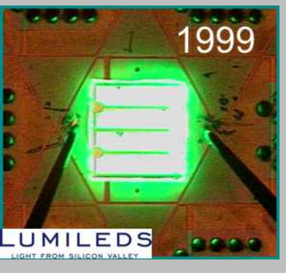
SAND2013-3300P

Comparison of LEDs and laser diodes for solid-state lighting



Jonathan J. Wierer, Jr. , J. Tsao, D. Sizov*, A. Neumann**, S. Brueck**, W. Davis***, and Y. Ohno***

* Corning Inc.
** Univ. of New Mexico
*** NIST

Sandia National Laboratories

Exceptional service in the national interest

IES Albuquerque Section Lunch Meeting, April 19, 2013

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

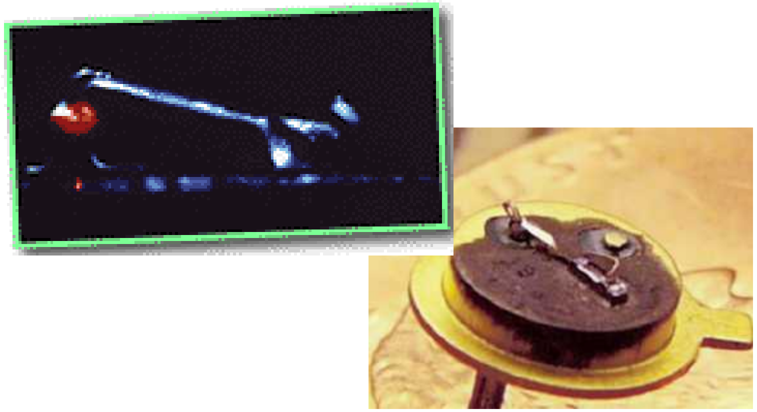
SSLS EFRC

Outline

- History and tutorial of LEDs, particularly blue III-nitride LEDs.
- Compare LEDs and LDs for solid-state lighting.
- Future projections of LED and LD efficiency and cost.

History and tutorial of LEDs

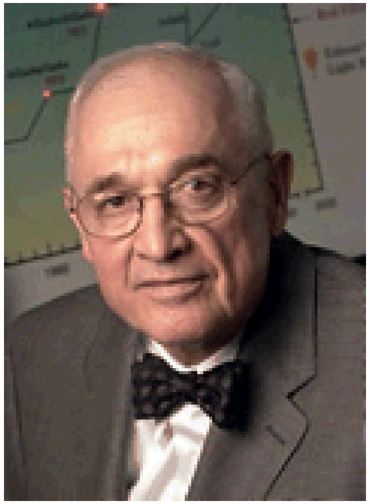
The LEDs beginning: Nick Holonyak, Jr.

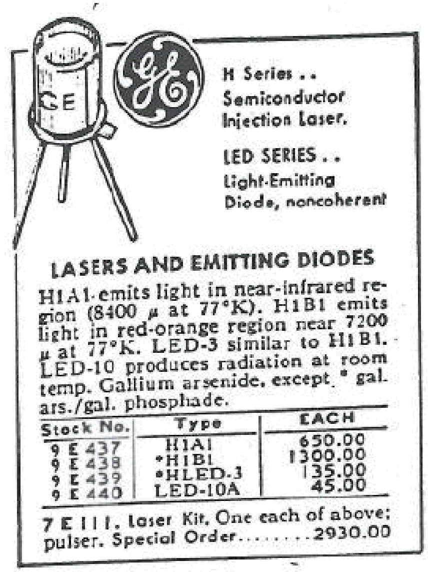


October 11, 1962

Yesterday, at Schenectady, we tried diode # (diffusion run 28) which we assembled here into a plane parallel structure on Tues., Oct 9, 1962 (afternoon, late). And G. Fenner spotted immediately that diode 28 (Ga[As.6P.4]) displayed superlinear ~~photo~~ photooutput. Subsequent investigation on J. Kingsley spectrum analyzer showed the narrowing that goes with "laser" action (13 Å wide). Then follow-up investigation with G. Fenner's "snooperscope" showed the expected diffraction pattern of a "lasing" pn junction. This diode is the first Ga(As.6P.4) "lasing" pn junction, and was left at the Res Lab for further measurements. These results are quite significant, and portend and indicate very significant things to follow.

Nick Holonyak, Jr.
Oct 11, 1962





H Series . .
Semiconductor Injection Laser.

LED SERIES . .
Light-Emitting Diode, noncoherent

LASERS AND EMITTING DIODES

H1A1-emits light in near-infrared region (8400 μ at 77°K). H1B1 emits light in red-orange region near 7200 μ at 77°K. LED-3 similar to H1B1. LED-10 produces radiation at room temp. Gallium arsenide, except * gal. ars./gal. phosphade.

Stock No.	Type	EACH
9 E 437	H1A1	650.00
9 E 438	*H1B1	1300.00
9 E 439	*HLED-3	135.00
9 E 440	LED-10A	45.00

7 E 111. Laser Kit. One each of above: pulser. Special Order........2930.00

1965 Allied Radio Catalog

- First visible laser in Oct of 1962.
- Made from GaAsP.
- A working laser suggested quantum efficiency was high.
- Further suggests efficient LED.

Light of Hope – Or Terror

February 1963 Reader's Digest 35¢ NE

a TV broadcast from the air and beaming it by invisible infrared light 275 feet to a receiver, with good reception. The bit of metal alloy they used was not a laser, for it did not comb the tangles out of the light beam, but its performance sparked a tremendous research drive. Last fall several outfits, including General Electric, IBM, RCA and Lincoln, produced metal lasers which emit "coherent" or tuned light. These appear to be destined for a great future in the communications field.

The latest dramatic laser discovery, made by General Electric, may someday make the electric light bulb obsolete. While the radiation from previous lasers was invisible, this one emits *visible* light in the red region of the spectrum. Research is continuing, and GE engineers hope to build lasers which will convert ordinary electric current into white light with a high degree of efficiency.

"We believe there is a strong possibility of developing the laser as a practical light source," says Dr. Nick Holonyak, head of General Electric's Advanced Semiconductor Laboratory. "Much more experimental work must be done, and it might be ten years or more before such a lamp could be ready for wide use. However, within a year we should have them ready for computer indicators and many other electronic devices, where they should be very useful because of the small size, and speed of action."

If these plans work out, the lamp of the future may be a speck of metal the size of a pencil-point which will be practically indestructible, will never burn out, and will convert at least ten times as much current into light as does today's bulb.

Light of Hope— Or Terror?

The present and potential uses of the laser—a new kind of light ray—sound like science fiction. In fact, the invention is one of the most amazing accomplishments of our time

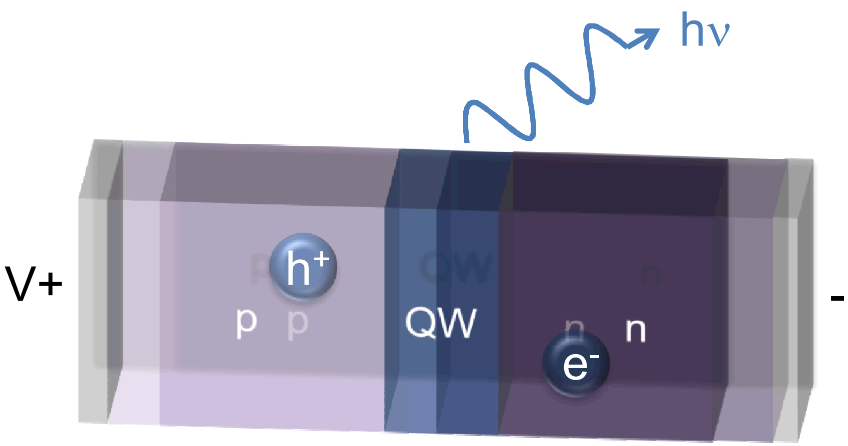
By Harland Manchester

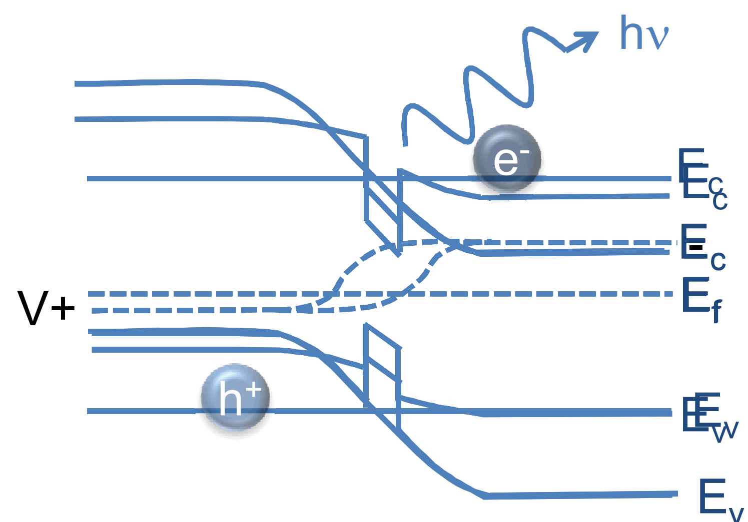
One evening last May, a thin streak of red light shot through space from the roof of M.I.T.'s Lincoln Laboratory at Lexington, Mass., hit the moon (then 250,000 miles away), and bounced back to an instrument which recorded its pioneering round trip. The light came from a new kind of electric torch, called a "laser," which emits a slender pencil of regimented light unlike anything known before. The beam of an ordinary searchlight aimed at the moon would fan out to a circle 25,000 miles wide; its reflection would be too faint to record. The laser beam made a dot only two miles across.

Laser stands for "light amplification by stimulated emission of radiation." Its invention is one of the most exciting events of this century. Since the new light first appeared three years ago, some 400 firms and universities have launched laser research projects, and an estimated 30 million dollars was spent last year in experimentation. Still in its early development stage, the laser prom-

Harland Manchester, a Roving Editor of The Reader's Digest, has specialized in reporting developments in the field of science for many years. His latest book, *Trail Blazers of Technology*, was published last November by Charles Scribner's Sons.

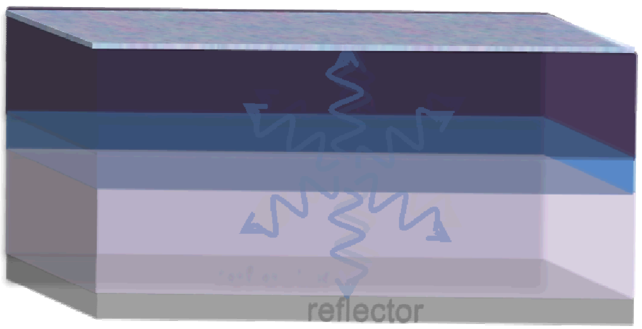
p-n junction light-emitters



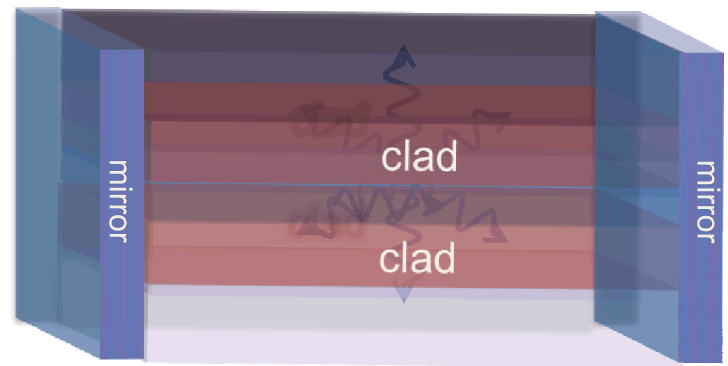


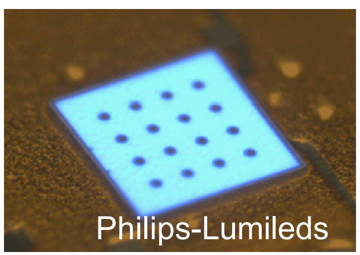
LEDs and laser diodes (LDs)

