SMART LIGHTING ENGINEERING RESEARCH CENTER
Lighting Innovation for a Smarter Tomorrow

Nanotechnology
in Smart Lighting

Kenneth A. Connor
Education Director
Smart Lighting ERC

Rensselaer BOSTON UNIVERSITY UNM HOWARD UNIVERSITY ROSE-HULMAN MORGAN

Overview

- Introduction
- Who am I & Why am I an Engineer?
- A Local Boy Does Good & How My Career Built on His Success
- Systems
- Smart Lighting ERC
- Light & Light-Based Activities
- Nano in Smart Lighting
- Additional thoughts

Who Am I?

- My name is Ken Connor

I am a Professor of Electrical, Computer, and Systems Engineering and Information Technology at Rensselaer Polytechnic Institute in Troy, NY

Rensselaer

K. A. Connor

Who Am I?

- I was born in Madison, WI

K. A. Connor

Who Am I?

- I have two brothers

Who Am I?

- I attended Mendota School from 1952 – 1958

K. A. Connor

SMART LIGHTING

Why am I an Engineer?

- October 1957 – Sputnik 1 **(Спутник-1)**
- 6th Grade Class – 4 students selected for advanced studies
- 7th & 8th Grade Math & Science Combined
- Began HS Math & Science in 8th Grade

Diameter = 58.5 cm

Inside

Sounds

http://www.nytimes.com/interactive/2007/09/24/science/space/20070924_SPUTNIK_GRAPHIC.html#tab1
http://www.mentallandscape.com/Sputnik1_WashingtonDC.mp3

In Mendota School 6th Grade

Hold Science Fair

What's Doing In Madison Schools
WEEKLY REPORT CARD

Me

Several weeks of scientific study and project work were climaxed recently when pupils of the sixth grade at Mendota School staged their second annual Science Fair. Various ingenious "gadgets" developed by each pupil were displayed and prizes were awarded for the best entries. An evening open house was held so parents could inspect the projects. The first-prize winner is in the picture at the upper left. The teacher, Carolyn Anderson is in the background. The others (rear to front) are Cheryl Moore, Eddy Gadsia, and Ronnie Trachte, who is dropping an egg into a pan, which is resting on an electric "stove" made by Ronnie. At the top, right, Steve Sprague (center) is demonstrating his water generator which won second prize. Watching are Polly Prihart (left) and Kim Klipstein. The group at the lower left includes Mary Joe Gross (left), who is watching closely as Leslie FaFard (center) and Ken Conner show off their respective electric eye and atomic generator devices. The three (lower right) include Mary Joe Gross (left); Jim Cron, pointing to simple machines made by him, and Janice Menge. **(Photos by Clarence E. Olson)**

29 March 1958

SMART LIGHTING

In Mendota School 6th Grade

Hold Science Fair

What's Doing In Madison Schools
WEEKLY REPORT CARD

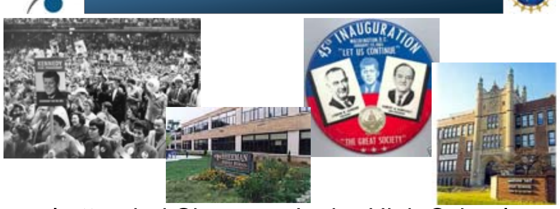
K. A. Connor

SMART LIGHTING

Several weeks of scientific study and project work were climaxed recently when pupils of the sixth grade at Mendota School staged their second annual Science Fair. Various ingenious "gadgets" developed by each pupil were displayed and prizes were awarded for the best entries. An evening open house was held so parents could inspect the projects. The first-prize winner is in the picture at the upper left. The teacher, Carolyn Anderson is in the background. The others (rear to front) are Cheryl Moore, Eddy Gadsia, and Ronnie Trachte, who is dropping an egg into a pan, which is resting on an electric "stove" made by Ronnie. At the top, right, Steve Sprague (center) is demonstrating his water generator which won second prize. Watching are Polly Prihart (left) and Kim Klipstein. The group at the lower left includes Mary Joe Gross (left), who is watching closely as Leslie FaFard (center) and Ken Conner show off their respective electric eye and atomic generator devices. The three (lower right) include Mary Joe Gross (left); Jim Cron, pointing to simple machines made by him, and Janice Menge. (Photos by Clarence E. Olson)

SMART LIGHTING

Who Am I?



