LEDs for lighting - the physical and materials basis

LEDs for lighting - the physical and materials basis

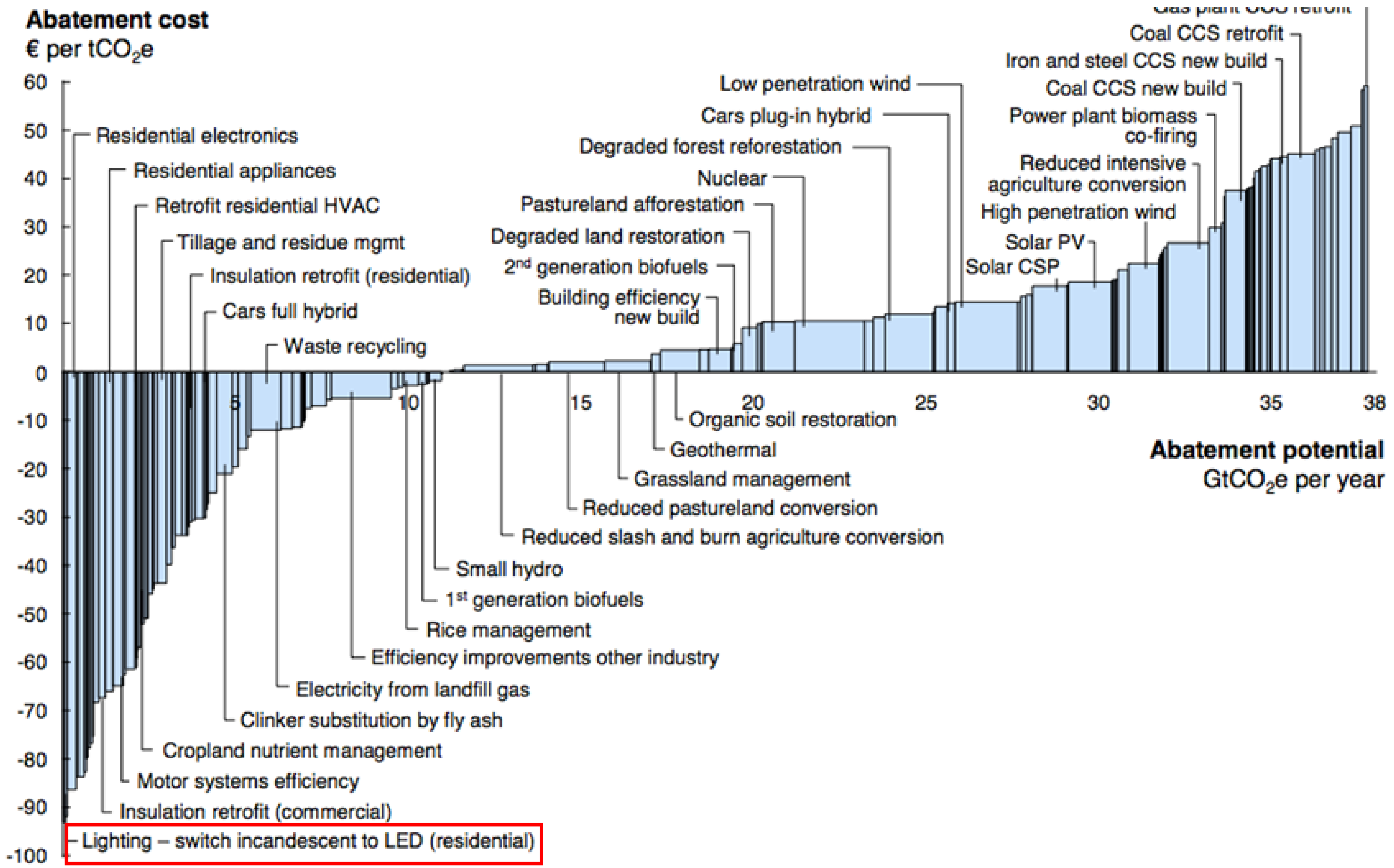
LEDs are a great topic for the international year of light

- The most effective way of saving energy and CO_2 abatment






Comparison of investment costs for technologies diminishing CO_2 emissions



Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per tCO_2e if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

McKinsey & Company | 14

McKinsey Impact of the financial crisis on carbon economy
Version 2.1 of the global greenhouse gas abatment cost curve

LEDs for lighting - the physical and materials basis

LEDs are a great topic for the international year of light

- The most effective way of saving energy and CO_2 abatment

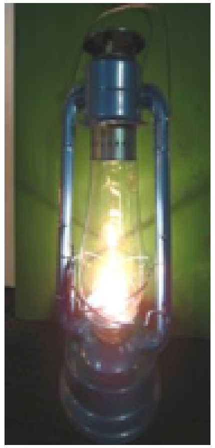
- changes lives for millions

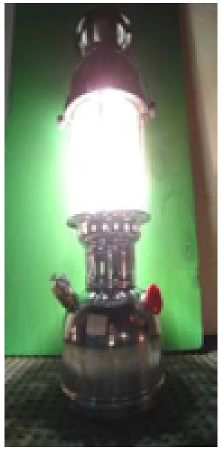






Photo by Evan Mills






Kellie Jo Brown 2012

LEDs for lighting - the physical and materials basis

LEDs are a great topic for the international year of light

-The most effective way of saving energy and CO_2 abatment

- changes lives for millions

- will bring new quality of life

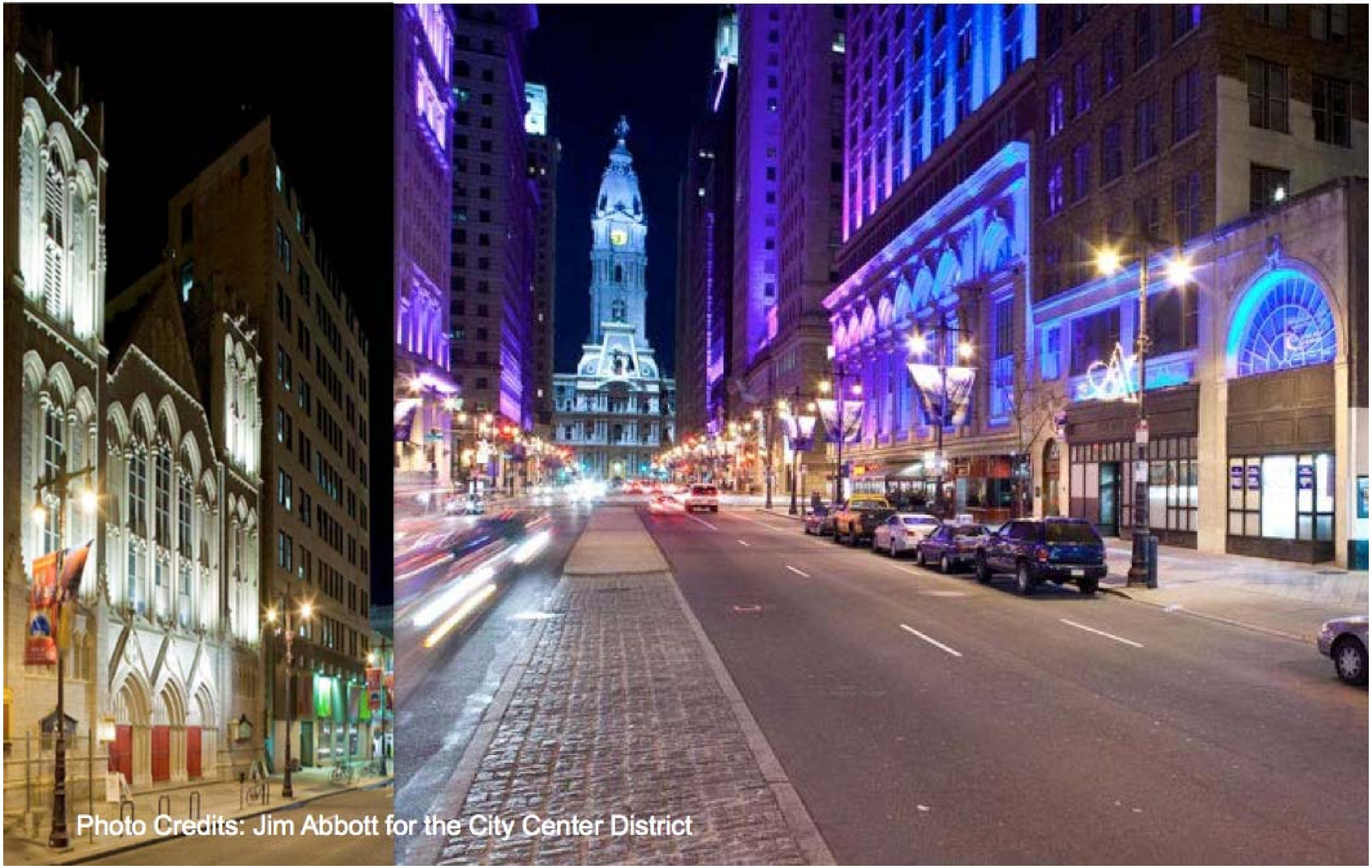
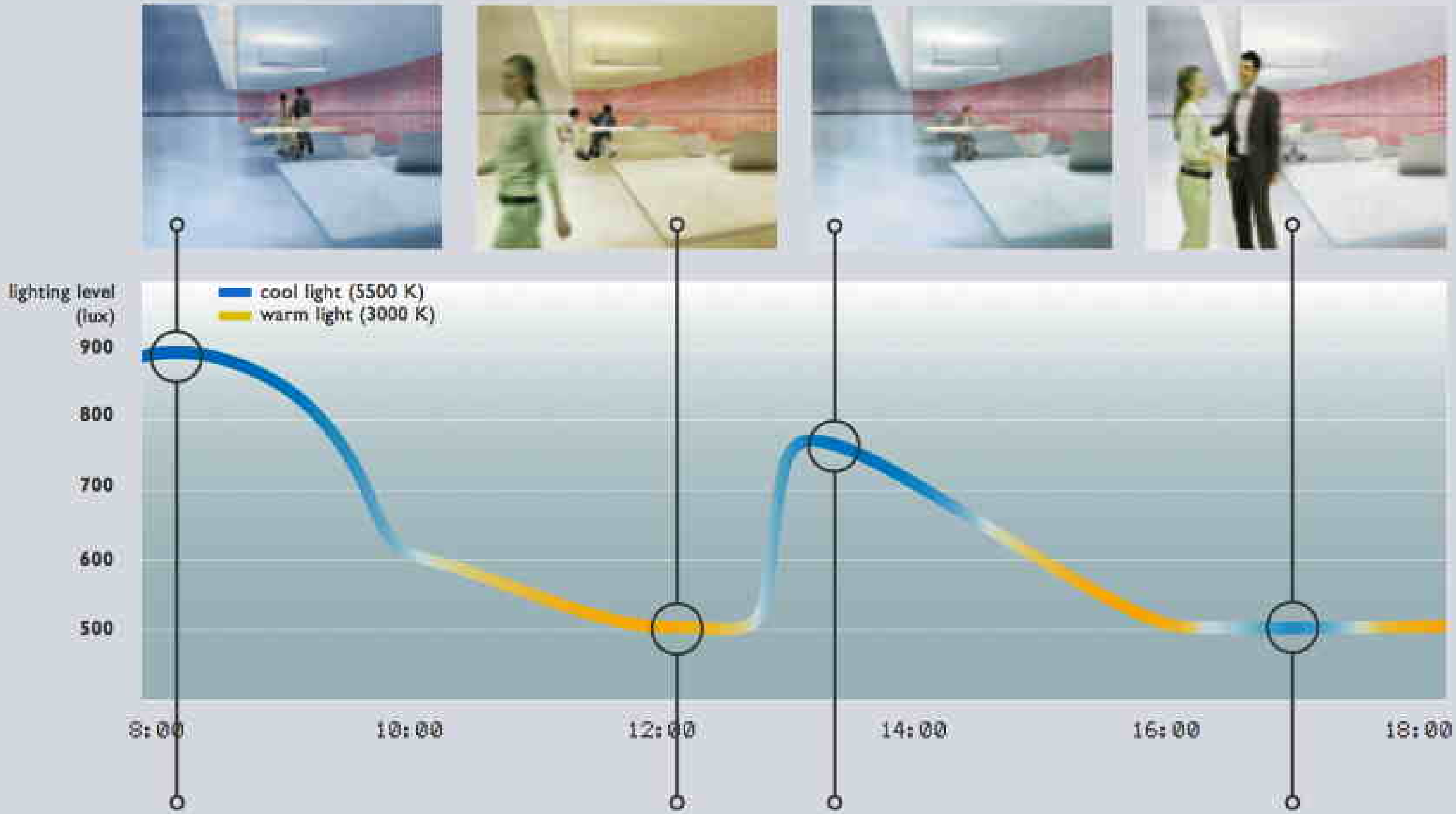


