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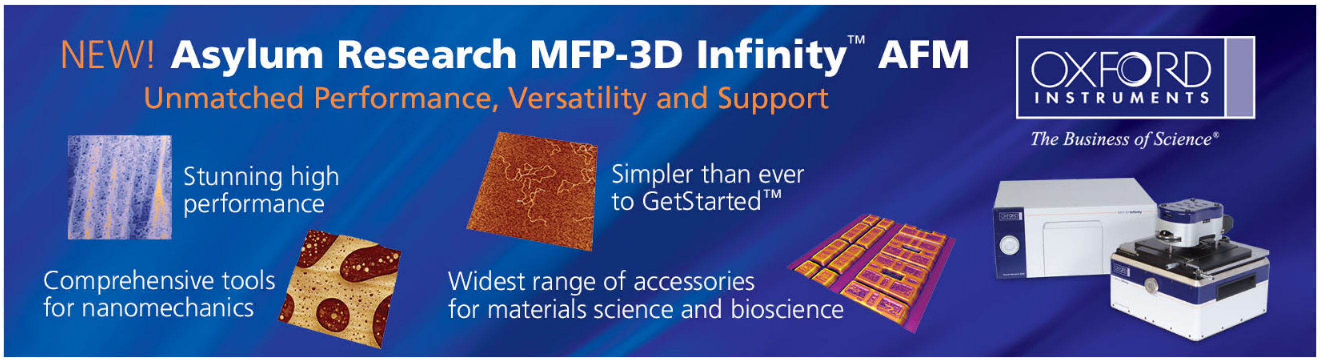

APPLIED PHYSICS LETTERS **101**, 112105 (2012)

Enhancing threshold voltage of AlGaN/GaN high electron mobility transistors by nano rod structure: From depletion mode to enhancement mode

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This paper presents an approach in fabricating normally off AlGaN/GaN high electron mobility transistors (HEMTs). The fabrication technique was based on the carbon-doped GaN epitaxy layers on silicon substrate and the nano rod structure of the gate region in AlGaN/GaN HEMTs. Using this method, the threshold voltage of AlGaN/GaN HEMTs can be shifted from −2 V in a conventional depletion-mode (D-mode) AlGaN/GaN HEMT to 2 V in an enhancement-mode (E-mode) AlGaN/GaN HEMT. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4752113]

The AlGaN/GaN high electron mobility transistors (HEMTs) have attracted much interest in the past decade due to potential applications in high-power and high frequency areas.[1] Recently, AlGaN/GaN HEMTs grown on silicon substrate have been demonstrated and encouraging results have been reported.[2] However, such normally on type HEMTs are not applicable to actual power switching applications in which safe operation is the main concern. The E-mode AlGaN/GaN HEMTs greatly require high drain current (I_{ds}) and low on-state resistance (R_{on}) during operation. To meet such requirements, it is necessary to reduce the 2-D electron gas (2DEG) density under the gate region.[3–5]

In this paper, we demonstrate a GaN-based normally off HEMTs. The 2DEG density under the gate electrode was selectively reduced by the nano rod structure. Therefore, the threshold voltage has been enhanced and the drain current sharp drop could be avoided.

Fig. 1 shows the cross-sectional view of the GaN/Si epilayers. The GaN-based epilayers were grown on 2 in. Si (1 1 1) substrate using a metal organic vapor-phase epitaxy (MOVPE) system. A 20 nm-thick unintentional doped $Al_{0.25}Ga_{0.75}N$ barrier layer was grown on the GaN layer (1.5 μm). The composition of AlGaN buffer (2.5 μm) layer is linear grading from AlN to GaN. The carbon doped at the AlGaN buffer layer to obtain a high-resistivity layer.[6] Tetrabromomethane (CBr4) was used as carbon source in this work. The epitaxy conditions of MOVPE system were as follows: (1) The carrier gas (H_2) was 10 l/min. (2) The ammonia gas (NH_3) was 3 l/min. (3) The growth temperature on wafer was 1050 °C. (4) The pressure of MOVPE reactor was 150 mbar. (5) The CBr4 flow rate was 1000 SCCM (keep in constant). (6) AlGaN buffer layer was growth by Al linear gradient (1 to 0.05) and the C/(Al+Ga) ratio was from CBr4/AlN $\sim 1 \times 10^{-4}$ to CBr4/GaN $\sim 5 \times 10^{-5}$. (7) The TMGa flow rate and growth rate were 13 SCCM and 1 μm/h. (8) The C/Ga ratio was 5×10^{-5}.[7]

