



the INSTITUTE *for*
ENERGY EFFICIENCY

White Paper Summarizing Findings of a One-Day Workshop

Fast-Tracking Widespread Adoption of LED Lighting

May 2010

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UC Santa Barbara

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Executive Summary

Lighting consumes approximately 19% of the electricity used in buildings in the United States.¹ Much of that electricity is consumed by technologies that are outdated or inefficient. Light emitting diode (LED) technology holds the promise of replacing those technologies with a solid-state solution that is long lasting, more efficient and has a lower total cost of ownership. LEDs are emerging in the general illumination market in applications ranging from commercial down lights to outdoor street lamps. In parallel with this nascent market penetration, LED researchers continue to make significant technological breakthroughs that improve light output, quality and efficiency while reducing cost.

The Institute for Energy Efficiency at the University of California Santa Barbara convened a one-day workshop to discuss the status of LED technology, evolving LED markets, and appropriate actions to support and facilitate greater market penetration. Several outcomes and recommendations flowed from this discussion, including:

- Support LED R&D activities –pre-competitive and competitive research that will improve efficacy and reduce cost, such as efficiency droop, thermal droop, phosphors, light extraction and driver performance. This may lend itself to the formation of a SEMATECH-type consortium of LED companies with government backing, or simply generate more support to existing projects and programs investing in LED IP.
- Support the development of industry testing standards that measure performance attributes of LED lamps and systems accurately and fairly. New technologies require the development of new standards and metrics, and equitable testing that enables comparison across a range of light source technologies will be important for LEDs to compete in the general illumination market. Supporting work like the development of the Color Quality System (CQS) and industry test standards like LM-79 (Electrical and Photometric Measurements of Solid-State Lighting Products) and LM-80 (Measuring Lumen Maintenance of LED Light Sources) will position LED technology for market adoption. Additional standards are being developed which will further clarify and improve methods of measuring LED product performance and compatibility.
- Encourage consumer education about lighting through marketing campaigns, product labeling, and quality marks (e.g., ENERGY STAR). Moving from the 60-watt incandescent lamp to understanding lumen packages and some essential light quality issues will enable consumers to make appropriate, informed choices, with the objective of helping customers recognize quality on the shelf.
- Develop quality performance specifications and link those to market transformation programs such as utility rebate schemes or other marketing efforts. This will minimize free-riding and will ensure consumers participating in the scheme receive a premium quality product. The LED quality performance specification could also be adopted by a regulatory entity that operates in the interests of consumers.
- Identify and develop policies to address affordability, initially targeting the commercial sector through tax incentives, enhanced capital allowance schemes, and/or direct subsidy, then later, as the technology improves and becomes less expensive, develop programs to support market adoption in the residential sector.
- Conduct enforcement testing of commercially available products on an on-going basis to protect consumers and honest companies alike. Unscrupulous manufacturers who exaggerate performance metrics can undercut honest companies, resulting in lost revenue and duped consumers. Expanding the CALiPER program, an on-going testing program can serve as an honest-broker in the market by constantly testing products sampled from store shelves and measuring performance against statements made on the packaging.

¹ Calculated from Buildings Energy Databook, 2010 U.S. Buildings Energy End-Use Splits, by Fuel Type <http://www.btscoredatabook.net/TableView.aspx?table=1.1.5>

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Acronyms and Abbreviations

AC	Alternating Current
BOM	Bill of Materials
CAGR	Compound Annual Growth Rate
CCT	Correlated Color Temperature
CQS	Color Quality System
CRI	Color Rendering Index
DC	Direct Current
EPA	Environmental Protection Agency
Hz	Hertz
IP	Intellectual Property
LED	Light Emitting Diode
lm/W	lumens per watt
MOCVD	Metalorganic Chemical Vapor Deposition
RGB	Red Green Blue
RGBA	Red Green Blue Alpha
SEMATECH	Semiconductor Manufacturing Technology
TV	Television
UCSB	University of California Santa Barbara
UCSD	University of California San Diego

1. Introduction

According to a global lighting study by the University of California Santa Barbara (UCSB), the market adoption of energy-efficient white-light LEDs could save the equivalent of 380 new power stations in general illumination applications world-wide.² The Institute for Energy Efficiency at UCSB convened a workshop in February 2010 to bring together industry leaders and market transformation experts to explore the barriers to and solutions for facilitating widespread market adoption of LED-based lighting systems. The workshop was designed to distill and focus on the most salient problems and solutions for accelerating market adoption of LED lighting technologies.

The conversations centered on barriers to widespread adoption of LED lighting, on solutions to expedite adoption, and on participants who can champion those solutions. The workshop was structured around four discussion topics: LED Research and Manufacturing, Lighting Applications and Systems, Commercialization, and Economics.

