Evolution of Solid-State Lighting: Market Pull and Technology Push

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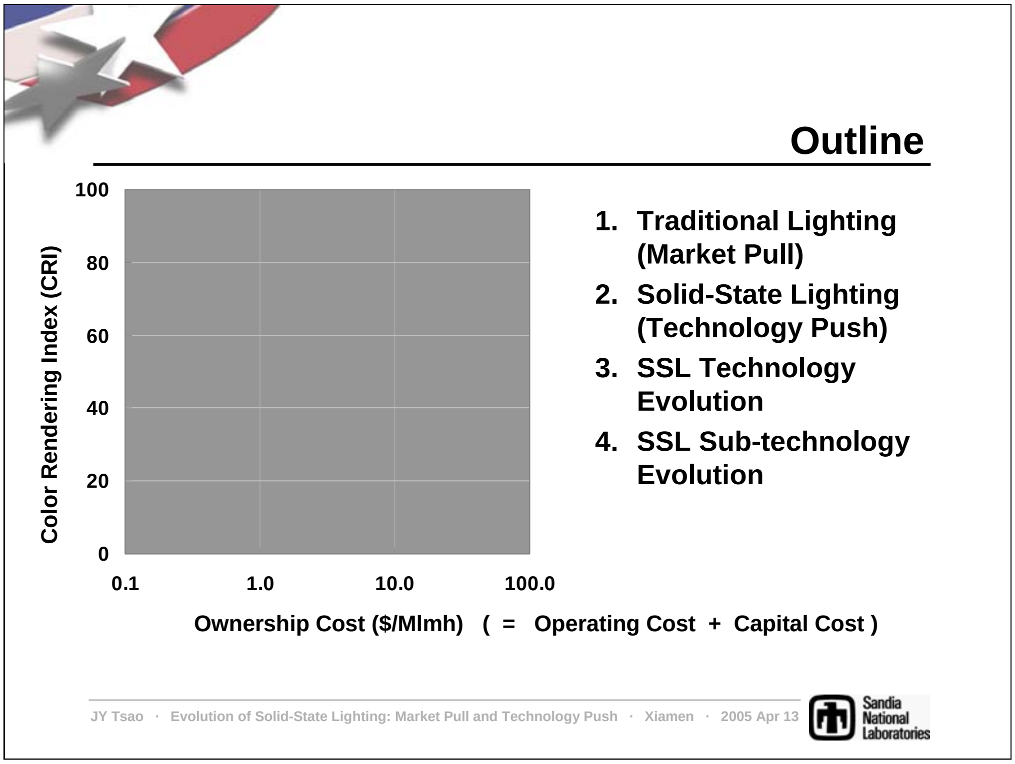
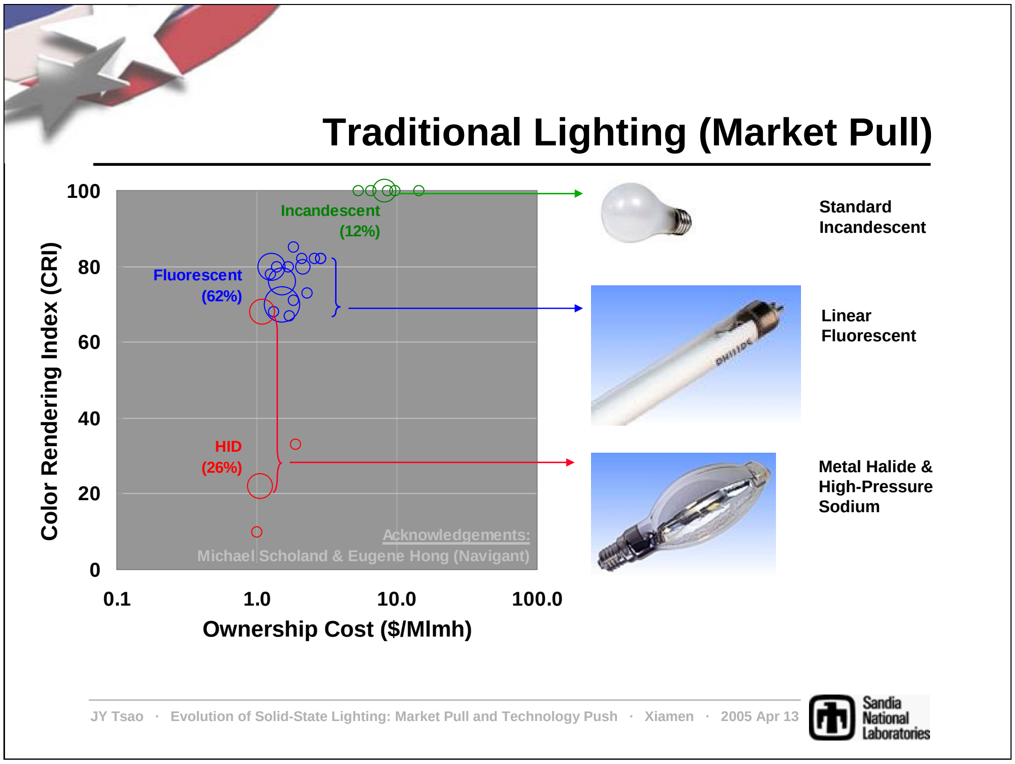
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Security Administration under Contract DE-AC04-94AL85000.

