High Extraction Luminescent Material Structures for Solid State LEDs

April 11, 2005

Developer's NAIC: 541710 Research and Development in the Physical, Engineering, and Life Sciences

Science/Technology Fields: Engineering & Materials

Arena NAIC: 334413 Light emitting diodes (LED) manufacturing

Library of Congress Subject Heading: QC- 350-467 Optics, Light

Technology Type: Product & Process

Supply Chain: Manufacturing

International Patent Classification: H 01 L SEMICONDUCTOR DEVICES; ELECTRIC SOLID STATE DEVICES NOT OTHERWISE PROVIDED FOR

Geographic Region: World

Prepared by
Norman Brown, PhD, JD
858-848-2951

Table of Contents

1 Executive Summary

The following is a non-proprietary description of this technology.

Non-Proprietary Description of Technology
The bulk of current solid state devices suffer from poor light extraction efficiencies of less than 25%. This technology offers energy conversion efficiencies of 50% and greater by reducing energy loss normally associated with phosphor-based LEDs. Such improved efficiencies may make LED-based lighting systems competitive with incandescent and fluorescent technologies currently in use.

Production of white light from LEDs involves using a blue or ultraviolet (UV) LED, surrounded by materials that will convert the blue or UV light into visible white light; this conversion introduces inherent efficiency losses into the light-generation system. The major energy loss mechanisms with both of UV and blue diode pumping schemes are the limitations due to Fresnel reflections and total internal reflection (TIR) losses; these losses result from the high to low refractive index transition between the GaN layer (n~2.4) and the traditional epoxy encapsulation (n~1.5).

What makes this technology a scientific/engineering innovation is:

Non-Proprietary Description of the Key Innovation(s) Underlying the Technology
The key innovation of this technology is a manufacturing technique for phosphor-based LEDs which provides a uniform and gradual change in refractive index

The invention involves the use of Graded Index (GIN) phosphor materials. Using a novel electrophoretic deposition process instead of vacuum thin-film evaporation, — Redacted — can produce a gradual and continuous change of index of refraction from a phosphor-based Light Emitting Diode (LED). Because the change in refraction index is gradual, there is less loss of light energy, compared to technologies where there are sharp barriers between refractive materials, each with different refraction indices. This technology provides more effective out-coupling of the energy by using a gradual and continuous change of the index of refraction between the LED die and surrounding medium. The traditional method for achieving graded structures is by vacuum thin-film evaporation, which is quite complex and expensive. This process instead uses a very economical and practical method for achieving graded index (GIN) structures using an electrophoretic (EP) deposition process. This approach is expected to yield improved LED efficiency and significant energy savings with minimum added cost.

— Redacted — wishes to commercialize its technology through sales of phosphor-based white LEDs and through licensing of its patent-pending manufacturing process to other LED manufacturers in the United States and abroad.

The end-user is defined as the person who ultimately uses the technology. Commercialization occurs when end-users buy your technology to utilize it in a practical application

End-User(s)
LEDs are sources of electric light; — Redacted — has indicated an interest in the market for LEDs for general lighting, such as in buildings and residences. An end-user who would purchase and install LED lighting is an electrician or electrical contractor. The Bureau of Labor Statistics describes the nature of an electrician's work as follows: Electricity is essential for light, power, air-conditioning, and refrigeration. Electricians install, connect, test, and

maintain electrical systems for a variety of purposes, including climate control, security, and communications. They also may install and maintain the electronic controls for machines in business and industry. Although most electricians specialize in construction or maintenance, a growing number do both.

Electricians work with blueprints when they install electrical systems in factories, office buildings, homes, and other structures. Blueprints indicate the locations of circuits, outlets, load centers, panel boards, and other equipment. Electricians must follow the National Electric Code and comply with State and local building codes when they install these systems. In factories and offices, they first place conduit (pipe or tubing) inside designated partitions, walls, or other concealed areas. They also fasten to the walls small metal or plastic boxes that will house electrical switches and outlets. They then pull insulated wires or cables through the conduit to complete circuits between these boxes. In lighter construction, such as residential, plastic-covered wire usually is used instead of conduit.

