Advances in MOCVD Technology for III-V Photonics

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Abstract

As several pundits have declared, "*The 20th century was the century of electronics. The 21st century will be the century of photonics*". Photonic devices are increasingly being integrated into consumer electronics, including mobile phones, advanced display technology, 3D sensing, biometric sensors, LIDAR and Doppler sensing, and optical data and communications. To realize the necessary cost-points and performance for very high volume mass-produced consumer electronics applications, there has been a continuous drive to lower the yielded wafer cost during metalorganic chemical vapor deposition (MOCVD) epitaxy processes as well as increase the overall capability of the technology.

To achieve lower cost of final devices, MOCVD processes are progressing towards larger wafer sizes, reduced particle and defect densities, higher throughput via reduced cycle times and higher uptime, along with more advanced in-situ controls to achieve better wafer-to-wafer, run-to-run, and tool-to-tool consistency. For the next generation of high performance photonic devices, MOCVD technology must continue to improve, with enhanced capability and flexibility in terms of alloy composition, dopant, and thickness control, within-wafer uniformities and reproducibility, and a stronger focus on thermal budget minimization to more precisely control and maintain interface quality.

INTRODUCTION

Over the past 30 years, MOCVD reactors have progressed from a typical home-built research apparatus to large-scale, controlled, manufacturing machines. This evolution has enabled many commercial products that we experience in our everyday life. It could not have occurred without many advances in photonics device design and fabrication, along with the MOCVD epitaxial growth technology itself. For MOCVD, great strides have been taken in precursor purity, deposition control, efficiency, and uniformity, along with overall throughput and capability to vastly lower the cost of creating optoelectronic devices.

Further advancements and refinements in this important technology will continue to help create the next generation of advanced photonic devices.

DRIVING DOWN THE COST OF MOCVD EPITAXY

The latest generation of Veeco MOCVD production systems focused on AsP-based photonics devices is the K475i reactor platform, a vertical flow, high-speed rotating disc geometry. The heart of this design is our Flow-Flange® technology, which uses a gas injection scheme composed of separated, alternating alkyl and hydride cavities. This injector flow arrangement provides laminar, uniform thickness, composition, and V/III ratio over a wide range of process conditions, inclusive of growth pressure, deposition temperature, growth rate, and hydride flows. Many aspects of the K475i design are incorporated to maximize throughput and lower the cost of ownership while achieving extremely high yield production in a 15 x 100 mm, 7 x 150 mm, or 3 x 200 mm wafer batch configuration.

To reduce the yielded wafer cost during MOCVD epitaxy, capital depreciation, operational expenses, and yield loss need to be minimized. For capital depreciation, throughput per capital expense, such as wafers per month per $ is a common metric, which needs to be maximized. MOCVD reactor throughput is a function of the growth recipe cycle time (elapsed run start-to-run start time), wafer capacity per run, tool uptime (and hence reliability), the mean-time between scheduled maintenance or failure (MTTM/MTBF) and the mean time to recover back to production (MTTR). There is a continuous motivation to extend the amount of production growth runs before scheduled maintenance cycle and also reducing the MTTR. Operational expenses include consumable costs from scheduled and unscheduled maintenance, precursor and source costs, labor costs, and overhead costs, such as cleanroom footprint, electricity, safety systems, etc. Epitaxial yield is affected by many factors, including scrapped runs, defect or impurity losses, and inconsistency of within-wafer and wafer-to-wafer properties, such as dopant, thickness, alloy composition, or interfacial excursions.

While per-wafer epitaxy costs are important, at the end of the day, the yielded packaged device cost is paramount. As photonic device complexities increases, the downstream fabrication cost can easily dwarf the cost of epitaxy. When this occurs, there is a strong drive towards larger wafer sizes, as typically the fabrication costs are fairly independent of wafer size. Another impetus for larger substrate sizes of 150 mm and 200 mm diameter is being driven by the promise of mini and microLED display technologies, which use transfer field techniques to move separated die from within a wafer onto a larger backplane. Larger wafer sizes offer a higher packing density of transfer fields, thus leading to higher utilization of the wafer area.

IMPROVING YIELD AND CAPABILITY

Once a given epitaxial device structure is defined, maximum yield in a MOCVD production line can be achieved by minimizing variations in run-to-run and tool-to-tool performance for a given recipe in terms of the growth rate, V/III ratio, alloy composition, dopant concentrations and interface quality for all layers of the structure. For example, in VCSEL epitaxial structures, small changes in layer thickness, alloy compositions, or grading profiles can misalign the DBR mirror stop-band center wavelengths or Fabry-Perot cavity dip wavelength relative to the MQW emission peak. Precise dopant concentrations and their placement within the DBRs are also critical to minimize absorption losses while retaining low resistivity DBR mirrors.