Photo Credits: Jim Abbott for the City Center District

Dynamic Lighting - supporting the natural rhythm of activity

Philips Lighting Application Center



Good morning
Cool, fresh light raises the energy level of people coming into the office and provides a good start to the day.

Lunch time
A short rest helps us to recharge our batteries. The light level decreases and the warm light facilitates relaxation.

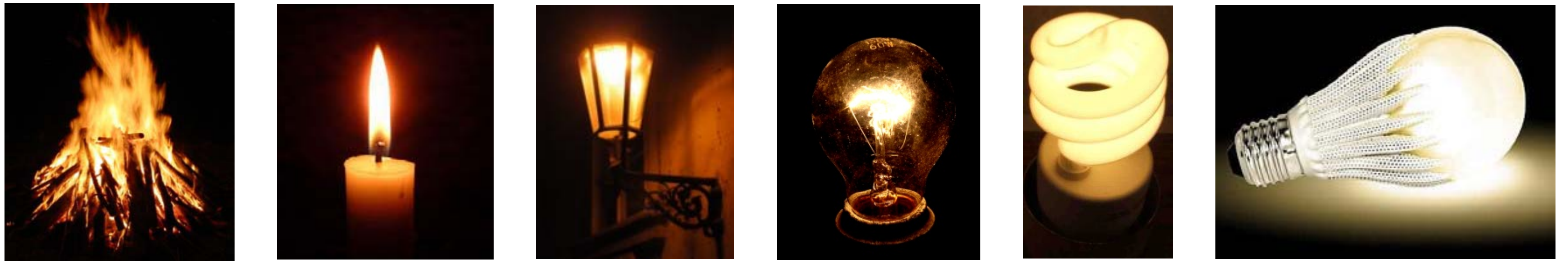
Post-lunch dip
After lunch, we usually feel sleepy. The light level rises again and changes to cool white to counter the 'post-lunch dip'.

Happy hour
Just before the end of the working day, a change to cooler white light provides an alertness boost ahead of the journey home. For people working late, warm white light creates a pleasant, 'homely' atmosphere.

LEDs for lighting - the physical and materials basis

Claude Weisbuch,[1,2]
[1] Materials Department, University of California at Santa Barbara, USA
[2] Laboratoire de Physique de la Matière Condensée, CNRS, Ecole Polytechnique, Palaiseau, France

Profs.: J.S.Speck, S. Nakamura, S. Denbaars



LEDs for lighting - the physical and materials basis

1. Light emitting diodes (LEDs) 101
2. Light sources – it is not just photons and watts - lumens
3. LED Ligthing = Visible LEDs, a long road from red to blue
4. The state of the art - the remaining challenges
5. The impact 1 energy savings
6. The impact 2 bringing safe and cheap light where there is none
7. The impact 3 improving quality of light

In just 25 years

Solid State Lighting

Decorative Lighting

Automobile Lighting

Displays

Agriculture

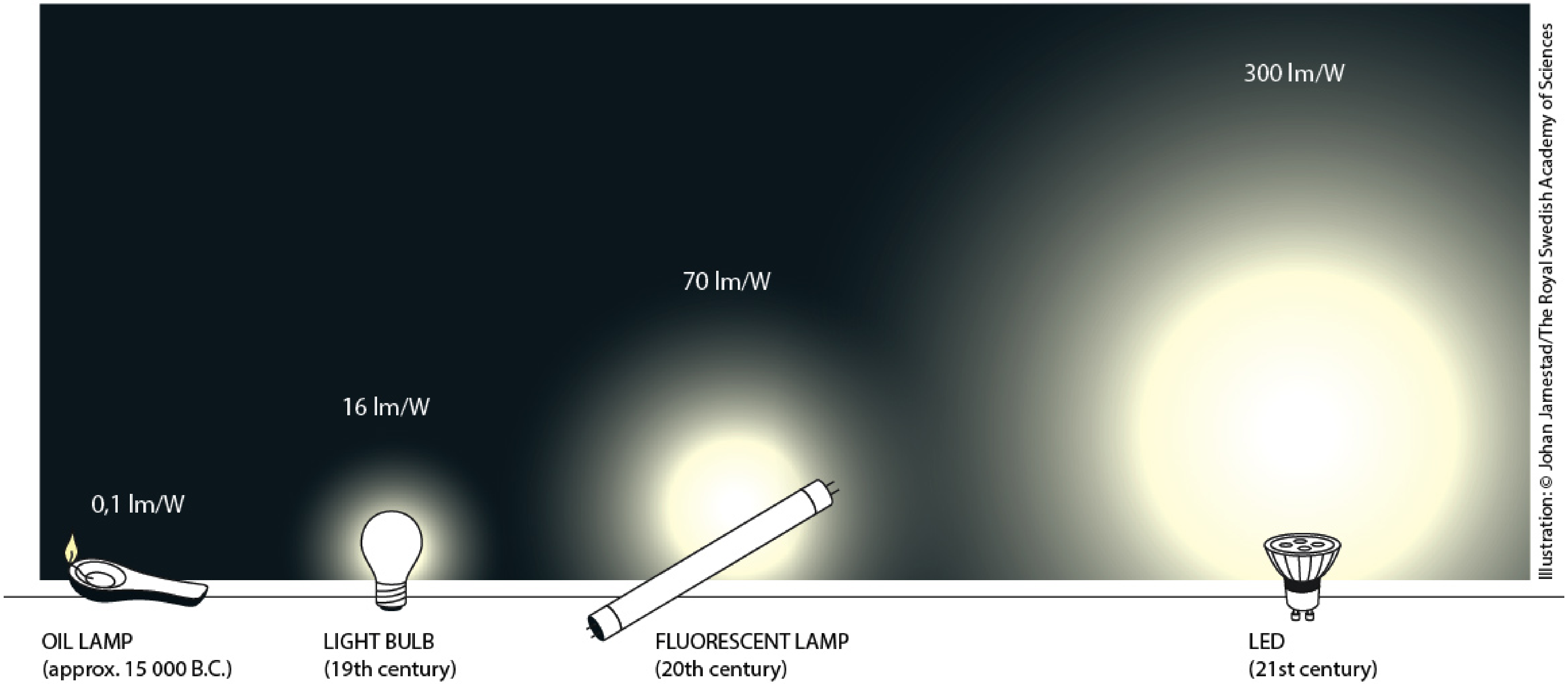
Indoor Lighting

Energy Savings Impact

~ **40 % Electricity Savings (261 TWh)** in USA in 2030 due to LEDs

Eliminates the need for **30+** 1000 MW **Power Plants** by 2030

Avoids Generating ~ **185 million tons of CO_2**



Sources: www.nobelprize.org, US Department of Energy

The Nobel Prize in Physics 2014

Isamu Akasaki, Hiroshi Amano, Shuji Nakamura

"for the invention of ***efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources****"*

" … They succeeded where everyone else had failed. Akasaki worked together with Amano at the University of Nagoya, while Nakamura was employed at Nichia Chemicals, a small company in Tokushima. Their inventions were revolutionary. Incandescent light bulbs lit the 20th century; the 21st century will be lit by LED lamps….
LED lamp holds great promise for **increasing the quality of life for over 1.5 billion people around the world who lack access to electricity grids**: due to low power requirements it can be powered by cheap local solar power."

Alfred Nobel's Will

"The whole of my remaining realizable estate shall be dealt with in the following way: the capital, invested in safe securities by my executors, shall constitute a fund, the interest on which shall be annually distributed in the form of prizes to those who, during the preceding year, shall have conferred the greatest benefit on mankind. The said interest shall be divided into five equal parts, which shall be apportioned as follows: one part to the person who shall have made the most important discovery or invention within the field of physics; one part to the person who shall have made the most important chemical discovery or improvement; one part to the person who shall have made the most important discovery within the domain of physiology or medicine; one part to the person who shall have produced in the field of literature the most outstanding work in an ideal direction; and one part to the person who shall have done the most or the best work for fraternity between nations, for the abolition or reduction of standing armies and for the holding and promotion of peace congresses.

to the person who shall have made the most important discovery or invention within the field of **physics**

Invention : something invented as
(1): a product of the imagination; especially : a false conception **(2) : a device, contrivance, or process originated after study and experiment**

Discovery : something seen or learned for the first time : something discovered

Progress in many areas was required

Materials science
Heterogeneous growth
of **device grade material**
Control of dislocations density

Materials engineering
Reliability of strained (susbstrate,mismatched) materials
Compare II Vis

Physics of semiconductors / of devices/ quantum physics
High intensity behaviour (droop) mechanisms ? Auger ?
hole transport - energy barriers, QWs vs DH
Crystal engineering for electric polarization
control – QCSE

Materials science
P doping
Race to green yellow
Incorporation / metallurgy high In

Nanoscience
High efficiency localization In fluctuations? Statistical or compositional?
From atom composition
To energy landscape
QW interfaces

Optics
Light extraction
Rough surfaces and interfaces for ergodic light distribution
Photonic crstals for high efficiency?,
directionality
polarized sources

