Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp923-924

Roles of Unintentionally-doped channel on Carbon doped GaN for high performance AlGaN/GaN HFET

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1. Introduction

AlGaN/GaN heterostructure field-effect transistor (HFET) has outstanding electrical properties such as low on-resistance and high breakdown field strength for high power switching devices[1,2]. For high power electric systems such as electrical vehicle, improving the upper bound of breakdown voltage is imperative issue. It is believed that the main source of the breakdown process is bulk punch-through effect in the GaN layer[3]. Therefore, doping of deep acceptors such as carbon which makes the GaN layer semi-insulating is essential for the suppression of bulk punch-through[4,5]. Unfortunately, 2DEG characteristics of AlGaN/GaN:C heterostructures were degraded by doping of carbon. To solve this problem, AlGaN/GaN/GaN:C heterostructure was suggested as a solution for high breakdown voltage without degradation of 2DEG[6, 7]. However, the effect of un-intentionally doped(UID)-GaN channel with the GaN:C back barrier on the 2DEG has not yet been fully understood, to the best of our knowledge.

In this report, electrical properties of 2DEG in AlGaN/GaN, AlGaN/GaN:C and AlGaN/GaN/GaN:C structures were compared by theoretical calculations and the capacitance -voltage measurement to explain the advantage of UID-GaN channel on carbon-doped GaN back barrier. Furthermore, the enhanced device performance by using UID-GaN channel was discussed in detail.

2. Experimental

AlGaN/GaN (wafer A), AlGaN/GaN:C (wafer B) and AlGaN/GaN/GaN:C (wafer C) heterostructures were grown on a 6-inch (111) silicon wafer using a metal-organic chemical vapor phase deposition (MOCVD) and each structure is depicted in Figure 1. The GaN:C back barrier contains carbon with $2\times10^{18}\text{cm}^{-3}$ confirmed by the result of second ion mass spectroscopy (SIMS). The UID-GaN channel inserted between AlGaN barrier and GaN:C back barrier was grown on wafer C. To measure the capacitance-voltage (C-V) profile and the device performance of each wafer, HFETs were fabricated with wafer A, B and C.

3. Results and discussion

The sheet carrier concentration (n_s) and electron mobility (μ_e) was obtained from Hall measurement (Table 1). The negative effect of GaN:C on 2DEG could be attributed to the role of carbon as deep acceptors and as impurities in AlGaN/GaN:C interface. The negative impact of carbon-doping on 2DEG is recovered to $n_s = 1.35\times10^{13}\text{cm}^{-2}$ and $\mu_e = 1880\text{cm}^2/\text{Vs}$ when narrow UID-GaN (50nm) is inserted between AlGaN barrier and GaN:C layer.

Energy band edge profile was calculated and the conduction band (CB) edge profile is presented in Figure 2. The CB energy below Fermi level at AlGaN/UID-GaN interfaces of wafer A and C are almost same. This indicates that the lifted CB of GaN:C below the UID-GaN channel rarely influences the CB at the interface between AlGaN and UID-GaN by sufficient band bending effect. Additional advantage is semi-insulating behavior of UID-GaN channel showed in wafer C. In the region under 50nm from the AlGaN/UID-GaN interface, CB energy linearly increases to 3.0eV. This means that the UID-GaN channel shows semi-insulating characteristics except near the AlGaN/UID-GaN interface.

Figure 3(a) and (b) show the depth profile of carrier concentration obtained from C-V measurement and theoretical calculation. Conserved carrier concentration with enhanced confinement of 2DEG of wafer C tells that the pinned Fermi level at the interface and the high level of CB in band calculation play important roles to improve the device performance. Figure 4 shows carrier concentrations depeding on the thickness of UID-GaN channel. The carrier concentration is almost saturated in the thickness over 30nm. This calculation result implies that the thickness of UID-GaN channel might be optimized around 30nm.

Device performances of HFETs using wafer A, B, and C were presented in Table 2. With the 50nm-thick UID-GaN channel, wafer C, on-resistance was decreased to 1.73 $\text{m}\Omega\text{cm}^2$ from 7.27 $\text{m}\Omega\text{cm}^2$ of wafer B. Furthermore, in Fig. 5, the off-state leakage current at $V_{D(OFF)}$ =500V of wafer C was reduced to 0.36μA which is smaller than 1% of the off-state leakage of the wafer A. The optimized thickness of UID-GaN channel predicted by simulation is under experiment and will be added to this study.

4. Conclusion

The physical and electrical characteristics of GaN layer comprised of UID-GaN channel on GaN:C back barrier has been investigated to improve the device performance. Through various experiment and theoretical approach, the advantages of UID-GaN channel that reduces the off-state leakage current and maintaining the sheet carrier concentration and the mobility of 2DEG were explained. Results would provide the physical background to the optimization of the thickness of UID-GaN channel by considering the conduction band lifting in GaN:C.