One control technique that has not been readily incorporated into MOCVD production to help achieve run-to-run consistency is by utilizing binary gas monitors, such as a Piezocon®, to regulate the flux of all organometallic (OM) source or dopant gases injected into the reactor. These sensors, utilized in real-time feedback control, can compensate for variability in OM and dopant gas concentrations. Piezocon® technology relies on very accurately measuring the speed of sound in a gas mixture, which is directly related to the density of that mixture. When using an ideal carrier gas, such as nitrogen or hydrogen, the concentration of the saturated vapor can then be very accurately determined. Incorporating Piezocons® in production systems have been demonstrated to increase the OM utilization in the source bubblers by allowing runs to be performed to very low fill levels while concurrently maintaining improved run-to-run growth rate, composition and dopant control.

We have also developed a special bubbler slice network, Acuflux HP, integrating a high sensitivity version of the Piezocon® sensor, which can be used to control very low vapor solid OM sources, such as Cp_2Mg and CBr_4 with a < 1% variation in flux from run-to-run. Controlling flux for the solid OM sources is especially important, as the magnesium (Mg) and/or carbon (C) dopant concentrations and profiles in many light emitting structures strongly affect the brightness and forward voltage of the devices.

In figure 1, we illustrate the capability of the Acuflux HP control system. Two versions of a test structure were grown, with an initial layer deposited using only a constant flow for Cp_2Mg flow (with the Piezocon® in monitor-mode), and a second layer utilizing feedback control to set the Cp_2Mg output to a given flux value. In the first run, the Mg bubbler pressure was set to 600 Torr (800 mbar) and in the 2nd run, the Mg bubbler pressure was set to 750 Torr (1000 mbar), with both having the same bubbler temperature of 20^{o} C. The constant flow layers show varying Mg atomic concentrations that are significantly different, however the layers utilizing the Acuflux HP technology in a feedback-control scheme have relatively constant Mg atomic concentrations matched within the SIMS measurement error limits.

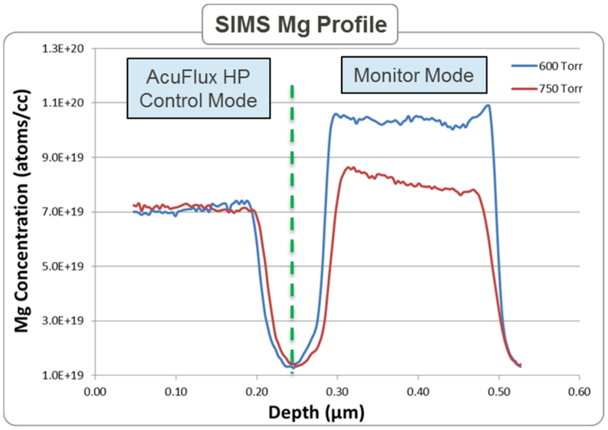

Fig. 1 Mg doping without control shows a large variation in doping, but with Acuflux HP in a control mode, repeatable layers with constant Mg atomic concentrations within the SIMS measurement limits are obtained.

Interfacial transitions between alloys and dopants can also greatly affect advanced photonic device characteristics, whether the layers incorporate abrupt transitions or sophisticated grading profiles. To easily achieve precise control of interfacial properties between layer transitions, a very short residence time of gases from the precursor source to the growth surface becomes necessary. Thus, care must be taken to minimize the transit time from the run/vent manifold and injector to the boundary layer, and within the boundary layer itself. Accurate pressure-balancing during source switching should also be established to properly and quickly transport precursors to the reactor. In the TurboDisc® technology, this gas-phase transit time is assisted by the high speed rotation of the wafer carrier, which pumps the high-speed gas towards the growth surface, creating a thin boundary layer that reduces the reactant residence and interaction times. An example of abrupt interfacial switching is shown in figure 2.

Another factor that is often overlooked in designing a MOCVD epitaxial recipe is considering its thermal budget. As much as possible, the thermal budget should be minimized, as the exposure of as-deposited layers to an extended period of time at high temperature necessary for the subsequent deposition steps results in dopant and alloy diffusion and migration, thus smearing the interfaces. To minimize the thermal budget and hence shorten the recipe time, increasing temperature ramp rates (both up and down)

