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Growth of AlN/GaN HEMT structure Using Indium-surfactant

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***Abstract*—We have grown AlN/GaN heterostructure which is a promising candidate for mm-wave applications. For the growth of the high quality very thin AlN barrier, indium was introduced as a surfactant at the growth temperature varied from 750 to 1070 ˚C, which results in improving electrical properties of two-dimensional electron gas (2DEG). The heterostructure with barrier thickness of 7 nm grown at of 800˚C exhibited best Hall measurement results; such as sheet resistance of 215 Ω/□, electron mobility of 1430 cm^2/V·s, and two-dimensional electron gas (2DEG) density of 2.04 x 10^{13}/cm^2. The high electron mobility transistor (HEMT) was fabricated on the grown heterostructure. The device with gate length of 0.2 μm exhibited excellent DC and RF performances; such as maximum drain current of 937 mA/mm, maximum transconductance of 269 mS/mm, current gain cut-off frequency of 40 GHz, and maximum oscillation frequency of 80 GHz.**

***Index Terms*—AlN/GaN heterostructure, indium surfactant, HEMT, hall measurement**

I. INTRODUCTION

AlGaN/GaN heterostructure has been widely researched for high frequency and high power applications due to the superior material properties of nitride-based material, such as wide bandgap, high saturation velocity and breakdown electric field [1, 2]. To obtain high cut-off frequency (f_T), it is essential to reduce the gate length and also the barrier thickness of the device must be reduced, otherwise the device suffers from severe short channel effects (SCEs), which causes a degradation of device performance [3, 4]. Unfortunately, the conventional AlGaN/GaN heterostructure shows poor electrical properties when the thickness of the AlGaN barrier becomes thinner than ~ 10 nm, reducing the two-dimensional electron gas (2DEG) density and decreasing the 2DEG mobility mainly due to the degraded crystalline quality of the AlGaN layer and insufficient piezoelectric polarization [5].

AlN/GaN heterostructure becomes an attractive alternative due to its strong polarization and large bandgap discontinuity [6-9]. The heterostucture even with ultra-thin AlN barrier has a great advantage of obtaining high 2DEG density, almost two times larger than that of conventional AlGaN/GaN heterostructure, which allows us to achieve excellent device performance in mm-wave applications.

In this paper, we report on the growth of AlN/GaN heterostructure using indium-surfactant with various growth temperature and thickness of AlN barrier [10, 11]. The 2DEG properties, epitaxial quality of AlN barrier, and surface roughness were estimated by Hall measurement, X-ray diffraction (XRD) and atomic force microscopy (AFM) measurement, respectively. In addition, the basic DC and RF performances were also measured from the high electron mobility transistor

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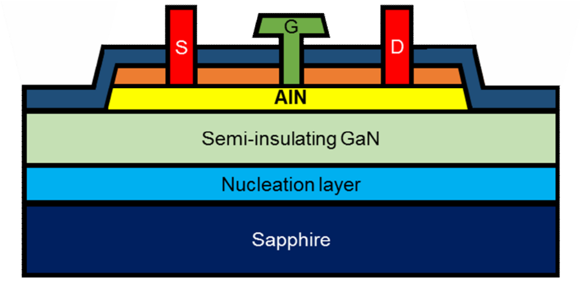


Fig. 1. Schematic of AlN/GaN HEMT with T shaped gate

(HEMT) fabricated on the proposed AlN/GaN heterostructure.

II. EXPERIMENTAL DETAILS

Fig. 1 shows the schematic of AlN/GaN HEMT with T shaped gate. The device structure was grown on the sapphire substrate by metal-organic chemical vapor deposition (MOCVD). Trimethylgallium (TMGa), trimethylaluminum (TMAl), ammonia (NH_3) and trimethylindium (TMIn) were used as the sources of Ga, Al, N, and In, respectively. 50 nm-thick initial GaN nucleation layer was grown at low-temperature of 525 ˚C. 2 μm-thick semi-insulating GaN layer was then grown at 1060˚C, which consists of 1st GaN layer grown with pressure of 50 Torr and 2nd GaN layer with 300 Torr. After then, the AlN barrier was grown with varying the growth temperature from 750 to 1070 °C under pressure of 100 torr. The flow rate of NH_3 and TMAl was 8000 and 55 sccm, respectively. The flow rate of TMIn was 500 sccm, which was used as a surfactant to improve the quality of AlN barrier and surface morphology. The growth temperature of the AlN layer must be very high, usually higher than 1200˚C, which would lead to the decomposition of underlying GaN layer due to the high growth temperature for the layer. In contrast, the In-surfactant plays a role of growing a high quality AlN barrier layer even at lower growth temperature, which also prevents the underlying GaN layer from being decomposed [11]. After growing the AlN barrier, GaN capping layer for 9 sec was grown sequentially with same temperature and pressure of AlN barrier growth.