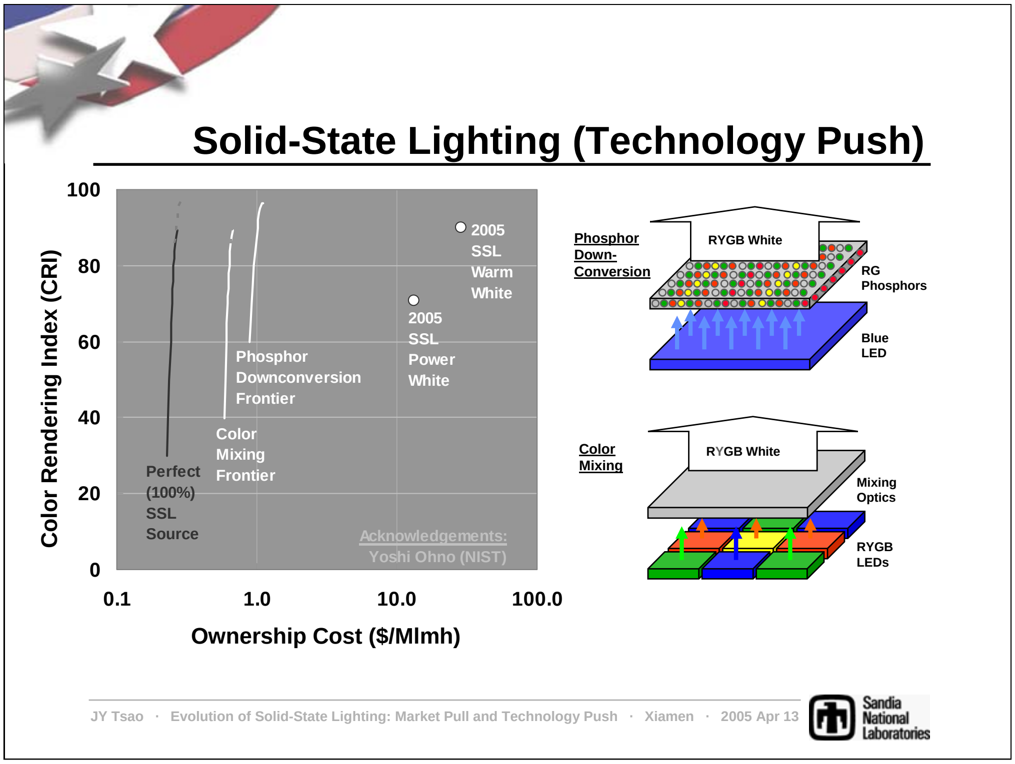
- 主席，男生们，怒士们 。我很感谢你们邀请我到厦门来参加这个会议。半导体真是一种育益於全球的科技。更兴奋的知道全世界对这种科技哟许多的研究活动。我很抱歉，因为我的中文讲得很差。我现在只好用英文来继续我的讲话。
- Mr. Chairman, ladies and gentlemen. I would like to thank the organizers for inviting me to visit Xiamen and to participate in this conference. Solid-state lighting is truly a technology with global benefits, and it is exciting to see so much activity throughout the world in it.
- At Sandia National Labs, we've been working on new ways to think about the evolution of technologies as a response to what one might call "market pull" and "technology push". In this talk, I'd like to describe some work where we are trying to apply some of that thinking to solid-state lighting. This work is in its initial stages, so the story is not very complete. But even at this early stage, I thought it might be interesting to this community.