2. Research and Manufacturing

Decades of research on LED technology are yielding dividends. LED technology is fulfilling its promise of offering the market the most efficient means of converting electrons into photons. For example, Cree recently announced it had achieved 208 lumens per watt (lm/W) in a single power white LED in the laboratory,³ and experts are now projecting a device-level efficacy maximum potential of 250 lm/W (UCSB) to 280 lm/W (Philips). The following figure depicts the improvement of lamp efficacy over time of incandescent, fluorescent and other conventional technologies as well as LED. The improvement of LED has occurred at a much more rapid pace, and promises to exceed the performance of all other conventional technologies within five years. Furthermore, in addition to being highly energy-efficient, good quality LEDs offer the market long life (in excess of 50,000 hours), have no filament or glass envelope to break, offer a small form factor and are mercury-free in their construction. Good thermal management of LED products will be critical to ensuring these performance attributes are met.

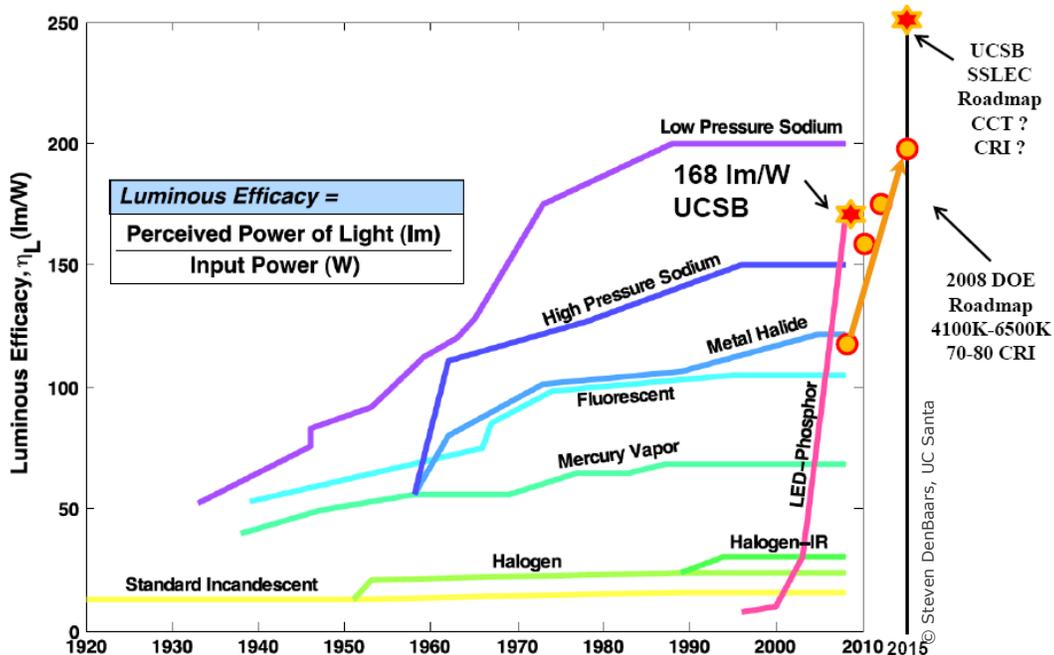


Figure 1. Trend of General Illumination Lighting Technology Efficacy over Time

² UCSB study assumes the widespread deployment (50% market penetration) of a 150 lm/W white-light LED.

³ Cree Press Release, February 3, 2010. Single power LED tested with a CCT 4579K, at standard LED test of 350 mA and room temperature. http://www.cree.com/press/press_detail.asp?i=1265232091259

Although LED devices operating in excess of 200 lm/W have been developed, there is still considerable research that remains to be done on the technology itself and on addressing the cost of manufacturing LEDs. Research to overcome and resolve this issue will be critical to ensure that high-brightness LED packages are available for general lighting applications. The five main priority areas for research to reduce the cost per lumen are as follows:

1. Efficiency droop – LED internal quantum efficiency declines as current increases, or, in other words, LEDs tend to be most efficient when operating at low-currents. The cause of this reduction in efficiency is not yet fully understood but is believed to be caused primarily by Auger recombination and Shockley–Read–Hall or other non-radiative recombination and defects. Tests have shown that the efficiencies can drop from 150lm/W to as low as 70 lm/W at higher current densities.
2. Thermal droop – heat in the LED chip also causes a reduction in efficacy. When LEDs are operating in a fixture, the junction temperature can get very hot - 120°C – and the efficiency can drop by 20 or 30%. More research is needed to fully understand this phenomenon, but it is believed that part of this problem is caused by Auger recombination. Researchers have found that some of the negative impact can be mitigated through good thermal management in the chip packaging.
3. Phosphor – good phosphors are critical to ensuring that consistent, quality white light is available for general illumination. The wavelengths driving these phosphors can also have an impact – shifts in the blue or UV source driving the phosphor can cause the white light to be noticeably different. MOCVD reactor manufacturers are working to improve production processes and tighten up the emission wavelengths.
4. Light extraction – packaged light extraction is currently at 80% efficiency and we believe another 15% can be achieved through roughening, high-reflectors, exotic structures and shapes, photonic crystals, and other extraction efficiency structures.
5. Electrical efficiency – the best DC-drivers for LED lamps are 92 to 93% efficient. Researchers are working on a new set of drivers, and several companies are working on “driverless” lamps which are directly driven by AC. Experts estimate driver efficiencies upward of 98% or higher can be achieved.