The average thickness and standard deviation of epilayers were 3.926 μm and 5.899% as shown in Fig. 2. The mobility, 2DEG density, and sheet resistance extracted by hall measurement was $1200\,\text{cm}^2/\text{V}_s$, $6.7 \times 12\,\text{cm}^{-2}$, and 688 Ω/sq., respectively. Fig. 3 shows the full width at half maximum of the (002) and (102) x-ray rocking curves was 505 and 1481 arc sec. The dislocation density was nearly $2 \times 10^9\,\text{cm}^{-2}$.[7,8]

Fig. 4(a) shows the framework of HEMTs with nano rod structure. The nano rod pattern on whole wafer surface was making by nano-imprinting lithography as shown in Fig. 4(b).[9,10] The diameter of hole and period was 225 nm and 450 nm, respectively. Second, the mesa etching mask was making by photo resistance and SiO_2. The nano rod recessed region was etched by chlorine gas (Cl_2) using inductively coupled plasma etcher (ICP) to define the

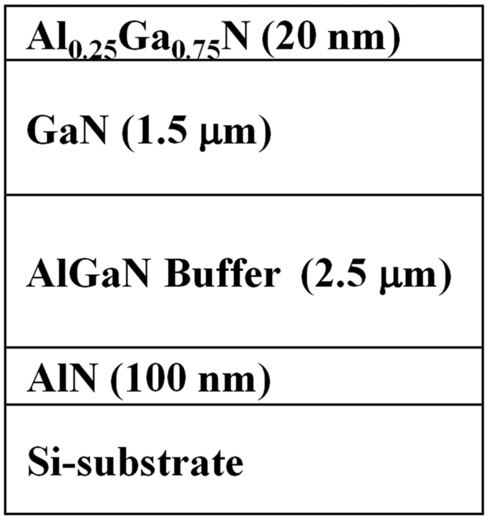

FIG. 1. The cross-sectional view of the GaN/Si epilayers.

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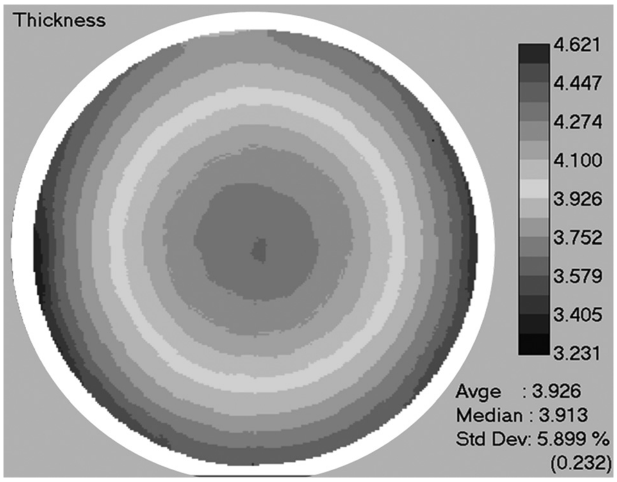

FIG. 2. The average thickness and standard deviation of the GaN/Si epilayers.

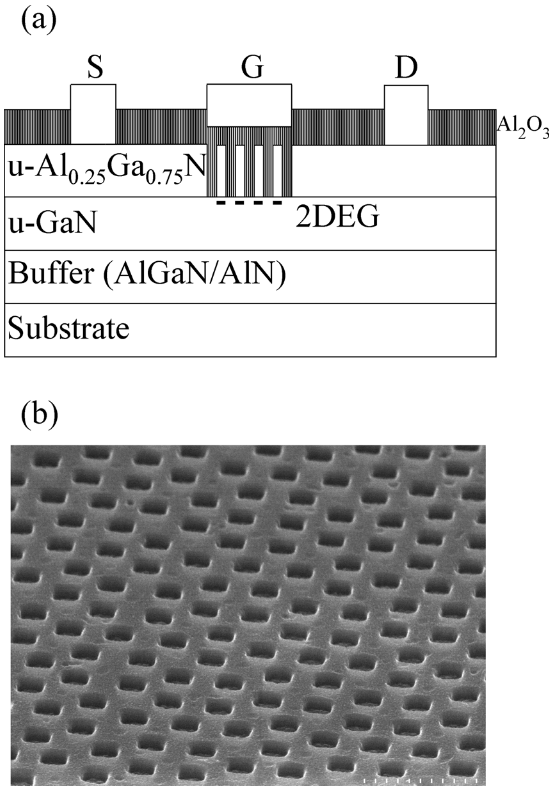

FIG. 4. (a) The framework and (b) nano rod structure of the HEMTs.

channel region. The etching depth of nano rod was over 20 nm. The photo resistance was removed and the wafer was cleaned with standard set of wafer cleaning steps (RCA). Then, A 100 nm-thick Al_2O_3 was deposited by atomic layer deposition (ALD) as a gate oxide.[10–12] Source and drain electrodes were formed by lift-off technique of the Ti/Al/Ni/Au followed by annealing at 700 °C for 1 min in nitrogen gas (N_2) ambient by rapid thermal processing (RTP). The gate electrode was fabricated with Ni/Au on the gate oxide by lift-off technique. The channel length was 2 μm, and the channel width was 350 μm.