- I attended Sherman Junior High School from 1958 – 1961
- I attended East High School from 1961 - 1964

Madison East High School
Go Purgolders!

K. A. Connor

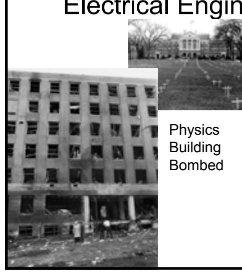
SMART LIGHTING

Who Am I?

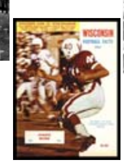
- I attended the University of Wisconsin from 1964 – 1970 receiving two degrees in Electrical Engineering

THE UNIVERSITY WISCONSIN MADISON

Students Kidnap Dow Recruiter



Physics Building Bombed



UW Football 11-45-3 during these years

Why am I an Engineer?

- Why did I go to engineering school when none of the other three accelerated students from my elementary school did?
- My theory – my dad was the 'go to' person for our extended family … if anyone had a problem they could not solve, they asked him to help. This made his sons problem solvers … it does not matter what the problem was, we do our best to find a solution.

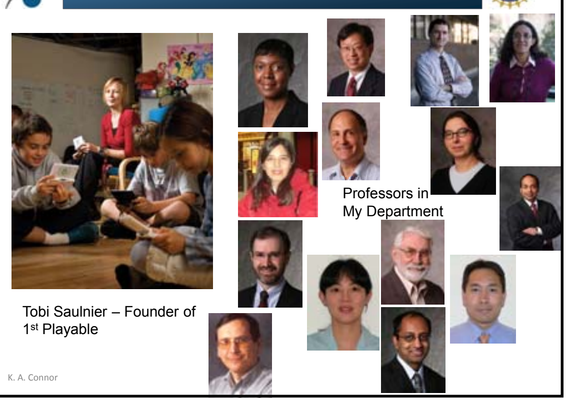
Who Am I?

- I attended the Polytechnic Institute of Brooklyn from 1970 – 1974 receiving a PhD in Electrophysics
- I have been a professor of Electrical Engineering at Rensselaer Polytechnic Institute in Troy, NY since 1974.

www.rpi.edu/~connor

K. A. Connor

I Get to Work with Really Great People



Tobi Saulnier – Founder of 1st Playable

Professors in My Department

K. A. Connor

My Brothers Today

Metso Minerals Industries, Inc.

Mining Services North America

Why Be an Engineer?

- Engineers make a world of difference
- Engineers are creative problem-solvers
- Engineers help shape the future
- Engineering is essential to our health, happiness and safety

From the NAE

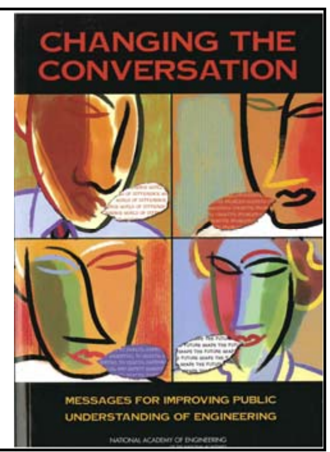
K. A. Connor

NAE Study

It is a good idea to read at least the executive summary of this document, which is free online, but cannot be fully downloaded for free.

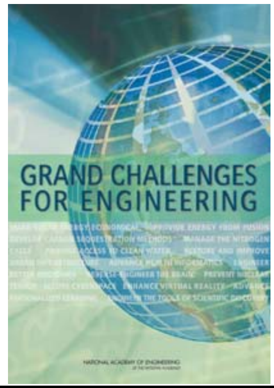
http://nae.edu/nae/naepcms.nsf/weblinks/MKEZ-7FWNXE?OpenDocument

