Solid State Lighting: *Innovations through Optical Science*

June 29, 2006

Introduction

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Optronic Laboratories, Inc.

Outline

- Introduction
- Energy Considerations
- Technology Briefing: How does an LED work?
- SSL Markets and the Industrial Perspective
- Public Policy and Government Programs
- Q & A

Courtesy of NASA

Presenters

- **Alexandre Y. Fong**, M.Sc., MBA, C.Eng. VP Sales and Marketing, Optronic Laboratories, Inc.
- **Jerry Simmons**, Ph.D., Deputy Director for Energy Sciences of the Center for Physical, Chemical, and Nano-Sciences, Sandia National Laboratories
- **Ghassan Jabbour**, Ph.D., Professor and Director, Optoelectronic Materials and Devices, Arizona State University
- **John Ekis**, Director, Sales, Lamina Ceramics

Key SSL Benefits

- **Basis of solid-state lighting, LEDs developed in US by N. Holonyak in 1962 at GE**
- **Potentially extremely energy efficient, ~22% electricity used in lighting. Smart LEDs could reduce the nation's total electricity use by 10%, at a savings of ~$30B/year**
- **Good for the environment – longer lifetimes (up to 10 years), less material, reduced carbon emissions, and no dangerous mercury (like in fluorescents)**
- **Unparalleled color-changing properties and controllability mean a wide range of applications such as architectural lighting or entertainment lighting, flat panel displays [30%]**
- **Optics and photonics are enabling technologies which are the basis for this technology**

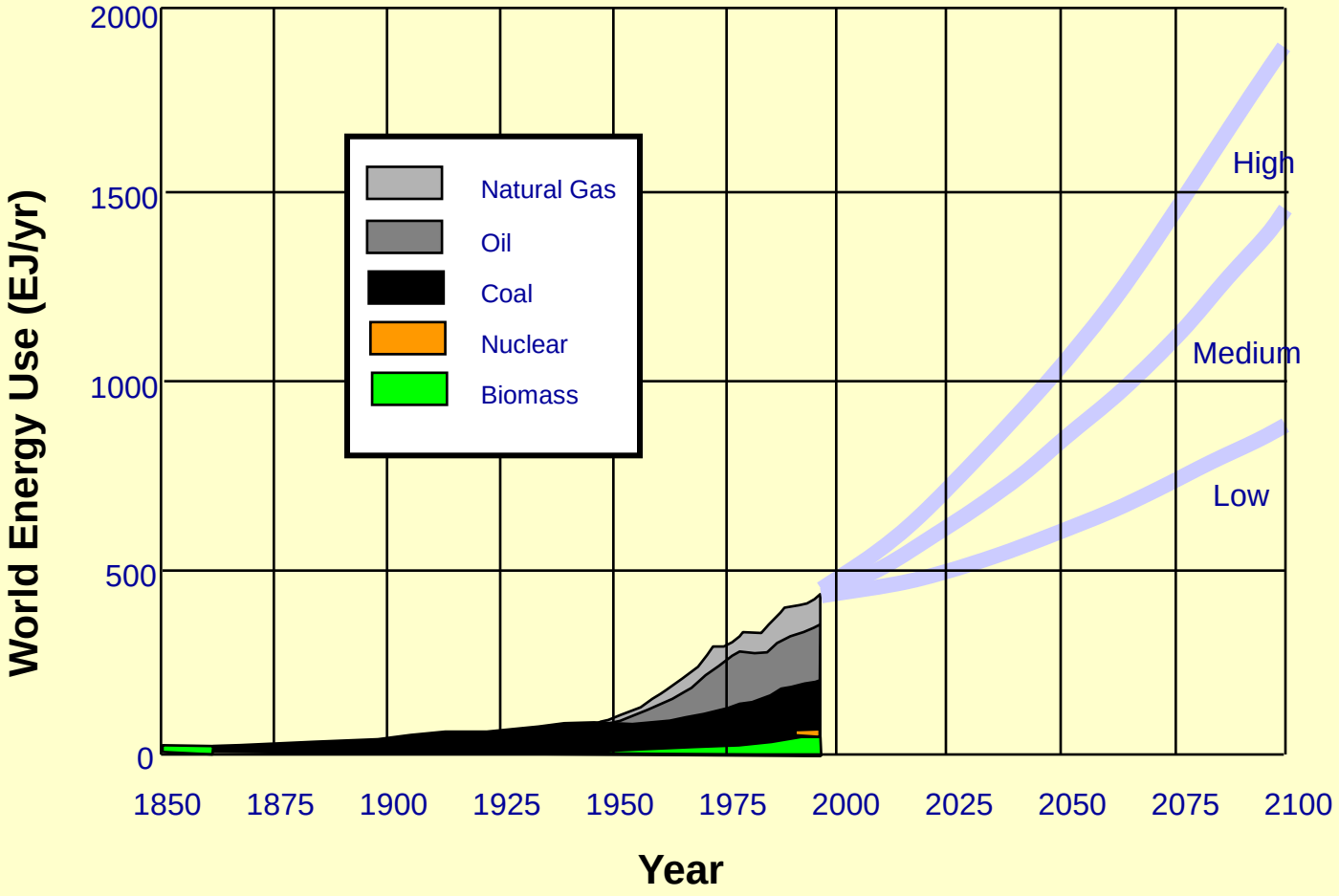
Role of Optics and Photonics

- Optics and photonics is the science behind SSL
- "Making, managing and measuring light": Semiconductor development, lens design and test and measurement of light
- Education in math and physical sciences are fundamental
- New advancements in SSL will depend upon our knowledge of optics and photonics

Energy

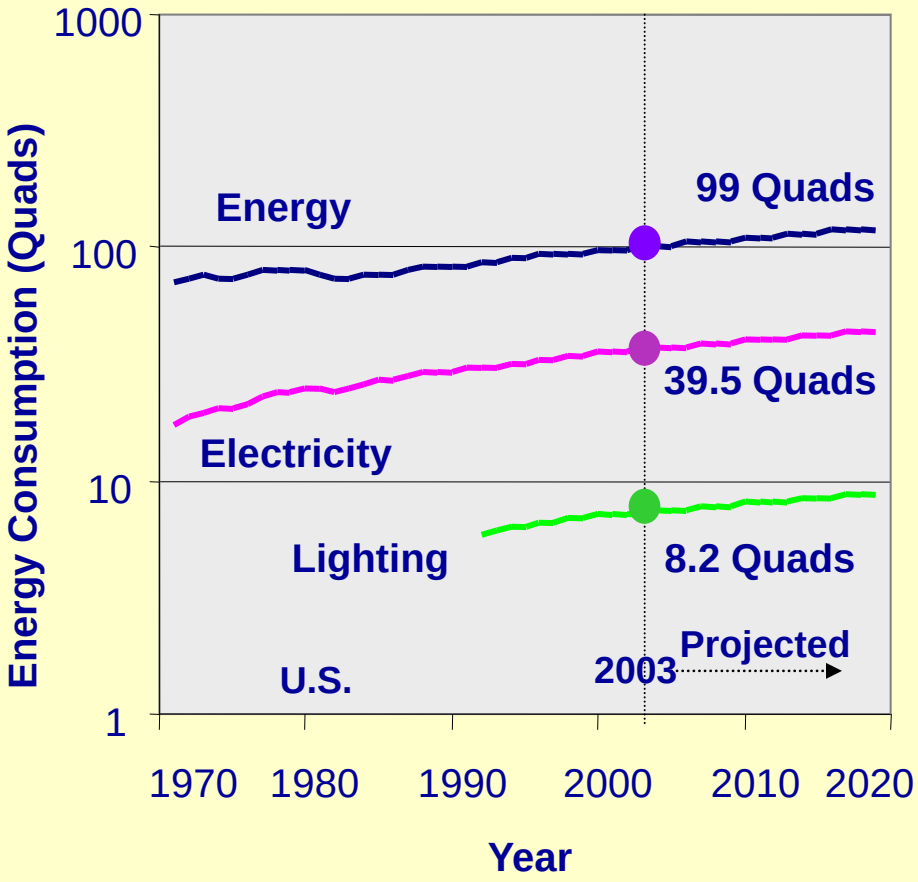
Jerry Simmons
Sandia National Laboratories

Energy security will be a major challenge of the 21st century



Lighting is a large fraction of energy consumption and is low efficiency

~22% of electricity consumption is for general illumination

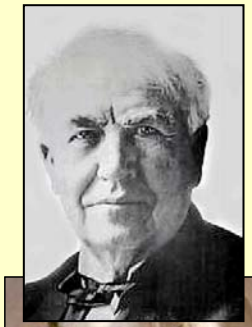


Efficiencies of energy technologies in buildings:

- Heating: 70 - 80%
- Elect. motors: 85 - 95%
- Fluorescents: **25%**
- Incandescents: **5%**

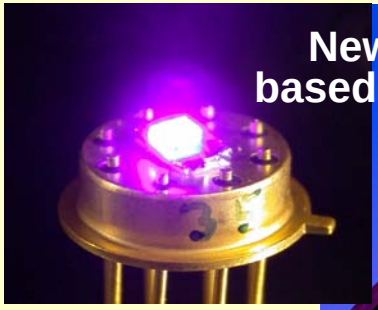
Lighting is a highly attractive target for reducing energy consumption.