- Here's an outline of my talk. I've divided it into four pieces. First, I'll talk about traditional lighting, which defines, in a way, the market that is "pulling" solid-state lighting technology. Second, I'll talk about solid-state lighting, which is the technology that is "pushing" the lighting market. Third, I'll talk about possible paths for the evolution of solid-state lighting technology in response to that market pull and technology push. And fourth, if there's time, I'll say a few words about the implications of this technology evolution on the sub-technologies which must evolve with the technology.
- To make the talk as clear as possible, I'm going to consistently use the coordinate axes illustrated here.
- The bottom axis is ownership cost, with the units $/Mlmh. It is the sum of the operating and capital costs – the cost to operate the light, and the cost to buy it. This is not a perfect metric, as not all consumers will weigh operating and capital costs equally. But as a coarse representation for the market economics of lighting it is a reasonable one.
- The left axis is color rendering index. And by this I mean our best understanding of human satisfaction with the rendering of colors by white light. In fact, our understanding of this is certainly imperfect, and is bound to improve over the next few years. So as an interim metric, I'll use the simple general color rendering index as currently defined by the CIE.
- The basic idea behind these two axes is that in understanding lighting technologies, one can't just think about ownership cost. One has to think also about color rendering quality.

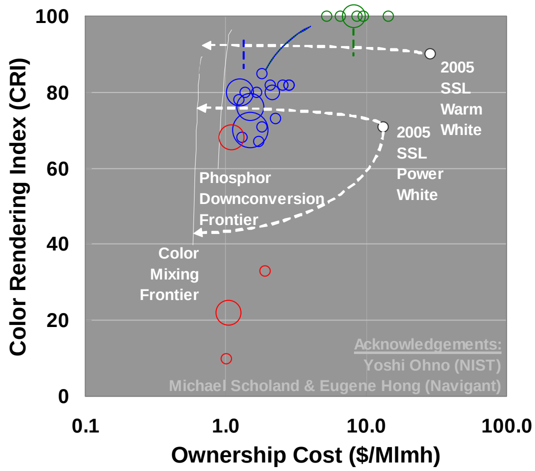


- So let's start with traditional lighting.
- Here, I've plotted the 26 lamps from the comprehensive 2002 inventory of lighting in the U.S. compiled by Michael Scholand and Eugene Hong of Navigant Consulting. The lamps fall into three overall families: incandescent, in green, fluorescent, in blue, and high-intensity discharge, in red. The area of each circle is proportional to the market size of the lamp in lumens. As indicated in the parentheses, fluorescent lamps as a family have the largest market share, 62%, HID lamps as a family have the second largest market share, 26%, and incandescent lamps as a family have the smallest, though still substantial, market share, 12%.
- To orient you a little better, these three large blue circles all represent linear fluorescent tubes – the 1.5 or 1.0 inch diameter ones that light many of our offices. The medium red circle here represents metal halide high-intensity discharge lamps – the kind often used to light high-bay areas such as warehouses and gymnasiums. The medium red circle down here represents high-pressure sodium lamps – the kind often used to light outdoor parking lots and highways. The medium green circle up here represents the standard incandescent lamp that lights most of our homes.
- As you can see from this map, the market is trifurcated into a high-CRI high-ownership-cost niche occupied by incandescent lamps, a medium-CRI medium-ownership-cost niche occupied mostly by fluorescent lamps, and a low-CRI low-ownership-cost niche occupied by high-intensity-discharge lamps.



