Process Condition Optimization for High Throughput and High Efficiency Growth of the AlGaN/GaN HEMT Structure in a Single Wafer Rotating Disc MOCVD Reactor

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Abstract

High throughput and high efficiency growth of the AlN/AlGaN super-lattice based HEMT structure on 200mm Si is presented using Veeco's Propel^{TM} rotating disk, single wafer vertical MOCVD reactor. Effect of process conditions (V/III ratio, disc rotation rate, chamber pressure, and total flow rate) on AlN/AlGaN growth rates was investigated based on advanced CFD and chemistry modeling. It was found that gas-phase parasitic reactions between aluminum source (TMAl) and ammonia (NH_3) can be dramatically reduced by careful optimization of those process parameters, which resulted in much higher AlN/AlGaN growth rates. Using the described optimization, the process time for a 100 pair AlN/AlGaN super-lattice based 5.4µm buffer stack for HEMT on Si was reduced ~ 50% from the baseline, while maintaining equivalent wafer bow, surface roughness, crystal quality (rocking curve for AlN(002), GaN(002), GaN(102)), film edge cracks and buffer breakdown voltage.

INTRODUCTION

Recently, AlGaN-based high electron mobility transistors (HEMTs) grown on Si substrates have attracted much attention for applications such as high power switching and radio-frequency amplification. Even though the adoption of readily available, large diameter Si substrates (200 mm) enabled reduction in manufacturing cost, GaN epitaxy by MOCVD is still the major component in the overall cost of HEMT devices. Improvements in MOCVD reactor design that can provide for better process uniformity and higher throughput have become a critical path for increasing process yield and reducing epitaxial wafer costs.

Veeco recently introduced Propel^{TM} MOCVD single wafer rotating disc reactor that, compared to batch reactors, provides for superior uniformity in epilayer deposition and doping profiles and enables significant increase in yield [1]. The advantages of a single wafer rotating disc reactor are based on its inherent symmetric and concentric thickness/alloy composition pattern, and elimination of the "leading/trailing" edge effects, characteristic for multi-wafer rotating disc reactors (due to a large temperature gradient between wafers and the wafer carrier). Besides the yield improvement, it is critical to enable high efficiency growth and high throughput in a single wafer reactor to help the market meet cost targets.

In most cases, the limiting steps in achieving high throughput during HEMT structure growth are associated with layers required to relieve the stress and create crack-free GaN on Si, due to the inherent large mismatch of lattice constant and thermal expansion coefficients between Si and GaN. The major problem during the epitaxial growth of such layers (low-temperature AlN nucleation, high Al content graded AlxGa1−xN buffer and/or AlN/(Al)GaN superlattices layers) is the enhanced gas-phase parasitic reactions between aluminum source (TMAl) and ammonia (NH_3), which typically results in very low growth rates, and thus, lower throughput.

In this work, we report a systematic study on effect of process conditions, such as V/III ratio, disc rotation rate, chamber pressure and total flow rate, on AlN/AlGaN growth rate and HEMT structure material quality in Veeco Propel^{TM} MOCVD reactor. This study includes a detailed theoretical analysis on the mechanism of parasitic losses in the gas phase, simulation results based on improved chemistry model, as well as experimental results.

RESULTS AND DISCUSSION

Figures 1(a)-(c) show contours of temperature, adducts mass fraction and particle density, respectively, for baseline conditions at 75Torr and 1000rpm and given NH_3 and H_2 flow rates ($Q(NH_3)_1$, $Q(H_2)_1$). Simulation results are based on advanced in-house CFD modeling, combined with the state-of-the-art chemistry module developed by STR Group [2]. Growth temperature used for the analysis was 1035ºC. The simulated AlN growth rate for the specified conditions was 0.53µm/hr, which matched closely experimentally obtained growth rate of 0.5µm/hr. Based on this, a systematic modeling analysis was performed to explore a process space for higher AlN/AlGaN growth rates and throughput. Figure 2 summarizes results on the effect of different process parameters on AlN growth rate and source efficiency. It is shown that for higher rotation rates, lower pressures and V/III ratios (lower NH_3 flow rate), parasitic reactions and particle formation in the gas phase dramatically decrease, which enables achieving much higher growth rates and operation under mass-transport limited regime (growth rate is only limited by TMAl flow rate). At the same time, source efficiency can be also significantly improved (lower TMAl flow rate can be utilized) for higher growth rates, as seen in Figure 2. Generally, lower operating pressures and NH_3 flow rates shift the adduct formation reaction equilibrium (TMAl+NH_3 ↔ TMAl:NH_3) towards TMAl, and thus, reduce or prevent subsequent gas-phase parasitic reaction pathway through the formation of large molecules such as amides, oligomers and clusters/particles, which do not contribute to the AlN growth [2,3]. On the other hand, higher growth rates observed for higher rotation rates can be attributed to the fact that majority of irreversible decomposition of TMAl:NH_3 (amide formation) and oligomerization occur within hot boundary layer where residence time is strong function of rotation rate [4].

