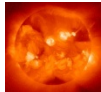


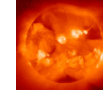
Solid-State Lighting: It's Also About Human Productivity!

Jeff Tsao · **Physical Chemical Nano Sciences Center** · **Sandia National Labs**



Full-disk view of the X-ray Sun and was produced by the Yohkoh solar observatory in 1991.
http://en.wikipedia.org/wiki/File:Yohkoh_image.gif

Full moon view from Earth in Belgium, courtesy of Luc Viatour.
http://en.wikipedia.org/wiki/File:Full_Moon_Luc_Viatour.jpg



Bridgelux Helieon Solid-State Lamp.
<http://www.bridgelux.com/products/helieon.html>



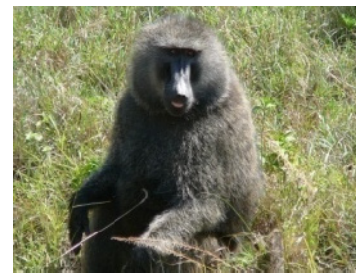
Asaphus species (Trilobite) picture taken by DanielCD.
http://en.wikipedia.org/wiki/File:Asaphus_species_trilobite.jpg



Red Lory (Eos bornea) upper body preening feathers.
http://en.wikipedia.org/wiki/File:Red_Lory_%28Eos_bornea%29-6.jpg



Gray wolf, canis lupus, courtesy of Chris Muiden.
http://en.wikipedia.org/wiki/File:Canis_lupus_265b.jpg

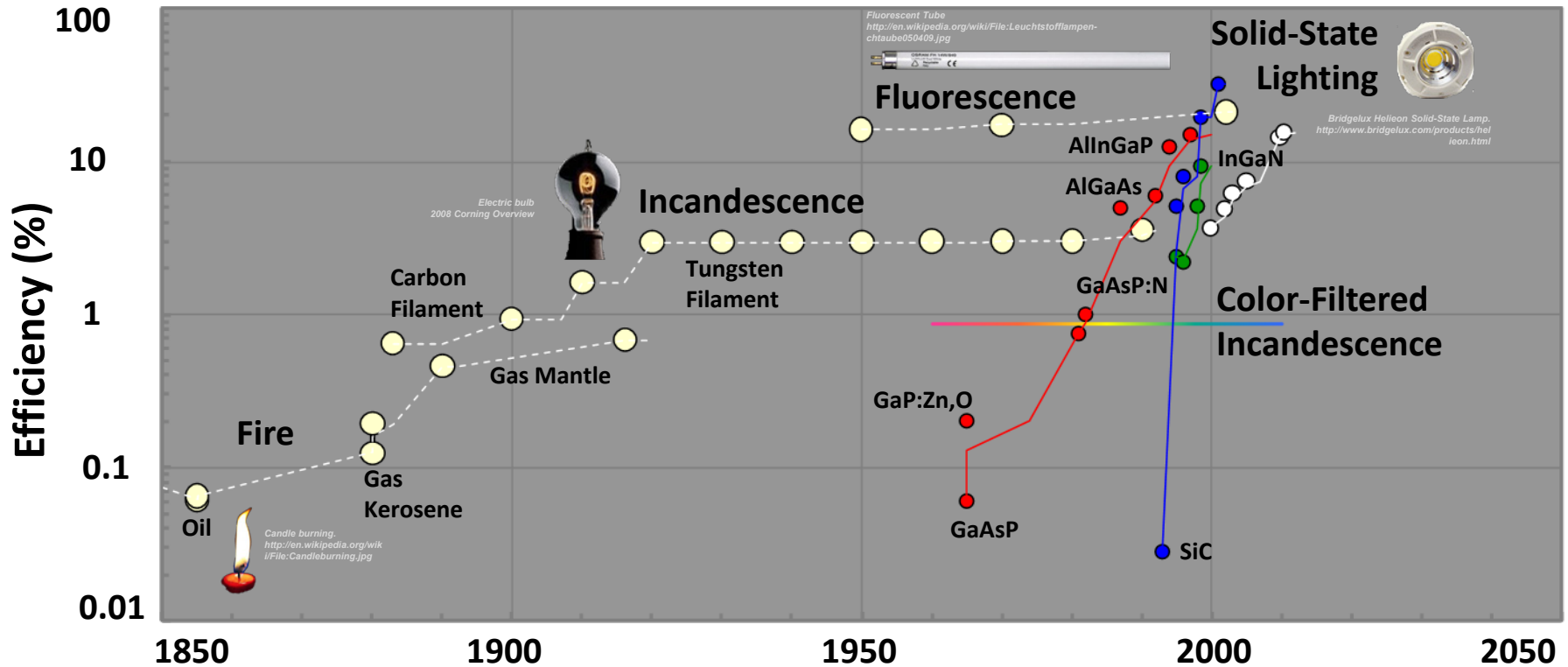
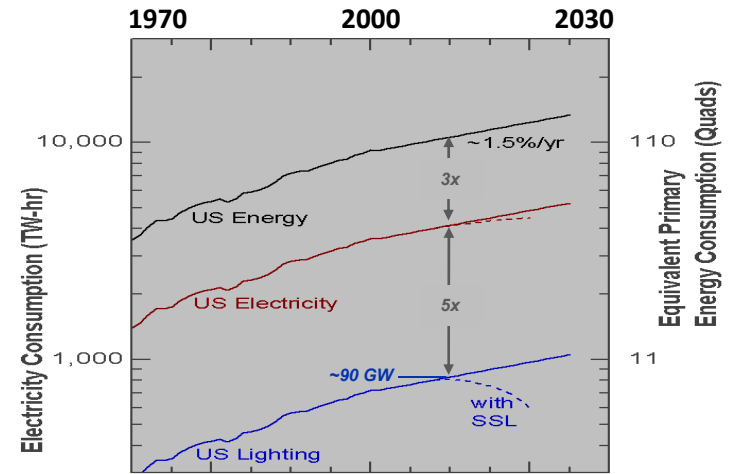


