Solid State Lighting LED Manufacturing Roundtable Summary

Introduction

On March 8th, 2011 13 LED experts gathered at the invitation of the DOE to develop proposed priority tasks for the Manufacturing R&D initiative. The meeting commenced with "soapbox" presentations from each of the participants, followed by a general discussion to define specific work needing attention. This report summarizes the conclusions of that meeting, including the proposed tasks, a summary of discussion points relevant to those selections, and a short summary of the soapbox presentations. The next step is to discuss these suggestions at the SSL Manufacturing Workshop. This work will guide the DOE in soliciting projects in the LED Manufacturing R&D Program during the coming year.

Proposed Priority Tasks

M.L1. Luminaire/ module manufacturing		
Support for the development of flexible manufacturing of state of the art LED modules, light engines, and luminaires. Suitable development activities will focus on advanced LED packaging and die integration (e.g. COB, COF, etc.), more efficient use of raw materials, simplified thermal designs, weight reduction, optimized designs for efficient manufacturing (such as ease of assembly), increased integration of mechanical, electrical and optical functions, and reduced manufacturing costs. The work should demonstrate higher quality products with improved color consistency, lower system costs, and improved time-to-market through successful implementation of integrated systems design, supply chain management, and quality control.		
Metric	**2010 Status**	**2015 Target**
Manufacturing throughput		2x increase
Downtime		50% reduction
OEM lamp price	\$50/klm	\$10/klm
Book-to-build time (weeks)	10	5
Assembly Cost (\$)		50% reduction every 2-3 years
Color Control (SDCM)	7	4

Discussion Points

- Some participants indicated that the move to automation is essential to reduce costs of manufacturing while maintaining a manufacturing presence in the US. However, it was also pointed out that there are situations where manufacturing processes were constantly changing and improving which tend to favor high labor content approaches. Once the process had been stabilized it would be ready to scale for high volume and would benefit from improved automation.
- Direct die attached to the heat sink could reduce both material and labor costs. We currently do not have a good process developed for printing the dielectric or sintering.
- It was suggested that there is a need to be more consistent in setting the white point for luminaires.
- It would be desirable to find ways to reduce or recycle the mechanical structures of luminaires. Particularly the aluminum, plastic, and glass materials which have the potential to significantly reduce costs and improve time-to-market. One suggested project was to replace the heavy

aluminum heat sinks with low temperature low pressure reaction injection molding that is thermally conductive.

- This task has been combined with certain elements from task M.L6 Advanced LED Packaging in order to emphasize the integral relationship between LED packaging and SSL luminaire manufacturing, and to ensure that such developments are driven by luminaire design/manufacturing considerations.
- It was indicated that we need to focus on reducing the cost of manufacturing optical structures on the chip for beam shaping. Currently, very few people are integrating structures on the chip because it is very expensive. However, this strategy has potential to reduce overall luminaire cost significantly.
- However, it was also stressed that there is greater need for a manufacturable design before we can focus on advanced LED packaging as a manufacturing priority task. Currently there is a lack of clarity on exactly which packaging equipment is needed.

M.L3. Test and inspection equipment		
Support for the development of high-speed, high-resolution, non-destructive test equipment with standardized test procedures and appropriate metrics for each stage of the value chain for semiconductor wafers, epitaxial layers, LED die, packaged LEDs, modules, luminaires, and optical components. Equipment might be used for incoming product quality assurance, in-situ process monitoring, in-line process control, or final product testing/binning. Suitable projects will develop and demonstrate effective integration of test and inspection equipment in high volume manufacturing tools or in high volume process lines, and will identify and quantify yield improvements.		
Metric	**2010 Status**	**2015 Target**
Throughput (Units per hour)		2x increase
Cost of Ownership		2-3x reduction every 5 years
$/Units per hour		