K. A. Connor



Grand Challenges

Grand Challenges



- Download the report
- Watch the PR video
- Select your favorite challenge

http://www.engineeringchallenges.org/cms/challenges.aspx

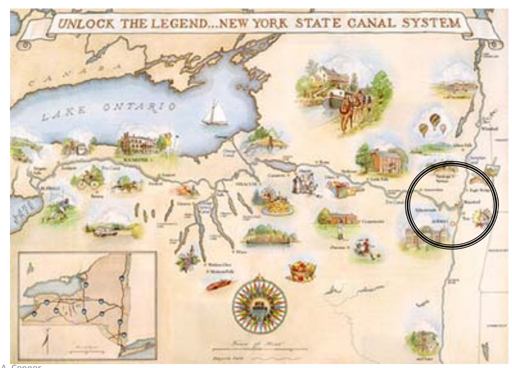
Thinking Like an Engineer

- There are many resources available from professional societies, etc.
- From the ASME, for example.
- ASEE has extensive K-12 support
- Links I have collected
  – http://hibp.ecse.rpi.edu/~connor/EOD/
- Historical Connection – Theodore Judah
  – http://cprr.org/Museum/Judah_Report_1863.html

One the most interesting people to have attended RPI

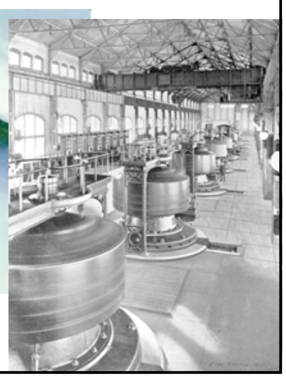
K. A. Connor

Why Are We Here?



K. A. Connor

Also

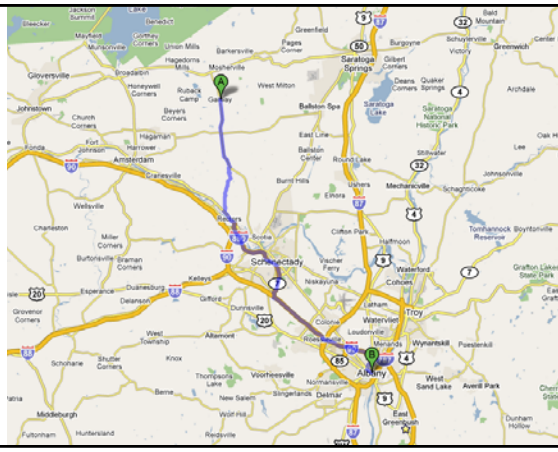


K. A. Connor

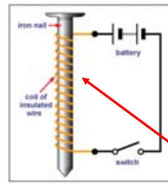
Joseph Henry

- http://maps.google.com look up Albany, NY

K. A. Connor



Joseph Henry



What is one of the keys to making a powerful electromagnet?

Insulation

Electromagnet

K. A. Connor

Joseph Henry

His key practical contribution to the electromagnet – how did he do it?

K. A. Connor

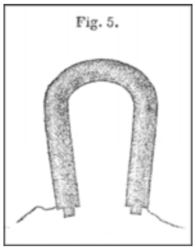
Joseph Henry

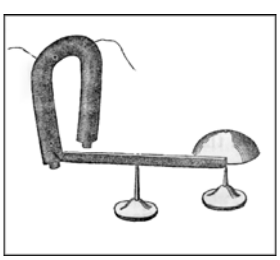
In 1820, Danish physicist Hans Christian Oersted had discovered that the flow of an electric current produced a magnetic field around the wire. This amazed scientists and many, including Henry and Faraday, began to experiment with magnetism. In 1829 Henry learned that William Sturgeon had built an electromagnet that could lift nine pounds. This was quite remarkable, but Henry believed he could create a magnet that was much stronger. ***The secret was to wrap more wire around the iron core, overlapping the levels. However, wire in that era was not insulated, so wrapping one level over another caused a short circuit. Henry got around the problem by the laborious process of insulating the copper wire by hand, using strips of his wife's silk petticoats.***

K. A. Connor

Joseph Henry

Fig. 5.