Regardless of the type of wire used, electricians connect it to circuit breakers, transformers, or other components. They join the wires in boxes with various specially designed connectors. After they finish the wiring, they use testing equipment, such as ohmmeters, voltmeters, and oscilloscopes, to check the circuits for proper connections, ensuring electrical compatibility and safety of components.

Electricians also may install low voltage wiring systems in addition to wiring a building's electrical system. Low voltage wiring involves voice, data, and video wiring systems, such as those for telephones, computers and related equipment, intercoms, and fire alarm and security systems. Electricians also may install coaxial or fiber optic cable for computers and other telecommunications equipment and electronic controls for industrial equipment.

Maintenance work varies greatly, depending on where the electrician is employed. Electricians who specialize in residential work may rewire a home and replace an old fuse box with a new circuit breaker box to accommodate additional appliances. Those who work in large factories may repair motors, transformers, generators, and electronic controllers on machine tools and industrial robots. Those in office buildings and small plants may repair all types of electrical equipment.

Maintenance electricians spend much of their time doing preventive maintenance. They periodically inspect equipment, and locate and correct problems before breakdowns occur. Electricians may also advise management whether continued operation of equipment could be hazardous. When needed, they install new electrical equipment. When breakdowns occur, they must make the necessary repairs as quickly as possible in order to minimize inconvenience. Electricians may replace items such as circuit breakers, fuses, switches, electrical and electronic components, or wire. When working with complex electronic devices, they may work with engineers, engineering technicians, or industrial machinery installation, repair, and maintenance workers. (Statements on these occupations appear elsewhere in the *Handbook*.)

Electricians use hand tools such as screwdrivers, pliers, knives, hacksaws, and wire strippers. They also use a variety of power tools as well as testing equipment such as oscilloscopes, ammeters, and test lamps.[1]

An application is a potential use for a technology that is based on end-user needs and could provide a feasible market opportunity for the technology. The following table presents our choice for an initial market entry application.

Recommended Application
High-Brightness white LEDs (HB-LEDs) in general lighting applications.

HB-LEDs are currently applied to a number of market applications. For example, large, full-color outdoor LED signs became possible in the 1990s as HB-LEDs became available in all three primary

[1] Bureau of Labor Statistics, U.S. Department of Labor, *Occupational Outlook Handbook, 2004-05 Edition*, Electricians, on the Internet at **http://www.bls.gov/oco/ocos206.htm** (visited April 07, 2005).

colors. Such signs are bright, colorful and can easily accept full video frame rates.[2] In addition to outdoor signs (26% of the total HB-LED market in 2001), HB-LEDs have also found application as backlights for mobile communication devices (30% of total HB-LED market); automotive dashboard, indicator and stop lights (26%); electronic equipment indicator lights (10%), traffic signals (4%) and general illumination (4%).[3] The area of primary interest by — Redacted —, the general illumination segment, is currently a very small part of the overall market for LEDs.

Description of Use in Practice
White LEDs produced by this process could be used in any of the niche markets described above, with little or no additional engineering; however, use of LEDs in general illumination applications will require significant adaptation to the needs of electrical and building contractors.[4]

Although the market potential of general lighting is huge, estimated at $10 - $15 billion,[5] it is also in many respects "the worst market for LEDs"[6] for essentially technical reasons. Most general illumination lighting is 110 volts, and the heat generated with current bulbs is dissipated through radiation; with LEDs, the voltage is significantly less and the heat is dissipated largely through conduction.[7] Current fixtures in place in the buildings of the world cannot accept LEDs in place of incandescent or fluorescent lamps without significant redesign. In short, to reach the general illumination market with LEDs, "you must completely redesign lighting as we know it."[8]

These end-users work in a segment of the economy. Forces in the arena can support or threaten commercialization.

Arena Dynamics
This is a highly competitive field with an increasing number of players seeking to develop interior lighting quality white light LEDs. — Redacted —, due to its DOE SBIR award represents one of these players.