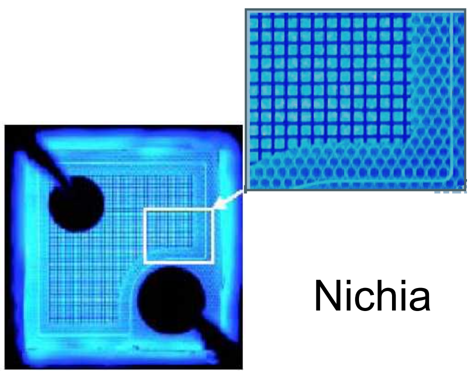
LED



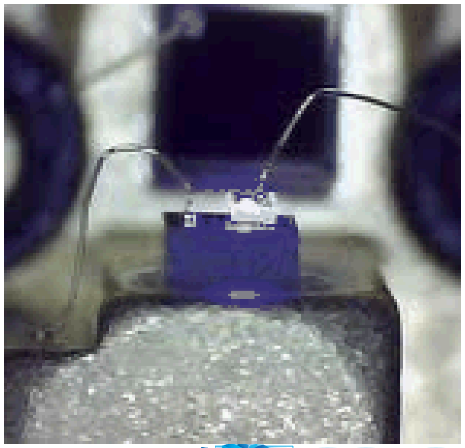
LD



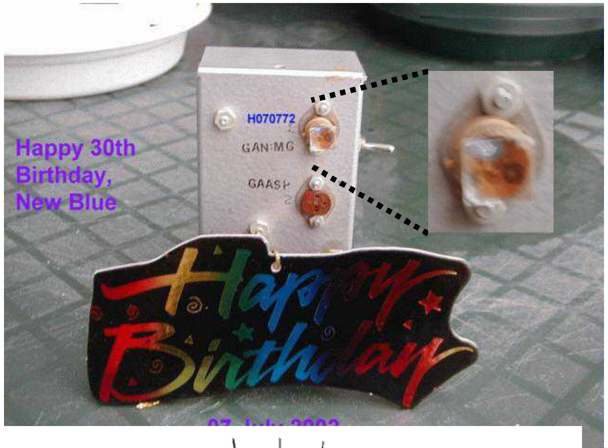


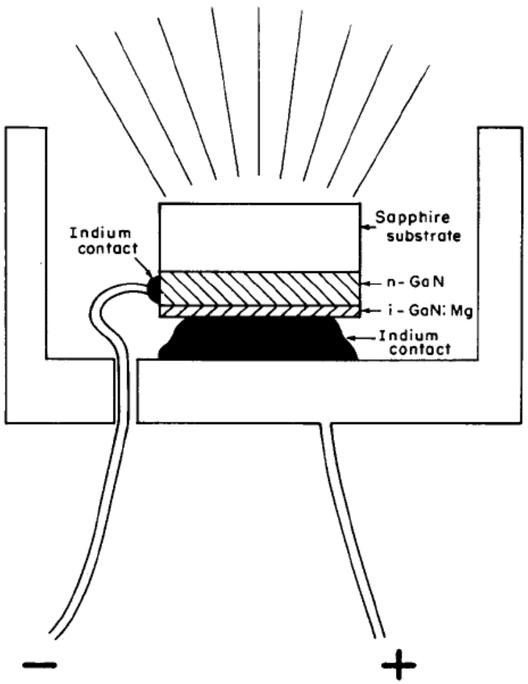


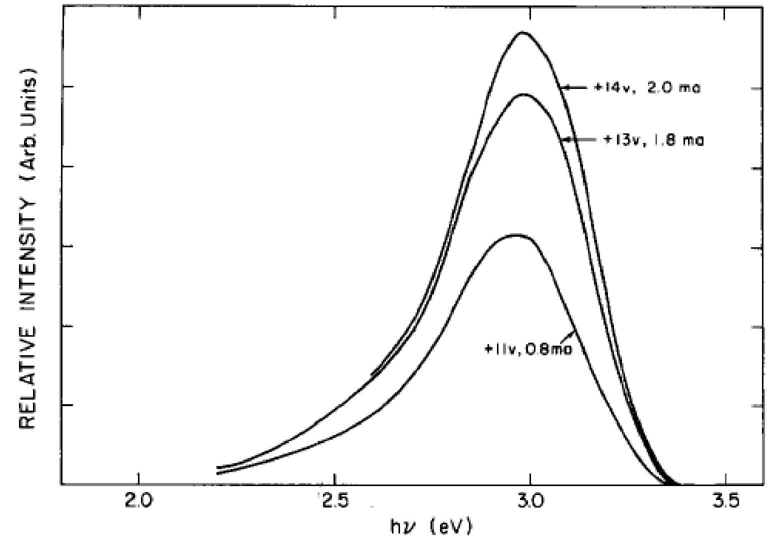
Nichia



Early III-nitride LEDs







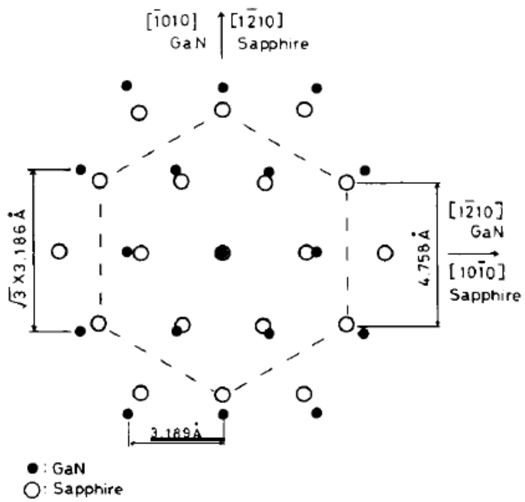
- J. Pankove and H. Maruska at RCA Laboratories in 1968-74.
- First vapor phased growth of GaN.
- Produced near blue emission

III-nitride breakthroughs

Renewed interest in late 1980's, but there were three problems to be solved.

1. No GaN substrates.

- Need to learn how to grow on lattice mismatched substrates.
- N. Akasaki and H. Amano demonstrated buffer layer growth on sapphire producing lower defect density layers of GaN. (1986)



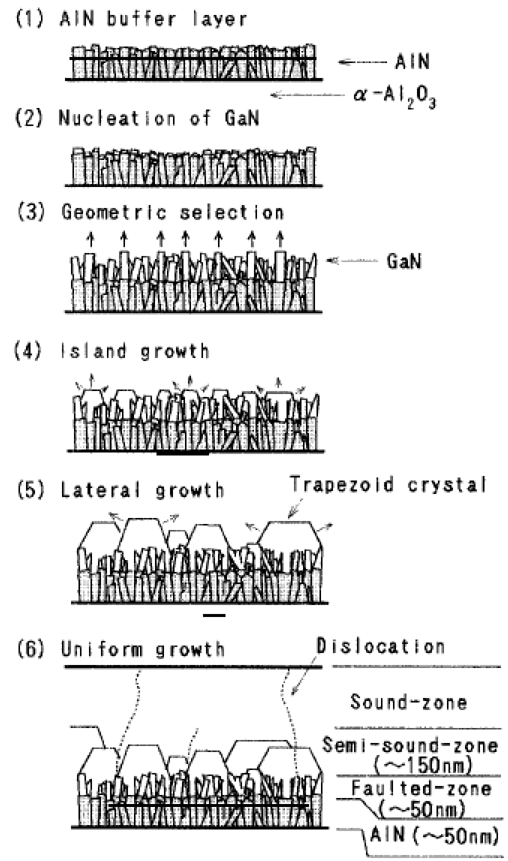
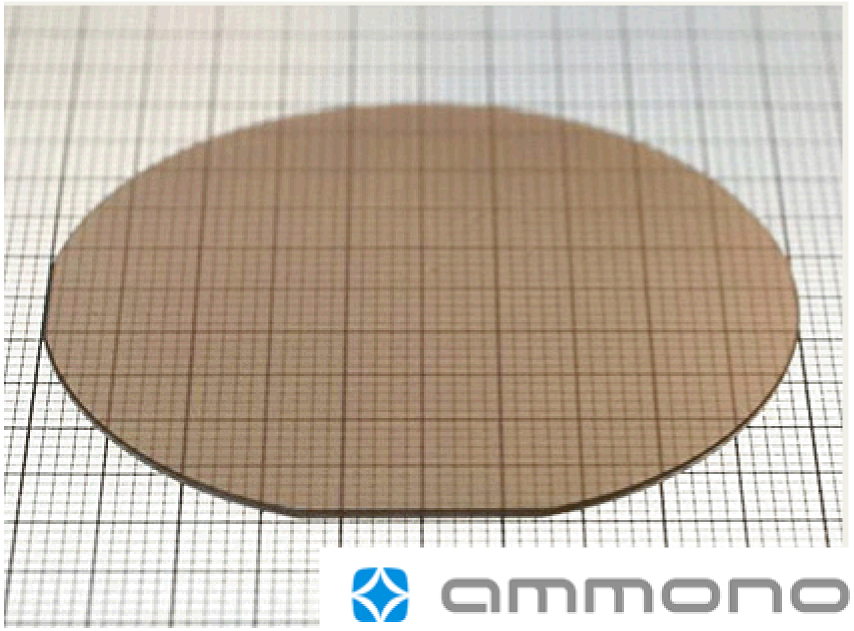


Fig. 6. Schematic diagrams showing the growth process of GaN on the AlN buffer layer as the cross sectional views.

I. Akasaki, H. Amano, et al. J. Crys. Growth, 98, 209, 1989.

III-nitride breakthroughs

GaN substrates!

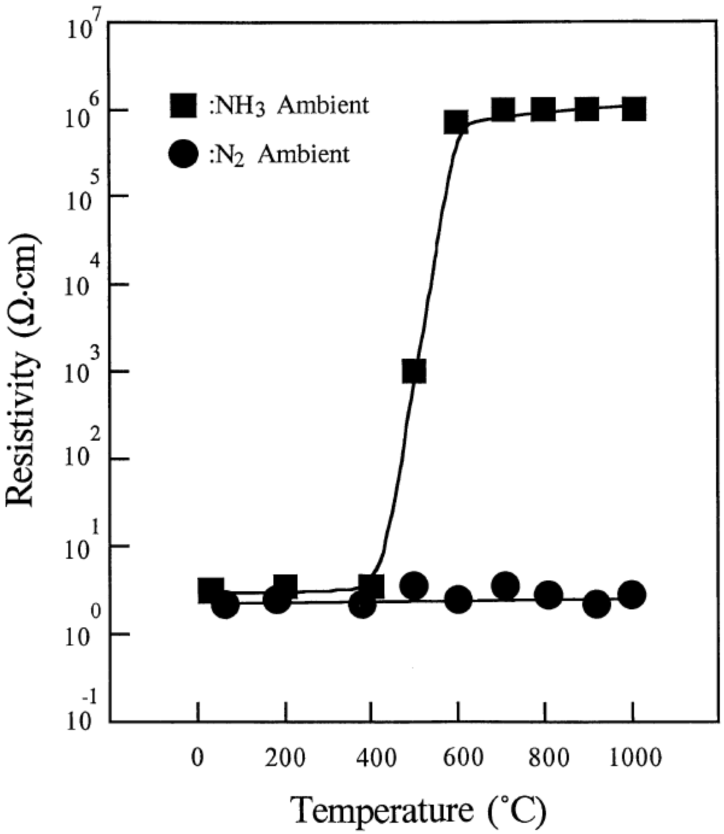


III-nitride breakthroughs

Renewed interest in late 1980's. But there were three problems to be solved.

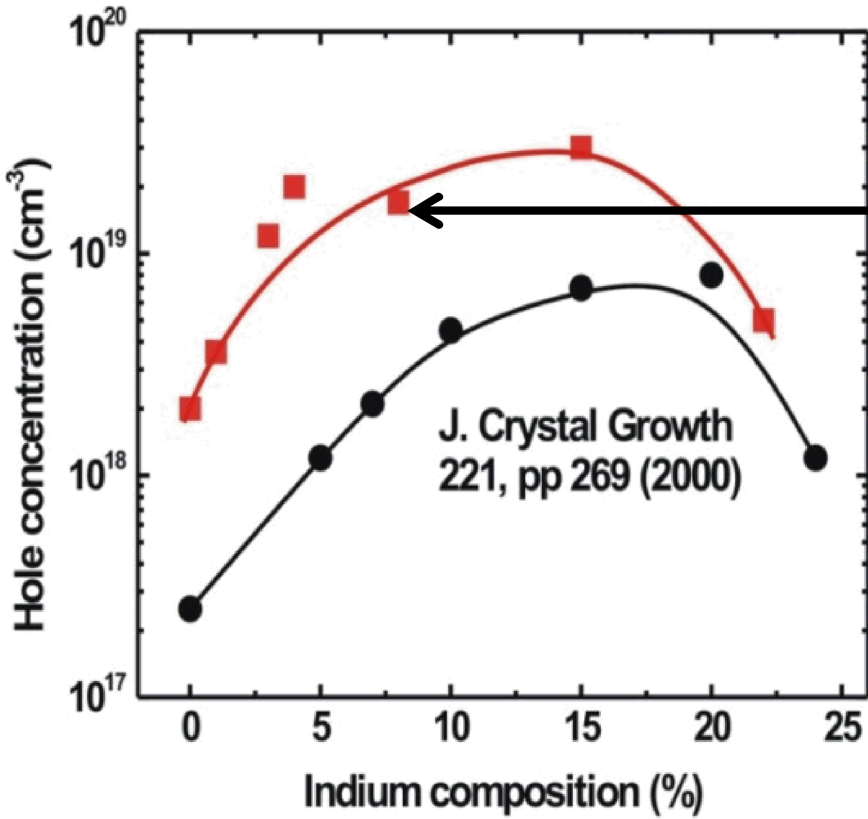
2. No p-type doping.

