Improve the performance of MOCVD grown GaN-on-Si HEMT structure

Dr. Xiaoqing Xu
Stanford Nanofabrication Facility

Abstract

The SNF installed a new metalorganic chemical vapor deposition (MOCVD) system for the growth of III-nitrides (i.e. GaN, AlN, InN). The capabilities of MOCVD have enhanced and propelled research of III-nitride in power electronics, optoelectronics, timing references, high frequency applications, and harsh environment sensors. One of the most powerful applications is in the fabrication of GaN HEMT which utilizes a two-dimensional electron gas (2DEG) layer that occurs at the interface of GaN and AlGaN. The properties of HEMTs are dependent on the sheet concentration and the electron mobility of the 2DEG layer.

Our initial effort had developed a HEMT structure with the sheet carrier concentration, electron mobility, and sheet resistivity being $1.1x10^{13}$ cm^{-2}, 1590 cm^2/Vs, and 362 ohm/cm^2, respectively. However, the sheet resistance variation over the 4" wafer was found to be 6%, which is higher than the Axitron specification (5%) of the tool. The goal of this project is to improve the uniformity of the electrical property to within 2.5% stdev% and thoroughly understand the dominant effects on HEMT performance and uniformity. High mobility uniformity with stdev% as low as 0.72% across the radius has been obtained on 4" wafer, and up to 1740.35 cm^2/Vs 2DEG mobility has been realized with low C and O incorporation. The influencing effects: Al% and distribution in AlGaN barrier, growth temperature and distribution, C and O impurities, and back end metal contact annealing et al. are discussed.

I. Introduction

The main factors influencing AlGaN/GaN 2DEG concentration and mobility are: Al% in AlGaN barrier, AlGaN barrier thickness, AlN spacer thickness, GaN cap thickness, and C% in GaN layer, all dependent on the growth temperature and its distribution. Table I is a summary of the preceding results in literature. Fig.1~Fig. 4 are copies of the corresponding plots[1-3].

Table I Main factors influencing AlGaN/GaN 2DEG concentration and mobility

	Al% in AlGaN barrier	AlGaN barrier thickness	AlN spacer thickness	GaN cap thickness	C% in GaN
Range	15%-90%	5-30nm	0-2nm	0.1-10nm	2e16-2e18 cm^{-2}
2DEG concentration	↑	↑	↓	↓	↓
Electron mobility	↓	↓	↑	↑	↓

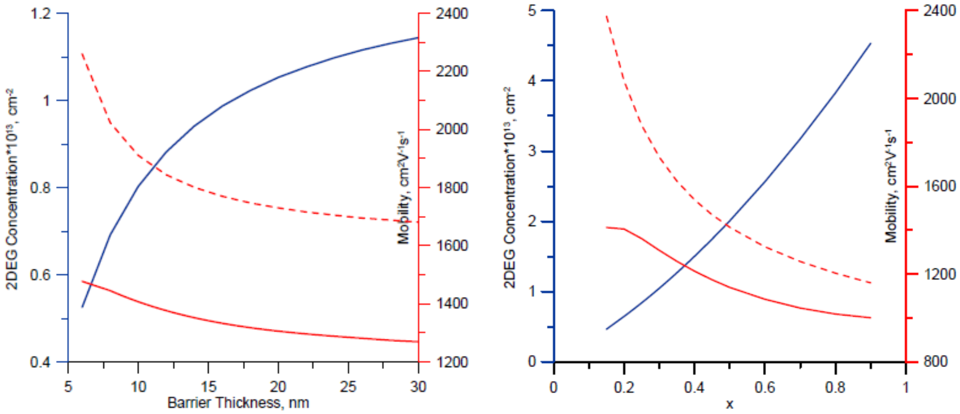


Fig. 1[1] Dependence of 2DEG layer concentration (left scale) and mobility (right scale) on (a) various barrier thickness values when Al%=0.3 and (b) Al% in the barrier layer. Dashed lines, mobility limited only by phonon scattering (polar and acoustic phonons).