Conventional lighting is the last technology that still uses vacuum tubes



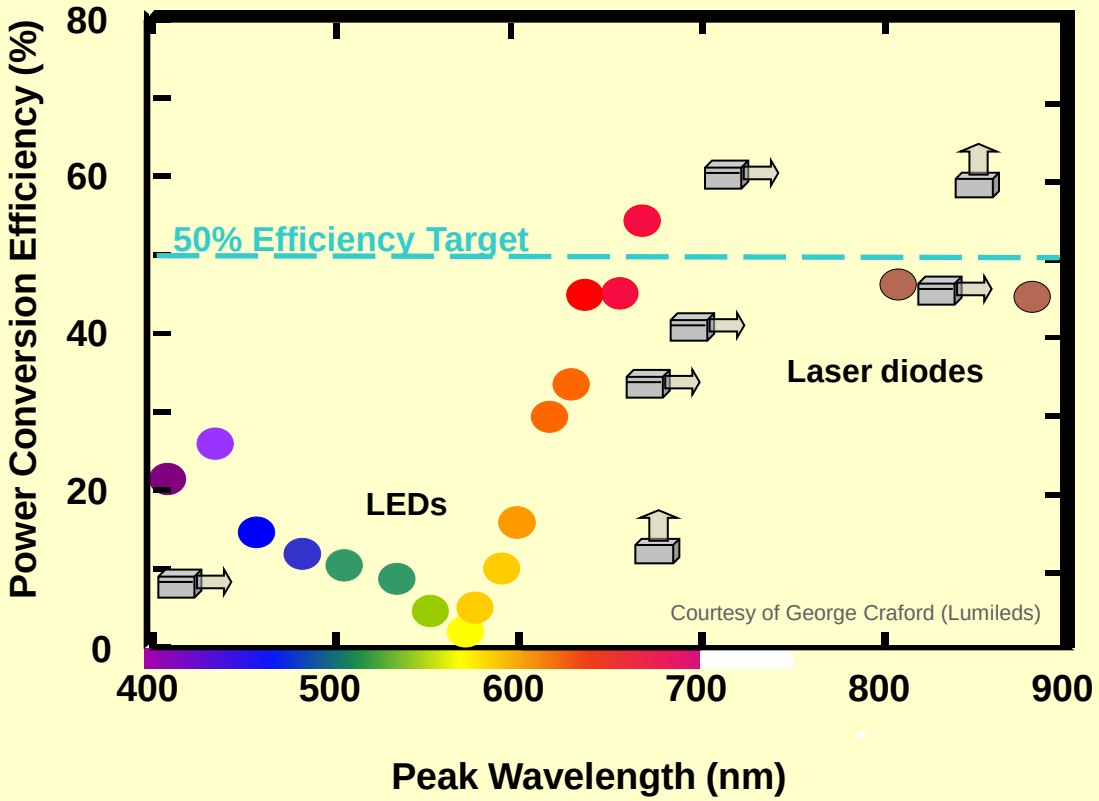
Thomas Edison

Old vacuum-tube based lighting



New semiconductor based solid state lighting

LEDs have the potential to exceed 50% efficiency throughout the visible spectrum

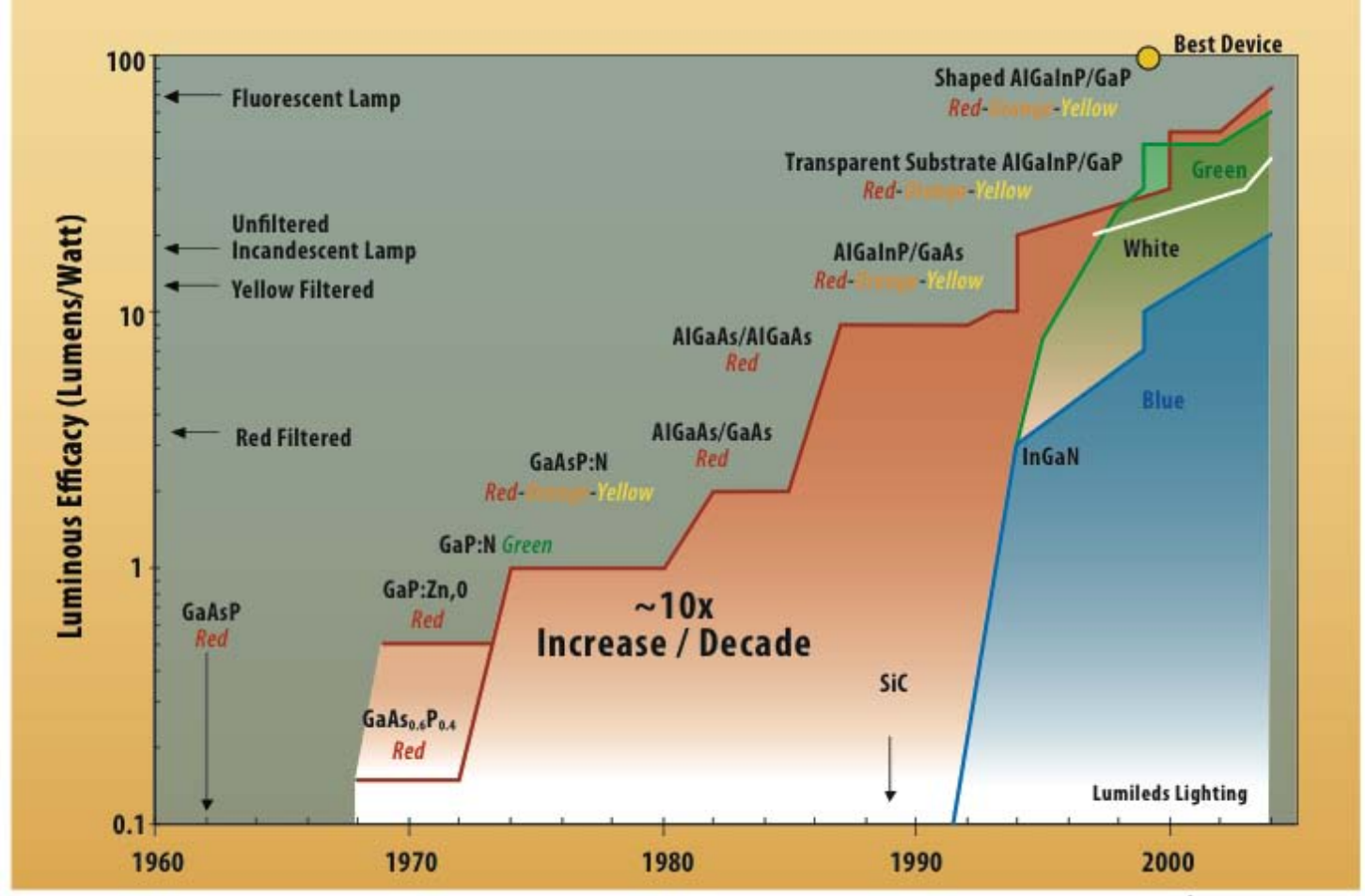


Lasers and LEDs have already achieved >50% efficiency in the red and infrared

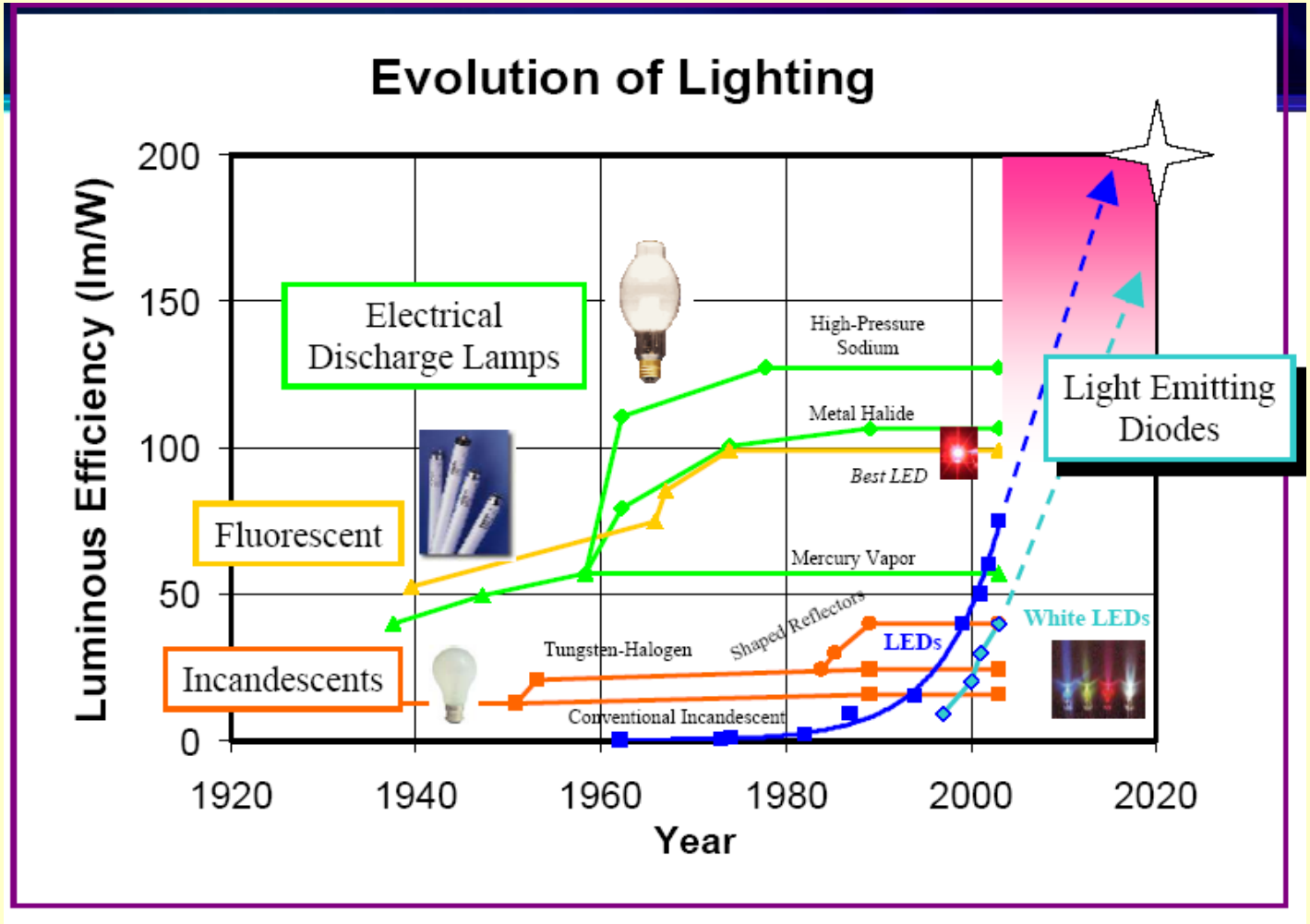
Consensus among experts is that this can be done in the visible too.

Energy Efficiency: Solid-state lighting is potentially **10X and 2X more efficient** than incandescent and fluorescent lamps, respectively.

LEDs Have Been Increasing in Efficiency (and Dropping in Cost) Following a Moore's Law

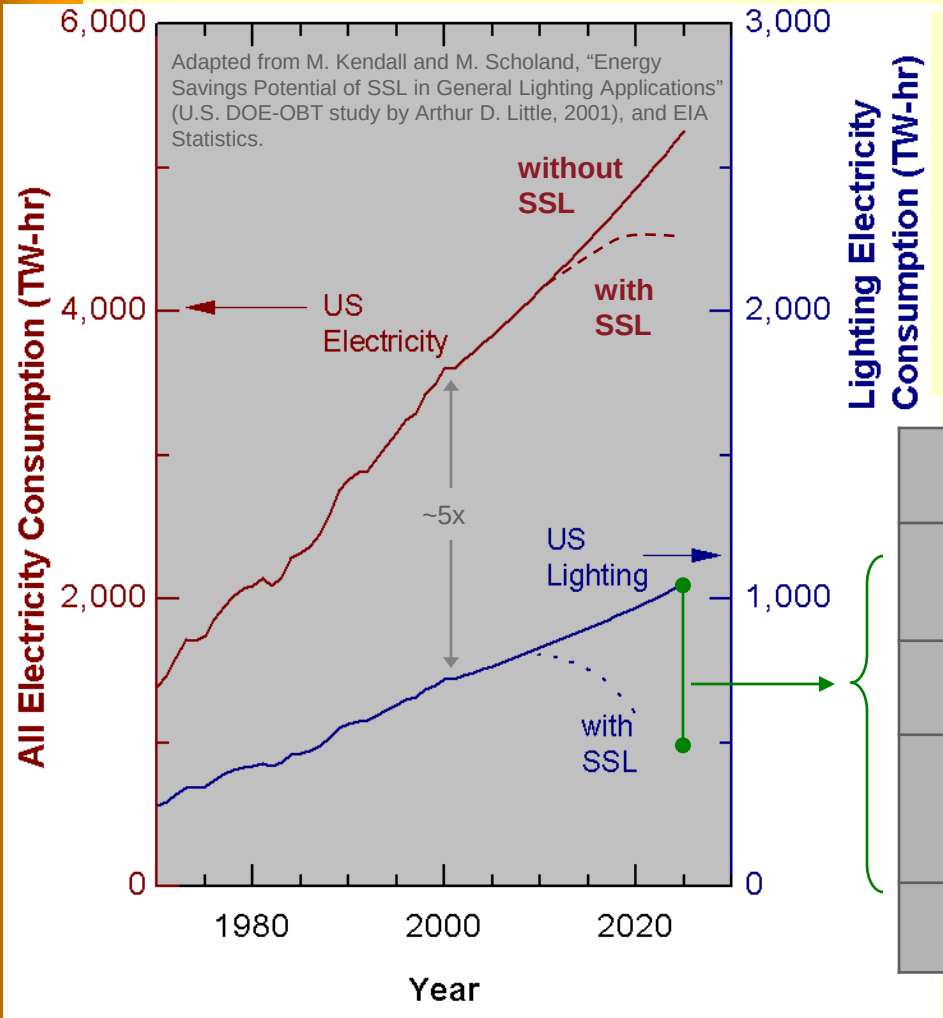


RED: lm/W has improved at 10X/decade, cost has decreased at 10X/decade.