- Mg doped GaN was not producing p-type conductivity. Why?
- Amano (1989) showed ion irradiation creates active Mg.
- Nakamura (1992) demonstrated that Hydrogen was passivating the Mg acceptors



III-nitride breakthroughs

Higher p-type doping.



$In_{0.08}Ga_{0.92}N$
$\rho = 0.05\ \Omega$-cm
$\mu = 6\ cm^2/Vs$
$p = 1.7 \times 10^{19}\ cm^{-3}$

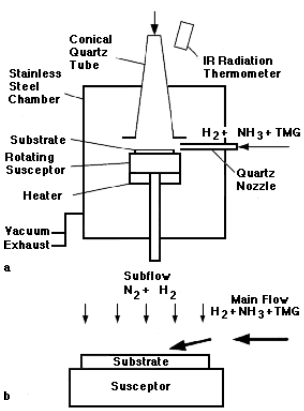
M. Moseley and A. Doolittle, GA Tech

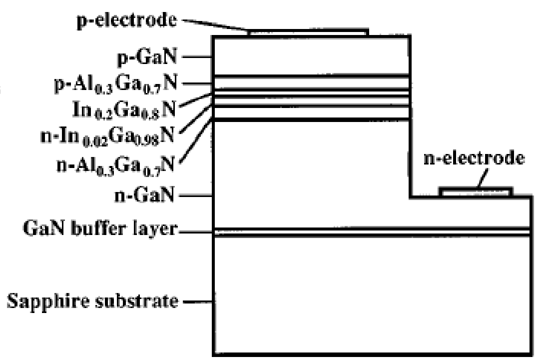
III-nitride breakthroughs

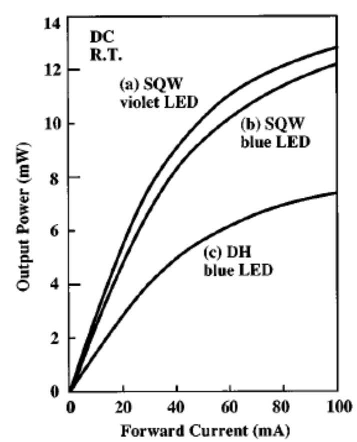
Renewed interest in late 1980's. But there were three problems to be solved.

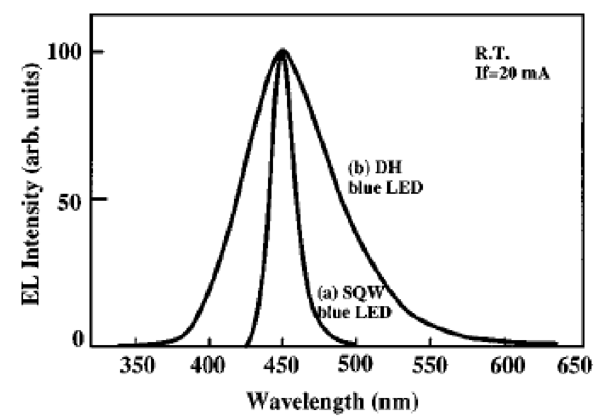
3. GaN emission is in the near-UV, not the visible.

- Need to learn how to grow lower energy InGaN material.
- Nakamura (1995) demonstrated blue LEDs with ~10% quantum efficiency.



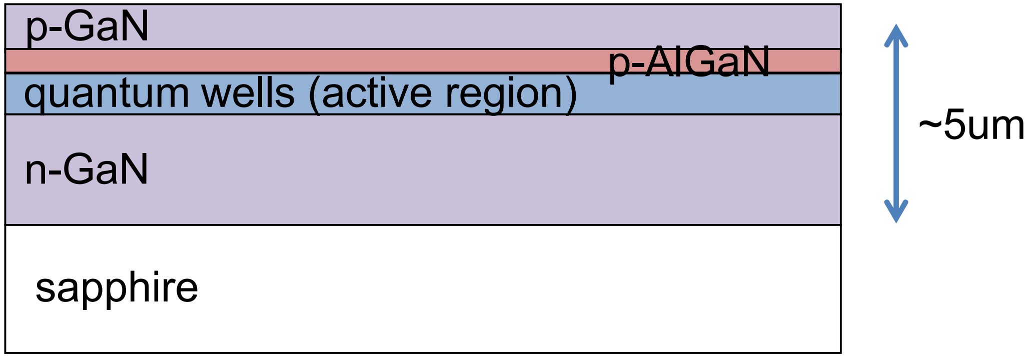


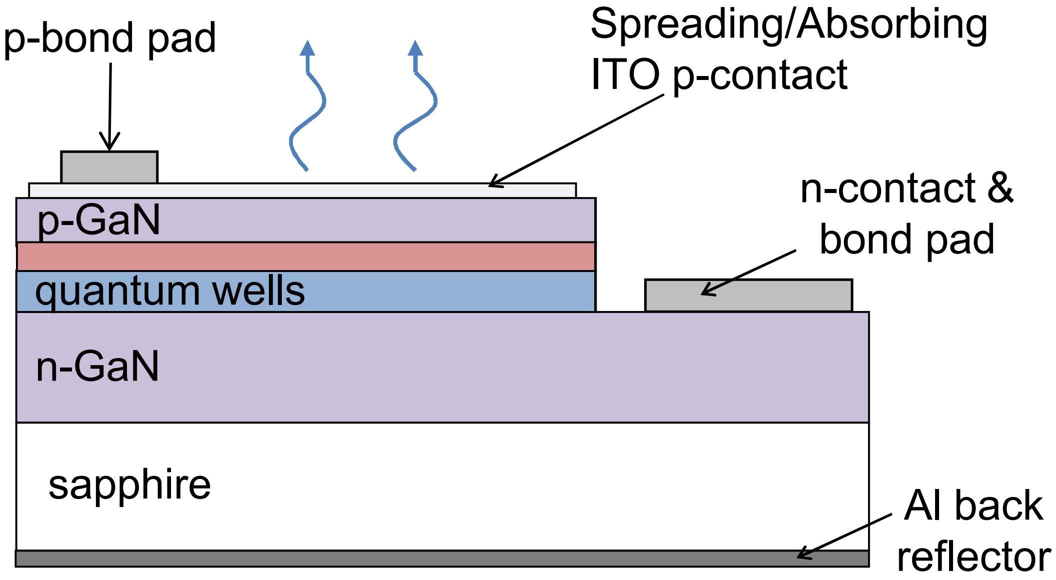


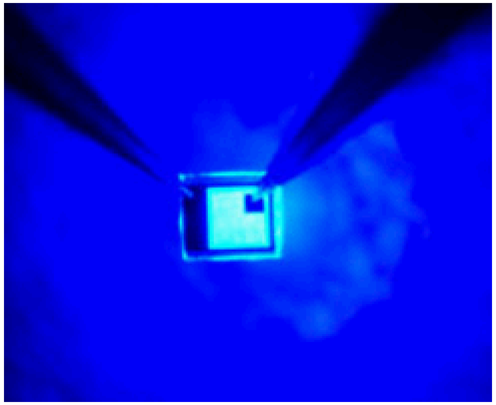


S. Nakamura, et al. ALP, 64, 1868, 1995.

Anatomy of an blue III-nitride LED

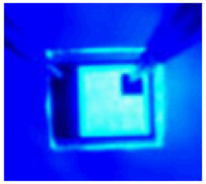




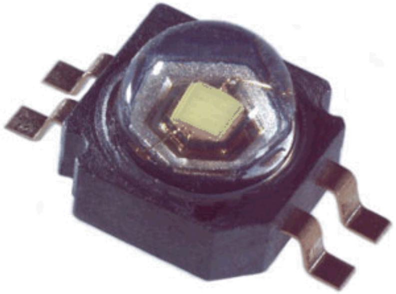


From indicators to illuminators

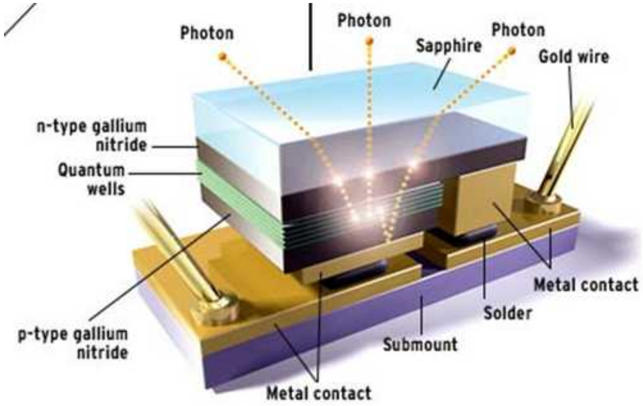
5mm LED:
Epoxy encapsulation
~0.2 mm x 0.2 mm die area
20mA max operating current
10’s of mW of optical power.



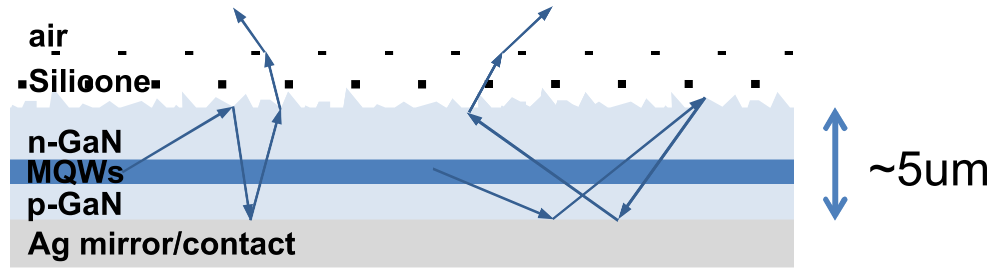
~2000

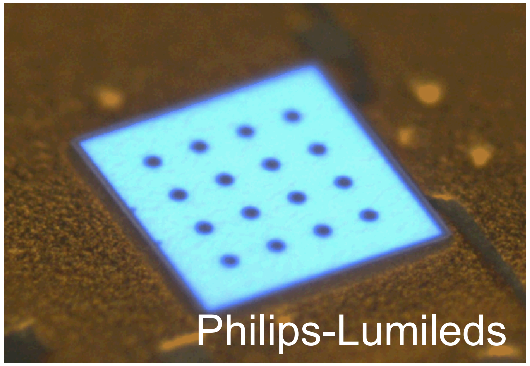


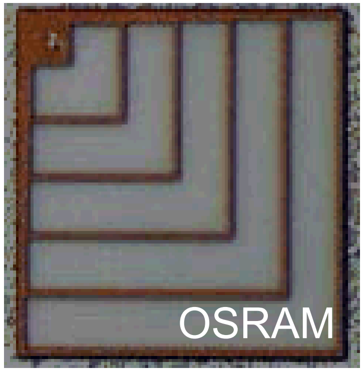
High power LED:
silicone encapsulation
~1mm x 1mm die area
700mA-1A max operating current
~1’s of W of optical power.