LEDs for lighting - the physical and materials basis

1. Light emitting diodes (LEDs) 101
   Why LEDS such special sources of light - 100%

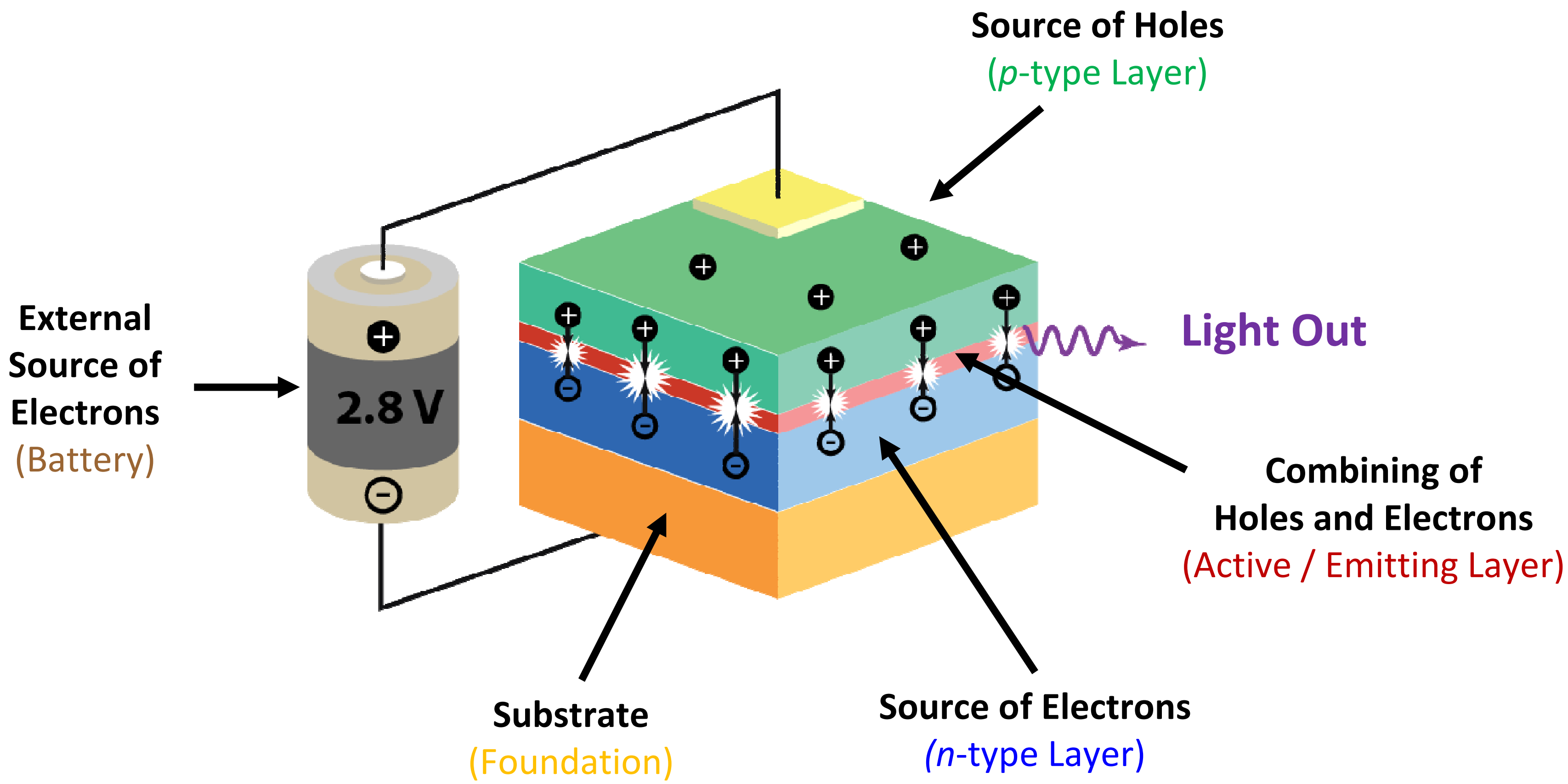
   Wallplug efficiency W_{opt}/W_{elect} WPE, Internal QE, Light Extraction Efficiency LEE
   Injecting electrons and holes p-n junctions

   Homo, hetero QW structures

1. Light sources – it is not just photons and watts
2. Visible LEDs, a long road from red to blue
3. The state of the art - the remaining challenges
4. The impact 1 energy savings
5. The impact 2 bringing safe and cheap light where there is none
6. The impact 3 improving quality of light

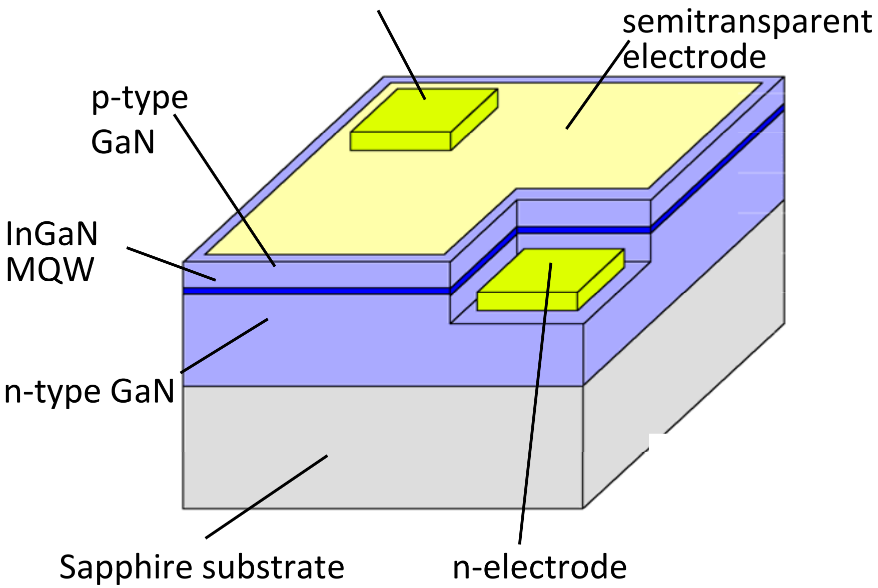
What is a light emititng diode (LED) ?

A Light Emitting Diode (LED) **produces light of a single color** by combining holes and electrons in a semiconductor.

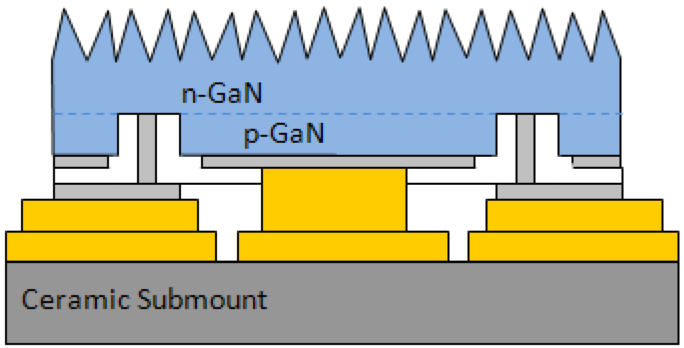


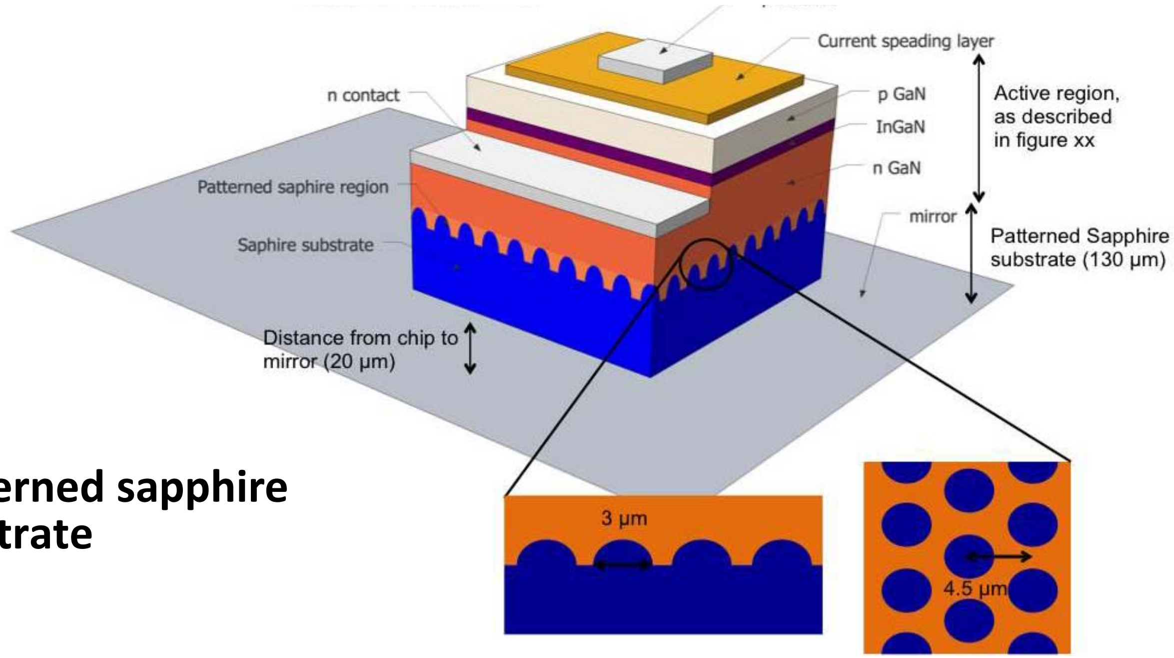
Typical Blue LED Structures on Sapphire

This would have a poor
Photon extraction efficiency



Roughened surface





Patterned sapphire substrate

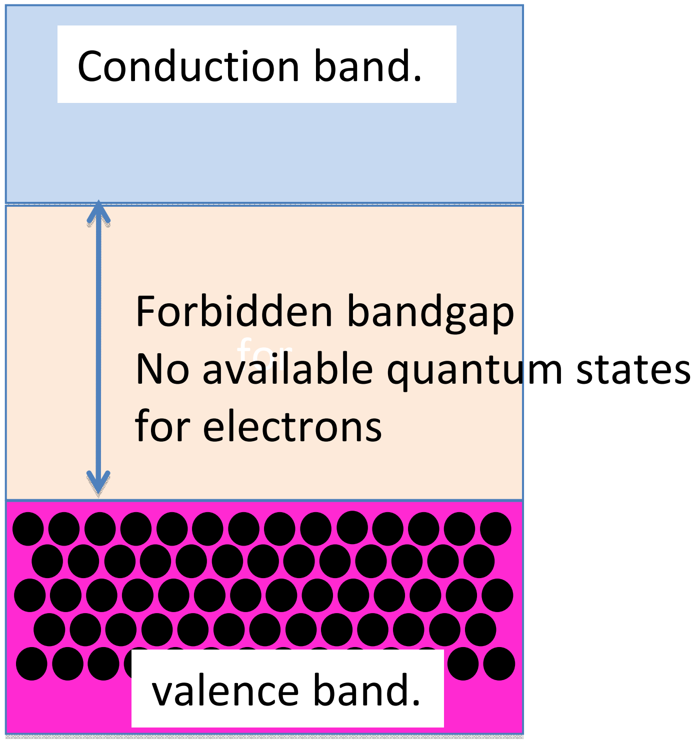
Semiconductors: electrons, holes, band structures

