SAND2010-8723P

Visit to New Mexico State Government Offices
Dec. 13, 2010

Solid-State Lighting: A New, Green Technology

Jerry Simmons
Mike Coltrin
Sandia National Labs

SSLS EFRC

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Company, for the U.S. Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000. This work is supported by Sandia's Solid-State Lighting Science Energy Frontier Research Center, sponsored by the Department of Energy Office of Science.

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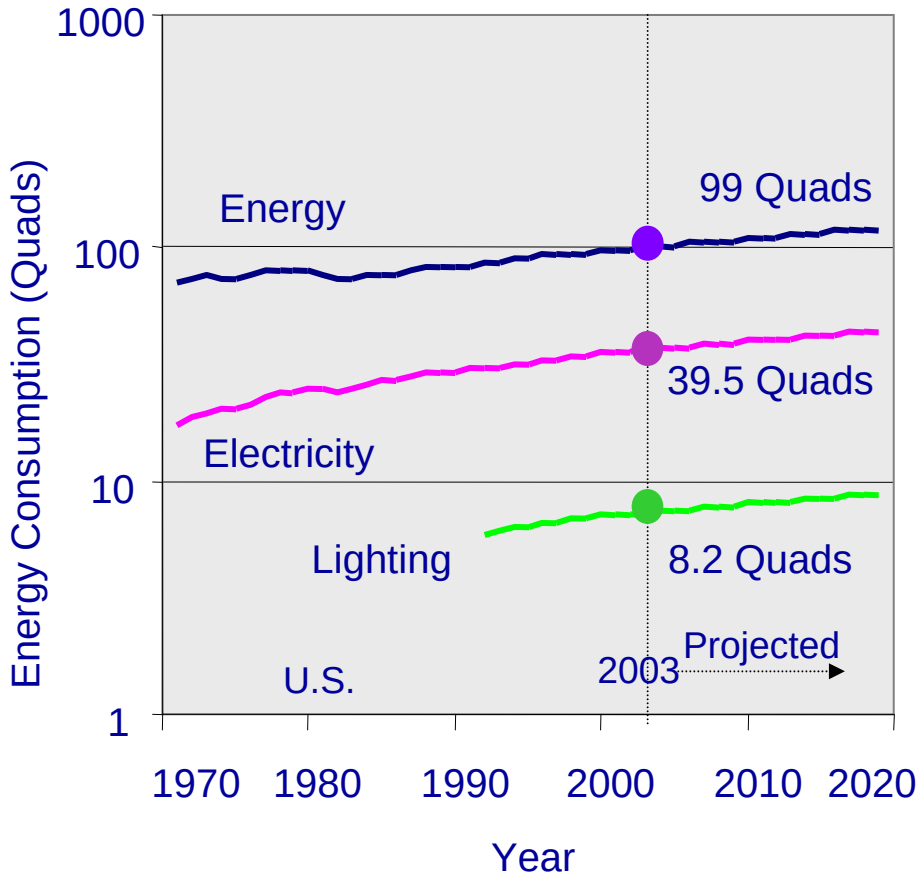
Lighting is a large fraction of energy consumption and is low efficiency

- ~22% of electricity consumption is for general illumination
- Lighting is a highly attractive target for reducing energy consumption!



Efficiencies of energy technologies in buildings:

Heating:	70 - 80%
Elect. motors:	85 - 95%
Fluorescent:	20-25%
Incandescent:	~5%

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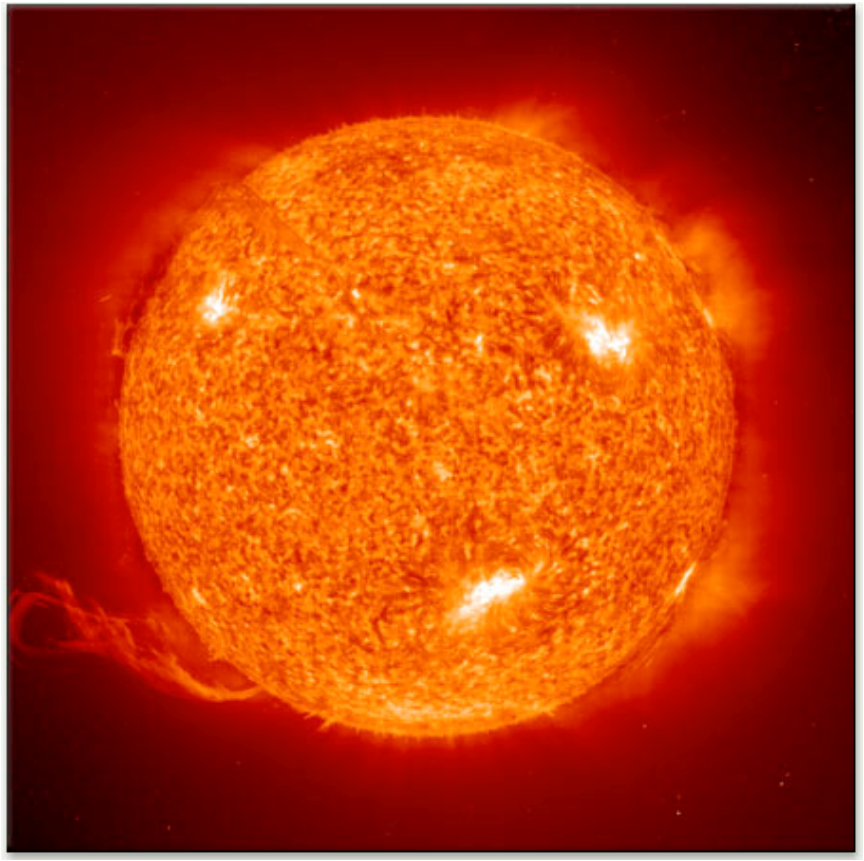
Lighting Technologies

The major ones are:

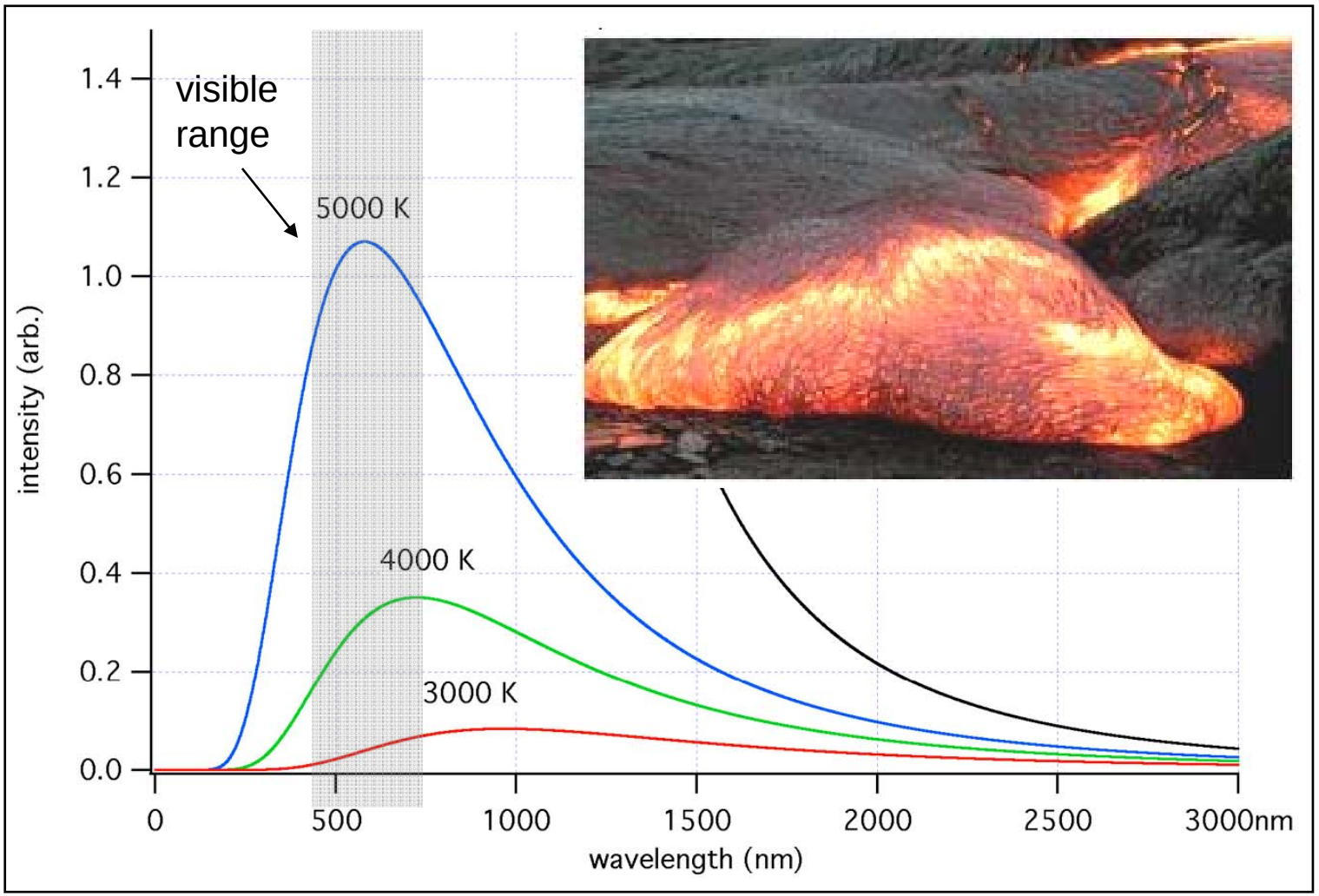
1. Incandescent
2. Fluorescent
3. Solid State Lighting (emerging)