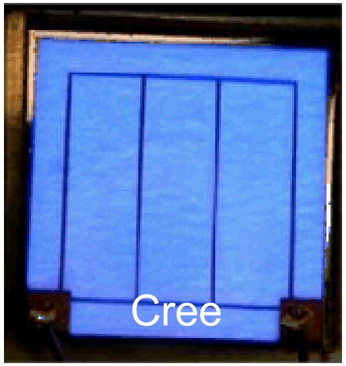


Thin-Film LEDs



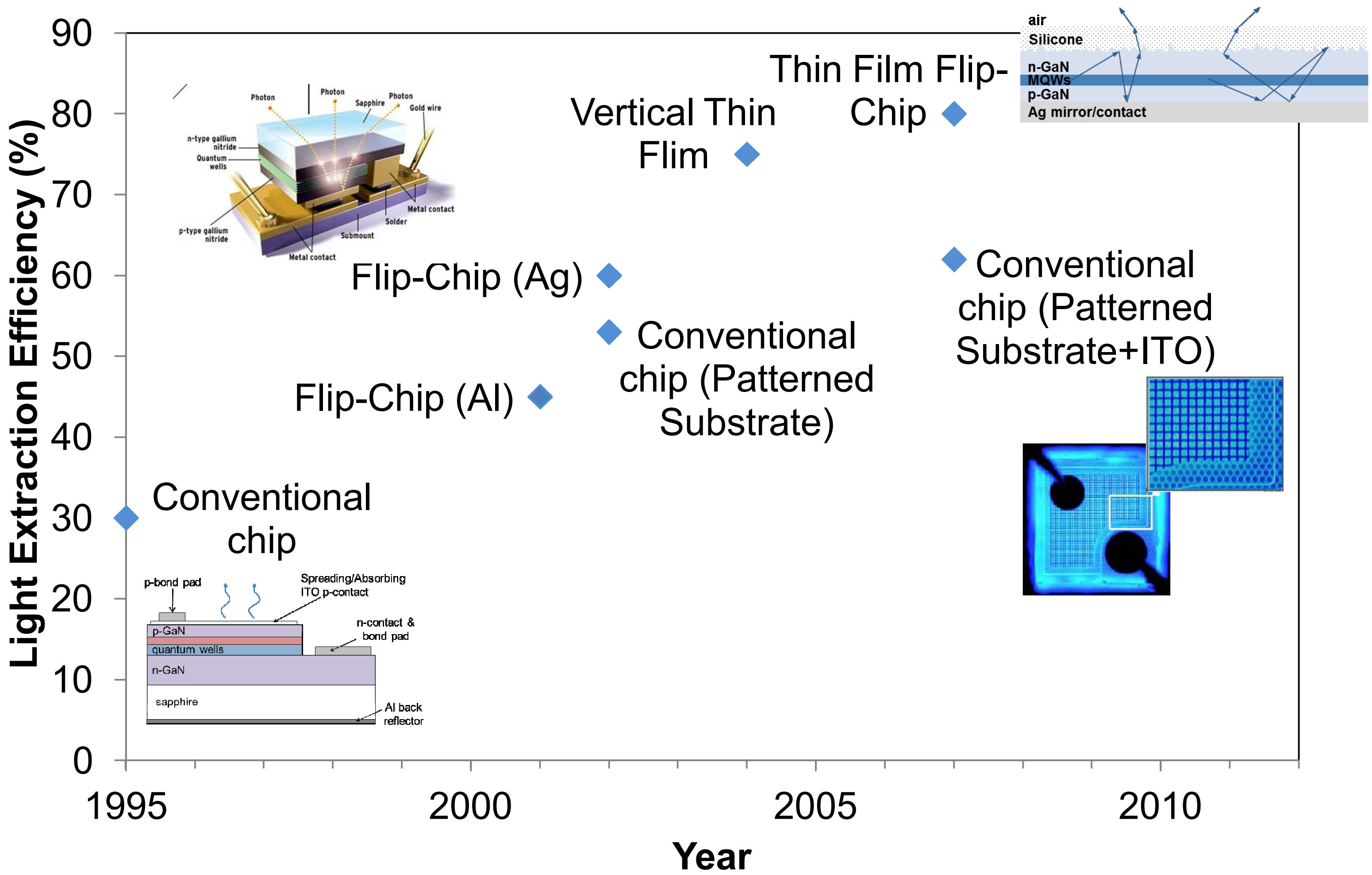






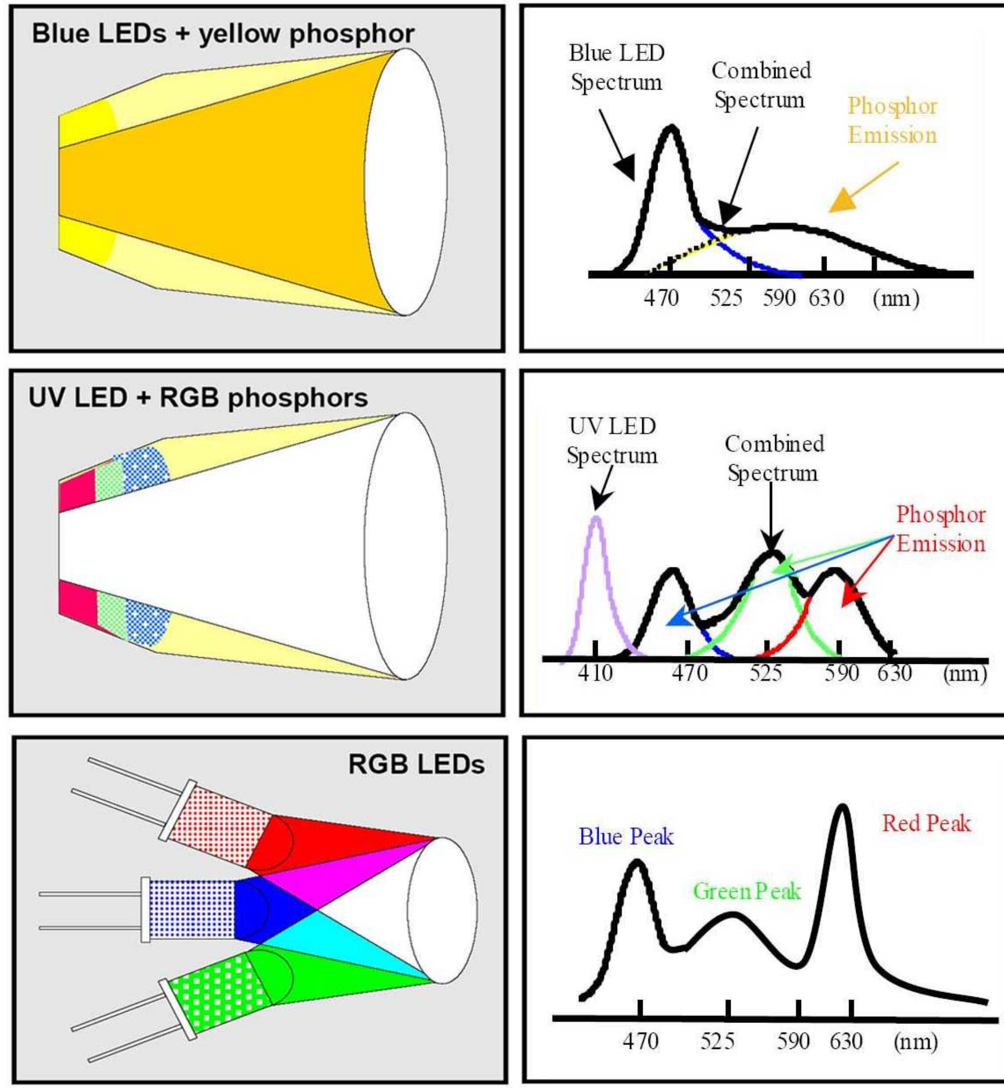
- Most LED manufacturers use the thin-film design in their high end chips.
- Chip sizes are ~1mm x 1mm or larger.
- Provides high extraction efficiency ~80%.

LED Extraction Efficiency Over Time

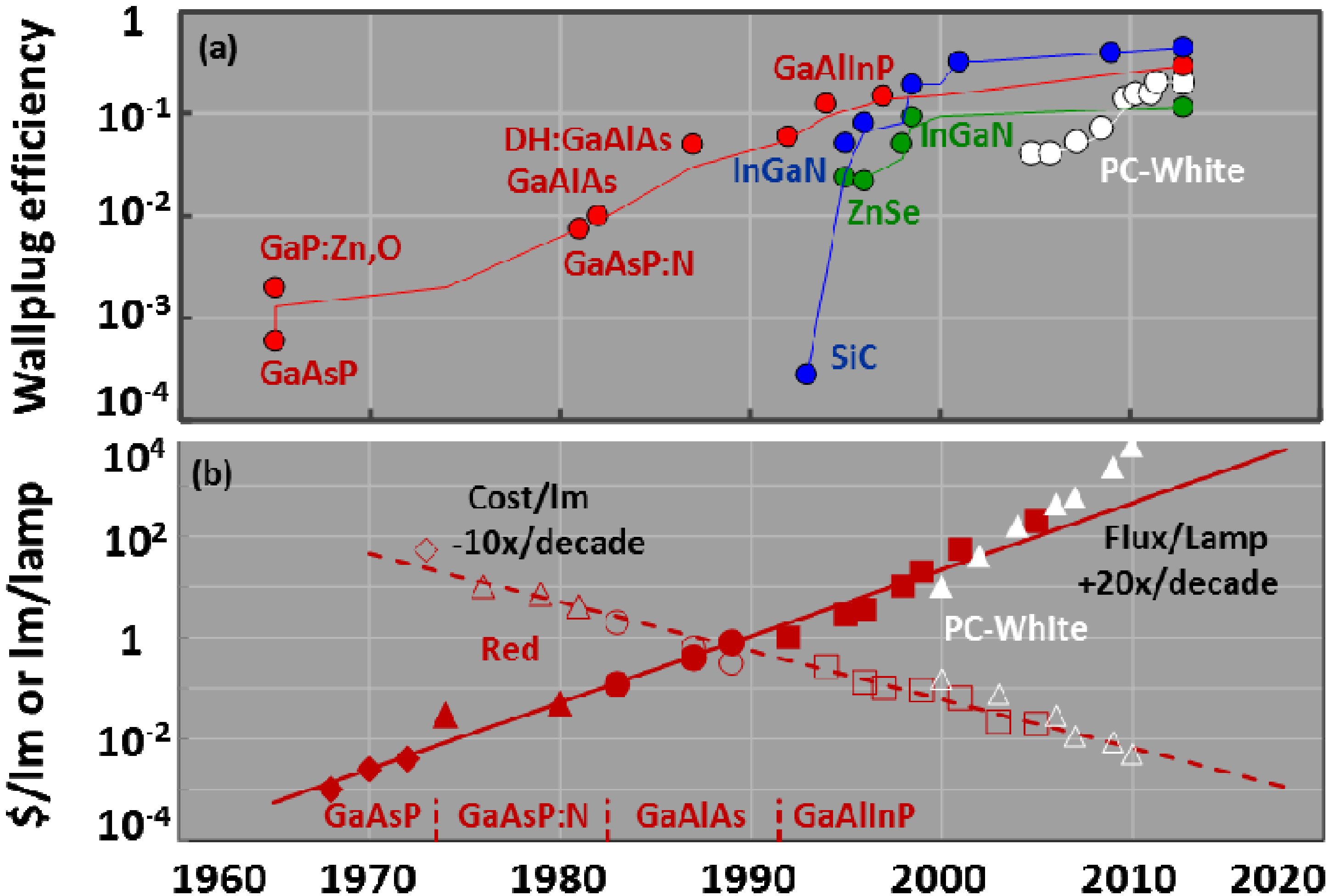


White LED Options

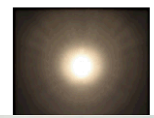
- Blue LED + yellow phosphor
  - Simple
  - Decent color rendering (R_a ~ 75)
  - Stokes-shift loss - blue → yellow
- UV LED + RGB phosphors
  - White determined by phosphors
  - Excellent color rendering
  - Stokes-shift UV → visible colors
- Direct – RGB LEDs
  - Potentially highest efficacy
  - Very large color range
  - Most efficient – tunable white



Efficiency and cost over time

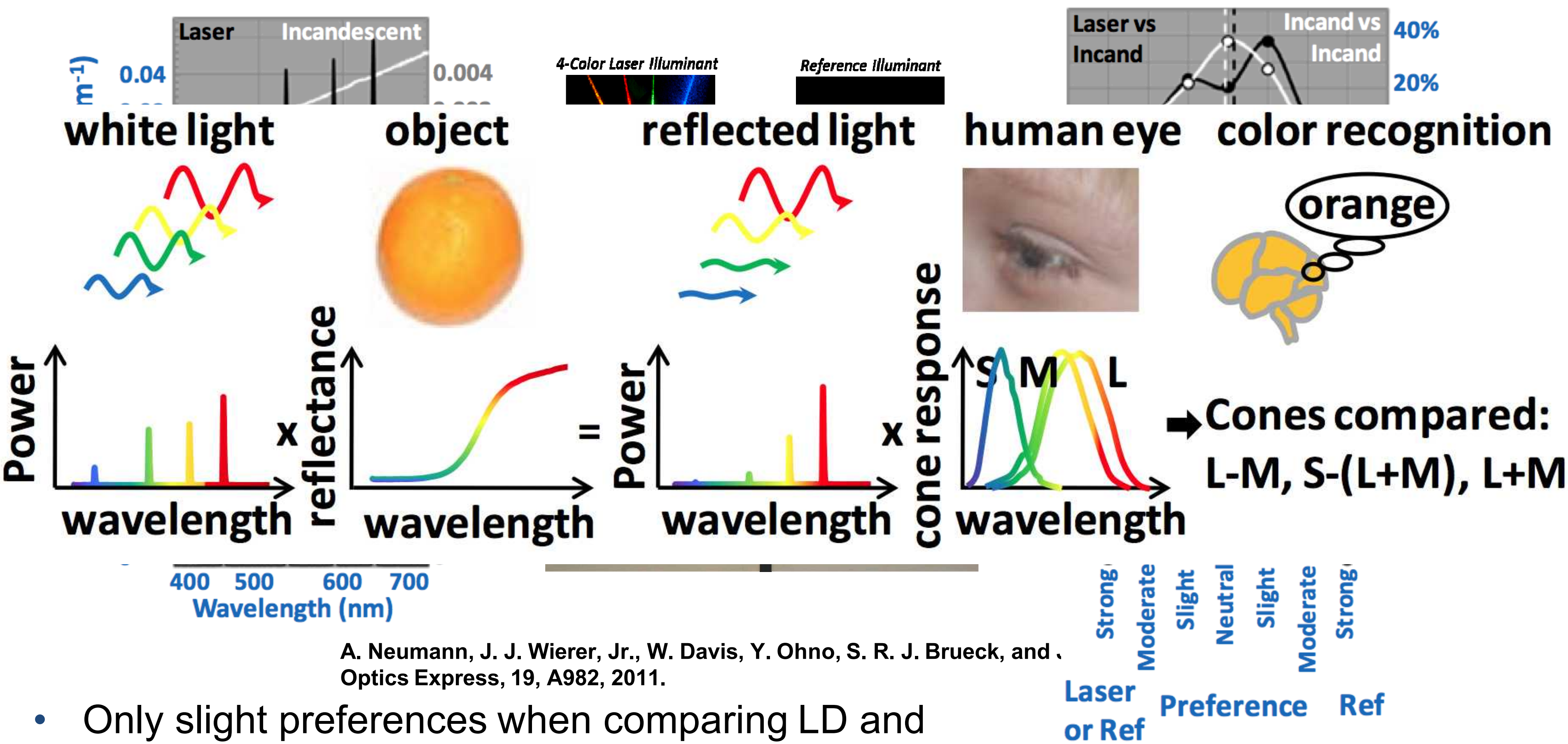


LED Retrofits

Lamp Type	SORAA	TYPICAL HALOGEN
		
Energy Consumption	12 Watts	50 Watts
CBCP @ 25°	2320cd (Premium); 1900cd (Vivid)	2400 cd
Lamp Life	25,000 hours	3,000 hours
Beams	10°,14°, 25°, 36°	10°,14°, 25°, 36°
Form Factor	ANSI	ANSI
CCT	2700, 3000K	3000K
CRI	80 (Premium); 95, R9>95 (Vivid)	95-100
Beam Profile		