For the fabrication of HEMT, MESA isolation was first performed by using transformer coupled plasma reactive ion etching (TCP-RIE) and 8 nm-thick Al_2O_3 layer was deposited by atomic layer deposition (ALD) to protect the AlN surface during thermal annealing process for ohmic contacts. After then, Si/Ti/Al/Ni/Au metal stack was deposited by electron-beam evaporator for source and drain ohmic contacts with rapid thermal annealing (RTA) at 500˚C for 20 s and 800˚C for 30s in nitrogen ambient. The results of transmission line method (TLM) measurement shows the contact resitivity of 2.97×10^{-5} Ω -cm^2, contact resistance of 0.84 Ω-mm and sheet resistance of 235.09 Ω/□. For forming the gate metal, Al_2O_3 dielectric layer and GaN cap layer under the gate were etched, and then the T shaped gate metal of Ni/Au was deposited by electron beam lithography with length and width of 0.2 and 100 μm, respectively.

Table 1. Properties of 2DEG for the AlN/GaN heterostructures with different AlN thickness grown under various growth temperatures.

Growth temperature, [˚C]		Sheet resistance [Ω/□]	Electron mobility [cm^2/V·s]	2DEG density [x 10^{13}/cm^2]
750 (5 nm)		17520	32	1.11
800	5 nm	323	1280	1.51
	6 nm	250	1330	1.88
	7 nm	215	1430	2.04
850 (5 nm)		350	1110	1.61
950 (5 nm)		632	569	1.71
1070 (5 nm)		18020	37	0.93
1090 (5 nm) (without surfactant)		8404	37.6	1.97

III. Results and Discussion

Table 1 shows the 2DEG properties depending on the growth temperature and thickness of the AlN barrier by using Hall measurement. When the thickness of the AlN barrier layer is 5 nm (or < 5 nm) the electrical properties of the heterostructure were not satisfactory regardless of the growth temperature from 750 and 1070 ˚C. The carrier concentration and the carrier mobility were far below than expected. However, the quite reasonable quality was obtained at the growth temperature of 800 ˚C, which might indicate that the temperature is the optimized growth temperature. The (002) HR-XRD 2θ-ω scan at Korea Basic Science Institute (KBSI) in Fig. 2 shows that the 5 nm-thick AlN grown at 800 ˚C has better crystalline quality than others, even though the difference was not apparent because the thickness of the

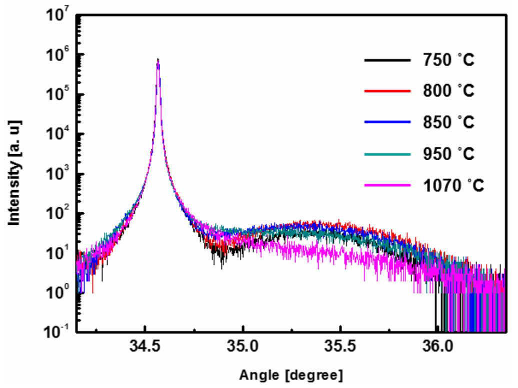
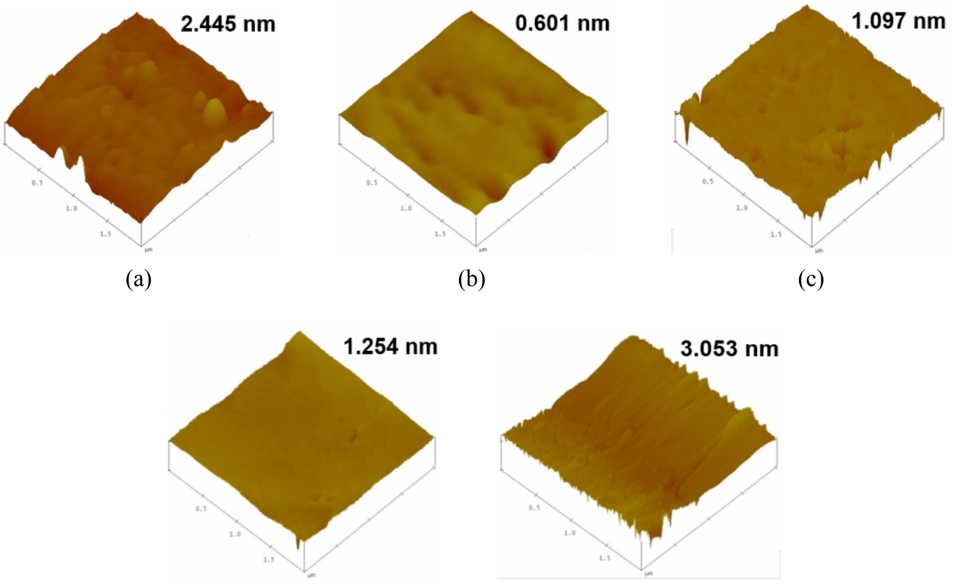