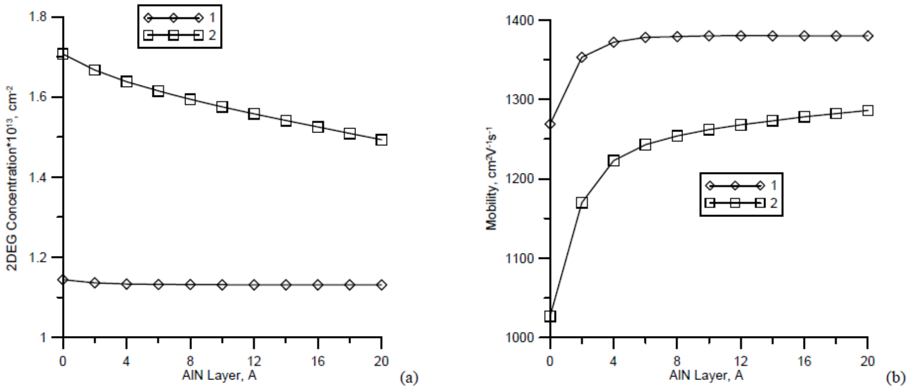


Fig. 2[1] (a) Dependence of 2DEG layer concentration on AlN layer width at various barrier doping. (1) Without doping, (2) with doping,10^{19} cm^{-3}. (b) Dependence of 2DEG mobility on AlN layer width at various barrier doping.

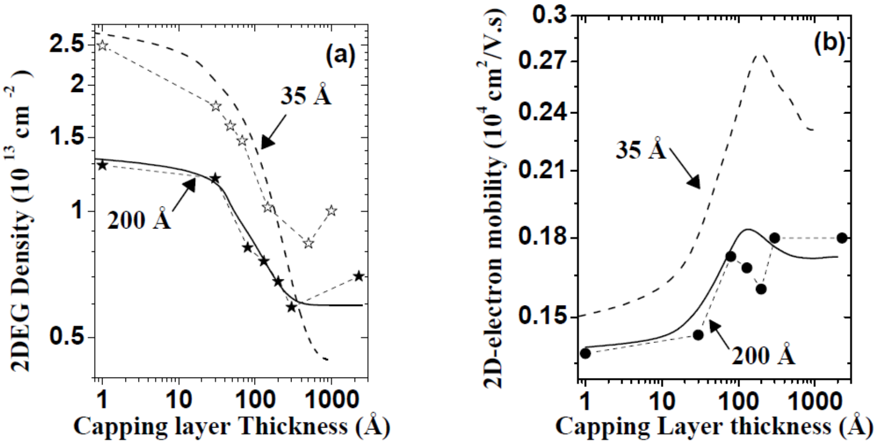


Fig. 3[2] (a) The 2DEG sheet density and (b) the mobility at 300K for the GaN/AlGaN/GaN HEMT as a function of GaN capping layer thickness with: the AlN barrier thickness is 35Å; and the Al$_{0.32}$Ga$_{0.68}$N barrier thickness is 200Å. Symbols represent experimental data from literature.

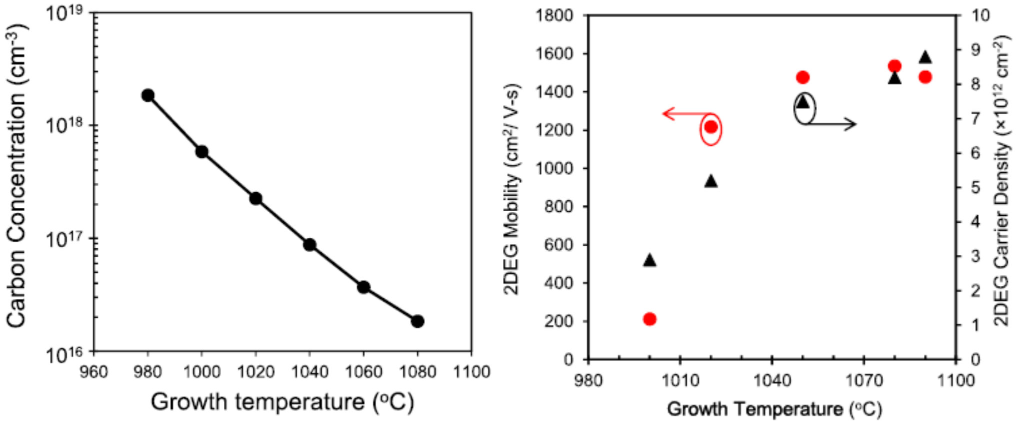


Fig. 4[3] (a) The carbon concentration versus growth temperature in GaN layer, (b) 2DEG mobility and carrier density in the Al$_{0.28}$Ga$_{0.72}$N/GaN heterostructures as a function of growth temperature.

