Final Technical Report

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Department of Energy Grant DE-EE0003252

“Driving Down HB-LED Costs:
Implementation of Process Simulation Tools and
Temperature Control Methods for High Yield
MOCVD Growth”

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Recipients

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in partnership with

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Philips-Lumileds, Inc. – San Jose, CA

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Abstract

The overall objective of this multi-faceted program is to develop epitaxial growth systems that meet a goal of 75% (4X) cost reduction in the epitaxy phase of HB-LED manufacture. A 75% reduction in yielded epitaxy cost is necessary in order to achieve the cost goals for widespread penetration of HB-LED's into back-lighting units (BLU) for LCD panels and ultimately for solid-state lighting (SSL). To do this, the program will address significant improvements in overall equipment Cost of Ownership, or CoO. CoO is a model that includes all costs associated with the epitaxy portion of production. These aspects include cost of yield, capital cost, operational costs, and maintenance costs. We divide the program into three phases where later phases will incorporate the gains of prior phases. Phase one activities are enabling technologies. In collaboration with Sandia National Laboratories we develop a Fluent-compatible chemistry predictive model and a set of mid-infrared and near-ultraviolet pyrometer monitoring tools. Where previously the modeling of the reactor dynamics were studied within FLUENT alone, here, FLUENT and Chemkin are integrated into a comprehensive model of fluid dynamics and the most advanced transport equations developed for Chemkin. Specifically, the Chemkin model offered the key reaction terms for gas-phase nucleation, a key consideration in the optimization of the MOCVD process. This new predictive model is used to design new MOCVD reactors with optimized growth conditions and the newly developed pyrometers are used monitor and control the MOCVD process temperature to within 0.5°C run-to-run and within each wafer. This portion of the grant is in collaboration with partners at Sandia National Laboratories. Phase two activities are continuous improvement projects which extend the current reactor platform along the lines of improved operational efficiency, improved systems control for throughput, and carrier modifications for increased yield. Programmatically, improvements made in Phase I are applied to developments of Phase II when applicable. Phase three is the culmination of the individual tasks from both phases one and two applied to proposed production platforms. We selectively combine previously demonstrated tasks and other options to develop a high-volume production-worthy MOCVD system demonstrating >3x throughput, 1.3x capital efficiency, and 0.7x cost of ownership. In a parallel demonstration we validate the concept of an improved, larger deposition system which utilizes the predictive modeling of chemistry-based flow analysis and extensions of the improvements demonstrated on the current platforms. This validation includes the build and testing of a prototype version of the hardware and demonstration of 69% reduction in the cost of ownership. Also, in this phase we present a stand-alone project to develop a high-temperature system which improves source efficiency by 30% while concurrently increasing growth rate by 1.3x. The material quality is held to the same material quality specifications of our existing baseline processes. The merits of other line item tasks in phase three are discussed for inclusion on next-generation platforms.

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Executive Summary

This report is the final technical discussion for the Department of Energy (DOE) grant DE-EE0003252 under the administration of the National Energy Technology Laboratory (NETL) from May, 2010 through April, 2012. During this period the DOE provided matching funds of \$4M which was further distributed in the amounts of \$2.4M to Veeco Process Equipment (Veeco) and \$1.6M to Sandia National Laboratories (SNL). Since nearly all the information contained has been previously disclosed in the routine reporting of the grant, this document serves as a consolidation of the work including goals, results, execution of the project and its impact to the overriding goals of the DOE roadmap for solid-state lighting (SSL).

Throughout the DOE SSL Initiative, the epitaxy portion of the LED luminaire is recognized as one of the principle cost drivers. According to the 2010 DOE SSL R&D Manufacturing Roadmap, the epitaxy portion of production accounts for as much as 40% of the overall cost. As such, the requirements to lower the cost of ownership of this portion of manufacture are evident. This grant performs multiple functions in driving the adoption of SSL in the U.S. market, and more generally the SSL market world-wide. The tasks as listed and the ultimate delivery of a lower-cost option for production are the first and necessary requirements. The domestic benefits of this production platform provide a more competitive entry point for U.S. manufacturers of LED's. And finally, Veeco is the only U.S.-based company delivering production-worthy MOCVD equipment, a necessary technology to build high-brightness LED's (HB-LED). The ability to accelerate development and deployment of research resulted in an increase in global market share. In summary, this grant helped develop a lower cost solution for SSL, created domestic jobs, and increased U.S. exports.

The major accomplishments contained herein align with the three-phase structure of the program – Enabling Technologies, Continuous Improvement, and Next-Generation Products. The end goal is the combination of as many of the line-item tasks into a consolidated platform to reach a simply stated objective of 75% reduction in the cost of ownership of this portion of producing LED's. Phase I involves Veeco and SNL combining efforts to develop two key components to enable further improvements. In part one, the chemistry model used to characterize the process environment of the sapphire wafer is improved and validated. With an accurate chemistry/CFD model in place, proposed hardware improvements can be vetted prior to the commitment of expensive and time-consuming hardware procurement. In the course of comparing actual growth parameters to the chemistry model, this research discovered an anomaly in the relationship of growth rate and precursor temperature. This new information resulted in an unexpected new understanding of the adduct reaction rates and is now the subject of extended funding at SNL. In part two, the teams rely on proven expertise in developing advanced pyrometers to build state-of-the-art in-situ temperature measurement base on a 405nm (near-UV) band-pass filter. To further demonstrate the viability of the device, Philips-Lumileds (PLLC) agreed to support demonstrations in a

high volume production setting providing standardized evaluation of run-to-run wavelength variability. With beta units provided and successful completion of the marathon at PLLC, the teams successfully demonstrated on-wafer temperature measurement and delivered the data necessary to begin product development.

Phase II involved a number of disparate line items which independently reduce the cost of ownership. Process control software (PCS) was implemented and tested to provide notification of non-standard processing. In the production environment, real-time analysis, detection, and notification allows for the early detection of potential yield-limiting events. The in-house demonstration included active monitoring of the most process-sensitive devices/indications. Another project objective was to develop an on-board photoluminescence mapping system for immediate post-growth analysis. The on-board solution provides a 50% decrease in data reduction time and an associated reduction in labor content. A direct effort at increasing throughput was the implementation of Model-Based Temperature Control (MBTC) which uses a multi-input/multi-output first-principles control scheme to provide more stable temperatures vs. time transitions in comparison with the more common PID temperature control scheme. The demonstration concluded with a 1.5x ramp rate increase and a 50% reduction in settle time. And, finally, an algorithm and manufacturing process for developing wafer carriers was developed that provides superior within-wafer uniformity of the thickness and composition of the deposited films. This methodology is now used to consistently deliver within-wafer uniformity of $< 1.5\text{nm}$ (1 sigma) and wafer-to-wafer uniformity $< 4\text{nm}$ (1 sigma).