Discussion Points

- In order to move to smaller color bins we need to have measuring equipment with high enough resolution. Such equipment would significantly help improve color control. Standards that ensure color measurement accuracy would also be helpful.
- There was a strong emphasis on the need to develop test equipment compatible with rapid, accurate and reproducible measurements of flux and color for devices under typical operating conditions (i.e. hot testing). It will also be essential that hot testing equipment have a reasonable cost of ownership and throughput.
- Integrating the metrology tool more closely with the manufacturing tool to improve yield, increase throughput, and reduce cost. This could include advanced in-situ monitoring tools for MOCVD equipment, or integration of the ex-situ metrology tool into the manufacturing equipment.
- In-situ monitoring of MOCVD is important to improve yield and uniformity, both of which need to be improved.
- It was also suggested that we needed to develop tools and testing equipment that focus on reducing the yield-critical defects. This could be accomplished through the implementation of

integrated photoluminescence (iPL) channels which can be used for enhanced classification of yield-relevant defects.

- For this task it was suggested that cost of ownership and cost per unit per hour be added as metrics with 2015 targets of a 2-fold increase and 2 to 3-fold reduction every five years respectively.

M.L7. Phosphor Manufacturing and Application		
This task supports the development of improved manufacturing and improved application of phosphors (including alternative down converters) used in solid state lighting. This could include projects focused on continuous processing of phosphors to increase production volume and manufacturing techniques to improve quality, reduce performance variation, and control particle size and morphology. This task also supports the developments of phosphor materials, application materials, and techniques which improve color consistency of the packaged LEDs and reduce the cost of LEDs without degrading LED efficacy or reliability.		
Metric	**2010 Status**	**2015 Target**
Phosphor Manufacturing		
Batch size (kg)	1-5	>20
Cost ($/kg)		50% reduction every 2-3 years
Material Usage Efficiency	50%	90%
PSD-range Uniformity	30	10
Duv Control	0.012	<0.002
Phosphor Application		
Thickness Uniformity (1 sigma)%	5	2
Cost ($/klm)		50% reduction
Device to Device Reproducibility (SDCM)	4	2

Discussion Points

- Continuous processing (as opposed to batch processing) has the potential to significantly reduce phosphor manufacturing costs.
- Areas for improvement of phosphors include: uniformity, chemical stability, thermal stability, and thickness control during application.
- Improving the excitation consistency of phosphor materials could improve downstream packaged LED yields. In other words, the emission profile should be made insensitive to slight variations in excitation wavelength. Though matching the pump to the phosphor is possible, it is very costly and not a long-term solution.
- Better control of particle size and morphology has the potential to reduce the phosphor cost by 50% and increase yield.
- Although the phosphor constitutes only a small portion of the overall packaged LED cost, reduction in phosphor variability could result in not only reduced phosphor cost, but also a large reduction in the packaged LED cost through improvements in yield. DOE should analyze the effects that yield has on cost.
- Deposition of phosphor materials without dams could also be a useful area of research.
- It was also mentioned that MacAdam ellipse is not an appropriate metric for color variation.

General Discussion Points

- The importance of improving wafer yield was stressed throughout the roundtable event, as well as stability and quality.
- It was also indicated that funding for moving to larger wafers (8" and beyond) should only be considered for leap frog advancements. The industry will provide incremental improvements.
- Some barriers associated with 8" wafers are: wafer bow, performance, wavelength uniformity, wafer thickness, and wafer handling.
- Some participants felt that there should be a focus on making LED manufacturing compatible with existing CMOS manufacturing lines in order to distribute costs until volumes increase. However, there are several barriers such as material incompatibilities (e.g., gold).
- Though GaN on Si has potential cost improvements, participants were concerned that by the time DOE funds this task, the industry will have already achieved those price points.
- Though there was a lot of discussion on this task, it was also mentioned that currently DOE is funding quite a few projects in this area and also planning to prioritize "Alternative Substrates" as a product development task. Perhaps many of the needs can be met through product development, rather than manufacturing, projects.
- It was suggested that machine utilization, operational efficiency and overall utilization and availability be incorporated as metrics.