The internal quantum efficiency droop is also an issue with red-green-blue (RGB) emitters, where researchers are working to fill the green light LED gap. One question being investigated is whether semipolar chip performance can be doubled to help solve the green gap, helping RGB emitters surpass the efficacy of phosphor-based LED packages.

The US Department of Energy's Solid-State Lighting roadmap projects a rapid reduction in the price of LED lighting (see Figure 2). This forecast anticipates that manufacturing costs will fall while light output is increased, particularly at high drive currents required for general lighting applications.

Experts are also looking to make LED lamps compatible with standard dimming circuits, designed for use with incandescent lamps. Through proper driver electronics design, an LED lamp can be made dimmable over a wide range of light output – either through lower current or

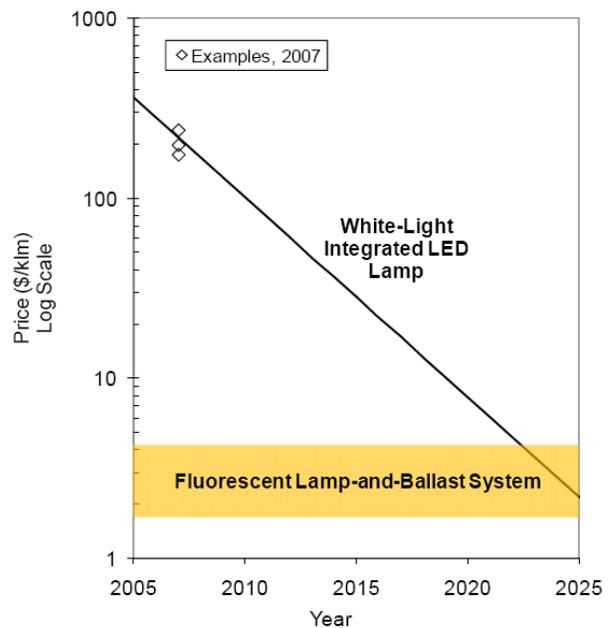


Figure 2. Price Forecast for White-Light Integrated LED Lamp

by modulating the power supplied to the LED. Furthermore, research is needed to facilitate the integration of LED systems with on-site renewable energy systems, smart grids, zero net energy buildings and utility demand response programs.

Researchers have an ambition to manufacture 250 lm/W white-light RGB LED systems that run on AC-current, have 100,000 hour lifetimes, offer a rugged form-factor, contain no mercury, are versatile and are cool in operation. Such devices would have the potential to dramatically transform the lighting market, providing people with reliable, attractive and high quality light sources that are as permanent as the plumbing and wiring in their homes.

3. Lighting Applications and Systems

As LEDs move into general illumination applications, the importance of color and light quality will become increasingly important. The LED market is evaluated and specified by correlated color temperature (CCT). Right now, the market is evaluated by CCT and so-called bins or groups of similar light-emitting devices. Standards committees have allowed for 7 MacAdam steps, or bins that limit the amount of variability you can have in color before it becomes noticeable. Figure 3 below presents 7-step MacAdam ellipses, around which the eight nominal CCT quadrangles are constructed (i.e., 6500K, 5700K, 5000K, etc.).