Phase III sought to demonstrate groupings of the tasks on advanced concept platforms to realize absolute cost of ownership values. These next-generation platforms included a high-throughput system which became a released product for Veeco. The production-worthy system matches all process specifications of the legacy product and demonstrated over a 3x increase in throughput and reduced the floor space required for an equivalent throughput by half. To support the new architecture a customized test bench was created to ensure the quality of the flow flange. Prescreening this critical hardware ensures growth-rate efficiency and minimizes downtime associated with tool-to-tool variation. Another next-generation component is the heated flow flange which was built and demonstrated to improve source efficiency by 30% with a concurrent 1.3x increase in growth rate. Finally, the most comprehensive demonstration was the large-architecture system currently under investigation to exceed the 75% cost of ownership goal. Items integrated into the platform are the chemistry-flow model, the heated flow flange, advanced wafer carriers, the flow flange test bench, and the near-UV pyrometer. As of writing the prototype has the capability to demonstrate $> 3\text{x}$ TPT/ft², $> 1.3\text{x}$ capital efficiency, and 0.69x reduction in cost of ownership.

Program Overview

Structure

Grant EE0003252 closely aligns with a significant portion of SSL R&D: Multi-Year Program Plan and the SSL R&D: Manufacturing Roadmap. Since cost of ownership is an aggregate metric of many factors, it is not surprising that this effort touches on each of the subtopics list in Table 1. Every factor in the growth of the epitaxy layers is an considered an opportunity for cost of ownership improvement – growth rate and efficiency, uniformity and process control, higher capacity and throughput, automation and factory integration.

Table 1 – Grant Association with DOE Objectives

2010 SSL R&D: Multi-Year Program Plan
A.4.4 Manufacturing Simulation (Capital Cost)
B.4.1 Yield and Manufacturability
B.4.2 Epitaxial Growth (Consumption)
B.4.3 Manufacturing Tools (Capacity / TPT)
2010 SSL R&D: Manufacturing Roadmap
2.3.1 Epitaxy Processes (Consumption)
2.3.3 Equipment (Capacity / TPT)
2.3.4 Process Control and Testing (Yield / SPC)

The program is subdivided by tasks and further by teams. There are eleven tasks loosely grouped into categories of enabling technology, continuous improvement, and next-generation products. Through the period of the grant, individual tasks have been moved between the groups for reporting purposes only; but, the goals and requirements of the individual tasks remain the same. Below is a listing of the task-level breakdown of the program. (Table 1) In this work there are three teams of resources, Veeco Process Equipment, Sandia National Laboratories, and Philips-Lumileds. The teams, principals, and locations are listed in Table 2. Table 3 indicates the participation by task.

Table 2 – Program Tasks

ID	Task	Deliverable
1.0	Project Management Plan	Completed Project Management Plan
2.1	Integration of Chemistry Model	2x improvement in the model accuracy in predicting the actual thickness of GaN, AlGaN and InGaN layers

ID	Task	Deliverable
2.2	Refined Model Predictions	Report comparing baseline model to refined model
3.1	Near-UV prototype Feasibility	Use prototype hardware to compare wafer wavelength to wafer temperature with an R^2 fitting value > 70%
3.2	Manufacture Near-UV Pyrometers	Delivery of pyrometers to Veeco lab and Philips-Lumileds
3.3	Near-UV Pyrometer Capability	Improve the LED run-to-run repeatability from +/- 4nm to +/- 2nm with the near-UV pyrometer in control mode
4.1	Mid-IR Pyrometer Feasibility	Use prototype hardware to compare wafer wavelength to wafer temperature with an R^2 fitting value > 50%
4.2	Mid-IR Pyrometer Capability	Improve the LED run-to-run repeatability to < +/- 2nm with the mid-IR pyrometer in control mode
5.1	PCS Implementation	Use pilot software to identify and actively monitor 4 devices which impact availability, repeatability, and yield
5.2	PCS Demonstration	Use pilot software to reduce unscheduled downtime by 25%
6.1	On-Board PL Mapping	Use prototype hardware to match wavelength within 1% and uniformity within 5% of the Nanometrics Vertex PL system
7.1	MBTC Feasibility	Use prototype MBTC to demonstrate ramp rate increase of 1.5x and 50% decrease in settling time vs. PID control
7.2	MBTC Demonstration	Demonstrate improved LED wafer yield with MBTC in production mode
8.0	Advanced Wafer Carrier Design	Use new carrier designs to improve LED uniformity to 1.5nm (1 sigma) and wafer-to-wafer variation to <4nm
9.1	High Throughput System	Demonstrate a high throughput MOCVD system with >3x TPT with equivalent epitaxial material metrics
9.2	MOCVD Flow Flange Test Bench	Use prototype hardware capable of detecting flow flange variations which impact process repeatability
9.3	Large Architecture System Feasibility	Report on CapEx, TPT, and Co potential of different architectures for large MOCVD system
9.4	Large Architecture System Demonstration	Demonstrate a large-scale MOCVD system with >3x TPT, 1.3x CapEx, and 0.7x CoO with equivalent epitaxial material metrics

ID	Task	Deliverable
10.1	Develop and Test Hot Flow Flange	Use prototype hardware to demonstrate 30% reduction in source use and 1.3x increase in growth rate
11.1	In-situ Chamber Cleaning Feasibility	Demonstrate in situ chamber cleaning

Table 3 – Program Team and Locations

Organization	Team Members	Facilities
Veeco Process Equipment, Inc. Somerset, NJ	William Quinn, Ph.D. (Principal) Veeco R&D Team Veeco Advanced Hardware Team Jay Montgomery, Ph.D. (Program Mgmt.)	Veeco R&D Labs
Sandia National Laboratories Albuquerque, NM	Bob Biefeld, Ph.D. Advanced Materials Sciences Group	SNL
Philips-Lumileds, Inc. San Jose, CA	Dave Vanderwater, Ph.D.	LED Manufacturing

Table 4 – Team Members by Task

ID	Task	Team
1.0	Project Management Plan	Veeco
2.1	Integration of Chemistry Model	Veeco, SNL
2.2	Refined Model Predictions	Veeco, SNL
3.1	Near-UV prototype Feasibility	Veeco, PLLC
3.2	Manufacture Near-UV Pyrometers	Veeco, PLLC
3.3	Near-UV Pyrometer Capability	Veeco
4.1	Mid-IR Pyrometer Feasibility	SNL
4.2	Mid-IR Pyrometer Capability	SNL
5.1	PCS Implementation	Veeco
5.2	PCS Demonstration	Veeco
6.1	On-Board PL Mapping	Veeco
7.1	MBTC Feasibility	Veeco
7.2	MBTC Demonstration	Veeco
8.0	Advanced Wafer Carrier Design	Veeco
9.1	High Throughput System	Veeco
9.2	MOCVD Flow Flange Test Bench	Veeco
9.3	Large Architecture System Feasibility	Veeco

Finances

Funding of the program followed a similar trend as the schedule; expenditures were biased toward the first year. The funding was exhausted in the 18th month of the 24-month term for an aggregate cash burn rate of 133%. There were no non-standard events in the expenses and invoices. Table 5 presents the two-year ledger of financial activity.