Figures 3(a)-(b) show comparison between modeling and experimental data for the effect of NH_3 flow rate as well as pressure, rotation and total flow rate on AlN growth rate, respectively. Excellent agreement between modeling and experimental results can be observed.

Based on the modeling exercise, we explored the effect of process conditions and AlN/AlGaN super-lattice growth

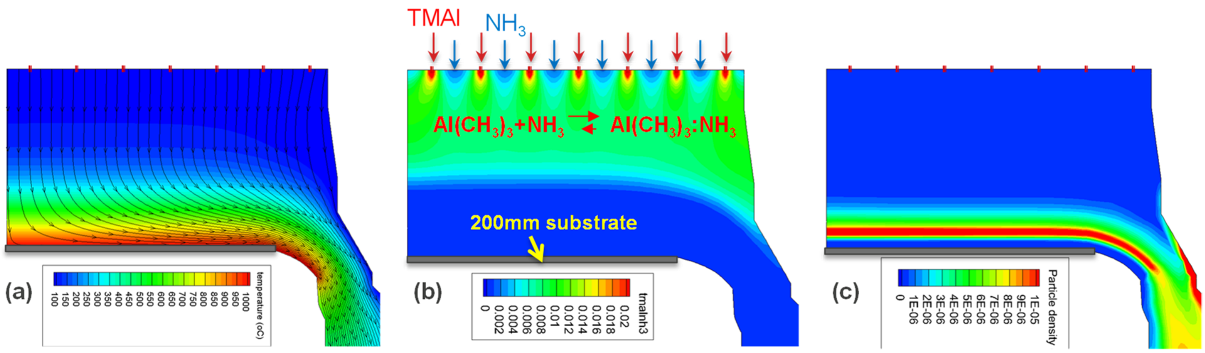

Fig. 1. Contours based on CFD and chemistry modeling: (a) Temperature and streamlines, (b) adducts (TMAl:NH_3) mass fraction, (c) particle density (kg/m^3).

