FY2010 Appropriations Request Form

Office of Congresswoman Jackie Speier
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Washington, D.C. 20515
Phone: 202/225-3531
Fax: 202/226-4183
Website: www.speier.house.gov

Individuals/Organizations must respond to all questions on the form. Incomplete proposals will not be considered.

All requests will be evaluated before the 12th Congressional District's Citizens Oversight Panel. Appointments to appear before the panel must be made through Cookab Hashemi, chief of staff, at 202/225-3531 or Cookab.Hashemi@mail.house.gov. The panel will convene on the following days; Saturday, March 7, Friday, March 13 and Friday, March 20, 2009. All proposals must be submitted by March 2, 2009.

Date Submitted: February 25, 2009 (follow up to meeting on February 5 with Erin Ryan and Peter Viola)

Project Name: FALCON (Fast Adoption of Solid State Lighting Consortium)

Individual/Organization: *(Is the grantee located in the 12th Congressional District?)*
There are seven organizations involved and while none is in the 12th district, Stanford University, KLA-Tencor, Applied Materials, and Philips-Lumileds have over a thousand employees in the 12th district.
Stanford University, 450 Serra Mall, Stanford, CA 94305
KLA-Tencor, One Technology Drive, Milpitas, CA 95035
Philips-Lumileds, 370 w. Trimble Road, San Jose, CA 95131
Applied Materials, 3050 Bowers Ave., P.O. Box 58039, Santa Clara, CA 95052
Veeco Instruments, Terminal Drive, Plainview, NY 11803
and 394 Elizabeth Ave., Somerset, NJ 08873
Sandia National Laboratory, P.O. Box 5800, Albuquerque, NM 87185
Crystal IS, 70 Cohoes Ave., Green Island, NY 12183

Amount Requested (*if requesting report language, please attach*.): $10,000,000
"$10M shall be provided within the Solid State Lighting Research and Development program of DOE for the member companies of the FALCON consortium to reduce the cost of GaN-based lighting."

Appropriations Bill/Account/Relevant Authorization law/bill/status (*e.g., "Public Law 107-111"; "FY2008 DOD Authorization", "Currently pursuing authorization through Agriculture Committee", "Safe Drinking Water Act" or "Hatch Act")*:
2007 Energy Independence and Security Act, HR6, section 321

Local Contact (*Please provide full contact information, including any relevant phone extensions, and indicate if there is a separate D.C. contact.*):
Dr. Richard Solarz, KLA-Tencor
Ms. Julie Pacquing, Pacquing Consulting

Organization's Main Activities. (*Please limit your response to 250 words and indicate whether it is a public, private, non-profit or private for-profit entity.*) Four of the organizations are large publicly traded companies (Applied Materials, KLA-Tencor, Veeco, and Philips-Lumileds), one is a start up (Crystal IS), one is a private university (Stanford) and one is a national laboratory (Sandia National Laboratory). Philips-Lumileds is the largest manufacturer of lighting in the world and Applied, KLA, and Veeco are all semiconductor equipment manufacturers. Crystal IS is a supplier of AlN substrates to the lighting industry. Sandia is the DOE center of excellence for solid state lighting.

Please show main items in the project and total cost in a simplified chart form. (*Please include the amount of any Federal/State/Local/Private funds, including any in-kind resources).*

FALCON COST SUMMARY	TOTALS	Eng Labor (hrs)	Tech Labor (hrs)	Labor Cost ($)	Materials Cost ($)	Total Cost ($)
		123,956	***84,666***	***43,557,600***	***19,174,000***	***64,729,600***

These are project costs for three years and include matching funds from industry. More detailed breakout of project costs has already been provided in the 60 page program plan submitted to Cong. Speier's office during the February 5th briefing.

Project Description, including a timeline, goals, expected outcomes and specific uses of Federal Funds. (*Your response must focus on the requested funds rather than the organization's mission and general activities. Please limit your response to 250 – 500 words.) The detailed program plan provided during the February 5th meeting provides detailed timelines and activities. Briefly, the consortium will develop and offer for sale improved MOCVD (metal organic vapor deposition tools) and real time inspection and metrology tools to the lighting industry at the end of the FALCON project. The consortium will also develop advanced substrates and lower cost packaging methods for use in the fabrication of solid state lighting. We believe that collectively these actions will accelerate the reduction of solid state lighting products significantly (by a factor of 5 or more) for enhanced acceptance residentially and commercially. Please refer to the program plan.*

How will this earmark serve to expand the capacity of your organization and how will your organization sustain this work beyond the federal funding? (*Your response must focus on the impact of the requested funds rather than the organization's long-term goals.*) Each of the industrial companies will expand their market share in this growing industry. The initial specialized equipment products will be offered to sale to Philips-Lumileds and to other solid state manufacturers. The lower cost solid state lights offered for sale by Philips-Lumileds will assist them in developing a commanding share of the energy efficient lighting market. The project will be completely commercially sustained after completion of the three year funding.

What is the local significance of this project? In addition to reducing total energy consumption locally and in the U.S. by as much as 4%, the FALCON project will serve to place Silicon Valley in a leadership position in the emerging green industry of solid state lighting, resulting in substantial high tech job growth for both lighting manufacturers and for specialized equipment makers who will provide tooling to this industry.

How many residents of the 12th CD will benefit from this project? *(i.e. jobs created, services rendered to, how many people, etc.) The world wide lighting industry is currently $65B per year and growing. At the completion of the project the increase of the nmber of jobs in California for equipment design and solid state lighting fabrication would be approximately a thousand people with over a hundred of these estimated to be in the 12th district.*

List any other organizations or state/local elected officials who have expressed support for the project in writing. (*Please submit copies of support letters along with the proposal*.) We are working closely with the Department of Energy and the people who can be contacted are:
Mr. James Brodrick, U.S. DOE, Office of Buildings Technology
Mr. Dave Rogers, U.S. DOE, Deputy Assistant Secretary for Energy Efficiency
In addition we have worked with the Alliance to Save Energy and the person to contact is: Jeff Harris, Vice President, Alliance to Save Energy

Does the organization have any other funding requests for this project? (*Federal, State,Local or private pending*?) We are currently working with the Department of Energy to provide funding to FALCON through Stimulus Package and FY09 Continuing Resolution funding. We will work with Cong. Speier's office and update her staff on these developments as they occur.

Has the organization previously received Federal funds for this project? (*Please list any funds received [by fiscal year] and briefly describe how those funds were spent*.) No.

Please attach a list of your organization's staff and board members (*if any*).
The best people to contact at each of the organizations are:

Dr. George Craford, CTO. Philips-Lumileds
Dr. Leo Schowalter,CTO
Dr. Richard Solarz, Sr. Director, KLA-Tencor
Prof. Bert Hesselink, Stanford University
Dr. Jerry Simmons, Sandia National Laboratory
Dr. Nag Patibandla, Director, Applied Materials
Ms. Deb Wasser, EVP, Veeco

Please attach any additional relevant materials

Draft Program Plan (10/26/08)
FALCON: Fast Adoption Solid State Lighting Consortium

Philips-Lumileds, Veeco, Sandia National Laboratory, Applied Materials, KLA-Tencor, Stanford University, and Crystal IS
Business Confidential

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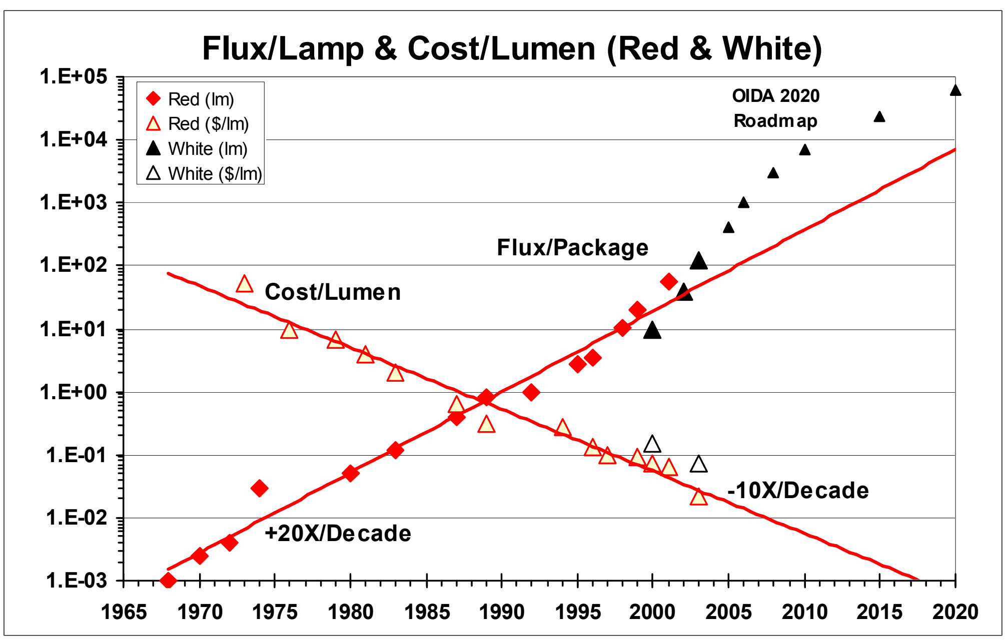
1. Introduction

Energy consumption is currently one of the most critical issues facing our nation as well as all other economically developed nations. It touches every issue in our daily lives ranging from severe economic and political impacts to global warming and its attendant impact upon our planet's climate and health. Competition for energy resources increasingly makes it clear that these resources need to be shared and used carefully, efficiently, and intelligently. Energy conservation and intelligent energy use are therefore indisputable goals for every nation, every company, and every individual.

Significant research and development in renewable energy is occurring on many fronts. Solar energy, solid state lighting, wind and wave power, biofuels, and improvements in fossil fuels and the development of more efficient machinery are all part of the conservation and energy generation equation. Many of these technologies have been demonstrated to be technically successful but implementation and harvesting of the resulting efficiencies have been hampered by the capital costs for adoption. This situation is dramatically the case for solid state lighting technology. This white paper addresses the developments needed to overcome this barrier and to accelerate the implementation and adoption of efficient, long lived, and cost effective solid state lighting technology world wide.

The dramatic improvements in LED efficiency and brightness have enabled modest increases in the adoption of these energy saving devices in many application areas. However, the purchase cost today of lumens from LED sources is still nearly 20 times higher than an incandescent bulb; $0.011/lm verses $0.0006/lm. Experience from the compact fluorescent lighting industry teaches us that LEDs will not penetrate the major energy saving application, residential and commercial lighting, until the purchase price for LED bulbs approach the prices for competing technologies, incandescent or compact fluorescent lighting (CFL). Specifically, using data from the market penetration of CFL, consumer adoption of 50% is expected to occur when 1200 lumen LED devices retail for $2 per bulb. Haitz's law, used by the lighting industry to track the improvements in LED brightness and reductions in prices for lumens from LEDs, predicts that at the current pace, LED prices will fall to $0.0018 per lumen resulting in a high volume retail price of over $10 per LED bulb in 2015, still a factor of five too high for major consumer market penetration.

Figure 1-1: (Courtesy of Roland Haitz) Haitz's Law is used to track and to project the price and performance of LEDs in a manner analogous to Moore's Law for silicon semiconductor microelectronics. Haitz's Law projects that pricing of white light LEDs will not result in full adoption of LED lighting until near 2020. Government stimulated partnerships will be required to accelerate the adoption of efficient LED based solid state lighting.



In order to accelerate manufacturing cost reductions there are a key number of manufacturing issues which need to be addressed. To date the Department of Energy and other government agencies have successfully demonstrated improvements in device performance. Now is the time to engage manufacturing disciplines for this emerging industry and to customize hardware, adopted from more mature industries, to the problems faced by the solid state lighting industry. Specifically the LED industry needs to adopt the sophisticated manufacturing and tooling of the silicon microelectronics industry but with equipment and manufacturing methods tailored to the lighting industry. As we will see in this white paper, improvements in MOCVD technology can deliver a number of cost reductions for solid state device growth. These will be addressed in detail in Section 3. The efficient consumption of growth materials is one area which needs to be addressed. Other areas include better process control for higher yields and faster learning for new device growth. These improvements are all linked in the customization of the MOCVD tools for GaN crystal growth.

Section 4 will address the improved diagnostics capabilities for MOCVD growth. These diagnostics will be customized to maintaining process window conditions for high yield solid state lighting crystal growth. This section of the report will also describe the building of process codes which describe the underlying factors operating as parasitics to optimum process yields. Deepening our understanding of these mechanisms and the factors that control them will further drive cost reductions by ensuring good process yield, reduced device binning, and will also assist in minimizing growth material consumption.

Section 5 is devoted to the production of improved substrates for GaN thin film growth. The low cost production of a substrate with exceedingly low threading dislocation density, superior thermal conductivity, non polar planes for eliminating electric fields across quantum wells, which is well lattice and expansion matched to GaN offers the possibility of producing exceedingly high current density, high brightness, robust solid state lighting.

Section 6 will describe the cost reductions gained through yield management tool customization from the silicon microelectronics industry. These process monitor tools accelerate learning and maintain high process yield not only during device film growth, but also for wafer processing steps and wafer packaging. In the silicon industry a state of the art fabrication facility (Fab) costs between 2 and 3 B$ to build and several hundred million to operate annually. The capital cost and operations costs are largely fixed, but the profitability of the Fab is highly variable. The main variables are time to ramp the Fab to full production, and yield once in production. Process monitoring tools help reduce costs for both of these main issues. Firstly, high sensitivity automated inspection tools are excellent learning vehicles for companies trying to eliminate systematic yield issues during product ramp as well as during the post-ramp phase of continual yield improvement. Secondly, high throughput in-line inspection tools help detect out-of-control (OOC) conditions that occur in a ramped high volume manufacturing Fabs. Rapid detection of these issues results in minimal lost yield due to the OOC condition. Finally, this industry also uses software for faster yield learning via end-of-line correlations. It is believed that the introduction of dedicated hardware and software for the LED manufacturing industry, yield management as well as deposition and processing tools, will achieve manufacturing efficiencies and cost reductions needed to accelerate the adoption of the energy efficient LED technology by roughly a factor of five.

The growth of green emitting LEDs is one of the most challenging regimes for GaN solid state lighting. Due to the very high surface mobility of indium on GaN films, indium rich InGaN green emitting LEDs tend to form films which exhibit a high degree of indium clustering. The degree to which these clusters form is controlled by several factors including substrate temperature and indium deposition rates, among other factors. Section 7 will describe the development of an in-line indium cluster monitor which can be used to optimize the growth of indium rich InGaN films. Section 7 describes the physical approach and also provides some review of the understanding of clustering and its effect on green emitting LED efficiencies.

Finally in Section 8 we describe the implementation of these developments at solid state lighting manufacturer as well as additional components of this program. Additional important elements of the proposed program are to also support the development of lower cost components such as substrates, heat sinks, phosophors, and OLED (organic based LEDs) based materials for the LED manufacturers. Importantly we will also describe the importance of improved and reduced binning strategies which are also key in providing low cost production of high quality and color consistent solid state lighting for the consumer.

Impact:

There are two key measureables which describe the impact of accelerated adoption of solid state lighting. The first of these is energy conservation or the use of reduced energy necessary to implement existing functions such as residential and commercial lighting. In order to more readily visualize the impact of these savings we will by way of example refer to scenarios in which this energy savings is all realized through the reduced need for oil. Clearly oil is not used for the production of the majority of the electricity used for lighting in this country. Nonetheless the available of electricity from existing power plants due to reduced demand for lighting will allow this capacity to serve other energy consuming applications such as transportation. If the transportation application were, for example, electric cars, this would then in turn reduce the reliance upon petroleum product consuming automotive solutions. Those preferring not to use this visualization may prefer to simply understand the impact of the FALCON program in terms of the Quads of energy saved (although this term is not generally used by the average consumer. One quad of energy is equivalent to 176,000,000 barrels of oil). For reference we also note that it has been calculated that in 2007 that $38B was spent directly on fuel based lighting and this before a major run up in fossil fuel product prices.

A few more comments regarding energy consumption in the U.S. and regarding the current lighting efficiency in each lighting sector (commercial and residential, with and without reflectors) are in order. Data can be obtained from various sources such as

United Nations publications, DOE documents, the Energy Information Administration, and papers in the scientific literature. We will use values which are approximate to the values presented in the paper by R. Devonshire and the First International Solid State White LEDs and Solid State Lighting (Tokyo, Nov.-Dec. 2007) and those contained within the DOE Solid State Lighting Program Documents. Prof. Devonshire exercised particular care to provide up to date values for lighting sectors which have upgraded recently to CFLs and related more energy efficient technology.

The second impact of the improvement in energy conservation is to convert the energy savings into the added benefit of equivalent carbon emissions reduction. The numbers in this white paper are based upon assuming that quads of energy saved would have been produced from fossil fuels. Again, the same caveat regarding scenarios discussed in the previous paragraph apply.

Table 1-1 below shows the impact in annual energy consumption and carbon emissions projected for 2015 assuming a LED lamp price of $10 per lamp (1200 lumens per lamp). Reduction of carbon emissions by 34.1 million metric tons (MMTC) and energy savings of 2.1 quads are projected based upon the adoption rates projected within each sector at this price per lamp. However, Table 1-2 shows that at a lamp price of $2 per lamp, carbon emission reduction of 82.8 MMTC and energy savings of 5.1 quads are realized per year. This is equivalent to 0.9 billion barrels of oil per year. The lower the price for the LED bulb, the more competitive it is to incandescent and CFL lighting, the larger the market share and savings.

Table 1-1. Energy savings and carbon emission reduction based on procedure in DOE call for adoption of LED lighting at 1200 lumen lamp prices of $10

	Typical LPW(*) New Source	PLLC LED(**)	Save (%)	Use quads	Market (%)	Savings (quads)	Save MMTC
Res. Inc. General	45	**115**	60.9	4.0	60	1.5	23.9
Res. Inc. Reflector	33	**115**	71.3	0.6	80	0.3	5.6
Com. Inc. General	15	**115**	87.0	1.8	10	0.2	2.5
Com. Inc. Reflector	11	**115**	90.4	0.8	20	0.1	2.2
Total Savings				7.1		**2.1**	**34.1**

* LPW is lumens per watt for a typical lighting source in each sector. Note that the commercial sector lighting has higher efficiencies today due to the greater use of fluorescent lighting compared to the residential sector.

** The LPW for currently demonstrated Philips Lumileds Corporation (PLLC) solid state white lights

Table 1-2. Energy savings and carbon emission reduction based on procedure in DOE call for adoption of LED lighting at 1200 lumen lamp prices of $2

	Typical LPW(*) New Source	PLLC LED(**)	Save (%)	Use quads	Market (%)	Savings (quads)	Save MMTC
Res. Inc. General	45	**115**	60.9	4.0	100	2.4	39.8
Res. Inc. Reflector	33	**115**	71.3	0.6	100	0.4	6.9
Com. Inc. General	15	**115**	87.0	1.8	100	1.5	25.0
Com. Inc. Reflector	11	**115**	90.4	0.8	100	0.7	11.2
Total Savings				7.1		**5.1**	**82.8**

We can also project the savings in carbon emissions and energy consumption possible once higher efficiency LED lighting is developed at introduced at $2 per 1200 lumen bulb. These projections are shown in Table 1-3.

Table 1-3. Energy savings and carbon emission reduction based on procedure in DOE call for adoption of LED lighting at 1200 lumen lamp prices of $2 for 150 LPW (lumen per watt) advanced LEDs.