Just as fluorescent and high-intensity lighting fixtures have provided industry growth the past few decades, Solid State Lighting (SSL) sources can potentially offer significant energy savings in general lighting. As the technology advances, it is likely to become better suited to a broader array of applications, light quality will improve, energy efficiencies will increase, and prices will fall. The potential national (SU) energy savings that will result by 2020 or 2025 depend on how quickly and to what extent these developments occur.[9]

The reason end-users find this technology attractive is:

Current Weaknesses and Improvements		
End-User Need	***Weakness of Current***	***Improvements Offered by***

[2] Vladimir Krylov, "Market Review: Superbright LEDs," *ATV Systems Magazine*, January 15, 2004, p. 1.
[3] Bob Steele, "LED market shines through high-tech slump", *Laser Focus World*, http://lfw.pennnet.com/Articles/Article_Display.cfm?Article_ID=140218&pc=gls, accessed April 3, 2005.
[4] Dr. Arpad Bergh (Executive Director, Optoelectronics Industry Development Association) in telephone interview with N. Brown, April 7, 2005 202-785-4426.
[5] Navigant Consulting, Inc.,, "Illuminating the Challenges", *Solid State Lighting Program Planning Workshop Report*, Crystal City, VA, February, 2004, p. 1.
[6] Dr. Arpad Bergh (Executive Director, Optoelectronics Industry Development Association) in telephone interview with N. Brown, April 7, 2005 202-785-4426.
[7] *Ibid.*
[8] *Ibid.*
[9] Mark Kendall and Michael Scholand, *Energy Savings Potential of Solid State Lighting in General Lighting Applications: Final Report*, Arthur D. Little, Inc., April, 2001, p. 23.

	Technology	*This Technology*
Reduced energy loss	All systems using phosphors to emit white light encounter energy losses[10]; the energy loss of current phosphor LEDs is exacerbated by scattering, absorption and sharp changes in refractive index as the emitted light passes through the phosphor coating..[11]	Light output is maximized by matching the refractive index of the various layers surrounding the LED and removing the index discontinuities responsible for much of the energy loss.

LEDs do not naturally emit white light; available LEDs emit red or yellow light ("warm" colors), blue or green light ("cool" colors), or light outside the visible spectrum (infrared and ultraviolet). In order to produce white light, the non-white LED is coated with a material which changes the base color into white as the light energy passes through the coating. In order for HB-LEDs to compete with existing fluorescent and incandescent light bulbs, their energy efficiency has to be at least as great as 50%.[12]

Market Size and Growth

— Redacted — specifically requested that this analysis focus on characterizing the market for HB-LEDs in general illumination. This is a complex issue, since penetration of this market at present by LED devices is "miniscule,"[13] consisting largely of accent or task lighting.[14] The lighting industry, itself, is characterized by a lack of investment or innovation; today, there is "negligible demand for innovation in commercial lighting,"[15] and the building industry in general spends only *one-seventh* as much on R&D as the average of US industry.[16] Additionally, product cycles in the lighting industry are exceptionally long, and the commercial building market in particular has been slow to accept new lighting products and technologies.[17] Substantive penetration of this market is years away[18] and will require substantial improvement in LED technology and economics.[19] Lacking current market data, and also lacking specific, finalized products or technology designed for the market, any market projection must be built from a series of assumptions. We will therefore build up a range of estimates of market size and share in a number of discrete steps.

<u>First</u>, we will look at the present market in terms of the types and amounts of light provided;
<u>Second</u>, we will look at projections of likely performance and price attributes of future LED developments aimed at addressing this market;
<u>Third</u>, we will project lighting usage to 2015 and 2020 without considering any possible effects from LEDs; and