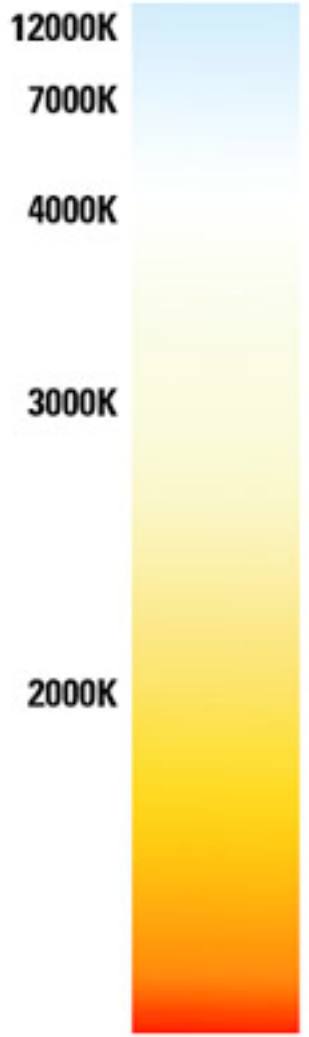
The Sun – mankind's first light source



Emits light using the same principle as incandescent bulbs…

Black Body Radiation: When a fireplace poker gets hot, it emits light





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Candles, lanterns, and gas lamps are also black body light sources

Candle:
0.05 lumens per watt
(0.015% efficient)

Gas Lamp:
0.5 lumens per watt
(0.15% efficient)

Incandescent bulb:
15 lumens per watt
(5% efficient)

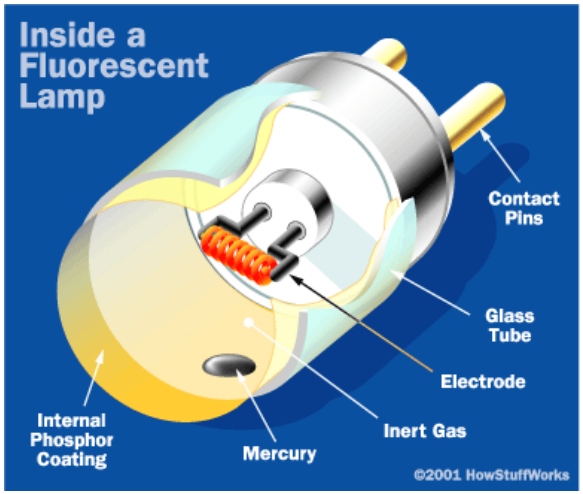
Each subsequent improvement in lighting led to increases in energy efficiency and major lifestyle improvements


Fluorescents operate based on a
completely different principle

The conversion of energy to light is more direct than black-body radiation

Fluorescents are a **“cold” technology**, meaning the energy is **more directly** converted into light.

Electrons are emitted at one end of the fluorescent tube, and flow through the mercury vapor in the tube to the other end.



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

The conversion of energy to light is more direct than black-body radiation

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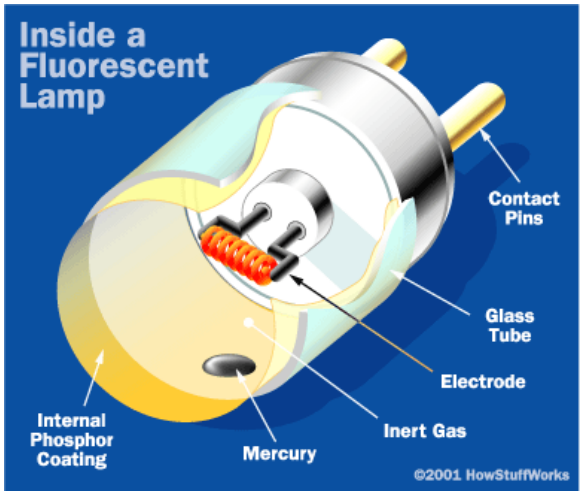


http://home.howstuffworks.com/fluorescent-lamp2.htm

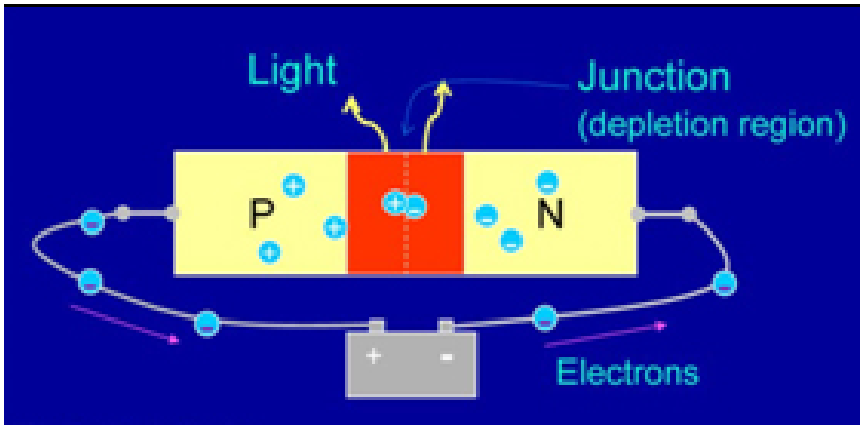
Fluorescents (and low pressure sodium) have a low Color Rendering Index (CRI)

"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	*CRI*
Sunlight	**100**
Tungsten filament incandescent light	**100**
Fluorescent light	**60 – 85**
Low Pressure Sodium vapor light	**~10**

Efficiencies of fluorescents are now 20 -25%, and are believed to have reached their physical limits!

Solid State Lighting is the use of LEDs for general illumination



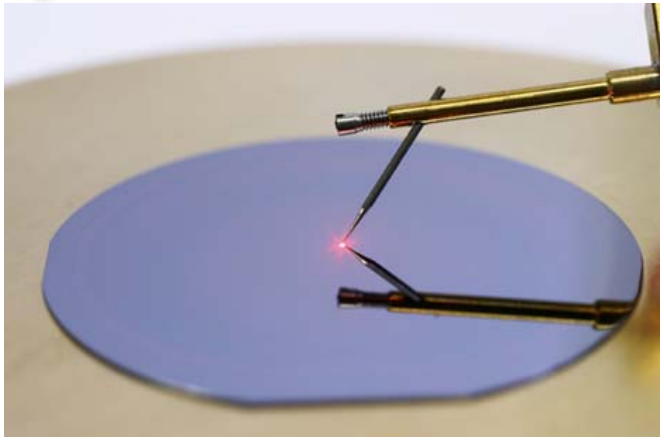
• An LED is a chip of semiconducting material treated to create a structure called a p-n (positive-negative) junction.