	Typical LPW(*) New Source	PLLC LED(**)	Save (%)	Use quads	Market (%)	Savings (quads)	Save MMTC
Res. Inc. General	45	**150**	70.0	4.0	100	2.8	45.7
Res. Inc. Reflector	33	**150**	78.0	0.6	100	0.5	7.6
Com. Inc. General	15	**150**	90.0	1.8	100	1.6	25.8
Com. Inc. Reflector	11	**150**	92.7	0.8	100	0.7	11.4
Total Savings				7.1		**5.5**	**90.6**

Clearly a range of numbers can be used to understand the various sensitivities. Even clearer *the most sensitive number is adoption due to price.* More evident yet the savings in energy and carbon emissions for the U.S. are enormous.

As a measure of the impact of FALCON we can further refer to data available from the U.S. Energy Information Administration for 2007. In 2007 the U.S. total petroleum consumption was 7.55 billions barrels of oil (crude plus petroleum products) per year of which roughly 30.2% were imported with OPEC countries. 5.1 quads of energy are contained in 0.9 Billion barrels of oil and thus the OPEC imports represent 13.0 quads of energy. The energy savings from the FALCON program then can be stated to be a significant fraction of the U.S. OPEC oil imports per year or a reduction between 15-45% of all OPEC crude and petroleum product imports in the various scenarios called out in this white paper.

Table 1-4: U.S. Annual crude and petroleum product consumption and OPEC imports for 2007 (taken from http://www.eia.doe.gov/neic/quickfacts/quickoil.html)

7,550,755,000	total U.S. annual petroleum consumption in barrels
42.90	total U.S. annual petroleum consumption in quads
2,281,250,000	petro plus crude annual barrels imported to U.S. from OPEC
12.96	quads of OPEC petroleum energy imported per year to the U.S.
30.2%	fraction of U.S. oil consumption due to OPEC oil (per cent)
39.2%	FALCON upper case savings of OPEC oil imports (per cent)
15.4%	FALCON lower case savings of OPEC oil imports (per cent)

There are additional benefits to the U.S. and to the U.S. economy and these include:

- state of the art U.S. based equipment supply chain serving the LED industry and creating jobs
- development of LED process equipment customized to U.S. LED supplier products thereby increasing U.S. manufacturing share
- development within the U.S. of high yield underlying component technologies such as substrates and submounts produced for LED ready manufacturing operations
- optimized manufacturing operations and yields for overall lowest cost LED production and accelerated ramp of the U.S. market share

2. Partnership Overview

The partner companies and institutions are leaders in each of the critical skills and technologies needed for a successful FALCON project. A brief summary of each company:

Philips-Lumileds Corporation: Formed in 1999 in Silicon Valley as a joint venture between Agilent and Philips Lighting, Philips-Lumileds is now the leading manufacturer world wide of high power LED lighting. Luxeon is its trade name for leading edge LED products dissipating more than one watt of power.

Veeco: Veeco is the leading U.S. manufacturer of MOCVD tools which can be used for many applications including thin film deposition for GaN LEDs. Annual sales are approximately $0.5 B per year and include a number of metrology and system solutions. Corporate offices are located in Plainview, New York and MOCVD Systems are located in Somerset, New Jersey.

Sandia National Laboratory: Sandia is a multi-program, multi-disciplinary laboratory dedicated at the forefront of cutting-edge wide-bandgap semiconductor technology. Sandia is the lead laboratory for the Department of energy in Solid State Lighting and is now conducting a major R&D project devoted entirely to this topic.

KLA-Tencor: Formed in 1976, KLA-Tencor is the leading yield management solutions provider for the silicon semiconductor electronics market world wide, with annual sales of $3B. KLA-Tencor is located in Silicon Valley.

Stanford University: Located in Palo Alto, California Stanford will concentrate on the development of in line optical monitoring tools of unprecedented resolution for the GaN solid state lighting industry.

Crystal IS: Spun out of Rensselaer Polytechnical Institute in 1997, Crystal IS is now the leading supplier of bulk aluminum nitride wafers for high brightness LEDs and related applications. Crystal IS is located in Green Island, New York.

Applied Materials: Located in Santa Clara, California, Applied is a leading manufacturer of deposition and processing equipment for silicon based microelectronics and cluster tools with annual sales over $10B.

3. MOCVD Growth of GaN crystals and planned projection of savings

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Metal-Organic Chemical Vapor Deposition (MOCVD) is the preferred technique for growing epitaxial films of nitride materials. The technique provides all aspects needed to manufacture LED structures in high volume with good yield; source materials are readily available in large quantities, growth rates are sufficient to produce multiple runs per day, ternary compositions can be produced, n and p doping are easily controlled, and high volume production MOCVD systems are readily available. Veeco is the sole US supplier of high volume MOCVD systems.

Veeco purchased the TurboDisc Division of Emcore in 2004 to enter the MOCVD equipment segment. Over the past 4 years, Veeco has invested over $20 million for equipment and process R&D. In the past year 2 new GaN tools and one new As/P tool were introduced. All newly introduced tools are targeted for high volume production of epitaxial materials.

TurboDisc Technology

There are three types of MOCVD reactors; horizontal, showerhead and rotating disc. Horizontal reactors were the first MOCVD systems. The characteristics are low gas flow, depletion across the deposition zone and material deposition above the substrates, which creates particles, and requires frequent removal. Showerhead systems inject the precursor gases directly into the boundary layer above the substrate. These reactors are capable of producing good uniformity, but the showerhead becomes coated and clogged due to its proximity to the growing wafers. Rotating disc reactors inject the precursors above a rapidly rotating disc. The injector is well above the boundary layer to eliminate clogging and particle formation. The rotating disc acts as a pump to draw the precursors to the heated disc where the precursors react to form the desired materials. Advantages of rotating disc reactors are high gas velocity, which allows for rapid gas switching and abrupt interfaces, minimal coating of the reactor interior, which extends the time between reactor cleanings, and optical access to the growing films, which enables in-situ monitoring and control of critical growth parameters.

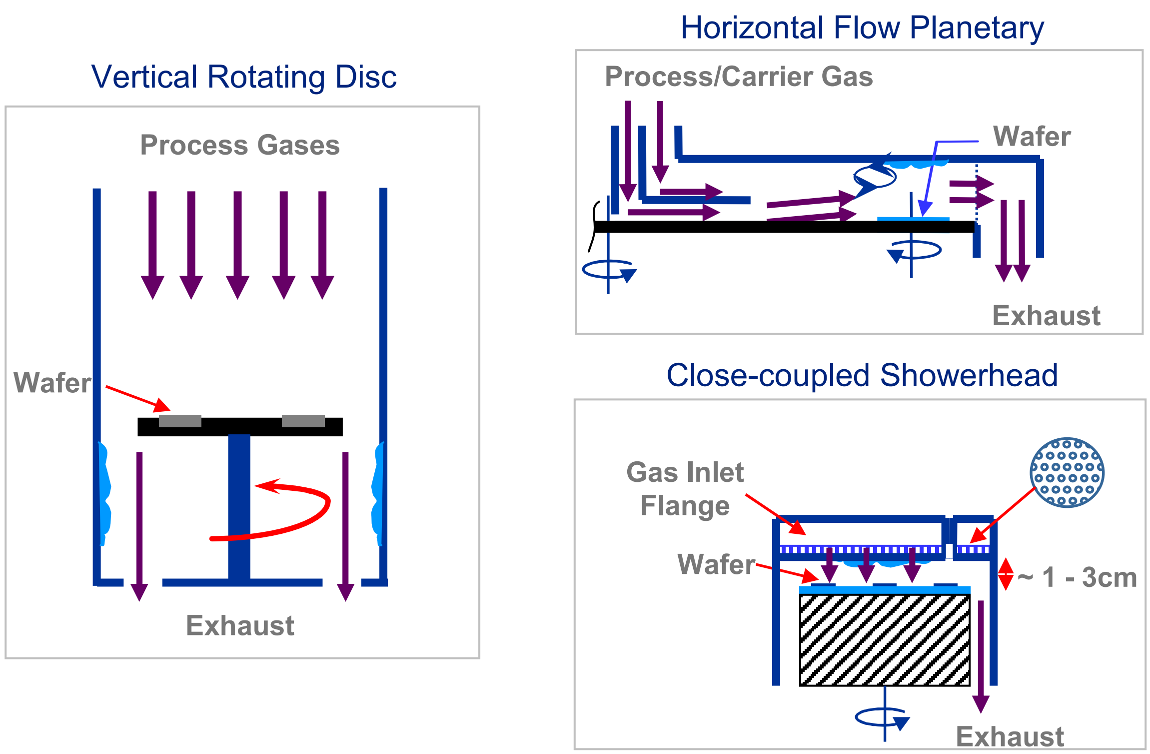


Figure XX. Schematic representations of the three types of MOCVD reactors showing location of reactor wall deposition.

Cost of Ownership

One of the most important aspects of any semiconductor manufacturing tool is the cost of ownership (CoO). Cost of ownership is a model of the total cost of using to tool to produce semiconductor devices. The model includes all aspects of the tool cost; capital cost, operational costs, maintenance cost, cost of yield, and disposal cost at the end of useful life. The goal of the MOCVD part of this program is to reduce the CoO for MOCVD tools.

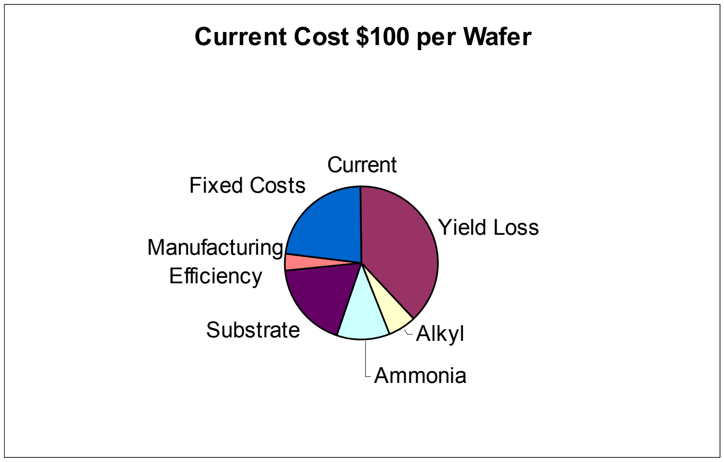


Figure XX+1. Cost of ownership categories and relative weighting for growing GaN LED structures by Veeco MOCVD system.

Figure XX+1 shows the cost contributors to MOCVD growth of blue LED structures. The largest category is yield loss caused by the distribution in material properties in each wafer, between wafers in a single growth run, and between growth runs. Fixed costs include depreciation and floor space occupied by the tool. Manufacturing efficiency refers to operational aspects of using the tool. These include maintenance schedules, idle time and tool calibration and qualification. Source material utilization (ammonia and alkyls) contributes significantly to the cost of wafers produced. The final category listed is the substrate used for LED growth, which is addressed in section 5.

Source Efficiency

The degree to which a precursor material is incorporated in to the films grown on the wafer is determined mostly by the design of the reactor and can be influenced by the growth recipe or growth parameters (substrate temperature, precursor flow, and concentration, and inert gas flow). Computational Flow Dynamic (CFD) models are used extensively to design MOCVD growth systems. These models accurately predict the gas flows and delivery rates of precursors to the growth surface and can estimate the uniformity (in terms of thickness and composition) of growth achieved in the system. The uniformity and growth rate predictions, however, often underestimate the non-uniformity, because the models do not include details of the chemical reactions that take place in the gas above the wafer and on the surface of the wafer. Figure XX+2 is the output of a CFD model from an older rotating disc reactor, showing the predicted and actual GaN thickness uniformity. The actual non-uniformity is about four times greater than predicted due ignoring the effects of chemistry in our models.

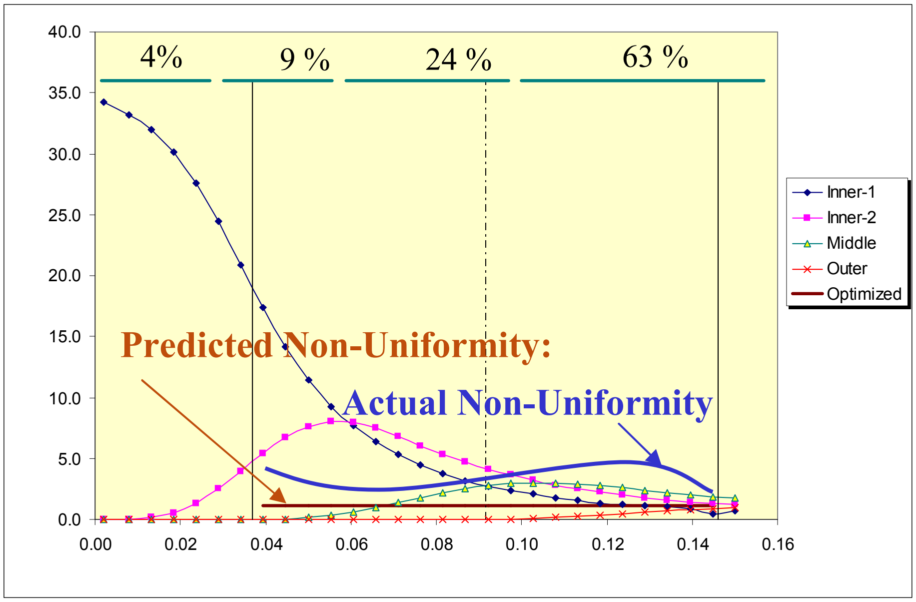


Figure XX+3. Output of CFD model for multi-zone rotating disc reactor showing predicted and actual thickness uniformity.

Section 4 of this proposal and section (Sandia) add chemistry to CFD models. Inclusion of chemistry in the CFD models will allow us to design deposition systems that minimize parasitic gas phase reactions, increase efficiency of precursor use and grow materials at a faster rate. We will also work with Rutgers University to develop laser fluorescence techniques to accurately measure the velocity and concentration of reactants flowing into the reactor under actual process conditions.

Epitaxial Material Yield

The most important category in our CoO is cost of Yield. Figure XX+4 shows a yield Pareto for typical GaN based LED structures. Wavelength is the largest category, and it includes both wavelength variation and wavelength centering. Wavelength variation has a number of sources. During growth, the wavelength within a wafer is not monotonic, but rather a distribution of wavelengths. Production MOCVD systems make number of wafers simultaneously, and each wafer may have a different average wavelength and a different wavelength distribution. Wavelength centering generally refers to a small shift in wavelength from one run to the next.

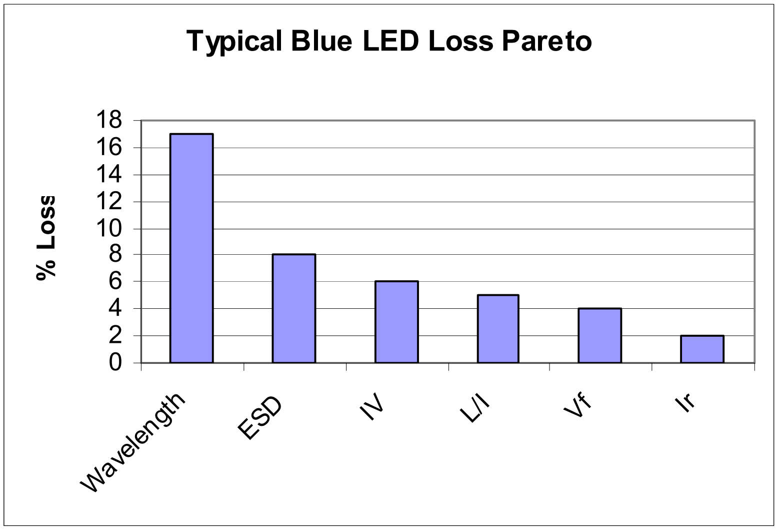


Figure XX+4. Yield Pareto for a typical blue LED structure.

Wavelength variation and centering issues are caused by flow, temperature and chemistry effects while the structure is being grown.

Flow effects have been briefly discussed above and can be fundamentally altered by changes in the process conditions and reactor design. Small changes to reactant flow are partially responsible for changes in run to run average wavelength. These changes are produced by drift in MFC performance and by changes in the reactor caused by wall deposits.

Temperature has the greatest effect on uniformity, within wafer, wafer to wafer and run to run. Temperature and temperature uniformity must be controlled to several tenths of a degree to achieve good yield. Each degree change in temperature produces a 2nm change in wavelength for blue LEDs and a 3nm wavelength shift for green LEDs.

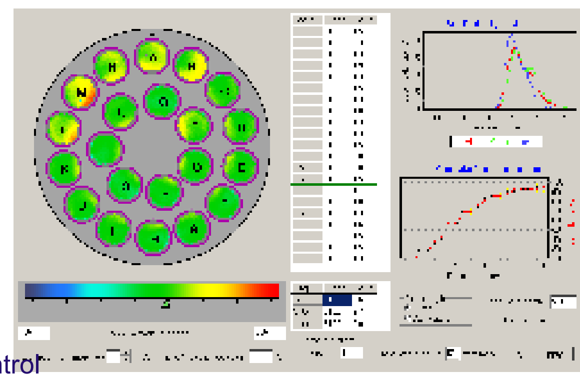
Yield improvement will be addressed with two separate strategies. The first is use the results of CFD + Chemistry models to design a new growth system. The current generation of systems has been designed using only CFD, therefore, the predictions of growth rate and uniformity do not take into account any effects of chemistry (kinetics and thermodynamics). Stanford University and Sandia will collaborate with Veeco to develop and verify the combined SCD +Chemistry software. The models will be verified by comparing predicted results for current systems to the actual growth data. These models will then be used to design a new system with capability to actively compensate for effects of chemical reactions in the gas phase and on the wafer surface.

The second strategy for yield improvement is to add in-situ monitors to existing tools. Veeco will work with Sandia and Stanford to develop in-situ monitors for accurate substrate temperature measurement and growth rate monitoring of very thin layers (several nm in thickness). The tools will then be incorporated into the MOCVD control system for real time control of wafer temperature and layer thickness. Accurate measurement of wafer temperature is difficult at present, because the substrate (sapphire) is transparent at the wavelengths typically used for optical pyrometry. Longer wavelengths cannot be used because the gas ambient contains ammonia (precursor for nitrogen), which is not transparent at these longer wavelengths. Short wavelength pyrometers with high resolution will be developed as part of this program so that wafer temperature can be measured.

Growth rate is typically measured using reflectometry, however the minimum thickness that can be measured is several 100s of nanometers. The active (light emitting) layers of an LED structure are 10s of nm thick. Sandia will develop reflectometer technology that is capable of measuring the QW active regions of LED devices. This thickness information will be used to control the thickness (and therefore wavelength) of the active regions.

Sources of wavelength non-uniformity

- **Gas dynamics**
- **Wafer temperature**



Solution for Gas Dynamics:
Monitor growth rate and composition

Phase 1 – discrete monitoring
Phase 2 – scanning monitor
Phase 3 – scanning with feed-back control

Solution for Wafer Temperature
Monitor transparent wafer temperature

Phase 1- discrete wafer temperature feedback control
Phase 2 – scanning wafer temperature control with area optimization.

Figure XX+5 sources of wavelength non-uniformity and proposed solutions

We estimate that incorporation of new in-situ monitors combined with a new reactor designed using CFD+Chemistry models will decrease the cost to manufacture a blue/green LED wafer by over 50%.