He recognized that the magnet could be the key part of a long distance signaling device – this became the telegraph

K. A. Connor

Joseph Henry

- Simple idea – properly insulate the wires so that many turns could be added to a magnet – which he called intensity magnets
- Saw the potential of the more powerful device as the beginning of long distance communication
- Also demonstrated that a motor could be made, although his did not turn
- His work made motors & generators and essentially all electric power equipment possible

K. A. Connor

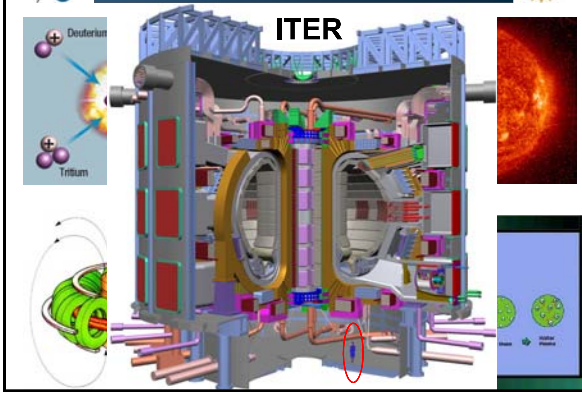
Telegraph

Send messages to people over very long distances

What can we do with a strong magnet?

K. A. Connor

Nuclear Fusion Research



Thinking Like an Engineer: Systems

- What is a system?

Concept: A *system* is something made from a collection of simpler things – usually called components, parts, or subsystems. Each part has a function and the collection of parts have relations among them that let the assemblage accomplish some larger function.

- Can we think of any examples?

Systems Examples

Systems Concepts

Concept: *There is no answer to the question "is A better than B" unless you know the larger context, the system, in which A or B will be used and how A or B will interact with the other components of that system!*

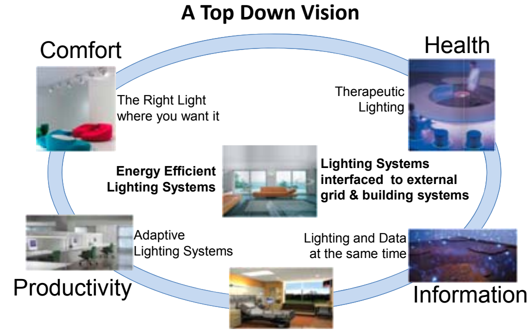
Example: Using hydrogen as a transportation fuel. The usual rationale is that when hydrogen burns the result is pure water, so no pollution. That's true, but it's not the whole story. Hydrogen isn't something that you can pump out of the ground; it has to be *made*. A hydrogen-powered vehicle, then, is part of a larger system that includes at least the process of making hydrogen, transporting it to where it will be used, storing it on board the vehicle, and perhaps more. Whether using hydrogen as a transportation fuel is a good idea depends on whether all of these things *taken together* are a good idea.

Example: Is an electric car better than a gasoline car?

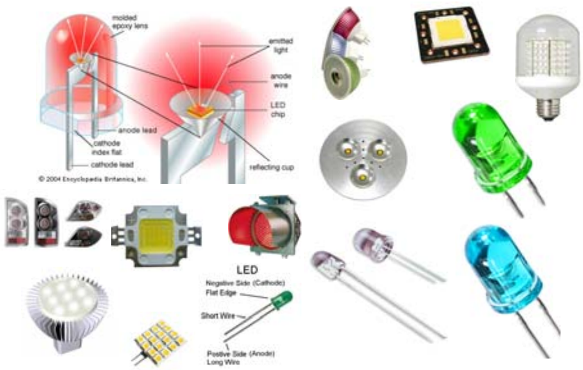
Lessons from Bill Wulf, former President of NAE

Smart Lighting ERC

A Top Down Vision

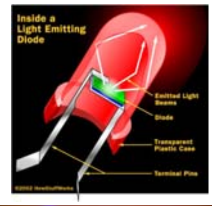


Solid State Lighting



Making Light Smart

- Light Source
  - LED
- Power for Light Source
  - Battery (DC Voltage)
- Control
  - Computer (Processor)



K. A. Connor

What Are We Up To?