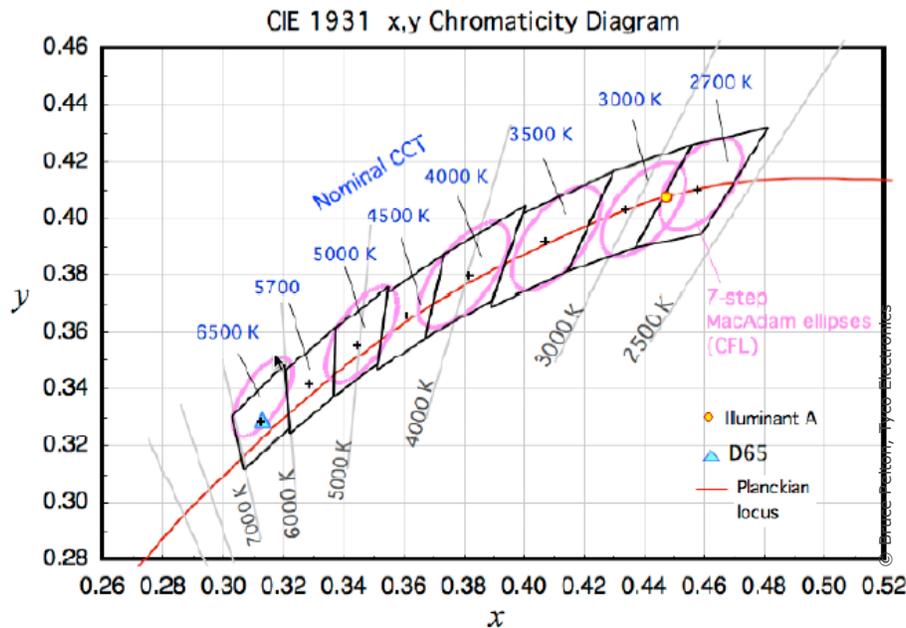


Figure 3. CIE 1931 Chromaticity Diagram Showing the Eight Nominal CCT Quadrangles

Although 7-step MacAdam ellipses are allowed by industry standards, the market has found this flexibility on the quality of white-light is too coarse and results in perceivable differences in light color from the same nominal CCT quadrangle. In general, manufacturers have found that using LEDs that are greater than four MacAdam steps will result in excessive color variance and will not constitute a quality product that consumers will support. Manufacturers have therefore established sub-bins (i.e., A, B, C, D) within the eight CCT color bins to improve the quality of light. Purchasing LEDs exclusively from one of these sub-bins comes at a price premium (approximately 30% more), but is necessary to ensure that a lamp or luminaire supplied to market will have consistent, quality light over a typical product lifespan of 3-years.

In addition to CCT, another quality measure of a light source is the color rendering index (CRI). The CRI is a metric intended to measure how well a light source is able to render colors accurately. However, the index was developed through the use of eight non-saturated colors, under an incandescent reference lamp, with a limited group of subjects. Experts have recognized its shortcomings, particularly as a measure of light quality for LEDs. Wendy Davis and Yoshi Ohno of the National Institute on Standards and Testing (NIST) have developed a new system to replace CRI called the Color Quality System (CQS) – see Figure 4 below. CQS uses true, saturated colors, across the full spectrum. It's a much more realistic measurement across the spectrum, and really measures the source for how well it illuminates the colors. CQS is being reviewed as a possible new international standard metric for color rendering, and is accepted by the EPA as an alternative to CRI measurements for LED luminaires.



Color Rendering Index (CRI)



Color Quality System (CQS)

© Yoshi Ohno, NIST

Figure 4. Color Palette Comparison Between CRI and CQS

These measures are important because they are quality metrics that will further ensure consumer satisfaction with LED products. A key challenge of LED products is to take a monochromatic light source and transform that source to cover a broad color spectrum. The most common solution today is similar to a fluorescent lamp, where phosphors are excited by a blue or UV-light LED. The new approach, and potentially more efficient method, is to blend together the light emission from red-green-blue (RGB) light sources, to create better quality white light. And, during this transitional period, there are hybrid products appearing on the market that blend the light of a cool-white LED source with red and amber LEDs, to create a warm-white.

In addition to quality issues on the light emission, there are also quality issues that relate to the physical construct of the LED product. As discussed earlier, thermal droop is responsible for reducing the efficacy of the LED device, but it can also affect the performance of the phosphor, causing the light color to shift and the spectral coverage to shorten. To address thermal droop, manufacturers are looking at heat sinks, thermal heat pipes, fans and other means of improving heat extraction from the LED package. One group of researchers addressed the problem of phosphor heating by using a remote phosphor (i.e., separating the LED package and the phosphor), significantly reducing the thermal impact on the phosphor.

Another critical aspect of providing a quality LED product to market is to have efficient, long-lasting LED drivers that incorporate reliability engineering into their designs.⁴ However, it is difficult to find drivers which will be able to last as long as the LEDs they are controlling. Furthermore, ensuring electrical system compatibility of LED drivers is critical to enable LED products to withstand common everyday electrical disturbances (e.g., voltage sags, voltage surges, etc.) that can shorten the life of electronic lighting products. Industry has already demonstrated that one cause of short LED driver life are electrolytic capacitors, which cause the drivers to fail before the LEDs themselves. Related to commercially viable products, when used in outdoor and industrial applications, LED drivers must incorporate voltage surge protection to reduce the likelihood of damage LED product from surges that occur in the electrical system.

4. Commercialization

LEDs represent a complex system with a great deal of interplay. Factors that have to be taken into consideration include the driver, the control, the optics, the LEDs, thermal issues, surge protection and interconnection. Addressing these factors will enable the construction of an acceptable mass-market product. Could a future market evolve where consumers pay for the light itself – the quality and controllability of the light, not just the style of the light fixture?