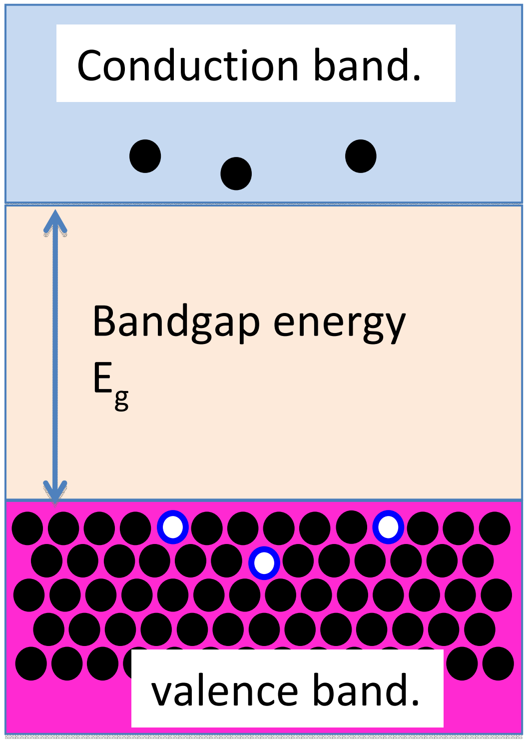
Semiconductor are materials where electrons fill completely the available energy levels in the valence band. The next energy band, the conduction band, is empty of electrons.

Under normal conditions a semiconductor does not conduct electricity, or it does it "poorly".

At finite temperatures some electrons are excited from the valence band to the conduction band, leaving behind them a hole.

Both the electrons in the conduction band and the holes in the valence band can be accelerated and conduct electricity.





Semiconductors: obtaining free electrons, holes by doping

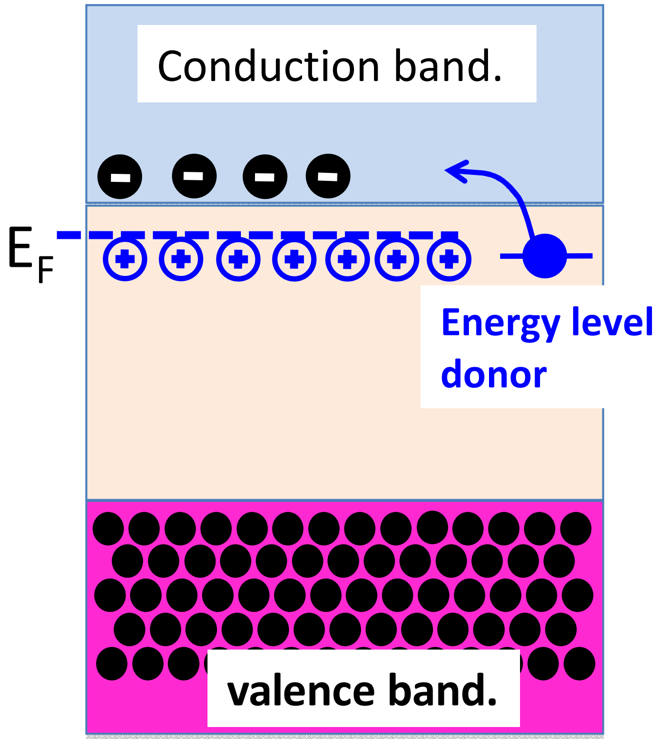
Semiconductor can be made conductive by doping them with active impurities

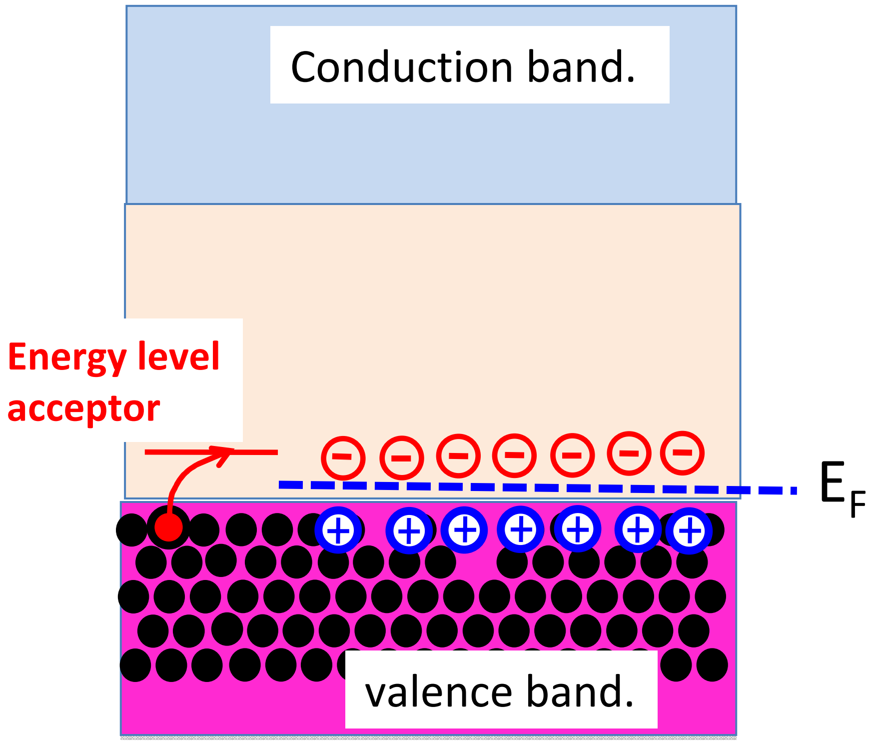
Donor impurities release electrons in the conduction band

n-type semiconductor

Acceptor impurities capture electrons from the valence band, thus releasing a hole in the valence band

p-type semiconductor



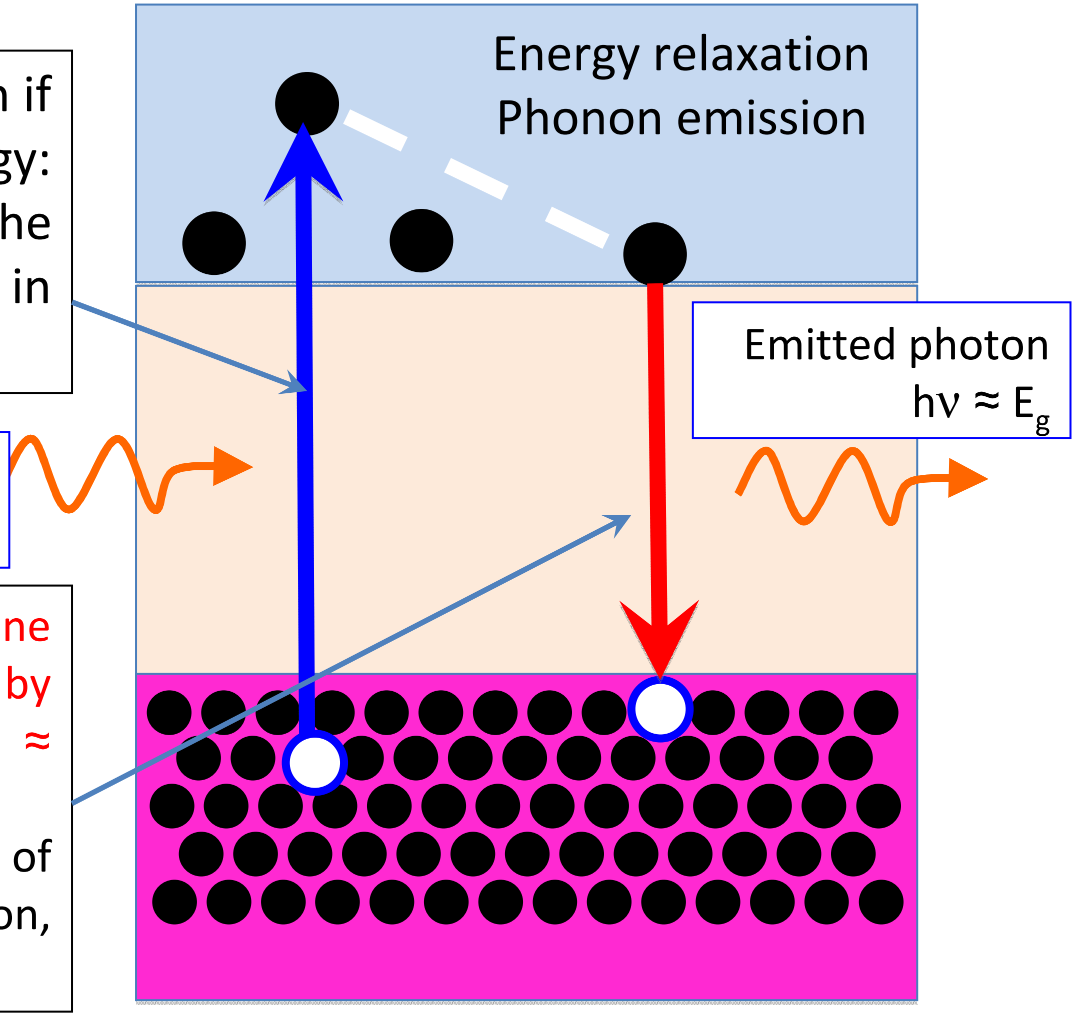


Semiconductors are the only materials where conductivity is chemically controlled by doping

Semiconductors and Light: absorption and recombination

Semiconductor can absorb a photon if its energy is greater than gap energy: it creates a free electron in the conduction band and a free hole in the valence band

Incident photon
$h\nu > E_g$



A conduction electron can recombine with a hole in the valence band by emitting a photon with energy ≈ bandgap E_g

A direct macroscopic measurement of a quantum mechanical phenomenon, the bandgap

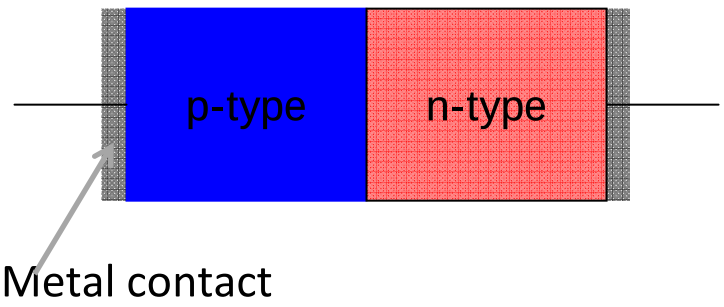
- Electrons and holes emit light by recombining together