Overall projections/contributions to cost reduction

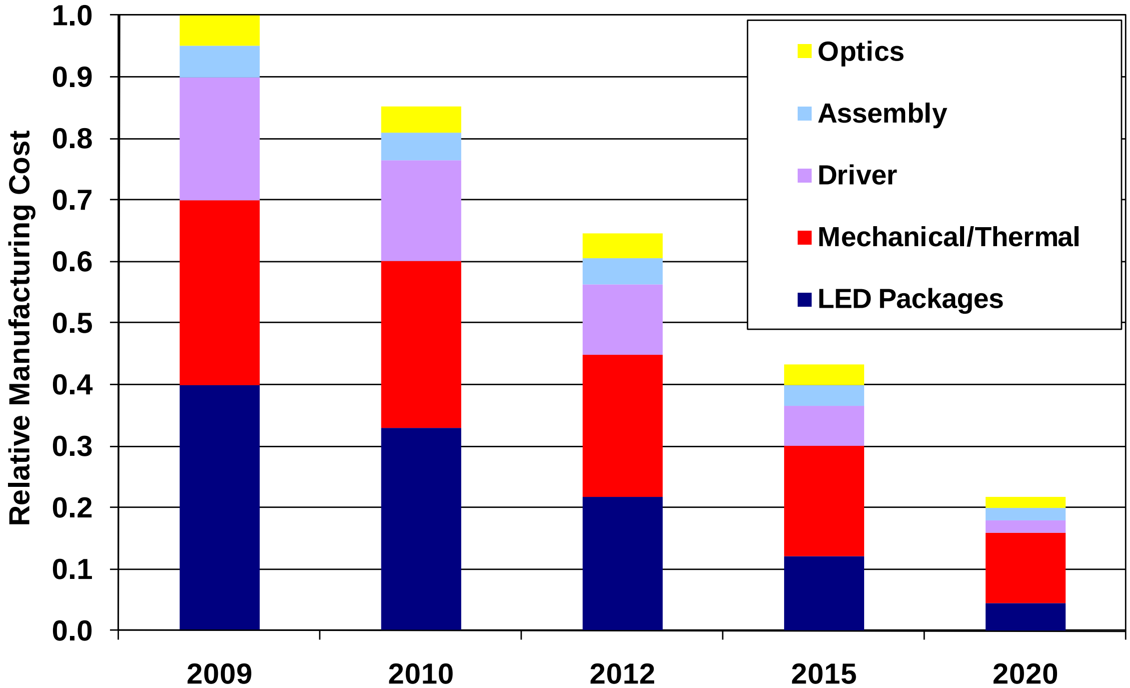

Figure 1. Projected LED Luminaire Cost Track
Source: DOE Manufacturing Workshop consensus

Discussion Points

- It was indicated that the 2020 goal is not aggressive enough, and it was suggested that the $/klm for an LED luminaire will reach 35% of the 2010 price by 2013, and that by 2015 the price will be $10/klm, and $5/klm by 2020 (warm white) compared to approximately $50/klm in 2010.
- It was determined that the 2012 (similar to now) price breakdown for a downlight is 15% mechanical/thermal, 50% LED packages, 20% driver, 10% optics and 5% assembly. These numbers need to be verified.
- For an outdoor or commercial fixture the price breakdown is approximately 40% mechanical/thermal, 15-20% optics and 30% LED package. These numbers need to be verified.