Other practical factors of commercialized products include the ability to have equivalent replacement parts over a period of years, when the market for LEDs is moving so quickly. Also, warranties must be offered for products, to protect consumer interests – particularly for this new, unfamiliar technology. Finally, installer training is a critical part of the LED revolution, so that the electrical contractors who are charged with installing these products receive the necessary specialist training to ensure they handle LED luminaires safely and properly.

There are a number of standards-making bodies who are working on LED standards now. Many standards are established or are under development, including the Illuminating Engineering Society, Underwriters Laboratories, American National Standards Institute, the National Electrical Manufacturers Association, the International Commission on Illumination, and several others. These groups are working in partnership with stakeholders to develop standards which will protect consumer's interests and in the process, the LED market.

Manufacturing scale will continue to drive down production costs. As production volumes increase, companies will gain a competitive advantage as fixed price per unit LED declines. Using data from Cree's 2008 annual report, McKinsey estimates that companies operating at 2 billion units per annum are able to produce LEDs for approximately 20% less than those producing a half billion per year, based on assumptions on fixed and variable cost, and cost of expanding production.

One factor that will greatly facilitate commercialization of LED technology will be the standardization of the interconnects used. On an international level, Philips has initiated the establishment of the Zhaga consortium⁵ to discuss and develop a set of LED interconnects. This consortium has broad support from a range of players in North America, Europe and Asia, including Cooper, Philips, Toshiba, OSRAM, Panasonic, Zumtobel, Acuity Brands, Havells Sylvania, General Electric and Tyco Electronics. With over 23 members participating in Zhaga, the group is defining interfaces for a variety of application-specific light engines. These standards will address physical dimensions, as well as the photometric, electrical and thermal behavior of LED light engines. By standardizing the interconnects for lamps, consumers will be able to replace LED light engines that fail in their new fixtures rather than have to purchase a whole new fixture and/or have it installed.

⁴ Keebler, P.F., Fortenbery, B.D., Phipps, K.O. "LED Lighting Systems: Market Status, Applications, and Power Quality Concerns and Performance", EPRI Power Quality Applications Conference, 2006.

⁵ Zhaga consortium is an industry-led effort aimed at the development of standard specifications for the interfaces of LED modules within fixtures. Zhaga will enable interchangeability of LED modules between products made by various manufacturers. For more information, visit: <http://www.zhagastandard.org/>

The high brightness LED application market growth rate is extremely high. McKinsey estimates that this market, consisting of general lighting, backlighting (for TV, monitors, computers), and automotive lighting is projected to grow from \$10bn in 2009 to \$78bn in 2015. In the next 2-3 years, players in the backlighting market will dominate, but eventually general lighting applications will constitute the largest market share. General lighting grows from \$2bn in 2009 to \$38bn in 2015, a CAGR of approximately 66%.

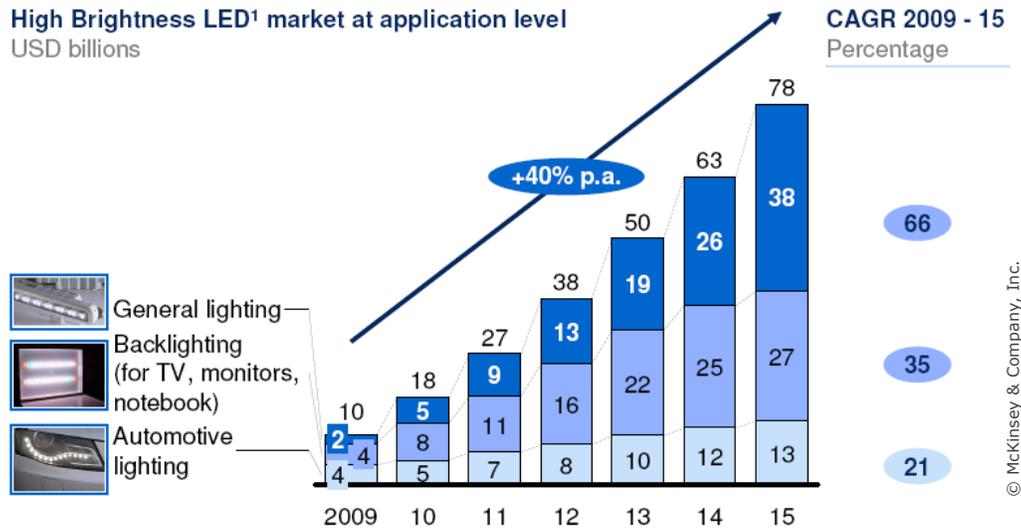


Figure 5. Projected High Brightness LED Growth 2009 to 2015 for General Lighting (2009)

The global LED general lighting value chain is concentrated for epitaxy/chip and packaging with ~80% of the market covered by four players, contrasted with a very fragmented module and luminaire manufacturers space with dozens of players with small market shares. Five players dominate the epitaxy / chip manufacturing upstream part of the value chain for general lighting – Philips Lumileds, Osram, Cree, Nichia and Epistar. And moving along the value chain to the LED module and luminaire manufacturers, literally hundreds of players that must be accounted for in order to reach 80% market share. On this value chain, there is really only one vertically integrated company – Philips – which, through its acquisitions of Lumileds, Color Kinetics and Genlyte in the last years, has a relatively strong presence in all stages of the value chain.