SSL Laboratory and Commercial Curves, revised September 2004

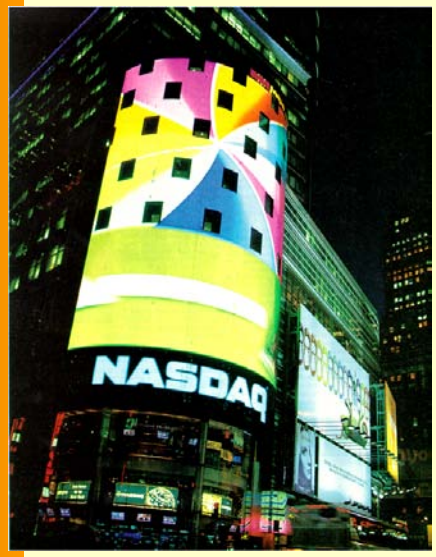
Potential Pay-offs of 50% Efficient SSL are Huge



- Assuming major government investment, we expect, by 2025, to:
  - decrease electricity consumed by lighting by 50%
  - decrease total electricity consumption by 10%

Projected Year 2025 Savings	US	World
Electricity use at site (billion kWh)	500/ year	1,700/ year
$ spent on Electricity per year	25B	105B
Electricity generating capacity (GW)	50	~175
Carbon emissions (Mtons)	50	~175

Solid State Lighting is *The Second Semiconductor Revolution*

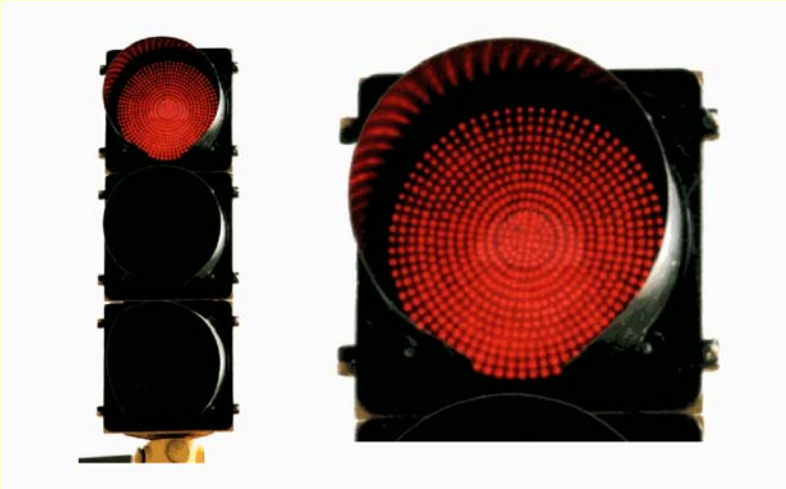


Disruptive Technology: SSL will have huge advantages.

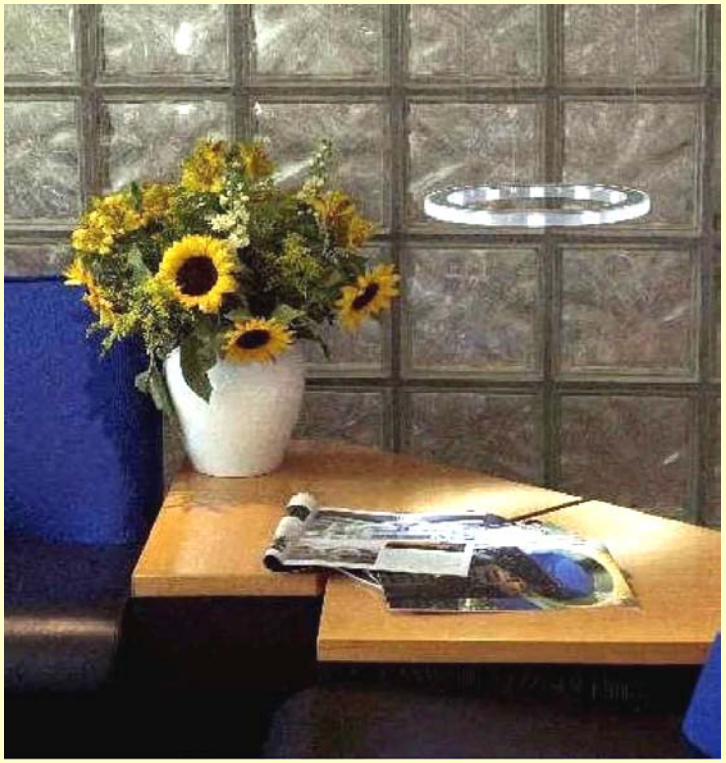
- Compact
- Low Heat
- Shock resistant
- Long lifetime (100,000 hours)
- Easily integrated w/ intelligence
- ***Exquisite control over spectral distribution***

LEDs Are Already Superior for Monochrome Applications

- Red LEDs are now 10X more efficient than red- filtered incandescents
- Today, ~1/2 of US traffic lights are LED-based
- Payback time for LED traffic lights is ~ 1 year
- After that the cost savings are ***$1,000/year per intersection***



The Future: complete replacement by SSL for general illumination



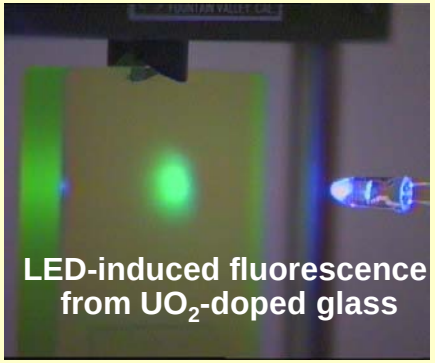
This will be harder to accomplish…

Materials developed for SSL are becoming important for National Security

The large energy band-gaps of GaN-based materials are uniquely suited to:

- **semiconductor UV optoelectronics**
  - *chem-bio detectors*
  - *water purification*
  - *surface decontamination*
  - *solar blind missile plume detectors*
- **high-power, high-frequency electronics**
  - *THz electronics*
  - *High frequency radar*

Predator UAV

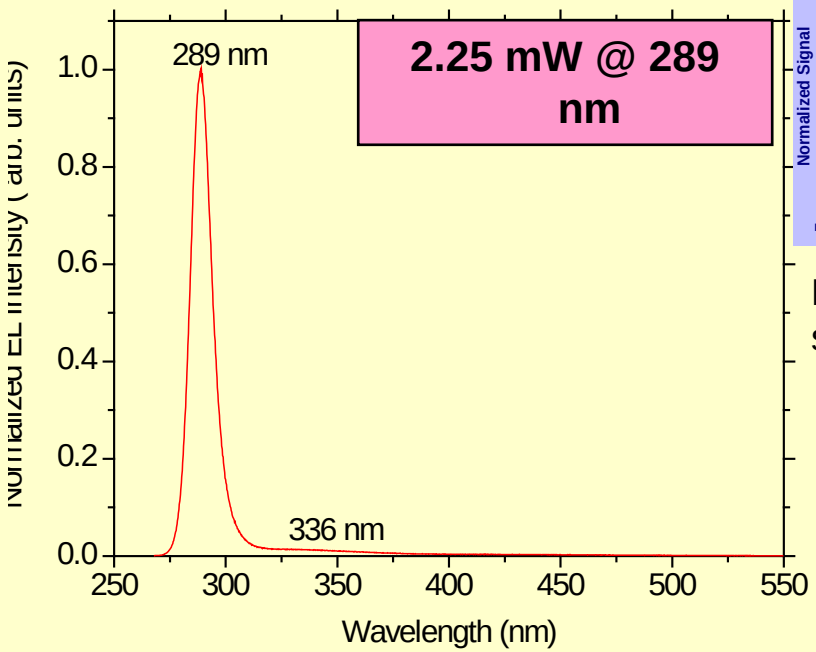


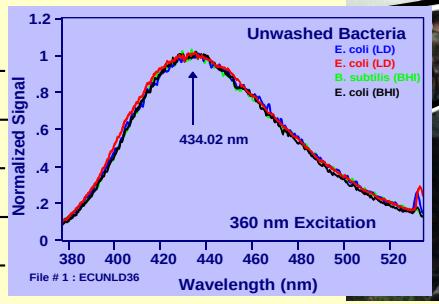
Radar Antenna Assembly

Detection of Biological Weapons is an emerging application for UV LEDs

DARPA has had several programs

- Compact, low-cost, fluorescence-based anthrax detector





Bacteria fluorescence spectrum

Micro-UAV application

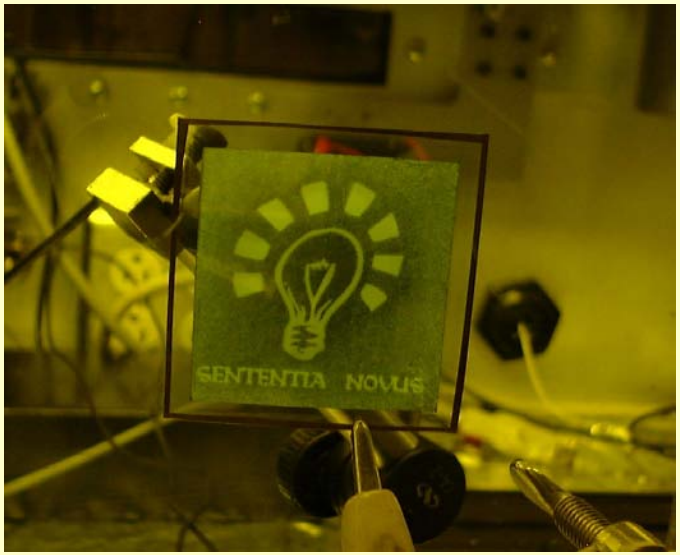
Packaged UV-LED

The Military is also interested in SSL…

What is an LED?

Ghassan Jabbour
Arizona State University

LEDs/OLEDs for Solid State Lighting



Ghassan E. Jabbour, Ph.D., *SPIE Fellow*
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Flexible Display Center
Chemical and Materials Engineering
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Some Human-Made Lights!

Fire

Candles

Lanterns

Incandescent Lamps

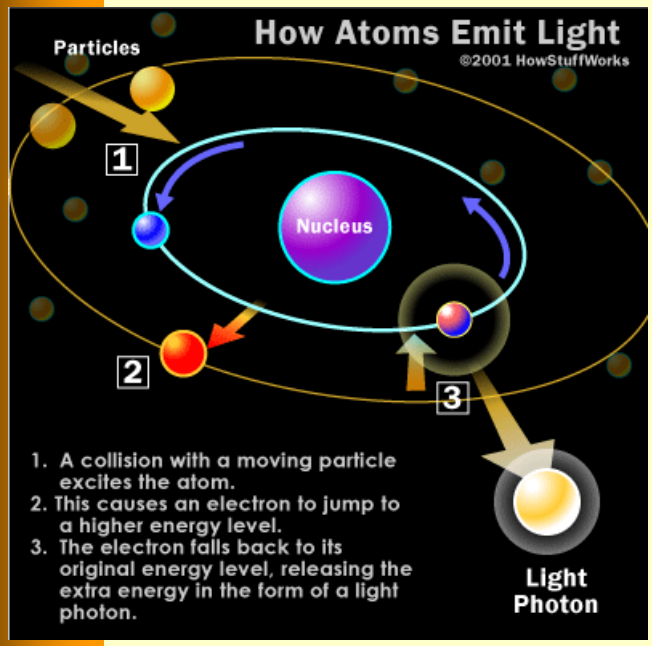
Fluorescent Tubes

Compact Fluorescent

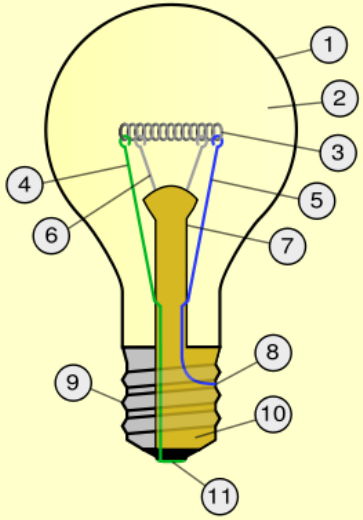
High Pressure Sodium

Halogen Lamps

How Do We Get Light?



Excite the electrons!