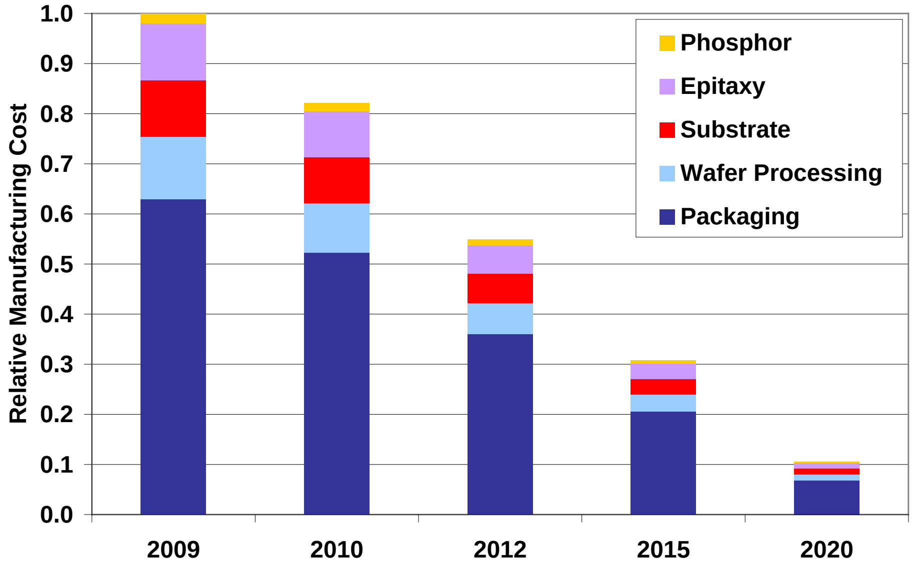

Figure 2. Projected LED Package Cost Track.
Source: Preliminary data provided by the Cost Modeling Working Group

Discussion Points

- In mid-2011 the breakdown of LED package cost was estimated at 35% for packaging, 20% for epitaxy, 20% for wafer processing, 10% for substrate, and 10-15% for phosphor.
- It was indicated that the relative cost in 2015 should be changed to 0.1 and that overall the packaging component will drop much faster than originally projected.
- There was also a suggestion to project LED costs on a $/klm basis. It was predicted that on the $/klm scale we will see a factor of four improvement in four years.
- It was suggested that the charts for luminaire and package be merged as we look forward to 2013.

Table 1. LED Metrics Roadmap (Updated)
Source: DOE MYPP

Metric	Unit	2010	2012	2015
LED Efficacy (2580-3710K, 80-90 CRI)	lm/W	88	128	184
LED Price (2580-3710K; 35 A/cm2)	$/klm	25	11	3
LED Efficacy (4746-7040K, 70-80 CRI)	lm/W	134	173	215
LED Price (4746-7040K; 35 A/cm2)	$/klm	13	6	2
OEM Lamp Price	$/klm	50	28	11

Discussion Points

- The LED lamp price is at $50/klm for 2010 and will be approximately $10/klm by 2015. These values should also be reflected in the DOE SSL Multi-Year Program Plan (MYPP).

Presentations

1. **LED Yield Management**
   Rich Solarz, KLA-Tencor

2. **GaN Deposition Thermodynamics and Kinetics**
   Bill Quinn, Veeco

- We now have chemistry models that are capable of analyzing what is happening at the molecular level on the surface of wafers
- Veeco has developed a three dimensional chemistry model that utilizes simplified K465i reactor geometry for flow dynamic (FLUENT) and gas phase/surface chemistry modeling (CHEMKIN)
  - o The model provides both the concentrations and temperatures in the deposition layers
- The model indicates that during deposition there are a few forces that you need to balance, and that there is a natural buoyancy which can be negated by heating the gases as they are released
- These higher temperatures produce a larger stability region and a larger stable process window. At the higher gas temperatures we get a higher growth rate of GaN, as well as an increased metal-organic efficiency of 30%. Also, this allows for a reduction in gas flow by 40%.
  - o Interestingly, the model was excellence at predicting the flow dynamics; however, it did not predict the greater deposition. Therefore, we need to continue the model development in order to more accurately predict this type of phenomenon.
- Questions/Comments:
  - o How accurate were the chemical predictions at lower temperatures?
    - ▪ The predictions are within a 10% accuracy, but are only within a 60% accuracy at high temperatures
  - o Very little study has gone into what happens to gases during deposition phases. And to make a new chemistry model we need to redo equipment. For instances we would want to modify the chamber and insert measurement probes since understanding the chemistry is essential to designing better future reactors.