Table 6 – Cumulative Ledger

DOE Grant - Cumulative Ledger							(In Thousands)			
	Cumulative	2010Q2	2010Q3	2010Q4	2011Q1	2011Q2	2011Q3	2011Q4	2012Q1	2012Q2
Totals	\$ 22,077	\$ 1,685	\$ 3,856	\$ 4,757	\$ 3,350	\$ 3,025	\$ 1,801	\$ -	\$ -	\$ -
Personnel	\$ 5,470	\$ 463	\$ 768	\$ 1,776	\$ 580	\$ 987	\$ 897	\$ -	\$ -	\$ -
Goods & Services	\$ 10,466	\$ 1,223	\$ 2,018	\$ 2,583	\$ 2,378	\$ 1,360	\$ 904	\$ -	\$ -	\$ -
Test Runs	\$ 2,540	\$ -	\$ 1,071	\$ 398	\$ 392	\$ 679	\$ -	\$ -	\$ -	\$ -
Veeco	\$ 15,866	\$ 1,399	\$ 3,197	\$ 4,165	\$ 2,951	\$ 2,584	\$ 1,570	\$ -	\$ -	\$ -
Personnel	\$ 4,773	\$ 386	\$ 640	\$ 1,606	\$ 503	\$ 858	\$ 781	\$ -	\$ -	\$ -
Goods & Services	\$ 8,960	\$ 1,013	\$ 1,674	\$ 2,230	\$ 2,112	\$ 1,142	\$ 789	\$ -	\$ -	\$ -
Test Runs	\$ 2,133	\$ -	\$ 883	\$ 329	\$ 337	\$ 584	\$ -	\$ -	\$ -	\$ -
DOE	\$ 2,400	\$ 286	\$ 659	\$ 592	\$ 399	\$ 441	\$ 22	\$ -	\$ -	\$ -
Personnel	\$ 602	\$ 76	\$ 128	\$ 170	\$ 77	\$ 128	\$ 22	\$ -	\$ -	\$ -
Goods & Services	\$ 1,391	\$ 210	\$ 344	\$ 353	\$ 267	\$ 218	\$ -	\$ -	\$ -	\$ -
Test Runs	\$ 407	\$ -	\$ 187	\$ 70	\$ 55	\$ 95	\$ -	\$ -	\$ -	\$ -

Discussion and Results

Phase I: Enabling Technology

2.X Advanced Chemistry Model

Overview

The complexity and expense of the MOCVD process combined with novel hardware and control systems necessitate the need for modeling prior to any manufacturing of new options/solutions. Computational fluid dynamics, a suitable method to forecast hardware performance, would provide only half of the visibility into the MOCVD equipment. The chemistry of the reaction is essential to fully understand the gas-phase dynamics during the growth of the epitaxy layer. SNL provided the expertise to help combine the FLUENT chemistry model with the existing Veeco library of reactor geometry and CFD solutions. Task 2 was an exercise in software configuration and data exchange to allow for integration and further collaboration. Veeco provided the initial reactor geometries for CFD and also provided the actual growth runs for model validation. SNL, the developers of Chemkin, provided the detailed thermochemistry and transport models used and in prior model solutions. The opportunities for feedback and improvement were numerous. SNL challenged the Chemkin model assumptions with

actual growth runs. Veeco ran models of process space to identify suitable reactor configurations.

Results

The challenge of managing and merging such complex software and models was evident in the first months. The integration of Fluent and CHEMKIN required a unique computing environment with parallel software licenses running simultaneously on one system. The first trials of the Sandia GaN model and more realistic reactor conditions did not converge on meaningful solutions. Following the software merger and debugging, model validation began with an un-doped-GaN layer for which there is extensive experimental data for comparative analysis

In comparison of the GaN growth rate profile with and without CHEMKIN in the modeling software, the combined model predicts a lower growth rate with a uniformity improvement of 3%. See Figure 1. The results here are not directly applicable to experimental data (simplified geometry, recipe conditions) but the model is self-consistent and showed promise.

Figure 1 The modeled GaN growth rate profile is presented here with and without the CHEMKIN module. Uniformity is improved by 3% and the results are self-consistent given the simplified reactor geometry in use.

With the Fluent/CHEMKIN interface issues resolved, 2D and 3D models were refined to better correlate with existing experimental data. With an element count of ~200k, more than 10 2D runs and more than 5 3D runs were completed and evaluated for refinement. Figure 2 is the type of output used in the development of new hardware and validation of the chemistry model.

Streamlines from one alkyl injector line

Injector Contours: $\text{Ga}(\text{CH}_3)_3$ mass fraction (upper)
Surface Contours: Deposition rate on wafer carrier (lower)

Figure 2 The images above show the detailed modeling available to test and modify the reactor environment. The upper image presents characteristic streamlines from a single alkyl injector line. The lower image shows both mass fraction contours of precursors and deposition rate contours at the wafer surface.

Following this work, the teams turned attention to modeling the heated flow flange (Task 10). The full chemistry model was translated to the new heated flow flange geometry. In a surprise to both Veeco and SNL, where the model indicated a decrease in growth rate, actual growth rates of the new hardware increased. This information provided the basis for extended research and modeling improvements. In other applications the combined platform was used to further the understanding of magnesium precursors. The model provides visibility into the surface concentrations of low-volatile adducts which play a role in the ultimate brightness of the LED.

Significance

- Design cycle duration reduced from years to months.
- First-principles comprehensive CFD and chemistry model.
- Advancement of the model having identified a much more relevant reaction path for adducts.

3.X Near-UV Pyrometer

Overview

The near-UV pyrometer is designed to measure the wafer surface directly in the temperature control loop. Temperature is the primary yield determining factor during the deposition of the multi-quantum well portion of the LED structure. As such, the yield of each wafer is determined by the capability of the temperature control loop to maintain a constant wafer-surface temperature to within $\pm 0.5^\circ\text{C}$. The current system is incapable of delivering this level of performance since the control loop utilizes the carrier temperature instead of the wafer temperature. The ability to measure wafer temperature directly will significantly improve the run-to-run repeatability of the reactor. Veeco and PLLC worked together to demonstrate the capability of prototype devices. During the first year Veeco manufactured and tested a number of units. Preliminary data on these units indicated a 35% reduction in the run-to-run (RtR) variability. In the second year, PLLC performed a marathon to further validate the projected gains of device. Currently, the units are proceeding through the product development cycle having proven to be a valid option for yield improvement. The challenges of this program have remained the same throughout: 1) stability of the units through the duration of the process run, 2) susceptibility of the units to environmental factors, and 3) the sensitivity of the units to stray light both external and internal. Table 6 below is a list of parameters and associated specifications of the device.

Table 7 – Near-UV Pyrometer Parameters and General Specifications

Parameter	Demonstrated Prototype Performance
Wavelength	400nm with 25nm bandwidth
Temperature Range	700 - 1200C

Parameter	Demonstrated Prototype Performance
Calibration Accuracy (Tool-to-Tool)	$\pm 1.5^{\circ}\text{C}$
Run-to-Run Repeatability	Estimated as $\sim \pm 0.5^{\circ}\text{C}$
Temperature Precision	0.1°C at 740°C (32 second averaging)
Acquisition Rate	10 kHz

Results

In the early development of the device, specialized tests were constructed to establish functionality and sensitivity. The most productive demonstration utilized a specially design wafer carrier with three distinct tab heights. In these carrier designs, the tab height is the distance from the carrier pocket bottom to the backside of a flat wafer. Since the photoluminescence (PL) peak wavelength (Wp) is dependent on the wafer temperature, multi-quantum wells (MQW's) grown on this carrier will have three distinct peak wavelengths. Figure 3 shows the resulting wavelength distribution on this carrier and the three groups of pocket tab heights.