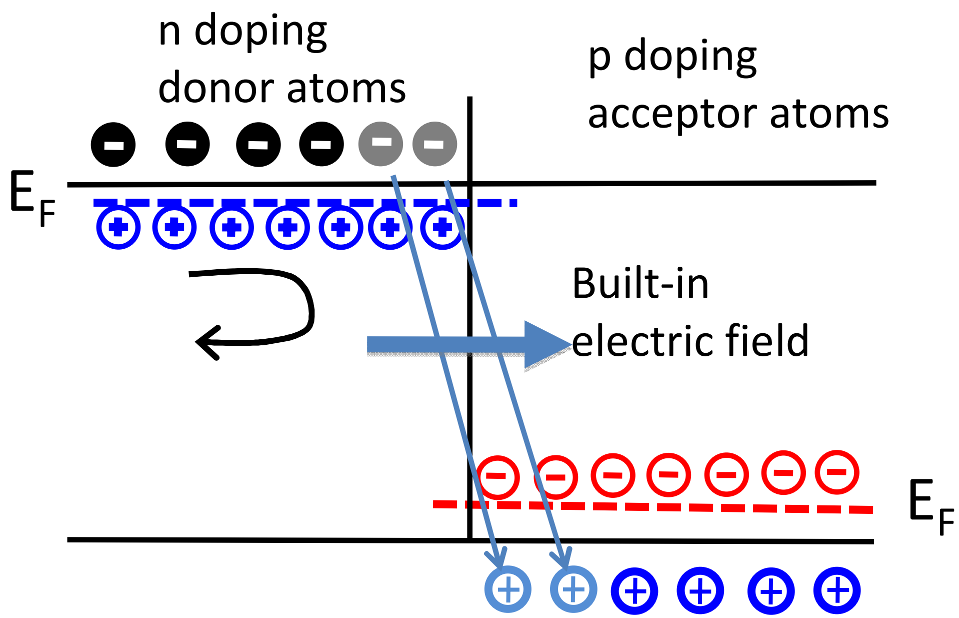
- How to obtain electrons and holes in a semiconductor?

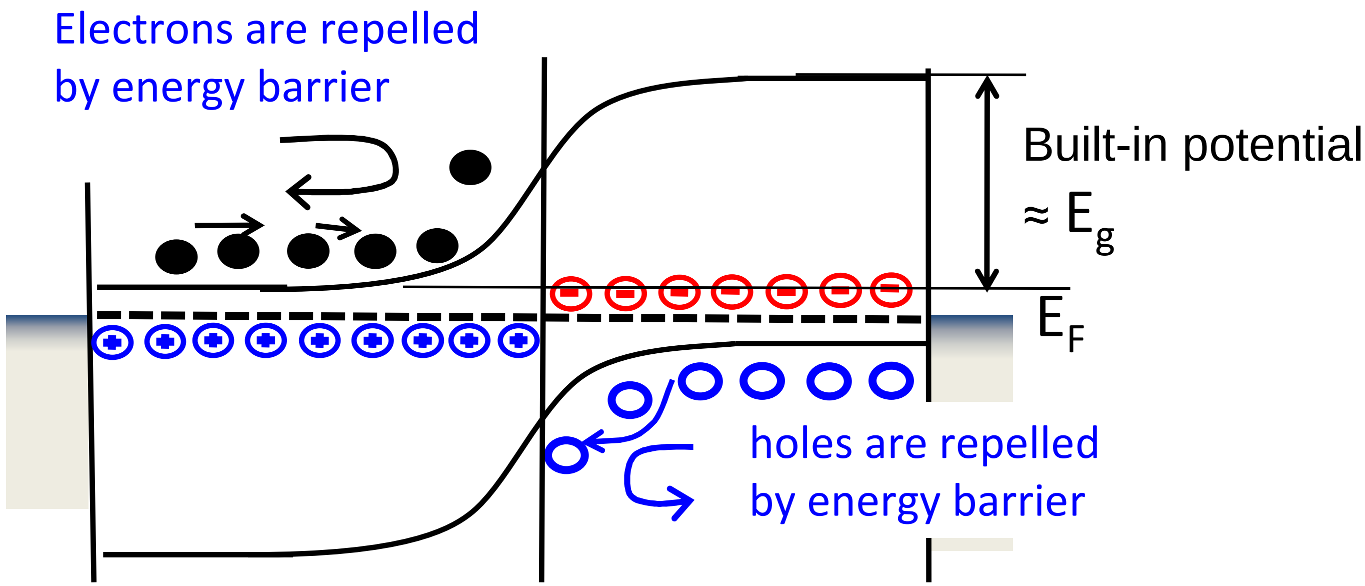
- Carrier injection in a p – n junction

Brief background on semiconductors: the p-n junction

Two regions of semiconductor doped with donors or acceptors

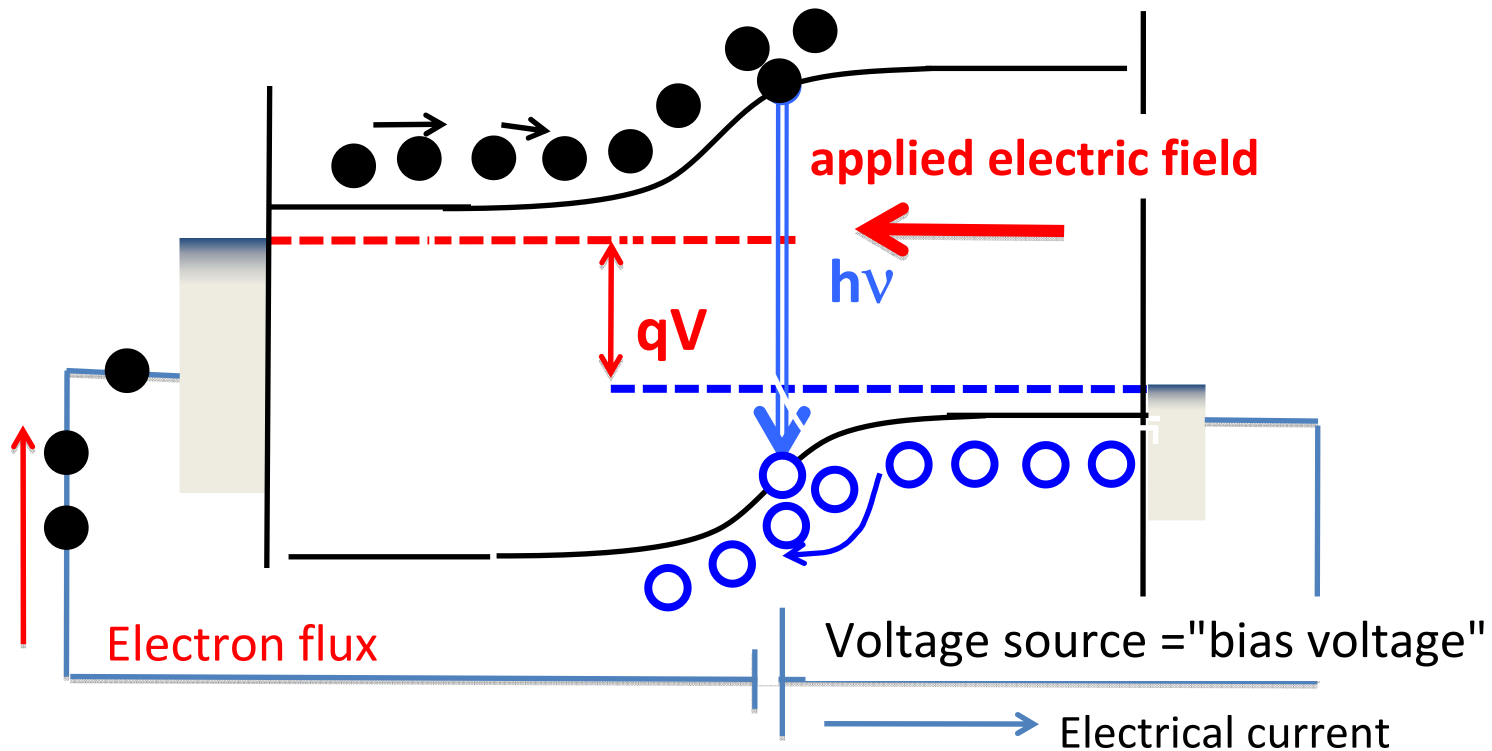






An LED is a semiconductor p-n junction… which emits light under forward bias voltage

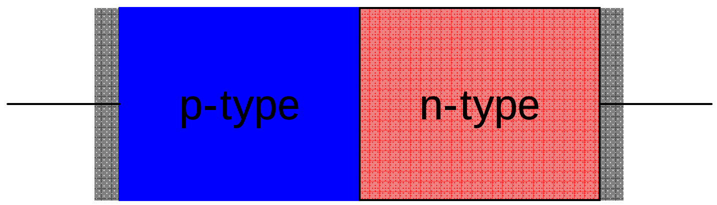
Positive charges (holes) and negative charges (electrons) are injected from the p and n layers of a p-n junction in the depletion layer where they recombine by transforming their energy difference as photons with an energy characteristic of the forbidden bandgap of the semiconductor



At strong bias, "flat band potential", V applied ≈ V_{bi} ≈ E_g bandgap

Photons have the energy of a recombining pair hν ≈ E_g bandgap

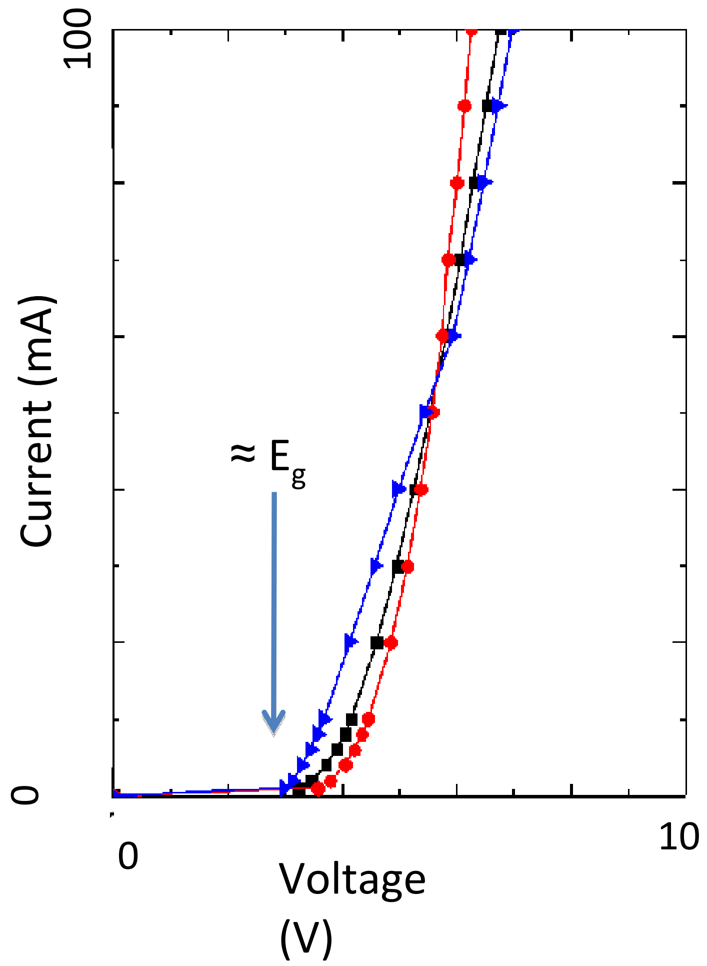
Current voltage characteristics of a p-n junction