Olive baboon in Kenya; courtesy of Ryan Harvey;
http://en.wikipedia.org/wiki/File:Male_Olive_Baboon_2.jpg

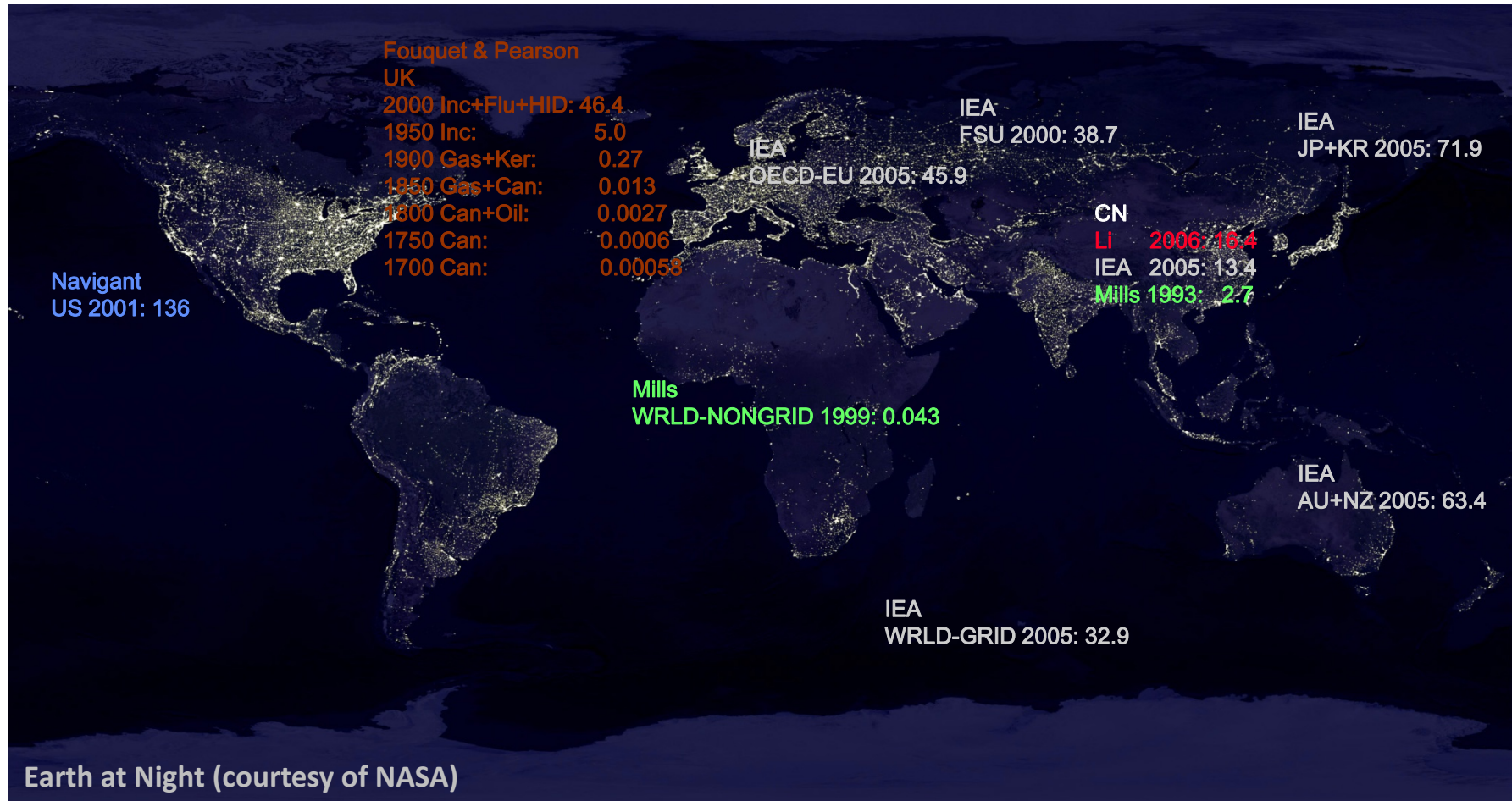


A baby wearing many items of winter clothing: headband, cap, fur-lined coat, shawl and sweater. Courtesy of Andrew Vargas, Clovis, United States.
http://en.wikipedia.org/wiki/File:Well-clothed_baby.jpg