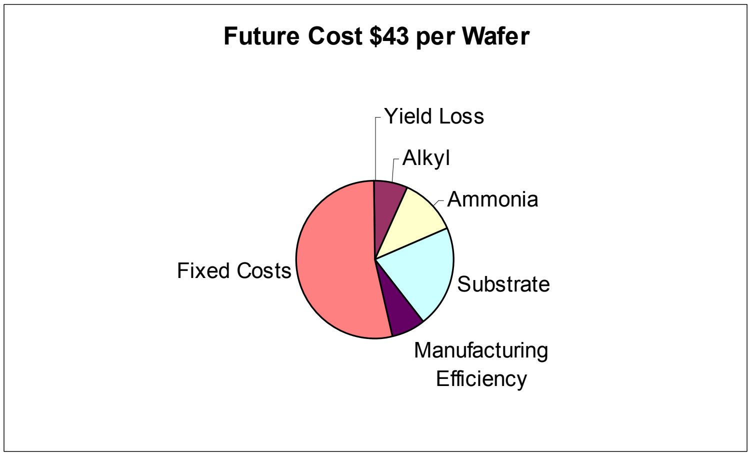


Figure XX+6 Wafer cost after completion of FALCON program.

4. Improved Diagnostics, Models, and Processes for InGaN growth

Since the late 1980's, Sandia National Laboratories has invested heavily in science and technology that is foundational to solid-state lighting. These include capabilities in compound semiconductor materials synthesis and processing, solid-state and heterostructure physics, and heterostructure design, fabrication and characterization. Sandia has been engaged in research on various aspects of Solid State Lighting (SSL) for over ten years. Sandia's formal involvement in solid-state lighting stems from Dr. Jeff Tsao and Dr. Jeff Nelson's co-authorship in 1998, with scientists from Hewlett-Packard, of the foundational white paper that outlined potential energy savings due to, and called for a national research initiative in, solid-state lighting.

In 2001 Sandia National Laboratories leveraged these capabilities and initiated a major four-year $8.1M Grand Challenge Laboratory Directed Research and Development (LDRD) project on solid-state lighting. The project established Sandia as the leading national laboratory in inorganic-materials-based solid-state-lighting science and technology. Managed by Dr. Jerry Simmons and others on the management and senior scientific team for the proposed EFRC, the project involved about 30 scientists, including many of the investigators on the current proposal. The project was extremely successful, and is one of the showcases within the history of Sandia National Laboratories' LDRD project portfolio.

In parallel with, and subsequent to, the Grand Challenge LDRD project, Sandia's management and scientific team has led and executed fifteen follow-on projects in solid-state lighting under DOE sponsorship. Three of these projects are particularly relevant to the work proposed here. These projects are: 1) "Development of key technologies for white lighting based on light-emitting diodes," a joint project with Philips Lumileds on novel substrates, quantum dot phosphors, and *in-situ* monitoring – resulting in the integration of advanced *in-situ* pyrometry onto Philips Lumileds' GaN epitaxial growth reactors, and an R&D 100 Award in 2004 for cantilever epitaxy; 2) "Precise temperature control using pyrometry during InGaN epitaxy" which demonstrated improved temperature control as well as better In incorporation using two different types of pyrometers; and a current program 3) "InGaN growth chemistry studies to optimize growth of green LEDs" which has the goal of understanding the influence of growth conditions and the chemical composition of the gas and surface on the In incorporation and efficiency of the resulting LEDs. The projects proposed here will build on this previous work and attempt to incorporate our pyrometry and chemical models into improved equipment and processes that are being developed by the industrial partners of FALCON.

Sandia National Laboratories will work in the following areas under the FALCON program. All of these areas are of interest to one or more of our industrial partners in FALCON. These areas are 1) MOCVD growth chemistry, 2) reactor design and optimization, 3) *in situ* diagnostics, 4) low dislocation GaN growth on m-plane AlN, and 5) development of nonpolar substrates using nanostructures. We will explore these areas as outlined below in collaboration with our partners in FALCON. All of these areas, as indicated in the previous discussion, are of importance to the rapid advance of technologies necessary for the production of solid state lighting.

4.1. MOCVD Growth Chemistry

4.1.1 Gas-phase chemical issues for InGaN MOCVD

Our previous research (DOE/EERE funded) demonstrated the importance of gas-phase nanoparticle formation during InGaN MOCVD conditions. Understanding the details of the chemistry for InGaN growth and being able to optimize the growth conditions should lead to improved InGaN materials and higher efficiency LEDs as well as higher utilization efficiency of the gases used in the growth process. Typical results for a light scattering experiment for the growth of InN in our research reactor are shown in Figure 4.1. One complication of this earlier work is that the light-scattering measurements were performed in an inverted stagnation-point flow reactor (ISPR), rather than in a commercial MOCVD platform, such as a rotating disk reactor (RDR). The ISPR was operated at conditions that should closely mimic the RDR gas-phase environment, so we are confident that the results are qualitatively "transferable" to the RDR platforms. However, for quantitative comparisons of the nanoparticle measurements to the InGaN composition and growth rate measurements it would be highly desirable if both types of experiments were performed in the same reactor platform. Existing commercial-grade MOCVD reactors typically have very poor optical access, particularly along the directions needed to perform the light scattering experiments. We will modify one of our Veeco D-125 reactors in order to conduct light scattering measurements of nanoparticles during InGaN growth. This will allow for direct comparisons with our extensive InGaN database we have developed in our D-125 systems. It will also facilitate InGaN MOCVD model development and validation for the commercial systems. There is a possibility that the complexity of the gas injectors in the D-125 reactors will make the nanoparticle measurements and analysis extremely difficult. So in parallel with the D-125 effort, we will also perform a similar set of experiments in our "research" RDR where we have more control and flexibility of the gas-injection characteristics. Our research RDR will also require some hardware modifications in order to be compatible with the light scattering measurements, and it will be necessary to establish at least an abbreviated InGaN growth "database".

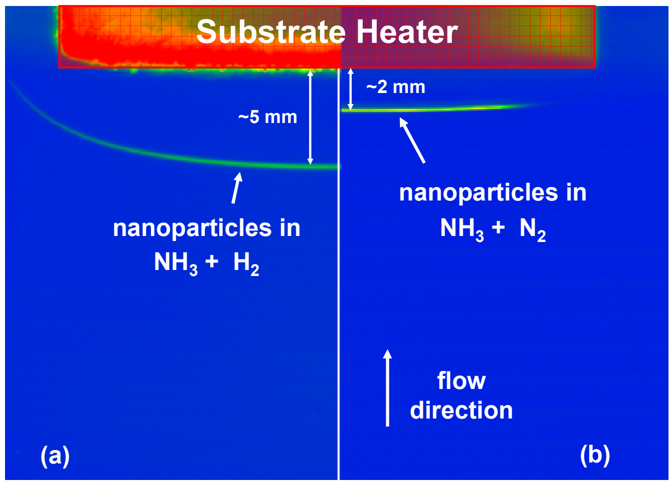


Figure 4.1. Laser illumination reveals a sharp layer of particles residing 5 mm (in H_2) and 2 mm (in N_2) from the heated surface during InN MOCVD near 800°C, 200 Torr (inverted stagnation point flow geometry). The outline of the heater has been highlighted with the red rectangle.

4.1.2 Chemistry models of particle nucleation and growth

Sandia has done a great deal of research into the role of parasitic (unwanted) gas-phase particles during AlGaN and GaN MOCVD. This work showed that a significant fraction of the group-III (Al, Ga) atoms that enter the reactor at the inlet never reach the deposition surface to grow the desired III-Nitride films. Instead, parasitic chemical reactions in the gas-phase were found to form nanometer-scale particulates. This work has recently been extended to InGaN and InN MOCVD conditions under DOE/EERE funding, which will end in 2009.

Sandia's research into the basic mechanisms of the particulate growth involved a close collaboration between theory and experiment. In order to understand the gas-phase nanoparticle formation chemistry we have performed chemically reacting flow calculations of the fluid flow (gas temperature and velocity fields), chemical reactions (TMG / TMI reactions and particle growth mechanism), and particle / species transport. Our modeling has been based on the Chemkin Suite of software (developed at Sandia, and now distributed commercially by a company called Reaction Design). We have used a previously developed in-house version of a stagnation-flow / rotating disk model (called SPIN) that included a crude particle formation and transport model.

The previous modeling work was significantly limited in two important ways. First, the physical model of the particulate nucleation and growth is very simplistic, employing a mean-field picture that calculates an average particle size and number density. However, the model yields nothing about the actual particle size distribution and, further, does not rigorously model particle transport within the flow field. Secondly, the SPIN software treats the MOCVD reactor using an "ideal-disk" approximation; that is, it treats the reactor as a 1-D, infinite-radius rotating disk or stagnation-flow reactor.

To overcome this first limitation, Sandia will work with Reaction Design to implement a more rigorous treatment of particle formation chemistry, tracking of particulate size distribution, and particle tracking. Reaction Design has recently developed this capability for their combustion modeling application codes with a new particle tracking module. However, this capability has not been ported to any of their chemical vapor deposition (CVD) codes. Sandia will sub-contract Reaction Design to make the necessary modifications in their particle tracking software to allow us to model particulate formation during nitride MOCVD. This will allow more rigorous comparisons between our chemistry modeling and Sandia's light scattering experiments described in Section 4.1.1, above.

4.1.3 Surface and thin-film chemistry of InGaN MOCVD

The limited thermal stability of InGaN films is often thought to be the dominant reason for the indium incorporation difficulties at temperatures above 700°. Recent observations of gas-phase nanoparticle formation indicate that there may also be a significant gas-phase component to this problem. One goal of a currently funded DOE/EERE project (ending in 2009) is to ascertain the relative importance of the surface and gas-phase processes at various operating conditions. In the current project we are using reflectometry at 405 and 550 nm to measure the thermal stability of ~30 nm InGaN films. For FALCON, we will use the advanced reflectometer developed in 4.3.3 to extend these types of measurements to much thinner InGaN films, hopefully achieving surface sensitivity.

4.1.4 Incorporate growth chemistry with reactor fluid flow / temperature modeling (collaborate w/ Veeco, start with existing Fluent code for D-125)

Detailed modeling of the gas flow and temperature fields using Computational Fluid Dynamics (CFD), has proven to be a very useful tool in designing and optimizing modern MOCVD reactors. Veeco has made extensive use of CFD modeling in developing their state-of-the-art rotating-disk reactors. They primarily have used a commercial CFD code called Fluent for this reactor modeling work. This modeling provides detailed descriptions of the complex 3-dimensional gas-phase fluid flow and temperature profiles within their reactors.

Most MOCVD reactor simulations, including those at Veeco and other major equipment vendors, concentrate on the fluid and thermal modeling but growth chemistry is treated very simply or not at all. However, Sandia has world-recognized MOCVD chemistry modeling capabilities developed over the last 25 years.

In partnership with Veeco, Sandia will work to incorporate the detailed chemical reactions (in the gas and at the growth surface) into CFD models of a commercial Veeco D-125 reactor.

Fluent also has the capability of including complex reaction chemistry (in the gas-phase and at the surface) in its simulation. In fact, Fluent has an optional module to include the Chemkin package, developed at Sandia National Laboratories, to handle the chemistry. This compatibility between Fluent and Chemkin will enable us to bridge the current gap between Sandia's current modeling efforts (simple 1-D geometries, using in-house software, but incorporating very detailed chemistry) with Veeco's current work (modeling complex 3-D reactor geometries, using commercially supported software, but employing very simple chemistry descriptions).

4.2. Reactor Design and Optimization

4.2.1 Optimization of existing reactors

Sandia has done much work to understand and quantify the parasitic chemistry that leads to nanoparticle formation during nitride MOCVD (discussed in the previous section). Sandia will use our newly developed InGaN model to optimize the operating conditions (e.g. pressure, flow rates, spin rates, etc) that improve yield. For instance, any condition that lowers the temperature dependence of indium incorporation will improve yield, provided the desired InGaN material properties are maintained. The modeling may also suggest some minor hardware changes to the reactor platforms.

4.2.2 Revolutionary reactor designs

Current state-of-the-art commercial nitride reactors are able to grow high-quality GaN, but there is still the potential for dramatic improvements in yield and manufacturability with the aid of CFD modeling. Sandia will pursue several different ideas for revolutionary designs of MOCVD reactors.

Initially two classes of reactor designs will be investigated. The first approach is to design a different gas-injection system that eliminates the need for injector screens that are currently used to ensure reactant mixing and uniformity. Such a screenless reactor would provide ultimate access for reactor diagnostics, which is discussed in the next section. It would also obviate the need to periodically clean the reactor injector and therefore increase reactor up-time.

The second revolutionary design is a reactor with an inverted geometry, i.e., reactant gas would enter from below with the heated substrate and wafer at the top of the reactor. Such a reactor could be beneficial in minimizing buoyancy-driven instabilities in the current reactor configurations, in which upwardly directed thermal convection is directed opposite to the incoming gas stream directed downward. For an inverted geometry, natural convection due to the heated substrate and forced convection from the inlet gas flow are both aligned upward, eliminating these inherent reactor instabilities. After extensive design and optimization work on these designs (as well as designs suggested by Veeco), Sandia and Veeco will jointly identify the most promising idea for a next-generation reactor with revolutionary improvements in manufacturability. In work performed at Veeco, with modeling support and proof-of-concept experiments from Sandia, a prototype reactor will be constructed and tested.

4.3. *In situ* Diagnostics

4.3.1 Adaptation of near-UV pyrometry to high-volume MOCVD systems

Irreproducible indium composition is a major cause of yield loss and is often due to inaccurate temperature measurements. In an earlier DOE/EERE-funded project Sandia adapted a near-UV (NUV) pyrometer to work on a Veeco D-125 platform (Figure 4.2). The NUV emissivity-correcting pyrometer (NUV-ECP) is one of two approaches that measure the true GaN wafer temperature, with the other being a mid-IR (MIR) method. The adaptation of the NUV-ECP onto a multiwafer reactor was non-trivial and required many reactor modifications and trade-offs in optical performance. Sandia will work with Veeco scientists and engineers in order to develop a robust NUV-ECP system that is also compatible with the hardware requirements of high-volume MOCVD systems.

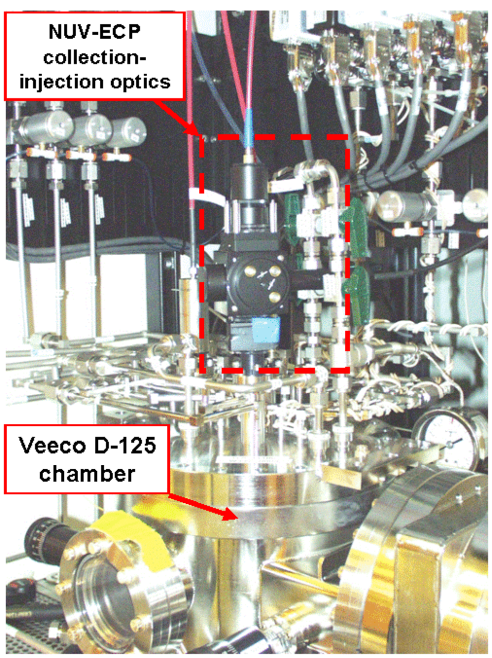


Figure 4.2. NUV-ECP installed on Veeco D-125 multiwafer MOCVD reactor

4.3.2 *In situ* measurement of wafer temperature non-uniformity

Wafer temperature non-uniformities also significantly affect yield, but until recently we didn't have a method of measuring the true temperature. Using our advanced MIR and NUV pyrometers we will investigate the extrinsic (e.g. wafer pocket geometry) and intrinsic (e.g. wafer curvature due to stress) causes of temperature non-uniformities. The MIR pyrometer appears to have the spatial resolution and signal-to-noise ratio necessary to perform this measurement at InGaN temperatures (700-800°C) with only a few modifications. The NUV pyrometer does not have the ability to do a spatially-resolved measurement at InGaN conditions, but it could be modified to do measurements at GaN conditions (e.g. ~1000°C). The MIR-ECP is, however, much more complex than the NUV-ECP, so we plan to try both approaches. Temperature profiles will be correlated with *in situ* wafer curvature measurements.

4.3.3 Optimized reflectometry for InGaN monitoring

Reflectometry is a standard method for monitoring GaN deposition, yielding growth rates, and qualitative characteristics of the buffer layer evolution process. It also serves as a component in most emissivity-correcting pyrometers. However, most reflectometers operate at wavelengths greater than 550 nm and have poor sensitivity for monitoring the growth of InGaN quantum wells. We will develop and test reflectometers at wavelengths (probably well into UV) that maximize the sensitivity towards InGaN quantum well detection.

4.4 Low Dislocation Density m-plane GaN on m-plane AlN Substrates.

Currently, all commercial III-Nitride LEDs used for solid state lighting are grown along the c-axis direction of the GaN wurtzite crystal. These devices suffer performance limitations that are intrinsically related to the polar nature of the GaN crystal along the c-axis. These limitations arise from the large, intrinsic electric fields resulting from the spontaneous and piezoelectric polarization present at the interfaces of the epitaxial layers making up a LED.

Fortunately, devices grown along a non-polar axis of GaN do not suffer from these internal electric fields and thus present a pathway to ultimately achieving higher output power and efficiency. LEDs grown on the m-plane of GaN (m-GaN) have been shown to be free of the polarization effects that plague commercial LED devices. Devices on m-plane GaN exhibit less shift in emission wavelength with drive current which would yield LEDs that have a more stable color rendering index. Nitride materials grown on the m-plane also exhibit higher hole concentrations, which ultimately would reduce the operating voltage of a LED and thus increase wall plug efficiency.

Unfortunately, in spite of years of research world wide, no viable approach has been reported that produces m-plane GaN substrates with commercially relevant areas (~ 2in diameter wafer). Current laboratory demonstrations of LEDs on m-GaN have been on substrates less than 1 cm^2. These m-GaN substrates are derived from cross sections of GaN wafers grown several millimeters thick along the c-plane. The roughly 4 mm x 10 mm cross sections are individually polished and have 50x less area than the 2in diameter wafers used for LED production today. This cross section technology is not a viable production method to realize the cost objectives necessary for the wide scale adoption of nitride LEDs for SSL.

We propose an alternative approach to producing large area, m-plane GaN substrates. This involves developing a method to grow a high quality m-GaN epilayer on m-plane AlN substrate. This substrate would then be used by commercial LED manufacturers to fabricate the higher performing, lower priced LEDs needed for SSL. This approach takes advantage of existing production methods for producing m-plane AlN substrates and well established MOCVD growth technologies. Crystal IS, the leading domestic producer of AlN substrates, is partnering with Sandia National Laboratories in this effort and describes their work on producing m-plane AlN substrates in another section of this proposal.

The performance of LEDs fabricated on m-GaN is directly related to the quality of the crystal structure, especially the density of threading dislocations and stacking faults. Sandia will conduct research to understand both the strain relaxation mechanisms and the associated formation and propagation of threading dislocations and stacking faults in heteroepitaxial layers grown on m-plane AlN. The goal of the studies is to provide the fundamental knowledge needed to develop schemes for reducing the density of threading dislocations in strain-relaxed epitaxial layers on m-plane AlN. This understanding will then be used to develop and test methods to produce m-plane GaN epilayers that have dislocations densities below $1x10^7$ cm^{-2} which will serve as starting platforms for improved InGaN LEDs.