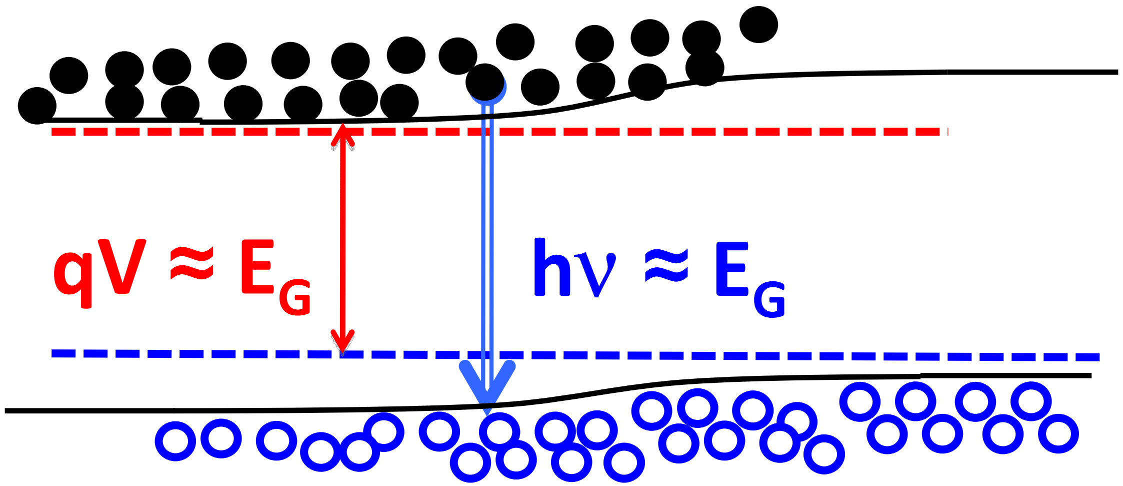
The voltage V_{onset} at which "significant" current appears is such that

$$eV_{onset} = E_G$$

A direct macroscopic measurement of a quantum mechanical phenomenon, the bandgap!



Principle of operation of LEDs at strong bias



Strong bias, "flat band potential"
V applied ≈ V_{bi} ≈ E_g bandgap

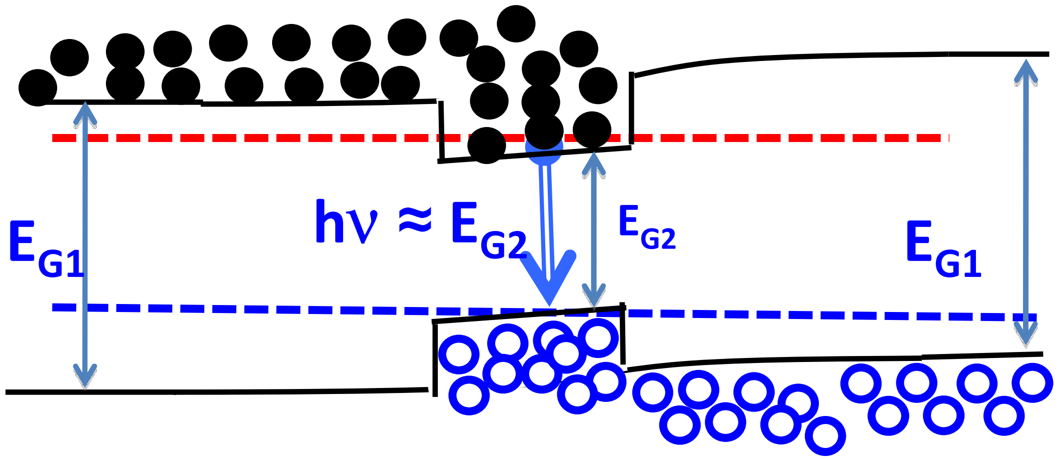
Carriers are distributed along a carrier diffusion length thickness

Carrier density is too small to have good recombination probability' proportional to carreir densities

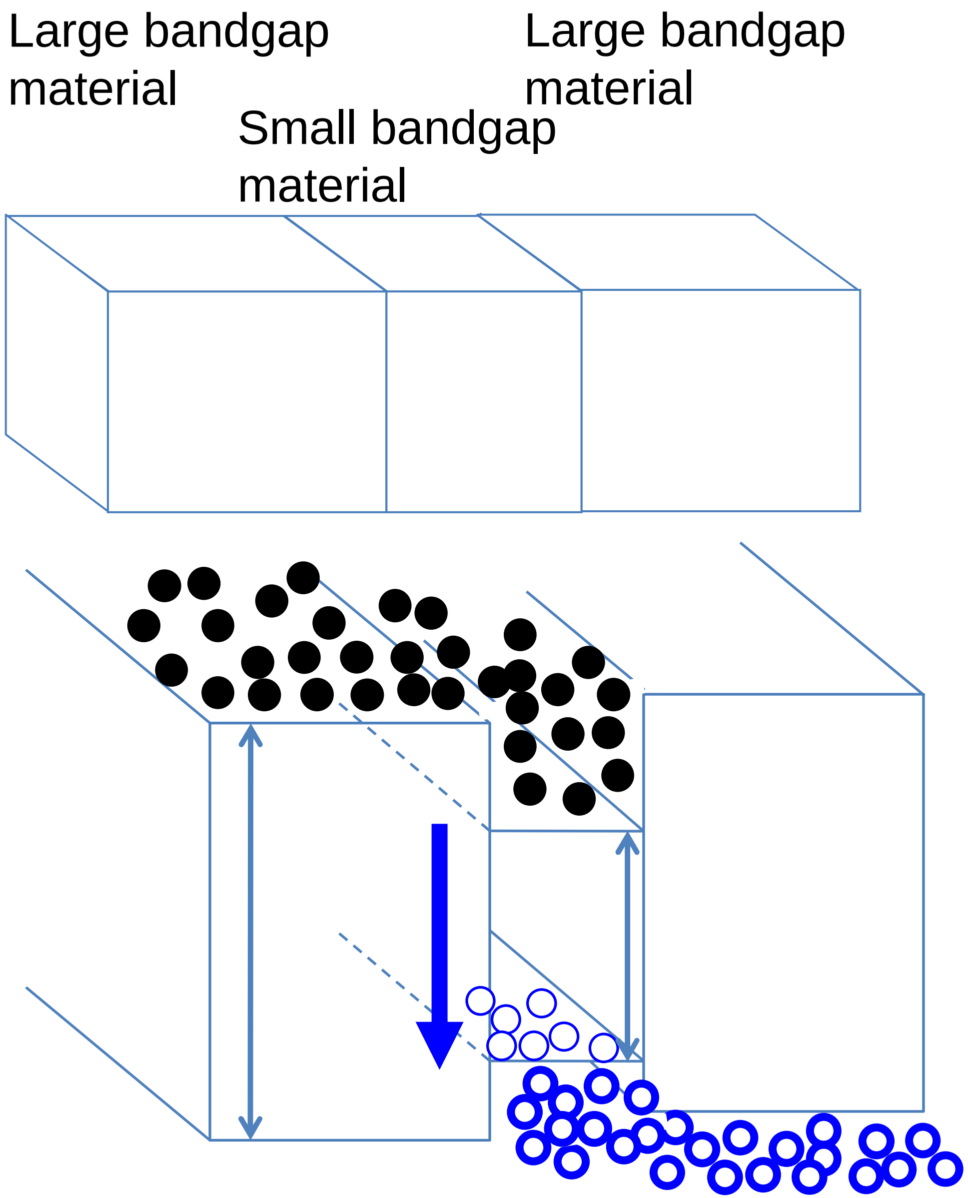
Need to concentrate carriers
=> Use double heterostructures

So far, only one semiconductor, with spatially different dopings
"homostructures"

Now, semiconductors with different chemical compositions
"Heterostructures" – "double" because sandwich