Overall consideration, our HEMT growth structure is designed as Fig. 5. In this report, we will focus on four dominant effects: 1. 2DEG mobility uniformity across 4” wafer, which is a combined effect of Al% and thickness distributions in AlGaN barrier, AlN spacer and GaN cap thickness distributions, and C% distribution in GaN layer, all dependent on the growth temperature and its distribution; 2. Influence of C and O impurity incorporation on the 2DEG mobility; 3. Influence of Al% in AlGaN barrier on the 2DEG performance; 4. Influence of metal contact annealing on the HEMT structure performance.

Fig. 5 GaN-on-Si HEMT structure

II. Methodology and results

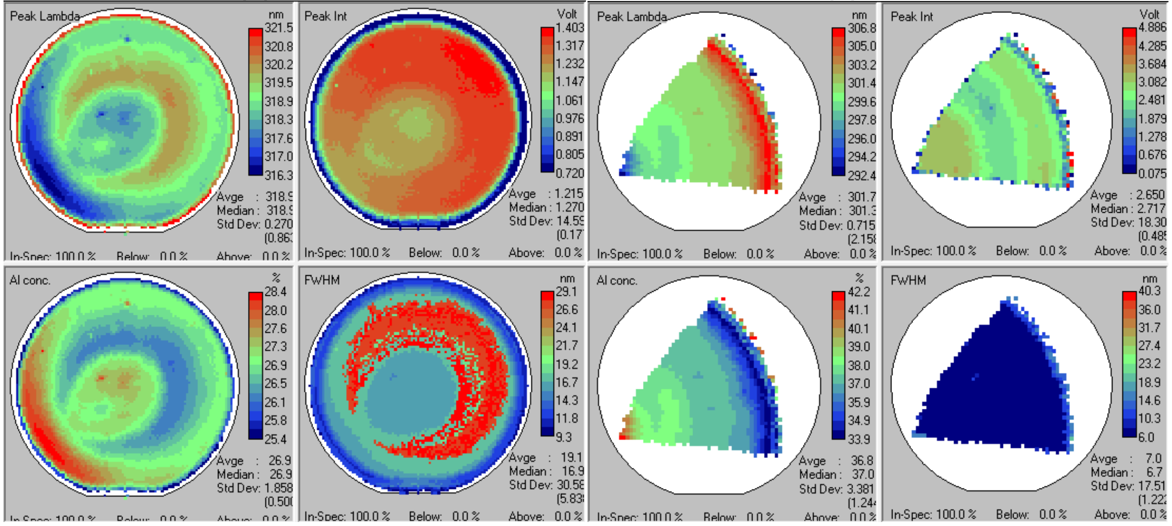
1. 2DEG mobility uniformity across 4” wafer

a. Influence of growth temperature on Al%

While the 5 parameters, Al% and thickness distributions in AlGaN barrier, AlN spacer and GaN cap thickness distributions, C% in GaN layer, are all dependent on the growth temperature and its distribution, it is hard and destructive to precisely determine the thickness distribution of such thin layers (1~25nm) and the C impurity elemental mapping of low concentration (down to $1x10^{16}cm^{-3}$). The Al% distribution, however, can be determined nondestructively by photoluminescence (PL) mapping. The Al% distribution, is an indication of the growth temperature distribution, and thus can be a representative of all the 5 parameters.

To test the growth temperature dependence of Al%, we grow 3 AlGaN/AlN/Si testing samples at 1000 ^oC, 1040 ^oC, and 1080 ^oC (sample surface temperature), respectively. Fig. 6(a)~(c) show the PL mappings of the three samples, and Fig. 6(d) plots the growth temperature dependence of Al%. It’s found that the Al% is highly dependent on the growth temperature variation, 0.24%Al increment per ^oC shift, at the commonly used temperature range, 1000~1080 ^oC.