---

[10] David Talbot, "LEDs vs. the Lightbulb," MIT Technology Review, May 2003 http://www.technologyreview.com/articles/talbot0503.asp?p=1
[11] Dale Work (Legislative Liaison, Philips Company), in telephone interview with N. Brown, April 8, 2005, 202-962-8547.
[12] Navigant Consulting, Inc.,, "Illuminating the Challenges", *Solid State Lighting Program Planning Workshop Report*, Crystal City, VA, February, 2004, p. 2.
[13] Bob Steele, "LED market shines through high-tech slump", *Laser Focus World*, http://lfw.pennnet.com/Articles/Article_Display.cfm?Article_ID=140218&pc=gls, accessed April 3, 2005.
[14] Yoshiko Hara, "White LED lamp market brightens," *EE Times*, July 18, 2002, http://www.eet.com/pw/fo/OEG20020718S0013, accessed April 3, 2005.
[15] Office of Building Technology, Energy Efficiency and Renewable Energy, Vision 2020: The Lighting Technology Roadmap, US Department of Energy, June, 2000, p. 9.
[16] *Ibid.*
[17] *Ibid.*
[18] Vladimir Krylov, "Market Review: Superbright LEDs," *ATV Systems Magazine*, January 15, 2004, p. 2.
[19] Navigant Consulting, Inc.,, "Illuminating the Challenges", *Solid State Lighting Program Planning Workshop Report*, Crystal City, VA, February, 2004, p. 6.

Fourth, we'll project a range of "possible LED development scenarios," depending on which of the assumed development milestones are reached, and predict how each scenario is likely to impact overall demand.

All this detailed analysis will be limited to the US market, where data is easily available; following this, extrapolations to worldwide markets can also be made.

Step One — Characterization of Present Lighting Market

The following chart shows key attributes of incandescent, fluorescent and solid state lighting in 2002:

Current Lighting Specifications[20]			
Factor	**Incandescent**	**Fluorescent**	**SSL-LED**
Luminous Efficacy (lumens/Watt)	16	85	25
Lifetime (kilohours)	1	10	20
Flux (lumens/lamp)	1200	3400	25
Input power (Watts/lamp)	75	40	1
Lumens cost ($/kilolumen)	$0.40	$1.50	$200
Lamp cost ($/lamp)	$0.50	$5	$5
Color Rendering Index (CRI)	95	75	75
Lighting market penetrated	ALL	ALL	Low-Flux

As can be seen from the previous chart, HB-LEDs have already achieved an energy efficiency greater than incandescent lamps, but still trail the energy efficiency of fluorescent lamps; the SSL industry has targeted an efficacy goal of 100 lumens/Watt as a basis for competing head-on with existing lighting technology.[21] However, energy efficiency is not the only key variable; another is flux output, or total light output, expressed as lumens per lamp. A typical 75-Watt incandescent puts out roughly 1.2 kilolumens, and a typical fluorescent bulb puts out 3.4 kilolumens; these outputs are yet another two orders of magnitude beyond currently available SSL-LEDs.[22]

A second key variable is cost; as can be seen from the above chart, incandescent light costs only 40 cents per kilolumen; fluorescent bulbs cost $1.50 per kilolumen; these are cost levels the lighting industry is familiar and comfortable with. LEDs, however, cost a whopping $200 per kilolumen, making LEDs clearly not price-competitive with the industry norm; cost for LEDs is still a couple of orders of magnitude off. Even though LEDs can point to being much more energy efficient, that advantage is not yet seen as offsetting the initial cost; as poignantly put by Frank Steranka, vice president for research and development at LumiLEDS, "Nobody will pay 20 bucks for a light bulb, even if it lasts 500 times longer and uses half the electricity."[23]

---

[20] Optoelectronics Industry Development Association, *Light Emitting Diodes for General Illumination: An OIDA Technology Roadmap Update*, OIDA, Washington DC, November, 2002, p. 4.
[21] James Broderick, *DOE Solid State Lighting Status and Overview*, US Department of Energy, Building Technologies Program, February 3, 2005, p. 4.
[22] Optoelectronics Industry Development Association, *Light Emitting Diodes for General Illumination: An OIDA Technology Roadmap Update*, OIDA, Washington DC, November, 2002, p. 6.
[23] Quoted by David Talbot, "LEDs vs. the Lightbulb," MIT Technology Review, May 2003