Fig. 2. Results of (002) HR-XRD 2θ-ω scan for 5 nm-thick AlN barrier with various growth temperatures

AlN layer is very thin. As shown in Fig. 2, it is true that the AlN layer grown with In-surfactant may not be a perfect AlN layer in composition, but rather results in growth of $Al_xIn_{1-x}N$ layer with very small In-composition, expected from the peak position of AlInN and AlN layer [12]. The heterostructure grown at 800 ˚C also has better surface morphology with RMS roughness of 0.601 nm as shown in Fig. 3. The effect of In-surfactant are shown clearly in Table 1, which indicates the poor sheet resistance of 8404 Ω/□ and electron mobility of 37.6 $cm^2/V{\cdot}s$ for the AlN/GaN heterostructure grown without In-surfactant. The quality of the heterostructure was improved as the thickness of the AlN layer increased to 7 nm, exhibiting 2DEG density of 2.04 x 10^{13} $/cm^2$ (approximately two times larger than the value obtained from the conventional AlGaN/GaN heterostructure), electron mobility of 1430 $cm^2/V{\cdot}s$, and sheet resistance of 215 Ω/□, which are comparable to the values obtained from other groups [13, 14]. Growth optimization is still needed to further increase the 2DEG density and the carrier mobility.

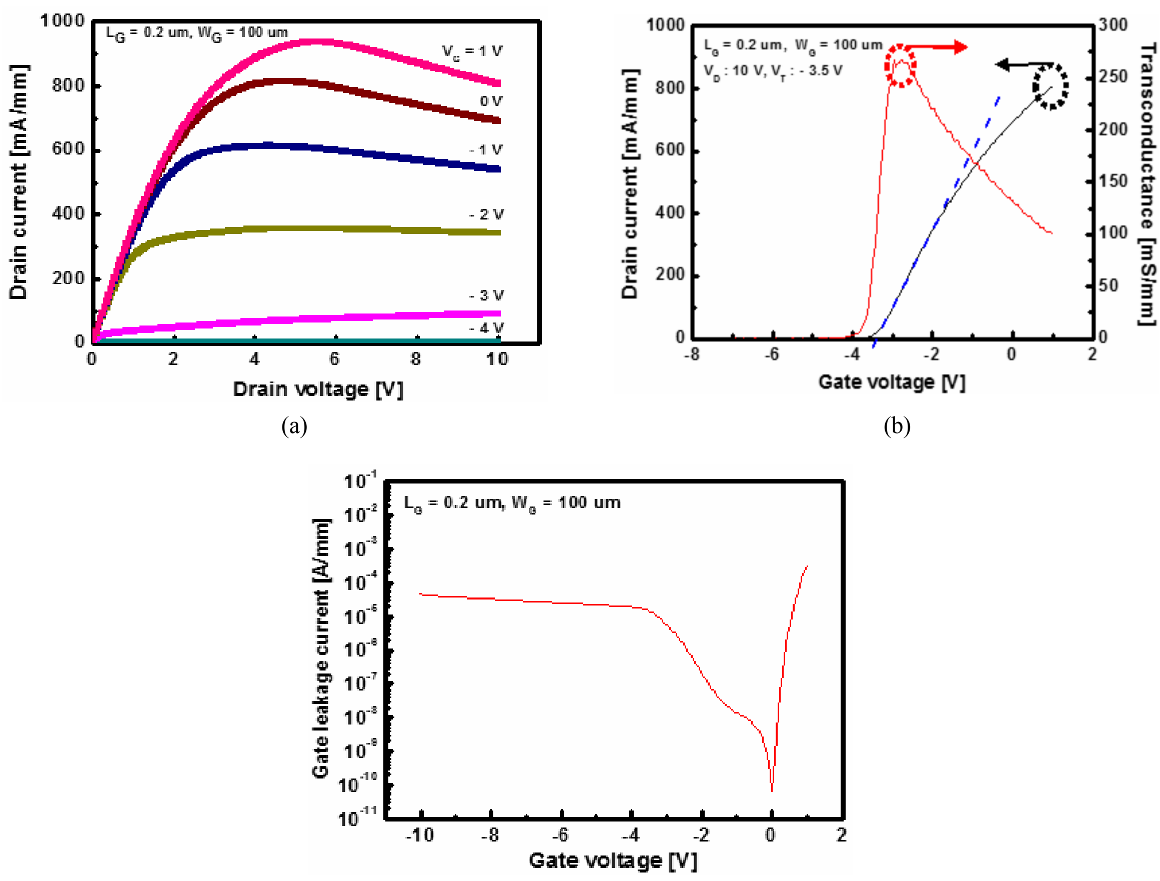
The 7 nm-thick AlN/GaN heterostructure grown at 800˚C was used to fabricate HEMT with the gate length and width of 0.2 and 100 µm, respectively. The threshold voltage of the device was about - 3.5 V extrapolated from transfer I-V characteristics and the device exhibited high maximum drain current ($I_{D,max}$) of 937 mA/mm at a gate bias of 1 V and high maximum extrinsic transconductance ($g_{m,max}$) of 269 mS/mm at a drain bias of 10 V as shown in Fig. 4. These excellent DC performances are believed to be due to high 2DEG