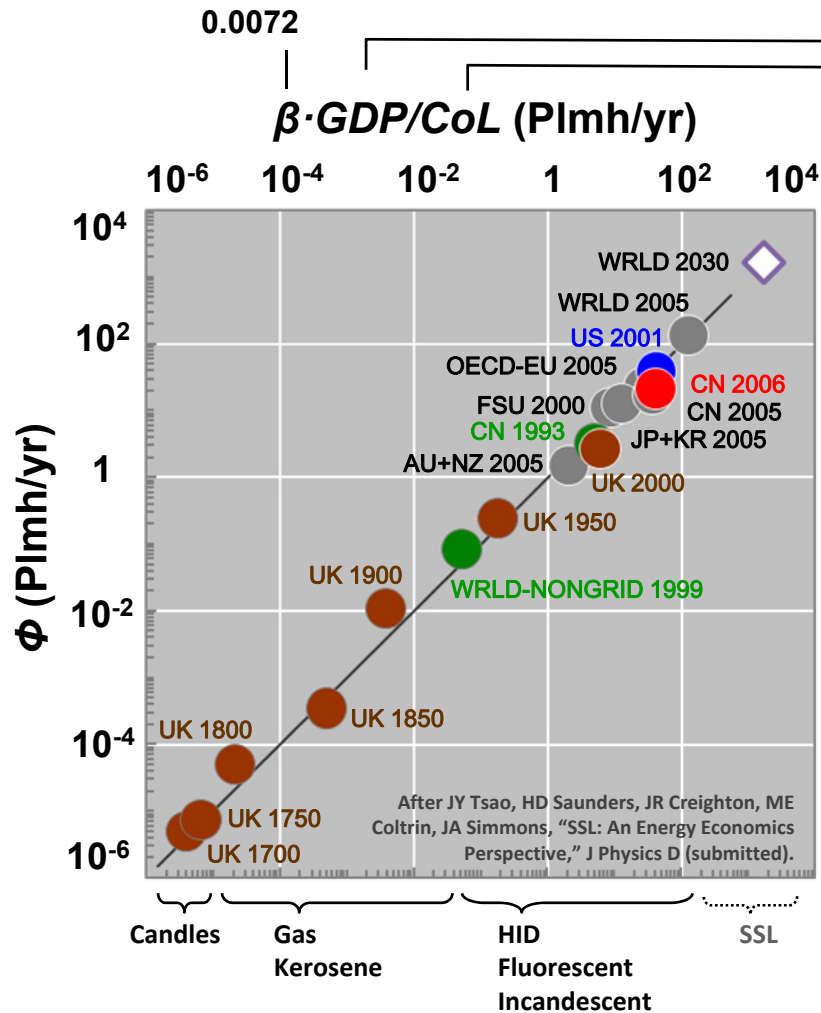
Lighting Efficiency and Energy Savings



per capita Consumption of Light: ϕ , in Mlmh/(person·year)



Historical and Projected Consumption of Light



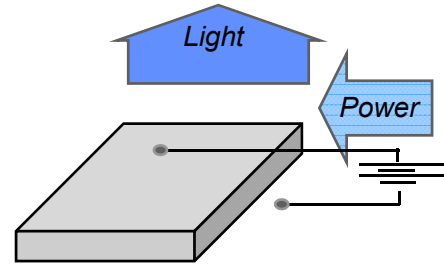
Nation or Nations	Year	$\text{CoL} \sim \text{CoE} / \eta$			$\text{GDP} = N \cdot \text{gdp}$		Φ	ϕ
		Cost of Light $\frac{\$}{\text{Mlmh}}$	Cost of Energy $\frac{\$}{\text{MWh}}$	Luminous Efficacy $\frac{\text{lm}}{\text{W}}$	Gross Domestic Product $\frac{\text{G\$}}{\text{yr}}$	Population Gper	per capita gross consumption of Light $\frac{\text{Plmh}}{\text{yr}}$	per capita consumption of light $\frac{\text{Mlmh}}{\text{per-yr}}$
Wrlld	2030	0.6	119	268.0	139,091	8.3	16,704	1,688.00
Wrlld	2005	3.3	119	47.5	60,670	6.4	9,445	129.52
US	2001	2.0	76	49.7	12,039	0.3	42,237	41.99
Wrlld Non-Grid	1999	600.2	183	0.3	4,404	2.0	2,202	0.05

Chip area needed to light the world



<http://tan-moneyonline.com/wp-content/uploads/2008/03/earthatnight-asia1.jpg>

$$\Phi_{Demand} \cong \frac{\overset{0.0072}{\beta} \cdot GDP}{\underset{\text{Cost of energy}}{CoE} / \underset{\text{Luminous efficacy}}{\eta}} = \overset{\text{Input power density}}{p} \cdot \underset{\text{Area}}{A} \cdot \overset{\text{Luminous efficacy}}{\eta} \cdot \underset{\text{Duty cycle}}{D} = \Phi_{Supply}$$



Area

$$A = \frac{\overset{\sim 1.3 \text{ km}^2}{\beta} \cdot GDP}{\underset{119 \text{ \$/MWh}}{CoE} \cdot \underset{300 \text{ W/cm}^2}{p} \cdot D^{1/4}}$$