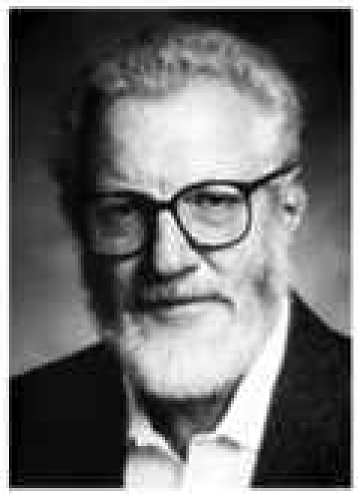


Heroes of semiconductor light emitters: the heterostructures

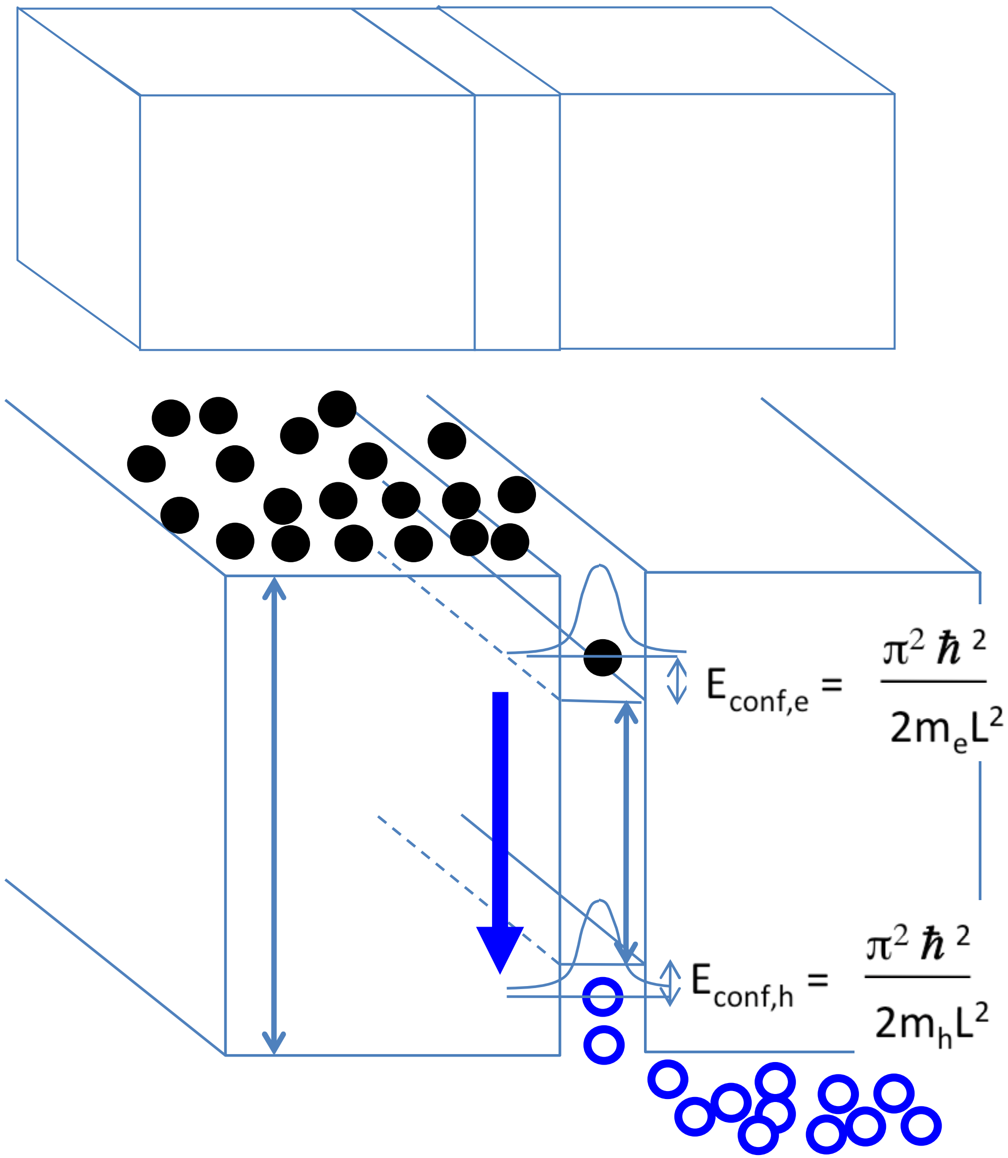


The Nobel Prize in Physics 2000

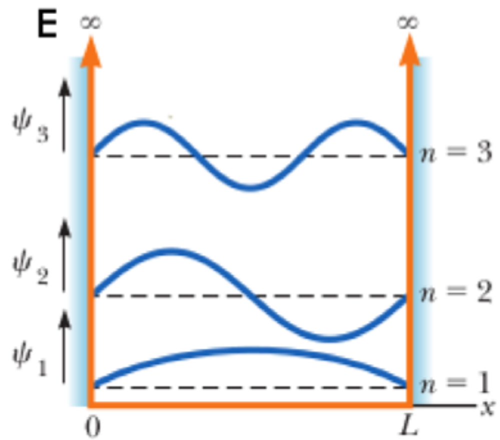
Zhores I. Alferov and **Herbert Kroemer**
"for developing semiconductor heterostructures used in high-speed- and opto-electronics"



The next (smaller) step: quantum wells still better LEDs, better lasers



Infinite well approximation



$$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi(x) = E\cdot\psi(x)$$

$$\psi_n(x) = \sin\left(\frac{n\pi}{L}x\right)$$

$$E(n) = \frac{\hbar^2\pi^2}{2mL^2}n^2$$

What makes a p-n junction a good LED

Is any p - n junction a LED? (does it emit light "efficiently", i.e. with a good conversion efficiency of electron-hole pairs to photons)?

Required:

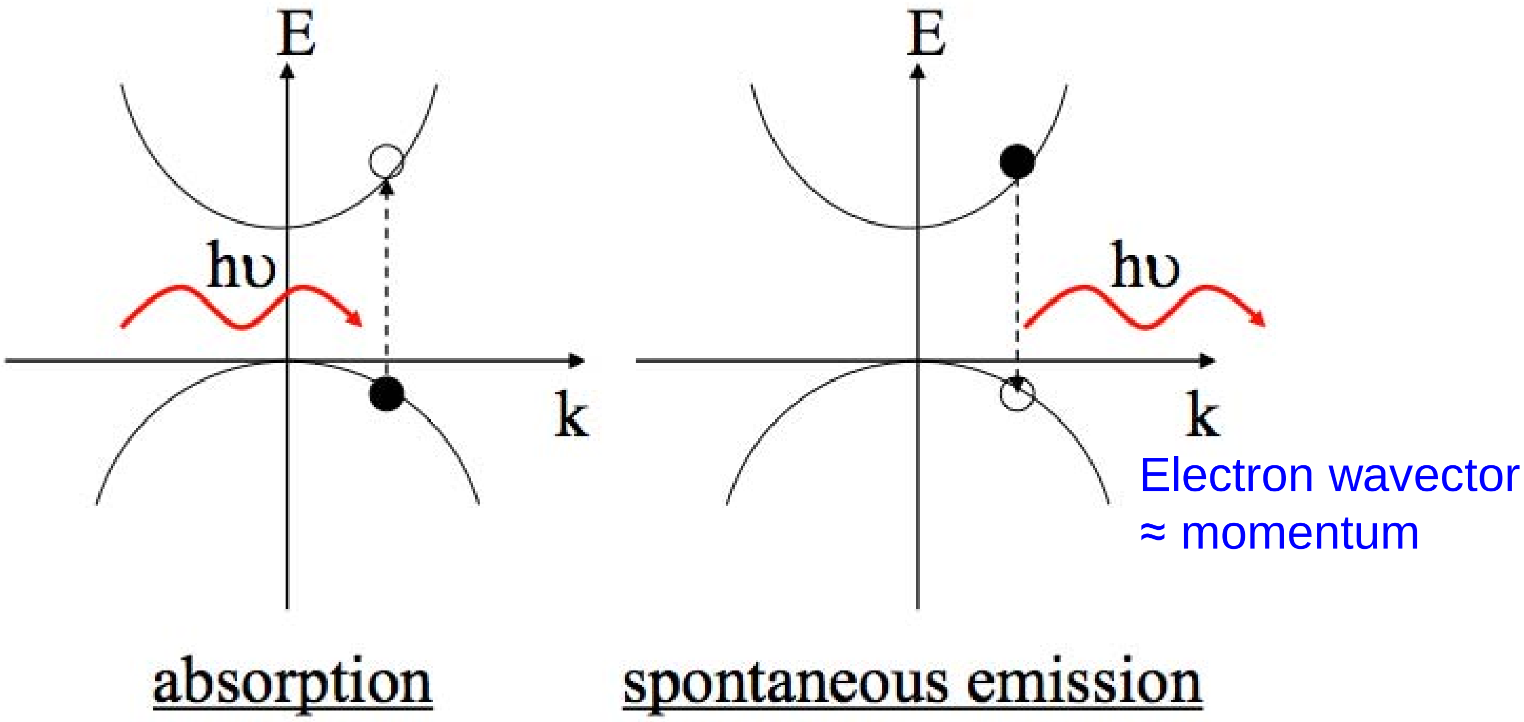
- Direct bandgap

-Low defects density (few non radiative recombination centers)

$\Rightarrow$ Electrons and holes recombine preferentially "radiatively" by emitting a photon instead of recombining "non radiatively" by giving their energy to the lattice

- Double heterostructures possible

Optical transitions are vertical

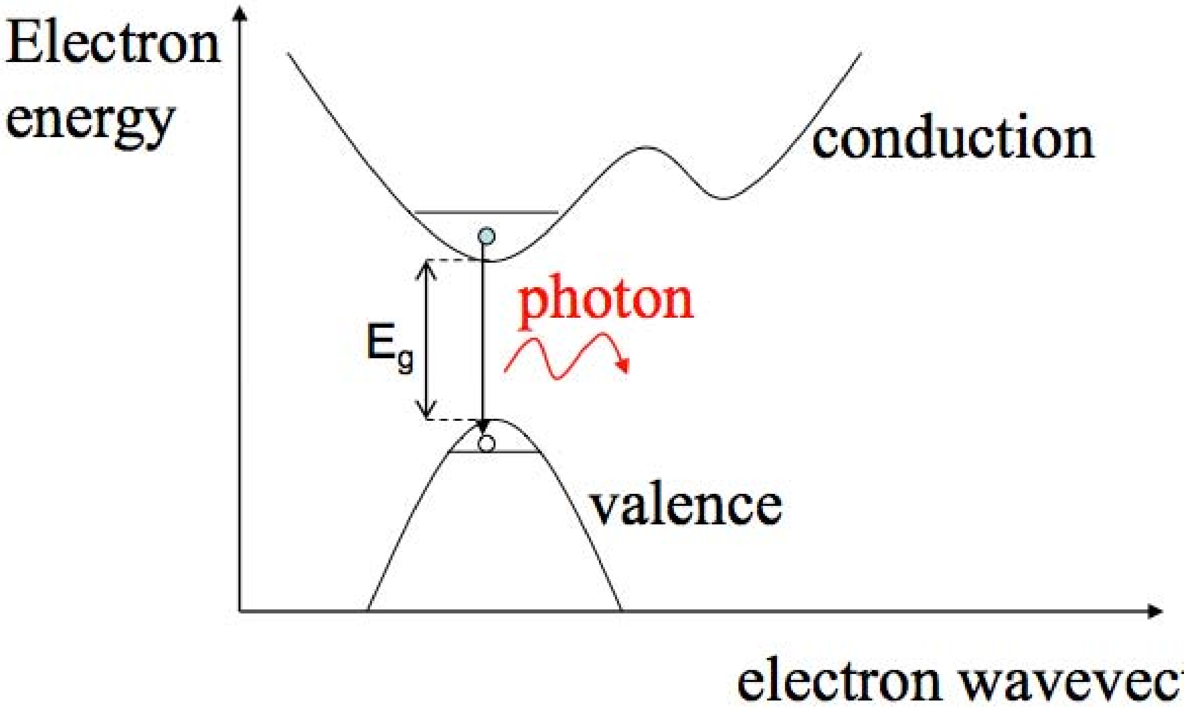


- Optical transitions are "vertical" in the band diagram because the *photon momentum is very small*.
- Electrons and holes ***recombine*** when they *collide* with each other and shed extra energy.
- The electron can lose energy by *photon* emission.