References

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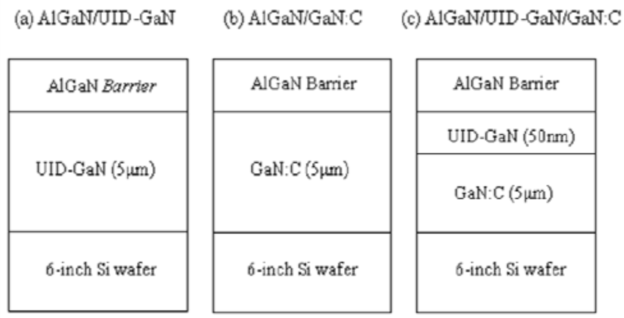

Figure 1. Schematic picture of (a) AlGaN/UID-GaN, (b) AlGaN/GaN:C and (c) AlGaN/UID-GaN/GaN:C heterostructure

	Sheet carrier concentration (cm^{-2})	Mobility ($cm^2/V\cdot s$)
AlGaN/UID-GaN	1.26×10^{13}	1780
AlGaN/GaN:C	5.85×10^{12}	448
AlGaN/UID-GaN/GaN:C	1.35×10^{13}	1880

Table 1. Sheet carrier concentration and mobility of 2DEG in AlGaN/UID-GaN, AlGaN/GaN:C and AlGaN/UID-GaN/GaN:C obtained from Hall measurement.

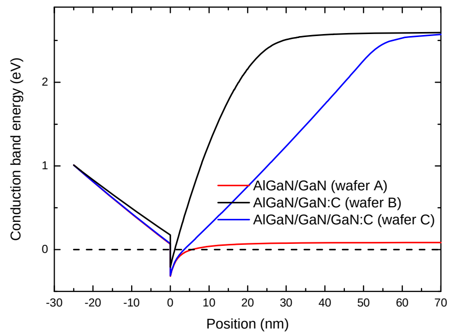

Figure 2. Depth profile of conduction band edge of each structures resulted from theoretical calculation. The dotted line is the Fermi-level which is determined by the pinning of the surface barrier height.

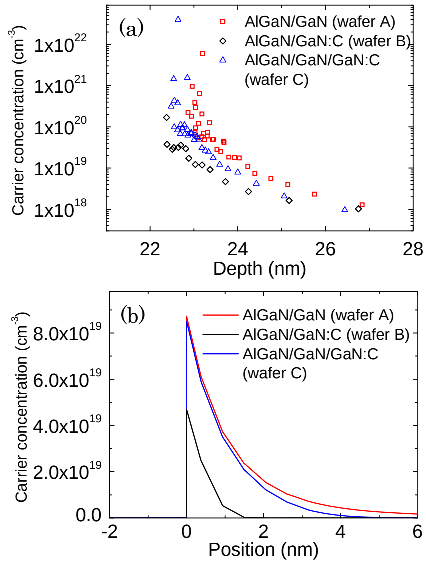

Figure 3. Depth profile of the distribution of 2DEG obtained from (a) C-V measurement and (b) theoretical calculation.

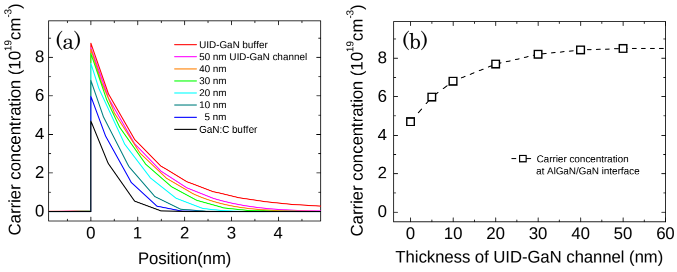

Figure 4. (a) Calculated distributions of 2DEG with the thickness of UID-GaN channel and (b) dependence of the carrier concentration at the AlGaN/GaN interface on the thickness.

	$R_{DS(on)}$ ($m\Omega cm^2$)	V_D (V) at $I_{D(off)}=1.0\times10^{-4}$A
AlGaN/UID-GaN	1.96	320
AlGaN/GaN:C	7.27	951
AlGaN/UID-GaN/GaN:C	1.73	904

Table 2. The performance of normally-on device : $R_{DS(ON)}$ and V_D

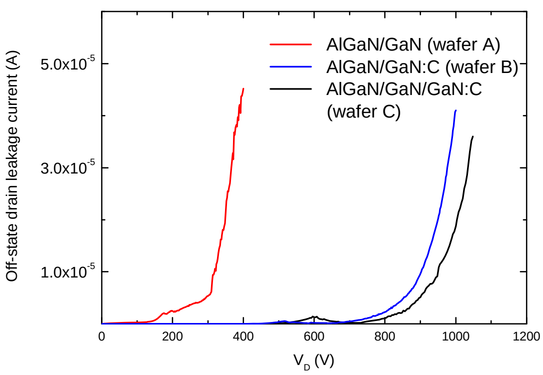

Figure 5. The off-state leakage current depending on the drain voltage.