- **The vision of the Smart Lighting: The Right Light Where and When You Need it.** Accomplished by an integration of advanced light sources, sensors, and adaptive control.
- Efficient LED (Light Emitting Diode) bulbs are only the ***first wave of solid-state lighting.*** *The Smart Lighting Engineering Research Center (ERC) will create* ***the second wave of solid state lighting,*** *consisting of lighting systems with adaptive functionality, able to measure and control the many different and largely unused properties of light. Smart Lighting will provide additional significant systems-level energy savings and add a whole new range of capabilities to displays, communications and biosensing.*

What Are We Up To?

- The **transformative technologies** being developed by the ERC will help the U.S. recover a position of prominence in the development of Smart Lighting, with tremendous implications for lighting, medical, energy, and information technology sectors.
- The ERC will **educate a new generation of students** with the interdisciplinary skills, global technology exposure and business sense to bring new ERC technologies to market.
- ERC is forging **deep working relationships with industry** to help define the future of Smart Lighting. Industry is engaged in our translational technology activities and is driving the innovation, ***educational outreach***, and diversity efforts that are critical parts of the ERC mission.

LIGHT

K. A. Connor

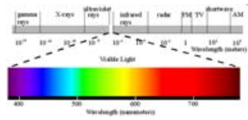
LIGHT – How Do We Use It?

- Illumination – Lighting in our homes and work, for our cars, etc.
- Imaging – Microscopes, telescopes, photography, etc
- Displays – Television and Computer Monitors (CRT, Plasma, LCD, etc.)
- Signaling – Traffic lights (cars, trucks, trains, boats, etc.), laser pointer, etc.
- Information – Optical fibers, read-write for storage (CD, DVD, Blu-Ray, etc), barcode, etc.
- Cutting, etching, etc.

K. A. Connor

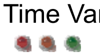
Characteristics of Light

- Spectrum (Color)



- Polarization

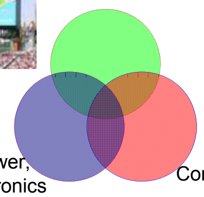
- Time Variation (Blinking)



- Direction

K. A. Connor

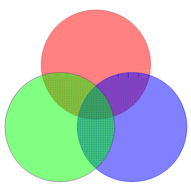
Smart Lighting



Smart Lighting System

K. A. Connor

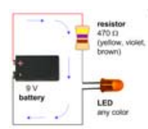
Similar to Robotics



K. A. Connor

Making Light Through Electronics

- LED (Light emitting diode)
- Resistor
- Wires
- Battery



We have made a solid state light

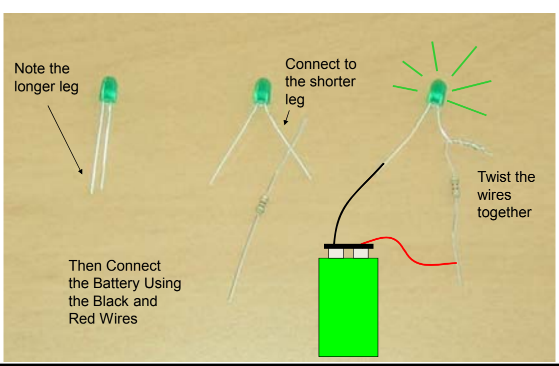
Such a light could be used to send flashing signals

This is what the stop and go lights (red, yellow, green) are made from these days

http://www.robotroom.com

K. A. Connor

At Home Without the Protoboard



Flashing Lights Sending Information

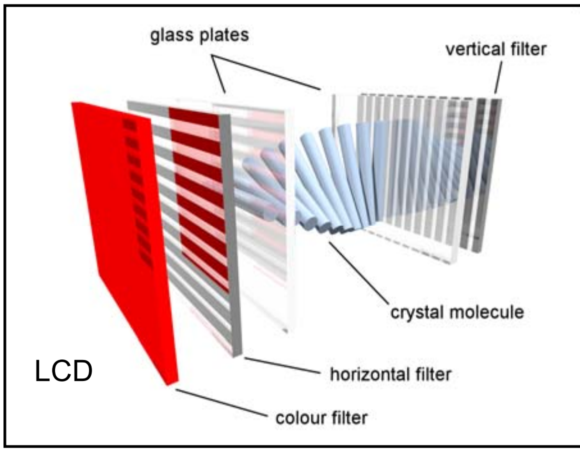
- Remote Control – See it on a camera
- Music Traveling on Light
- Hearing a Remote
- Sound Activated Switch
- Polarization & Displays
- Others?