This work will be divided into three tasks as follows:

4.4.1 Develop growth conditions (temperature, pressure, V/III, G-III flux etc.) that result in m-GaN and m-AlGaN epilayers on m-plane AlN with smooth morphology. Correlate material properties of epilayers and m-AlN substrates with growth conditions with a goal of producing specification for m-AlN substrates. (12 months)

4.4.2 Characterize threading dislocations, stacking faults and strain relaxation in epi-layers on m-AlN using various techniques such as cathodoluminescence (CL), transmission electron microscopy (TEM) and x-ray diffraction (XRD). (12 months, concurrent with 4.4.1 and 4.4.2)

4.4.3 Based on information from 4.4.1, develop approaches to enhance strain relaxation and reduce dislocation formation and/or propagation that result in m-GaN epilayers with dislocation densities below $1x10^7$ cm^{-2}. (24 months, starting after completion of 4.4.2)

4.5 Inexpensive Nonpolar GaN Substrates via Nanowire-Templated Growth on Sapphire

As mentioned above in section 4.4, LEDs based on nonpolar GaN orientations, including the (1-100) *m*-plane and (11-20) *a*-plane, are free from detrimental polarization-related internal electric fields, and thus have the potential to improve upon the efficiency of polar *c*-plane devices. Accordingly, research efforts in developing nonpolar InGaN/GaN LEDs have increased dramatically recently. Improvements in nonpolar LED performance over earlier results have been reported by the use of free-standing bulk *a*-plane and *m*-plane GaN substrates with low TDD (10^6 cm^{-2}), and confirm that low dislocation density material is necessary for high efficiency nonpolar nitride LEDs. Unfortunately, the size, availability, and cost of nonpolar freestanding bulk GaN substrates (about 5000 times more expensive than sapphire) is a serious barrier to the development and adoption of inexpensive and expensive nonpolar LEDs. As an alternative to the approach mentioned in section 4.4 above using AlN, we propose here to develop high quality nonpolar a-plane and m-plane GaN buffers on inexpensive sapphire substrates via a novel technique known as “nanowire templated lateral epitaxial growth,” or NTLEG. In the NTLEG technique, vertical GaN nanowire arrays serve as dislocation-free strain-relief templates for the lateral growth and nucleation of low dislocation density GaN. The NTLEG process is illustrated schematically in Figure 4.3. An array of aligned, dislocation-free GaN nanowires is first epitaxially grown on a substrate via metal-catalyzed vapor-liquid-solid (VLS) growth. Following growth of the aligned nanowire array, the growth conditions are then changed, *in-situ* and without the need to transfer the wafer to a separate chamber, to quench axial nanowire growth and nucleate GaN film growth at the top of the nanowire template until a continuous film is formed. The process is thus completed without the need for growth interruption or expensive patterning steps, providing a potential path to high quality nonpolar GaN at a cost comparable to direct GaN growth on sapphire substrates using standard nucleation layer techniques.

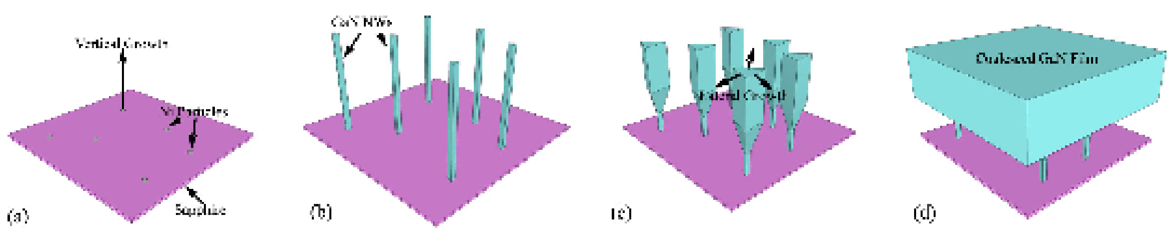


Figure 4.3. Primary steps in the NTLEG process scheme

The NTLEG process differs fundamentally from and enjoys several advantages over current ELO schemes. In the NTLEG process the nanowire templates act as 3D-compliant nanoscale features, or “bridges”, that connect the epilayer and underlying substrate, making possible a reduction in defects by minimizing the strain energy in the epilayer, a theory also known as nano-heteroepitaxy. Additionally, the VLS-grown nanowire arrays provide an essentially dislocation-free template, as they are not bound by epitaxial lattice mismatch constraints as are two dimensional films, and can relax in the lateral direction. Another advantage of NTLEG is that the technique may eventually enable growth of high quality GaN on inexpensive Si substrates, providing a breakthrough technology that could further reduce SSL costs and accelerate their penetration into the marketplace. This could also enable same-chip integration with Si-based device technology leading to a new class of advanced optoelectronic devices.

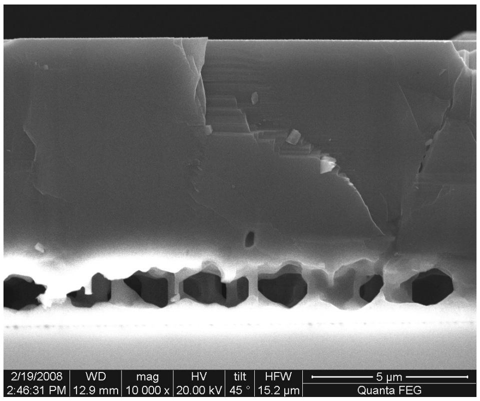


Figure 4.4. Fully coalesced NTLEG *a*-plane GaN film suspended on sapphire by nanowire bridges.

We were recently able to successfully demonstrate proof of concept of the NTLEG technique to produce nonpolar *a*-plane GaN from highly aligned, vertical nanowire arrays on *r*-plane sapphire. Full coalescence of the nanowire arrays was achieved resulting in flat, *a*-plane NTLEG GaN films, as shown in Figure 4.4. Due to the [11-20] orientation of the vertically aligned nanowires, a nonpolar (11-20) *a*-plane orientation results in the coalesced NTLEG film. Based on TEM analysis of preliminary *a*-plane NTLEG GaN films, stacking fault (SF) and threading dislocation densities (TDD) of $\sim 1.5\times10^{5}$ cm^{-1} and $\sim 1\text{-}2\times10^{9}$ cm^{-2} were achieved, respectively. This compares favorably with previously reported SF densities of $4\text{-}7\times10^{5}$ cm^{-1} and TDD of $\sim 3\text{-}7\times10^{10}$ cm^{-2} for *a*-plane GaN grown on *r*-plane sapphire using a low temperature nucleation layer. Thus, the TDD of our preliminary *a*-plane GaN NTLEG films are ~30-50 times lower than reported using standard nucleation layer techniques. We note that since these results represent initial NTLEG samples, we expect significant further improvements as we optimize the NTLEG process and film quality. In addition to nonpolar *a*-plane GaN on *r*-plane sapphire, we will also demonstrate and optimize the growth of nonpolar *m*-plane GaN films on *m*-plane sapphire using the NTLEG technique. We believe that the large majority of performance gains from reducing TDD can be achieved by material in the low 10^{8} cm^{-2} to mid 10^{7} cm^{-2} range, based on the performance of *c*-plane LEDs grown on sapphire. Thus, we believe that this represents an attractive TDD milestone target for nonpolar *a*-plane and *m*-plane GaN buffers that can be achieved with the NTLEG technique over the funding period, and that this material will be suitable for high efficiency nonpolar LEDs. To establish the overall quality of the *a*-plane and *m*-plane nonpolar NTLEG GaN layers and to help optimize the NTLEG growth process, we will use a combination of structural, optical, and electrical characterization tools, including scanning and transmission electron microscopy, photoluminescence and cathodoluminescence, atomic force microscopy, and x-ray diffraction.

The growth of a- and m-plane GaN layers by NTLEG will be divided into two tasks as follows:

4.5.1 Growth and characterization of NTLEG a-plane and m-plane GaN films with dislocation density targets of $\leq 5\times10^{8}$ cm^{-2} and $\leq 1\times10^{9}$ cm^{-2}, respectively. This first task will take place over the first 18 months of the project.

4.5.2 Improved growth and characterization of nonpolar NTLEG GaN films with dislocation densities targets of $\leq 1\times10^{8}$ cm^{-2}. This second task will take place over the remaining 18 months of the project.

5. Quality substrates for high efficiency GaN LEDs

Project Objectives:

Large diameter, high quality III-nitride substrates are needed to take advantage of recent work demonstrating high efficiencies at high current densities in near UV and visible light emitting diodes (LEDs) when fabricated on low defect substrates, particularly non-polar substrates. Crystal IS has developed a cost-effective approach to the growth of large diameter aluminum nitride boules and is working with Philips Lumileds and with Sandia National Laboratories to develop approaches to grow high quality GaN templates on these substrates and test their efficacy for high efficiency, high brightness LEDs. Under the proposed project, we will develop a cost-effective approach to grow large aluminum nitride (AlN) single-crystal boules along the non-polar direction. These boules will be processed to produce 2-inch diameter, non-polar AlN substrates which will be used to prepare high quality (low dislocation density) GaN epitaxial layers in collaboration with Sandia National Laboratories. The key objective of this proposal is to demonstrate 2" diameter, cost-effective substrates of non-polar GaN/AlN with a dislocation density below 10^{6} cm^{-2} and with no stacking faults.

Technical Approach

Technical Approach and Anticipated Outcomes and Results

Approach to growing non-polar 2" diameter boules

We propose an integrated and innovative program to develop large diameter, cost-effective non-polar substrates with very low defect density. We are currently investigating seed preparation and seed mounting. During the FALCON program, we will build on these initial efforts to produce large diameter boules of AlN and then produce substrates that are satisfactory for large volume production of LEDs.

Stability/Control of non-polar bulk growth

Critical to commercial production of large diameter, nonpolar substrates will be the ability to grow large diameter AlN boules with high yield. Under the FALCON program, we propose to optimize the baseline control parameters to enable stable growth in a 2-inch crucible geometry. A metric for this task is the demonstration of greater than 5 mm stable growth on a non-polar seed without increasing bulk defects compared to the seed material. Special techniques applied at this stage include:

- Thermal modeling
- Characterization of the growth zone by thermocouples and optical pyrometers
- RGA to monitor hot zone gas species

A global thermal model of our growth system will be a significant aid in understanding the thermal environment and in optimizing specific growth conditions required for the growth of non-polar AlN bulk crystals. Using state-of-the-art simulation packages we have established an in-house modeling capability at Crystal IS, supported by personnel with an internationally recognized expertise in the field of numerical simulation of high temperature crystal growth processes. We have already successfully applied this modeling capability to improve our c-axis AlN growth process. Using simulation will significantly speed up design cycles and the testing of materials with different thermodynamical properties.

For the characterization of the thermal field during AlN growth, we have developed a novel protective shield, made of hafnium oxide (HfO_2), for the thermocouple (TC) probes. These shields are compatible with the Al-vapor, which is always present in the growth system and which can rapidly deteriorate standard probes in this environment. To achieve stability of the non-polar growth face, we expect a precise temperature control of the seed and source to be critical to avoid parasitic nucleation of different crystal orientations. The use of TC probes at different points of the growth system will also allow us to feed this information back to our simulation effort for further optimizations of the growth zone. Additionally, optical pyrometers will be used to measure apparent surface temperatures and will be correlated with TC data.

The c-axis orientation with aluminum polarity of AlN has the lowest free energy which makes this orientation the most stable. When growing non-polar we will determine how to suppress parasitic grain formation during ramp up and spontaneous nucleation during growth. To control undesired grain nucleation we anticipate using the following approaches:

- Controlling the partial pressured of the growth cell gasses to decrease the likelihood of secondary grain and defect formations (RGA monitoring multiple species gas flow).
- Active heat flow management to enhance axial growth rates, minimizing lateral overgrowth from parasitic nuclei based on anisotropic growth rates.

Optimal non-polar or semi-polar growth conditions
Closely related to the favorable orientation of the seed plate we will determine a favorable growth regime (temperature, temperature gradients, gas species, partial pressure etc.). We will develop the necessary control conditions to sustain non-polar growth for the full growth cycle, accounting for any change of thermal conditions during the run.

<u>Collaborators on Substrate Development Project</u>

Crystal IS will work closely with Sandia National Laboratories and with Philips on this project. Sandia will develop approaches to grade an epitaxial from pure AlN to GaN while maintaining a low defect density. Philips will evaluate the 2” diameter (or larger) GaN template wafers for improved manufacturability of high performance LEDs.

Scientific Merit

In today's solid-state lighting technology, III-nitride LEDs are fabricated on c-plane substrates of either sapphire or on SiC. However, due to the belief that the piezoelectric effect has a deleterious effect on both laser and high performance LED performance due to the quantum confined Stark effect (QCSE), there have been substantial efforts in fabricating both devices on non-polar or semi-polar substrates. Recently, two groups have announced 400 nm range lasers on M-plane GaN substrates[i]. Prior to 2007, growth of epitaxial layers on a-, m- and semi-polar orientations have been almost entirely investigated on foreign substrates such as r-plane sapphire to obtain a-plane GaN[ii] or m-plane SiC to obtain m-plane GaN[iii]. The quality of these layers has not been good despite using techniques such as epitaxial layer overgrowth (ELOG), since stacking faults in excess of 10^5 cm^{-1} are present[iv]. In order to overcome this difficulty, a- or m-plane GaN obtained from slicing a c-plane boule, produced by thick hydride vapor phase epitaxy (HVPE), has been used to obtain both low dislocation and stacking fault density[v,vi]. These, relatively low defect, non-polar GaN substrates have been the source of all recent non-polar optoelectronc device successes. However, the size of these a- and m-plane GaN substrates has been limited to 10 mm × 20 mm (and are generally half this size), due to the difficulty in growing thick layers by HVPE. In addition, the cost per unit area of these substrates is very high and will likely remain high given the relatively low growth rate of the technique and the amount of special handling required. We believe that m-plane boules can be directly grown by sublimation, in a similar manner to the c-plane boules that are currently being produced by Crystal IS, and up to 50 mm in diameter. This approach, if successful, will provide a much lower cost non-polar III-nitride substrate.

Production process of 2" AlN wafers

Under the FALCON project, we will focus on developing a robust and high yielding growth process for the commercial production of non-polar 2" AlN wafers. Along with a further reduction of bulk defects, this development effort will specifically target the increase of wafers per boule and a reduction of wafer costs. Combined optimization efforts in the growth area, wafering and polish operations will be necessary to achieve this goal.

We will create a self-sustaining crystal growth process, which is used both for 2" wafer and 2" seed production. The growth conditions will have to be optimized to allow for a very repeatable and homogeneous nucleation over a full 2" diameter and a stable non-polar growth over an increased boule length. The ultimate milestone of this project will allow approximately 15 × 2" m-plane AlN wafers to be produced per boule. The wafer quality and yield will be the key metrics in this phase. We expect this to be a three year effort.

How the Proposed Project with impact the FALCON Mission

It has been understood by the nitride semiconductor community for some time now that the non-polar orientation might offer significant advantages to high power, high efficiency LED manufacture. In particular, the lack of large electric fields due to the piezoelectric effect from strain and due to the spontaneous polarization across interfaces in the non-polar orientation, means that wider quantum wells can be used without the quantum confined Stark effect (QCSE) significantly reducing the internal quantum efficiency (IQE). These wider quantum wells should allow higher current densities with high efficiency resulting in much brighter LEDs. However, it has proven difficult to take advantage of these predictions because of the poor quality of non-polar materials. In particular, a wider quantum will not do any good if the defect density is high since a wider quantum well will simply increase the non-radiative recombination rate resulting in decreased efficiency. Result successes for non-polar devices have only been achieved because of the superior quality of non-polar III-nitride substrates that have recently become available.

However, it will not be possible to take advantage of this new approach to obtaining much higher IQE at high current density unless a cost effective approach is developed to provide large diameter III-nitride substrates. This need is addressed by this proposal.

Comparison of the proposed approach to current SSL device technology

Present commercial III-N LED crystal growth relies on polar growth (along the c-axis) on foreign substrates such as sapphire or SiC. Such structures exhibit relatively high densities of extended defects such as dislocations (>$1x10^8$ cm^{-2}) and, in addition, have large electric fields generated across the semiconductor interfaces due to the piezoelectric effect and spontaneous polarization. These large electric field cause the electrons and holes to be separated in the quantum well (quantum confined Stark effect [QCSE]) which decreases the radiative efficiency of these devices. Using narrower quantum wells is a successful way to overcome the problem associated with the QCSE but narrow quantum wells also reduce efficiency of the device at high current density as a result of the higher carrier concentration in the quantum well. This observation is consistent with current $In_xGa_{1-x}N$ LED technology which loses efficiency at high current densities. However, high power, high efficiency LED chips are needed since they will lead to an overall reduction in $/lm in the LED white lighting market. With high power, high efficiency, fewer high power LEDs will be required to achieve the desired radiometric power or radiance (depending on the application) leading to cost savings in chip processing, packaging and fixturing.

Calculation of estimated cost and efficiency benefits

<u>Current position for low defect density, non-polar nitride substrates</u>

Current non-polar nitride substrate prices are just not cost effective for this SSL application at several thousand dollars for low defect substrates and it is simply more cost effective to use several low power, white LEDs built on c-face oriented substrate to achieve the required luminescence. However this approach is limited due to the additional packaging costs involved and will not result in the significant long-term reductions in cost of lumens from SSL that are potentially possible with the availability of non-polar substrates. However, this requires that an approach be developed which is capable of delivering high quality non-polar substrates at much lower cost.

The current non-polar nitride substrate market consists of quasi-bulk growth on a foreign substrate and then slicing along the c-axis.

Quasi-bulk GaN growth takes advantage of the HVPE process on a foreign substrate (usually sapphire or GaAs), where HVPE thicknesses are up to 10mm and the GaN is sliced into multiple substrates along the c-axis. Currently, this process suffers from very low yield and the quality of the GaN varies as one moves along the c-axis on the substrate. Cost reduction is limited by the low growth rate needed to produce high quality crystal. In addition, the process will always remain inefficient in that excess Ga will need to driven past the sample (while recovery efforts can be put in place, they will add extra cost). The cost of Ga is going to remain fundamentally higher than that of Al which is much more abundant. While Ga remains needed in the device layer itself, it is not needed in the substrate. Finally, the cost is going to remain high because of the extra handling that is required by this approach. All other successful semiconductor technologies have benefitted from the development of large bulk crystals of the same semiconductor material which can be rapidly processed into high quality substrates.

The sublimation-recondenstion method of growth, as employed by Crystal IS has only been demonstrated for the growth of AlN, but is more akin to a standard semiconductor substrate growth process which uses a native seed crystal to form long very low defect boules of AlN, with EPDs normally in the region of $10^2/cm^2$. These boules are then sliced and polished into many substrates. The process can lead to an inherently lower cost substrate from the other techniques mentioned above due to higher growth rates and longer boules. Although GaN growth has not been demonstrated by this method, epitaxial layers of GaN (~2µm thick) can be grown on the AlN substrates with EPDs in the region of $10^5/cm^2$.

Current pricing of AlN substrates is also high and is in the region of $8,000 for 2-inch substrates. Pricing is currently high due to the immaturity of the process and the low volumes manufactured for commercial sale. Immaturity of the process leads to very low yields, both at a crystal growth level and through the substrate manufacturing process of cutting and polishing. Low volumes and high development levels lead to very high overheads. The combination of low yields and high overheads lead to a substrate price which cannot be competitive in the white lighting market.

Price Roadmap

Prices will drop dramatically initially and we expect to $1,000 when volumes increase from the current level of 10 per month to ~500 2-inch substrates per month. This price drop comes about from yield improvements, both in the boule growth and in the substrate manufacturing process and from cost reduction in the boule process. Yield improvements are expected as the process starts to gain some level of maturity. Cost reduction mainly comes from a reduction in consumable costs, which comes from improved utilization through more production experience. Crystal IS currently has a roadmap to reach this roadmap within the next 2 years.

