Real-Time Control of Layer Thickness and Thickness Uniformity for Single Wafer Reactor MOCVD Systems

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Abstract

The ability to achieve repeatable layer thicknesses of excellent uniformity is very important to realize key device characteristics in the growth of High Electron Mobility Transistors (HEMTs) for power and RF applications. For example, thickness uniformity of the AlGaN barrier is critical to maintain threshold voltage variation within ±5% of target. In this work, we present a method to perform real-time high resolution (~0.3 nm) control of layer thickness and uniformity on the Veeco Propel® single-wafer reactor MOCVD system. The method uses specifically developed white light reflectometers in conjunction with the unique axisymmetric flow tuning capability of the Propel® single-wafer reactor to measure and control thicknesses in real time during growth. Such real-time control can improve productivity by reducing tuning runs, improving fleet repeatability, as well as increasing maintenance intervals. Results are presented showing repeatable and uniform control of both the AlGaN barrier as well as the total HEMT stack using the developed method. We also discuss some extensions of the method on the single wafer system.

INTRODUCTION

Layer-thickness, repeatability, and uniformity are of critical importance in AlGaN-based HEMTs grown on large-size (200 mm diameter) Si wafers. These devices are used in a broad range of applications including high-power switching, radio-frequency amplification, and potential integration with Si-based CMOS technologies. The top AlGaN barrier, typically around 20-40 nm thick, requires tight control across the total population (within wafer, wafer-to-wafer, and system-to-system). This is required to achieve uniform device characteristics, increase yield, and reduce epitaxial wafer costs. In a manufacturing environment that demands high process capability, to keep threshold voltage (V_{th}) variation in the final device to ±5% of target, AlGaN barrier thickness control to ±1 nm or better is typically required. In addition to the AlGaN barrier, controlling the thickness of the underlying GaN-based stack to <1% (σ/mean) may be necessary for repeatable post-epi wafer processing, such as etch and regrowth especially for enhancement-mode devices.

The standard method to achieve desired target thickness and thickness uniformity is to empirically tune process flow parameters based on customer specific growth conditions and underlying stack, and requires multiple test runs. Once the appropriate flow set points are determined, the Veeco MOCVD system remains stable during the period in between maintenance activities for several hundred runs, outside of which there may be minor shifts in thickness profiles. In this work, we developed a method on the Veeco Propel® single-wafer reactor system [1] that provides for real-time *in situ* measurement and control of key device layer thicknesses and uniformities. This real-time control thickness control method can improve productivity by reducing or eliminating test runs for tuning, increasing system maintenance intervals, and tightening performance across a fleet of systems in a manufacturing environment.

METHOD

As the first step in this work, we developed a high-resolution white light reflectometer that can be used to measure real-time film thickness during growth. Mathematically fitting the modeled Fabry-Pérot interference signal to a wide visible spectrum (500 – 660 nm) reflectivity allows the thickness of the film to be determined with high repeatability (~0.2 nm) and resolution (~0.3 nm) while retaining a high dynamic range of measurement (up to 7 µm). Fig. 1 illustrates how this fitting can calculate a thickness with high resolution even when the film is too thin for multiple interference fringes to be observed.

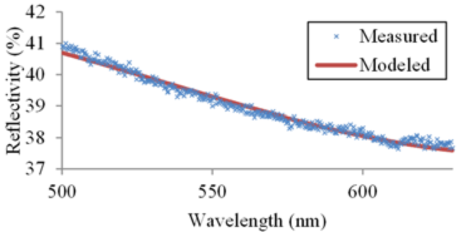

Fig. 1. Example of reflectivity fit for a thin AlGaN layer: modeled thickness is 15.7 nm.

As the next step, we positioned two such white light reflectometers across the viewport on the Propel® MOCVD system in order to measure the thickness near the center and edge of the wafer *in situ* and in real time. The feedback and control of thickness uniformity using these white light reflectometers leverages the unique design of the Propel® system that allows for axisymmetric growth rate control. This is achieved by providing the two-point measurement to a control system that adjusts the flow of carrier gases through the Propel® reactor's diametrical central injector, relative to the process gases in the main injector. Veeco's unique injector design produces a radial thickness tune with the highest response in the center of the wafer that tapers out towards the edges. When implemented in a closed-loop control system as shown in Figure 2, this axisymmetric tuning response can automatically and efficiently correct axisymmetric non-uniformities typically seen in single wafer rotating disk reactors, resulting in flat thickness profiles.