(a) 1000 °C (b) 1040 °C



(c) 1080 °C (d)

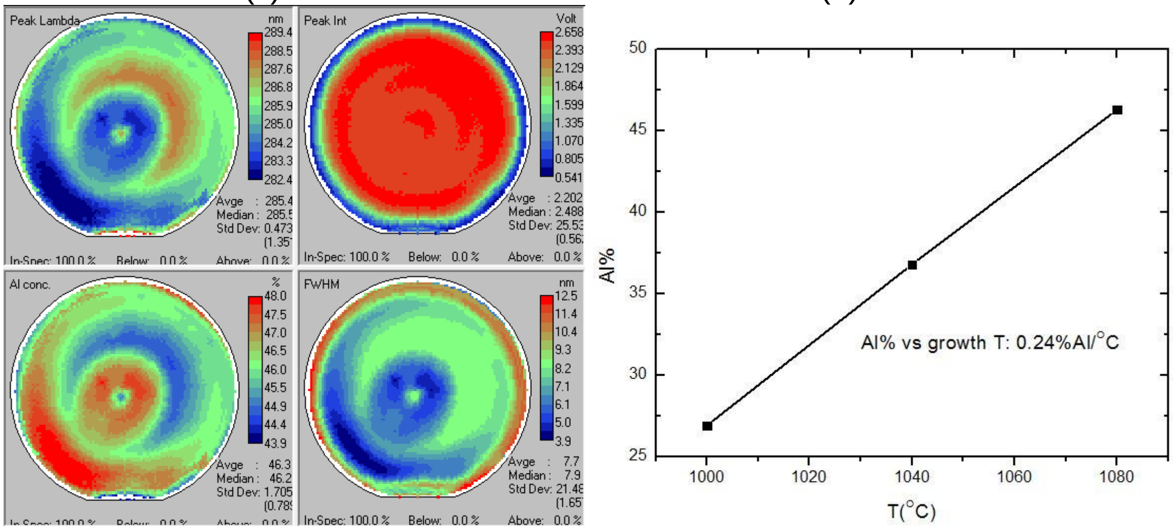


Fig. 6 AlGaN/AlN/Si testing samples grown at (a) 1000 °C, (b) 1040 °C, and (c) 1080 °C, respectively, (d) The growth temperature dependence of Al%, 0.24%Al/°C.

b. *Tuning growth temperatures for high uniformity*

Table II Growth temperatures and heating zone power percentages of the top 4 layers

	GaN-1st step	GaN-2nd step	AlN spacer	$Al_xGa_{1-x}N$ barrier	GaN cap
Heater set temperature (°C)	1270	1295	1295	1295	1295
Zone power% A/B/C	58/65/62	58.5/65.5/62	58.5/65.5/62	58.5/65.5/62	58.5/65.5/62
Sample surface temperature (°C)	~1050	1050~1067	~1032	~1032	~1032

There are three heating zones, A, B, and C, as illustrated in Fig. 7(a). Due to the strain variation and the wafer bow development as the film layers are increased, it is much harder to control the uniformity of the full HEMT structure than the simple AlGaN/AlN/Si test structure. After many tunings of the three heating zone power percentages in the top 4 layers, the settings in Table II (the sample surface temperatures of different layers are read out from Fig. 7(b)) result in a good Al% uniformity, 2.4% stdev% at 25% average Al%, and a good thickness uniformity, 3.2% stdev% at 2.76µm average thickness of the full GaN-on-Si HEMT structure. The PL mapping of the resulting $Al_xGa_{1-x}N$ barrier and the thickness mapping of the full HEMT structure are shown on Fig. 8(a) and 8(b).