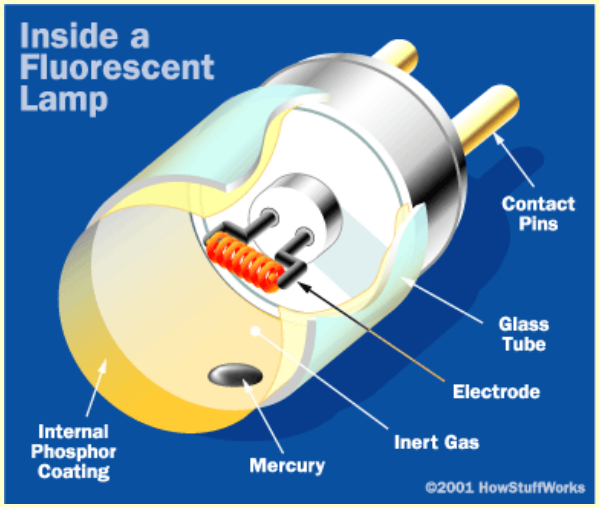


Incandescent light bulb

1 Glass bulb (or "envelope")
2 Low pressure inert gas
3 Tungsten filament
4 Contact wire (goes to foot)
5 Contact wire (goes to base)
6 Support wires
7 Glass mount/support
8 Base contact wire
9 Screw threads
10 Insulation
11 Electrical foot contact

http://en.wikipedia.org/wiki/Incandescent_light_bulb#Operation

Fluorescent lamp



http://home.howstuffworks.com/fluorescent-lamp2.htm

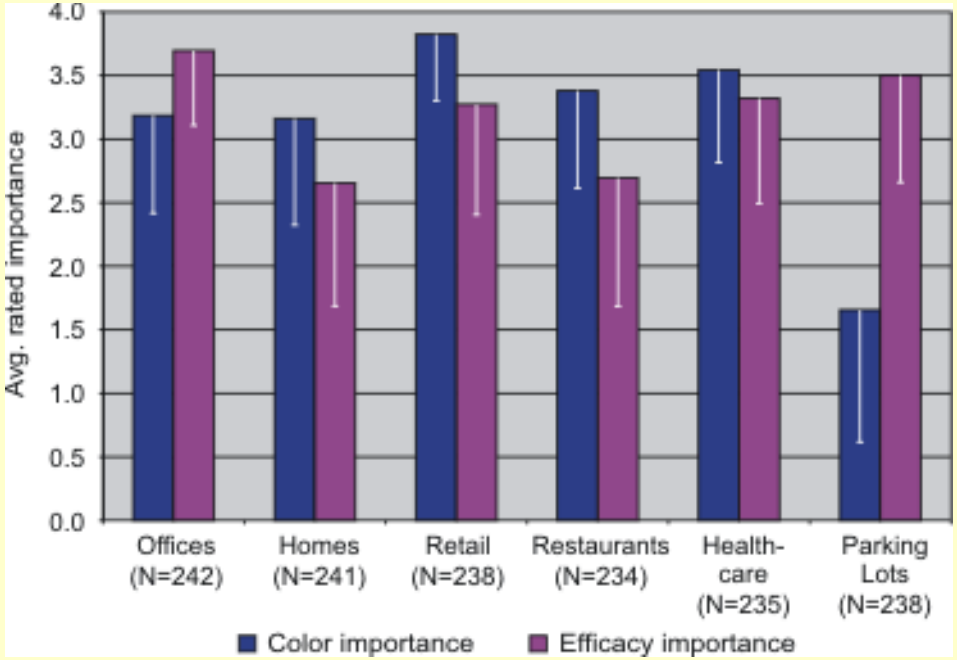
Color Rendering Index

"The color rendering index (CRI), is a measure of the ability of a light source to reproduce the colors of various objects being lit by the source (100 is the best CRI)."

Light source	*Color rendering index*
Sunlight	100
Quartz halogen W filament light	100
W filament incandescent light	100
Fluorescent light	60 – 85
Phosphor-based white LEDs/OLEDs	60 – 90
Trichromatic white light LEDs/OLEDs	60 – 90
Hg vapor light coated with phosphor	50
Na vapor light	40
Hg vapor light	20
Dichromatic white light LEDs	10 – 40

F. Schubert LED 2001 (updated by G. E. Jabbour)

Lower CRI leads to faded (dead look) images!



National Lighting Product Information Program (NLPIP) survey on the importance of lamp color and efficacy (2004)
http://www.lrc.rpi.edu/programs/nlpip/lightinganswers/lightsources/importance.asp

Why LEDs/OLEDs for Solid State Lighting?

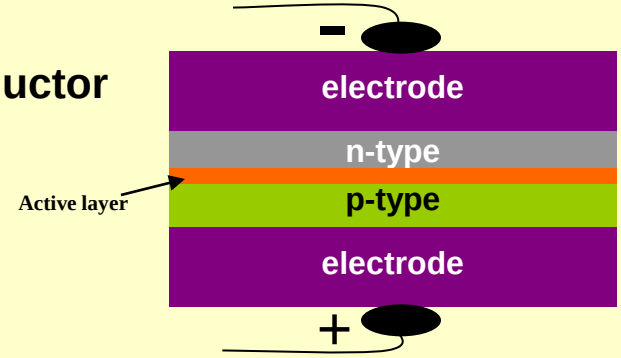
LEDs/OLEDs offer an unprecedented route not only to high CRI, but also energy efficient solid state lighting sources that are extremely important for various security and economical reasons. LEDs/OLEDs also offer:

- **Light weight (a solider normally carries more than 100 lbs!) lights**
- **Rugged lights**
- **Low Power consumption**
- **UV-Visible-IR capable**
- **Low fabrication costs (OLEDs) including printing techniques can be used**
- **Flexible lights and displays (OLEDs)**

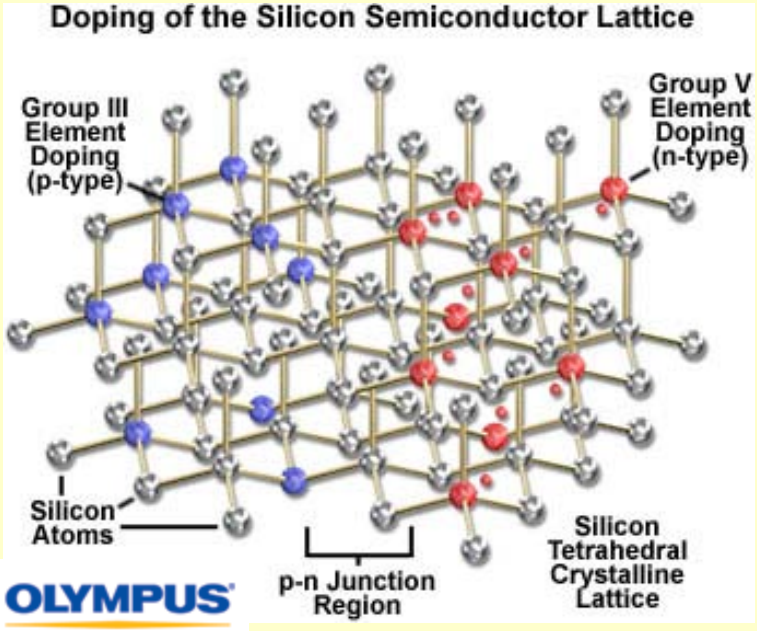
What is an LED?

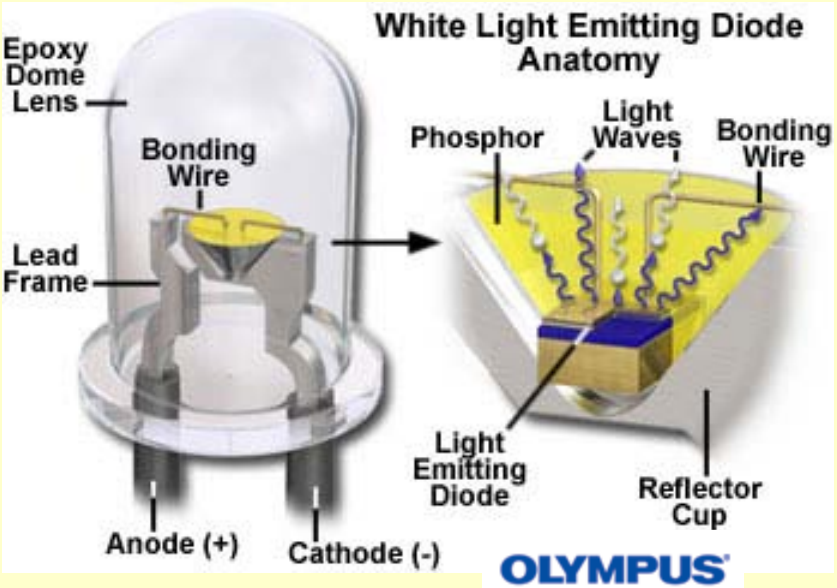
A simple LED is a single crystal sandwich of semiconductor layers:

- Negative type layer (n-type to carry electrons)
- Positive type layer (p-type to carry holes)
- Active layer where electrons and holes recombine (annihilate) to produce a photon



Simple LED structure

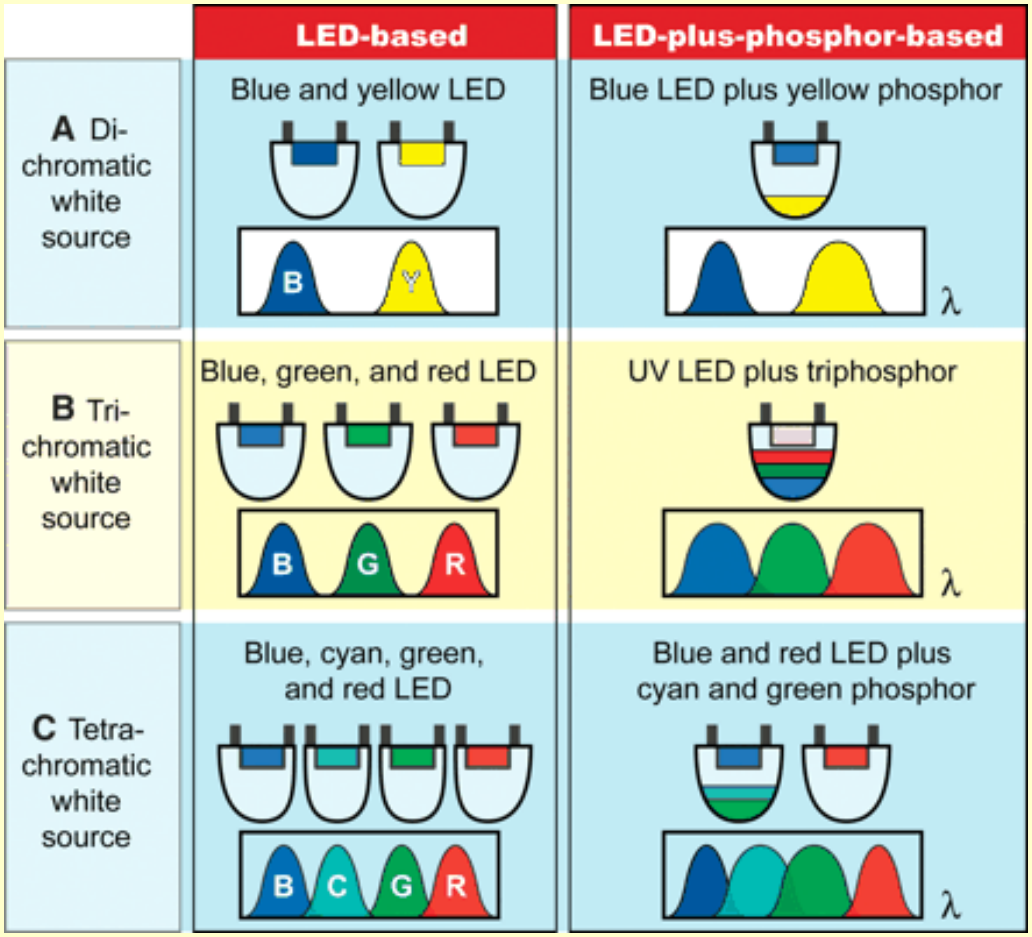




Atoms must be placed within certain order with respect to each other. This means special fabrication techniques (e.g. Molecular Beam Epitaxy, Chemical Vapor Deposition).

How to Make White LEDs?

Combine various monochromes!