K. A. Connor

Displays

K. A. Connor

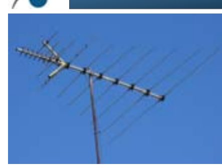
http://www.dlp.com/tech/what.aspx



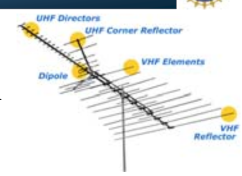
Nano in Smart Lighting

- How can we use nanotechnology to improve or realize smart lighting?
- Any ideas?
- Think of optical properties of materials
- Think of waves more generally
- Are there other properties that matter?
- What about sensors?

Photonic Crystal



$$\lambda = \frac{c}{f}$$



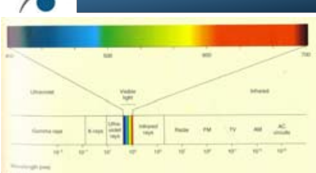
- VHF Frequency – 100 MHz
- UHF Frequncy – 500 MHz

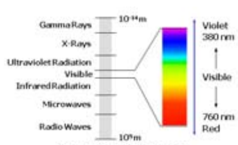
Remember TV Antennas?

$$\lambda = \frac{c}{f} = \frac{3x10^8}{10^8} = 3m \qquad \lambda = \frac{c}{f} = \frac{3x10^8}{5x10^8} = 60cm$$

Antenna elements are typically one half wavelength long

Photonic Crystal



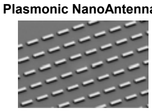


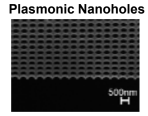
- Dimensions of light waves are smaller.

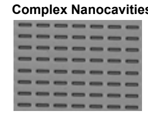
$$\lambda_{violet} = \frac{c}{f} = \frac{3x10^8}{7.9x10^{14}} = 380nm$$

Nano Structures

Plasmonic NanoAntennas **Plasmonic Nanoholes** **Complex Nanocavities**

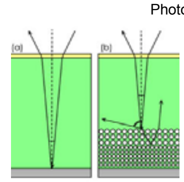


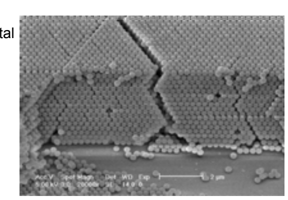




Boston University – Hatice Altug

Photonic Crystal





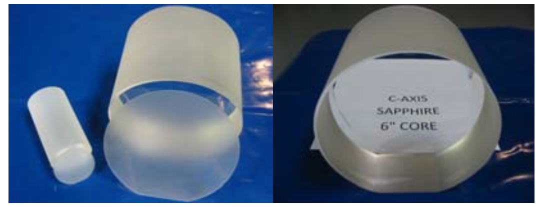
Catholic University of Leuven

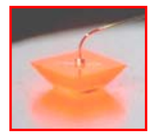
Index of Refraction

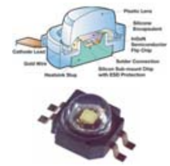
Can someone describe your Wednesday experience on *Light Scattering: Effect of Refractive Index ?*

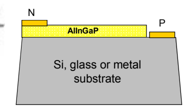
- What was the most recent big news on the GLOBALFOUNDRIES (AMD) plant being built nearby?
- Wafers will be 18” (450mm)
- We build electronic and photonic devices on substrates.
- What is different about the substrates we use for LEDs and other electronic devices?
- They must be transparent.

Index of Refraction



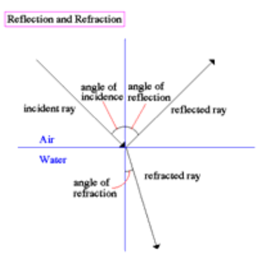






LUMILEDS

Index of Refraction



We get reflection unless the difference in index is very small.

