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Impact of Substrate off-angle on the *m*-plane GaN Schottky Diodes

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Abstract

Effects of substrate off-angle on the *m*-plane GaN Schottky diodes were investigated. GaN epitaxial layer, on the off-angle of 0.1° toward [000$\bar{1}$], consisted pyramidal hillocks and contained carbon (>10^{17} cm^{-3}) and oxygen (>10^{16} cm^{-3}) impurities. The diode showed large leakage current caused by the defects. The residual carbon and oxygen impurities were decreased <10^{16} cm^{-3} by increasing off-angle of the substrate. The leakage current was efficiently suppressed by using off-angle of 5.1°. The off-angle of the *m*-plane substrate plays an important role in obtaining high performance Schottky Diodes.

1. Introduction

Homo-epitaxial vertical GaN on GaN devices, Schottky diodes (SBDs)[1][2] and p-n junction diodes[3][4], have been reported by using free-standing GaN substrates. At present, the most important issue is to eliminate the carbon contamination in the drift layer to realize lower specific on-resistance and higher breakdown voltage. In the *c*-plane GaN by metal-organic chemical vapor deposition (MOCVD), the V/III ratio >4000 is needed to obtain carbon concentration <10^{16} cm^{-3}.

We recently reported undoped and lightly Si-doped *n*-GaN on *m*-plane GaN substrates[5]. We demonstrated a sufficiently low oxygen and carbon residual concentrations <10^{16} cm^{-3} at a growth condition of a low V/III ratio of 1000. In this study, Ni/*n*-GaN SBDs on *m*-plane GaN with various off-angles were demonstrated. The correlation between surface structure, impurities concentration, and electrical properties was investigated.

2. Experimental

The SBD structure consisted a Si-doped (2x10^{16} cm^{-3}) *n*-GaN epitaxial layer on the off-angle *m*-plane *n*-GaN substrates at 1120°C with the V/III ratio of 1000 (the growth rate of 100 nm/min) by MOCVD. TMG, NH_3, and SiH_4 were used as group III, V, and *n*-type dopant precursors, respectively. The off-angle *m*-plane GaN substrates were prepared by slicing from *c*-plane free-standing hydride vapor phase epitaxy (HVPE) grown GaN crystals. The off-axis angles toward the [000$\bar{1}$] (N-polar direction) were 0.1° (on-axis), 1.1°, 1.7°, and 5.1°. The substrates have threading dislocation densities (TDDs) less than 5x10^6 cm^{-2}.

The microscopic and macroscopic surface morphology was measured by atomic force microscope (AFM) and confocal differential interference contrast microscope (CDICM). The silicon, oxygen, and carbon concentrations in the epitaxial layers were measured by secondary ion mass spectroscopy (SIMS) with Cameca Cs negative ion beam. The Ni/Au (50/150 nm) Schottky contacts were formed on the *n*-GaN surface. The diodes have the electrode diameter of 250 μm without field plate structure. The carrier concentration, N_D-N_A, was analyzed by capacitance-voltage (*C-V*) measurements at a frequency of 1MHz. The forward and reverse current-voltage (*I-V*) measurements were characterized at room temperature.

3. Results and discussions

Figure 1 shows 500x500 nm^2 scan AFM images of the GaN surface on *m*-plane GaN with an off-angle of (a) 0.1°, (b) 1.1°, (c) 1.7°, and (d) 5.1°. The steps and terraces were clearly observed toward [000$\bar{1}$]. Increasing the off-angle from 0.1° to 5.1° resulted in the reduction in the terrace width from 60nm to 11nm.

Table 1 summarizes atomic (Si, O, C), and carrier (N_D-N_A) concentrations of Si-doped *n*-GaN on *m*-plane off-angle of 0.1°, 1.1°, and 5.1°. The 0.1° off *m*-plane GaN contained oxygen (3.9x10^{17} cm^{-3}) and carbon (3.6x10^{16} cm^{-3}) impurities. The oxygen and carbon concentrations were decreased by increasing the off-angle from 0.1° to 5.1°. We suggest that carbon desorption is enhanced at the (000$\bar{1}$) N-polar step edges.

The forward and reverse *I-V* curves for SBDs on *m*-plane off-angle of 0.1° and 5.1° are shown in fig 2 (a), and (b), respectively. The ideality factor (*n*) and Schottky barrier height ($q\phi_B$) for 0.1°/5.1° were analyzed as 1.10/1.05 and 0.71/0.76, respectively. The 0.1° off *m*-plane showed large leakage current under reverse bias up to 10V. The pyramidal hillock under Schottky electrodes in fig. 3 is attributed to the origin of the leakage current. The leakage current was greatly suppressed by using off-angle of 5.1°.

3. Conclusions

We have investigated effect of substrate off-angle on the *m*-plane GaN Schottky diodes. The residual oxygen and carbon impurity concentrations into *m*-plane GaN layer was decreased by increasing off-angle toward [000$\bar{1}$]. The leakage current was sufficiently suppressed by using off-angle of 5.1°. The off-angle of the *m*-plane substrate plays an important role in obtaining high performance SBDs.