Comparison of III-nitride LEDs and LDs

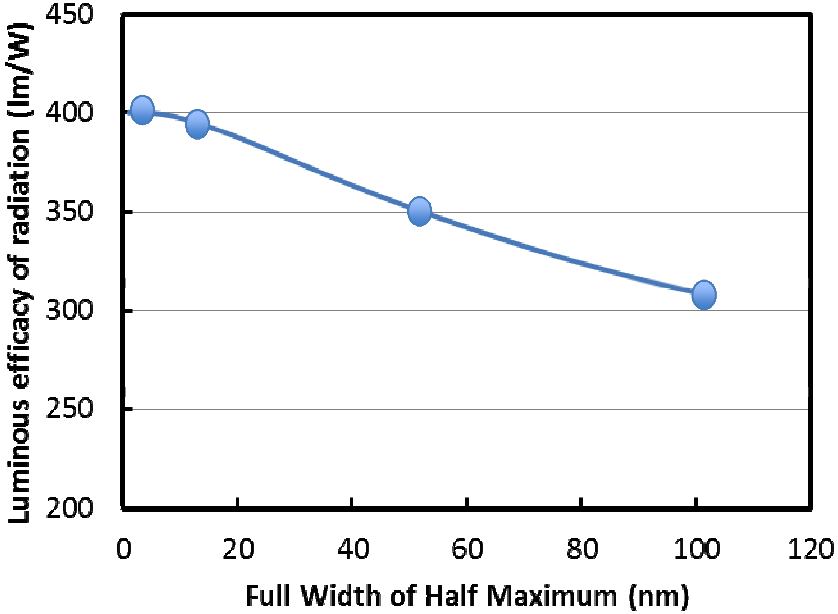
Color rendering of a laser white source

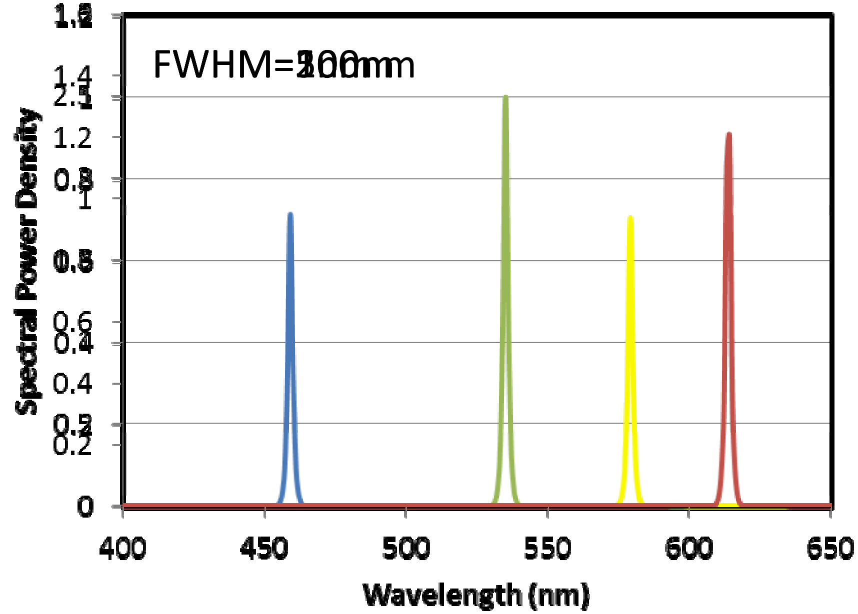


A. Neumann, J. J. Wierer, Jr., W. Davis, Y. Ohno, S. R. J. Brueck, and
Optics Express, 19, A982, 2011.

- Only slight preferences when comparing LD and traditional sources.
- LD white is a good color rendering source. Why?

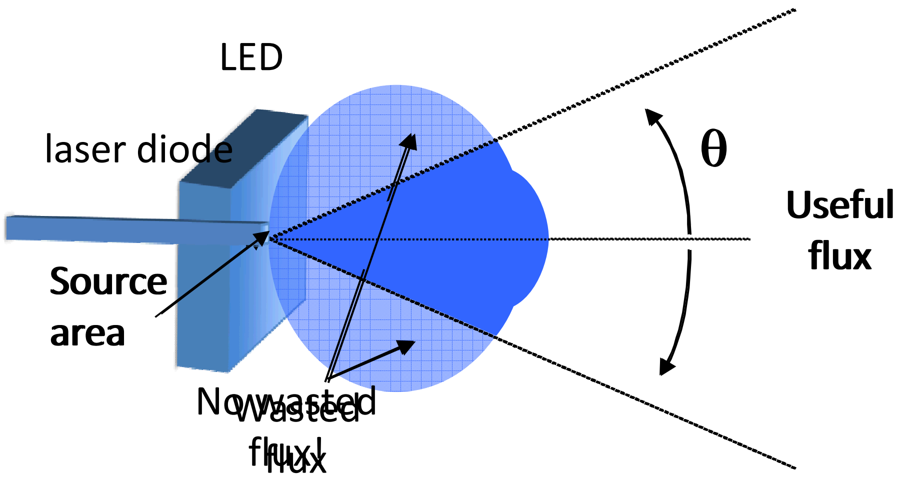
High Luminous efficacies of radiation

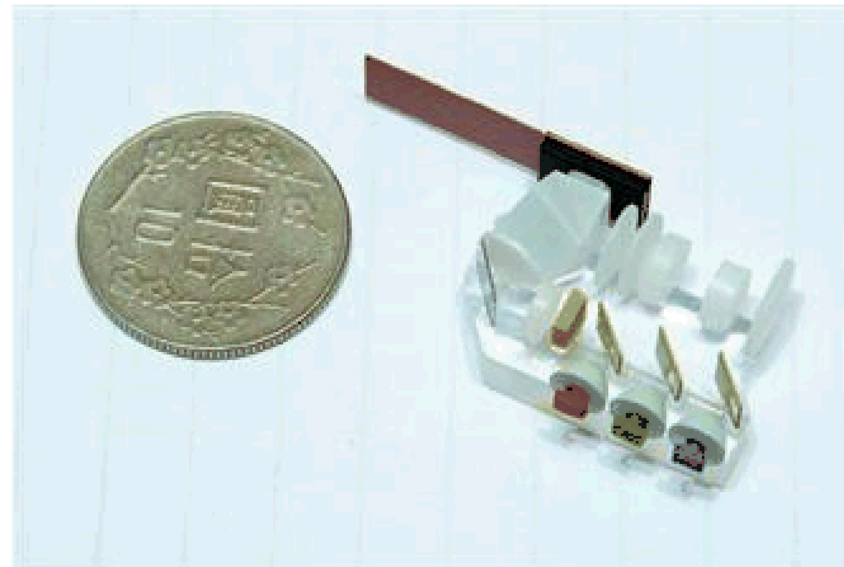


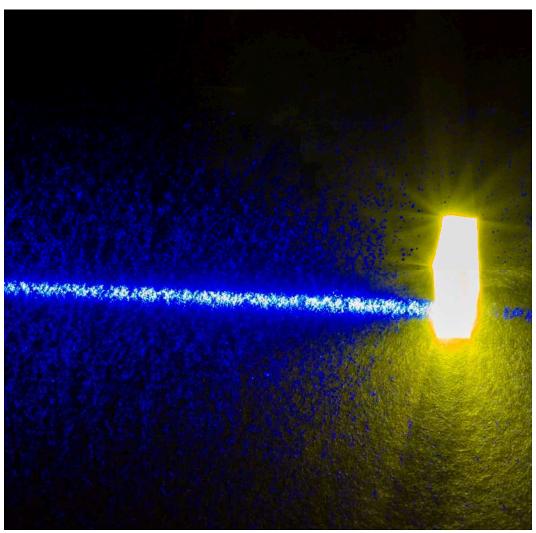


- Spiky sources give highest luminous efficacies of radiation (lm/W)
- Red/yellow power varied to give CCT=3800, Ra=85

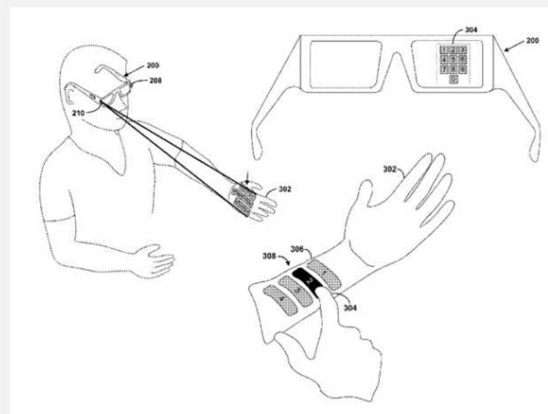
LD has improved directionality







Laser diode micro-projectors



Google dreams up tiny laser projection system to control Project Glass

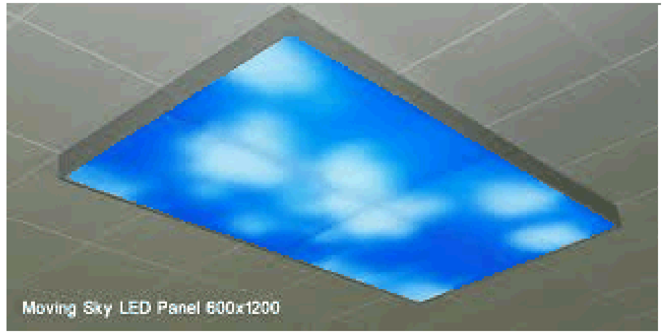
By Sharif Sakr posted Jan 17th, 2013 at 8:09 AM 122

- Probably many other applications for directed light.
- For example it could enable novel luminaries.