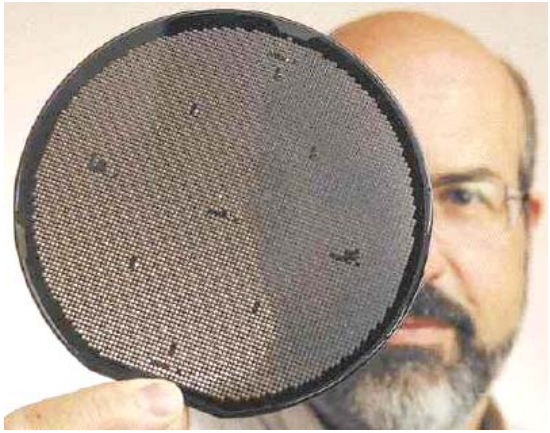
• Current flows from the p-side or anode to the n-side, or cathode. Charge-carriers (electrons and electron holes) flow into the junction.

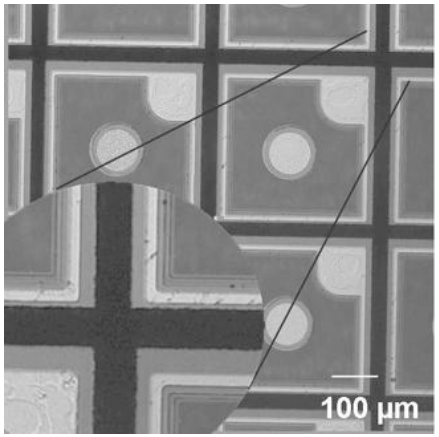
• When an electron meets a hole, it falls into a lower energy level, and releases energy in the form of a photon (light).

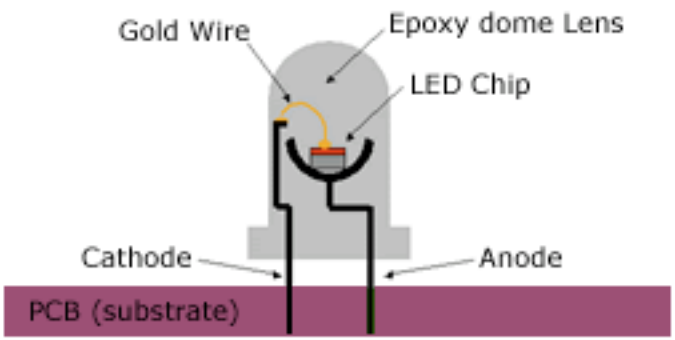
• Depending on the composition of the semiconducting material, different colors of light are emitted.

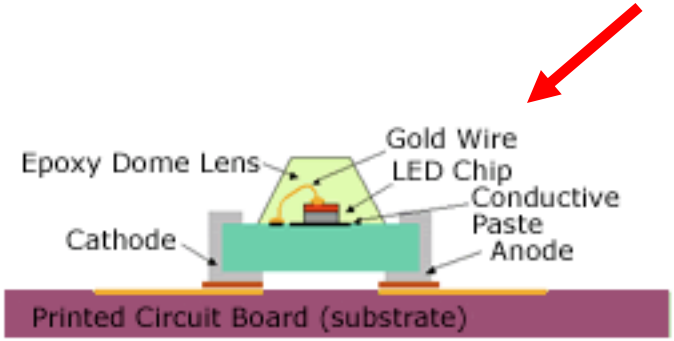
LEDs are grown on semiconductor wafers, then patterned, diced, and packaged











Atom by atom precision is expensive!

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More than simply energy savings!

- Directional light emission – directing light where it is needed.
- Size advantage – can be very compact and low-profile.
- Breakage resistance – no breakable glass or filaments.
- Cold temperature operation – performance improves in the cold.
- Instant on – no "warm up" time.
- Rapid cycling capability – lifetime not affected by frequent switching.
- Controllability – electronic control to change light levels / color characteristics
- No IR or UV emissions - do not emit infrared or ultraviolet radiation.

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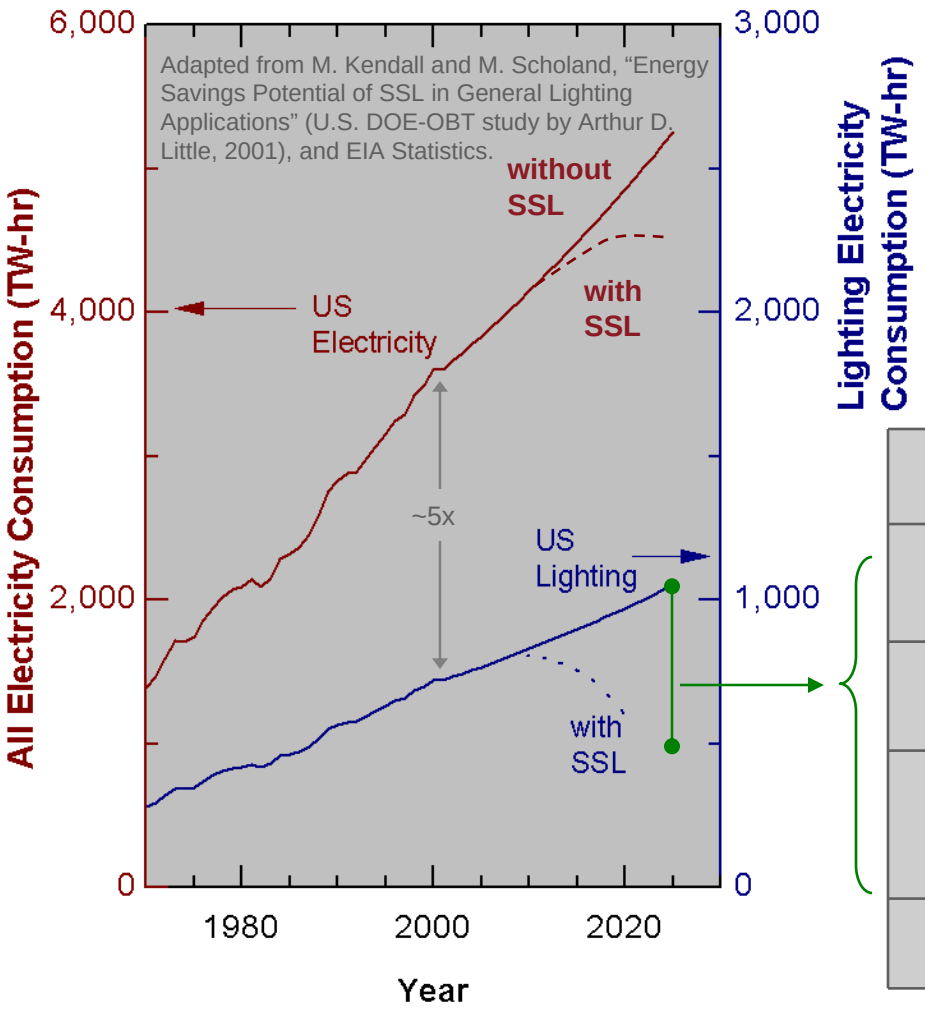
Potential pay-offs of 50% efficient SSL are huge



- **SSL has the potential, 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)	525/ year	1,800/ year
Money spent on Electricity	$35B/ year	$120B /year
Electricity generating capacity (GW)	75	~260
Carbon emissions (Mtons)	75	~260

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LEDs Are Already Superior for Monochrome Applications

MGM Grand's Teatro

Providence Performing Arts Center

Programmable Lights Ben Franklin Bridge, Philadelphia (Color Kinetics)

LED Flash Camera Phone (Motorola E815)

Rear Combination Lamp (LumiLeds)

LED Backlit LCD Display (Sony Qualia)