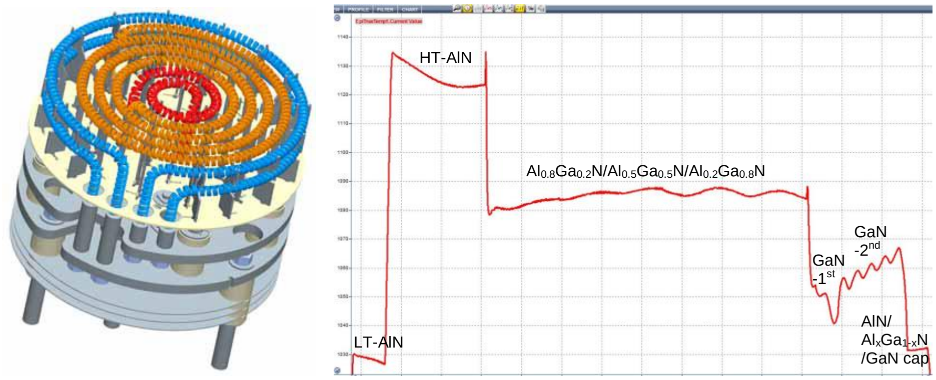


Fig. 7 (a) Heater coils: Zone A: Centre (red), Zone B: Middle (orange), Zone C: Outside (blue), (b) Sample surface temperature measured by in-situ EpiTT pyrometer.

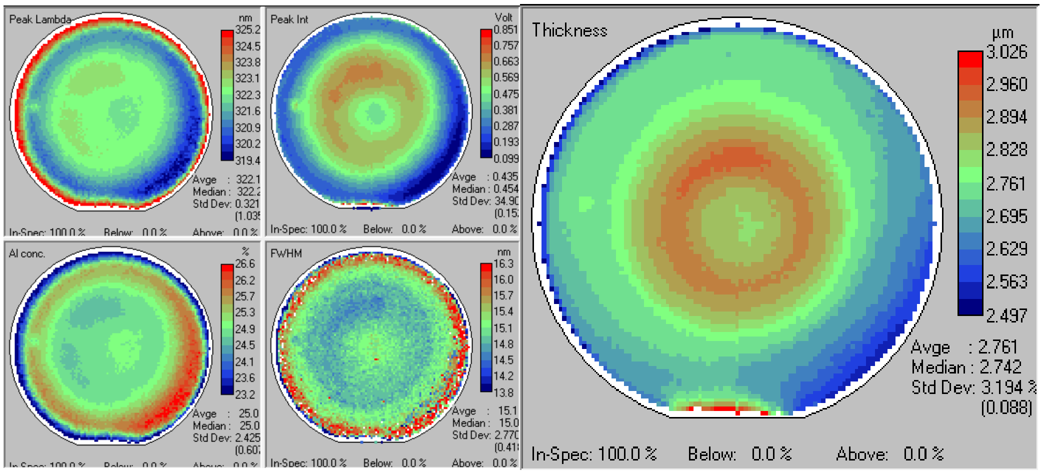


Fig. 8 (a) The PL mapping of the $Al_xGa_{1-x}N$ barrier and (b) the thickness mapping of the full HEMT.

c. High uniformity of 2DEG mobility achieved on 4” wafer

To test the electrical property uniformity, we diced the above sample into pieces of 1.08cm x1.08cm and made four metal contacts at the corners of each piece. The metal layers are 20nm Ti/100nm Al/40nm Pt/80nm Au from bottom to top, deposited by an Innotec E-Beam evaporator. Hall measurement was done on 5 pieces across the radius of the 4” wafer. Each piece is measured twice and the average value is recorded. The measured results are collected in Table III. The 2DEG mobility has a high uniformity with a stdev% of 0.72% across the radius of 4” wafer, much better than the initial goal of this work, 2.5% stdev%. Fig. 9 shows the SEM cross section of the HEMT structure at the center of the wafer. The films are smooth and exhibit sharp interfaces between different layers, indicating good film growth. The total thickness of 2.70µm matches pretty well with the average thickness of 2.76µm from thickness mapping.

Table III 2DEG mobility of 5 pieces across the radius of 4” wafer

	#1	#2	#3	#4	#5	Average (cm^2/Vs)	Stdev%
µ1 (cm2/Vs)	1205.7	1218.1	1217.8	1206.4	1230.6	--	--
µ2 (cm2/Vs)	1210.5	1207.7	1206.6	1206.4	1226.2	--	--
µ (cm2/Vs)	1208.1	1212.9	1212.2	1206.4	1228.4	1213.6	0.72%