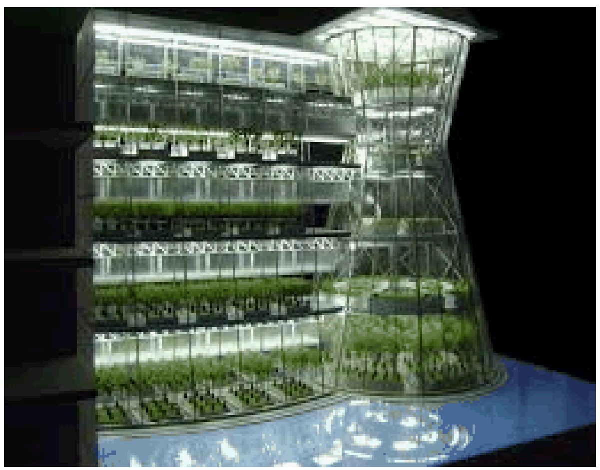
Smart lighting

"2nd Wave Lighting: Smart and Feature Rich

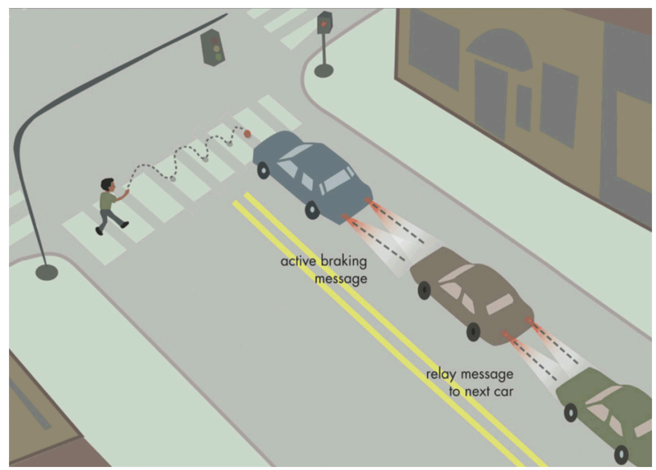
Integrated Illumination and Displays



Human Health, Well Being and Productivity



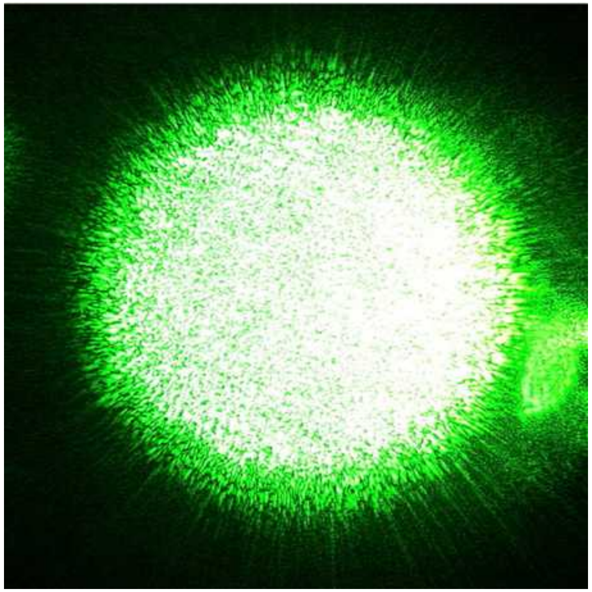
Agriculture



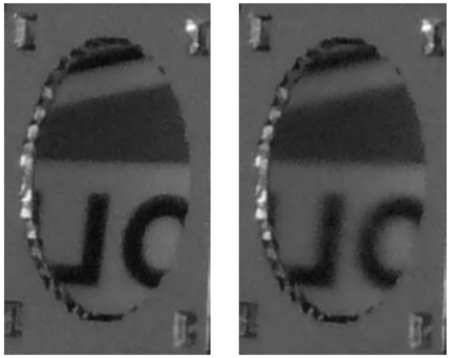
Communication

Light-Field Mapping

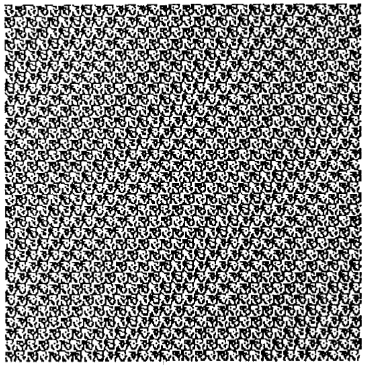
Speckle



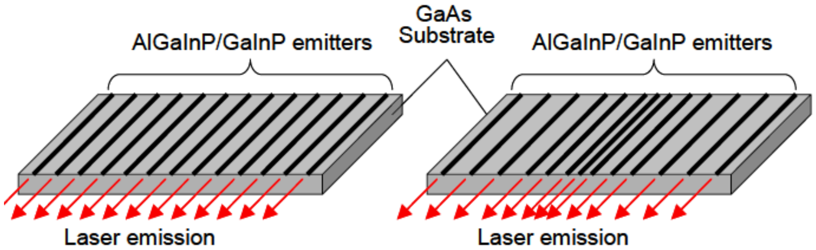
Deformable mirror



Diffractive optical elements



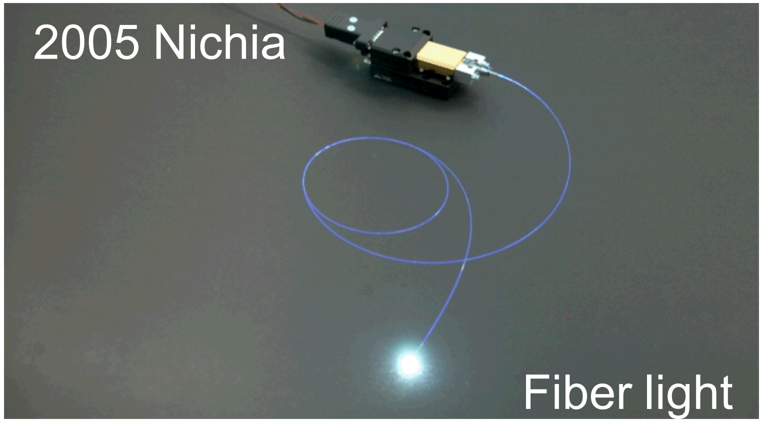
Arrays of different lasers

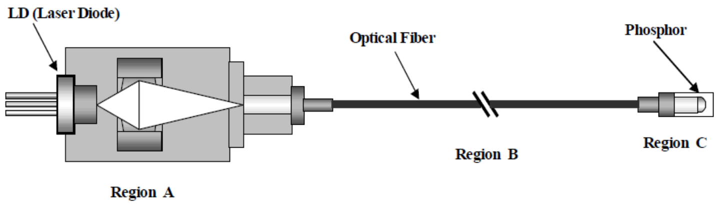


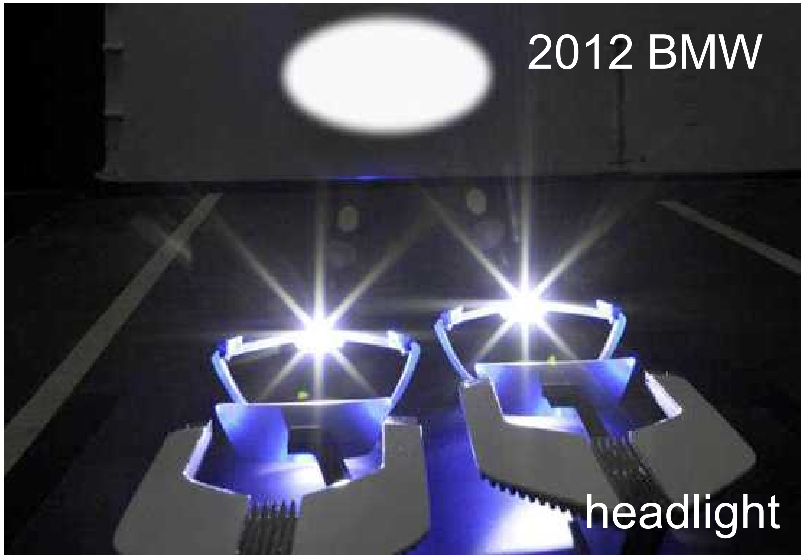
(a) Standard (evenly spaced) (b) Modified (unevenly spaced)

- Solutions consist of modulating the laser light in space or frequency.

LD white examples

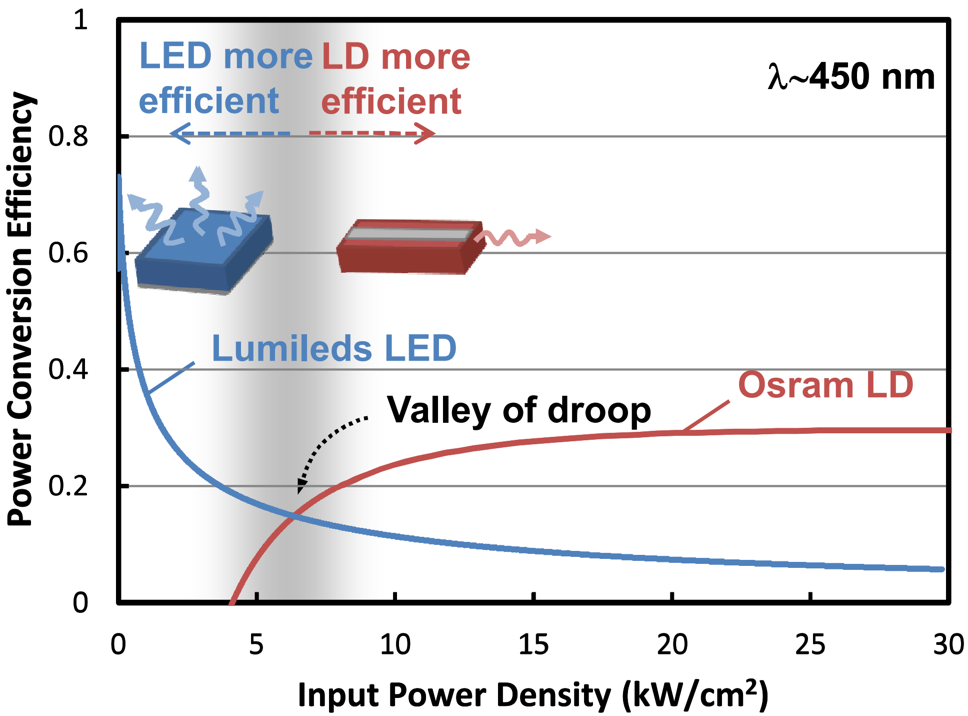


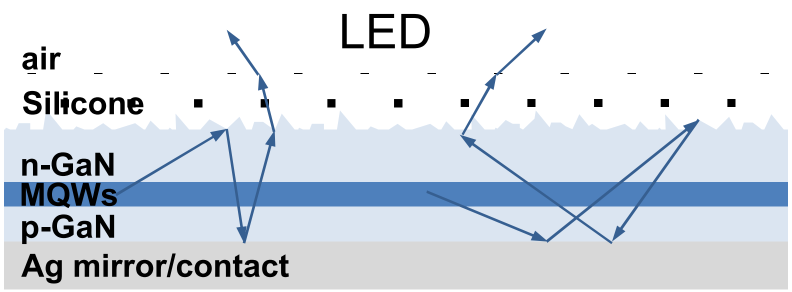


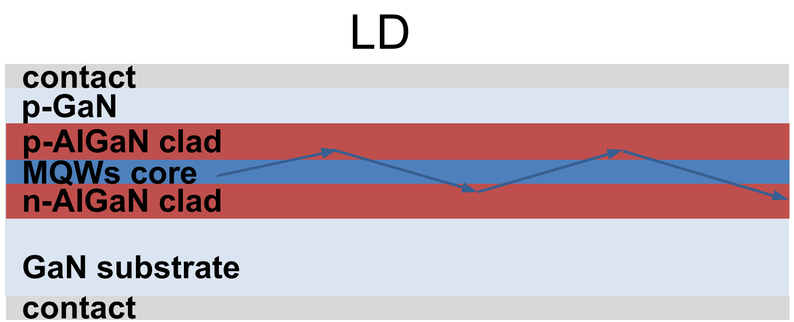


Efficiency and cost comparison of LEDs and LDs

III-nitride LEDs vs. laser diodes (LDs)







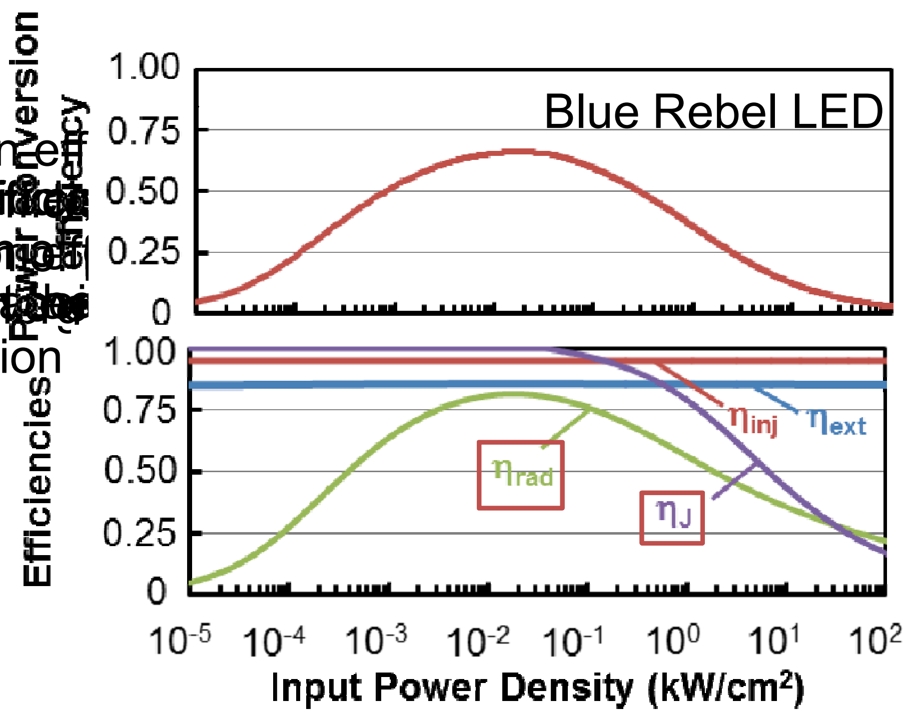
- After threshold LDs are not affected by efficiency droop.
- LDs are more efficient at higher input power densities.