A third key variable is light quality. One measure of light quality is the Color Rendering Index, which measures how closely a color illuminated by a light source matches that same color in natural sunlight. As seen from the previous chart, incandescent bulbs do a good job of this, earning a CRI of 95 (out of 100), while fluorescents and LEDs are both at a CRI of 75. If CRI were the only color standard, LEDs would seem to fare as well as fluorescents, which have made deep inroads in industrial and commercial lighting, though much less in residential. But there is also a characteristic called "color temperature," which is an index of how the color is perceived by the human eye, compared with sunlight. Color temperature is "really important," and current LED light is seen as too cool or too amber for normal use.[24]

Total Current Inventory of Lighting (in Teralumens / hour / year)[25]				
	Residential	**Commercial**	**Industrial**	**Other**
Low CRI	9	3,097	2,016	2,119
Medium CRI	1,095	13,508	3,833	59
High CRI	51	421	70	66
Very High CRI	1,875	913	27	81
TOTAL	3,030	17,939	5,946	2,325

Step Two — Projecting Future Lighting Demand

Lighting demand is assumed to grow at the same rate as square footage of floor space; these rates are projected at 1.22% annual growth for residential, 1.43% for commercial, and 1.00% for both Industrial and Other.[26] Applying these growth rates to the total lumen inventory, we derive the following projections for total light demand in the US through 2025:

Teralumen-hours of Annual Lighting Demand by Technology Type[27]					
Lamp Source Type	**2005**	**2010**	**2015**	**2020**	**2025**
Incandescent	4,717	5,067	5,429	5,767	6,108
Fluorescent	23,618	25,255	27,058	28,862	30,703
Mercury Vapor	12,717	13,478	13,303	15,150	16,026
Solid State	5	5	6	6	6
TOTAL	41,056	43,806	46,796	49,785	52,844

The overall lighting market, expressed above in Teralumens, can also be seen in the number of light bulbs providing this light; these figures were also projected through 2025, using the assumption that the growth rates computed for Teralumens is analogous to the growth rate of lamps. This projection is laid out in the following table:

Estimated Inventory of Lamps in the US, through 2025 by Technology Type(in Millions)[28]

http://www.technologyreview.com/articles/talbot0503.asp?p=1

[24] Judie Porter (Director, Architectural Energy Corporation), in telephone interview with N. Brown, April 7, 2005 303-444-4149.

[25] Mark Kendall and Michael Scholand, *Energy Savings Potential of Solid State Lighting in General Lighting Applications: Final Report*, Arthur D. Little, Inc., April, 2001, p. 23.

[26] Navigant Consulting, Inc., *Energy Savings Potential of Solid State Lighting in General Illumination Applications*, a study prepared for Building Technologies Program, US Department of Energy, November, 2003, p. 6.

[27] Navigant Consulting, Inc., *Energy Savings Potential of Solid State Lighting in General Illumination Applications*, a study prepared for Building Technologies Program, US Department of Energy, November, 2003, p. 7.

[28] 2005 estimate taken from Navigant Consulting, Inc., *Volume I: National Lighting Inventory and Energy Consumption Estimate*, Final Report prepared for Building Technologies Program, US Department of Energy, September, 2002, p. 35; estimates for later years computed using growth rates from previous chart.

Lamp Source Type	2005	2010	2015	2020	2025
Incandescent	4,397.4	4,723.7	5,061.2	5,376.3	5,694.2
Fluorescent	2,473.1	2,644.5	2,833.3	3,022.2	3,215.0
Mercury Vapor	105.4	111.7	110.3	125.6	132.8
Solid State	1.8	1.9	2.0	2.2	2.3
TOTAL	6,977.7	7,481.8	8,006.7	8,526.2	9,044.3

The overall lighting market in the United States consists of almost 7 billion lamps in 2005, growing at a Compound Annual Growth rate of less than 2% through the projection period and reaching slightly over 9 billion lamps in 2025. An installed base of lamps, however, does not reflect a realistic market opportunity for — Redacted —, because only about 1% of floor space per decade undergoes lighting retrofits purely for energy savings.[29] — Redacted — addressable market is therefore practically limited by the rate at which lights are ***replaced*** in buildings. This rate is determined by three principal variables:

1. *New Construction* — new light fixtures installed each year due to floor space growth in a particular sector.
2. *Replacements* — lamps that burn out in a given year and are replaced.
3. *Retrofits* — lamps and fixtures replacing existing lamps and fixtures during renovation or remodeling

Both A.D. Little and Navigant Consulting have prepared estimates of these market factors; A.D. Little found a total of 33% lumen turnover from the combination of these three factors,[30] while Navigant found 39%.[31] The two studies' findings are averaged in the table below:

Lumen Market Turnover per Year (Average of A.D. Little and Navigant Estimates)[32]				
	Unchanged	**Replacement**	**Retrofit**	**New Installation**
Turnover	64%	30%	5%	1%

A total of 36% of the general illumination market is thus targetable by — Redacted — in any given year; the bulk of this opportunity, however, is the simple replacement of burned out bulbs. To capitalize on the replacement market, this assumes that — Redacted — will have developed LED lights which can fit in existing light fixtures without additional retrofit; otherwise, — Redacted — addressable market would be limited to retrofits and new installations, where totally different fixtures and technologies could be used.

Step Three — Projecting Future LED Development

The tricky part of projecting the market for LED general lighting is that not enough is known about key performance characteristics which are likely to emerge from current LED research; except in a few highly-specialized applications there are no LED products currently available for the general illumination market. If cost and efficacy of white-light LEDs do not advance beyond their present level, their market

[29] Mark Kendall and Michael Scholand, *Energy Savings Potential of Solid State Lighting in General Lighting Applications: Final Report*, Arthur D. Little, Inc., April, 2001, p. 7.
[30] Ibid.
[31] Navigant Consulting, Inc., *Energy Savings Potential of Solid State Lighting in General Illumination Applications*, a study prepared for Building Technologies Program, US Department of Energy, November, 2003, p. 10.
[32] Mark Kendall and Michael Scholand, *Energy Savings Potential of Solid State Lighting in General Lighting Applications: Final Report*, Arthur D. Little, Inc., April, 2001, p. 7; and Navigant Consulting, Inc., *Energy Savings Potential of Solid State Lighting in General Illumination Applications*, a study prepared for Building Technologies Program, US Department of Energy, November, 2003, p. 10.

share will continue to be negligible and their applications limited to specialty or architectural lighting. If, on the other hand, the performance efficacy of LEDs is advanced to equal or surpass current lighting, and at the same time the cost-per-lumen falls to the same neighborhood as present lighting technologies, then the consensus is that LED lighting will completely dominate the general lighting market. So, what prediction makes most sense?

The US Department of Energy approached this issue by devising a series of three “scenarios” which each made different assumptions about the technical development of white-light LEDs. A description of each scenario is referenced below:[33]

- *Base Case* — No change in present development curve: by 2010, medium-CRI LED technology efficacy reaches 45 lumens/Watt and its price falls to $36/kilolumen.
- *Technology Breakthrough Case* — More aggressive SSL technology development rate than the Base Case; medium-CRI LED technology achieves 110 lumens/Watt by 2010 at a price of $14/kilolumen.[34]
- *Price Breakthrough Case* — This reflects a radical drop in LED price, compared to the Base Case, with the same technology development as the Technology Breakthrough Case, plus, the price of the medium-CRI LED drops to $7/kilolumen by 2010 and to $0.50/kilolumen by 2020.

These projected developments are shown together in the following table:

Projected Light Source Attributes in 2020[35]

Technology	**Scenario**	**Efficacy (lm/W)**	**Price ($/klm)**
Medium CRI LED Technology	Base Case	50	$8.30
	Tech Breakthrough	120	$8.00
	Price Breakthrough	$120	$0.50
Conventional Technology	Incandescent	14	$0.55
	Fluorescent	69	$0.70
	High-Intensity	99	$0.61