Simultaneously, the near-UV pyrometer monitored the wafer temperature (T_w) and the legacy pyrometer monitored the carrier temperature (T_c) and controlled

the power to the heaters. These data provide direct correlations between Wp , T_w , and T_c . If T_w is a better predictor of the resultant peak wavelength, then the new pyrometer has value in providing better run-to-run control. Figure 4 illustrates the much stronger correlation of T_w than T_c to peak wavelength.

Subsequent testing sought to establish the device capabilities in the context of a manufacturing environment. The initial challenges reduced to the following:

- PMT degradation: Variation by up to $\sim 1^{\circ}\text{C}/\text{month}$
- PMT temperature sensitivity: 10°C ambient drift $\rightarrow -2^{\circ}\text{C}$ error
- Stray light: At 405nm, outer filament brightness is $\sim 3x$ that of the carrier
- Initial 5-Run demonstration exhibited drift up to $\pm 1^{\circ}\text{C}$

After transfer of pyrometers to PLLC, the first controlled runs provided an estimate of the benefit of wafer temperature control. With no changes to the production tool and using the pyrometer in monitor mode, the projected gains ranged from 35% to 43% reduction in RtR standard deviation of the PL wavelength. Data from a series of runs is shown in Figure 4. In carrier temperature control mode, there is very little correlation of Wp to the temperature setpoint used in the control loop, 768 and 775C in this dataset. However, the temperature as measured by the near-UV pyrometer is able to account for approximately 62% of the wavelength variation. Additional series of controlled runs both at Veeco and PLLC confirm the value of on-wafer measurements.

PLLC completed the production marathon of the near-UV pyrometer in monitor mode with a total of 78 runs. The second-order factors continue to be investigated and include the wafer carrier in use, recipe tweaking during the series of runs, PM and tool-based activities between runs and the idle time between runs. Prototype hardware remains in continuous data collection mode to assess stability and variability. New units are being built to compensate for ambient drift and minimize the variation in the PMT signal stability.

Significance

- Reduction in the run-to-run variation from errors caused by using carrier temperature to control wafer temperature
- Run-level scrap rate reduction by eliminating manual temperature adjustments based on a particular carrier or tool.

4.X Mid-IR Pyrometer

Overview

The mid-IR pyrometer has the same goal as the near-UV pyrometer, on-wafer temperature measurement and control. For this task, prototype hardware was built and for to test concept and feasibility. Inherent advantages over the near-UV device include ~10x more signal at InGaN growth temperatures (700-800C), 5-10x lower temperature noise in the 700-750C range, higher spatial resolution (2-5 mm vs. 5-15 mm), and a more robust detector. During the course of the grant, a legacy D125 Veeco reactor was used as the platform for hardware demonstrations. The installation is shown in Figure 5.

Results

There are significant challenges to the implementation of a mid-IR pyrometer in comparison to the near-UV device:

- Temperature sensitivity (dS/dT) is ~30X smaller
- Emissivity correction is a requirement and must be to a high level accuracy
- Absolute accuracy is more uncertain
- More sensitive to environmental factors

Through the course of the grant, it became apparent that implementing this device in manufacturing would be a significant challenge.

Significance

- Reduction in the run-to-run variation of peak wavelength is a key advantage for increasing yield.
- The difficulty in demonstrating this device in control mode has solidified the necessity of the near-UV pyrometer or other in-situ technique.

Phase II: Continuous Improvement

5.X Process Control Software

Overview

In a production environment, the ability to isolate discrepant wafers or runs translates directly to yield. Historical analysis of system performance provides a basis for monitoring future performance and the predictability of the process and wafer yield. In this task, process control software (PCS) was commissioned and tested to demonstrate the benefits of both historical analysis and predictive notification of tool performance. On deployment of this process control software, there are direct cost-of-ownership gains related to productivity/availability and indirect gains associated with avoiding the cost of excursions.

The first phase was the necessary integration of the hardware and software to communicate with the tool directly for data acquisition. Figure 6 shows the architecture of the system. The Veeco toolset has the benefit of an on-board server to allow for uninterrupted process while the analysis server pulls data in real time. The data is

transferred to a dedicated analysis server where custom algorithms parse the data to isolate information of interest to process and equipment personnel. Once these events in the data are identified, reports and/or notifications can be generated to provide near, real time response to excursion potential. The second phase was the historical analysis to correlate equipment trends with process performance such as growth rate, within wafer uniformity, brightness, etc. Phase three was the live implementation of data analysis models which operate in real time to automatically detect and notify of anomalous or predictive conditions.

Results

Six models were developed and tested to demonstrate the value of the PCS software. Two models provided active notification of run conditions. The remaining four were

Figure 6 Process Control System Software Architecture. Data from the process tool on-board database is transferred to a separate analysis server. The analysis server application screens the data for anomalies and can generate reports and alarms to provide a quicker response to excursion events.

developed and used to help troubleshoot errant tool performance. The primary test case for active notification was a comparison of reactor pressure and exhaust line pressure over the course of several maintenance cycles. Having determined that this pressure differential predicts particle filter accumulation, the active models of PCS were set to notify (email) supervisory personnel when a prescribed difference limit was attained. Knowing the state of particle filter in a predictive manner allows proper scheduling of resources, full utilization of the particle filter capacity, and excursion management by avoiding a poor process regime due to the filter conditions.

Figure 7 illustrates the pressure delta trend in time for a given particle filter, the failure trend, the intermediate maintenance, and the recovery of the pressure delta. The Veeco Somerset laboratories have used this predictive nature to better schedule resources and activities.

More elaborate models that were used for specific failure modes include:

- Power vs. Temperature:
Trend the power necessary to maintain a temperature setpoint.
Indication: Changes in the reactor coating of parasitic effluent

- Silane Depletion
Trend the pressure of the silane network upstream of the reactor injector network for indications of cross-seat leaks and/or proper network pressure
- Mass Flow Controller (MFC) / Pressure Controller (PC) Stability
Compute statistics at particular steps in a recipe as an indication of process stability and/or failing MFC/PC
- Temperature Stability
Trend the overshoot/undershoot during step transitions as an early indicator of filament health.

For this demonstration, the analysis server was configured to track data from five laboratory tools. Following the successful integration and demonstration, the project transitioned to the internal PLC (Product Life Cycle) process.

In the path of product development, the beta software was been deployed at a customer site based on the Veeco configuration. The software was well received for fault detection. The Veeco software group was involved in defining a more robust production

interface based on input from the beta customer. Additionally, a second server was installed at the Veeco Taiwan Technology Center to provide a demonstration platform for customer evaluation.

Significance

The process control software demonstrated six distinct models addressing both productivity and yield. The examples in the laboratories of Veeco Somerset account for a 5% reduction in unscheduled downtime.

6.X On-board Photoluminescence Mapper

Overview

The PL mapper demonstrates the ability to integrate on-board metrology to replace or augment the stand-alone in-fab procedures for post-growth measurements. The most common implementation of PL process control is the sequence of grow - measure - correct using separate tools with the associated and requisite transfer and queue times. By providing on-board measurement capability, process control, error rates, and labor content can be improved.

In Task 6, a PL mapper was developed to provide process control near real-time as a step closer to automated process control and a productivity increase.