240 football fields

Area Turnover

$$\frac{dA}{dt} = \frac{\overset{\sim 0.15 \text{ km}^2/\text{yr}}{A} / Y}{\underset{25 \text{ khr}}{\tau} / D^{1/4}}$$

28 football fields/yr

MOVPE Reactors

$$\# \cong \frac{\overset{\sim 800}{dA} / dt}{\underset{\text{Area of 4" wafer}}{a} \cdot \underset{\text{Wafers per day}}{w} \cdot \underset{\text{Runs per run}}{r} \cdot \underset{\text{Uptime}}{u}}$$

330 days/yr

The other electronics “killer apps”

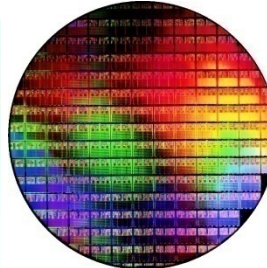
Sharp QuadPixel RGBY LED-backlit LCD Display.
http://www.macworld.com/article/145541/2010/01/sharp_quadpixel.html



http://en.wikipedia.org/wiki/File:Solar_cell.png



http://blog.elisehuard.be/wp-content/uploads/2007/12/wafer_200mm_90nm_1024k_dc.jpg



<http://tan-moneyonline.com/wp-content/uploads/2008/03/earth-atnight-asia1.jpg>



<http://www.itechnews.net/wp-content/uploads/2009/07/Nokia-3720-Classic-the-most-rugged-mobile-phone.jpg>



Market	Liquid crystal displays (2009)	Solar cells (2009)	Si electronics (2009)	GaN solid-state lighting (2030)	GaAs electronics (2009)
Approximate area turnover (km ² /year)	230	64	4.4	0.15	0.026
# football fields / year	43,000 (2.5 x Corning)	11,800 (Manhattan)	800 (2 x Monaco)	28 (Vatican City / 4)	5

Estimate from Steven S. Rosenblum, Corning, Inc

Assuming 9.6 GW_p (<http://www.displaybank.com/en/g/info/sread.php?id=5730>) at 15% efficiency

Estimate from Gartner (http://www.fabtech.org/news/_a/gartner_revises_silicon_wafer_demand_forecast/)

Estimate from A Anwar, Strategy Analytics

Anatomy of State-of-Art Commercial SSL

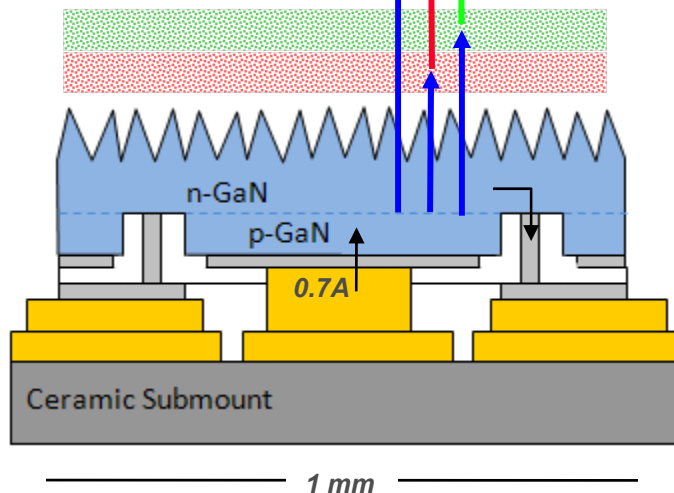
ε = 16%
 η = 66 lm/W
 CRI = 85
 CCT = 3,100K



Spectral 78%

Phosphor/Package 54%
 Internal quantum effic 90%
 Stokes deficit 76%
 Scattering/absorption 80%

Blue LED 38%
 Joule 90%
 IQE at low power 75%
 Droop at high power 70%
 Light extraction 80%