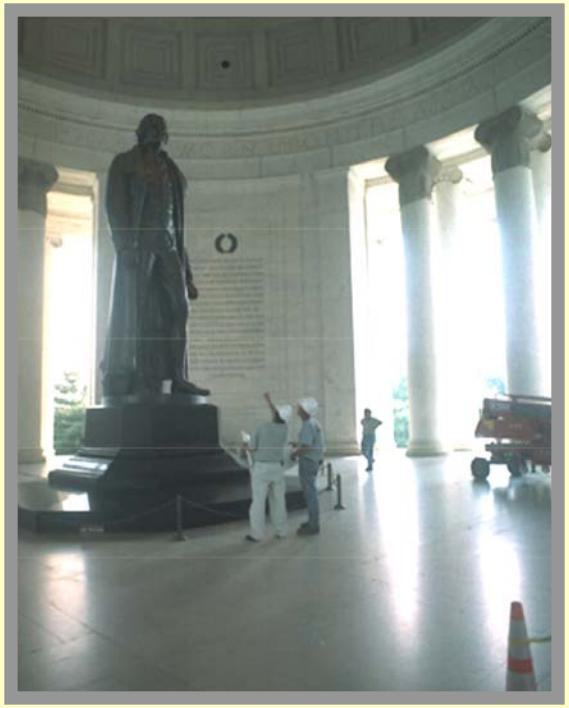


E. F. Schubert et al., Science 308, 1274 -1278 (2005)

Jefferson Memorial

LED Lighting!

NO lights were used in interior dome (difficulty maintaining them, due to the > 50 ft height!).



Jefferson's quote lighted with 17,000 light emitting diodes (750 linear feet of LED's)

From SYLVANIA

The Largest LED Display in the World
(Fremont Street Mall in Las Vegas, Nevada-USA)

- **1,500 ft long**
- **12.5 million LEDs**

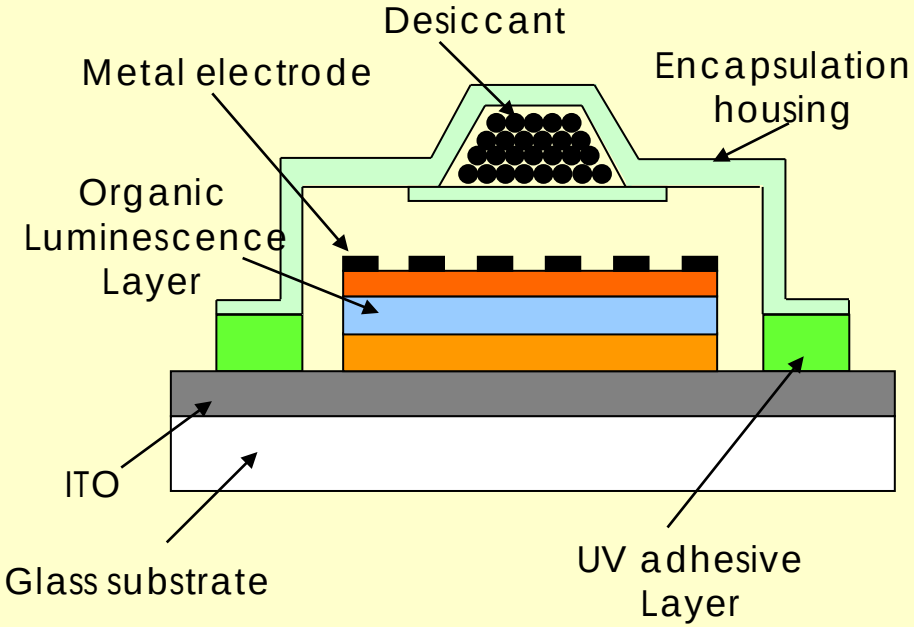
In addition to security, lighting and displays, some LED applications are:

- **Telecommunications**
- **Medical imaging and therapy**
- **Armed Forces (vehicles and outfits)**
- **Plant growth**
- **Architecture**
- **Optical measurements**
- **Airports**
- **Traffic signs and law enforcement vehicles**

What is an OLED?

A simple OLED is made of:

- p-type organic layer
- light emitting layer
- n-type organic layer

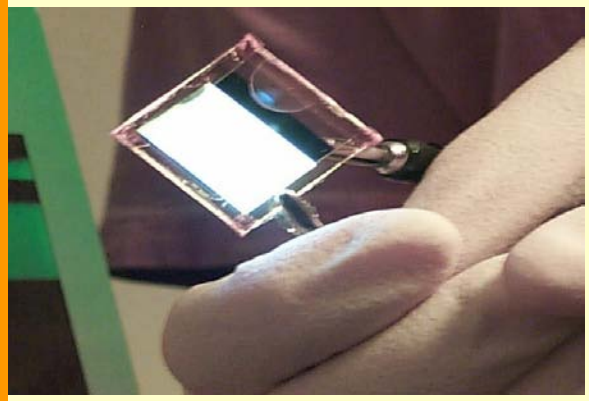


ALL layers are amorphous (no order is required for molecules!)

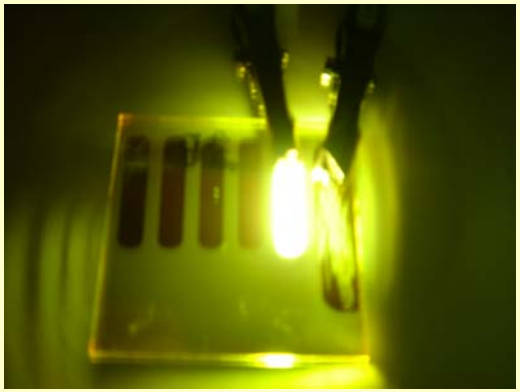
- **OLEDs can be fabricated with low cost techniques including: Inkjet and roll-to-roll printing tools!**
- **Large area DIFFUSE lights!**
- **White OLEDs can be obtained by either multilayer structure, or single layer based on nano-materials (recent progress)**

OLED SSL Examples

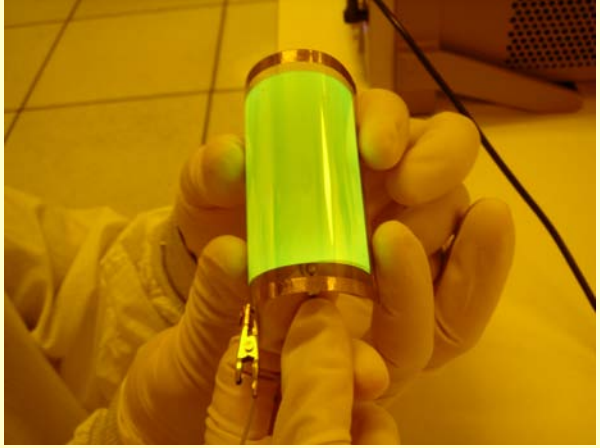
Jabbour's group at ASU



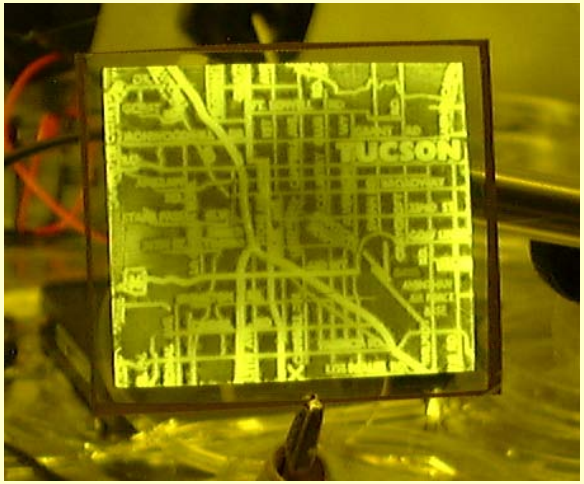
Screen printed white OLEDs



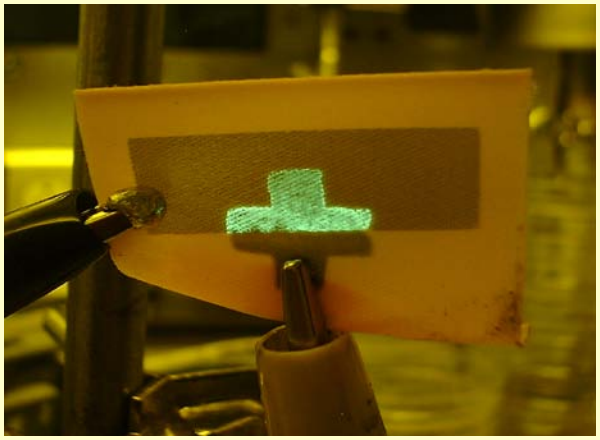
Bright OLEDs



Flexible plastic green OLEDs



Inkjet printed OLED maps



OLEDs printed on textile

Transparent OLEDs!

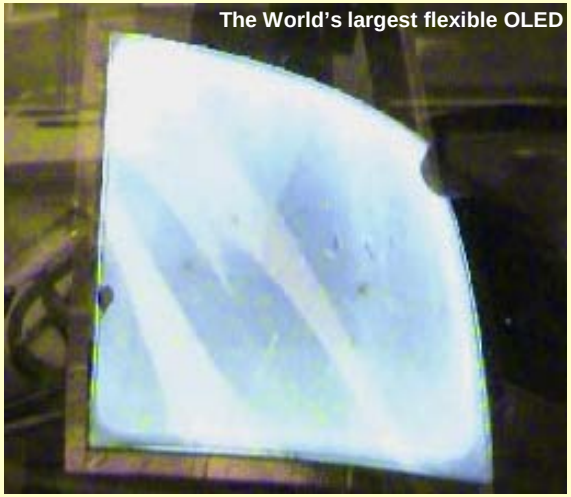
USA pat # 7015052

Recent Progress in White OLEDs

The World best voltage independent white OLED developed recently:

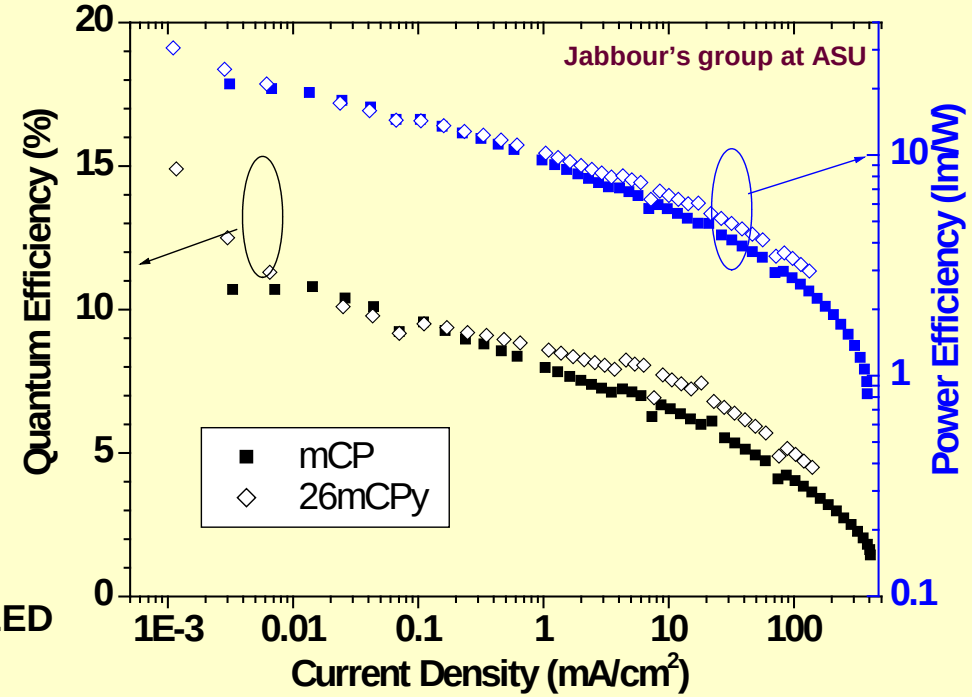
- **Luminous efficiency: 8 lm/W at about 900 cd/m^2**
- **Required for SSL application: at least 45 lm/W at 900 cd/m2**

white 5a.wmv



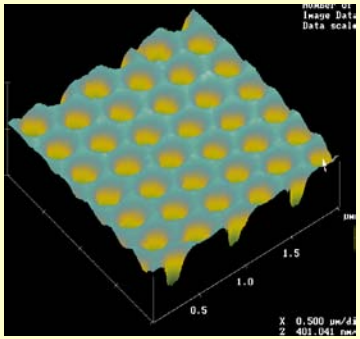
6"x6" Flexible "almost whitish OLED

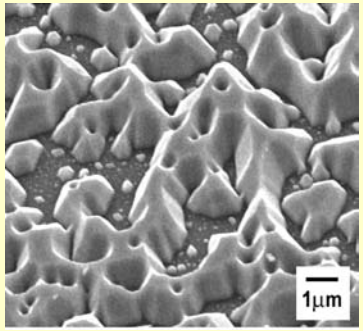
Jabbour's group at ASU

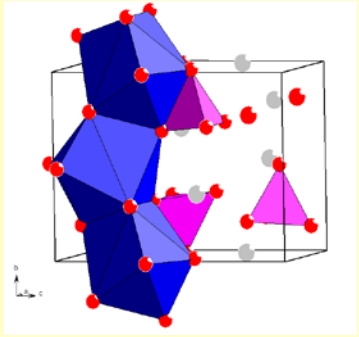


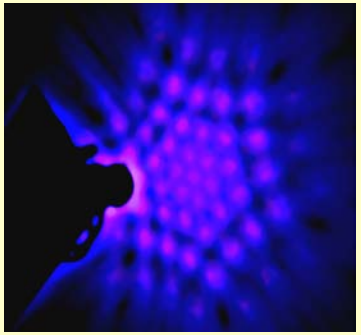
R&D Challenges to Achieving 50% Energy Efficient SSL

