pads with a diameter of 100 µm were placed on top of the c-GaN layer. Metal ohmic contacts were thermally evaporated consisting of a (15/50/15/50) nm Ti/Al/Ti/Au stacking structure [9]. The ohmic back contacts were realized by soldering the highly conductive 3C-SiC on Cu plates with In. Current-voltage (I-V) measurements were done with an Agilent Precision Semiconductor Parameter Analyzer 4156C. The measurements were performed under light-tight and electrically shielded environment.

3 Results and discussion The MBE growth of the 1 nm/2 nm QWs and the 3 nm barrier layers is a challenging task. To obtain the exact thickness of the layers RHEED technique was used. Figure 2 depicts the time transient of the RHEED intensity during initial carbon doped c-AlN:C growth.

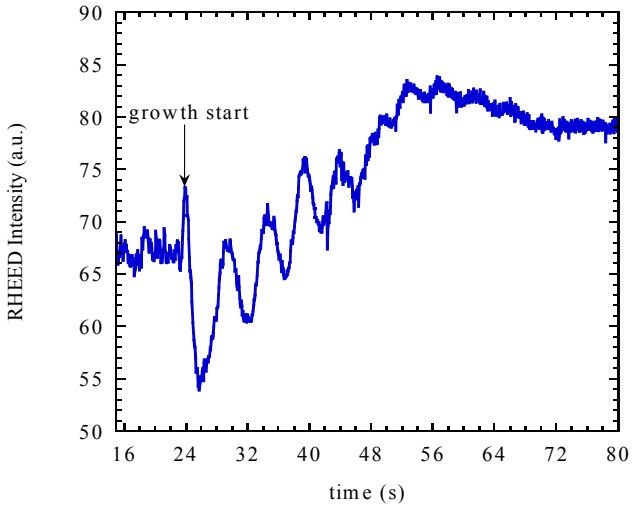

Figure 2 RHEED intensity transient during the initial growth of c-AlN:C. The oscillations indicate a two-dimensional atomically smooth growth. The growth rate of 0.2 ML/s was obtained from the oscillation period.

The growth oscillations indicate an atomically smooth two dimensional growth of the c-AlN:C layer. A growth rate of 0.2 ML/s was obtained from the oscillation period. The exact growth periods were calculated using the lattice parameters of c-GaN and c-AlN which are $a_{GaN} = 0.453$ nm [10] and $a_{AlN} = 0.437$ nm [11], respectively.

Using a 1D Poisson-Schrödinger-solver a detailed band structure analysis of the grown samples at room temperature (RT) was performed. QWs of 1 nm and 2 nm thickness were chosen to guarantee that the energy levels of the electron states are energetically well separated from the conduction band. Additionally the asymmetric QW structure ensures an energetic separation between the quantization levels of adjacent QWs. The thickness of the AlN barriers was selected to be 3 nm, which reduces the spatial overlap of adjacent wave functions to avoid interaction of neighbouring QWs and prevents carrier tunnelling.

Capacitance-voltage (C-V) measurements on cubic AlGaN/GaN metal-oxide-semiconductor (MOS) structures [12, 13] and on Schottky diodes [14-16] showed in unintentially doped epilayers a background carrier concentration N_D-N_A of about $9x10^{16}$-$2x10^{17}cm^{-3}$ for the cubic GaN

layer and about (1-4)x10^{18}cm^{-3} for AlGaN epilayers, respectively. On C-doped GaN a net carrier concentration of 2x10^{16} cm^{-3} was measured [3] and preliminary unpublished results for C compensated c-AlN gave an N_D-N_A value of about (1-3)x10^{17} cm^{-3}. These N_D-N_A values are tabulated in Table 1 and are used in our self-consistent band structure calculations.