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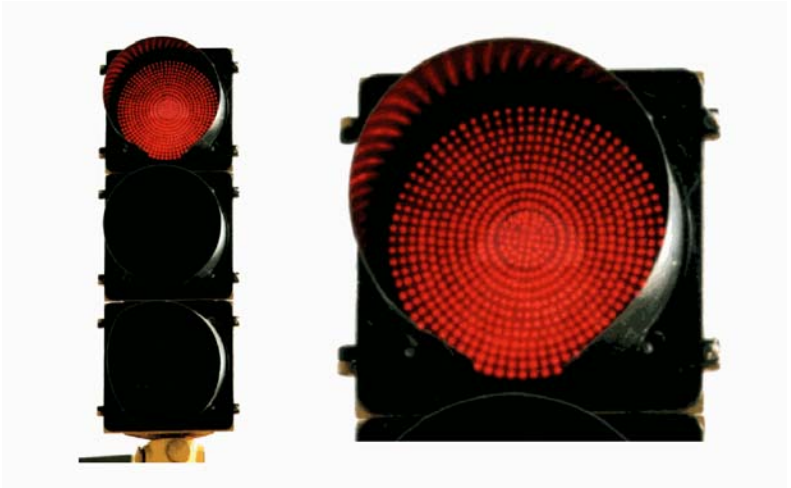
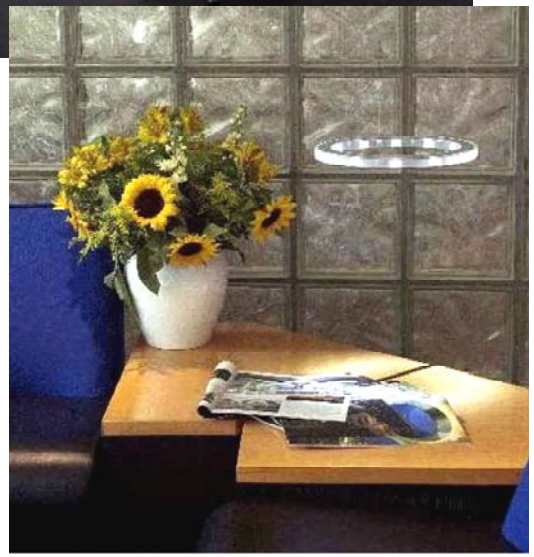
LEDs Are Already Superior for Monochrome Applications

- Red LEDs are now 10X more efficient than red- filtered incandescents
- Today, > 90% of US red traffic lights are LED-based
- Payback time for LED traffic lights (all colors) is ≤ 1 year
- After that the cost savings are ~***$1,000/year per intersection***



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

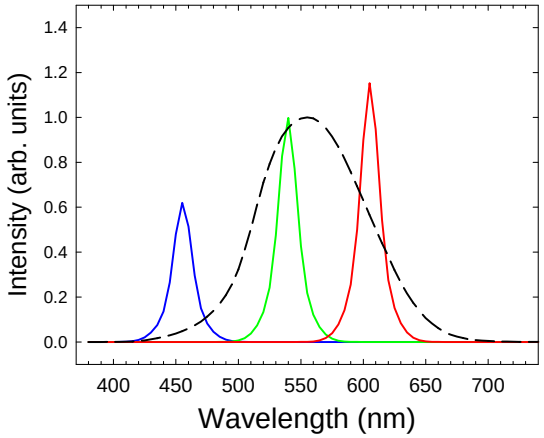


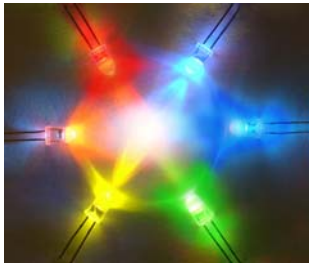
Technology breakthroughs must continue for white light SSL to compete with conventional lighting

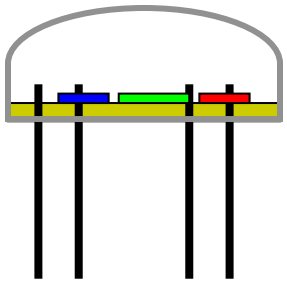
There are two basic approaches to making a “white” LED

Multi-LED:

Mix light from multiple LEDs







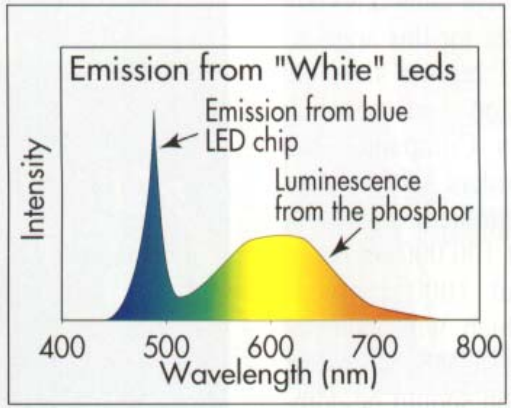
High Control

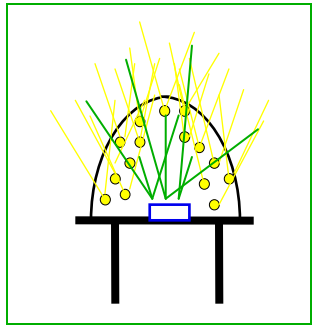
High Efficiency

High Cost

LED + Phosphors:

Use blue or near-UV LED to pump a mixture of phosphors





Lower Control

Lower Efficiency (typically)

Lower Cost

Blue or UV requires use of gallium nitride (GaN) based material

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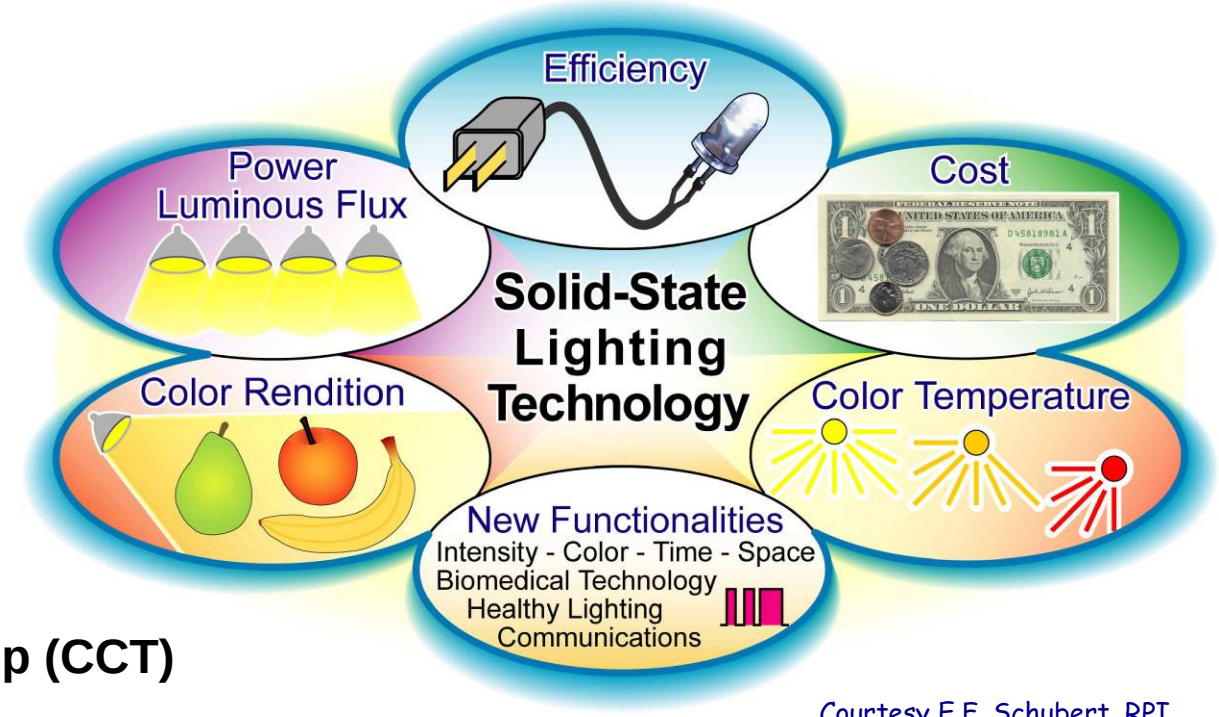
Additional performance metrics besides efficiency will be important

Other performance metrics for general lighting:

- **Cost**
- **Lifetime**
- **Directionality**
- **Heat dissipation**
- **Correlated Color Temp (CCT)**
- **Color Rendering Index (CRI)**