Snell's Law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Index of Refraction

- Low Index Materials

	Air	Water	Sapphire
Index	1.00	1.33	1.77

- High Index Materials

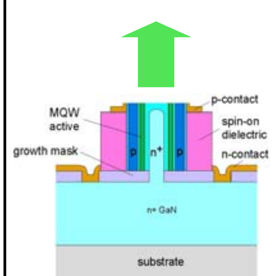
We need to be able to make materials with indices close to air and sapphire – can be done with nanotechnology

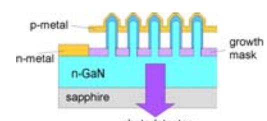
	Diamond	Gallium Arsenide	Silicon
Index	2.42	3.93	4.01

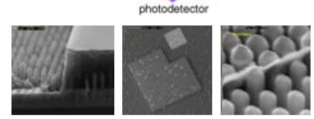
Example LED Companies

- Philips Lumileds
  - http://www.philipslumileds.com/
  - http://www.youtube.com/watch?v=048ApwN0NyU (1:25)
- CREE
  - http://www.cree.com/
  - http://www.youtube.com/watch?v=eVWxYyxc-9g&feature=PlayList&p=061D62548EE60704&playnext=1&index=21
- Nichia
  - http://www.**nichia**.com
- Osram
  - http://www.osram.com/osram_co

Making LEDs with Nanorods

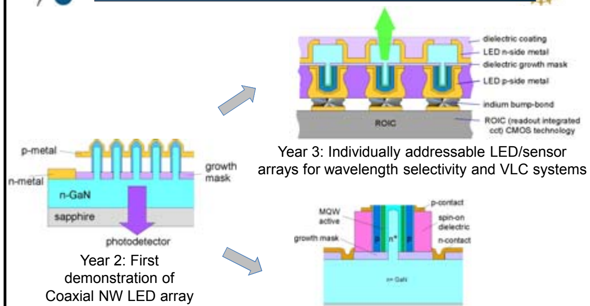






Coaxial Nanowire LEDs

Year 3 Coaxial Nanowire/Nanowall LEDs



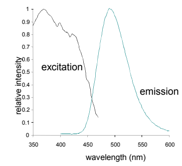
Year 3: Individually addressable LED/sensor arrays for wavelength selectivity and VLC systems

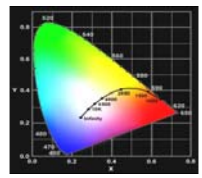
Year 2: First demonstration of Coaxial NW LED array

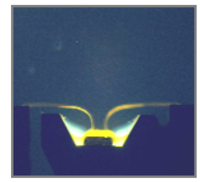
Year 3: Full InGaN active region growth for multiple wavelengths

How to Make a White LED

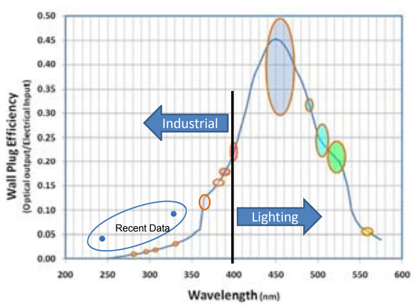
- Mixing colors can make white LED
  - Red, Green, Blue LEDs used together
  - Blue LED plus Yellow Phosphor
  - UV LED plus various Phosphors
- Phosphor - a material that absorbs light at one wavelength and emits it at another wavelength







Efficiency versus Wavelength



Nitride Based LEDs

What About Other Energy Efficiency Applications

Challenges with Phosphors?

- They already work very well for standard lighting … the large peak on the previous slide is for the blue LEDs used to make white phosphor LEDs.
- They scatter light
- They are slow
- Others?