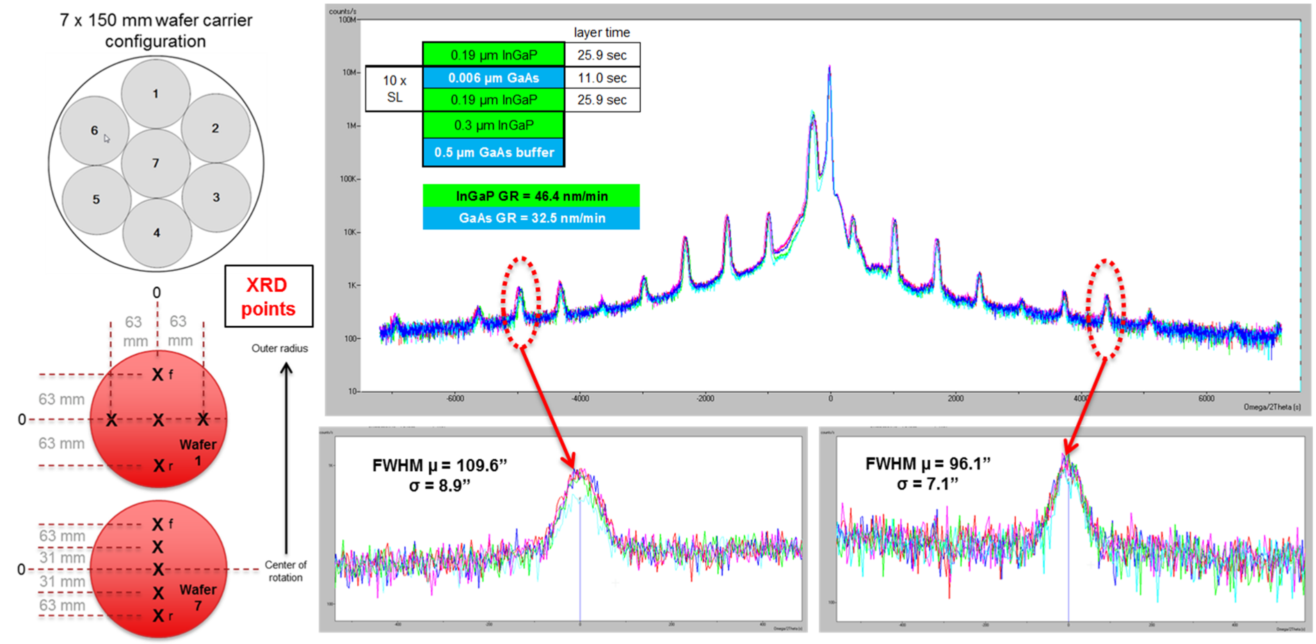

Fig. 2 An InGaP/GaAs superlattice exhibiting excellent resolved interference fringes in the x-ray diffraction rocking curve. The full width at half maximum (FWHM) of the outer fringes are similar across the disc radius, indicating uniform, abrupt interfaces.

and maximizing growth rates should be implemented, as long as material quality and deposition uniformity can be maintained. Reducing the recipe time also has the added benefit of increased throughput, thereby reducing the overall cost of growth.

For accurate and uniform temperature control, a concentric three-zone heating configuration is used in the K475i reactor. The surface temperature of the GaAs and InP substrates are measured using Realtemp® emissivity-compensated pyrometers, one each per zone, which provide continuous feedback to the heating elements in a closed-loop circuit. Using this control scheme, we have developed an innovative feed-forward algorithm to achieve very fast temperature ramping control during heat-up at > 150ºC/min with minimal undershoot and overshoot with a quick settling time. We have also focused on maximizing the cool-down rate through carrier and heater design to achieve a > 50ºC/minute rate for normal growth processes.

Particle and defect density reduction during the MOCVD production is a topic that is also gaining much recent attention. This interest is being driven by larger die sizes being fabricated, such as high-power laser bars and 2D arrays of either VCSELs or microLED devices. Extremely low particle densities can be achieved if both particle generation and particle migration are eliminated. To provide the highest throughput capability without excessive maintenance, it is better to prevent particle formation within the K475i reactor chamber than to need in-situ etching to remove the residual deposits creating the particles. Consequently, we continue to refine the flow and thermal management within our chamber design, from the gas injection through the exhaust collection. By maintaining fully laminar flow streamlines while eliminating all recirculation cells and stagnant flow zones, we reduce the chance of gas-phase memory effects and minimizing the propensity for gas-phase adduct formations. Furthermore, all condensation by-products are located entirely downstream of the deposition area. A large distance from gas injector to the hot carrier surface prevents deposition in the injection area. Moreover, the thin boundary layer results in a large temperature gradient and thermo-diffusion force (or thermophoresis) that repels any particles created within the boundary layer away from the hot growth surface, sweeping them downstream to the exhaust via the high speed rotation.

CONCLUSIONS

MOCVD technology continues to focus on driving lower cost of ownership with higher productivity, yield, and capability. Continued advancements in precision control of precursors, interface control, and impurities are improving optoelectronic device designs. A more intense emphasis on temperature control during static and ramped layers should be considered, to reduce the thermal budget and recipe cycle time, thereby reducing exposure of pre-grown layers to high temperatures for extended periods of time.

A stronger attention to defect and impurities is emerging, both on the types, sizes, and origins. By controlling the chamber design, and the wafer/wafer carrier handling and transport protocols, very low defect densities can be achieved.

The industry is also migrating towards larger wafer sizes and enhanced process space (in terms of temperature, pressure, and growth rates) for ultimate structure design flexibility. Excellent thickness, alloy composition, and doping uniformity must be maintained for all flow conditions and wafer diameters. All of these drivers are resulting in MOCVD reactors with much higher throughput, reliability, capabilities, and control for future production requirements.

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ACRONYMS

DBR: Distributed Bragg Reflector
LED: Light Emitting Diode
LIDAR: LIght Detection And Ranging
MOCVD: Metal Organic Chemical Vapor Deposition
MTTR: Mean Time To Recovery
MTTM: Mean Time To Maintenance
MTBF: Mean Time Before Failure
OM: Organo-Metallic
SIMS: Secondary Ion Mass Spectroscopy
VCSEL: Vertical Cavity Surface Emitting Laser