Courtesy E.F. Schubert, RPI

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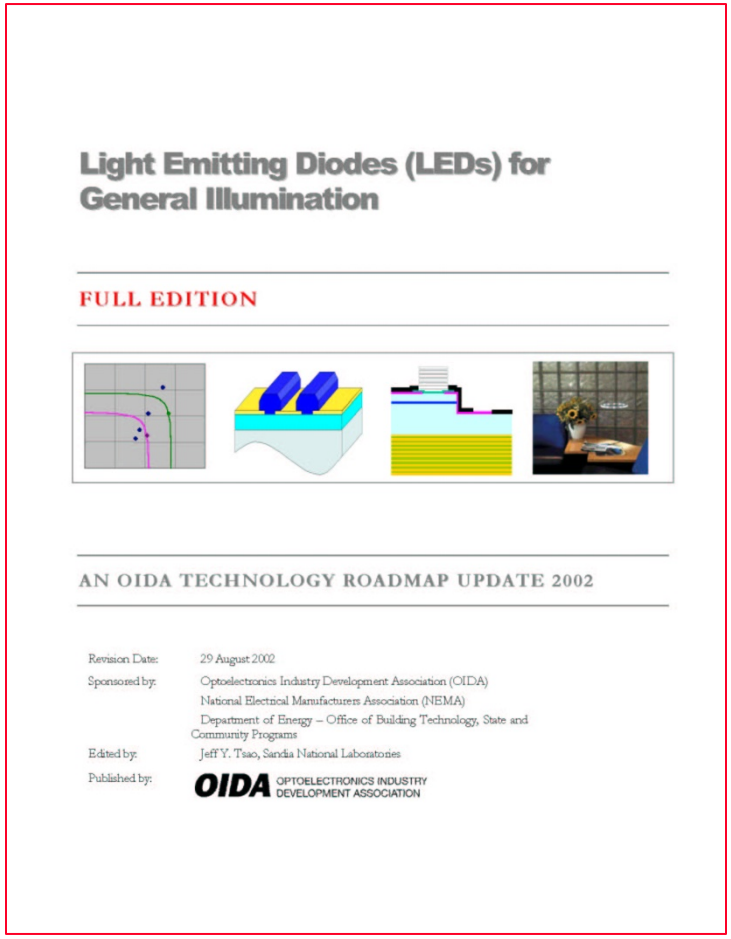
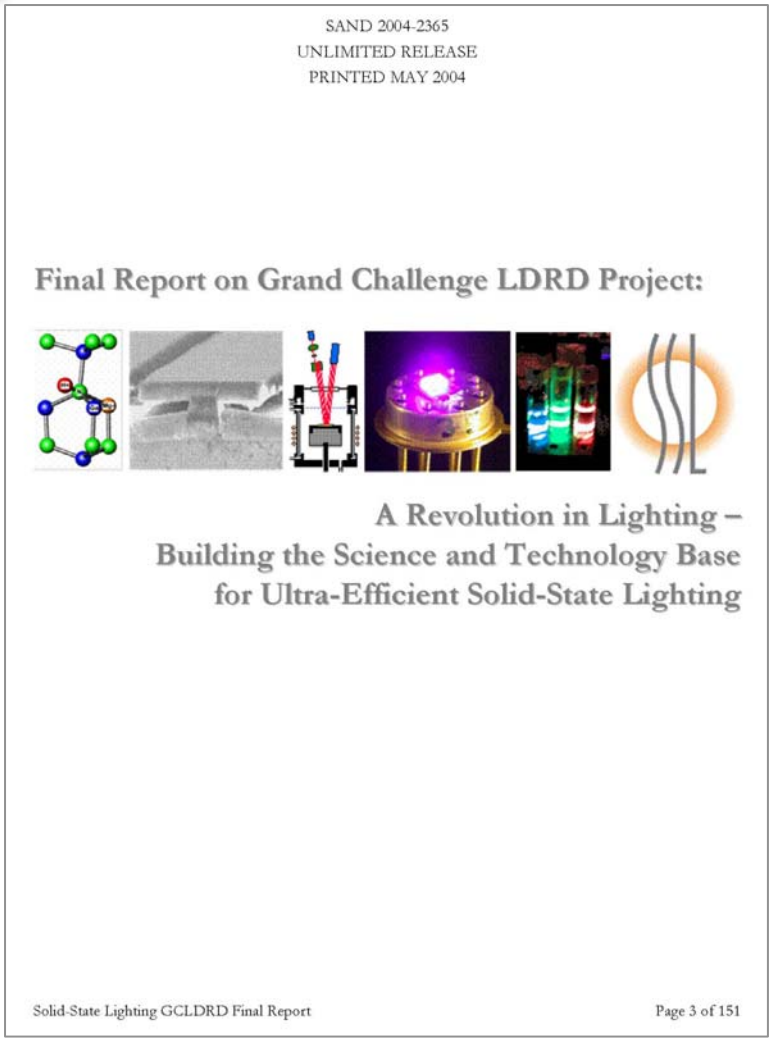
2001-2002:
Comprehensive US SSL-LED Roadmaps



Sponsors	OIDA (Arpad Bergh), DOE (Jim Brodrick), NEMA (Kyle Pitsor)
Editors	Mar 2001 Roadmap - Eric Jones (SNL) Aug 2002 Update - Jeff Tsao (SNL)
Technical Area Coordinators	Steve Denbaars, Bernd Keller, Mike Coltrin, Bob Davis, Tom Kuech, George Craford, Paul Martin, Jim George, Chips Chipalkatti
Workshop Speakers	Arto Nurmikko, Axel Scherer, Bob Davis, Weng Chow, Tom Kuech, Shuji Nakamura, Chips Chipalkatti, Nadarajah Narendran, Kevin Dowling, Alok Srivastava, Paul Martin
Chap 0 Contributors	Yoshi Ohno, Michael Scholand, Kate Bogart, Roland Haitz
Chap 1 Contributors	Dan Koleske, John Bumgarner, Christine Mitchell, Randy Creighton, Eric Jones, Sam Myers
Chap 2 Contributors	Weng Chow, Art Fischer, Mike Krames, Ed Stokes, Spilios Riyopoulos
Chap 3 Contributors	Dan Doxsee, Yongchoi Tian, Karel Vanheusden, Lauren Rohwer, Stan Weaver, Steve Richfield, Frank Steranka, Chuck Becker, James Gee

2000-2004:
Sandia's Grand Challenge LDRD


SAND 2004-2365
UNLIMITED RELEASE
PRINTED MAY 2004

Final Report on Grand Challenge LDRD Project:

A Revolution in Lighting –
Building the Science and Technology Base
for Ultra-Efficient Solid-State Lighting

Solid-State Lighting GCLDRD Final Report Page 3 of 151

Goals of GC-LDRD:

1. Help establish the fundamental science and technology base for SSL.
2. Develop the technology infrastructure of Gallium Nitride (GaN) material sciences for synergistic national security needs.

By the end of FY04, this project had invested ~$8M in Solid-State Lighting.

Built on our investment of *a few $100 M in compound semiconductor technology* over the past two decades.

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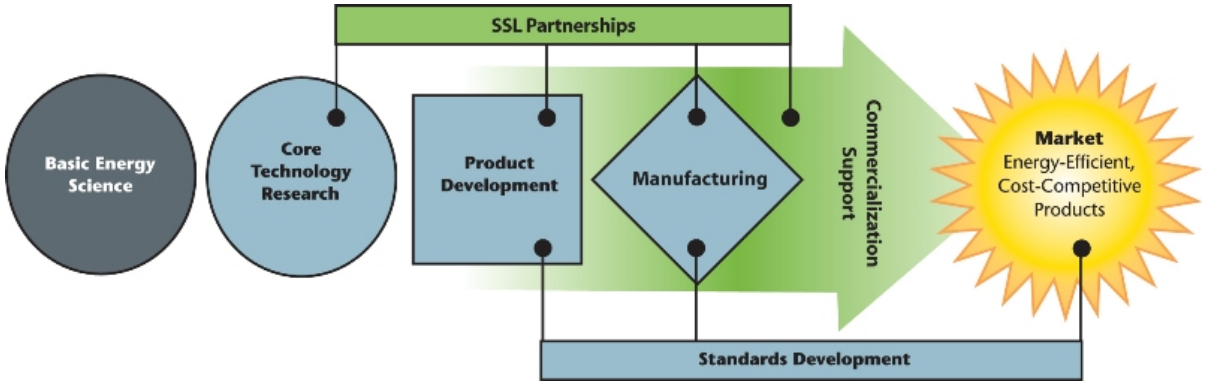
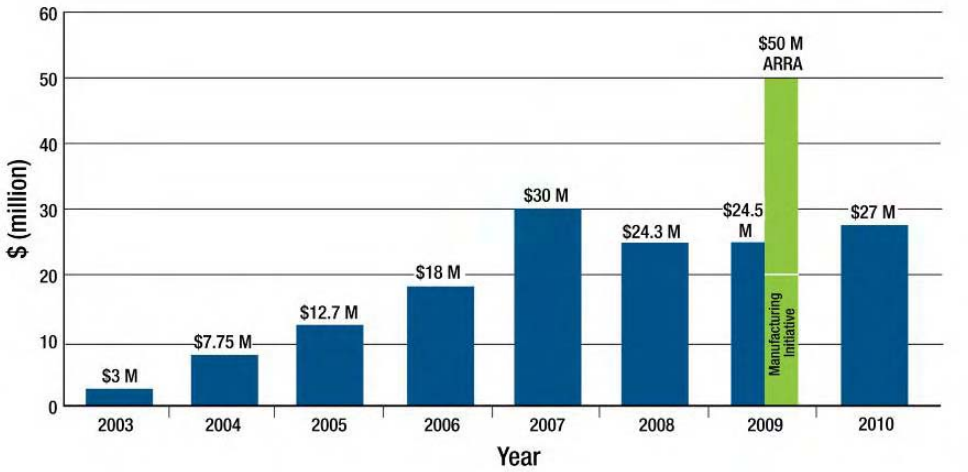
Department of Energy Solid-State Lighting programs