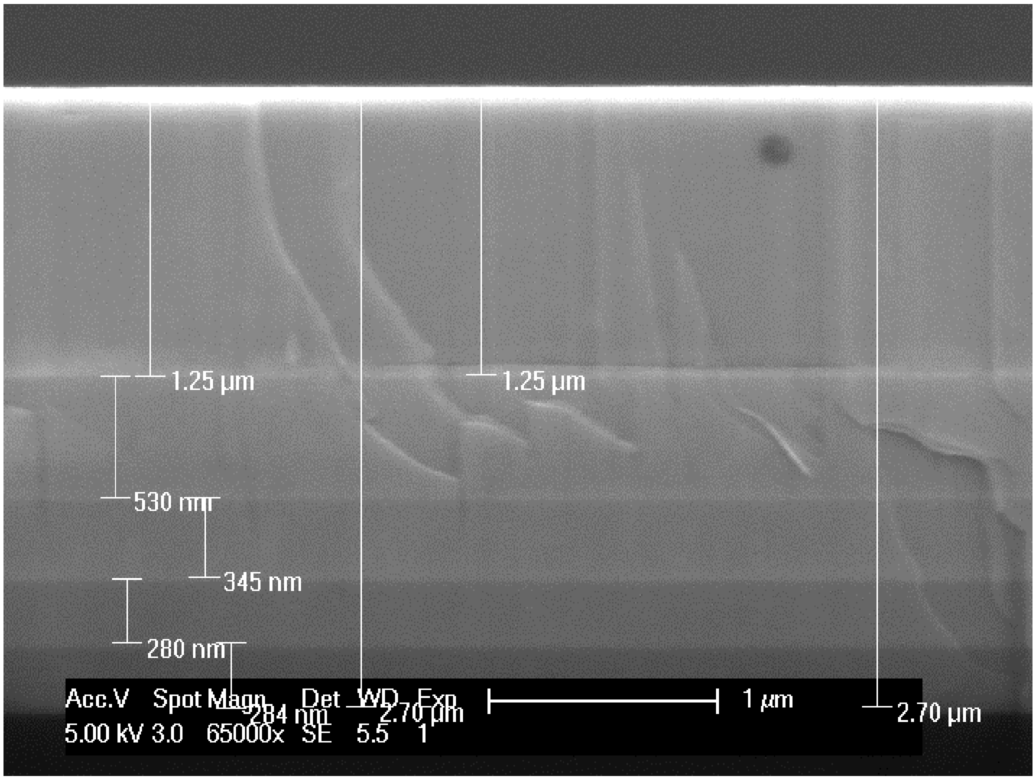


Fig. 9 SEM cross section of the HEMT structure at the center of the wafer.

2. Influence of C and O incorporation on the 2DEG mobility

Table IV 2DEG performances of samples with different C and O concentrations

	Mobility (cm^2/Vs)	**Sheet Number (cm^{-2})**	**Sheet Resistance (ohm/cm^2)**
A	1740.35	9.3368E+12	384.135
B	1224.6	1.2902E+13	395.04

The C and O impurity incorporation in the vicinity of the 2DEG channel can severely affect the 2DEG performance especially when the concentration is higher than $1x10^{17}cm^{-3}$. Table IV shows the different performance of two HEMT structures with very similar film parameters except for the C and O concentrations. It's noted that as high as 1740.35 cm^2/Vs electron mobility was achieved on sample A, while sample B has lower mobility and higher sheet carrier density. The SIMS data of Ga, C, and O for samples A and B are compared in Fig. 10.

The SIMS depth profiles were measured by a NanoSIMS with Cs ions along all the epi layers. It's noted that due to the fact of low depth resolution of NanoSIMS, although perfect surface resolution, the interfaces between the layers are not very sharp. The ultra-high C and O signals at the surface are a combined effect of surface molecules absorption and instable ion yields, so can be disregarded. Despite of the limitations of the measurement, sample B obviously has higher C and O signals in all the epi layers. This explains the lower mobility of sample B by enhanced trapping effect and ionized impurity scattering at higher impurities incorporation. It's also noted that sample B has higher sheet carrier density than sample A, so the dominant impurity in sample B is O other than C since O is a donor while C is an acceptor in GaN.

Therefore, to obtain high 2DEG performance, growth temperature of the GaN layer needs to be high enough and reactor condition including pretreatment and de-contamination processes needs to be controlled to reduce C and O incorporation.