3. **MOCVD Technology Trends Towards Higher Productivity**
   Rainer Beccard, Aixtron

- Rainer stressed that it is essential that manufacturers begin the conversion to larger wafers
- The conversion from 2” to 6” wafers offers a 30% throughput improvement without adding extra cost
- Furthermore, when looking at the potential for conversion to 8” wafers and beyond the technology is already there. There are issues with the substrate, but we also need to determine whether there is a need to go to wafers of this size.
  - o GaN/Si is standard for power electronics and we need to look to this for LED manufacturing
- There are several challenges associated with going to larger wafers, therefore we need more advanced in situ metrology, advanced automation and fabrication integration (MES/APC), as well as standards for large wafers, Si substrates and automation
- Questions/Comments:

    - Are there science questions that need to be solved before we can get to high efficacy on larger wafers?
        - We are more concerned about the basic chemistry, but we can do it.
    - Where does this fit into the SSL evolution? Is going to larger wafers something that we need to use our funding for? Will it go to HB LEDs in general (i.e. displays)?
        - A participant commented that we need 8" GaN on silicon. The industry can take care of the move from 2" to 3" and 4" to 5", but we need funding for a game changing size increase. Furthermore, we need to move to silicon to better the chances of keeping LED manufacturing in the US since the infrastructure is already there.
        - Lighting will drive the cost curve down – more so than displays – the lighting people have to solve more complex problems than the display industry does.

4. LED Manufacturing Workshop
Andrew Hawryluk, Ultratech

- The industry is now closely approaching the development of a 100 lm/W bulb and the opportunity for us to deploy these products will allow the U.S. to dramatically reduce energy consumption.
- We also need to focus on getting the cost down to roughly $10/bulb. Costs of this magnitude will allow for significant consumer adoption
- In order to reach these cost goals we need to focus on tying R&D improvements to LED manufacturers tools and equipment
    - We do not need more efficient LEDs that are not manufacturable and that do not have cost-effective equipment lined-up for deployment
    - R&D funding should be coupled to the manufacturer and it should be required in all proposals that a pathway to manufacturing is presented
- Questions/Comments:
    - What kind of manufacturers should get involved on the R&D side?
        - Depends on the project proposed. If the project submits a design for improvements to the LED driver, they need to have support from driver manufacturers.

5. Key Specifications and Jobs
Vivek Agrawal, Applied Materials

- There is a trend and focus on the binning of LEDs, therefore, considerable expense in the LED lighting supply chain is in managing LED non-uniformity.
- Impressive gains in the past five years have been made to reduce the size of those bins which is due to both improved process uniformity and epi tools.
- In addition, we also need to focus on driving electronics pricing down through various LED improvements including – higher luminous flux, higher QE, smaller chip size, fewer chips, and potentially the development of power electronics on GaN.
- Manufacturing jobs historically move closer to the customer and the growth of foreign LED manufacturers (number and size) poses a long-term risk to well-paying U.S. manufacturing jobs

in this sector. Therefore, US policy must drive not only LED adoption in the U.S., but help U.S. LED manufacturers compete financially as well as technologically.

  - To achieve this, the US should recognize manufacturing centers of excellence, provide subsidies for LED manufacturers and tool makers that are competitive with foreign governments and provide educational grants focused on LED manufacturing.

- Questions/Comments:
  - The wind and solar industries have focused on creating jobs in the U.S. We need to focus on how to do this for LEDs – we need to be able to say how many U.S. jobs LED manufacturing provides each year
    - We should be able to estimate how many jobs LED manufacturing has created through the use of an anonymous survey.