Further cost reductions will be realized as the monthly wafer volumes are increased as shown in the diagram below. We do not believe that there should be any significant difference in the price between polar and non-polar AlN substrates if this project is successful.

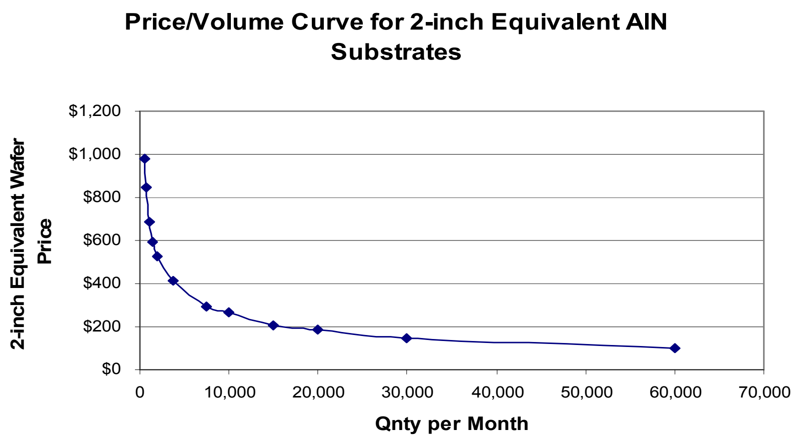


Fig. 1

The graph (Fig.1) shows price erosion for 2-inch equivalent AlN substrates, as the volume increases beyond 500 2-inch wafers per month. At this point, price reduction is realized through a transfer of the process from 2-inch diameter substrates to 3-inch diameter substrates, which will increase productivity of the manufacturing process. In addition, as substrate volumes increase beyond 500 2-inch equivalents per month, more of the business focus is directed to manufacturing and less to research and development; this will lead to a reduction in overhead. Overhead will continue to drop as the volume continues to increase and the focus shifts more and more toward high volume production.

During the initial introduction, we expect the production yields to drop, both for the boule growth and the substrate manufacturing. This does not lead to an increased 2-inch equivalent price however, because of the increased efficiencies gained from transferring to 3-inch production. As 3-inch volumes increase, the yield will recover through product maturity. This gives rise to a sharp drop in price to ~$350 per 2-inch equivalent at 5,000 2-inch equivalent wafers per month (~$790 per 3-inch wafer at a volume of 2,250 per month).

At approximately 1,000 2-inch equivalent wafers per month, we will begin to drop the net profit margin based on simple revenue/profit business assumptions. As overhead drops, we anticipate a gross margin of ~40% with a net profit of 7% at 10,000 2-inch equivalent wafers per month. Gross margin continues to drop, but at slower pace, to 60,000 2-inch equivalent wafers per month, where we anticipate the gross to be 35%, with a 5% net profit.

Manufacturing improvements will be realized as the volume continues to increase from ~2,000 2-inch equivalent wafers per month, which include cost reductions through improved efficiency and volume procurement of consumable parts, and increased productivity gained from increasing the boule length. Increasing the boule length allows better productivity both through crystal growth and substrate processing, as sawing efficiency will be maximized with the use of high capacity, multiwire, diamond slurry saws.

Cost reductions, yield improvements, production efficiency gains and reductions in gross margin will lead to eventual 2-inch equivalent prices of $200 at 15,000 2-inch equivalent wafers per month and $100 at 60,000 2-inch equivalent wafers per month.

Previous and On-going Related Work

NIST ATP program to develop 2” diameter AlN substrates

In September, 2007, we finished a NIST ATP program named “Process for Growing Large, Single Crystal Aluminum Nitride”. Some of the key goals of this Program included developing of 2” diameter AlN substrate, increasing crystalline quality, and demonstrating deep UV optical transparency. Fig. 2 shows a crack-free two-inch AlN substrate cut from bulk crystal. Bulk AlN single crystals were grown using proprietary sublimation-recondensation technique. The boules are then sliced into 2” wafers which are polished to obtain subsurface damage-free, epi-ready surfaces.

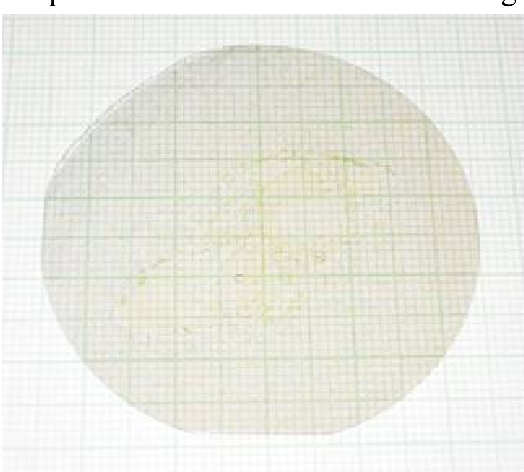
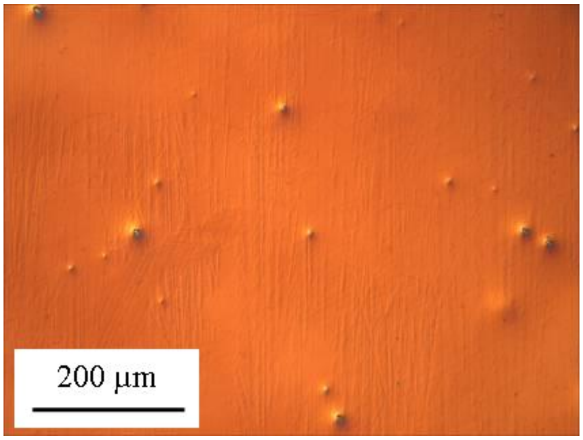
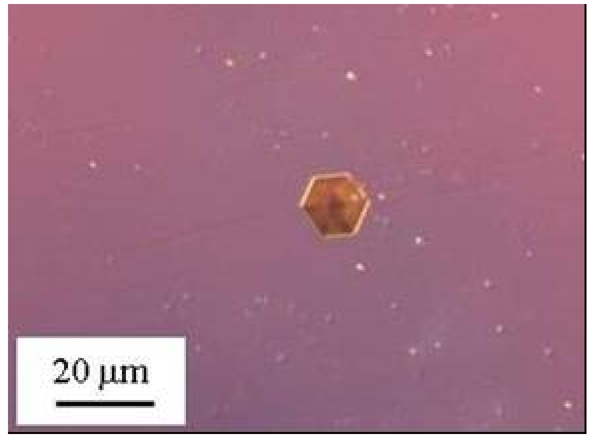


Fig. 2: A 2” AlN single crystal substrate

The crystallinity of these wafers was verified by a measuring the full width at half maximum (FWHM) of x-ray rocking curves. The FWHM of the symmetric (0002) and asymmetric scans $(10\overline{1}\overline{4})$ were found to be 65 and 83 arcsec, respectively indicating high crystallinity and low dislocation density. Further improvement and development of the 2” AlN substrates involves reducing the low-angle grain boundaries as well as increasing the single-crystal area of the substrate.

The dislocation density of the 2” AlN wafers were measured by EPD evaluation. Dislocations and other growth induced defects in AlN can be decorated using preferential chemical etching based on KOH melts and solutions. Figure 2 demonstrates etch pit pattern on the Al-face of AlN produced using two different techniques.





a b

Fig. 4.1.2: Etch pits revealed on the Al-face of AlN: a) after KOH enhanced CMP slurry treatment, EPD ≈ 4x10^3 cm^{-2}, and b) KOH-NaOH eutectic melt, 450ºC, 5 min, EPD ≈ 2x10^3 cm^{-2}.

The UV optical transparency of the AlN substrates was shown to be less than 50 cm^{-1} in the 210 – 280 nm range and even lower at longer wavelengths. The main obstacles that we overcame were maintaining the purity the source material and achieving very low Oxygen content (< 10^{18} cm^{-3} as measured by SIMS) in the AlN single crystals.

DOE Program to develop GaN-ready c-face AlN substrates

We recently started a DOE SSL program titled "GaN-ready aluminum nitride substrates for cost-effective, very low dislocation density III-nitride LEDs". The goal of this program, in which we teamed up with Philips Lumileds Lighting Company, is the development of cost effective, "GaN-ready" substrates by growing graded $Al_xGa_{1-x}N$ epitaxial layers on 2" diameter AlN substrates which will terminate with an unstrained GaN layer. The AlN substrates are sliced from bulk c-face crystals which can be produced at relatively low cost and have threading dislocation densities below 10^4 cm^{-2}. Recent work has demonstrated that it is possible to grade the lattice parameter of the AlN to a pure GaN layer with a threading dislocation density below 10^5 cm^{-2} even though the lattice parameter mismatch is 2.4%. The efficacy of the GaN-ready substrates will be tested by growing appropriate epitaxial $In_xGa_{1-x}N$ structures on top for state-of-the-art blue LEDs. These LEDs are expected to have threading dislocation densities below 10^6 cm^{-2} and will be compared to state-of-the-art blue LEDs grown on sapphire which have threading dislocation densities greater than 10^8 cm^{-2}. Most significantly, this project will determine the effect of lower dislocation density on the internal quantum efficiency (IQE) at both high and low current densities as well as assessing the efficacy of lower dislocation density on improving the lifetime of the LEDs.

Finally, approaches will be developed to obtain improved photon extraction from $In_xGa_{1-x}N$ LEDs grown on GaN-ready substrates. This will be a two-pronged approach. The first will consist of reducing the optical absorption of the AlN substrate in the 400 to 500nm wavelength range from its current typical value of 10 cm^{-1} to less than 1 cm^{-1}.

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The second will consist of designing and demonstrating appropriate substrate etching techniques which will result in improved photon extraction.

Cost

We estimate that this will be a 3 year project and are requesting $2M from the FALCON program. The total cost for developing high quality 2" diameter non-polar AlN substrates suitable for commercial deployment for LED production is estimated to be $10M. The FALCON project will be heavily leveraged with funds from commercial activities and from private-sector investment.

References

[i] Continuous-Wave Operation of m-plane InGaN Multiple Quantum Well Laser Diodes, K. Okamoto, H. Ohta, S.F. Chichibu, J. Ichihara and H. Takasu, Jpn. J. Appl. Phys., vol .46, n. 9, L187 (2007).

[ii] Structural characterization of nonpolar (11-20) a-plane GaN thin films grown on (1-102) r-plane sapphire, M.D. Craven, S.H. Lim, F. Wu, J.S. Speck and S.P. DenBaara, Appl. Phys. Lett., vol. 81, no. 3, 469 (2002).

[iii] Stability of (1-100) m-Plane GaN films Grown by Metalorganic Chemical Vapor Deposition, B. Imer, F. Wu, M.D. Craven, J.S. Speck and S.P. DenBaars, Jpn. J. Appl. Phys., vol. 45, no. 11, 8644 (2006).

[iv] C. Chen, J. Yang, H. Wang, J. Zhang, V. Adivarahan, M. Gaevski, E. Kuokstis, Z. Gong, M. Su and M. A. Khan, Jpn. J. Appl. Phys., vol. 42, L640 (2003).

[v] Optically pumped GaN/AlGaN separate-confinement heterostructure laser grown along the (11-20) nonpolar direction, H. Teisseyre, C. Skierbiszewski, A. Khachapuridze, A. Feduniewicz-Zmuda, M. Siekacz, B. Lucznik, G. Kamler, M. Krysko, T. Suski, P. Perlin, I. Grzegory and S. Porowski, Appl. Phys. Lett., vol. 90, 081104 (2007).

[vi] High-quality bulk a-plane GaN sliced from boules in comparison to heteroepitaxially grown thick films on r-plane sapphire, T. Paskova, R. Kroeger, S. Figge, D. Hommel, V. Darakchieva, B. Monemar, E. Preble, A. Hanser, N.M. Williams and M. Tutor, Appl. Phys. Lett., vol. 89, 051914, (2006).

6. Yield management, process manufacturing for GaN LEDs

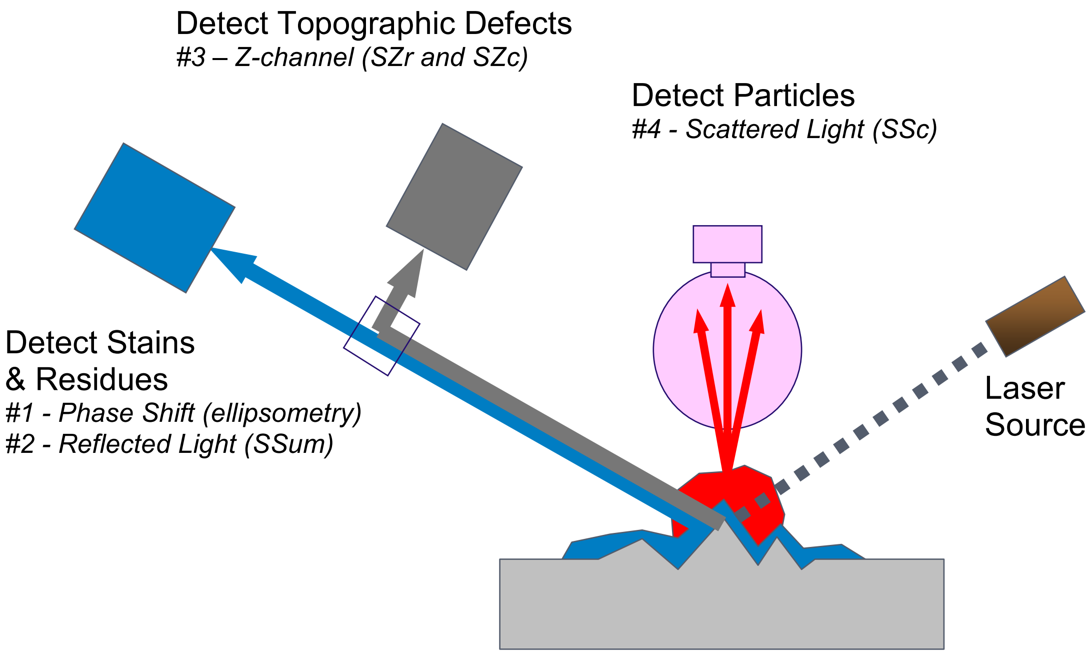
KLA-Tencor has served the silicon microelectronics since 1976 with yield management tools used to maintain high manufacturing yield, improve process development times, and accelerate the ramp of new facilities and new products in that industry. KLA-Tencor has recently begun to serve the LED lighting industry both with the adaptation of the CS20 Candela compound semiconductor wafer inspection tool to the solid state lighting market and through the recent acquisition of ICOS in Leuven, Belgium and its WI-2200 diced wafer inspection tools. Both tools have been developed primarily for the silicon semiconductor market and have been adapted to the GaN LED semiconductor manufacturing process albeit with drawbacks in performance for the lighting manufacturers.

The CS20 tool is a low resolution rotary stage tool capable of monitoring stains, residue, particles, and additionally can be used to map killer micropipes in sapphire substrates as shown in Figure 6-1. Typically a laser (either 780 nm, 635 nm, or 406 nm) is applied depending upon application. The laser spot size at the wafer plane is of order 4 microns by 8 microns and as call be seen in Figure 6-2 monitoring scattered light from the top surface and correlating it to light scattered from the bottom surface can be used to display a characteristic signature for a killer micropipe in such a wafer. Software has been written for this tool which allows binning of the defects for each wafer scanned according to signature as either a stain, residue, scratch, micropipe, variation in film thickness, etc.

The CS20 tool has already been adopted at several LED manufacturers. The tool is being used to a) perform quality control on sapphire substrates rejecting those with high concentrations of micropipe killer defects, b) monitor wafers prior to and after growth and film applications to locate key operations in the fab that generate unacceptable levels of particulate contamination, and c) monitor film growth to establish production conditions that consistently result in higher value (more efficient, tighter wavelength control, etc.) properties for LEDs and thereby upgrading overall product value and price.

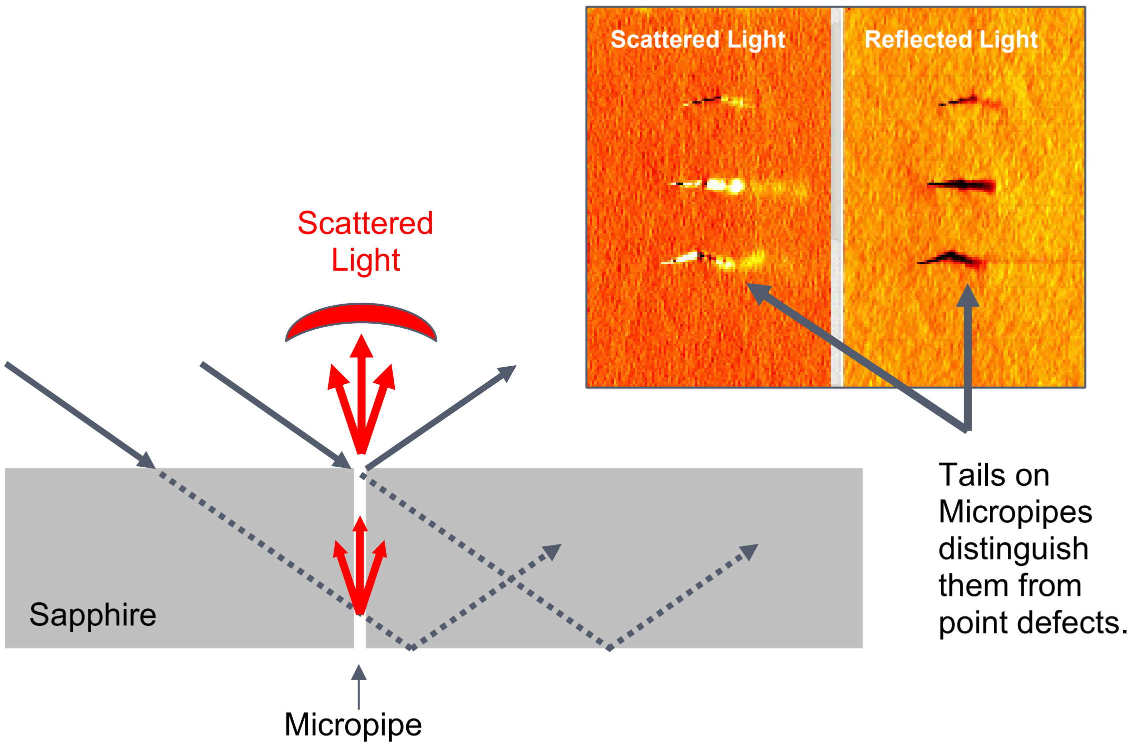
The CS20 tool has already resulted in substantial LED production cost reduction. However, additional savings can be achieved by added development of this tool specifically for the LED industry. The first of these would be to improve the sensitivity of the tool to micropipe size. Many manufacturers have stated that improving the sensitivity to 0,5 to 1 micron will result in significant added benefits in improving product quality. The current moderate sensitivity product, with sensitivity to about 3 micron micropits, has already resulted in a reduction of manufacturing costs sufficient for the tool to recoup its purchase price within 6 months simply through the monitoring of incoming sapphire for being “epi ready” and by providing substrate cleaning monitoring.

Figure 6-1. Four detection channels within the CS20 tool allow the laser light to be analyzed at each location to measure total scattering from the surface (channel #4), reflected light (channel #2), light phase shift/ellipsometry (channel #1), or topographic features (channel #3). Oblique laser illumination is applied to an unpatterned wafer and each channel is mapped as a function of radius and angle.