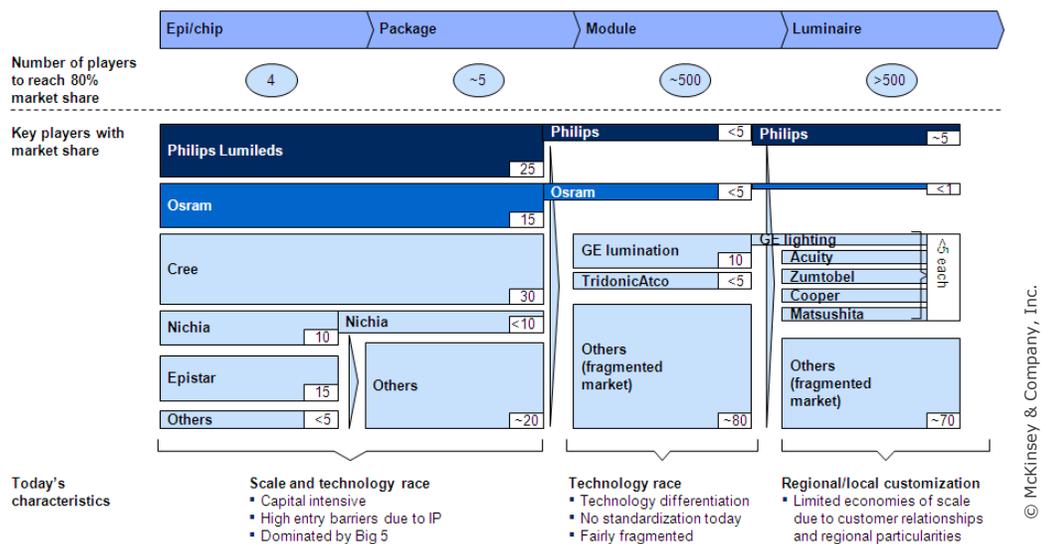


Figure 6. High Brightness LED Value Chain Assessment

The upstream players in the LED general lighting value chain are protected by high barriers to entry. Entrance into the epitaxy/chip and packaging part of the value chain, is intensive on both capital and intellectual property. For modules, the market is fairly fragmented, with limited technology differentiation, and there is no standardization on module interconnections in place, although the Zhaga consortium mentioned earlier is working toward standardization. Luminaire manufacturers are focused on local customization, and there are limited opportunities for economies of scale due to customer relationships and regional market differences.

In the general lighting value chain, the capital expenditure is much higher for upstream players, and associated margins are higher for this segment of the value chain as well. The largest players in epitaxy and chips, including Nichia, Osram Opto, Cree, and Lumileds, own most of the intellectual property licenses, and consequently have the highest gross margins in the business. Other smaller players in the business, both those in epitaxy growth and chip processing and packaging and applications, the margins are lower.

McKinsey sees four significant trends in the general lighting industry structure:

- 1) A small number of players will continue to dominate chip / packaging market and the industry is unlikely to fragment. Scale will drive down cost, but it won't be a winner-take-all, and litigious activity will be used to try to preserve the oligopoly market structure.
- 2) Modulung is a technology race and will be a short-term profit gainer in the value chain. Functions and value can be integrated into the modules, with the intensity and quality of light significantly influenced by smart modulung techniques. In the long run, modulung technology will get commoditized and low-cost players will gain market share.
- 3) Lamp and luminaire retrofit market – big players get bigger and a profitability gap opens up between established manufacturers and new entrants. Retrofit suppliers need to quickly scale-up in order to drive down LED chip cost. Companies like Philips and Osram will leverage their brand and existing relationships with retailers to ensure they get shelf-space.
- 4) Emerging market for LED solutions built around energy-efficiency, through down-stream market integration and software and building integration. This presents opportunities for new entrants to challenge the incumbents that own the current customer relations.

5. Market Economics

In order to quantify and track the LED market as it evolves, Canaccord Adams, a midmarket investment bank, has been analyzing the LED lighting market for several years. They have produced a study that starts from the supply-side, considering the installed base of MOCVD reactors, the yield rates from these reactors and the supply of LED chips/year. It then moves down the value chain, developing a demand-side analysis, looking at a broad range of market segments including applications such as backlighting for displays and general illumination.