6. SSL Manufacturing
Steve Paolini, Lunera

- Steve indicated that the most important themes that LED manufacturing funding should focus on are consistency, verification, cost, reliability, life cycle, and lifetime. Reliability being extremely important.
- We need to be investing in luminaire manufacturing in order to improve the reliability and quality of the products that we produce. Specifically we need to look at:
  - Improving the color control and quality
  - Making white light – need to look at phosphor manufacturing and deposition, as well as moving to RGBA
  - Finding ways to reduce or recycle mechanical structures – aluminum, steel, plastic, glass
  - Improving diffusers since a significant amount of light is lost here
- Questions/Comments:
  - Which is the most important factor with respect to manufacturing?
    - We need to be moving to better color control and the elimination of binning. The wavelengths should all be within a few nanometers.

7. Advanced Manufacturing Technologies for Affordable LED Lighting Products
Doug Seymour, Osram Sylvania

- Doug highlighted that many people do not like compact fluorescent lamps (CFL), and they would like to buy LEDs however, they look at the price of LEDs and are left with no alternative.
- In addition, people cannot synthesize the idea of how longer LEDs last. The concept of a 50,000 hour lifetime does not help influence their purchasing decisions.
- Therefore, we need to focus on reducing costs so that LEDs can begin to adequately compete with incumbent replacement lamp technologies.
- Furthermore, LED fixtures provide a lot of opportunities including intelligent controls, changing their color rendering, and new form factors which have the potential to create a higher level of customer value.
- LED manufacturing should also consider the development of supply chains that allow for mass customization where components can be combined to create custom luminaires cheaply and effectively. This mass customization would reduce production lead-time and lower inventory requirements.

- Questions/Comments:
  - Is it your option that we need to focus on means for assembly?
    - Yes, we need to think about how we are going to launch a new product and find more ways to mitigate these costs in the U.S.

8. Fred Maxik, Lighting Science Group

- Fred emphasized that SSL has evolved very nicely, however the technology is still in its infancy and what we know today is not what we will be making in the future. Therefore, we need to focus on what improvements will allow for leap frog advancements
- In addition, it is important that LED manufacturing remains in the U.S. which is possible considering the advanced materials research being conducted domestically. We need to look at the manufacturing space and determine which processes can be automated to maintain a technology base in the U.S.
- Questions/Comments:
  - Where should we automate?
    - Tack time – need to move to directly placing LEDs on substrate while eliminating extra stuff. We also need to consider how we could attach LEDs to different materials which could reduce tack time upwards of 30-40%. This would also reduce the cost of the lamp.

9. Mark Hand, Acuity

- Right now the focus is on developing a high power chip, however, this does not necessarily need to be the near term target for manufacturing. Customers always ask about the cost per lumen.
- In order to begin to see significant market penetration we need to get the die cost down to a negligible level
- Furthermore, the luminaire manufacturers are concerned with high efficacy, however, the package does not have to have high lumen levels. The efficacy is most important.
- Comments/Questions:
  - People think that SSL is the semiconductor industry which was primarily driven to larger wafer sizes by an increasing die size; however the same jump to large die area does not necessarily apply. Currently we do not know where SSL will go in the near term because for some applications it makes sense to keep the wafer small.

10. LED Manufacturing Now and in the Future
Steve Lester, Bridgelux

- GaN needs to start taking advantage of manufacturing technology used in the silicon industry. If this technology can be applied to LEDs this will have significant benefits in the form of lower substrate and wafer fabrication costs and the ability to leverage the existing silicon fabrication capacity. All of this will enable the development of new LED chip architectures that were not previously possible.
- The micro structure of GaN-on-silicon is similar to GaN-on-sapphire, and also allows for performance within 90% of the best sapphire-based LEDs.