A spectrum of funding from the most basic research through market introduction.

Sustained funding, including a new manufacturing initiative.



For more info: http://www.ssl.energy.gov

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Some major companies developing solid state lighting products

Does not include fixture production

Philips Lumileds (US; Netherlands)

Cree (US)

Osram-Sylvania [US; Germany (owned by Siemens)]

Nichia (Japan)

Toyoda Gosei (Japan)

Everlight (Taiwan)

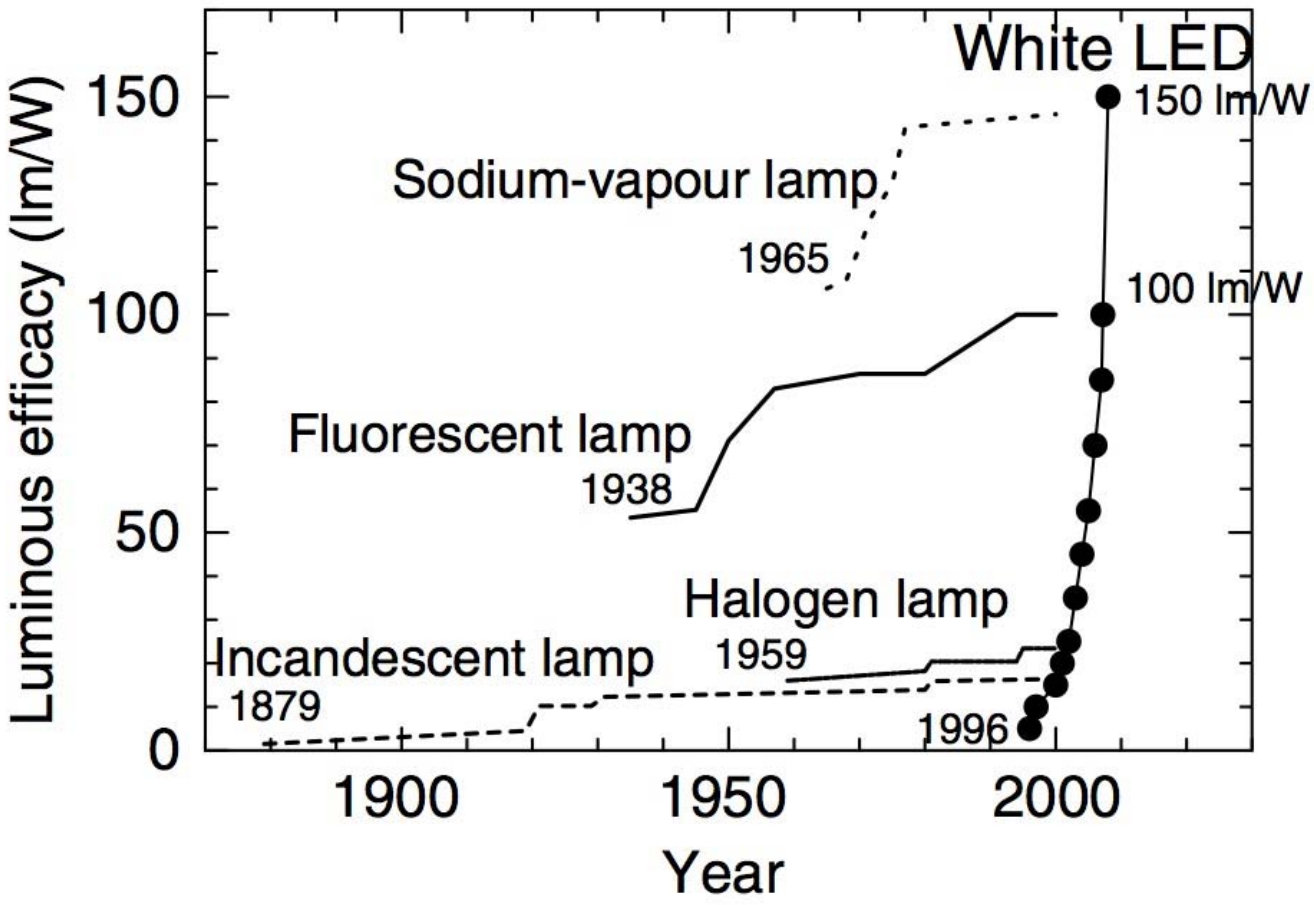
Lite-On (Taiwan)

Kingbright (Taiwan)

Samsung (Korea)

Seoul Semiconductor (Korea)

Luminous efficacies of commercially available white LEDs have skyrocketed



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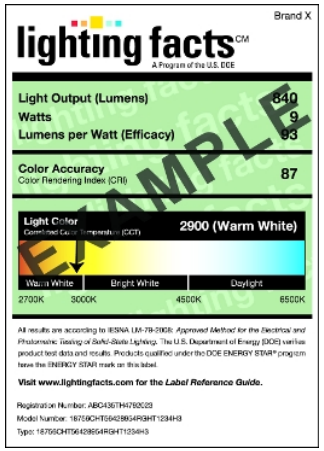
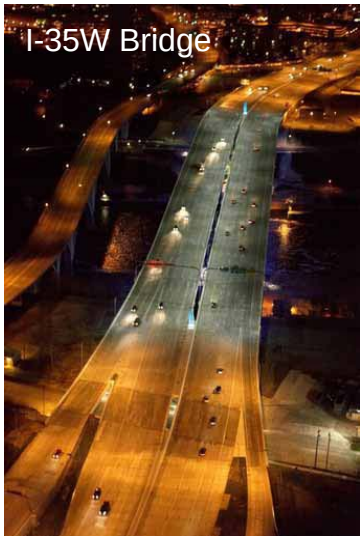
DOE EERE activities to help launch successful SSL products



Quick / simple summary of product performance data as measured by new industry standards.



DOE GATEWAY Demonstrations showcase high-performance LED products for general illumination in a variety of commercial and residential applications.

ENERGY STAR

Establishes the industry-wide criteria that manufacturers can use to promote qualifying products.

L PRIZE

Challenges industry to develop replacement technologies for two of today's most widely used and inefficient products: 60W incandescent lamps and PAR 38 halogen lamps.

CALiPER

Reliable, unbiased product performance information to foster the developing market for high-performance SSL.

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Cree LR6 Downlight

- **The LR6 is a downlight module for new construction and retrofit that installs easily in most standard six inch recessed IC or non-IC housings. The LR6 generates white light with LED's in a new way that enables an unprecedented combination of light output, high efficacy, beautiful color, and affordability.**

Cree LED Lighting

lighting factsCM
A Program of the U.S. DOE

Light Output (Lumens)	650
Watts	12
Lumens per Watt (Efficacy)	54
Color Accuracy Color Rendering Index (CRI)	92

Light Color
Correlated Color Temperature (CCT) 2700 (Warm White)

Warm White | Bright White | Daylight

2700K 3000K 4500K 6500K

All results are according to IESNA LM-79-2008: *Approved Method for the Electrical and Photometric Testing of Solid-State Lighting.* The U.S. Department of Energy (DOE) verifies product test data and results.