- Now let's consider solid-state lighting. Here, I plot two kinds of things.
- Over on the right, I've plotted two representative white LED lamps that you can buy today. Just as with traditional lighting, we can see that the white LED lamp market seems bifurcated, into this warm-white high-CRI high-ownership-cost niche, and this power-white medium-CRI medium-ownership-cost niche.
- Over on the left, I've plotted with these white lines what one might call the "frontiers of reasonable possibility" for solid-state lighting. These lines represent the lowest ownership costs that one can reasonably imagine achieving for a given CRI, given an overall approach to solid-state lighting. I've drawn frontiers for the two approaches that are currently being considered: the color mixing approach shown in the upper right, where one mixes red, yellow, green and blue primary light from LEDs to create white; and the phosphor downconversion approach shown in the lower right, where one mixes blue primary light from and LED with red, yellow and green secondary light from phosphors to create white. The phosphor downconversion approach, of course, suffers a Stokes-shift energy loss associated with the phosphor downconversion, so its frontier of reasonable possibility is shifted over to the right by about 1.5x.
- For both, though, there is a similar trade-off between color rendering and ownership cost. If you concentrate most of your lumens into the green, where the human eye is most sensitive, then you can increase your luminous efficacy, and decrease your ownership cost. But you will also decrease your CRI. Conversely, if you expand your lumens to fill the entire visible spectrum, then you will increase your CRI, but your eye will also be seeing colors it isn't very sensitive to, so your luminous efficacy will decrease, and your ownership cost will increase. So, basically, the higher the CRI the higher the ownership cost.
- I don't have time to talk in more detail about these curves, except to say that they were calculated using a luminous-efficacy-CRI simulator developed by Yoshi Ohno at NIST, and assumed a constant color temperature of 4000K, with no allowed deviation from Planckian white.
- For completeness, I've also drawn another frontier, to the left, in black. This is what one might call the "frontier of physical possibility," where all the LEDs (red, yellow, green and blue) of a color-mixed solid-state lighting source are 100% efficient. It's conceivable that as our scientific understanding expands, we will learn how to move the white frontiers of reasonable possibility over to the black frontier of physical possibility. But presumably we will never move beyond the frontier of physical possibility.
- Nevertheless, even if you don't consider the black frontier of physical possibility, current technology, over here on the right, has a lot of room to go before it reaches the white frontiers of reasonable possibility. Whether it does, and if it does, how it does, are extremely interesting questions, so let's consider that next.