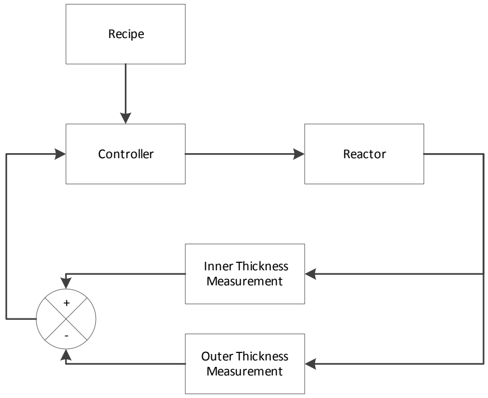

Fig. 2. Control diagram for achieving uniform thickness.

In addition to shape correction, the absolute thickness of the layer can also be controlled to a repeatable target. This can be done by simply ending a recipe step when the desired thickness is achieved. The target thickness can also be achieved by adjusting flows to modify the growth rate without changing layer time. Figure 3 illustrates such a control scheme.

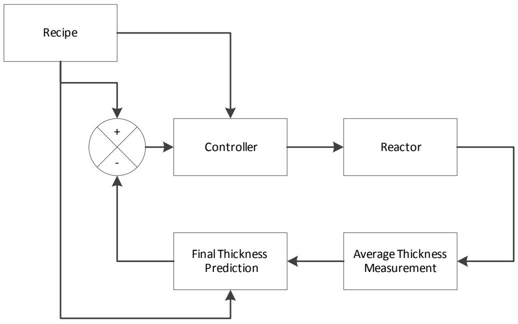

Fig. 3. Control diagram for achieving target thickness without modifying recipe time.

RESULTS

Some examples of the correction are provided in the plots below. In the first example (shown in Figures 4 and 5), we start with an intentionally un-tuned growth recipe that generates a non-uniform HEMT stack thickness profile. In a typical manual adjustment, such a profile is tuned by increasing the central gas dilution to flatten the profile. If the process tune is not done optimally (without an exactly correct prediction of system response) it can lower thickness due to overall dilution, and/or overshoot or undershoot the desired profile. In this case, this could have potentially resulted in at least two non-production test runs before the desired profile and thickness is achieved. However, when the real-time thickness control scheme is implemented, the control system detected and corrected the non-uniformity in real time and adjusted the recipes automatically to generate repeatedly radially uniform HEMT stacks with the desired overall thickness. It is important to note that by virtue of being a closed-loop real-time control system, specific system response knowledge is not required to achieve flat and repeatable profiles.

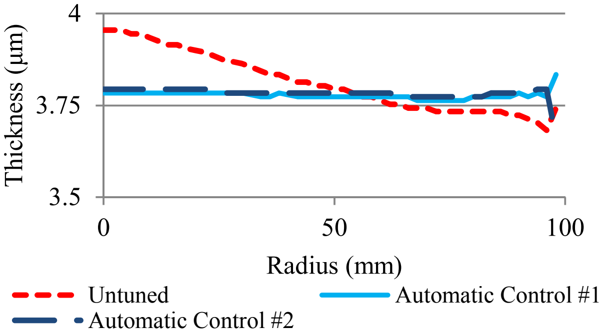

Fig. 4. Radially averaged thickness profiles of HEMT stack with manual and automatic adjustments.

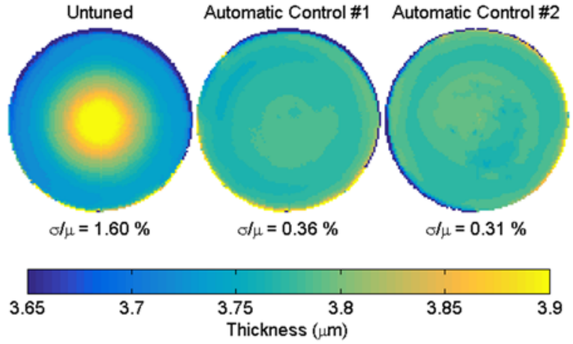

Fig. 5. Thickness maps of baseline HEMT stack and runs with automatic adjustments (σ: standard deviation, µ: mean).