Visit www.lightingfacts.com for the *Label Reference Guide.*

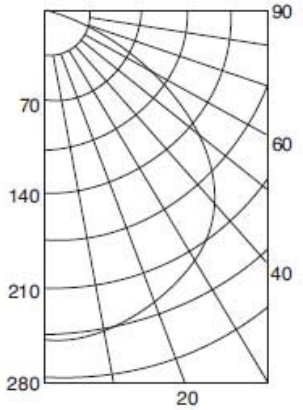
Registration Number: KBNH-YS1BDB
Model Number: LR6
Type: Recessed downlights

LR6

LR6C

Photometry

LR6
Lighting Sciences Inc. Certified Test #22226



Intensity (Candlepower) Summary

ANGLE	MEAN CP
0°	249
5°	248
15°	242
25°	228
35°	203
45°	165
55°	115
65°	62
75°	24
85°	6
90°	0

Zonal Lumen Summary

ZONE	LUMENS	%LAMP	%FIX
0°- 30°	197	30.39	30.39
0°- 40°	325	49.94	49.94
0°- 60°	556	85.35	85.35
0°- 90°	650	100.00	100.00

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Installation of LLF 6” downlights in a Westfield, MA *Friendly’s Restaurant*

BEFORE

Incandescent 65W BR30 - **Total Power = 5,135W**

LLF™ Light Reinvented.™

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Installation of LLF 6” downlights in a Westfield, MA *Friendly’s Restaurant*

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Cree LR24-32 Architectural Lay-in

- **The LR24 is designed for applications that require high ambient light levels, including offices, schools, and hospitals. It allows an optimal distribution of light that delivers high illuminance levels to horizontal surfaces balanced with an ideal amount of light to vertical surfaces resulting in an effective, attractive, and comfortable environment.**

Cree LED Lighting

lighting factsCM

A Program of the U.S. DOE

Light Output (Lumens)	3200
Watts	44
Lumens per Watt (Efficacy)	73
Color Accuracy Color Rendering Index (CRI)	90

Light Color
Correlated Color Temperature (CCT) 3500 (Bright White)

Warm White | Bright White | Daylight

2700K 3000K 4500K 6500K

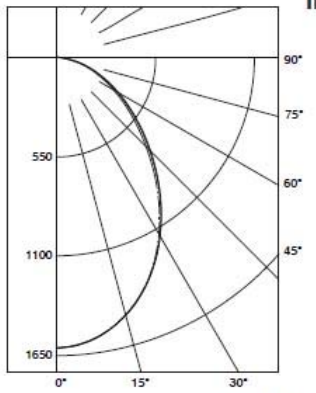
All results are according to IESNA LM-79-2008: *Approved Method for the Electrical and Photometric Testing of Solid-State Lighting.* The U.S. Department of Energy (DOE) verifies product test data and results.

Visit www.lightingfacts.com for the *Label Reference Guide.*

Registration Number: KBNH-F8TGNY
Model Number: LR24-32SKA35
Type: Ceiling-mounted fixtures with diffusers

Photometry

LR24-32SKA35 – Based on ITL Test 61450



Intensity (Candlepower) Summary

ANGLE	CP°	CP45°
0°	1600	1600
5°	1582	1584
15°	1467	1469
25°	1258	1263
35°	981	996
45°	695	721
55°	459	482
65°	276	294
75°	131	142
85°	2	5
90°	0	0

Zonal Lumen Summary

ZONE	LUMENS	%LAMP	%FIX
0°- 30°	1145	53.5	53.5
0°- 40°	1767	76.9	76.9
0°- 60°	2750	98.8	98.8
0°- 90°	3200	100.00	100.00

National Laboratories

Cree LRP-38 Replacement Lamp

- **The LRP-38 combines the beauty and intensity of Halogen with exceptional efficiency and longevity. It is the first LED lamp to deliver on the promise of LED lighting for retail lighting, museum lighting, and architectural accent lighting.**

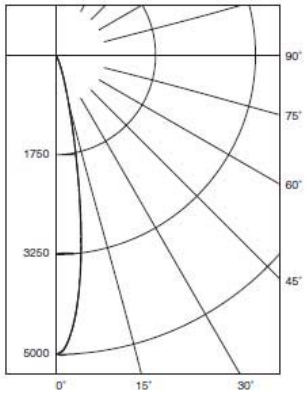
Performance Summary

- Utilizes Cree TrueWhite™ Technology
- Light Output = 600 lumens
- Beam Angle = 20°
- CBCP = 4800
- Input Power = 11 Watts
- CRI = 90
- CCT = 2700K
- Not dimmable
- Three Year Warranty

5 3/16”

Photometry

LRP38A92-20D48



Intensity (Candlepower) Summary

ANGLE	MEAN CP
0°	4800
5°	3955
15°	679
25°	85
35°	10
45°	8
55°	8
65°	9
75°	1
85°	0
90°	0

Zonal Lumen Summary

ZONE	LUMENS	%LAMP
0°- 30°	572	95.26%
0°- 40°	579	96.43%
0°- 60°	591	98.52%
0°- 90°	600	100.00%

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Philips 60W Incandescent Replacement

Entry for L-Prize competition:

- **Efficacy of more than 90 lumens per watt**
- **Energy consumption of less than 10 watts as compared to a 60 Watt incandescent.**
- **Output of more than 900 lumens**
- **Lifetime of more than 25,000 hours, which is 25X greater than a typical incandescent bulb**
- **Color Rendering Index (CRI) greater than 90**
- **Color Temperature between 2700 – 3000 Kelvin, which is "warm" white light comparable to that of incandescent sources**