Results

Figures 8 and 9 show the solid model and as-built hardware developed for on-board PL measurements. The modular design allows for integration on new and legacy platforms. Early design reviews included significant software participation and were geared towards both stand-alone operation and the future of automated process control. A significant portion of the time was spent detailing the specifications of the source and detector. A company agreed to build and deliver prototype hardware for evaluation. Reference wafers for the prototype evaluation were prepared and shipped for evaluation on the prospective detector. Summary statistics for the reference wafers are presented in Figure 10. The prototype system matched to within 1% with the exception of one wafer. On this success, patterned sapphire substrates were sent for a similar matching activity.

Figure 8 Solid model of the on-board photoluminescence device with the capability to measure the PL immediately after processing, reducing data handling and labor content.

Figure 9 Prototype build of the on-board PL analytical platform.

50mm			
Run	3D0711 MQW	11/9/2010	
Wafer	Slot	Vertex	Verity
26	1	452.8	456.61
27	2	452.6	454.13
28	3	454.5	456.00
29	4	453.4	455.03
30	5	453.7	455.24
31	6	453.3	454.82
32	7	453.4	454.99
33	8	453.0	454.51
34	9	452.2	453.73
35	10	452.9	454.51
36	11	453.0	454.58
37	12	451.8	453.60
38	13	452.5	454.28
39	14	452.7	454.49
40	15	452.5	454.31
41	16	453.1	454.75
42	17	453.6	455.22

100mm			
Run	3D0715-LED		
Wafer	Slot	Vertex	Verity
B	24	458.8	462.19
C	23	459.6	462.98
D	22	460.0	463.45
E	21	460.2	463.35
F	20	461.1	465.65
G	19	458.0	462.14
H	18	460.6	464.54
I	17	459.6	463.56
J	16	458.1	460.36
L	14	457.5	460.03

Figure 10 Round-Robin wafer trails on the Veeco Somerset analytical and the prototype analytical unit to be used with the on-board PL apparatus.

On-board PL analysis provides data error reduction, labor content reduction, and the infrastructure for advanced process control.

Overview

Model-based temperature control (MBTC) is a technique that supplants traditional PID control loops with first-principles based algorithms of heat transfer based on the reactor geometry, construction materials, and characteristic temperature ramp profiles. The

MBTC model drives the power supplies in a more controlled fashion to affect a more desirable temperature ramping profile during the recipe. A key advantage of MBTC is a significant reduction in the under/over-shoot of the temperature when approaching a new setpoint. In PID mode, stabilization time must be included in the recipe to account for this variation. This stabilization time can be eliminated when using MBTC and higher ramp rates can be used resulting in a reduction in the overall time of processing. Shorter process times translate directly to an increase in throughput of the system and a corresponding reduction in CoO.

Results

During the grant, MBTC was tested and deployed across three systems in the Veeco laboratories and completed 78 runs in demonstrating stability and reliability. The notable benefit of MBTC is a direct reduction in the recipe time, accounting for a 10% increase in throughput by significantly reducing or eliminating the temperature stabilization times necessary to ensure constant deposition temperatures. After significant integration efforts and software updates, the demonstration recipe was shorter by 32 min.

Standard Recipe: 361 min = 244 min (process) + 117 min (overhead)

MBTC with Fast Ramp: 329 min = 244 min (process) + 85 min (overhead)

Figure 11 shows sample temperature vs. time traces for PID and model-based temperature control. Overshoot is essentially eliminated with MBTC and the time-to-settle is dramatically reduced. This mode of operation meets the objectives set forth in Task 7: Ramp rate $\geq 1.5x$ the baseline and $\geq 50\%$ reduction in the time-to-settle. The demonstration case was the temperature transition during a two-temperature MQW deposition having a 3x increase in ramp rate with a 74% reduction in the time-to-settle.

Significance

The use of MBTC is a straightforward benefit to CoO. An increase in throughput allows a manufacturer to produce more from a smaller fleet of tools. There are secondary cost benefits such as a reduction in gas and power consumption.

8.X Advanced Wafer Carriers

Overview

Since there is a strong dependence of growth rate and InGaN composition (wavelength) on wafer temperature and, likewise, a strong dependence of wafer temperature on the gap between the wafer and carrier, the carrier geometry can be matched to the wafer bow during InGaN growth to achieve better wavelength uniformity across the wafer. Task 8 extended this approach in non-standard pocket surface geometries to improve the PL yield by as much as 10%. Specialized carriers were generated to test the methodology and perform in-house demonstrations. Figure 12 shows a time series plot of curvature during the growth of an LED. The key intervals are annotated for wafer curvature and the corresponding design method needed in the carrier pocket to ensure an optimal thermal profile on the wafer surface. A recursive algorithm is used to modify the pocket surface to compensate for non-uniformities observed in the resulting PL. As an advanced manufacturing technique, two U.S. suppliers were engaged to provide a domestic supply chain of this proprietary method and further reach of the grant.

Results

The program was highly successful in transferring a fundamental hardware-process relationship into improved performance. This fundamental relationship is the

dependence of PL on the wafer temperature. Figure 13. Temperature scans were then used to isolate the carrier non-uniformity. Once it was determined that the pocket surface region was the principal component in wafer temperature variation, design of the modified pocket geometry carrier began. As shown in Figure 14, non-uniformities in the resulting PL are translated in to pocket corrections during the machining of a new carrier. This process relies on the fact that the spatial uniformity distribution is predictable and can be translated to a

standardized carrier manufacturing procedure.

In the first demonstration on the baseline 12x4" carrier, the newly designed carriers demonstrated WIW wavelength values of 1.5nm vs. 1.8nm baseline and WTW wavelength values of 4nm vs. 6nm baseline. With a marked improvement, these carriers immediately became the carrier of reference for future R&D activities.

To extend the concept, additional carriers were order and tested including the 14x4" and the 6x6" carrier configurations. As of writing, the 54x2" carrier is in the design phase for eventual manufacture and testing to demonstrate the 2" wafer capability. In all cases, the new carriers outperformed the baseline carrier on equivalent process recipes. The 14x4 high-capacity carrier with the pocket shaping completed extensive testing and comparison with the 14x4 flat pocket counterpart. The within-wafer standard deviation decreased from 3.92 to 2.98 nm with a corresponding increase in yield from 82% to 92% per a 5nm bin. Figures 15 & 16. These changes from 12 to 14 wafers per carrier and flat pocket profiles to engineered pocket surfaces represent a 24% reduction in the cost of ownership. With this encouraging data in-hand, a beta agreement was put in place with a customer to execute a custom design for their 12x4" process. The customer demonstration completed successfully; and the carriers are qualified and used for production. In the follow-up report, the within-wafer standard deviation improved by 19% with no change in wafer-to-wafer variability.

Significance

- Yield improvement of 92% vs. 82% baseline on high capacity configuration.
- Domestic supply chain improvement.

- A stand-alone demonstration of 24% reduction in cost of ownership.
- A released product from concept to customer.

Figure 15: Comparison of WiW Distributions of 14x4" EPS and non-EPS Carriers.

Figure 16 Within Wafer Yield Maps for Comparison of 14x4" EPS and non-EPS Carriers. The green regions are within the 5nm acceptance criteria for peak wavelength. The engineered pocket surface (EPS) carrier shows a significant improvement.