- The development of 8” GaN on silicon could significantly reduce costs and, through the use of existing 8” CMOS fab capacity, would offer the potential to help keep LED manufacturing in the U.S.
- Comments/Questions:
    - What about in-compatibility of materials used in GaN processing with CMOS processing such as the use of gold?
        - A gold-free LED process would need to be developed, possibly using aluminum.

11. Testing Challenges
Iain Black, Lumileds

- The challenges for high brightness LEDs are manufacturing capacities, capabilities, process control, and color control. There is a pressing need for standards and for improved measurement accuracy. For example, equipment used to measure the chromaticity characteristics of LEDs requires ever higher resolution capabilities as the color bins continue to get smaller.
- Iain cited a variety of issues with current metrology and wafer testing. These include:
    - The underdevelopment of pyrometer technology which continues to be an effort on part of several companies.
    - Wafer bow measurement, is desirable but still not adequate.
    - Defect inspection tools like Candela are widely used but still being developed.
    - PL & Xray technology is underdeveloped. And in the case of Xray we are still using tools originally developed for other industries.
    - For wafer testing the resolution of testers and ability to match inside of one nanometer for color binning are potentially a serious concern for future.
- For device testing Iain also indicated that we need to move to specifying LED hot performance
- Furthermore, because there are no standards, manufacturers need to discuss how best to do hot testing or we may place funding and effort in the wrong equipment, in addition to adding more confusion to the specifications of LEDs.
- Questions/Comments:
    - Do all LEDs need to be hot tested?
        - No, they do not. The volumes are so large so even if testing 5% or 10% that should be a representative sample. Right now we do not have enough data and we need to do a significant amount of hot testing so that we can discover where the problem areas are.

12. Manufacturing of Nitride & Oxynitride Phosphors for SSL
Yongchi Tian, Lightscape Materials Inc.

- Nitrides and oxynitride phosphors are ideal color converters for pcLEDs, and the real advantages are their thermal stability and that the materials and processes employed are environmentally benign.
- However, the demand for these materials is expected to surge in the next 5-10 years and there is a limited production capacity which is mainly supplied by Asia.
- Therefore, in order for pcLED to transition to using nitride and oxynitride phosphors there are a variety of hurdles that need to be addressed. These include:
  - Scaling up the throughput process to multiple kg/batch, significantly shorten process cycle time, and simplify processes such as precursor preparation and post-treatments.
  - In addition, there needs to be a significant increase in batch-to-batch consistency and improved controllability of processes.
- Questions/Comments:
  - Is there IP that will limit U.S. manufacturing?
    - Yes, this field is highly IP sensitive. Currently IP is owned by Mistibushi and the National Institute of Material Science (Europe and Asia).

13. Mike Pugh, Intematix

- There is a significant amount of potential for phosphor manufacturing in the U.S. However, in order to realize this potential there is a need to standardize the processing which is currently a hybrid of batch and continuous processes.
- In addition, current LED phosphors use heavy rare earth metals which are 100 times less prevalent in nature and China supplies approximately 97% of these materials. Therefore, there is a need to move away from such phosphors and mitigate the risks associated with utilization of these rare earth metals.
- We need to utilize those phosphors that incorporate very little rare earth content, such as silicates and nitrides, or develop substitutes such as quantum dots. Furthermore, we need to find alternatives to what is used in the CFL Industry since about 70-80% of all rare earth material goes to the production of CFL and CCFL lamps.
- Lastly, we need to find materials that will limit IP interference.

DOE LED Roundtable Participants

Vivek Agrawal	Applied Materials
Rainer Beccard	Aixtron
Iain Black	Philips Lumileds
Mark Hand	Acuity
Andrew Hawryluk	Ultratech
Steve Lester	Bridgelux
Fred Maxik	Lighting Science Group
Steve Paolini	Lunera
Mike Pugh	Intematix
Bill Quinn	Veeco Instruments, Inc.
Doug Seymour	Osram Sylvania
Rich Solarz	KLA-Tencor Corporation
Yongchi Tian	Lightscape Materials, Inc.