In this paper, we fabricated conventional HEMTs and HEMTs with nano rod structure on the same epitaxy wafer. The breakdown characteristics of the AlGaN/GaN HFETs with nano rod structure and without it were almost the same. The breakdown was measured at the drain current (I_{ds}) $= 0.1$ mA/mm and the gate voltage (V_{gs}) $= -5$ V as shown in Fig. 5. The breakdown voltage has been improved from 279 V to 860 V by carbon doped effect. The carbon doping of GaN led to highly resistive state. The high resistivity

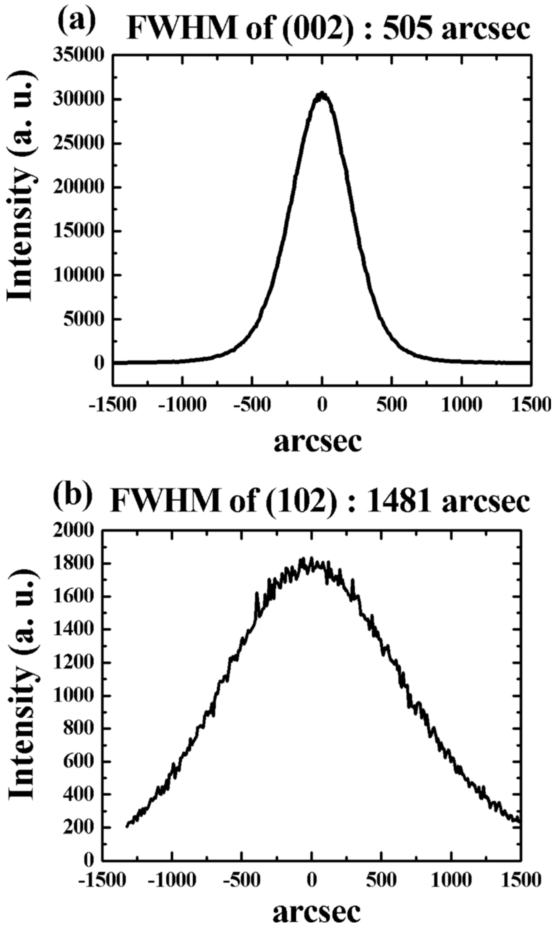

FIG. 3. (a) Full width at half maximum of the (002) and (b) (102) x-ray rocking curve of the GaN/Si epilayers.

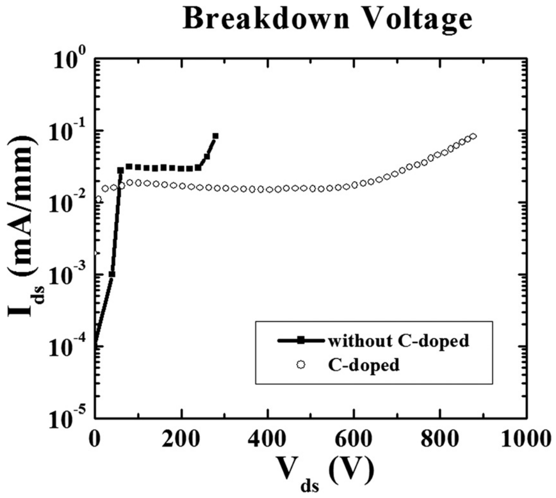

FIG. 5. The breakdown voltage of undoped and carbon doped epitaxy wafers.