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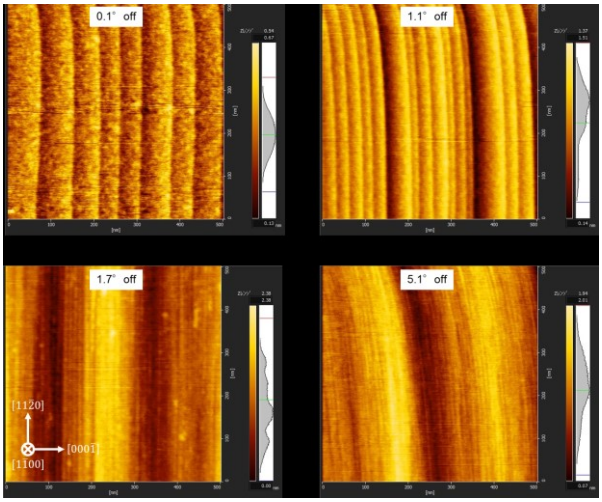

Fig. 1 500x500nm^2 scan AFM images of the n-GaN on *m*-plane GaN with an off-angle of (a) 0.1°, (b) 1.1°, (c) 1.7°, and (d) 5.1°.

Table. 1 Atomic (Si, O, C), and carrier (N_D-N_A) concentrations of *m*-plane *n*-GaN.

Off angle (degree)	[Si] (cm^{-3})	[O] (cm^{-3})	[C] (cm^{-3})	N_D-N_A (cm^{-3})
0.1	$2.0x10^{16}$	$3.9x10^{17}$	$3.6x10^{16}$	-
1.1	$2.0x10^{16}$	$2.0x10^{16}$	$1.3x10^{16}$	$3.7x10^{15}$
5.1	$2.1x10^{16}$	D.L. ($6.0x10^{15}$)	$5.0x10^{15}$	$1.7x10^{16}$

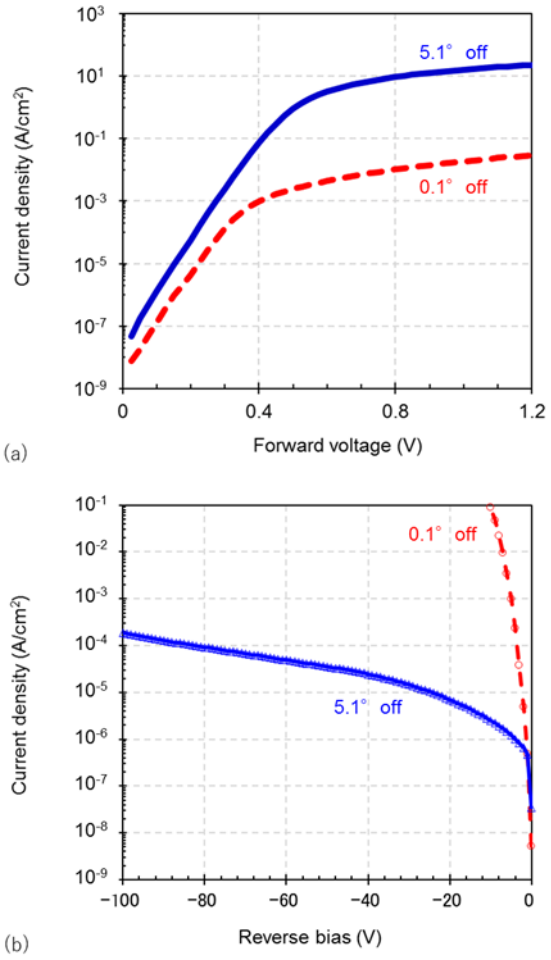

Fig. 2 *I-V* characteristics of the Ni/*n*-GaN Schottky diodes on *m*-plane GaN under (a) forward bias, and (b) reverse bias.

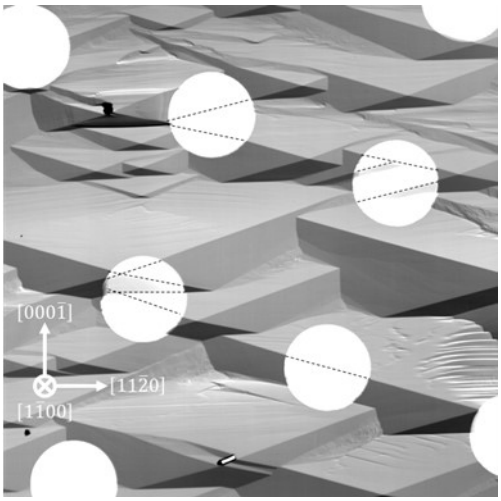

Fig. 3. CDICM image of SBDs on 0.1° off *m*-plane GaN.