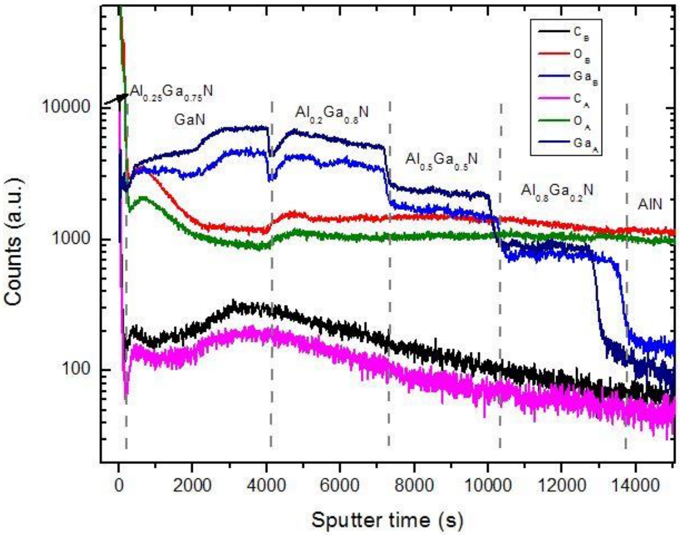


Fig. 10 SIMS depth profiles of C, O and Ga in samples A and B. Ga is used as a reference signal and also performs to distinguish different layers.

3. Influence of Al% in AlGaN barrier on the 2DEG performance

The influence of Al% in AlGaN barrier was investigated by comparing the 2DEG performance of two HEMT structure samples with different Al%, 26.3% and 38.2% as disclosed by PL mapping in Fig. 11(a) and 11(b), respectively. At higher Al%, the alloy scattering is stronger so the electron mobility is lower; meanwhile, the spontaneous polarization difference is larger and the piezoelectric polarization is stronger at the AlGaN/GaN interface, so the induced 2DEG charge density is higher. The sheet resistance, however, is a competing effect of the mobility and the sheet carrier density, following 1/ρ=neμ.

Table V 2DEG performance of samples with different Al%

Al%	**Mobility (cm^2/Vs)**	**Sheet Number (cm^{-2})**	**Sheet Resistance (ohm/cm^2)**
26.3%	1740.35	9.3368E+12	384.135
38.2%	730.5829	4.32E+13	197.7498

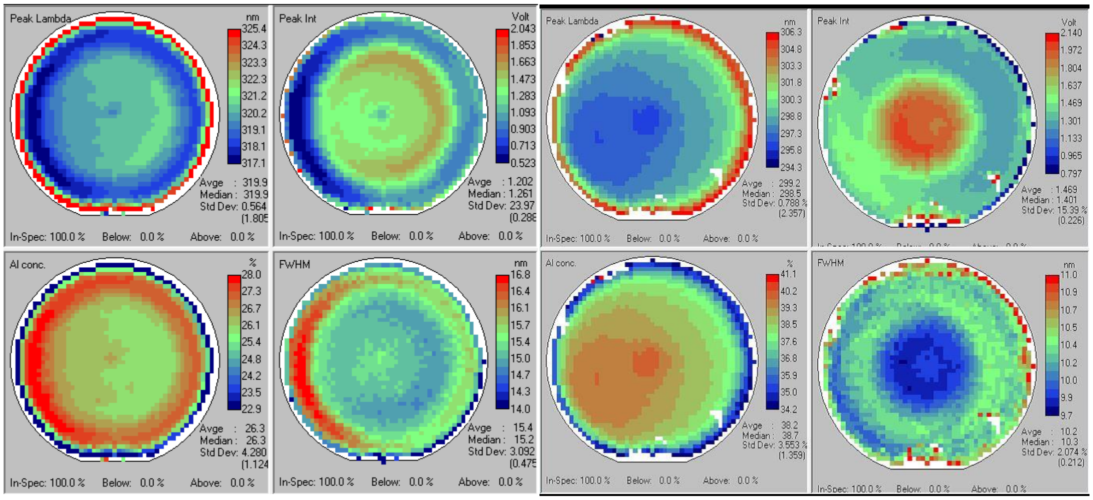


Fig. 11 PL mapping of HEMT structure samples at different barrier Al%, (a) 26.3% and (b) 38.2%.