Nano in Smart Lighting

- High and low index of refraction
- Nano-column and Nano-finger LEDs fabricated – high light extraction and exploration of strain field effects on droop reduction
- Polarized LED (green on m-plane GaN) and models of photonic crystal designs for RGB polarized LED manufacturing
- Nano-wire UV LED growth with very low dislocation density – droop and green gap implications
- Non-scattering graded composition phosphor for high performance white LEDs

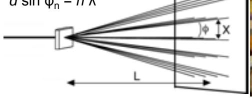
Optical vs. RF

- Lets look at the RF spectrum in a narrow but well used band.
- Consider the audio spectrum first
- Wi-Spy
- Fun last demo

Nano Outreach at BU

- Boston Upward Bound Math and Science Program (BUBMS): Nanophotonics & Nanofabrication (Altug)
- Optical: Provide a grating consisting of several different patterns with different periodicities
  - Students calculate the periodicities of each grating section using the far field pattern they obtain with a laser and the diffraction grating equation
  - The compare their experimentally determined values with the direct microscope method
- Soft lithography with PDMS

$d \sin \varphi_n = n \lambda$



http://mrsec.wisc.edu/Edetc/nanolab/PDMS/index.html

The Future

- We in the ERC, especially the education and outreach program, are charged to help promote interest in and quality education for STEM
- Please feel free to call on us at any time should you need some help.

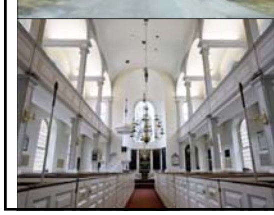
The End

- Best of luck
- Questions?

Early LED Use
Architainment (Architecture and Entertainment)

70

Solid State Lighting – Coming fast



- Many street lighting programs
- 100% SSL buildings are starting to appear (mostly in Asia)
- Many hundreds of start-up companies in Solid State Lighting
- Generally still not ready for prime time
  - Lack of good standards
  - Very high prices
  - Lots of "junk LED bulbs"

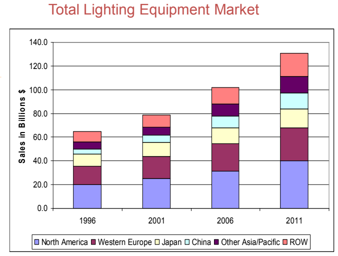
The Total Lighting Market is Huge

Global Lighting Market Size

(in billions)	2006	2011
Lamps (Front-end)	$20.9	$25.4
Fixtures (Back-end)	$81.1	$106.6
Total	$102	$132

North America approximately 29% of the worldwide market

Total Lighting Equipment Market



Source: Fredonia Group, Inc.

So there is a tremendous revenue opportunity for LEDs

72

SMART LIGHTING

Some Examples of MR-16 LED Products

73

SMART LIGHTING

DOE Testing – Many product claims are misleading

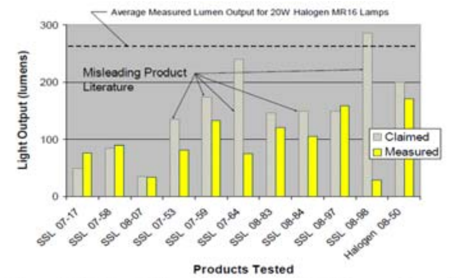


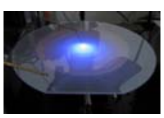
Figure 5. Measured Light Output of Halogen MR16 Lamps and LED Replacements Compared to Manufacturers' Reported Values

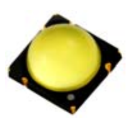
74

SMART LIGHTING

Square Source in a Round Lighting Hole?

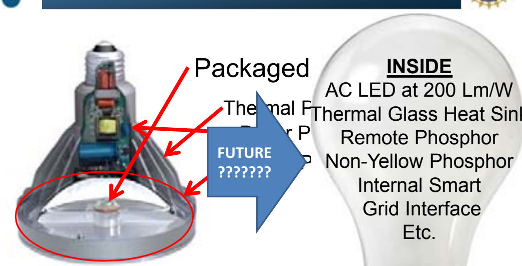
- DC device in an AC Powered World
- Cool light source with thermal management challenges
- Great LED Efficacy – High Lm/W
  ….But low Lumens per part
- Cost still way too high ($100 per 1000 Lm)
  Can Semiconductor "Thinking" do the job?





SMART LIGHTING

System – Putting it all together



Cree LRP-38™ @ 55 Lm/W
(Efficiency of system parts are approximate)

Will we still need a socket?