- Higher performance, better quality semiconductor crystal materials, especially green
- Higher performance, better quality organic materials
- New techniques and designs for light extraction (getting the light out of the LED) -- e.g. photonic crystals.
- More efficient phosphors and hybrids -- e.g. quantum dots.
- Higher performance packaging and encapsulation materials





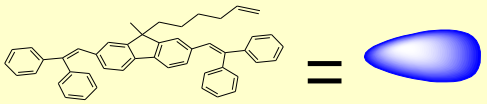




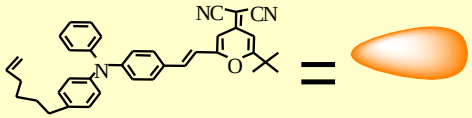
Nanoscience will help to overcome these challenges

R&D Challenges continued

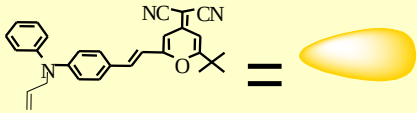
Novel Organic/Inorganic Nano SSL Materials



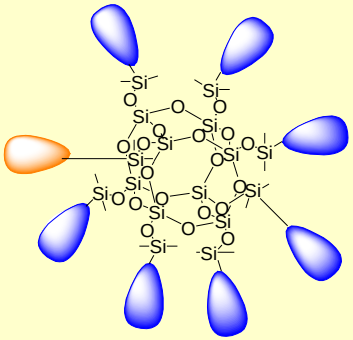
Free blue dye



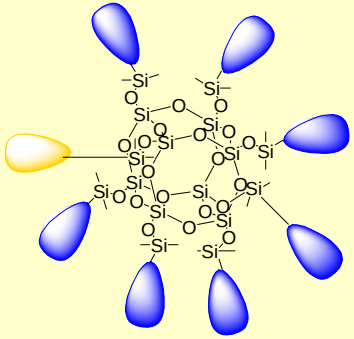
Free orange dye



Free yellow dye

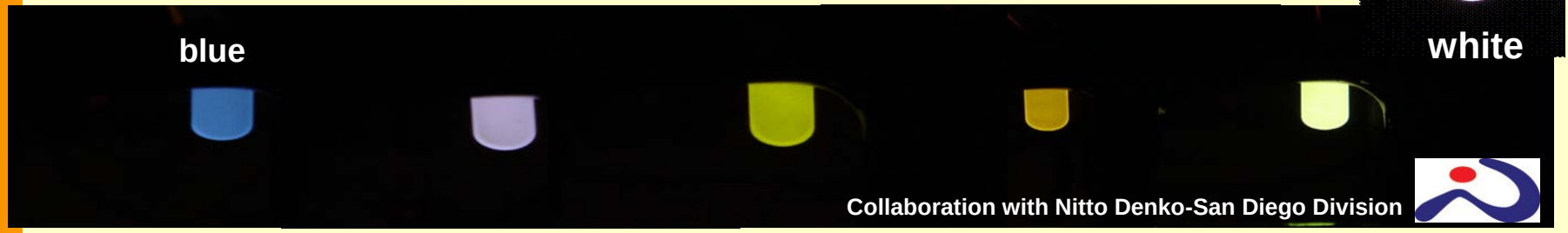


$POSS(orange)_1(blue)_7$



$POSS(yellow)_1(blue)_7$

By adjusting the content of the nano-material, one can control the color emitted:



Nanoscience & Nanotechnology will play a critical role in SSL

To achieve 50% effiency, we need to understand and control the complex interplay of:

- *charge carrier transport at the nanoscale*
- *quantum confinement*
- *radiative & non-radiative recombination*
- *point & extended defects*
- *how molecular structure controls function*

The obstacles to achieving 50% energy efficiency SSL are largely ***nanoscience problems.***

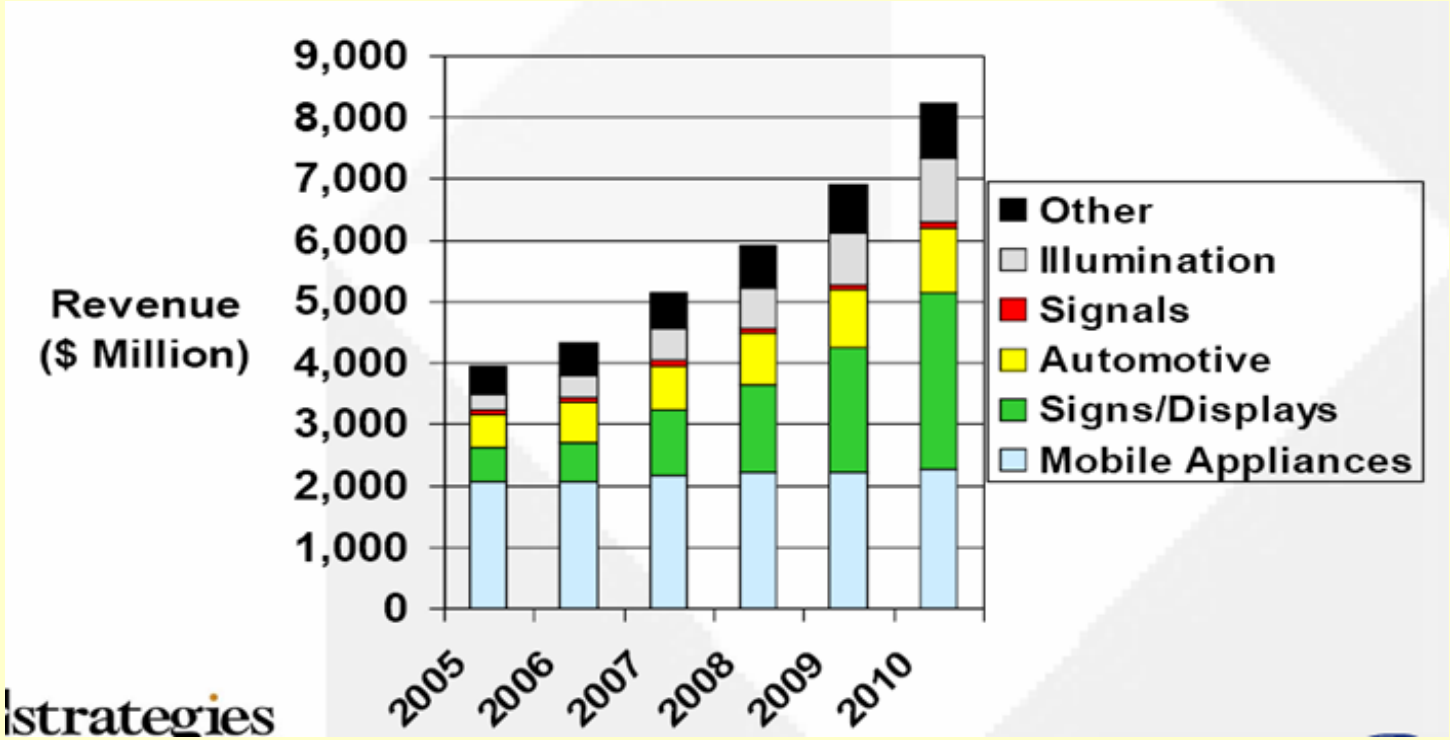
SSL Markets and the Industrial Perspective

John J. Ekis
Lamina Ceramics

Industrial Perspective

- Markets, Economic Drivers and Growth
- Global Competition
- Application Gallery
- Technology Demonstration

HB LED Summary Forecast By Application 2004-2010 ($ Million) †



† *Courtesy Robert V. Steele, Strategies Unlimited*

Growth in SSL†

- High-brightness LED market has grown from $300 million in 1997 to $1.8 billion in 2002.
- Growth has continued by 50% through 2004 to $3.7 billion.
- Forecast for the HB-LED market to grow to > $5 billion by 2007 and >$8 billion in 2010.

† *Courtesy Robert V. Steele, Strategies Unlimited*

Market Drivers ▶ Input for Roadmaps

Technology Roadmaps for LEDs

- End User Driven
  - New Possibilities
    - Design, branding, form factor, digital control, saturated colors
  - Reduced Cost of Ownership
    - Longer life, energy efficiency, reliability, lumen maintenance, safety
  - Environmental Impact
    - Mercury, lead, energy efficiency

Market Drivers ► Input for Roadmaps

Technology Roadmaps for LEDs

- Industry Initiatives
  - Next Generation Lighting Industry Alliance

    www.nema.org/index_nema.cfm/640/
  - Alliance for Solid State Illumination Systems & Technologies

    www.lrc.rpi.edu/programs/solidstate/assist/ASSISTHome.htm
  - European Photonics Industry Consortium:

    www.epic-assoc.com

Market Drivers ► Input for Roadmaps

Technology Roadmaps for LEDs

- Government Initiatives
  - US (www.netl.doe.gov/ssl), Japan, Taiwan, Korea, China
  - Objectives
    - Reduce
      - CO2 emissions from energy generation
      - Need for new power plants
      - Dependence on un-renewable fuels
      - Environmental impact – mercury, lead

Worldwide Competition

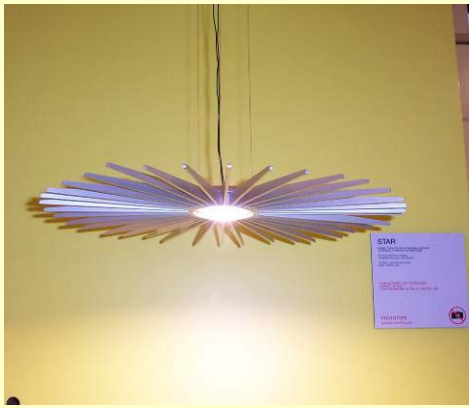
- Main production and consumption in US, Europe, Japan, Taiwan, South Korea, China and Southeast Asia
- Virtually all HB LEDs packaged in Asia
- Initial investment in 2004 from China in National SSL program of RMB 140 m ($17 m) from central government, involving 15 research institutions and more than 50 enterprises – Target to replace 40% of incandescent lighting with SSL

Times Square Ball to be Lit with LEDs

- The 1,070 pound geodesic orb, six feet in diameter, currently contains 600 clear and colored high-intensity halogen bulbs and 96 halogen strobe lights
- By New Year's Eve 2006/07 celebration, Philips Electronics will outfit the ball with an interior of more efficient LEDs.
- By 2007/08, entire sphere will be redesigned and completely illuminated by LEDs.