density and high carrier mobility of the AlN/GaN heterostructure. In addition, the gate leakage current of 4.3 x 10^{-5} A/mm is also comparable to that obtained from other groups [15, 16]. The device exhibited, as shown in Fig. 5, the f_T of 40 GHz and the maximum oscillation frequency (f_{max}) of 80 GHz extrapolated from the short circuit current gain and maximum stable gain at a gate bias of - 3.4 V and a drain bias of 10 V, respectively. These RF performances are



(a) (b) (c)

(d) (e)

Fig. 3. 3D views of AFM images and RMS roughness with various growth temperature (a) 750˚C, (b) 800˚C, (c) 850˚C, (d) 950˚C, (e) 1070˚C



(a)

(b)

(c)

Fig. 4. The DC characteristics of the device (a) I_D –V_D characteristics, (b) transfer I-V characteristics in saturation region, (c) gate leakage current

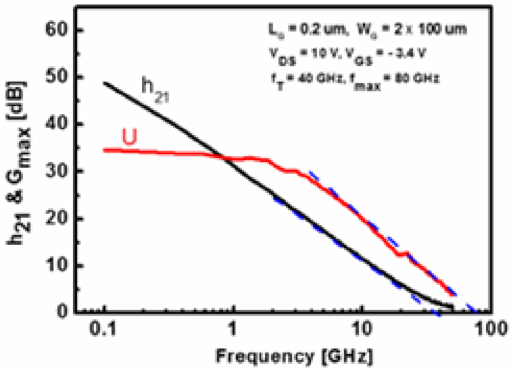


Fig. 5. The small-signal characteristics of the device: the current gain cut-off frequency (f_T) and the maximum oscillation frequency (f_{max})

reasonable, but not high enough considering the device exhibits excellent DC performances. To further improve the RF performances, it is required to optimize the device fabrication such as better ohmic contact formation and gate metallization process.

IV. CONCLUSIONS

High quality AlN/GaN heterostructure has been successfully grown by using In-surfactant. The optimized growth temperature of the AlN barrier was 800 °C. The HEMT fabricated on the proposed AlN/GaN heterostructure with AlN barrier thickness of 7 nm shows promising device performances for mm-wave applications such as $I_{D,max}$ of 937 mA/mm, $g_{m,max}$ of 269 ms/mm, f_T of 40 GHz and f_{max} of 80 GHz.

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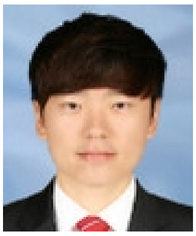

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