A related improvement to the CS20 tool would be to replace the rotary stage with a Cartesian stage. This would allow the tool to be used to monitor diced die and therefore improved process control at additional fabrication steps. Additional value could be provided if the tool were designed to identify defects which are critical in later stages of the process. An example of these additional defects might be to identify defects which occur (and these are important killer defects) in the GaN films after laser liftoff is used to separate the substrate from the GaN films on die which have been bonded to submounts. Laser liftoff has been found to be a key step in improving the outcoupling of light from the high index GaN LEDs. The added outcoupling is a result of the extraordinary roughening of the GaN film surface which occurs during the liftoff process. The steep angles on the roughened surface substantially reduce the internal reflection at the surface of high angle light rays and can improve light outcoupling substantially. The defects that occur in the film however a) occur in substrates which are patterned and require x-and y-Cartesian stages for inspection b) require extremely good registration of the stage to the diced die in order to perform die-to-die subtraction to defect “excursions” c) require imaging modes capable of detecting the defect of interest, namely, they must be able to identify the defect which is within a micron of the light scattered at the surface and d) algorithms must be written which can sort and bin the liftoff epi defects of interest from the sea of surrounding nuisance defects such as die dimensional variation, color variation due to varying film thicknesses from die to die and so forth. In summary, substantial work needs to be done to modify this tool to optimize its value to the emerging LED lighting industry. The proposed upgrades will enhance its capability in detecting killer micropipe defects, enable the tool to perform post dice inspections for defects related to chipping, blocked vias, improperly aligned insulator features, and finally enable its ability to automate the detection of subsurface scattering defects created by laser lift off.

Figure 6-2. Scattered light from the upper surface as measured in the scatterometer and from the bottom surface as measure from channel #3 can be used to display the characteristic signatures of killer micropipes



The proposed milestones for yield management enhancement are given as milestones M6.1-M6.6 below.

M6.1: Engineering conceptual design complete for LED yield management tool. Design to include improved motion control, upgraded sensitivity from CS20, improved autofocus, possible review mode optics, and improved software for high nuisance environment LED diced chips. Software to include binning for defects of interest. (9/30/10)

M6.2: Key engineering subsystems specified, ordered, and tested at the manufacture. Key subsystems to include motion control stage, imaging optics, sensors, autofocus subsystem, and image computer. (6/30/11)

M6.3: Alpha tool mechanical assembly. Initial data to verify optical performance in static mode (non-scanning), sensitivity, and autofocus operational specifications achieved. (9/30/11)

M6.4: Alpha tool operated in serpentine scanning mode on test wafers. Initial software tests to verify defect capture on defects of interest to customer. Capture rate versus defect size characterized. Imaging modes upgraded. (1/31/12)

M6.5: Software modifications to achieve binning on defects of interest. (5/31/12)

M6.6: Initial testing at customer site for yield management at the following customer manufacturing points: a) incoming substrate qualification, b) post epi film inspection c) post dicing die to die inspection, and d) post lift off die inspection. (9/30/12)

7. In line monitor for indium rich InGaN device growth

One of the most difficult problems in LED film deposition is the growth of LEDs that emit light in the green region of the electronmagnetic spectrum. In general, LEDs are manufactured from indium gallium nitride ($In_XGa_{(1-x)}N$)(wherein X varies as indicated below and is deleted for simplicity hereafter). Indium compositions of only a few percent are required for "blue" LEDs. However, indium content from ten to twenty percent is required for bandgaps that provide light in the green region of the electromagnetic spectrum. As used herein, this content percentage of indium is referenced as "indium rich" InGaN.

Unfortunately, it is well known that indium rich InGaN quantum wells do not grow with uniform film composition. Due to the difference in surface mobilities, strain between the indium rich InGaN quantum wells and its corresponding GaN confinement layers, and other physical considerations, the indium rich InGaN material generally exhibits "clustering" of the indium. Namely, the quantum well is no longer homogeneous in indium composition but instead exhibits a film of widely varying indium composition. Individual indium clusters are generally formed with characteristic diameters of the order of 10nm each.

Numerous studies have been reported to understand the detailed nature of the clustering and its effect on device performance. It is generally agreed that clustering severely affects device performance with the result that "green" LEDs are 3-5 times less efficient than "blue" or "red" LEDs (wherein efficiency can be measured by Lumens Out/Watts In). This effect is called the "green gap" in the LED industry. This severe reduction in internal quantum efficiency for green devices severely constrains white light LED brightness, color balance, and thermal packaging considerations for all applications in which three primary color LEDs (i.e. green, blue, and red) are used to generate "white light".

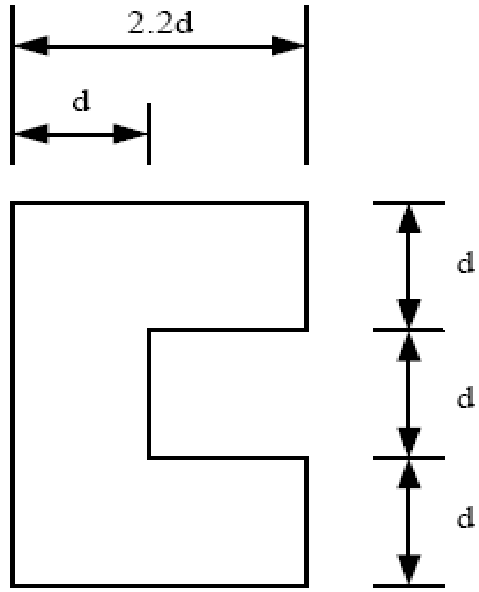
Currently, photoluminescence, electroluminescence, and transmission electron microscopy can be used to monitor post-epitaxial growth (i.e. a thin film of single crystal material formed over a single crystal substrate). Photoluminescence is typically performed with a tool that paints a spot size of roughly 5 microns diameter on the wafer. The use of a low NA (numerical aperture) lens and the wavelength of the light source yield this spot size. The result is that the average photo luminescence performance over a relatively large area of the wafer can be probed. Unfortunately, this area is roughly 2.5 to 3 orders of magnitude larger than the size of individual indium clusters. As a result, the fingerprints (i.e. any properties that can be measured and characterized) of indium clusters, which can indicate processed device performance, cannot be obtained using photoluminescence. Efforts have been made to improve the resolution of optical probes. For example, a common device now in use is an NSOM (near-field scanning optical microscope) in which tapered fiber lasers have a very sharp end, e.g. a radius of approximately 50 nm, which can deliver a sub-wavelength spot of light to a sample. However, the transmission of an NSOM is far less than a part in 10^3 single pass. As a result, very weak beams of sub-wavelength light are delivered to the sample under observation. Therefore, images gathered using NSOM are taken very slowly due to the necessity to integrate signal for long periods to overcome detector noise.

Alternately, the use of electroluminescence and TEM have been proposed. Electroluminescence probes even large areas of the wafer of course and therefore has even greater disadvantages. In contrast, transmission electron microscopy (TEM) can be used to probe device morphology at high resolution. However, electron microscopy is very slow, expensive, and does not provide information on the manner in which morphology affects carrier mobility and recombination in quantum well (such information being highly representative of LED performance).

The c-aperture is a sub-wavelength transmitting aperture which can be used to probe with of order 10 nm resolution the surface composition of an indium rich InGaN quantum well. The c-aperture is described by Matteo, et. al. (J.A. Matteo, D. P. Fromm, Y Yuen, P.J. Schuck, W.E. Moerner, and L. Hesselink in App. Phys. Lett. Vol. 85(4), July 26, 2004, pp. 648-650 and references therein). Notably, the c-aperture has wave-guiding properties that can overcome the exponential decay of film thickness (for a metal or dielectric) in transmitting wavelengths of light larger than the aperture. Therefore the c-aperture luminescence probe will provide the required resolution for the indium rich InGaN film monitoring and it will also provide sufficient signal that rapid pixel by pixel data acquisition will be possible. It is therefore expected that the c-aperture will serve as an effective process window line monitor for clustering which is know to be exceptionally sensitive to deposition conditions such as organometallic deposition gas flow rates, prior layer composition, as well as substrate temperature.

While c-apertures have been built at Stanford University with moderate resolution, of order 100 nm point spread functions, it will be necessary to fabricate c-apertures (Figure 7-1) with dimensions as small as 10 nm or less for this application. Initial tests have shown that this dimension is just at the state of the art of focused ion beam (FIB) tools.

Figure 7-1. A c-aperture can be milled into a metallic substrate with characteristic dimension "d" as shown below. The resulting point spread function of the near field is of order "d".



Therefore considerable effort will need to be expended to properly manufacture the c-apertures themselves. In addition, it is well known that the photoluminescence signal from the GaN thin films diminishes strongly as the temperature is raised towards room temperature. It will be necessary to build an apparatus for the state of the art c-apertures which will permit their use with liquid nitrogen cooled GaN wafers.

The proposed milestones for indium rich InGaN film growth in line process window monitoring are given as milestones M7.1-M7.6 below.

M7.1: Initial demonstration of c-aperture fabrication with characteristic dimension, "d", of 10 nm or less (3/31/10)

M7.2: Conceptual design of c-aperture test bed with liquid nitrogen cooling of sample, diagnostics, focus control and sample positioning (4/30/10)

M7.3: Bench test of transmission and point spread function or optical sensitivity of 10 nm or better from c-apertures fabricated in M7.1 (9/30/10)
M7.4: Initial photoluminescence at liquid nitrogen temperature maps from customer furnished wafers of indium clustering on several indium rich wafers. (12/31/10)

M7.5: Comparison of maps from M7.4 to maps from same wafers obtained using TEM, NSOM, and other diagnostics. (4/30/11)

M7.6: Fabrication of LEDs from each of the wafers used in M7.4 and M7.5 for correlation of indium clustering maps versus chip performance. (8/31/11)

M7.7: Engineering conceptual design for c-aperture in-line monitor tool (3/31/12)

M7.8: Completion of alpha tool for c-aperture in-line indium rich InGaN clustering monitoring tool. (9/30/12)

8. Growth, monitoring, and packaging activites at Lumileds

- Growth on Si substrates
- GaN-on-Si chip development
- In-situ monitoring of InGaN growth for III-N LEDs
- Low-cost copper electroplating for high-power density Thin-Film Flip-Chip (TFFC) devices
- High-Resolution die inspection for Thin-Film Flip-Chip (TFFC) devices

Project: LED Growth on Si substrates

Owner: Werner Goetz

Problem addressed
Currently all commercial GaN based LEDs are grown on either sapphire or SiC substrates. Both substrates enable epitaxial growth of high crystalline quality GaN and InGaN layers enabling LEDs with high internal and external quantum efficiencies. For example, blue LEDs with emission wavelength of about 450 nm typically used to pump phosphors to create LEDs with white emission now routinely exhibit an internal quantum efficiency of about 70 % and an external quantum efficiency of about 50 %. However, both sapphire and SiC are expensive. In the case of sapphire, the cost of the substrate contributes a fraction of about 25 % to the epi manufacturing cost of an LED chip. Si is only 1/10th of the cost of sapphire. A significant cost reduction could be achieved if the epi growth of high quantum efficiency LED structures could be transferred to Si substrates. Another promise that Si substrates hold is that they should enable the use of larger diameter substrates leading to higher throughput and additional cost reduction. Sapphire is available in diameters of 4 inch and above, however, its poor thermal conductivity and mechanical properties demand thicker and thicker substrates (>1.3 mm for 6 inch) adding cost and leading to large bow at growth temperature preventing epi manufacturing with desirable yield and quality. SiC is not available in diameters above 4 inch.

Technical challenges
Si substrates not only have a large lattice mismatch with GaN but also a large mismatch in thermal expansion coefficients (about 2x). Another problem is a chemical reaction that occurs in the GaN growth environment with Si (Ga melt back etching). However, these problems have fundamentally been solved in the literature and thick GaN films have been grown on large diameter Si substrates (up to 8 μm of GaN on 6 " Si). What is lacking is

the demonstration of LED growth on Si substrates that rival sapphire or SiC based structures in efficiency. Technology must be developed that reproducibly generates high quality GaN base layers on Si substrates as well as growth of InGaN active regions reaching similar quantum efficiency currently achievable on sapphire or SiC substrates. Further, development has to be directed towards large diameter Si substrates with the intent to significantly reduce manufacturing cost while maintaining all required LED performance parameters. While cost reduction is essential for LEDs to be used in general illumination the performance in terms of efficiency and reliability cannot be compromised.

Key deliverables:

M8.1 Development of GaN base layers on 6 inch Si substrates suitable for overgrowth of InGaN active regions with good thickness and doping uniformity and smooth morphology.
M8.2 Development of InGaN based active regions (MQW or DH) on GaN on Si base layers. Internal quantum efficiency must be higher than 70 % at current density of 50 A/cm^2 and above.
M8.3 Development of full LED structures that provide external quantum efficiency higher than 50 % at current density of 50 A/cm^2 and above (in combination with suitable chip design) and reliability comparable to sapphire or SiC based solutions.
M8.4 Development of robust epitaxial process that combines excellent repeatability with good uniformity suitable for high volume, high yield epi manufacturing.

Project: GaN-on-Si chip development

Owner: Mike Krames

Problem addressed
Extensive penetration of the general lighting market by solid-state lighting requires substantial reduction in the initial costs for LEDs. Besides improvements to efficiency and drive power density, which increases lumens per $, there is considerable opportunity to reduce chip cost by reducing BOM and in scaling up to larger-diameter wafers. The latter are well addressed by moving state-of-the-art GaN LED chip technology from its current base on sapphire wafers, to Si substrates.

Technical challenges
State-of-the-art performance requires that the LED is optimized in both optical as well as electrical aspects. It is not acceptable to compromise on efficiency, even if a lower chip cost strategy is provided. Within this program, we intend to adapt our thin-film-flip-chip (TFFC) technology to Si substrates. Since the substrate is removed in the final device, the typical concern about light extraction from Si-based LEDs is removed, and excellent performance levels can be anticipated.

Compared to standard InGaN on sapphire, InGaN on silicon presents several challenges. 1) A higher film stress and greater wafer bow are expected. Process recipes and equipment for lithography, annealing, dicing and other steps must be re-engineered to accommodate the greater bowing, e.g. installation of vacuum chucks. 2) Accurate optical wafer level testing (before substrate removal) will be more difficult. Our experience in characterizing AlInGaP on GaAs will be helpful in designing optical test structures into the lithographic masks and interpreting the results. And 3) A new Si substrate removal technology for realizing the TFFC LED must be developed.

Philips Lumileds Advantages
We have several advantages key to meeting these challenges. Our unique TFFC process flow retains the growth substrate through die attach providing a higher die fab yield. Then the removal of the Si will be performed on chips attached with gold to ceramic tiles, a highly chemically resistant submount. And a newly developed compliant bonding layer will permit a controlled degree of relaxation of the InGaN layers as the Si substrate is etched away. Furthermore our same side p- and n-contacts provide greater freedom in the epitaxial design since nonconductive buffer layers may be explored, e.g. SiNx. Device performance will be benchmarked by comparison to the large volumes of devices we produce with very similar packaging.

Key deliverables

M8.5 By Year 1, install necessary equipment to be able to handle wafer-fab and die-fab for 4” GaN-on-Si wafers. Includes installation of Si substrate removal station.

M8.6 By Year 2, demonstrate fully fabricated crack-free GaN LED wafer on 4” Si and wafer-level test.

M8.7 By Year 3, demonstrate 1st TFFC LEDs from GaN-on-Si 4” wafers

M8.8 By Year 4, demonstrate optimized TFFC LEDs from GaN-on-Si 4” wafers; performance to be within 10% of GaN-on-sapphire “controls”.

Project: In-situ monitoring of InGaN growth for III-N LEDs

Owner: Werner Goetz

Problem addressed
Ternary InGaN layers are utilized in visible-spectrum III-N based LEDs as light emitting material. Consequently, the deposition conditions of InGaN are extremely critical. Not only is high materials quality required to reduce parasitic, non-radiative recombination but also InN composition and layer thicknesses (for example in InGaN quantum wells) must laterally be homogenous to achieve emission spectra with reasonable width. However, some compositional clustering or thickness inhomogeneity appears to be required in high efficiency quantum wells; these characteristics have been credited for shielding carriers from non-radiative recombination sites such as dislocations which remain to be present in commercial LEDs at densities greater than 10^8 cm^{-2}. The challenge is to control deposition conditions such that the “right” amount of clustering occurs and further to determine quantitatively right after epi manufacturing whether the InGaN layers exhibit the desired properties.

Technical challenges

InGaN clustering occurs on a length scale of 10s of nano-meters. It would be extremely desirable to quantitatively characterize the degree of clustering early on in the process to avoid processing wafers that will not yield the desired characteristics. Optical and structural techniques typically do not provide the desired lateral resolution. Near-field scanning optical microscopy (NSOM) has been used to characterize epitaxial InGaN layers, however, NSOM is barely reaching the desired resolution as it is diffraction limited at the wavelength of visible light (100s of nano-meters). New technology is being developed using special apertures (“Z” apertures) which provide a path of optical interrogation into the realm of 20 to 30 nm lateral resolution. Such technology will be developed at Stanford University as part of this program (Prof. Bert Hesselink). For Philips Lumileds, the goal will be to establish a correlation between high resolution optical characterization and LED performance so that this technology can be applied to manufacturing of visible-spectrum LEDs. Early screening of production wafers has significant potential of reducing manufacturing cost because processing of compromised wafers will be avoided.

Key deliverables

M8.9 Establish correlation between high resolution mapping of InN composition with LED performance (efficiency, reliability, uniformity). Measurements taken at Stanford.

M8.10 Install a high-resolution optical scanning system at Philips Lumileds (KLA Tencor).

M8.11 Characterize production wafers and establish yield improvement.

Project: Low-cost copper electroplating for high-power density Thin-Film Flip-Chip (TFFC) devices

Owner: Dan Steigerwald

Problem addressed

Operation of light Emitting Diodes (LEDs) at high current-density is a critical item for reduction in cost of a Solid State Lighting (SSL) system. Higher current-density operation enables a significant increase in flux from a given amount of LED semiconductor material. The maximum current-density which an LED can be operated is often limited by considerations of the dissipation of excess heat. In addition, the temperature uniformity within the LED die is critical, as thermal gradients often lead to mechanical stresses and potential reliability concerns.

Philips Lumileds Lighting Company employs a Thin Film Flip Chip (TFFC) architecture for high power InGaN LEDs, capable of operation from the near-UV through green, including phosphor converted white. Figure 1 displays a cross-sectional view of a phosphor-converted TFFC die mounted into a surface-mount capable ceramic package. The electrical connections to the LED die are made on the bottom side, leaving the top emitting surface completed open for attachment of a ceramic phosphor platelet with high efficiency. The interconnects are made using an elemental metal (gold) for high thermal conduction and reliability. In such an architecture, the ability to create an interconnect to the package with high area coverage is critical for thermal dissipation and for reduced thermal gradients. Figure 2 shows infrared thermal images of two TFFC LEDs where the area of the interconnect metal is either 15% or 90%. The reduction in thermal gradient is greatly reduced for the larger interconnect area. To achieve such a large interconnect area, the interconnect material is gold, plated directly onto the LED.

Figure 1. Schematic cross-section of an InGaN phosphor-converted TFFC LED on a ceramic surface mount package

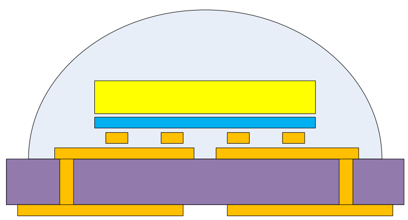
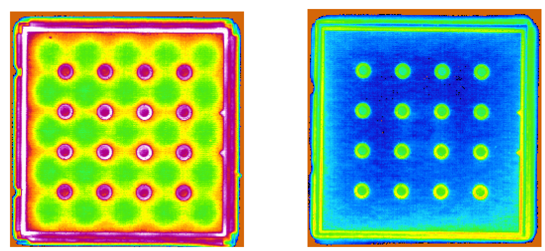


Figure 2. Thermal images of InGaN TFFC dice. The picture on the left corresponds to an interconnect with 15% area coverage and the image on the right corresponds to an interconnect with 90% area coverage.