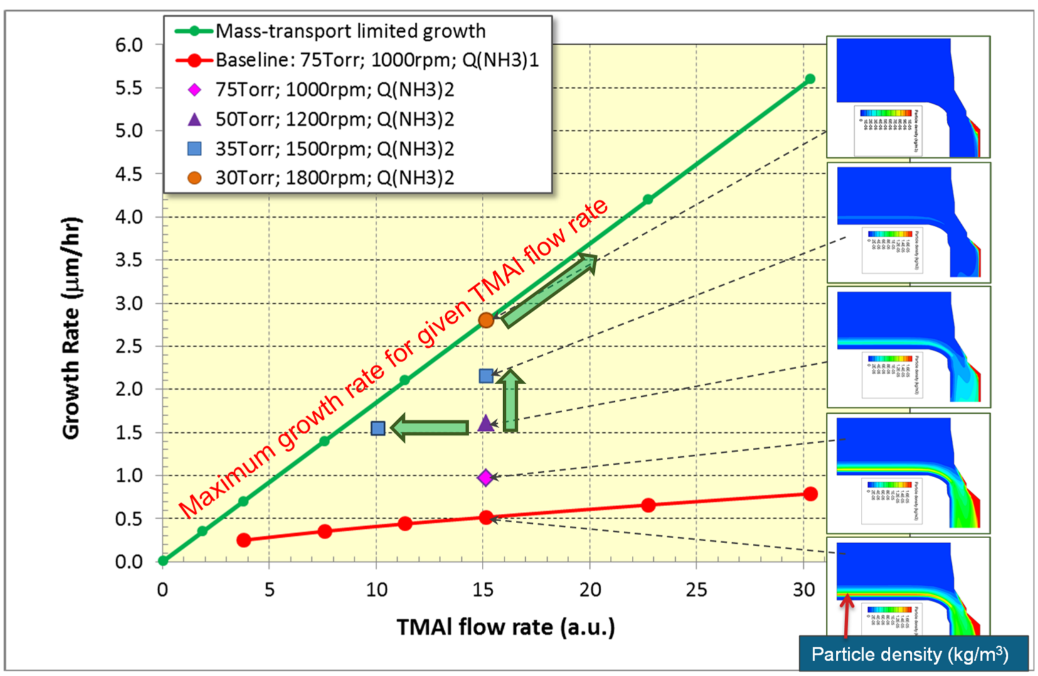

Fig. 2. Effect of process conditions on AlN growth rate and source efficiency in Veeco Propel^{TM} MOCVD single wafer reactor at 1035 ^{o}C growth temperature, based on advanced CFD and chemistry modeling. $Q(NH_3)_2=0.2\cdot Q(NH_3)_2$

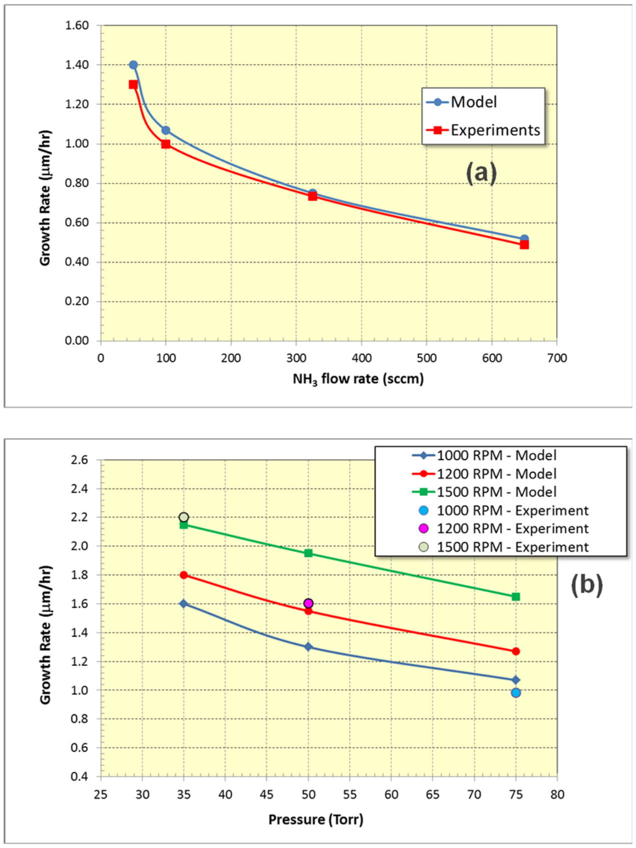

Fig. 3. Comparison between modeling and experimental data: (a) Effect of NH_3 flow rate at 75Torr, 1000rpm; (b) Effect of pressure, rotation and total flow rate.

rate on HEMT structure material quality. Figure 4 shows the schematic of the AlGaN HEMTs grown experimentally on 200mm Si (111) substrates. A 200 nm AlN is used as the nucleation layer. Intrinsically carbon-doped AlN/AlGaN SLs with periods of 4-6nm/20-30nmm are used both as stress control and current blocking layers. The stress in the alternating AlN and AlGaN layers in SLs are engineered through the growth conditions, such as V/III ratio, growth pressure and growth rates. Full stack with total thickness of ~ 5.4µm shows crack free (< 3 mm edge) and controlled wafer bow (< 40µm) at room temperature.

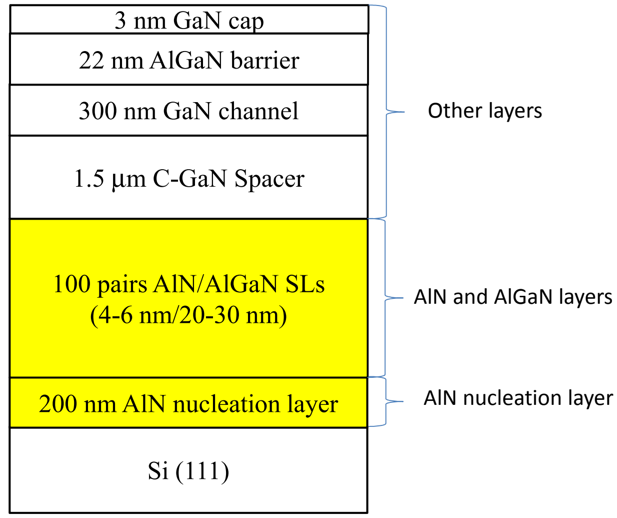

Fig. 4. Schematics of AlGaN HEMTs with 100 pairs of AlN/AlGaN SLs.