Courtesy LEDs Magazine – January 6, 2006

Gallery - Powered by LED's



Gallery - Powered by LED's

Gallery - Powered by LED's

IVision
Key Floodlight

Desert Star
SharkEye Sea floor survey strobe

Allayes LED Instruments
Jewel on Spike

AGO Environmental
Subsea
Zip Subsea

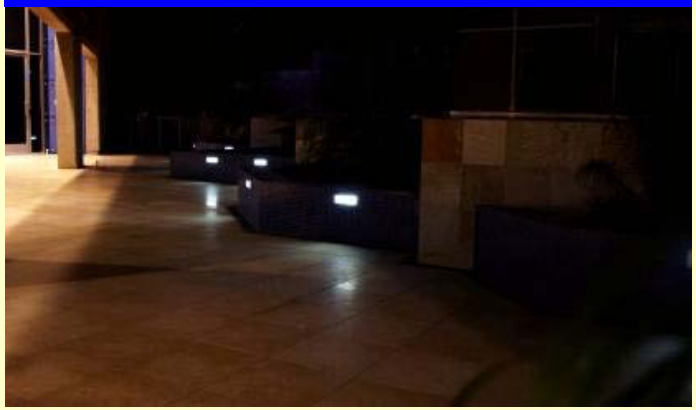
Gallery - Installations

Bellagio - Sensi Restaurant

MGM Grand's Teatro

Providence Performing Arts Center

SunCal Corp. Headquarters

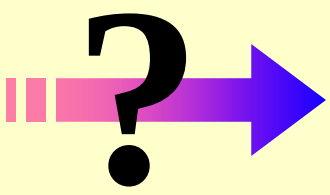


U.S. Government Programs

Jerry Simmons
Sandia National Laboratories

For *General Illumination*, replacing conventional lighting will be harder

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.



Technology breakthroughs must continue to take place for white light SSL to compete with conventional lighting

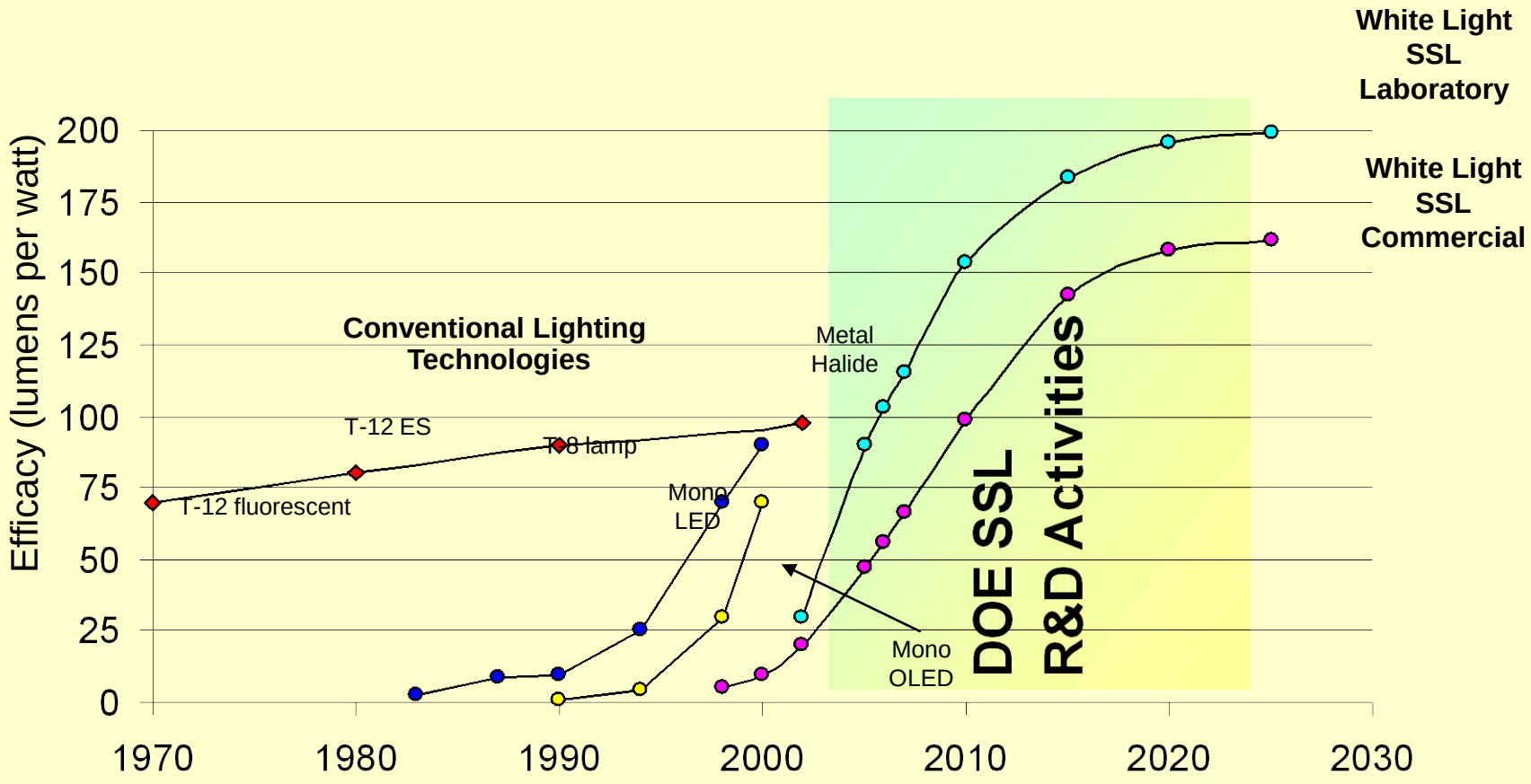
DOE/Office of Energy Efficiency and Renewable Energy has an SSL program

DOE/EERE Solid-State Lighting Program Goal

By 2025, develop advanced solid state lighting technologies that, compared to conventional lighting technologies, are much more energy efficient, longer lasting, and cost-competitive, by targeting a product system efficiency of 50 percent with lighting that accurately reproduces the sunlight spectrum.

http://www.netl.doe.gov/ssl

Accelerated R&D for White Light SSL



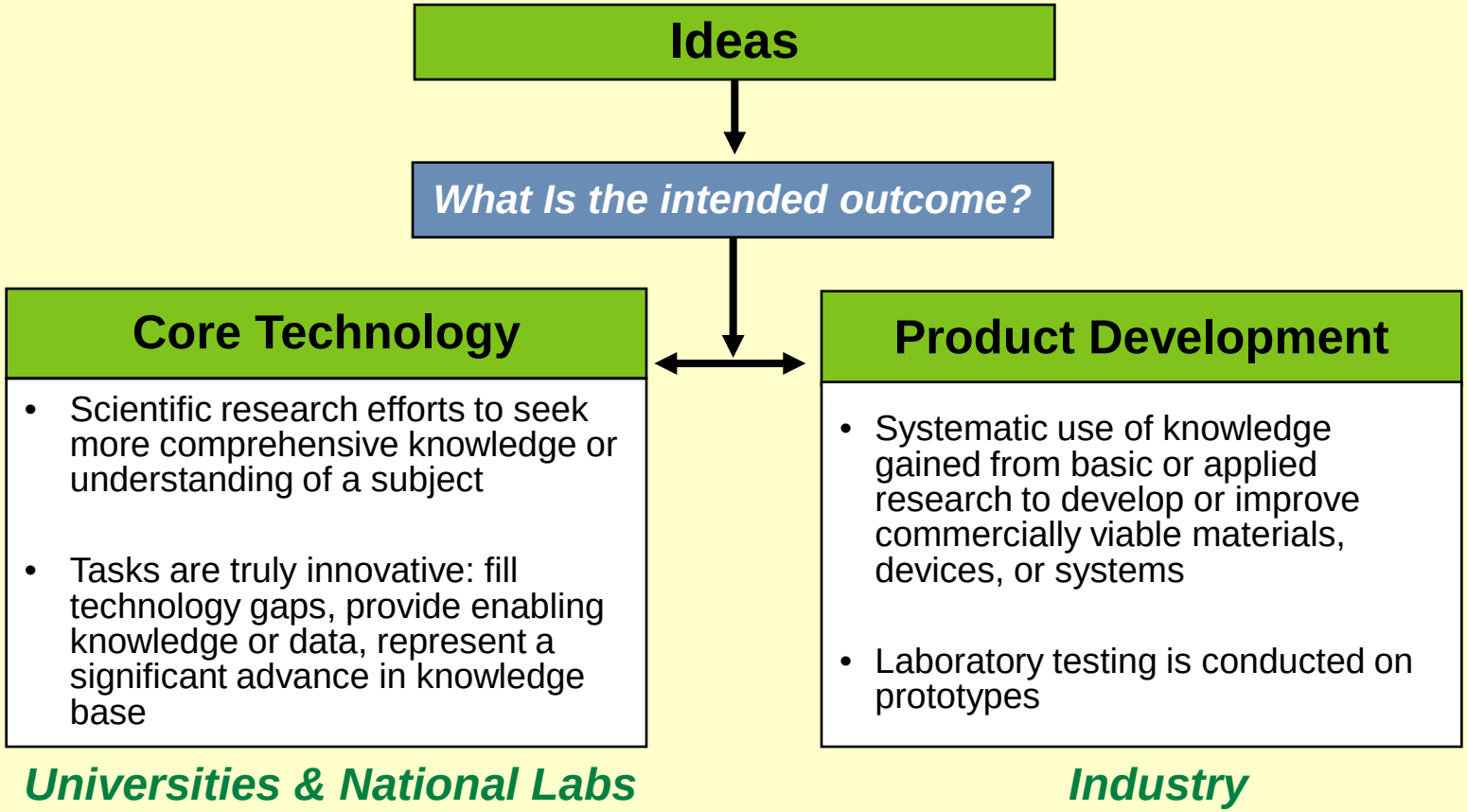
DOE/EERE Technology Roadmap goals

TECHNOLOGY	SSL-LED 2002	SSL-LED 2007	SSL-LED 2012	SSL-LED 2020	Incande-scent	Fluore-scent
Luminous Efficacy (lm/W)	25	75	150	200	16	85
Lifetime (hr)	20,000	>20,000	>100,000	>100,000	1,000	10,000
Flux (lm/lamp)	25	200	1,000	1,500	1,200	3,400
Input Power (W/lamp)	1	2.7	6.7	7.5	75	40
Lumens Cost ($/klm)	200	20	<5	<2	0.4	1.5
Lamp Cost ($/lamp)	5	<5	<5	<3	0.5	5
Color Rendering Index (CRI)	75	80	>80	>80	95	75

Taken from the 2002 DOE/OIDA LED Technology Roadmap

The SSL community is just about on target in 2006.

DOE/EERE SSL Research Plan



The Energy Policy Act of 2005 is supportive of increased SSL R&D

Subtitle A - Energy Efficiency

SEC. 912. NEXT GENERATION LIGHTING INITIATIVE

"The Secretary shall carry out a Next Generation Lighting Initiative in accordance with this section to support research, development, demonstration, and commercial application activities related to advanced solid-state lighting technologies based on white light emitting diodes."

Authorizes $50M/year for 2006 through 2013 (8 years)

Subtitle F: Science

SEC. 966. SOLID STATE LIGHTING

"The Secretary shall conduct a program of fundamental research on advanced solid state lighting in support of the Next Generation Lighting Initiative carried out under section 912."