Phase III: Next-Generation Products

9.1 High-throughput System

Overview

The goal of Task 9.1 was to use the current building blocks of reactor and system architecture and integrate into a clustered, high-throughput system. A model of the four reactors oriented around a central transfer hub is shown in Figure 17. The technical risk was minimized by utilizing, as much as possible, existing reactor hardware, systems components, and software. The equipment followed the PLC system for product release and was introduced to the market during the course of the grant.

Results

After significant design reviews and sub-system manufacturing, the demonstration hardware was installed and tested Q3 2010. An automation paper study was completed to confirm $\geq 3x$ throughput increase. Following the testing and validation of the growth process on each reactor, the test for cluster operation of running four reactors simultaneously was completed. The first throughput multiplier established for four reactors was $2.94 \text{ wfrs/hr/ft}^2$. This first system was then shipped to a customer for a beta demonstration. A second system was then installed which has further modifications to reduce the cost of ownership. This second system had a remote power and pumping module, which allows for more efficient use of clean room floor space. An added process risk in this configuration is the extended process exhaust lines which are $> 3x$ the standard platform. In-house process testing and pump speed characterization confirmed the necessity to rework the exhaust configuration equivalent conductance vacuum system.

Having demonstrated the platform, received customer sign-off of the system, and retired the risk associated with the configurable layout, a third system was installed and became the basis for composite demonstrations necessary to meet the end goal of the grant. In Q1 of 2011, this system was released as a product that is known as MaxBright™ pictured in Figure 18.

Figure 17 Solid Model of the Four Reactors, Central Transfer Hub, Buffer Station, and Load Station.

Figure 18 Pictured here is the production release of the linear, 4-reactor version of the system. This highly configurable platform offers a 3x improvement in combined throughput and capital efficiency over four single-reactor systems.

Significance

- 3x improvement in throughput
- A released product from concept to customer
- Acceleration of the time-to-market for a U.S. supplier of manufacturing
- Quarter-over-quarter revenue share increase over non-U.S. based competition

9.2 Flow Flange Test Bench

Overview

The flow flange test bench was designed as a quality control check of cross-seal leaks between alkyls, hydrides and the isolation gas curtain. Growth rate efficiency has been linked to flow cross-talk in these three regions. See Figures 19. It was not predetermined that this tool would be sold or utilized by our customers; but, after it was determined to be a good predictor of flow flange integrity, units have been staged worldwide to assist customers with troubleshooting flow related issues and reduce unscheduled downtime for production.

Results

This test jig (Figure 20) was developed and deployed to reduce evaluation time of a given flow flange from 14 to 2 hrs. Previously, the flow flange would have to be installed and tested with growth runs. In addition to the units staged around the world in support of customer troubleshooting, the flow test bench is now fully integrated in the QC procedures for in-house manufacturing. Modifications to the flow flange screen, screen retainer, and edge seal have virtually eliminated the gross leaks originally observed

during the first trials with the bench; but, the test bench remains in use having proved value as a quick-turn test for assembly integrity prior to running process.

Figure 19 Flow Flange – Flow Regions of Interest. The bench test for the upper reactor assembly measures undesirable flow between the alkyl flow path, the hydride flow path, and the gas curtain flow region.

The prototype test fixture includes a vacuum pump, pressure transducers, and specialized clamping/sealing hardware.

Figure 20 Model of the Flow Flange Test Bench.

Significance

- 12 hour reduction in the test time of flow flanges
- Customer support hardware to minimize production downtime associated with flow flange diagnostics.

9.3 Large-scale Architecture Demonstration

Overview

Task 9.3 is a combination of paper studies and hardware to prove the feasibility of a composite platform to reach the 75% reduction in cost of ownership. At the completion of the grant, the hardware had been installed in laboratories at Veeco and was proceeding through initial start-up activities. Although a number of design types were considered, the system pursued for the quickest time to market is that of a conventional radial cluster architecture as shown in Figure 21. The requirements and assumptions for purposes of forecasting the gains of this platform are listed below.

Figure 21 Conceptual Architecture for the Large-scale System Demonstration.

- Clustered reactors
- Full cassette-to-cassette automation
- Space efficiency 50% > 4-reactor MaxBright
- K465i basis with the heated flow flange and adv. Carriers
- Source consumption 40% < K465i reactor, per wafer
- Split process capable
- Within wafer yield >90% in 5nm
- Operations capital efficiency >2800 cm²/day/\$M

Results

Four configurations of the reactant injector plate were evaluated using the advance chemistry models from Task 2.X. From these results the best candidate for the large-scale reactor was selected and submitted for manufacturability studies. In parallel work, the power supplies and pump packages were identified based on the expected power and flow requirements of the large-scale reactor. The initial large-scale wafer carrier

design resulted in significant temperature non-uniformities. As this is typically an iterative process, the part was returned for re-machining. The large scale system completed the first comprehensive design review in Aug. 2011. At that time, most sub-system components had been ordered or are nearing final sign-off for prototype build. Early evaluation components such as wafer carriers arrived May, 2012 and began acceptance testing prior to integration onto the system. Prior to move in, the lab infrastructure had to be modified to handle the size of and access to the system. The software for the system is new and required extensive teams of developers to handle the integration of complex MOCVD process and reactors and the complexity of multi-chamber scheduling and timing sequences. In Oct. 2011, the major components were landed in the laboratory space to begin the installation and test plans. At the conclusion of the grant, the equipment had not yet run process. All subsystem, safety, and integrated systems checks had been completed and passed. The heater assembly was tested to 1050°C (sustained) and 1175°C (peak) without issue. Response testing of the temperature control systems in process ambient of nitrogen and hydrogen was on-going to determine boundary conditions for ramp rates and acceptable temperature zone differences. A preliminary, full software build was been released to the process and equipment engineering teams on time and ready for use. Recipe creation and automated sequences are under evaluation to build the recipes for use on process runs. The system completed software and signal validation up to the limits of running a recipe automatically.

Significance

The feasibility of the large scale reactor has been demonstrated having been able to manufacture and test every subcomponent required. The entire system, as currently installed and tested, is the demonstration platform to achieve 75% reduction in CoO.

10.X Heated Flow Flange

Overview

The purpose of Task 10 was to test the concept that preheating of the precursors will enhance the growth rate and efficiency of the deposition. With the capability of an advanced chemistry model (Task 2), the design was validated within the model and forecasted a larger process space. Figure 22 shows the model prediction that a higher inlet temperature of precursors increases the area of stable operation and reduces the areas of recirculation and buoyancy phenomena.

Figure 22 Illustration of Gas Inlet Configuration and the Process Regimes. As T_{inlet} is increased from the baseline process of 50C, the process space broadens into regions typically dominated by buoyancy and recirculation. The ability to move to higher pressure and lower rotation can produce improvements in both growth rate and efficiency.

On that basis, a prototype heated flow flange (HFF), which supports a hot oil heat transfer loop was designed and developed as an upgrade to the K465i platform. This was the most challenging task in the program since the heated flow flange created a new process environment and an associated new process space for chemistry effects and tuning parameters to achieve the material property specifications. Add to the process challenges new hardware containing hot oil for controlling flange temperature and the extended duration of reliability testing, and the large number of process runs was justified.