Figure 6 shows another example where the real-time thickness control system automatically corrected a radially non-uniform AlGaN barrier layer to produce a radially uniform profile.

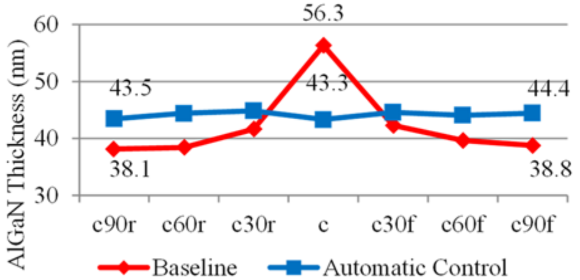

Fig. 6. XRD Thickness measurements of AlGaN barrier layer showing uniformity tuning.

Figure 7 shows yet another example where real time control is applied to AlGaN barriers from different HEMT runs, showing capability of achieving flat profiles of repeatable thicknesses. In this example, the real-time thickness control maintained the uniformity of the AlGaN barrier while reducing its thickness to a new target repeatedly over two runs by automatically adjusting layer timing.

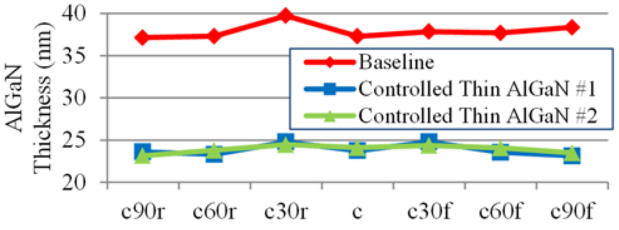

Fig. 7. XRD Thickness measurements of thickness controlled AlGaN repeats.

Al composition uniformity of <1% (range) was typically maintained in the controlled runs. Although the experiments did not attempt to control the Al composition of the AlGaN, characterization showed that the aluminum concentration became more uniform when the overall thickness was made more uniform via closed-loop control. One example is shown in Figure 8. However, the overall increase in flow led to an overall reduction in aluminum concentration. While this could be compensated for with manual tuning, which is typical in regular process tuning, it is envisioned that further work could attempt to automatically adjust the aluminum precursor (trimethylaluminum) flows to compensate for the changes made to achieve uniform thickness.

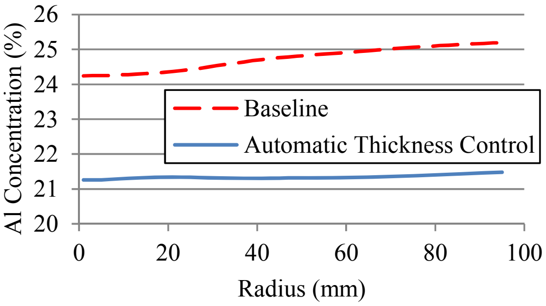

Fig. 8. Uniformity of aluminum concentration improved from a range of 0.94% to 0.22%.

CONCLUSIONS

The white light reflectometer developed in this work was able to provide high-resolution, real-time *in situ* measurement of a growing epitaxial film. Leveraging two such measurements and the axisymmetric tuning capability of the Propel® reactor, a control system was able to successfully achieve high-uniformity and high-repeatability epitaxy without any human intervention. The thickness control was successfully demonstrated on both the critical thin AlGaN barrier layer, as well as the thicker GaN layers for overall stack thickness control.

These capabilities facilitate rapid development of production-quality epitaxy growth for AlGaN-based HEMT devices. The time and material costs of trial-and-error recipe adjustments can be reduced and qualities can be repeated without expert monitoring and adjustment over longer maintenance cycles. This can improve device productivity and yields over a fleet of tools in a production environment. While this work details the application of the thickness control method to GaN/AlGaN layers, they can also be used to enhance performance of more advanced material systems such as InAlN/GaN for next generation power and RF applications [2].

REFERENCES

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[2] J. Lu, et al., "Epitaxial Growth of InAlN/GaN Heterostructures on Silicon Substrates in a Single Wafer Rotating Disk MOCVD Reactor", *MRS Advances,* doi: 10.1557/adv.2017.174, 2017

ACRONYMS

HEMT: High Electron Mobility Transistor
MOCVD: Metal Organic Chemical Vapor Deposition