In the second edition of this study, Canaccord Adams estimates that the supply chain has over 1,200 production reactors working to produce roughly 54 billion LEDs annually (assumes a 62% yield and average of 400 micron squares). On the demand side, the study is built up on sixteen separate market segments and three penetration scenarios. Lighting demand in 2009 was estimated at 48 to 57 billion LEDs, growing to 88 to 128 billion LEDs by 2012 (16-22% CAGR), driven primarily by increasing demand in display back-lighting.

Canaccord Adams believes that at least one manufacturer will be at cost-parity for LED back lighting of 42 inch TVs by 2011, and that will force the rest of the industry to introduce LED back-lit products to avoid market share losses. Due to the anticipated high rate of adoption in LED back-lit TVs and monitors, updated drafts of the study are estimating another 600 to 900 total MOCVD reactors must be installed between 2009 and 2012, even taking into account higher brightness LEDs which enables a reduction in the number of LEDs per TV.

In terms of reactor yields, there is a definite shift in the market place from 2 inch to 4 inch wafers, with some R&D effort at 6 inch. It is expected that this six-inch will become the mainstream by about 2012. And as the tooling configuration changes to larger wafer size, there will be a yield increase – the average chips per tool. A two-inch tool produces approximately 50 million units per year, and a four-inch tool can produce approximately 80 to 90 million units per year. Generally, the bowing issue for larger wafers has been solved, and researchers have found greater thermal stability at the larger wafer size which results in a tighter sigma for color binning.

As an example of how LEDs can transform products, in 2008, Apple started marketing their laptop computer with an 8-hour battery life, which took advantage of the energy-efficiency benefit from using LED backlighting. This also enabled Apple to have a super-thin form factor. Then, the collapse of the financial markets saw utilization as low as 20 to 30% for some LED manufacturers, and the market experienced a one-year decline in average selling prices of LEDs of approximately 50%. This lower price contributed to corporate decisions by HP, Dell, Acer and other companies to develop competing products to Apple. As a result, at the start of 2009, approximately 15% of computer monitors were LED lit, and by the end of the year it was 75%. Now, we are witnessing a similar phenomenon in the TV market. This is driven by the fact that in 2-3 years, it will be cheaper to have LED than fluorescent technology, plus you get a great marketing benefit of “green” branding, better color saturation and small form-factor.

In the third draft of the Canaccord Adams’ study, the market researchers are anticipating that following the excessively high demand for LEDs in TVs and monitors, there will be an excess of chip capacity in the market-place, and we will find an accelerated decline in price. Compounding this oversupply will be research advances that will increase internal quantum efficiencies, both in terms of scale of manufacture and improvements in efficiency. Thus, LED pricing will come down and that will stimulate the general lighting market. Looking across the material supply chain for any bottlenecks, there is some concern over the sapphire supply chain, and we have already observed a 40% increase in the last year for sapphire wafers. Fortunately, however the substrate still is only 5% of the LED BOM, and this increase can be readily eclipsed by higher reactor yields and migration to larger wafer sizes.

The LED IP landscape is still complicated and highly litigious, surpassed only perhaps by the biotech industry. As real customers have emerged, there appears to have been some reduction in the level of incestuous IP litigation. This isn’t because the value of LED IP has diminished, but at a chip-level, it is hard to litigate. It is expected that in the coming years, phosphor IP will become more important, as it is easier to define and to litigate, and it will be highly valuable in general lighting applications.

6. Conclusions

The general illumination market is not homogeneous. There is a diversity of lamps, fixtures and applications which call for a range of different solutions. Solid-state lighting, and in particular LEDs, holds promise as being a high-quality source that is efficient, rugged, and offers the lowest life-cycle cost. There is research, engineering, commercialization and market development that remains to be done before LEDs can achieve their full potential in the market, however it is clear that their value proposition is compelling and LED lighting is going to be a dominant light source in the future. Philips, for example, recently stated that it anticipates 75% of its lighting sales will be LED by 2020.

Overall, the greatest single barrier to entry to LED technology is its high first cost. This is currently being tackled by a two-pronged approach of research to develop more efficacious devices and through the manufacturing innovations associated with scaling up production. As LEDs are commercialized and are supported by market transformation programs, consumers in certain areas may benefit from different policies, incentives, and financing mechanisms that could be applied to help alleviate the cost of LED lamps and luminaires.

It was recognized that the market would benefit from improving testing standards like the Color Quality System (CQS), a better means of measuring color performance of light sources than Color Rendering Index (CRI). The market would also benefit from developing new testing standards that measure efficacy, lifetime and other critical performance attributes such as reliability and compatibility in a consistent manner. This will help to alleviate the problem of unscrupulous manufacturers making excessive performance claims, while also providing a basis for regulators to regulate against poor performing product and market transformation program designers to encourage market adoption. Furthermore, pending an improvement in the efficiency of green LEDs, the technological pathway for LEDs is toward an RGB where color mixing enables production of excellent quality white light.