Current State of the Art

Laboratory White LEDs are breaking the 200 lm/W barrier

Nichia: Laboratory White LED*

Current	350 mA
Lumens	203
Lumens per Watt	183
CCT (K)	4700

* 2010, Journal of Physics D

Cree Lighting: Laboratory White LED*

Current	350 mA
Lumens	208
Lumens per Watt	208
CCT (K)	4600

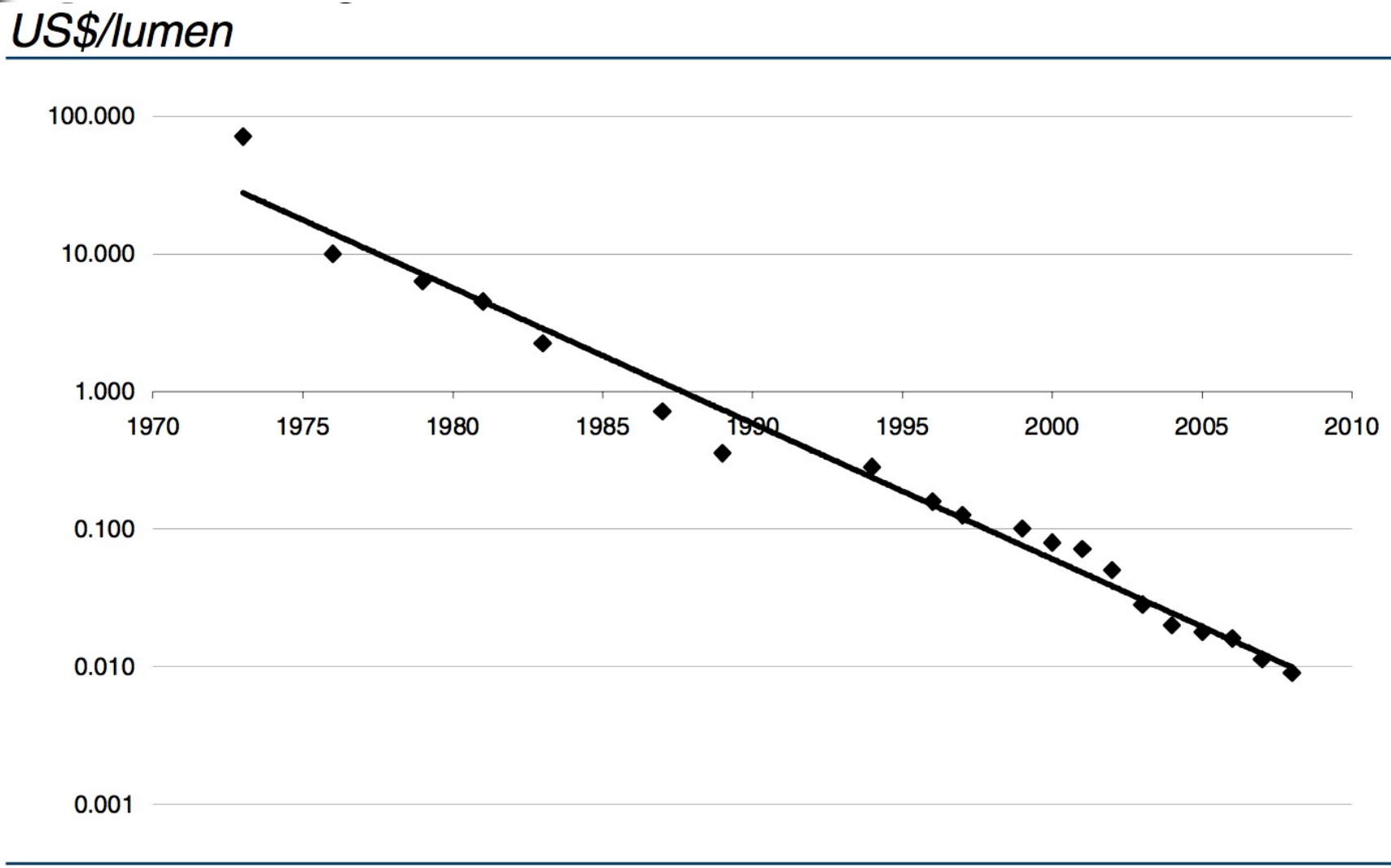
* 02/22/2010 press release

Cree Lighting: Commercial Xlamp XM White LED*

Current	350 mA	2000 mA
Lumens	160	750
Lumens per Watt	160	110
Watts	1.0	6.8
CCT (K)	4685	

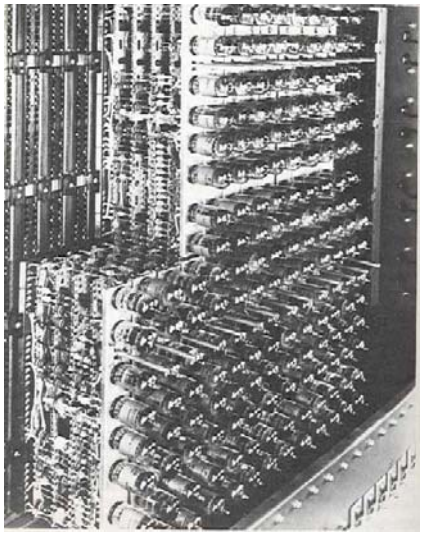
* 04/12/2010 press release

Rapidly decreasing purchase costs for solid state lighting



Sandia National Laboratories

Vacuum tubes have been replaced by solid state technology in most other applications

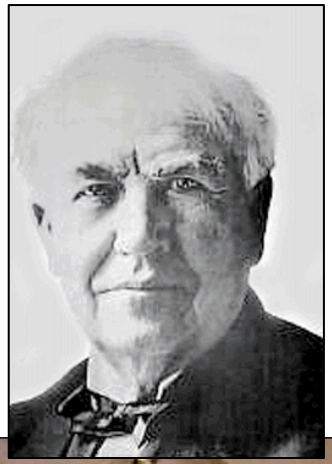


IBM 701 Defense Calculator, 1952

Electronics & Computing

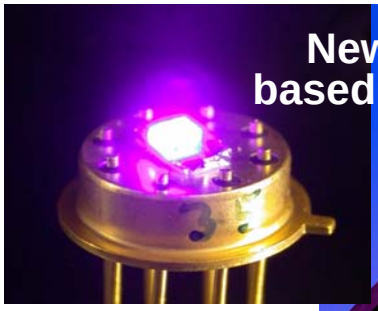
Displays

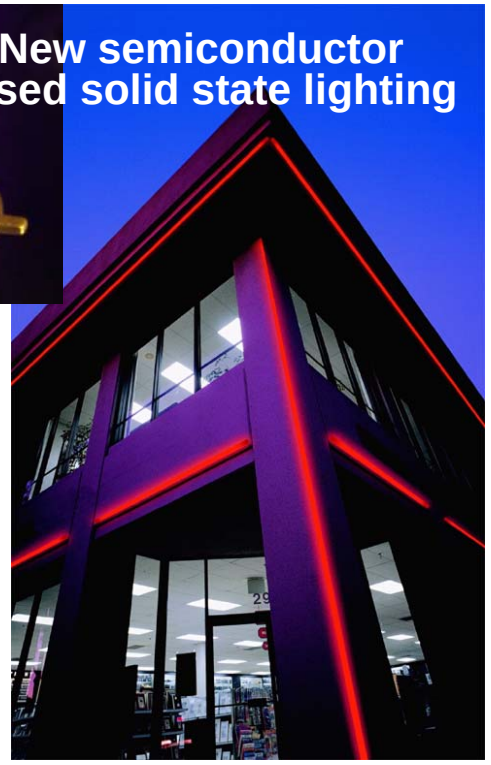
Basic science research is needed to eliminate vacuum tubes from lighting too



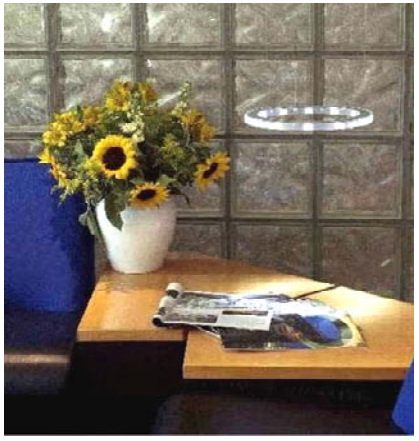
Thomas Edison

Lighting





New semiconductor based solid state lighting

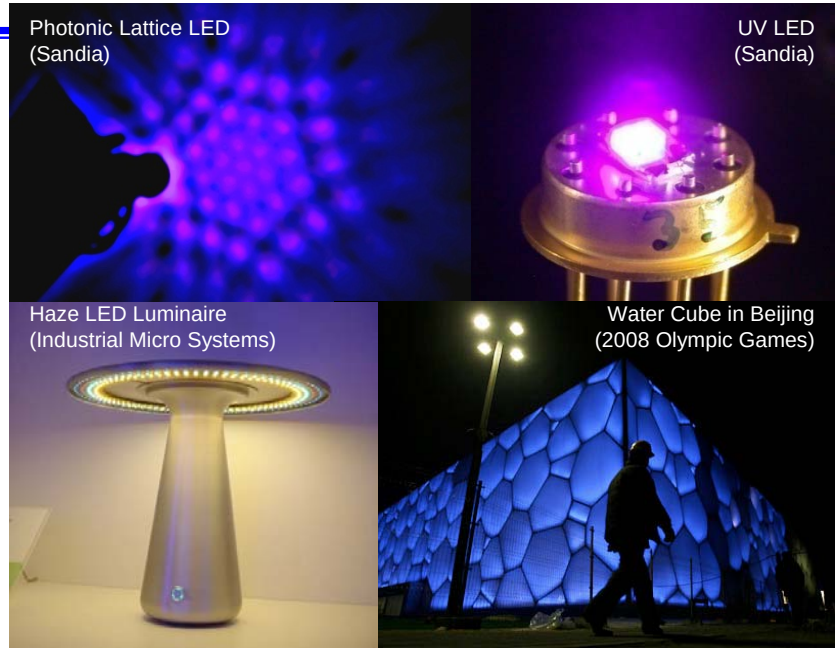


Old vacuum-tube based lighting

Sandia National Laboratories

EFRC for Solid-State Lighting Science
Jerry Simmons & Mike Coltrin

Goal: **Improve the energy-efficiency in the way we light our homes and offices, which currently accounts for 20% of the nation's electrical energy use. Solid-State Lighting (SSL) has the potential to cut that energy consumption in half – or even more.**



Research plan: **Investigate conversion of electricity to light using radically new designs, such as luminescent nanowires, quantum dots, and hybrid architectures; study energy conversion processes in structures whose sizes are even smaller than the wavelength of light; understand and eliminate defects in SSL semiconductor materials that presently limit the energy efficiency.**