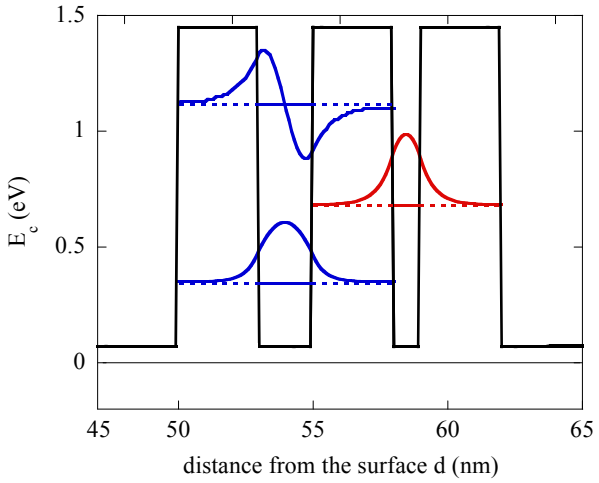

Figure 3 Conduction band edge and quantized electron states for the first pair of a 2 nm c-GaN QW and 1 nm c-GaN embedded between 3 nm thick c-AlN barriers. The electron wave functions are also plotted. The solid line at 0 eV marks the Fermi level.

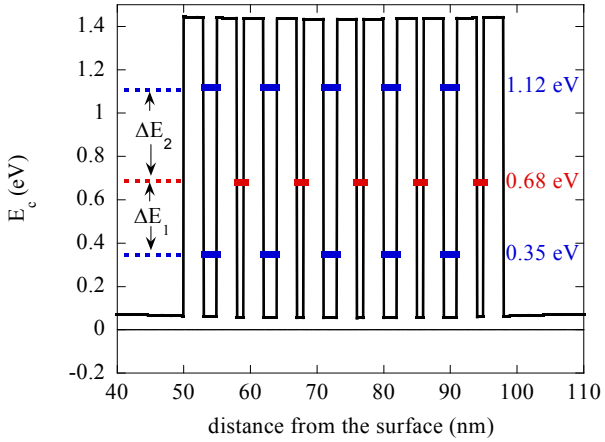

Figure 4 Conduction band edge as a function of the distance from the surface. The quantized electron states within the QW structure are also shown (blue for 2 nm QWs, red for 1 nm QWs).

Table 1 Electronic parameters of the grown samples

Parameter	Sample A	Sample B	Sample C
N_D-N_A (cm^{-3}) (c-GaN)	2x10^{17}	2x10^{17}	2x10^{16}
N_D-N_A (cm^{-3}) (c-AlN)	1.5x10^{18}	1.5x10^{18}	1.5x10^{17}
E_c(GaN)-E_F (eV)	--	-0.02	0.08
E_1/E_2 (eV) 2 nm QW	--	0.26/1.04	0.35/1.12
E_1 (eV) 1 nm QW	--	0.59	0.68

In Fig. 3 the calculated conduction band edge, the quantized states and the electron wave functions of the carbon doped sample C are depicted. In the 2 nm wide QW two electron states around 0.35 eV and 1.12 eV above the Fermi level are formed whereas in the 1 nm c-GaN QW the electron state is at 0.68 eV. To avoid electron wave function overlap of quantized electron states, 3 nm c-AlN layers were grown as barriers. The approximate penetration depth of the electron wave functions is 2.5 nm in the 1 nm QW and 1.9 nm in the 2 nm QW. Figure 4 shows the entire MQW structure of sample C.

The c-AlN/GaN conduction band discontinuity was assumed to be 1.4 eV as reported in Ref. [2]. Using alternating 2 nm and 1 nm QWs ensures a maximum energetic difference of the quantized states of the adjacent QWs. The energetic difference of the three quantized states is ΔE_1 = 0.33 eV and ΔE_2 = 0.44 eV indicated by arrows in Fig. 4. The same calculations were performed for the UID structure of sample B. The results are summarized in Table 1. Due to the higher background carrier concentration the energy E_c(GaN) – E_F is negative, however in all cases the lowest quantized states are well above the Fermi energies and therefore are not occupied by free carriers. In addition, the wave function overlap is insignificant and adjacent QWs are decoupled and tunnelling is negligible.

To investigate the isolation properties of the grown layers I-V measurements were performed. According to Fig. 1 ohmic top and back contacts were used. The voltage was varied from -5 V to 5 V. The results of the measurement are plotted in Fig. 5.