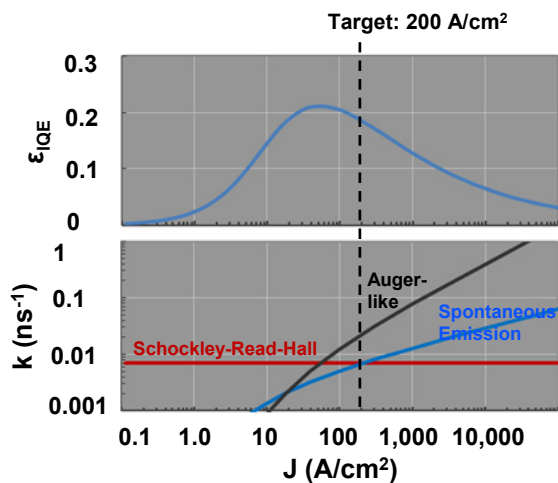


Thin-Film Flip Chip (TFFC)
 schematic courtesy of Jon Wierer

Two Grand Challenges for Efficiency

One for Functionality

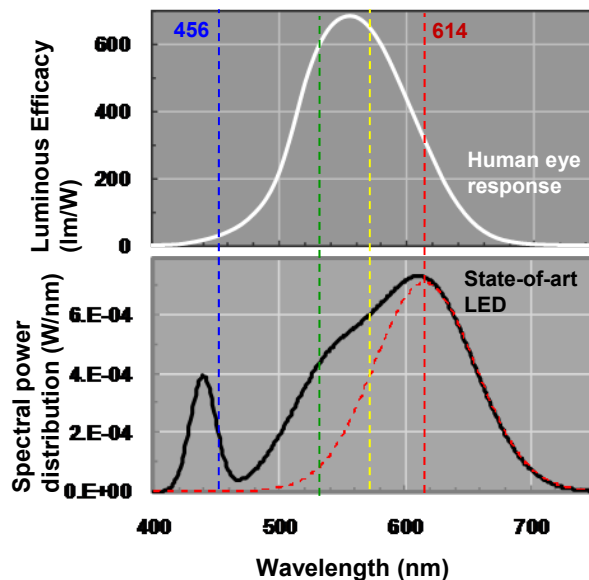
①a Eliminate blue LED droop



$$\epsilon = \left(\frac{V_{ph}}{V} \right) \cdot \epsilon_{INJ} \cdot \frac{Bn^2}{An + Bn^2 + Cn^3} \cdot \epsilon_{EXT}$$

Shockley-Read-Hall
Spontaneous Emission
Auger-like

①b Fill in the shallow-red EL gap



② Bring luminaire functionality to the chip



<http://www.irradianthq.com>



Asaphus species (Trilobite) picture taken by DanielCD.
http://en.wikipedia.org/wiki/File:Asaphus_species_trilobite.jpg



Red Lory (Eos bornea) upper body preening feathers.
http://en.wikipedia.org/wiki/File:Red_Lory_%26Eos_bornea%29-6.jpg



Gray wolf, canis lupus, courtesy of Chris Muiden.
http://en.wikipedia.org/wiki/File:Canis_lupus_265b.jpg



Olive baboon in Kenya; courtesy of Ryan Harvey;
http://en.wikipedia.org/wiki/File:Male_Olive_Baboon_2.jpg



A baby wearing many items of winter clothing: headband, cap, fur-lined coat, shawl and sweater. Courtesy of Andrew Vargas, Clovis, United States.
http://en.wikipedia.org/wiki/File:Well-clothed_baby.jpg

Acknowledgements:

Sandia (Mary Crawford, Randy Creighton, Mike Coltrin, Jerry Simmons)
IEA (Paul Waide), Decision Processes Inc (Harry Saunders), Philips Lumileds (George Craford)

Work at Sandia National Laboratories was supported by Sandia's Solid-State-Lighting Science Energy Frontier Research Center, funded by the U.S. Department of Energy, Office of Basic Energy Sciences. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.