There are five billion screw-based sockets globally, along with millions of outdoor street and roadway lighting, commercial office lighting, industrial high-bay and other niche markets. LED manufacturers have strategically targeted the most promising applications first – some in general illumination such as directional lamps and downlights – but others are in practical applications where form factor and efficiency add to the value proposition. For example, backlighting of TVs and displays with LEDs are more expensive now, but they will be less expensive than the incumbent fluorescent technology in the next 2-3 years, and they enable manufacturers to offer super-thin products with better color saturation, and which are more efficient and eco-friendly. Automotive is another market where the vibration-resistance and small package size of LEDs make them flexible and ideally suited for day-running lights and eventually, head lights. These applications and others are driving cycles of growth in the supply chain, establishing the infrastructure, the production know-how and the quality specification that will enable LEDs to eventually graduate to general illumination applications.

In order to reach their full market potential, there are a number of technical issues that still need to be resolved for LEDs. This technology is not yet perfected, and there are many poor-quality market entrants who risk tarnishing the reputation of the technology. Research still needs to be done on critical issues such as efficiency droop, thermal droop, phosphors, light extraction and driver performance. This market need may lend itself well to the formation of a SEMATECH-type consortium, to develop and preserve IP and capture market share in this global industry.

The onset of international regulations, phasing in between 2012 and 2014, will be eliminating the \$0.25 incandescent lamp. It's unclear whether consumers will turn to compact fluorescent lamps, halogen infrared reflector, or LED technology in response to the removal of incandescent lamps from the market. Each light source has its respective value proposition, however LEDs are likely to offer the lowest cost of ownership and the general illumination market may well soak up the excess supply capacity following the TV and monitor market transition to LED back-lighting. In this market transformation, triggered by the removal of incandescent lamps, it will be critical to have performance and quality standards in place, establishing an 'honest' floor, and getting the worst performers out of the market.

The LED IP landscape is still complicated and highly litigious, surpassed only perhaps by the biotech industry. As real customers have emerged, there appears to have been some reduction in the level of incestuous IP litigation. This isn't because the value of LED IP has diminished, but at a chip-level, it is hard to litigate. It is expected that in the coming years, phosphor IP will become more important, as it is easier to define and to litigate, and it will be highly valuable in general lighting applications.

Bearing these findings in mind, the group had the following recommendations that flowed from this discussion:

- Continue to support LED R&D activities – both pre-competitive and competitive research that will improve efficacy and reduce cost such as efficiency droop, thermal droop, phosphors, light extraction and driver performance. This may lend itself well to the formation of a SEMATECH-type consortium of LED companies with government backing, or simply more support to the existing projects and programs investing in LED IP.
- Support the development of industry testing standards that measure performance attributes of LED lamps and systems accurately and fairly. New technologies require the development of new standards and metrics, and for LED to compete in the general illumination market, equitable testing that enables comparison across a range of light source technologies will be important. Supporting work like the development of the Color Quality System (CQS) and industry test standards like LM-79 (Electrical and Photometric Measurements of Solid-State Lighting Products) and LM-80 (Measuring Lumen Maintenance of LED Light Sources) will position LED technology for market adoption. Additional standards are being developed which will further clarify and improve methods of measuring LED product performance and compatibility.
- Encourage consumer education about lighting through marketing campaigns, product labeling, and quality marks (e.g., ENERGY STAR). Moving on from the 60-watt incandescent lamp to understand lumen packages and some essential light quality issues will enable consumers to make appropriate, informed choices about their lighting. Several possible approaches could be employed to achieve this objective of enabling consumers to recognize quality on the shelf.
- Develop quality performance specifications and link those to market transformation programs such as utility rebate schemes or other marketing efforts. This will minimize free-ridership and will ensure consumers participating in the scheme receive premium quality product. The LED quality performance specification could also be adopted by a regulatory entity who operates in the interests of consumers.
- Identify and develop policies that address affordability. Consider targeting the commercial sector in the first instance through tax incentives, enhanced capital allowance schemes, or direct subsidy / coupon for LED technology that meets certain quality and efficacy requirements. Later, as the technology improves and becomes less expensive, start to develop programs to support market adoption in the residential sector.
- Conduct enforcement testing of commercially available product on an on-going basis to protect consumers and honest companies alike. Unscrupulous manufacturers who exaggerate performance metrics can undercut honest companies, resulting in lost revenue and duped consumers. Perhaps as an expansion of the CALiPER program, an on-going testing program can serve as an honest-broker in the market, constantly testing product sampled from store shelves and measure performance against statements made on the packaging.



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