Results

At the beginning of the grant, the prototype hardware was already in place and completing low-level functionality testing which required a number of hardware modifications to reliably control the hot-oil heat transfer loop. In the following tests of Q2 2010, recipe tuning demonstrated equivalent uniformity to K465i platform. During Q3 2010, the process space was pushed to high temperature and high growth rates for process space mapping. During these runs, GaN growth rates of 21 $\mu\text{m/hr}$ were demonstrated. The reference GaN growth rate is $\sim 4 \mu\text{m/hr}$, a $>4\times$ increase. The linearity of growth rate vs. TMGa flow was acceptable through the range tested and only limited by the size of the gas delivery system. In an effort to demonstrate new benchmarks, using a more conservative growth rate of 8.5 $\mu\text{m/hr}$, a consumption efficiency of 3.3 $\text{g}/\mu\text{m}$ TMGa was demonstrated versus a typical process of $\sim 5 \text{ g}/\mu\text{m}$ TMGa. See Figure 23. All other material properties were confirmed equivalent or better.

Figure 23 Comparison of Precursor Efficiency for 50C and 200C Conditions of the HFF. The 200C condition nearly doubles the efficiency of deposition for an equivalent growth rate and other material properties. Source consumption and the cost of the source material is a direct factor in the CoO calculation.

At this point, the demonstration was able to confirm the following benefits:

- Growth rate increase of 2.1x (vs. 1.3x goal) and associated source reduction of 35%.
- 20 $\mu\text{m/hr}$ GaN growth rate achieved and no evidence of growth rate saturation
- 37% reduction in alkyl flows
- $>40\%$ reduction in total flow

Table 8 contains additional details of the flows used and growth rates demonstrated.

Table 8 – Process Conditions: Heated Flow Flange vs. Standard K465i

Run	Standard K465i	High GR Conditions	Flow Reduction per Run
GaN Growth Rate	3.6 mm/hr	15.5 mm/hr	
Flow Flange Temp	50°C	200°C	
TMGa flow - Recovery	188	156	-17%
TMGa flow - Bulk GaN	300	808	-37%
Main N ₂ Flow	64	37	-43%
Main H ₂ Flow	120	73	-39%
Main NH ₃ Flow	50	27	-46%
Total N ₂ Flow	84	48	-43%
Total H ₂ Flow	142	91	-36%
Total NH ₃ Flow	53	29	-45%

Following the successful prototype demonstration, the production version of the heated flow flange was built and tested. The hot-oil heat exchanger design and reliability were evaluated and improved. Safety and system design of high-temperature organic fluids plumbing evolved using outside industry experts. Across more than 400 runs, the process space and customer use cases were evaluated for material properties, defect levels, device performance, and chamber aging. Again, with such promising results 2 of 5 in-house reactors were converted to the heated flow flange to accelerate the product development. Entering the last stages of the PLC cycle, four beta magma upgrade kits were shipped and installed in production environments. Each will be monitored closely over the next few months to check process performance and manufacturability.

Significance

Task 10 represents the positive interaction between organizations and the advanced research necessary to advance initiatives by U.S. funding. Veeco and SNL created a comprehensive model of reactor processing that was confirmed experimentally with the advent of the heated flow flange. An example of the sensitivity of the model is shown in Figure 24 where the model closely predicts the performance of the 200C conditions of growth rate vs. TMGa flow. With this level of accuracy, performance projections of new designs and improvements to existing hardware become more reliable and remove a significant amount of risk when committing large sums of money to capital.

Another advantage of this work was the determination of a much more influential reaction path in the chemistry model which has resulted in a continuation of funding for

SNL and a more exact account of the reaction kinetics. The original models predict very little dependence of efficiency/growth rate on flange temperature. In fact, earlier models, based on low-flow regimes, predicted much lower growth rate than measured. However, updating one rate constant (gas-phase nucleation) in the SNL model accounted for the TMGa flow-rate and pressure dependence measured at Veeco. Although the inlet-temperature dependence is still unexplained, the accuracy of the model provides an advanced platform for hardware development. As to the new understanding of the chemical reaction model, the question was taken up by SNL and received continuation funding to further investigate the new phenomenon.

At the product level, the HFF hardware is continuing in beta demonstrations at four customer sites with sign-off expected Q3 2012. With substantial experimental data, efficiency gains, and growth rate increases, this option on the 465i platform offers a 17% reduction in the CoO.

Figure 24 Comparison of Theoretical vs. Experimental Growth Rate vs. TMGa Flow. The combined FLUENT-Chemkin model has the confidence level necessary to predict hardware performance.

11.X In-situ Chamber Clean

Overview

The objective of Task 11 was to determine the feasibility of an in-situ clean. The practicality of an in-situ clean on the K465 reactor proved insurmountable. The temperature profile of interior reactor surfaces proved too cold for available chemistries. With the parasitic deposition that needs to be addressed in the lower section of the

reactor at the entry ports of the exhaust ring, the reactor would need to be significantly redesigned to incorporate a uniform heating system for the entire reactor assembly (hot-wall design). Additionally, a majority of the internal surfaces of the reactor are incompatible with the chlorine-based chemistries in consideration. With these two facts, the return on investment for the non-recurring engineering costs alone posted negative results.

Results

Typical availability of the K465 system in production is greater than 90%. Consider a three-hour in-situ clean that is run at the current rate of the open-reactor maintenance ($\approx$ 2wks) which takes 6 hrs. and replaces 7 of 8 open-reactor events. In this scenario, the availability improvement is approximately 1.2%. This constitutes less than 0.1% reduction in the CoO.

Significance

The in-situ clean remains a desirable feature of any production-level semiconductor deposition system. However, in the GaN system, the parasitic deposition is so chemically stable that exceptional means are required to chemically scrub the chamber. For this level of improvement in availability, a number of additional projects would be considered. For example, the current, limiting MTBM factor is the particle filter lifetime. There are several industry solutions that could be evaluated to address a higher performance filter and/or particle trap configuration.

Composite Demonstrations

Overview

By the second year of the grant, most of the individual tasks were completed successfully. Each on its own could not reach the goal of 75% reduction in CoO. Most of the second year was spent in combining tasks and techniques to show integrated capability to reduce CoO. The final stage in the combined demonstrations involved forecasting projected gains based on the highest quality data available from task-level demonstrations and the most accurate models of performance. Below are the combined demonstrations supported by experimental data on 4" wafers and the respective CoO reduction referenced to the standard K465 single-reactor platform.

Table 9 – Combined CoO Demonstrations – Validated Experimentally

Platform	Task 10.1 Heated FF	Task 7.2 MBTC	Task 8.1 Adv. Carriers	CoO Reduction
465				0%
465i (Task 9.2)				10%

Platform	Task 10.1 Heated FF	Task 7.2 MBTC	Task 8.1 Adv. Carriers	CoO Reduction
465i (Task 9.2)		✓		12%
465i (Task 9.2)	✓			17%
465i (Task 9.2)	✓		✓	19%
465i (Task 9.2)			✓	25%
465i (Task 9.2)		✓	✓	28%
465i (Task 9.2)	✓	✓	✓	30%
MaxBright (Task 9.1)				26%
MaxBright (Task 9.1)		✓		31%
MaxBright (Task 9.1)			✓	37%
MaxBright (Task 9.1)		✓	✓	39%

The highest performance demonstrated on the K465 platform included 465i (9.2) + Heated Flow Flange (10.1) + Advanced Carriers (8.1) which translates to a 19% reduction in cost of ownership. Figure 25 shows the WiW yield maps for this combined demonstration on the 12x4" carrier configuration. At the conclusion of the grant, the 6x6" carrier configuration was being manufactured.