4. Influence of metal contact annealing on the HEMT structure performance

The influence of metal contact annealing on the HEMT structure performance was investigated by measuring I-V curve and Hall data of samples annealed at different temperatures. After depositing the metal layers, 20nm Ti/100nm Al/40nm Pt/80nm Au, and sample dicing, the pieces were annealed in an RTA at 550ºC~850ºC in N_2 environment. I-V measurement was done between two adjacent metal contacts of the 1.08 cm x1.08 cm pieces. The I-V curves are shown on Fig. 12(a). It's found that the I-V curves are not exactly linear until 850ºC annealing, and the higher the annealing temperature is, the higher the current is (the lower the resistance is). The inset is a magnification of the I-V curve at low voltage. Although the I-V curves below 850ºC annealing are not perfectly linear, they are almost linear at low voltage range as was shown in the inset, indicating near ohmic contact for all the samples at -0.1V~0.1V.

The Hall measurement was done within the linear region, and the contact annealing temperature dependences of the 2DEG mobility, sheet resistance, and sheet number are shown on Fig. 12(b). At higher annealing temperature, the carrier sheet density is increased while the 2DEG mobility is decreased. Therefore, although the ohmic contact seems to be improved after annealing, the 2DEG mobility of the HEMT structure, is actually degraded. The increased carrier density and current are due to the doping effect of the metals which could have diffused into the 2DEG layer at high temperatures, or the C/O et. al. impurities are activated at high temperature treatment. Therefore, the as prepared sample exhibits the highest mobility while the 850°C annealed sample exhibit the lowest mobility, although highest current. The mechanism behind this is still to be verified.

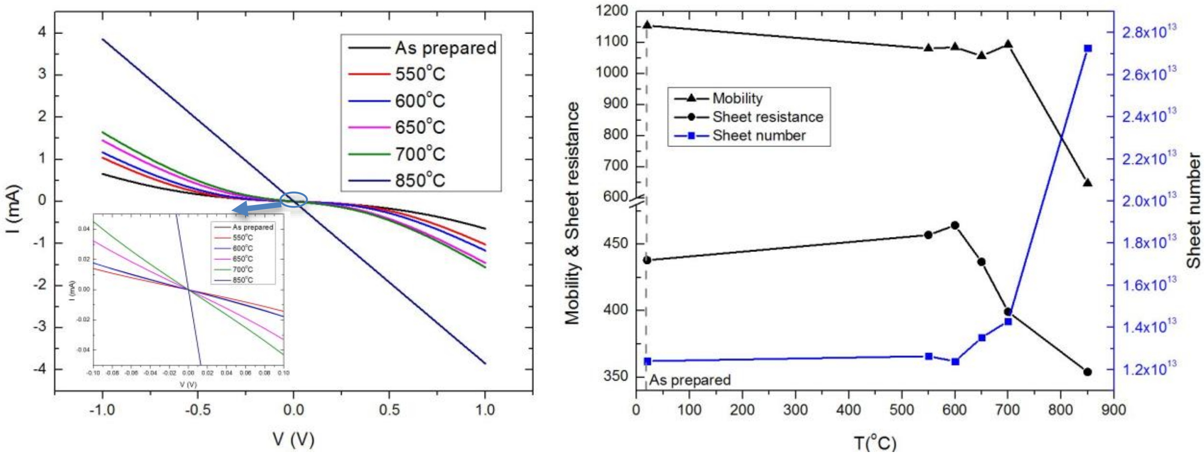


Fig. 12 (a) I-V curves between two adjacent metal contacts of the 1.08 cm x1.08 cm Hall samples annealed at different temperatures. The inset is a magnification of the I-V curve at low voltage. (b) Contact annealing temperature dependences of the 2DEG mobility, sheet resistance, and sheet number.

III. Summary and future work

In summary, we have successfully achieved high uniformity of 2DEG mobility with stdev% as low as 0.72% across the radius of the 4” GaN-on-Si HEMT wafer, and up to 1740.35 cm^2/Vs 2DEG mobility has been realized. The dominant effects on 2DEG performance and uniformity are deeply investigated and understood.

For future work, the influence of C and O impurity on the back end contact property, and the influence of possible metal diffusion during high temperature annealing on the 2DEG performance need to be further investigated and verified. The growth condition needs to be strictly controlled, including sample cleaning, reactor pretreatment and de-contamination, and carrier wafer selection, to limit the C and O incorporation.

IV. Acknowledgement

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V. References

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