<u>Step Four — Presenting Future Market Scenarios</u>

Applying the three scenarios to the market, we find that future market share is a function of payback period. Although Solid State Lighting proponents emphasize their high payback, the energy savings and reduced replacement cycles must be compared against the initial capital cost of the SSL lighting. While theoretically, purchasers should weigh all factors over time in a discounted cash flow model, the reality is that most decisions in the building sector are made using a simple payback period — the ratio of first year incremental purchase price to first year incremental savings.[36] The payback curves for each of the general lighting sectors is shown below:[37]

---

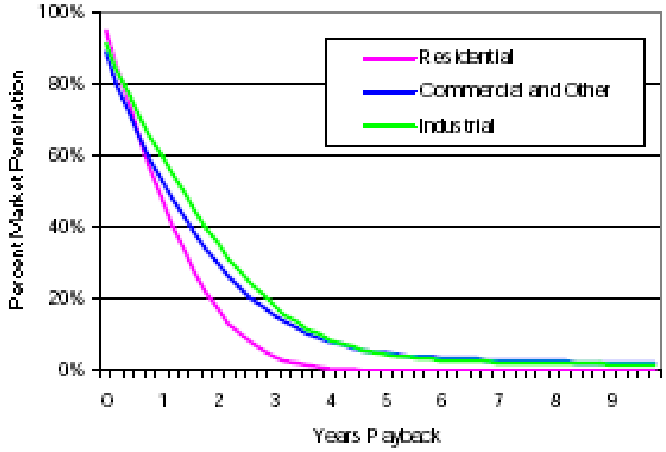
[33] Mark Kendall and Michael Scholand, *Energy Savings Potential of Solid State Lighting in General Lighting Applications: Final Report*, Arthur D. Little, Inc., April, 2001, p. 7

[34] T. Drennen (Sandia), R. Haitz (Agilent), J, Tsao (Sandia), *Transforming the Lighting Sector with Semiconductor Lighting Technologies*, paper presented at USAEE/IAEE Conference, Philadelphia, PA, September 24-27, 2000.

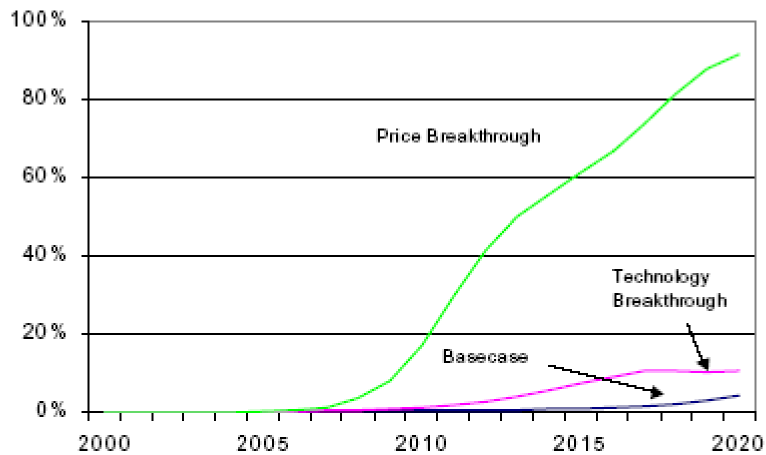
[35] Mark Kendall and Michael Scholand, *Energy Savings Potential of Solid State Lighting in General Lighting Applications: Final Report*, Arthur D. Little, Inc., April, 2001, p. 13.

[36] Susan Kulakowski, *Large Organizations' Investments in Energy Efficient Building Retrofits*, Lawrence Berkeley National Laboratory, University of California, March, 1999.

[37] From Mark Kendall and Michael Scholand, *Energy Savings Potential of Solid State Lighting in General Lighting Applications: Final Report*, Arthur D. Little, Inc., April, 2001, p. 16.