Two different process conditions are explored for both AlN and AlGaN in the SLs; (1) baseline conditions using chamber pressure of 75 Torr and disc rotation rate of 1000rpm, and, (2) using 35Torr and 1500rpm, based on modeling guidance. Flow rates of H_2 and NH_3 as well as the growth temperature were kept the same. Table I shows

TABLE I
GROWTH TIME COMPARISON BETWEEN RECIPES WITH BASELINE AND OPTIMIZED SLS PROCESS CONDITIONS

Layers	100xSL Baseline (1)				High Throughput Recipe (2)		
	Growth Rate (nm/min)	Thickness (nm)	Time (sec)	Percentage	Growth Rate (nm/min)	Time (sec)	Percentage
AlN	3.1	200	3840	13.1%	11	1091	6.4%
AlN-SLs	2.7	500	11100	38.0%	6.4	4688	24.4%
AlGaN-SLs	32.3	2800	5200	17.8%	75	2240	13.1%
Other layers		1900	4440	15.2%		4440	25.9%
Overhead time (sec)			4650	15.9%		4650	27.2
Total recipe time (sec)			29230	100.00%		17109	100.00%
Total growth time (excl. overhead)			6hr 50min			3hr 28min	
Total recipe time (hr)			8hr 7min			4hr 45min	
Runs per day			2.95			5.1	

growth time comparison between recipes with baseline and optimized SLs process conditions. It can be seen that for conditions (2), both AlN and AlGaN growth rates increased 2-3 times which resulted in ~ 50% reduction of growth time. Also, the overall recipe time was significantly reduced which enabled much higher throughput.

TABLE II
COMPARISON OF MATERIAL PROPERTIES

Parameters	**Baseline Recipe**	**High Throughput Recipe**
Total thickness (µm)	~5.4	~5.4
Wafer warpage (µm)	-36	-25
AlN (002) FWHM	986	932
GaN (002) FWHM	585	582
GaN (102) FWHM	976	1006

The full stack with optimized process conditions show similar wafer bow, crystal of quality of AlN and GaN, surface roughness and edge cracks, as show in Table II. The electrical properties of buffer stacks (stacks up to GaN channel) are evaluated by transmission line measurement (TLM) using a 100x100µm^2 ohmic metal contact grid with vertical configuration. For an optimized buffer stack with higher growth rate SLs, both forward and reverse blocking voltage show VBD of > 800V @1µA/mm^2 at 25^{o}C, which is comparable to the results from buffer stack with the baseline SLs growth conditions. It should be also noted that , based on Figure 2, there is a significant upside for additional reduction of growth time for AlN/AlGaN layers, and thus throughput, by further optimization of process parameters. Generally, vertical rotating disc reactors enable operation under wide range of stable process conditions [5], so that both high AlN/AlGaN growth rates and desired material quality can be achieved by adjusting the growth parameters.

CONCLUSIONS

The influence of process conditions (V/III ratio, disc rotation rate, chamber pressure and total flow rate) on AlN/AlGaN growth rate and HEMT structure material quality was investigated based on the systematic modeling and experimental study. It was demonstrated that parasitic gas-phase reaction pathway between TMAl and NH_3 can be dramatically reduced by operating at lower pressures, higher disc rotation rates and using lower NH_3 flow rates. Significant improvement in process time (~50%) and source efficiency is achieved during AlN/AlGaN super-lattice HEMT structure growth on 200mm Si substrate while maintaining the desired material quality.

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ACRONYMS

MOCVD: Metal-Organic Chemical Vapor Deposition
HEMT: High Electron Mobility Transistors
CFD: Computational Fluid Dynamics
FWHM: Full Width at Half Maximum
SL: Super-Lattice