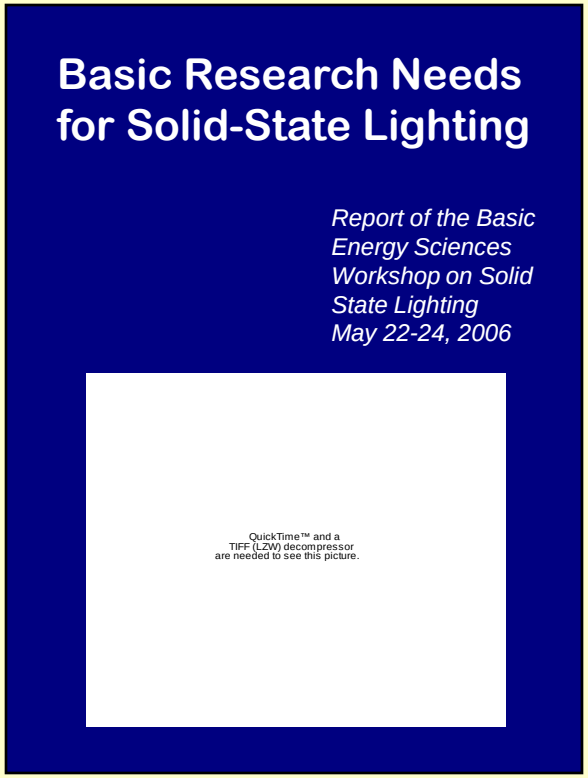
DOE/Office of Science is interested in basic research relevant to SSL

Basic Energy Sciences (BES) interest:

1) BES held a contractors meeting in Orlando Feb.1, in conjunction with the EERE/Building Technologies SSL Workshop

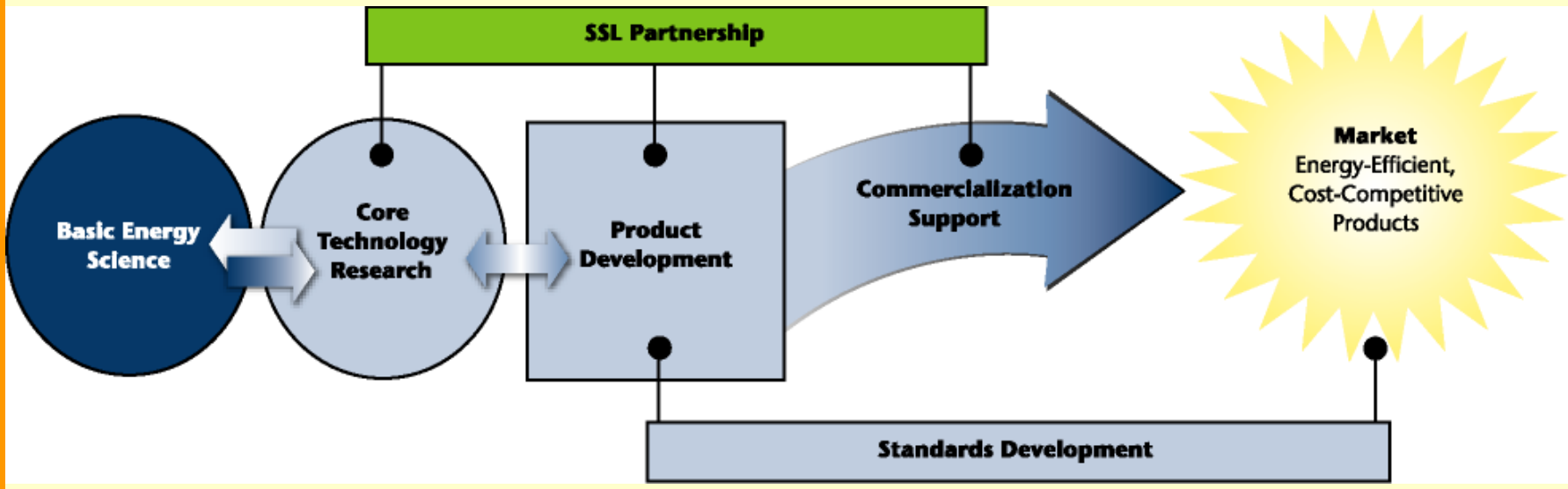
2) BES held a workshop on "Basic Research Needs for Solid State Lighting" in Bethesda May 22-24, 2006. A workshop report is expected in July.

3) A program would likely include basic research by the nation's universities and government labs.



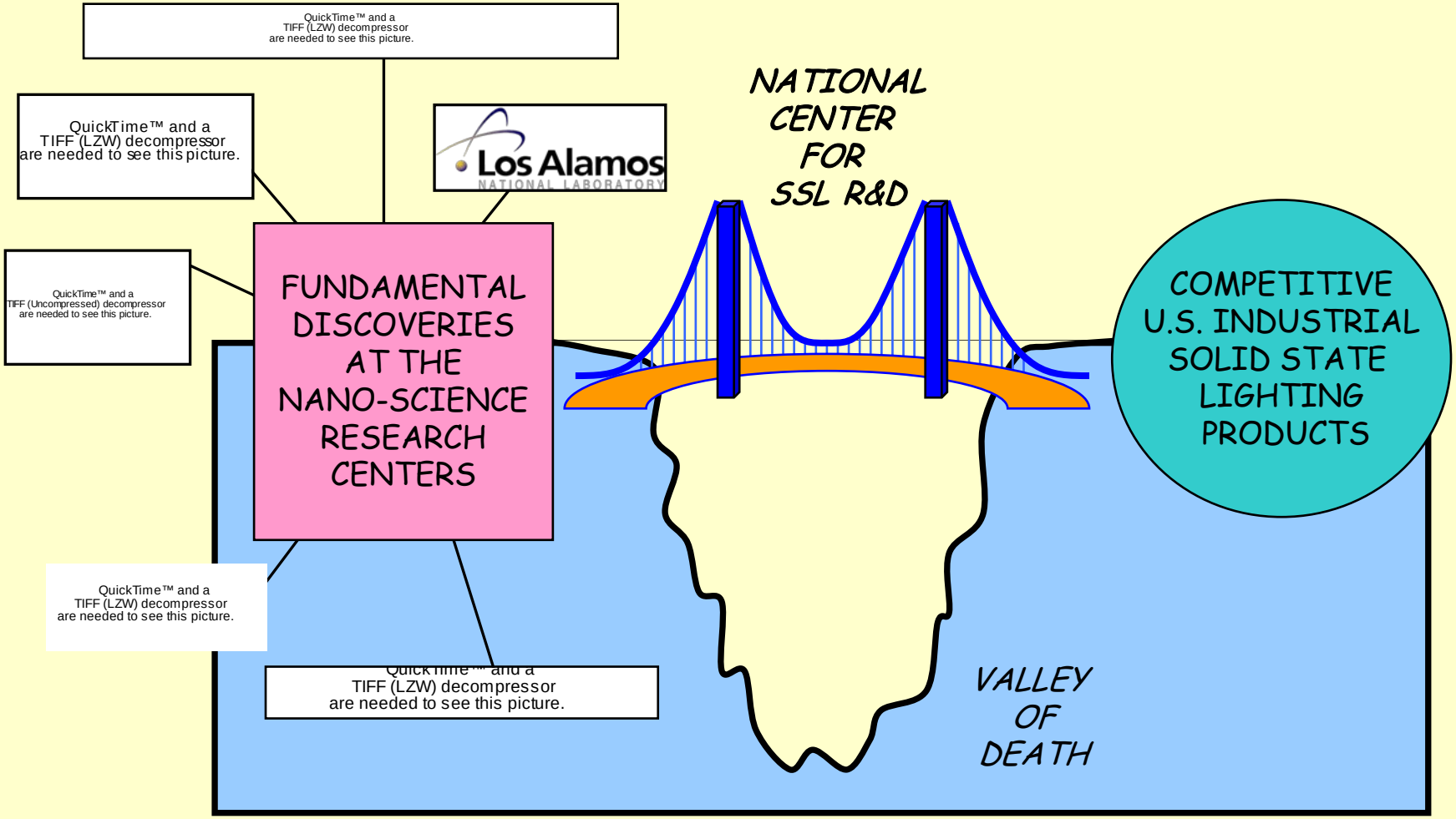
An unauthorized mock-up of the cover

A Five-Thrust Total SSL Program is Being Implemented by DOE

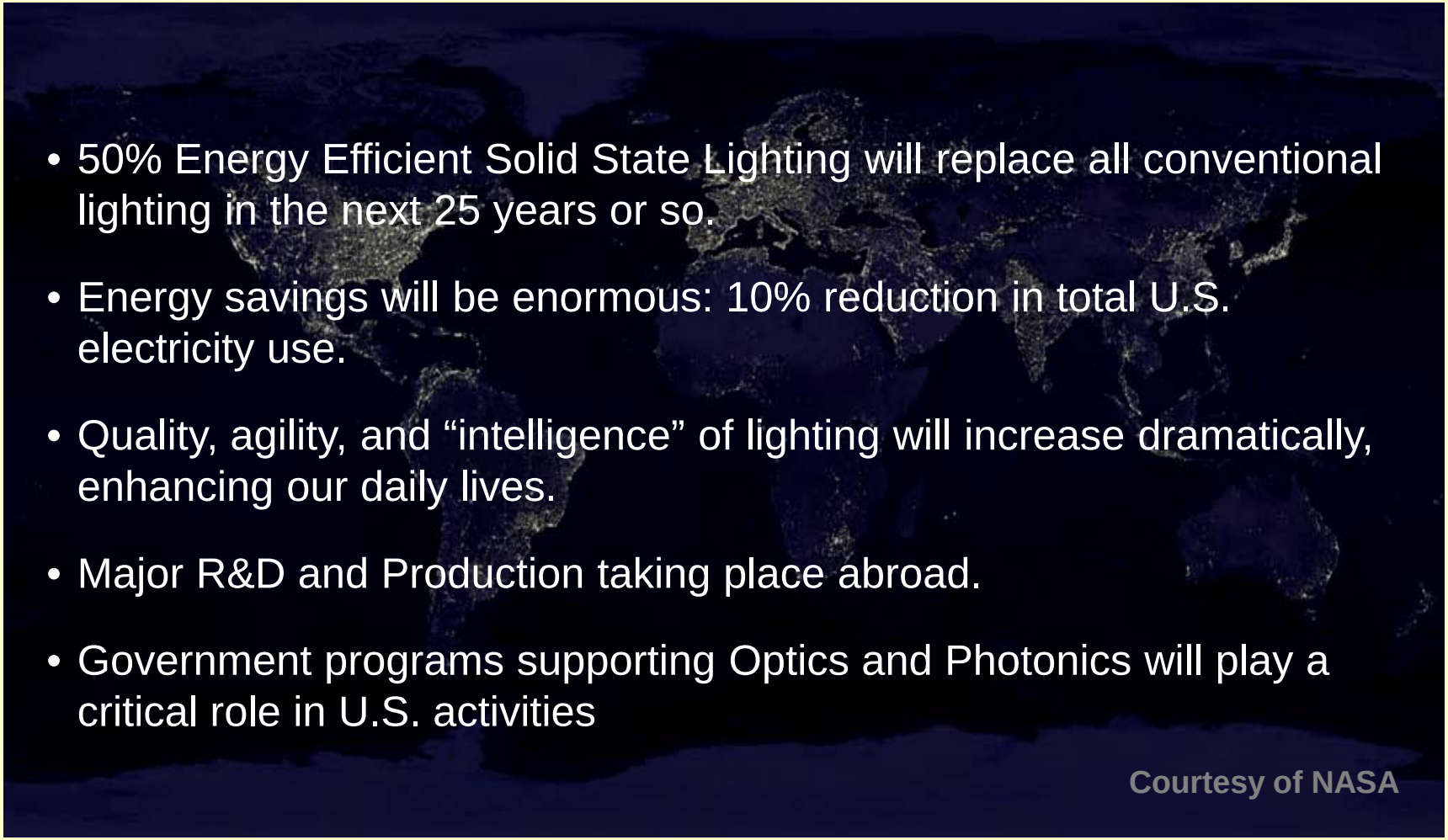


Guiding technology advances from laboratory to marketplace

A National Center for SSL will be established to transition SSL nanoscience to industry



Summary



- 50% Energy Efficient Solid State Lighting will replace all conventional lighting in the next 25 years or so.
- Energy savings will be enormous: 10% reduction in total U.S. electricity use.
- Quality, agility, and “intelligence” of lighting will increase dramatically, enhancing our daily lives.
- Major R&D and Production taking place abroad.
- Government programs supporting Optics and Photonics will play a critical role in U.S. activities

Courtesy of NASA