Technical challenges

The major challenges to the approach described above relate to the wafer level electroplating operations and to the metal-metal interconnect. The devices shown in figure 2 are based on gold-gold interconnects, where both the plating processes and the interconnect processes are well established. However, the cost associated with the gold interconnect layers is significant and will need to be cost-reduced to become a prominent technology in Solid State Lighting. The prime choice for replacing the gold layer is copper, deposited as a Cu/Ni/Au structure. This proposal is intended to develop high-volume manufacturing processes based on Cu/Ni/Au to enable high performance InGaN LEDs with reduced cost.

Key deliverables

M8.12 The key deliverables for this program are the development of high-volume electroplating processes of Cu/Ni/Ag, as well as all of the associated processes such as choice of plating seed layer deposition and removal. Additionally, demonstration of the thermal performance and reliability of this technical approach will be generated.

Project: High-Resolution die inspection for Thin-Film Flip-Chip (TFFC) devices

Owner: Dan Steigerwald

Problem addressed

One central promise of Solid State Lighting (SSL) with Light Emitting Diodes (LEDs) is long lifetime for the devices and a clear improvement in Total Cost of Ownership for the end user. LEDs are semiconductor devices where the wear-out regime can be accurately modeled and lifetime models can be predicted with sufficient accuracy. However, as with all products, and with semiconductor products in particular, defects in materials or construction can lead to premature failure well ahead of the desired wear-out regime of operation. The early identification and elimination of such defects is critical to the adoption of SSL and realization of the large energy savings based on higher efficiency and reduced maintenance.

Technical challenges

Analogous to the development of silicon-based semiconductor integrated circuits, proper inspection equipment and protocols are required to identify defects. Identification of critical defects can be used to improve manufacturing processes and also to remove defective devices from the population prior to shipment to customers. Currently available Automated Visual Inspection (AVI) equipment is limited to identification of defects with a minimum dimension of 3-5um. However, several classes of defects are present in the range of 1-3um, which cannot be routinely detected in a non-destructive manner. These defects include particles and mechanical damage to the thin epitaxial layers utilized in InGaN TFFC LEDs. Development of improved inspection equipment and protocols is critical for reducing the cost of SSL systems and also for increasing the reliability of such systems.

Key deliverables

M.8.13 The deliverables in this study, in partnership with equipment manufacturer KLA Tencor, is to co-develop the appropriate AVI equipment and inspection protocols, with ability to detect defects in the 1-3um range.

9. Cluster tool development and GaN growth at Applied Materials IMPROVED EPI TOOLS FOR HB-LED DEVICES

Project Technical Contact: Nag Patibandla [nag_patibandla@amat.com]

Solid-state lighting (SSL) in general, light emitting diodes (LEDs) in particular, has the potential to revolutionize the lighting market through the introduction of the most energy-efficient light source. LEDs have penetrated a range of niche market applications involving colored light emission such as exit signs, traffic signals, and electric signage. Recent advances have enabled the use of high brightness light emitting diodes (HB-LEDs) into applications such as automotive lights; back lighting of liquid crystal displays (LCDs) on cell phones to laptop computers to flat-panel televisions; and even some general lighting applications such as street lights. In a recent report, the US Department of Energy (DOE) has estimated that in 2007, the current level of penetration of the LEDs has resulted in an annual electricity savings of 8.7 TWh. The report further estimates that when HB-LEDs become the mainstay in the indoor white-light applications, 108 TWh per year of electricity savings is possible, equivalent to about 13% of electrical energy consumption for lighting in the U.S. in 2007. This report concludes that for all possible LED applications, the annual electricity savings potential is 180 TWh.

The HB-LED used today are gallium nitride (GaN) based devices. These devices used in LCD display backlighting, general illumination, and automotive applications are being realized at an industry average price of $0.12 per LED chip. The worldwide market for HB-LED devices is estimated at $4.6 billion in 2007 and is forecasted to grow to $11.9 billion in 2012 at a compound annual growth rate (CAGR) of 21%. It is generally accepted that this anticipated growth in HB-LED will require cutting the manufacturing cost by one-half and doubling of the device efficiency.

HB-Led device manufacturing is a complex multi-step process similar to that used in the semiconductor/microelectronics chip manufacturing. An overview of the manufacturing process flow is shown in Figure 1. The heart of the HB-LED device is made up of compound semiconductors of gallium nitride (GaN) family and is processed using epitaxial deposition (see step 2 in Fig 1). The doped and undoped layers of GaN of varying thicknesses, generally of several nanometers to micrometers, are deposited on a starting wafer made of sapphire (alumina), aluminum nitride, silicon with buffer layers, etc. This critical process step is carried out in a vacuum chamber via metal organic chemical vapor deposition (MOCVD) [MOCVD is also referred to as metal organic vapor phase epitaxy (MOVPE)] or hydride vapor phase epitaxy (HVPE). The more widely used MOCVD starts on a 2-inch (0001) sapphire substrate and builds up a LED device consisting of uGaN, nGaN, GaInN/GaN multiple quantum wells (MQWs), pGaN, and AlGaN. These individual epitaxial layers need to be grown in high quality crystal lattices with minimal defects to achieve high performance HB-LEDs. Improvements in MOCVD / HVPE technology can deliver a number of cost reductions for solid state device growth.

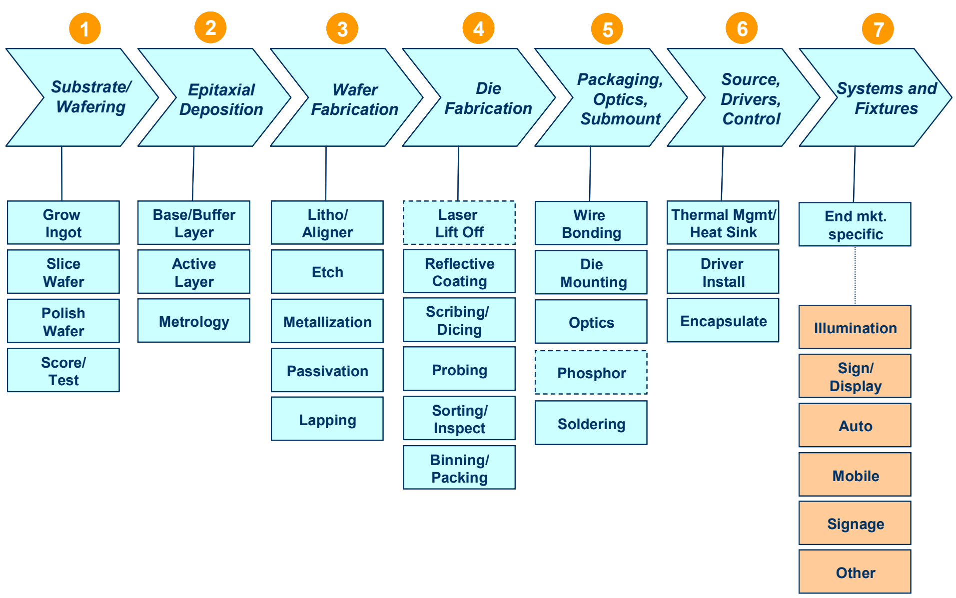


Fig 1: LED Device Manufacturing Process Flow-Chart

Applied Materials Inc (AMAT) manufactures epi-equipment (Step 2, Fig 1) needed to deposit buffer and active (including multi quantum well – MQW) layers of compound semiconducting GaN materials such as GaInN, AlGaInN suitable for use in manufacturing HB-LEDs. AMAT's Epi-tools are well accepted into manufacturing of HB-LEDs used in backlighting of LCDs which is the dominant growth sector for these devices. These HB-LEDs operate at moderate current levels and demand reasonable light output efficiency. It is well established that even higher efficiencies and luminous flux (light output) are necessary to penetrate the general illumination market, where drive currents larger than 350 mA for each HB-LED chip of 1x1 mm^2 may be employed. HB-LED efficiency generally is highest at low currents - typically at a few milliamperes; and as the injection current increases, the efficiency decreases gradually. This phenomenon called **efficiency droop** must be solved for devices operating at high powers. AMAT's Epi-equipment will need to be designed and optimized to manufacture HB-LEDs intended to operate at high currents with minimal reductions in external quantum efficiency of light output.

Eliminating Efficiency Droop

A major obstacle for the compound GaN – specifically GaInN - based HB-LEDs to further penetrate into the general illumination market is that their efficiency suffers a substantial decrease as the injection current increases. These devices typically hit peak efficiencies at drive currents of 100 mA/mm^2. Currently, the popular operating current for a conventional HB-LED (1x1 mm^2) is 350 mA to emit 100 - 150 lumens. However, in order to realize a "single LED chip (1x1 mm^2) light bulb," the operating current should be higher than two amperes and the device must be capable of emitting 1000 lumens (which is equivalent to the luminous flux of conventional 60 watt light bulb). With today's HB-LED devices, the internal quantum efficiency of a HB-LED device falls by 25% at a drive current of 350 mA/mm^2 and by as much as one-half at 1 A/mm^2. Therefore, understanding and mitigating efficiency droop is critical to attaining viable penetration of HB-LEDs in general illumination lighting applications.

In the literature, various explanations ranging from electron leakage, lack of hole injection, carrier delocalization, Auger recombination, high defect concentrations to junction heating have been proposed as the causes of efficiency droop. Considering different explanations proposed, the physical origin of the droop is not well understood. However, it has been shown that

(a) reductions in dislocation density, attained with the use of GaN bulk substrates (in stead of sapphire substrates), can influence the magnitude efficiency droop. Fig 2 (adopted from Schubert et al of RPI) shows that sample A of lower dislocation density has a peak efficiency that is more than double that of sample B. The peak efficiency for sample A occurs at approximately 12 mA; however, as the forward current is increased to 100 mA, efficiency is reduced by 23%. Devices with low defect density have a high peak in efficiency, followed by the significant efficiency droop as the current increases. In contrast, high-defect-density samples have low peak efficiency, but also show much lower efficiency droop at higher currents. Schubert and co-workers explain the phenomenon as follows: At low currents, carriers are often lost to a trap-assisted process – Shockley-Reed-Hall recombination, which becomes more severe as the dislocation density increases. Cranking up the current initially improves efficiency through an increase in spontaneous emission. However, EQE then falls due to increased competition from an additional carrier-loss mechanism causing the efficiency droop.

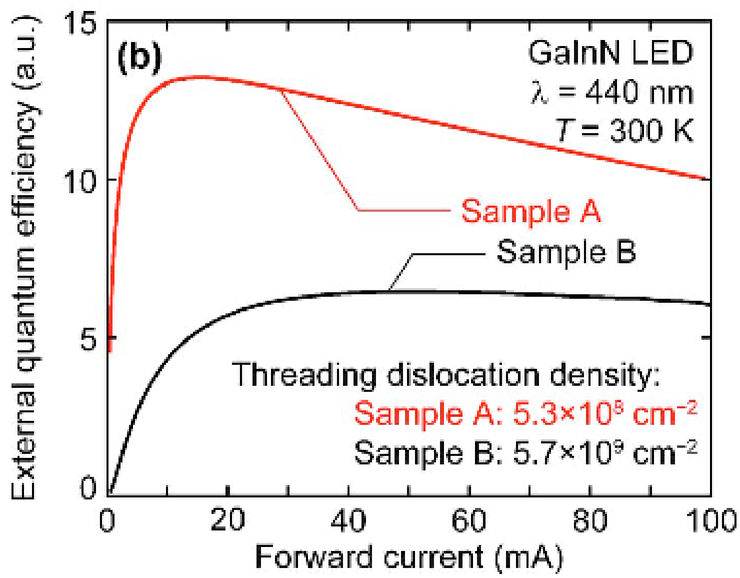


Fig 2 External Quantum Efficiency of two samples with different dislocation densities

(b) efficiency droop can be mitigated through reductions in material polarization contrast across GaN and quantum well/barriers and/or electron blocking layers (EBL). Figure 3 (adopted from Kim et al of Samsung and RPI) plots the internal quantum efficiency (IQE) and the electron leakage current across the EBL as a function of the forward current for a reference LED and LEDs in which the quaternary AlGaInN MQW quantum barriers and EBL are polarization matched to the quantum wells and then to GaN, respectively. Kim et al proposed that in general electron leakage from the active region is driven by the polarization mismatch between the quantum well, quantum barrier, and the EBL. It was postulated that the polarization mismatch which occurs at hetero-interfaces results in the formation of large sheet charges which modify the bands to form large triangular barriers in the MQW active region and the EBL. These barriers create obstacles for carriers, and require high forward voltages for significant currents to flow, so that the conduction band on the n-side of the device is significantly higher than the conduction band on the p-side. This makes it energetically favorable for electrons to escape to the p-side of the device.

These researchers further argued that reduction in IQE (/efficiency droop) is caused by a non-radiative carrier loss mechanism that becomes dominant as the injection current increases. The efficiency droop, defined as (ηpeak □η350 mA)/ ηpeak, is 25% for the reference LED. They have tied the decrease in efficiency to the increase in electron leakage current, which is significant even at low currents and becomes larger as the forward current increases. This is partly attributed to the reduced effectiveness of the AlGaN EBL due to the effect of polarization charge. When an AlGaInN EBL is polarization matched to GaN, the light output increased by 49.5% at 350 mA and the droop decreased to 22%. However, electron leakage still constitutes more than 40% of the total injected current, due to the remaining polarization charges in the MQW. When polarization-matched AlGaInN quantum barriers are used, the light output increases by 138% at 350 mA and the droop decreases to only 5%. Thus, polarization fields in the MQW active region and the EBL are the physical origin of the efficiency droop occurring in GaInN LEDs. Structures with polarization-free EBL and MQW show the highest light output power and virtually no efficiency droop.

In a more recent work by the RPI team, Xu et. al. (of RPI) published that use of GaInN/GaInN MQWs minimized electron leakage current from the active region as evidenced by the greater separation of the electron quasi-Fermi level from the conduction band edge in the p-type region. They showed that at the same forward current density the GaInN/GaInN MQW design reduced electron leakage from active region as compared to the reference GaInN/GaN MQW structure. At the maximum forward current density of 300 A/cm2, an 18% increase in the light-output power is achieved by for the GaInN/GaInN MQW structure.

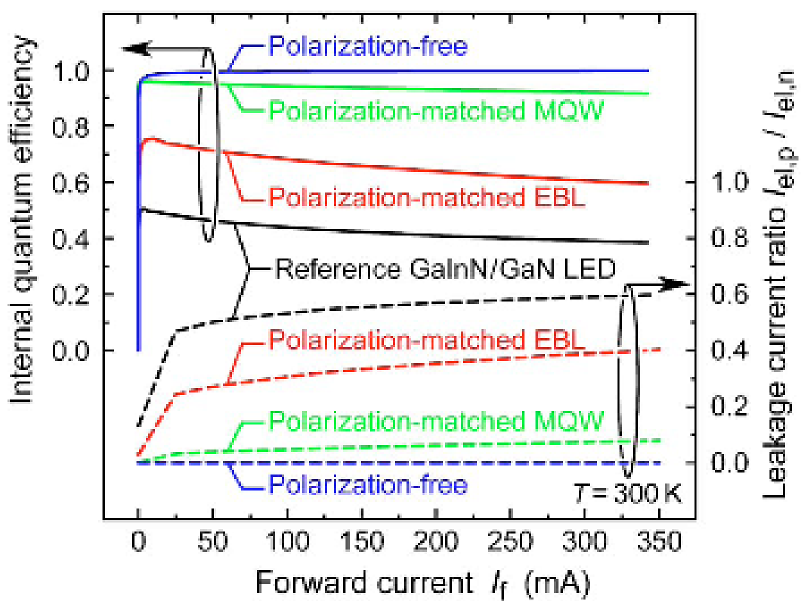


Fig 3: IQE and leakage current ratio of LEDs with and without polarization effect in the MQW and/or EBL (Adopted from Kim et al)

Manufacturing Droop-Free Devices

Based on the above discussion, it is evident that HB-LEDs capable of penetrating the general illumination must be built on low defect, i.e. low dislocation density, GaN and

MQW layers that have matching-polarization across them and the EBL layer. Compositional and thickness uniformity is paramount as appropriate selection of the MQW well/barrier and EBL layers results in good electron confinement and reduction in the polarization mismatch. This market imminently requires specifically designed set of Epi-tools with high throughput and manufacturing yield as well as the ability to deposit carefully controlled multi-layered device structures of polarization matched materials at extremely low defect densities. To this end, AMAT intends to develop multi-chamber Epi-tools capable of (a) growing defect free buffer and uGaN layers on lattice-matched substrates, (b) precise multi-zone process temperature control with ramp up and cool down rates in the range of 5 C/sec, (c) accurate and controllable reaction and dilutant gas flows, (d) growing MQW barrier and well layers at different temperatures allowing compositional changes and polarization matching across sharp MQW interfaces, and (e) with high thickness and emission wavelength uniformities both within a wafer and across multiple wafers on a carrier. In this project AMAT will pursue the development of such Epi Tools via the following tasks.

Epi-Tool Development _ Task 1:

One specific difficulty facing epitaxial growth of "defect-free" multi-layered HB-LED devices is the non-availability of high-quality, single-crystal GaN substrates or other single-crystal substrates with similar lattice parameters as GaN. Sapphire (commonly used) and SiC (by some like Cree) substrates are industry standards for epitaxy of group III-nitrides. These substrates are preferred due to their thermal and chemical stability at high temperature, excellent structural and surface morphology, and availability in large volumes. Unfortunately, there is lattice mismatch as well as thermal mismatch between GaN and sapphire substrate. A comparison of available substrates is listed in table 1.

Table 1. Structural Properties of Various Substrates for GaN Epitaxy

Substrate	**E_g (eV)**	**Lattice parameter a (Å)**	**Lattice parameter c (Å)**	**Lattice mismatch (%)**	**Thermal expansion coefficient (10^{-6} K^{-1})**	
					a	**c**
	3.36	**3.189**	**5.18**	**0**	**5.6**	**3.17**
GaN – wurtzite	**6.2**	**3.112**	**4.98**	**2.5**	**4.2**	**5.3**
AlN – wurtzite	**2.9**	**3.08**	**15.1**	**3.5**	**4.2**	**4.7**
6H-SiC – wurtzite	**6.8**	**4.758**	**12.991**	**16.1**	**7.5**	**8.5**
Al_2O_3 – wurtzite	**3.35**	**3.21**	**5.21**	**1.94**	**2.9**	**4.8**
ZnO - wurtzite	**6.1**	**5.1687**	**6.2679**	**1.5**	**7.1**	**7.5**
$LiAlO_2$ – tetragonal	**4.1**	**5.402**	**5.007**	**0.9**	**6**	**7**
$LiGaO_2$ – orthorhombic						
GaN – zinc blende	**3.17**	**4.53**		**16.57**	**5.20**	
3C-SiC – diamond	**2.3**	**4.36**		**3.9**	**2.7**	
GaAs – zinc blende	**1.42**	**5.65**		**19.87**	**6.0**	
Si (111) – cubic	**1.12**	**5.83**		**20.5**	**6.2**	

Uniformity of light emission wavelength within a wafer is very critical to achieve high yield of HBLEDs production. Undoped GaN grown on (0001) sapphire substrate results in high density of dislocations stemming from the 16% lattice mismatch between GaN and sapphire. The threading dislocations originating from this high lattice mismatch propagate into MQWs and act as non-radiative recombination centers. Such non-radiative carrier loss mechanism was identified as the dominant cause for the IQE reduction and efficiency droop.