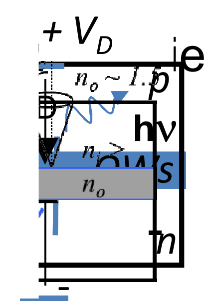
The LED is the ultimate lamp

… but a III-nitride LED is not perfect.

Power conversion efficiency=Power out/Power in =100%

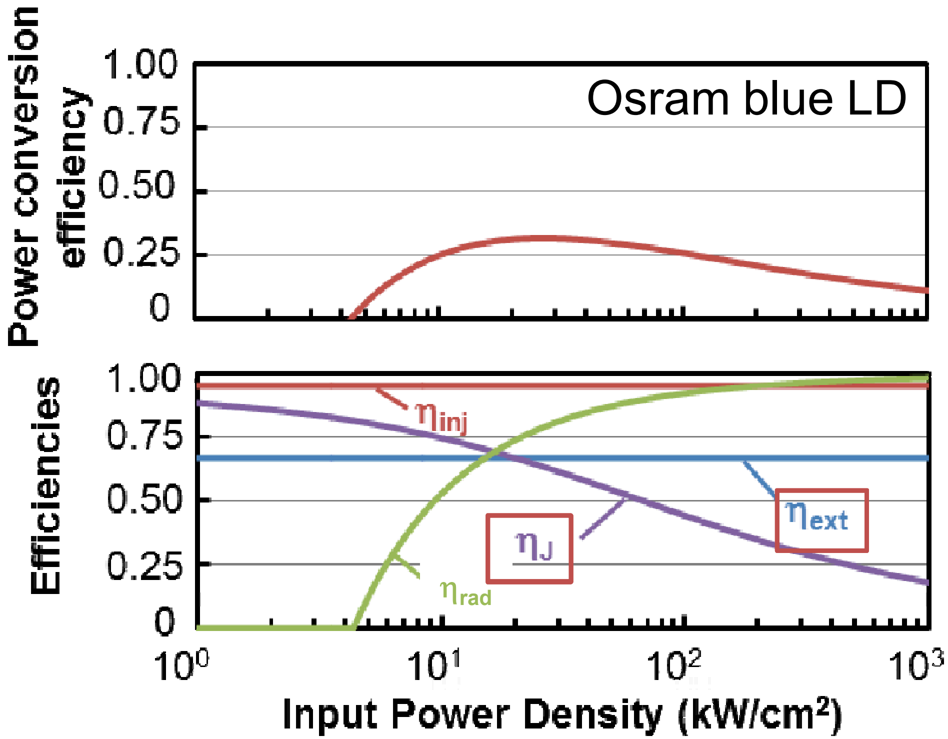
- Power conversion ef… iencies:
  - 1)
  - 2) Fraction of
  - 3)
  - 4) Extraction



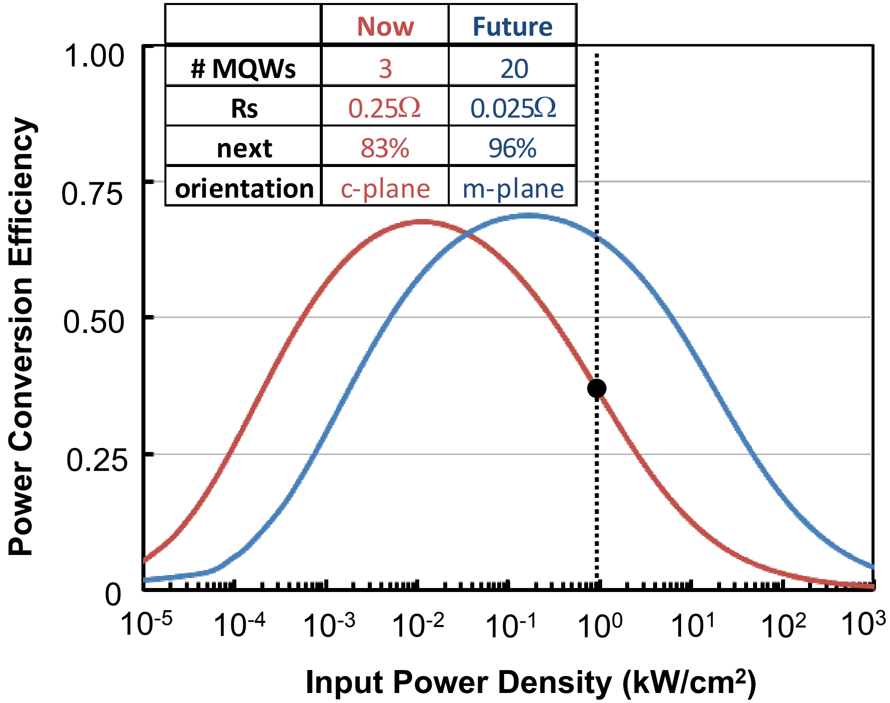


LD efficiency deficiencies

Power conversion efficiency = $\eta_J \eta_{inj} \eta_{rad} \eta_{ext}$

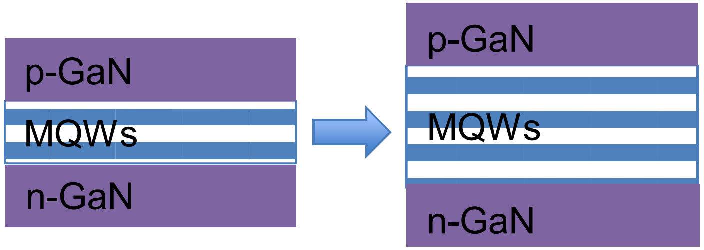


Future Efficiency of LEDs and LDs

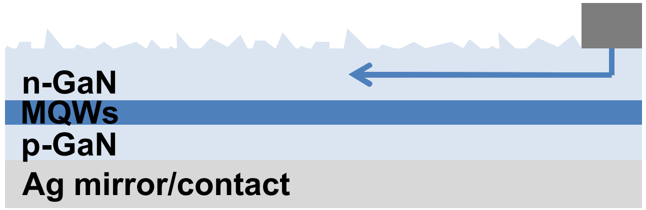


	Now	Future
# MQWs	3	20
Rs	0.25Ω	0.025Ω
next	83%	96%
orientation	c-plane	m-plane

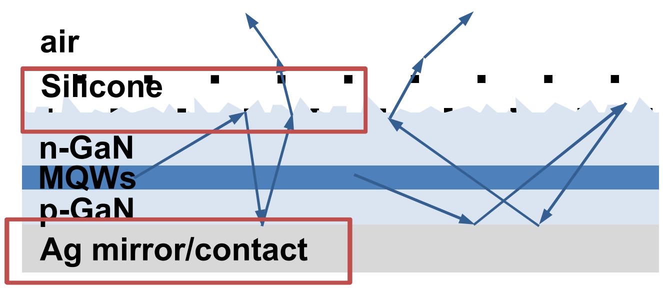
1. Increased active layer thickness:



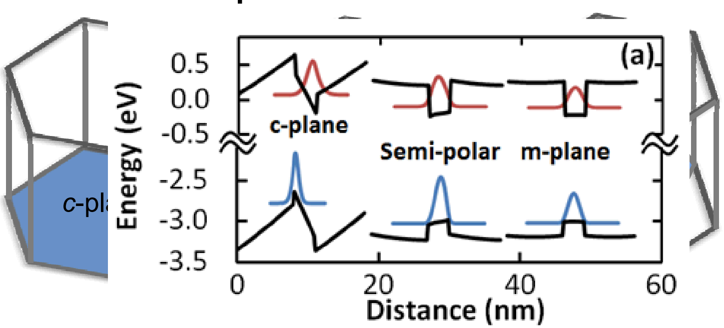
2. Reduced series resistance:



3. Increased extraction efficiency:

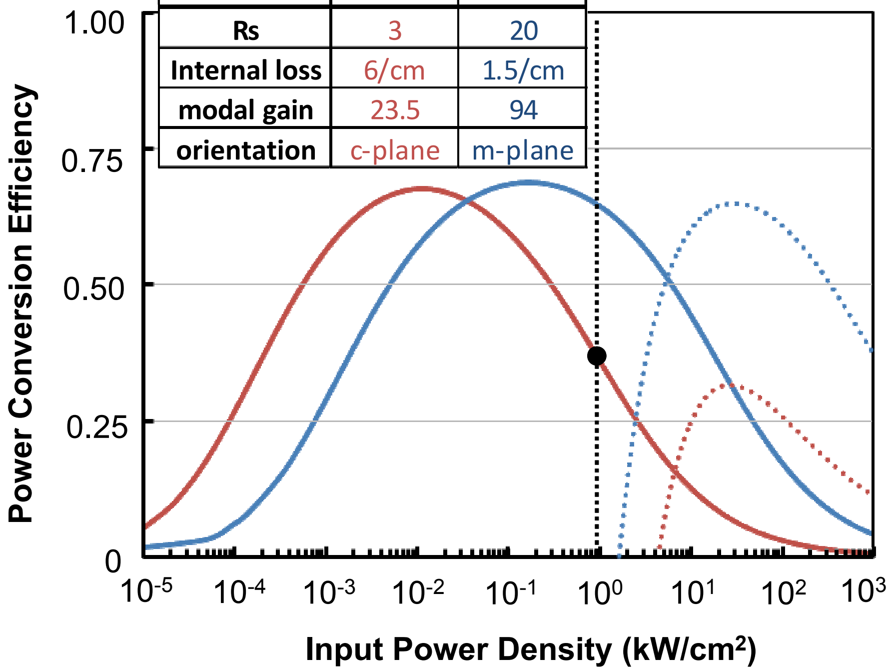


4. Non-c-plane orientations:

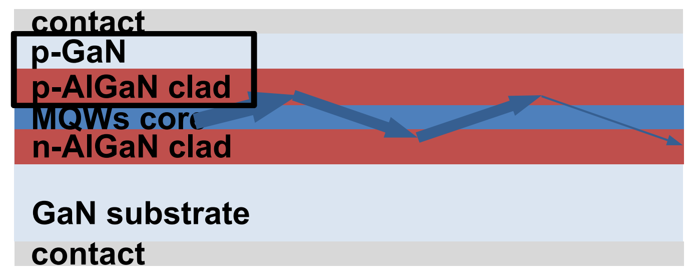


Future Efficiency of LEDs and LDs

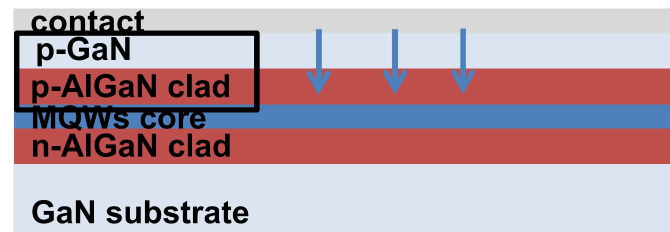
	Now	Future
Rs	3	20
Internal loss	6/cm	1.5/cm
modal gain	23.5	94
orientation	c-plane	m-plane



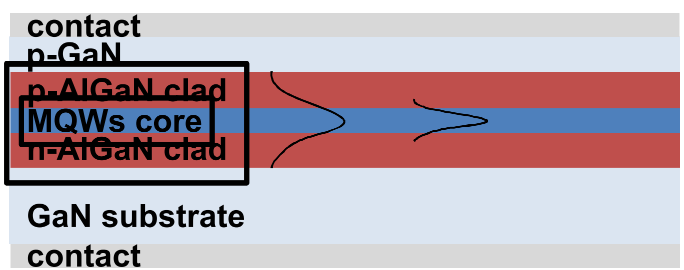
1. Decreasing optical loss:



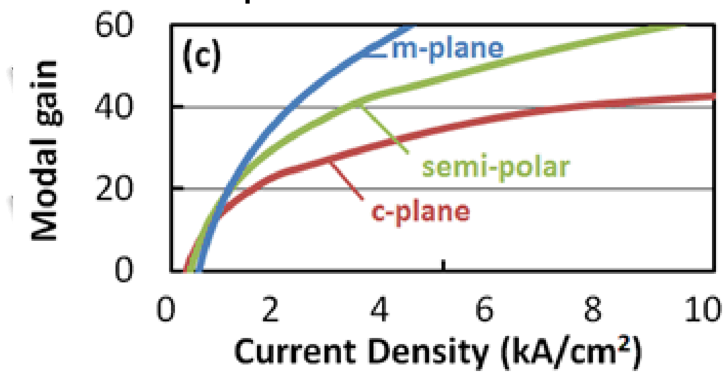
2. Reduced series resistance:



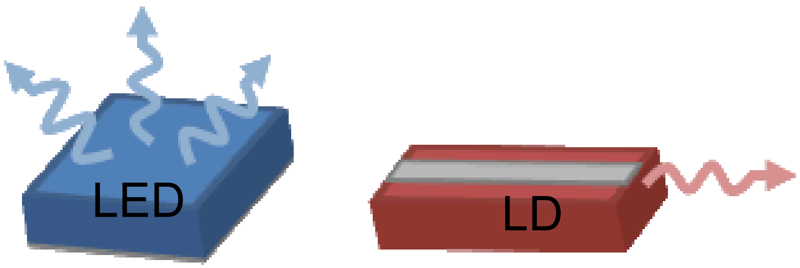
3. Increasing modal gain:

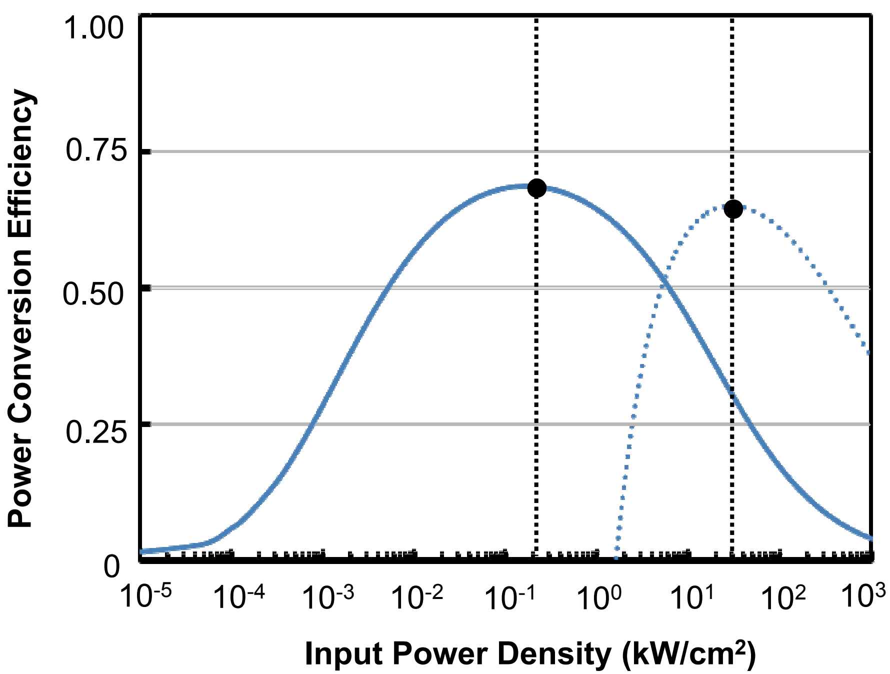


4. Non-c-plane orientations:



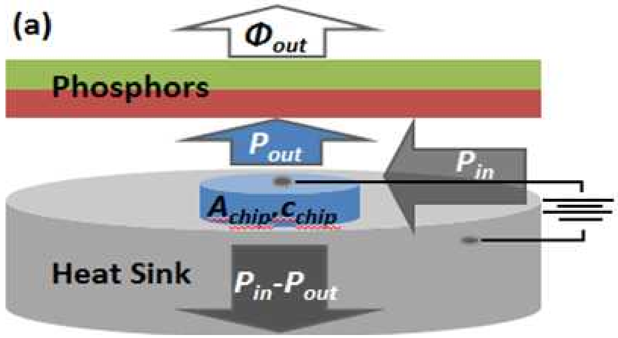
Economics of LEDs and LDs



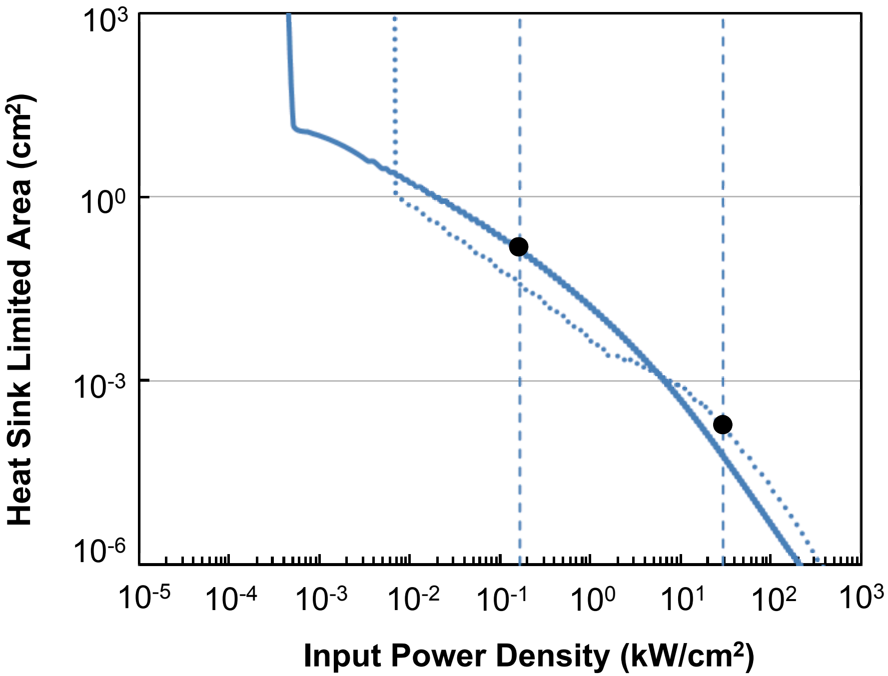


- Assume operation is at peak efficiency.
- Input power density is different for LEDs and LDs.
- Two different input powers will drive chip size and cost.

Economics of LEDs and LDs



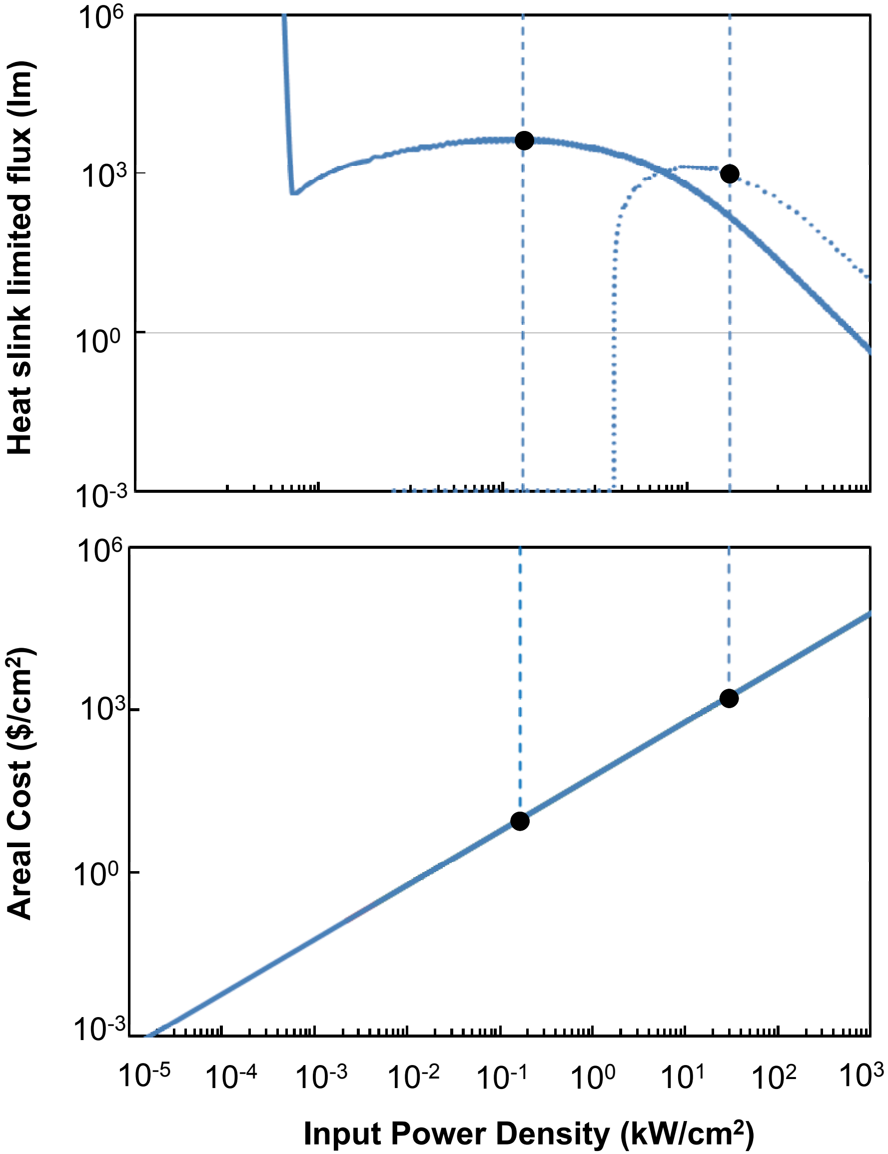
- Assume a simple heat sink geometry.
- Calculate the heat-sink-limited area.



LED~0.14 cm^2 = 0.37cm x 0.37cm

LD~1.6×10^{-4} cm^2 = 16um x 1mm stripe

Economics of LEDs and LDs



- Use the area and efficiency to find the heat sink limited flux.

Two vastly different areal costs.

LED: ~$10/cm^2

LD: ~2000/cm^2

Conclusion

- The LED is over 50 years old and has come a long way!
- Advances in III-nitride materials and device designs have resulted in a remarkable transformation from simple indicators into illumination sources.
- Lasers are interesting because:
  - Efficiency droop is no longer a problem.
  - High efficiency at high input power densities, directionality, and higher LER.
- Despite the higher cost of lasers their high single chip powers make them competitive if improvements can be made.

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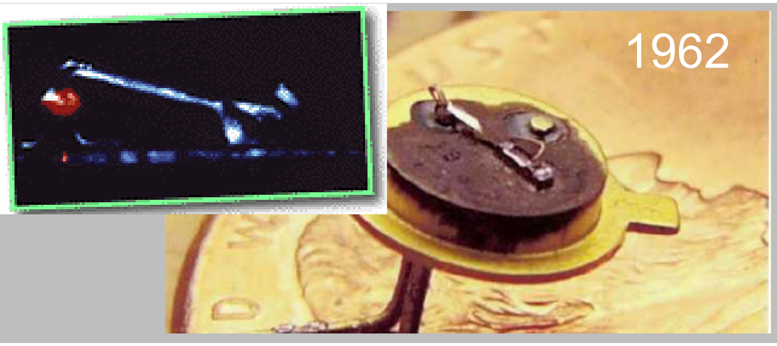
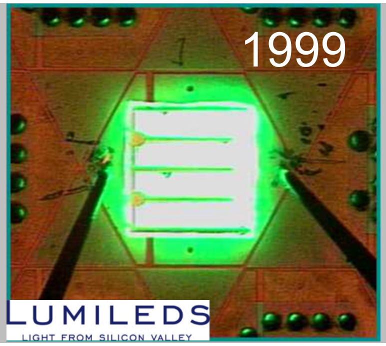
Exceptional service in the national interest

Sandia National Laboratories





Brief history of III-nitrides for SSL: From LEDs to laser diodes?

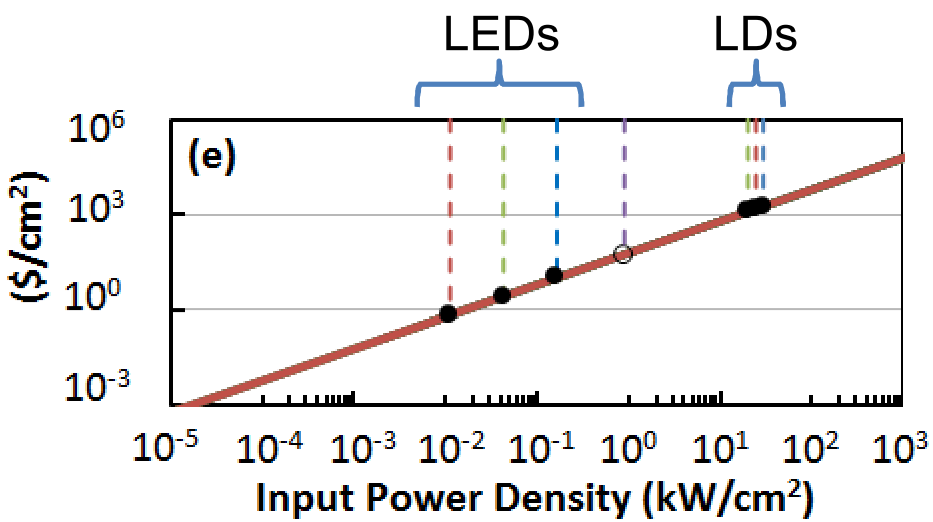
Jonathan J. Wierer, Jr.

SSLS EFRC

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Economics of LEDs and LDs



Two different implications for LDs and LEDs:

1. LD: Chip cost/area can be extremely high ~$1000/cm^2
   Promising result because IR LDs are ~$150/cm^2
   LDs should be cost effective for SSL once improvement are made.

2. LED: To operate at peak efficiency chip cost/area needs to be <$1/cm^2 for current technologies.
   Drives motivation for improved chip technologies.
   Requires 20x reduction over currents costs!
   Clear why we don’t operate at peak efficiency.