Figure 25 Comparison of the 5nm bin within wafer yield maps for the standard (a.) and the heated flow flange (b.) processes. This first-revision 12x4" EPS carrier demonstrated a 7% increase in within wafer yield.

The highest overall performance confirmed experimentally was the use of MBTC (7.2) on the MaxBright (Task 9.1) with Advanced Carriers (8.1). This combination reduces the cost of ownership by 39%. Although the runs were not difficult to complete, the integration of MBTC with the new MaxBright systems architecture proved to be more challenging.

Although not planned initially, a second PCS server (5.1) was obtained and commissioned on a MaxBright system (9.1). The fortunate turn of events was the opening of the Veeco Taiwan Technology Center (TTC) and having the MaxBright as the centerpiece. Our software partners recoded database scripts to be compatible with the MaxBright software architecture and initialized the PCS algorithms without issue. Since the TTC is also a demonstration site for customers in the region, a significant number of customers were introduced to the PCS system in live demonstrations. This grouping of tasks represents a 27% reduction in CoO.

The next series of combinations were not ready by the end of the grant. By way of completeness, a forecast was computed to understand the ultimate reach of the program. Our best calculations indicate that the fully configured MaxBright could drop the CoO by as much as 50% on 4" wafers and that the large-scale system would be needed to reach the grant objective. The forecasted results are compiled in Table 10.

Table 10 – Combined CoO Demonstrations – Forecasted

Platform	Task 10.1 Heated FF	Task 7.2 MBTC	Task 8.1 Adv. Carriers	CoO Reduction
MaxBright (Task 9.1)	✓	✓	✓	50%
Large Architecture (Task 9.3)	✓	✓		52%
Large Architecture (Task 9.3)	✓	✓	✓	59%

To obtain these numbers for the Large Architecture System (9.3), we once again returned to the combined CFD/chemistry model of Task 2. With confidence in the model established, we could use the fundamental outputs of growth rate and temperature to forecast WiW statistics. The temperature profiles used as one component in forecasting the yield of the new system are shown in Figure 26.

Figure 26 Comparison of K465 and Large-Scale System Temperature Profiles. The temperature variance calculated by the advanced chemistry model is combined with gas temperature and concentration simulations to forecast the yield of the reactor.

Finally, we extend the conclusions to the general case of manufacturing LEDs. Not all manufactures use 4" wafers as has been the case through these experiments and models. There is a large installation of tools continuing to use 2" wafers and a select few industry leaders have moved to 6" wafers. Table 11 lists the dramatic difference between wafer size and the gains of the various combinations of the grant. Sapphire costs represent the largest driver in the CoO model. For manufacturers using 2" wafers, comprehensive gains of the program reached a 69% reduction in the cost of ownership in the epitaxy portion of building LEDs.

Table 11 CoO Combinations vs. Wafer Size

System Configuration	K465i	K465i MBTC	K465i HFF	K465i Adv.Car.	K465i H+M+A	K465iC4 4x12x4"	K465iC4 H+M+A	Large Scale
2" % Improvement over K465 Basis	10%	13%	17%	28%	33%	36%	58%	69%
4" % Improvement over K465 Basis	10%	12%	17%	25%	30%	26%	50%	59%
6" % Improvement over K465 Basis	10%	11%	14%	24%	27%	25%	42%	50%

(H ≡ Heated Flow Flange, M ≡ Model-based Temperature Control, A ≡ Advanced Wafer Carriers)

Significance

The combined demonstrations are the true output of the grant. The ability to translate these tasks to market products is a measure of success in utilizing DOE funding to help accelerate U.S. manufacturing and wide-spread adoption of solid-state lighting. The following examples represent the tangible impact of this grant.

During the course of the grant Veeco became the leading equipment supplier for large, high-growth LED & solar markets and remains the market-share leader through Q2 2012. Figure 27. The DOE funding accelerated product development to allow earlier adoption of higher performing hardware. Nearly all high-volume, domestic LED manufacturers have purchased and/or are now evaluating the hardware developed with the assistance of this grant, an indication of the growth of the U.S. LED market/industry.

Figure 27 Percent Unit Shipments by Quarter by Product. The 465i and MaxBright Veeco products have taken the lead market share since Q3 2010. DOE funding helped accelerate product development, secure domestic jobs, and growth the U.S. LED industry.

In relation to the impact of this grant on the U.S. economy, the grant sustained 5 FTE federally-funded R&D jobs. Additionally, the grant contributed indirectly to hundreds of jobs involved in the full supply chain of goods and services for developing and manufacturing the K465i, the MaxBright, and the Large-scale System. Also, >95% of the Veeco equipment is sold worldwide providing a highlight for U.S. exports.

As a manufacturing-centered effort, the level of product development can be used as an indication of success. At the conclusion of the grant:

- 3 of 10 product-oriented line items now generate revenue
- 2 of 10 product-oriented line items are in customer beta evaluations
- 3 of 10 product-oriented line items continue to be funded

Media Exposure

[DOE Budget Period 1](#) Peer Review – 2011
[DOE Manufacturing](#) Workshop – 2010
[DOE Manufacturing Mfg.](#) Workshop – 2011
[DOE Manufacturing Mfg.](#) Workshop – 2012 – Invited

Presentations

- 9th International Conference on Nitride Semiconductors, Glasgow Scotland, July 10-15, 2011; *An Overview of Operating Parameters Effect on Parasitic Gas-phase Chemistry During group III-nitride MOCVD*, Mitrovic, B (presenting); Armour, EA; Zhang, A; Gurary, A; Paranjpe, A
- 9th International Conference on Nitride Semiconductors, Glasgow Scotland, July 10-15, 2011; *Investigation of MOCVD Growth Parameters on the Quality of High Growth Rate GaN, InGaN and AlGaN Epitaxial Layers*, Armour, E (presenting); Zhang, A; Pophristic, M; Mitrovic, B; Gurary, A; Paranjpe, A
- Semicon West – 2011, San Francisco, CA, Extreme Electronics Symposium, July 11-15, 2011; *Trends in Production Scale MOCVD Systems to Reduce the Cost of Solid State Lighting*, Quinn, W. E.
- 15th US Biennial Workshop on Organometallic Vapor Phase Epitaxy, Monterey, California, July 31 - August 5, 2011; *Role of MOVPE in Energy Efficient Solid State Lighting*, Quinn, Bill
- 15th US Biennial Workshop on Organometallic Vapor Phase Epitaxy, Monterey, California, July 31 - August 5, 2011; *Effect of Growth Conditions on Mg Incorporation in GaN and AlGaN*; Pophristic, Milan; Lee, Soo Min; Zhang, Alex; Mitrovic, Bojan; Berkman, Erkan Acar (presenting); Armour, Eric; Paranjpe, Ajit