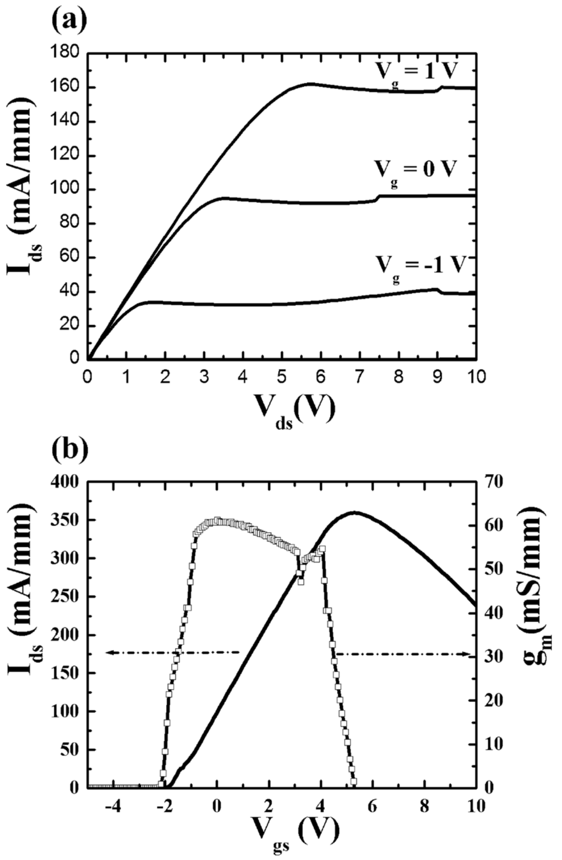

FIG. 6. (a) The I_{ds}–V_{ds} characteristics and (b) the I_{ds}–V_{gs} and gm–V_{gs} characteristics of the conventional HEMTs.

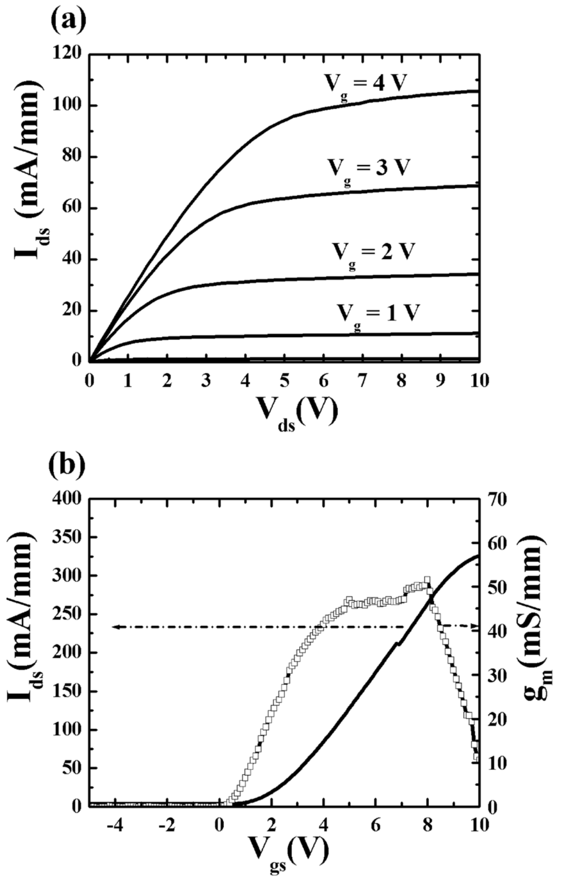

FIG. 7. (a) The I_{ds}–V_{ds} characteristics and (b) the I_{ds}–V_{gs} and gm–V_{gs} characteristics of the HEMTs with nano rod structure.

was caused by strong compensation due to carbon acceptors and by consequently induced large potential barriers at subgrain boundaries.

Fig. 6(a) shows the I_{ds}–V_{ds} characteristics of the fabricated conventional D-mode HEMTs. The drain current was 160 mA/mm at $V_{gs} = 1$ V. The resulting specific R_{on} was 13.9 mΩ cm^2. Fig. 6(b) shows the applicable forward gate voltage was limited below 6 V with the threshold voltage of −2.0 V. The maximum transconductance and drain current was 60.7 mS/mm and 359.2 mA/mm, respectively.

The etching depth of the nano rod was higher than the thickness of the $Al_{0.25}Ga_{0.75}N$ layer. The 2DEG channel has been discontinued intermittently with the nano rod structure. The HEMTs have been converted to E-mode and the drain current sharp drop could be avoided. Fig. 7(a) shows the I_{ds}–V_{ds} characteristics of the fabricated E-mode HEMTs with nano rod structure. The drain current was 110 mA/mm at $V_{gs} = 4$ V. The resulting R_{on} is 19 mΩ cm^2. Fig. 7(b) shows the applicable forward gate voltage is up to 10 V. A normally off operation with the threshold voltage of 2.0 V is achieved. The maximum transconductance and drain current was 51.5 mS/mm and 325 mA/mm, respectively.

In summary, we developed the normally off AlGaN/GaN HEMTs with nano rod structure on silicon substrate. The resulting R_{on} and the breakdown voltage was 19 mΩ cm^2 and 860 V, respectively. The threshold voltage can be shifted from −2 V in the D-mode HEMTs to 2 V in the E-mode HEMTs. The maximum transconductance decreased slightly from 60.7 mS/mm to 51.5 mS/mm.

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