The light emission wavelength uniformity is also affected by uGaN thickness uniformity as well as that of AlGaN - the electron blocking layer. Thus to produce high quality HB-LEDs that are capable operating at high currents, it is very important to have highly uniform GaN and MQW layers of high crystal quality with minimal crystal defects. Presence of highly defective materials might not preclude luminescence of a HB-LED, rather they degrade the lifetime of the device by generating short-circuits and "dark line defects," which are non-luminescent areas of material associated with magnesium or zinc electromigration at dislocations. For these reasons, crystal quality is of paramount importance for the fabrication of devices.

The ideal solution to this quandary is to grow gallium nitride epilayers - where charge carriers combine to produce the photons - on gallium nitride substrates. In such a case, the subsequent film merely continues the crystal structure of the substrate without discontinuity at the film/substrate interface, thermal or lattice mismatches that generate stress-induced dislocations, microtwins, microcracks, or macrocracks. As a result, electromigration and solid-state diffusion of dopants and contact materials are suppressed, and hence short-circuits, dark-line defects, and mechanical failures are reduced.
AlN substrates have been shown to be attractive for III-Nitrides device fabrication due to their high thermal conductivity and minimal thermal expansion between AlN and GaN. AlN substrates may be necessary for high efficiency, long life time UV HB-LEDs where conventional sapphire or SiC substrates are unsuitable.

In this task, AMAT will develop MOCVD systems capable of epitaxial growth of high quality GaN compounds (ternary and quaternary alloys) with excellent uniformity. In response to the challenges mentioned above, process development will focus not only on growing the best possible crystal quality and uniformity but exploring process parameters to obtain better understanding of GaN, GaInN, AlInGaN epitaxial growth mechanism. AMAT will specifically engage in the design and assembly of Epi-tools capable of producing high quality HB-LED devices on substrates that are thermally compatible and lattice matched with uGaN thereby alleviating many of the difficulties associated with growing device quality material. These substrates with homoepitaxially-grown films will contain fewer defects than films grown upon other substrates, the resulting devices will be more reliable and of higher quality, and most importantly ones that will be capable of operating at high drive currents with minimal efficiency droop.

Epi-Tool Development _ Task 2
Hydride vapor phase epitaxy (HVPE) is another highly desirable method for the growth of nitride semiconductors. In conventional HVPE of GaN, the Ga source is gallium monochloride (GaCl), which is produced by the reaction of liquid gallium with hydrogen

chloride (HCl) gas. The typical source of nitrogen is ammonia gas. HVPE of GaN has a high growth rate of up to a few tens of micrometers per hour and uses relatively simple growth chemistry. The high growth rate of HVPE offers the possibility of preparing very thick GaN films, which can even be removed from foreign substrate. HVPE has been used primarily in the manufacture of GaN substrates or templates and recently GaN wafers are now becoming available in small quantities from a few producers. Despite the technological progress, there are only a few commercial HVPE systems that operate with one 2-inch or one 3-inch in diameter substrate.

In this task AMAT intends to pursue development and commercialization of a multi-wafer nitride HVPE system for high volume production. AMAT's approach allows combining nitride HVPE and MOCVD chambers into one cluster deposition system. It will significantly increase the process throughput. Several concepts of reagent's injection into the reactor chamber will be tested to create the best mixing and uniform distribution of reagent gases. The main objective will be to identify a chamber design and compatible process conditions to produce high crystal quality GaN at a high (several micrometers per hour) growth rate. The growth parameters such as temperature, pressure, V:III ratio, flow rate of carrier and total gas flow will be optimized. In addition, careful attention will be paid to uGaN and MQW layer uniformities both within wafer (w-i-w) and wafer to wafer (w-2-w) across a multi wafer carrier. The standard deviation for GaN wafer thickness uniformity will be aimed at less than 2%. The contaminants levels will be minimized down to 10^{16} atoms/cc for chlorine and oxygen. The chamber design will be optimized for the requisite temperature control.

Epi-Tool Development _ Task 3

In LED production, the MQW emission wavelength in the blue range (~470nm) along with minimum w-i-w and w-2-w variability is critical to improve the yield. Operating parameters such as chamber pressure and susceptor temperature have a strong effect on the convection and diffusion of the reactive precursors on the growth surface. Careful control of these process parameters is necessary to avoid phase separation of InN and GaN, and the highly temperature sensitive indium incorporation that affects the light emission wavelength uniformity.

The Epi-process on sapphire substrate consisting of uGaN, nGaN, InGaN/GaN MQWs, pGaN, and AlGaN layers takes several hours to complete. In single chamber process the HT-GaN (4 micrometers) was deposited followed by several InGaN/GaN MQW (typically 3 nm Well and 13 nm Barrier) layers. It is found that in the single chamber GaN + MQW growth, the PL wavelength of emission drifts from run to run and sometimes even within a single run. The PL wavelength drifts significantly not only within a wafer but also from wafer to wafer across a carrier. This necessitates temperature tuning within a run and/or after each run requiring establishment of baseline trends and careful tuning of the tool operating parameters at the expense of valuable production time.

In this task AMAT will aim at developing Epi-tools with dual chambers split process with a goal to minimize PL wavelength drift and to reach up to 20 MQW runs without the need to open or clean chambers. In a dual chamber process, HT-GaN template can be grown in a different chamber and MQW process can be run in another chamber. The total thickness of MQW process is less than 100 nm and it would be possible to maintain high thickness and composition uniformities of both well and barrier MQW layers. Both w-i-w and w-2-w PL wavelength uniformity will be targeted to be about 2 nm or better. The precise multi-zone temperature and process gas flow controls necessary to achieve the targeted PL wavelength uniformity will be integrated into the production ready Epi-tool. The two-chamber process can result and higher throughput and improvements in PL uniformity can enhance the yield with minimal tuning efforts required prior to running the production.

Epi-Tool Development _ Task 4

The complexity of reactions between the organometallic precursors and NH_3 in the MOCVD chambers results in the formation of adducts and low vapor species on the chamber parts such as the showerhead surface, the susceptor, and the exhaust holes. The deposits can cause particles, drift the growth conditions, and affect the process reproducibility and uniformity. These parasitic deposits necessitate regular chamber cleaning thus reducing the reactor efficiency. Commercially available MOCVD systems require ex-situ cleaning by opening the reactor and wiping or vacuuming the surfaces, or by partially dissembling the chamber and cleaning some parts with hydrochloric or phosphoric acids. Long recovery periods including a thermal bake-out would be required after closing the chamber to remove the moisture.

There is a strong demand for nitride MOCVD systems with in-situ cleaning capability. In this task, AMAT will pioneer the development of an in-situ cleaning process using halogen-based etching gases. The capability of in-situ chamber clean for nitride MOCVD systems will significantly increase the process throughput and could potentially revolutionize the current MOCVD process used in the LED industry. The in-site clean process coupled with the optimized reactor design will aim at reducing the clean requirement down to every ten runs from the current practice of every run. A clean showerhead with minimal residual $GaCl_3$ will be demonstrated in the AMAT Epi-tools. With an optimal recovery procedure, the chlorine level in the GaN is minimized to the detection limit of the SIMS analysis ($<10^{15}$ atoms/cc). The crystal quality of GaN will not be affected after the chamber clean, the alloy of InGaN and AlGaN is not influenced, and the incorporation of Mg and Si will not be observed. We will focus on reducing the total clean and recovery time by enhancing the conversion and removal efficiency of $GaCl_3$.

10. Cost Summary

The table below is an approximate cost and timeline for the overall FALCON Program

FALCON Program Financial Summary

Milestone	(mos ARO)	Duration (mos)	Projected Completio n	Eng Labor (hrs)	Tech Labor (hrs)	Labor Cost ($)	Materials Cost ($)	Total Cost ($)
M3.1 Develop Chemistry Models		3		4400		968,000		968,000
M3.2 Integrate Chemistry and CFD		9		4800		1,056,000	30,000	1,086,000
M3.3 Design Reactor		18		7200	1600	1,824,000	750,000	2,574,000
M3.4 Construct MOCVD System		24		3200	6000	1,604,000	2,500,000	4,104,000
M3.5 Test/Refine MOCVD System		36		5000	7500	2,225,000	2,200,000	4,425,000
M3.6 Test and Integrate Short Wavelength Pyrometer		18		2500	1500	775,000	500,000	1,275,000
M3.7 Test and Integrate Multi-Wavelength Reflectometer		18		2500	1500	775,000	500,000	1,275,000
M4.1.1 Gas Phase Chemistry		1 to 36		2700	1700	1,020,000	300,000	1,320,000
M4.1.2 Chemistry Models		1 to 18		2200	0	510,000	100,000	610,000
M4.1.3 Surface/Thin Film Chemistry		13 to 24		825	275	255,000	-	255,000
M4.1.4 Couple Chemistry to Fluid Flow		6 to 18		1700	0	400,000	100,000	500,000
M4.2.1 Growth Using Model Predictions		1 to 18		440	660	255,000	50,000	305,000
M4.2.2 New Reactor Designs		13 to 36		4000	600	1,100,000	-	1,100,000
M4.3.1 NUV Pyrometer		1 to 18		1000	100	255,000	-	255,000
M4.3.2 Temperature Uniformity		13 to 30		1300	300	380,000	100,000	480,000
M4.3.3 Reflectometry for InGaN		1 to 18		900	200	255,000	25,000	280,000
M4.4.1 Growth on m-plane AlN		1 to 12		550	550	250,000	150,000	400,000
M4.4.2 Characterize Growth on m-plane AlN		13 to 24		2250	2250	800,000	50,000	850,000
M4.4.3 Improved GaN m-plane AlN		25 to 36		1750	1750	600,000	400,000	1,000,000
M4.5.1 Growth of NTLEG GaN m&a-plane		1to18		2250	1500	700,000	50,000	750,000
4.5.2 Improved GaN m&a-plane		19 to 36		2250	1500	700,000	50,000	750,000
								-

M5.1 AlN growth year 1	12		9/30/2010			0	0	666,000
M5.2 AlN growth year 2	12		9/30/2011			0	0	666,000
M5.3 AlN growth year 3	12		9/30/2012			0	0	666,000
M6.2 Key engineering subsystems	21	10	6/30/2011	2800	1100	642,600	750,000	1,392,600
M6.3 Alpha tool assembly	24	6	9/30/2011	800	1800	370,800	350,000	720,800
M6.4 Scanning mode operation on test wafers	28	4	1/31/2012	600	800	208,800	0	208,800
M6.5 Software mods for binning on defects of interest	32	6	5/31/2012	1600	0	288,000	0	288,000
M6.6 Initial testing at customer sites	36	4	9/30/2012	400	800	172,800	0	172,800
M7.1 Fab 10nm charac. dimension c-aperture	6	6	3/31/2010	600	900	221400	400,000	621,400
M7.2 conceptual engineering bench design	7	7	4/30/2010	1800	1100	462,600	550,000	1,012,600
M7.3 Bench test c-aperture tranmission and psf	12	5	9/30/2010	200	800	136,800	0	136,800
M7.4 Initial InGaN photoluminescence maps	15	3	12/31/2010	200	800	136,800	0	136,800
M7.5 Comparison of c-aperture maps to NSOM, TEM	19	4	4/30/2011	200	800	136,800	250,000	386,800
M7.6 LED fabrication from test wafers	23	4	8/31/2011	100	400	68,400	20,000	88,400
M7.7 Conceptual design engineering tool	30	6	3/31/2012	2500	1800	676,800	0	676,800
M7.8 Completion of alpha clustering tool	36	8	9/30/2012	2300	2500	729,000	850,000	1,579,000
M8.1 GaN base layers on 6 inch Si substrates		12	9/30/2010	8320	4160	1,050,000	450,000	1,500,000
M8.2 InGaN based active regions (MQW or DH) on		12	9/30/2011	8320	4160	1,050,000	450,000	1,500,000
M8.3 Development of full LED structures		12	9/30/2012	8320	4160	1,050,000	450,000	1,500,000
M8.4 Development of robust epitaxial process		12	9/30/2013	8320	4160	1,050,000	450,000	1,500,000
M8.5 wafer- and die-fab equipment for 4” GaN-on-Si		12	9/30/2010	2080	4160	600,000	400,000	1,000,000
M8.6 fully fabricated crack-free GaN LED wafer		12	9/30/2011	4160	4160	850,000	150,000	1,000,000
M8.7 1st TFFC LEDs from GaN-on-Si		12	9/30/2012	4160	4160	850,000	150,000	1,000,000
M8.8 optimized TFFC LEDs from GaN-on-Si		12	9/30/2013	4160	4160	850,000	150,000	1,000,000
M8.9 correlate high res. map InN comp. w/ performance		16	1/30/2011	2767	2767	533,000	133,000	666,000
M8.10 Install a high-resolution optical system		16	5/30/2012	2767	2767	533,000	133,000	666,000
M8.11 Characterize product wafers and establish yield		16	9/30/2013	2767	2767	533,000	133,000	666,000

M8.11 Characterize product wafers and					400,000	100,000	500,000
M8.12 develop electroplating processes	48	9/30/13	10400	8320	1,800,000	700,000	2,500,000
M8.13 co-develop AVI equipment/inspection	48	9/30/13	6240	4160	1,050,000	400,000	1,450,000
M9.1 Polarization matched HB-LEDs	36				5,800,000	1,800,000	7,600,000
M9.2 Multi-Wafer HVPE Chamber	18				1,800,000	750,000	2,550,000
M9.3 Epi Tools w/ Dual Chamber Process	12				1,400,000	850,000	2,250,000
M9.4 In-Situ Cleaning Process	18				1,800,000	600,000	2,400,000
		TOTALS	**Eng Labor (hrs)**	**Tech Labor (hrs)**	**Labor Cost ($)**	**Materials Cost ($)**	**Total Cost ($)**
			84,455	***55,565***	***32,358,600***	***19,075,000***	***64,233,602***

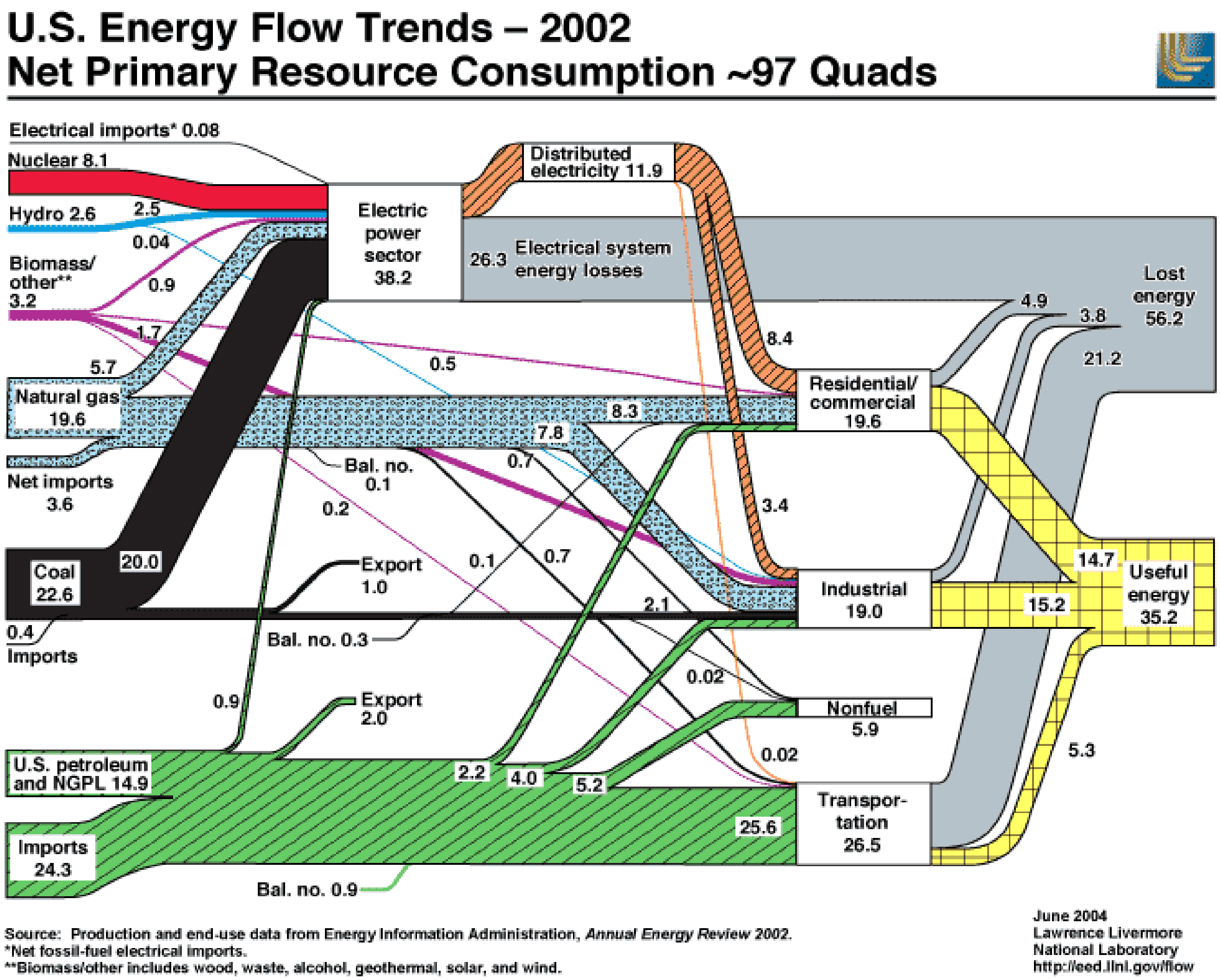
11. Key Personnel

KLA-Tencor:

Dr. Richard Solarz, Senior Director for Corporate Technology, obtained his S.B. degree from the Massachusetts Institute of Technology and Ph.D. from the University of Chicago. He co-founded and led the Advanced Laser Program at LLNL until 2000 when he joined KLA-Tencor as a specialist in optical sources and key subsystems for semiconductor inspection applications.

Frank Burkeen, Director for ………..

Others…….


U.S. Energy Flow Trends – 2002
Net Primary Resource Consumption ~97 Quads
Electrical imports* 0.08
Nuclear 8.1
Hydro 2.6
2.5
0.04
Biomass/ other** 3.2
0.9
1.7
5.7
Natural gas 19.6
Net imports 3.6
Coal 22.6
20.0
0.4
Imports
Electric power sector 38.2
Distributed electricity 11.9
26.3
Electrical system energy losses
0.5
8.3
7.8
Bal. no. 0.1
0.2
0.7
Export 1.0
0.1
0.7
2.1
Bal. no. 0.3
0.9
Export 2.0
0.02
0.02
U.S. petroleum and NGPL 14.9
Imports 24.3
2.2
4.0
5.2
25.6
Bal. no. 0.9
8.4
3.4
Residential/ commercial 19.6
Industrial 19.0
Nonfuel 5.9
Transpor- tation 26.5
4.9
3.8
21.2
Lost energy 56.2
14.7
15.2
Useful energy 35.2
5.3
Source: Production and end-use data from Energy Information Administration, Annual Energy Review 2002.
*Net fossil-fuel electrical imports.
**Biomass/other includes wood, waste, alcohol, geothermal, solar, and wind.
June 2004
Lawrence Livermore National Laboratory
http://eed.llnl.gov/flow