SSL Technology Evolution



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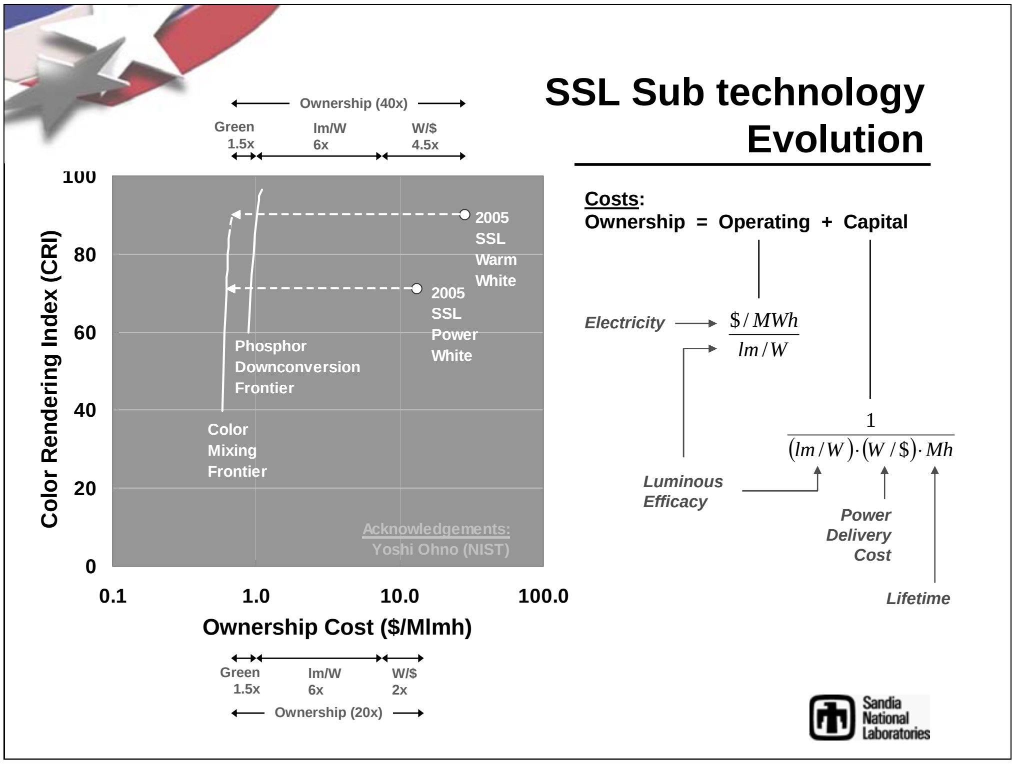
- So here I've combined the two maps, for traditional and solid-state lighting. And on this map I've also drawn dashed white lines indicating hypothetical routes by which solid-state lighting might evolve.
- For example, the power-white technology could evolve by mainly decreasing ownership cost, with perhaps incremental increases in CRI, eventually competing with fluorescent lamps. It could also spawn another technology with lower CRI but even lower ownership cost, to compete with HID lamps.
- Or, for example, the warm-white technology could evolve by mainly decreasing ownership cost, with perhaps incremental increases in CRI, eventually competing with incandescent lamps. But will it become competitive as soon as its ownership cost crosses below that of incandescent lamps, or will it not do so until its ownership cost crosses sufficiently below that of incandescent lamps to compensate for its slightly lower CRI? Eventually, it might also compete with fluorescent lamps. But, again, will it do so only when its ownership cost crosses below that of fluorescent lamps? Or will it do so even when its ownership cost is still slightly higher than that of fluorescent lamps, due to its improved CRI? And, finally, when it does begin to compete with fluorescent lamps, will it also compete with the power-white technology, with the two technologies either merging or with one of them becoming extinguished?
- These are all open and interesting questions. And if the markets for traditional lighting illustrated by these colored circles were the only markets pulling solid-state lighting technology, we might be able to begin answering them. But, and this is one of the reasons I said at the beginning of my talk that we are at the initial stages of this work, these are not the only markets pulling solid-state lighting technology. Indeed, one might argue that these are not even the most important markets pulling solid-state technology.
- In fact, the most important markets are the intermediate markets that Bob Steele talked about – traffic lights, display back-lighting, camera flashes, automotive lighting, signage, etc. Because these markets value other performance attributes in addition to CRI and ownership cost (e.g., compactness and ruggedness), they will pull solid-state lighting in directions that will not be obvious on this simple plot.
- In fact, I think it is possible to analyze this, and it will be interesting to do so, but we haven't yet done so, so for now the story is incomplete.



- In the meantime, assuming that these other markets do also value ownership cost, there will still be a steady evolution to the left, and we can ask a separate question, which is: how must the various sub technologies evolve in order to accommodate the overall technology evolution? I won't spend much time on this, but, very briefly, one can break the ownership cost down into various figures of merit, as illustrated here.
- There's operating cost, which depends on the cost of electricity and the luminous efficacy. Then there's capital cost, which depends on luminous efficacy, something that might be called the power delivery cost, and lifetime. The cost of electricity we can't control, and lifetime is already high enough for general illumination, so for our purpose here we won't worry about either of these.
- That leaves these two: the power delivery cost, the amount of power you can sink at the chip for a given cost, and the luminous efficacy, the lumens you can create given the power you're sinking at the chip. Each of these can be improved, and if each is improved to its frontier of reasonable possibility, one can calculate the impact on ownership cost.
- The results are shown up here for warm white, and down here for power white. Warm white is roughly 40x away from the color-mixing frontier, with 4.5x due to power delivery cost, 6x due to luminous efficacy, and 1.5x due to the difference between color mixing and phosphor downconversion. Power white is roughly 20x away from the color-mixing frontier, with 2x due to power delivery cost, 6x due to luminous efficacy, and 1.5x due to the difference between color mixing and phosphor downconversion.
- In other words, one could say that the advances that have the greatest immediate potential to push the technology to the left are, at this stage, and in decreasing order: luminous efficacy, power delivery cost, and high-efficiency green enabling color mixing.
- Again, it will be interesting to break this down further, and I think it's possible, but we haven't yet done so.

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- With that, let me close by saying that we've taken some initial steps towards understanding the evolution of solid-state lighting as a response to a combination of market pull and technology push. It will be interesting to take further steps, and I welcome your comments and questions along those lines.
- Thank-you.