As these payback curves show, market penetration is much more sensitive to price than to efficiency, energy savings, or similar variables: If it takes three years to achieve payback, market share in the industrial sector is likely to be only 20%; if it takes only two years, market penetration doubles to 40%; for paybacks which take only a year or less, market penetration is projected at 60% to 95% or more. Another graphic representation of the importance of a price breakthrough is shown in the following chart, which specifically addresses likely market share changes:[38]



To compute the dollar value of these share projections, we apply the share percentages for each scenario to the total dollar value of the market, plus the lumen growth rates from the two tables in Step Two, and applying those growth rates to the total dollar value of the lighting industry in the US. The total dollar value of the lighting market through 2025, under each of the three projected LED development scenarios, is shown in the following table:

Estimated Lighting Market in the US, through 2025 (in Billions of Dollars)[39]					
	2005[40]	**2010**[41]	**2015**	**2020**	**2025**[42]

[38] *Ibid*., p. 20.
[39] 2005 estimate taken from Navigant Consulting, Inc., *Volume I: National Lighting Inventory and Energy Consumption Estimate*, Final Report prepared for Building Technologies Program, US Department of Energy, September, 2002, p. 35; estimates for later years computed using growth rates from previous chart.

Total Market	$13.5	$14.2	$15.0	$16.4	$17.4
BASE CASE: LED Share	N/A	0.8%	1.4%	4.6%	4.6%
BASE CASE: LED Dollars	N/A	$0.1	$0.2	$0.8	$0.8
TECH CASE LED Share	N/A	1.8%	8.4%	11.1%	11.1%
TECH CASE LED Dollars	N/A	$0.3	$1.3	$1,8	$1.9
PRICE CASE LED Share	N/A	22.5%	63.8%	91.5%	91.5%
PRICE CASE LED Dollars	N/A	$3.2	$9.6	$15.0	$15.9

Depending on which LED development scenario evolves over time, the US market for HB-LEDs in the general illumination sector will:

- Grow to $100 million in 2010 and to $800 million by 2025;
- Grow to $300 million in 2010 and to $1.9 billion by 2025; or
- Grow to $3,2 billion in 2010 and to $15.9 billion by 2025.

What — Redacted — can expect as a targetable market in the general lighting sector clearly depends on [1] whether LED technology achieves a Technology and/or a Price Breakthrough; and [2] whether — Redacted — is one of the companies achieving these breakthroughs. If — Redacted — should be the only company achieving the breakthroughs, it would enjoy the lion's share of the addressable market; if it is one of several LED companies achieving the breakthroughs, it will have to share the market with other companies achieving similar level of performance; and if does not achieve any breakthrough, but others do, then it is likely not to be a significant player in the general lighting market.

If there is no price or technology breakthrough, no meaningful share of general lighting for LEDs can be expected until 2015, whereafter it rises to roughly 6% by 2020. If there is a technology breakthrough, but no price breakthrough, LED market share will become noticeable about 2011 or 2012, rising to a roughly 10% market share in 2017 or 2018 before leveling off. The "magic bullet" is obviously the combination of Technology and price breakthroughs; under this scenario, meaningful market penetration begins in 2008 and 2009 and accelerates rapidly to dominance of the entire market segment, achieving 50% market share by 2013 or 2014, and reaching 90+% by 2020.

Though — Redacted — requested examination specifically of the general lighting market for its LED technology, we also identified other potential applications which the company might want to consider.

Other Applications Identified	
Application	***Potential Competitive Advantages of Technology***
Backlighting for mobile devices	Small size, combined with high brightness.
Automobile Lighting	Small size, combined with ruggedness (LEDs not as susceptible to vibration or impact damage, compared to other lamp types)
Outdoor Signage	Brightness and refresh rates equivalent to video.
Electronic Equipment Indicator Lights	Small size, shape flexibility
Traffic Signals	Brightness, energy efficiency, long life.

[40] Robert Steele, Director of Optoelectronics at Strategies Unlimited, estimated $12 - $15 billion for the total US lighting market, quoted in "Ultra-high Lumen Aterion LED White Light Engine Questions and Answers," http://www.laminaceramics.com/docs/Questions%20and%20Answers%20-%20Aterion%20White.pdf; midpoint of $13.5 billion used as base year.
[41] Years 2010, 2015 & 2020 computed from lumen inventory growth rates applied to base year.
[42] Year 2025 assumed to grow only at lumen-growth rate.