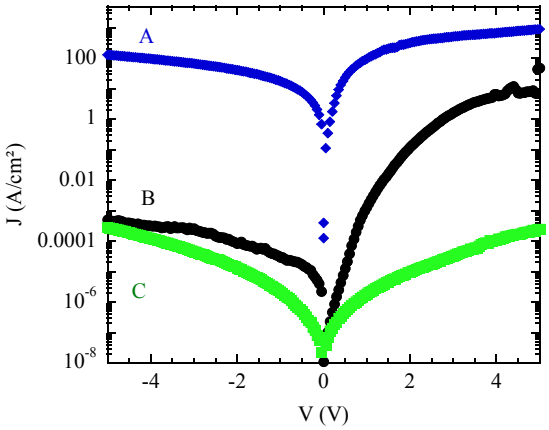

Figure 5 Current density of the fabricated samples plotted versus the applied voltage. Sample A is the reference sample (blue diamonds), sample B is the sample with UID asymmetric MQW structures (black circles) and sample C contains carbon doped asymmetric MQW structures (green squares).

Sample A was used as a reference sample. The current density vs. applied voltage curves show a slightly non-ohmic behavior affected by the hetero-interface between the 3C-SiC substrate and the c-GaN buffer layer. The measurement at sample A yields the maximum current density at +5 V the current density amounts 925 A/cm². This high conductivity originates from UID of the c-GaN

during the MBE growth process and from the high conductive 3C-SiC substrate. The current density in sample B is reduced to 48 A/cm² at 5 V of applied voltage. The reduction of the current flow is a clear evidence for the isolating properties of the MQW structure. However, the reason for the asymmetry in forward and reverse bias direction is unknown up to now and needs further clarifications. Due to a large conduction band offset between c-GaN and c-AlN electrons have to cross eleven barrier layers. In addition the asymmetric arrangement of the QWs suppresses the tunneling current. In case of sample C – in which the residual background doping has been compensated by C-doping - the current density at 5 V is further reduced to $25x10^{-3}$ A/cm². Thus the serial resistivity is increased to a maximum. At the adjusted carbon flux we expect a decrease of the donor density by one order of magnitude [3]. Thus the conduction band edge of the c-GaN QWs is 0.08 eV above the Fermi level on the energetic scale. Whereas in sample B the conduction band edge is 0.02 eV below the Fermi energy as shown in Table 1.

From the linear increase of the IV curves in forward direction, the serial resistivity of the samples is calculated. The results are depicted in Fig. 6.

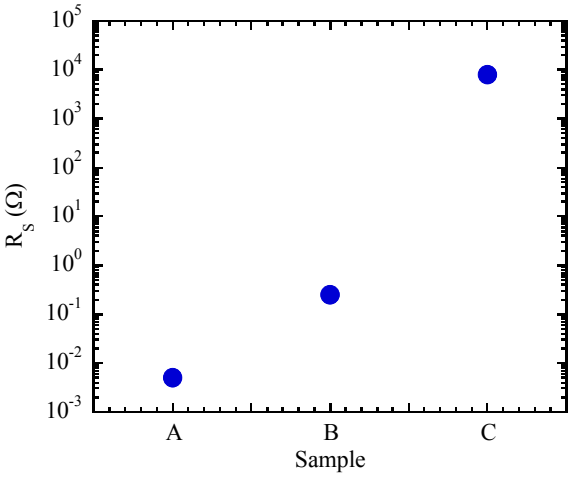

Figure 6 Serial resistivity R_S of the fabricated samples A, B and C. The values were obtained from the linear increase of the current vs. voltage characteristics in forward direction.

The values for the serial resistivity of samples A, B and C are 5 mΩ, 0.25 Ω and 8 kΩ, respectively. Therefore, in sample C an increase of the serial resistance by more than six orders of magnitude is reached compared to the unstructured reference sample A. This extraordinary high resistivity is mainly caused by three factors. The first is the large c-GaN/AlN conduction band offset forming potential barriers for electrons. The second circumstance is the asymmetric arrangement of the MQW structure causing the energetic separation of the quantized electron states of the adjacent wells. Additionally the penetration depth of the electron wave functions is below the c-AlN barrier thickness. Thus the tunnelling current is reduced to a minimum. The third factor is the compensation of the donor concentration in the UID layers by carbon incorporation during the MBE growth.

4 Conclusions We have grown non-polar carbon doped cubic AlN/GaN asymmetric quantum well structures for the electrical separation of devices from the underlaying substrates. In situ MBE growth control by RHEED ensured the intended layer thickness. Current voltage measurements have shown that the carbon doped samples are of extraordinary electric isolation quality in comparison to asymmetric undoped quantum wells and to cubic GaN bulk structure. A reduction of the serial conductivity of six orders of magnitude was observed.

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