Direct-bandgap semiconductors

- *Electroluminescence* occurs most efficiently in semiconductors that are *direct-bandgap* - electrons and holes on either side of the energy gap have the *same* value of electron wavevector **k**

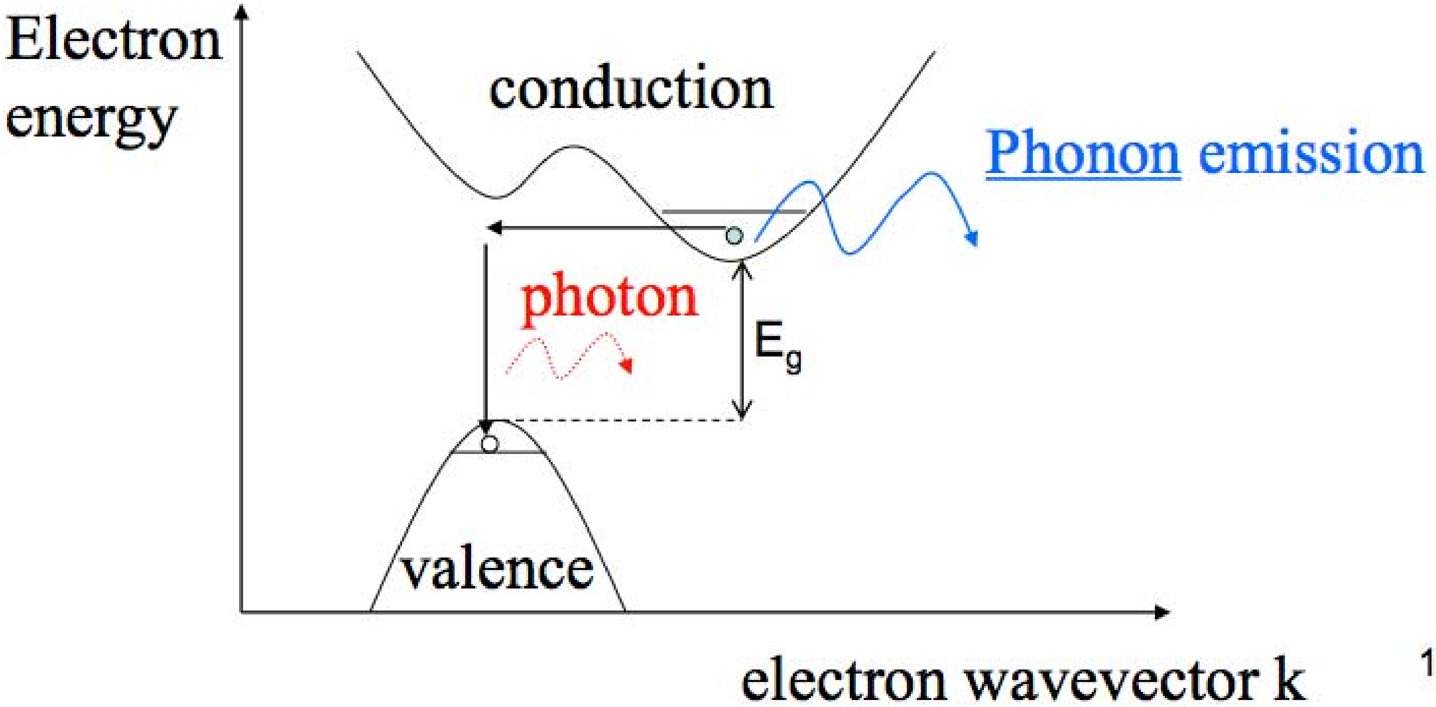
=> ***direct radiative recombination*** is possible



Indirect-bandgap semiconductors

- The maximum energy of the valence band and the minimum energy of the conduction band occur at *different* values of electron wavevector.

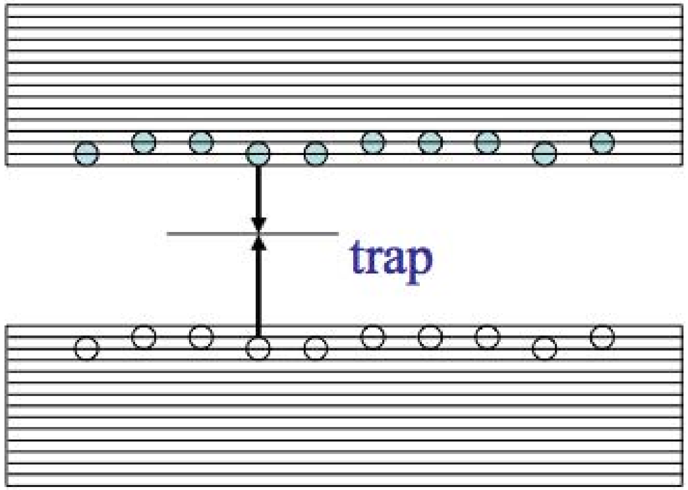
⇒*For electron-hole recombination to occur* it is essential that the electron *loses momentum* such that it has a value of momentum corresponding to the maximum energy of the valence band (*to conserve momentum*).



Nonradiative recombination

• ***Nonradiative recombination*** occurs via a number of independent competing processes including the transfer of energy to *lattice vibrations* (creating one or more *phonons*) or to *another free electron* (Auger process).

• Recombination may also take place at *surfaces*, and indirectly via *"traps" or defect centers*, which are energy levels that *lie within the forbidden band* associated with impurities or defects associated with *grain boundaries*, *dislocations* or other *lattice imperfections*.



*An impurity or defect state can act as a *recombination center* if it is capable of trapping both an electron and a hole. *Impurity-assisted* recombination may be *radiative* or *nonradiative*.

Some direct- and indirect-bandgap semiconductors

material	Bandgap energy (eV)	Recombination coeff. ($cm^3\ s^{-1}$)
GaAs	*Direct*: 1.42	7.21×10^{-10}
InAs	*Direct*: 0.35	8.5×10^{-11}
InSb	*Direct*: 0.18	4.58×10^{-11}
Si	Indirect: 1.12	1.79×10^{-15}
Ge	Indirect: 0.67	5.25×10^{-14}
GaP	Indirect: 2.26	5.37×10^{-14}

**Silicon is not an emitter material, as its holes and electrons do not recombine directly, making it an inefficient emitter.*

In the infrared, we got LEDs and room temperature lasers

1956 – 1980

From 0.8 μm to 1.6 μm

LEDs for lighting - the physical and materials basis

1. Light emitting diodes (LEDs) 101
2. LED for Ligthing– it is not just photons and watts – lumens

   Lumens, Candelas, Lux, etc.

3. LED Ligthing = Visible LEDs, a long road from red to blue
4. The state of the art - the remaining challenges
5. The impact 1 energy savings
6. The impact 2 bringing safe and cheap light where there is none
7. The impact 3 improving quality of light

History of photometric units

- Photograph shows **plumber's candle**
- A plumber's candle emits a **luminous intensity** of 1 candela (cd). The cd is historical origin of all photometric units.

- **First definition** (now obsolete): **The luminous intensity of a standardized candle is 1 cd**.
- **Second definition** (now obsolete): **1 cm^2 of platinum (Pt) at 1042 K (temperature of solidification) has a luminous intensity of 20.17 cd**.
- **Third definition** (current): **A monochromatic light source emitting an optical power of (1/683) Watt at 555 nm into the solid angle of 1 steradian (sr) has a luminous intensity of 1 cd**.
- *Candlepower* and *candle* are obsolete units. *Candlepower* and *candle* measure luminous intensity and are approximately equal to one cd.

Luminous flux, illuminance, and luminance

- **luminous flux**: A light source with a luminous intensity of 1 cd emits a luminous flux of 1 lm into a solid angle of one steradian
- An isotropic light source with a luminous intensity of 1 cd emits a total luminous flux of 4π lm = 12.56 lm

- **Illuminance**: If a 1 m^2 surface receives a luminous flux of 1 lm, then the illuminance of the surface is 1 lux
- Example: Moonlight 1 lux; reading light $10^2 - 10^3$ lux; surgery light 10^4 lux; direct sunlight 10^5 lux

- **Luminance** is the luminous intensity emitted per unit area of a light source. Luminance is a figure of merit for displays. Typical displays have a luminance of 100 – 500 cd/m^2.

Light and Lighting – Definitions I

Radiometry **(physics)**

Φ_e	Radiant flux – energy flow (W)
$I_e(\lambda) = d\Phi_e/d\omega$	Radiant intensity - (W/sr)
$S(\lambda) = d\Phi_e/d\lambda$	Spectral power distribution (W/m)

Photometry **(includes human response!)**

Φ_v	Luminous flux – **Lumens (lm)**
V(λ)	CIE luminous efficiency function

$$\Phi_v = 683 \text{ lm/W} \int S(\lambda)\, V(\lambda)\, d\lambda$$

K	**Luminous efficacy** **Lumens/optical watt (lm/W)**
$\eta_e = \Phi_e/P$	Radiant efficiency (P = input power)
$\eta_v = \eta_e K$	**Luminous efficiency** **Lumens/electrical watt (lm/W)**

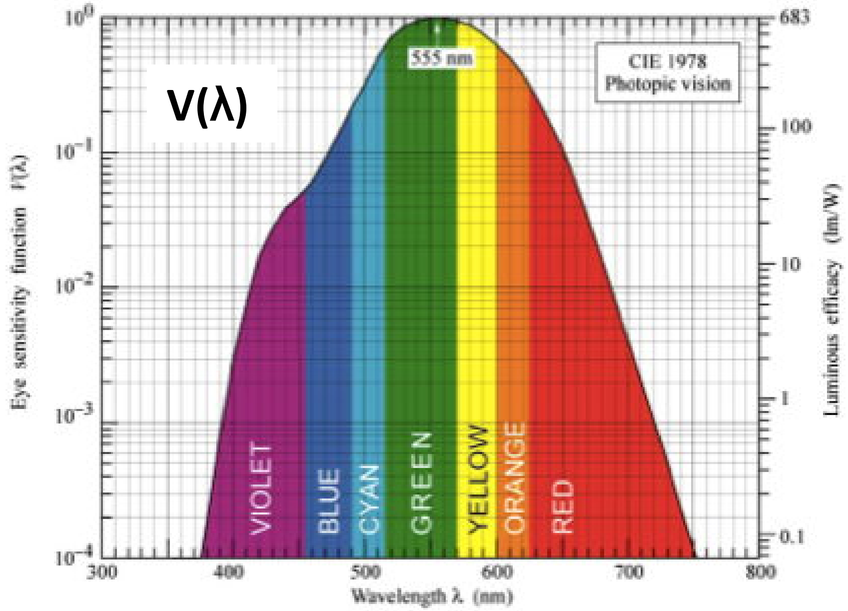


Fig. 16.7. Eye sensitivity function, V(λ), (left ordinate) and luminous efficacy, measured in lumens per Watt of optical power (right ordinate). V(λ) is greatest at 555 nm. Also given is a polynomial approximation for V(λ) (after 1978 CIE data).

E. F. Schubert

Lumen - Eye-weighted radiant flux

Light and Lighting – Definitions

Lumen (lm): **Luminous flux** = Luminous intensity x solid angle

e.g., sphere 4π sr

A candle: 1 cd x 4π sr = **12.6 lm**

100 W incandescent lightbulb: **~1300 lm (i.e, 13 lm/W)**

Illumination 1lux = 1lm/m²

Correlated Color Temperature (CCT):

Apparent blackbody temperature of a light source

e.g, Incandescent bulb, warm light LED lamp: CCT ~2800 K ‘Cold white: CCT ~5000+ K

Color Rendering Index (CRI):

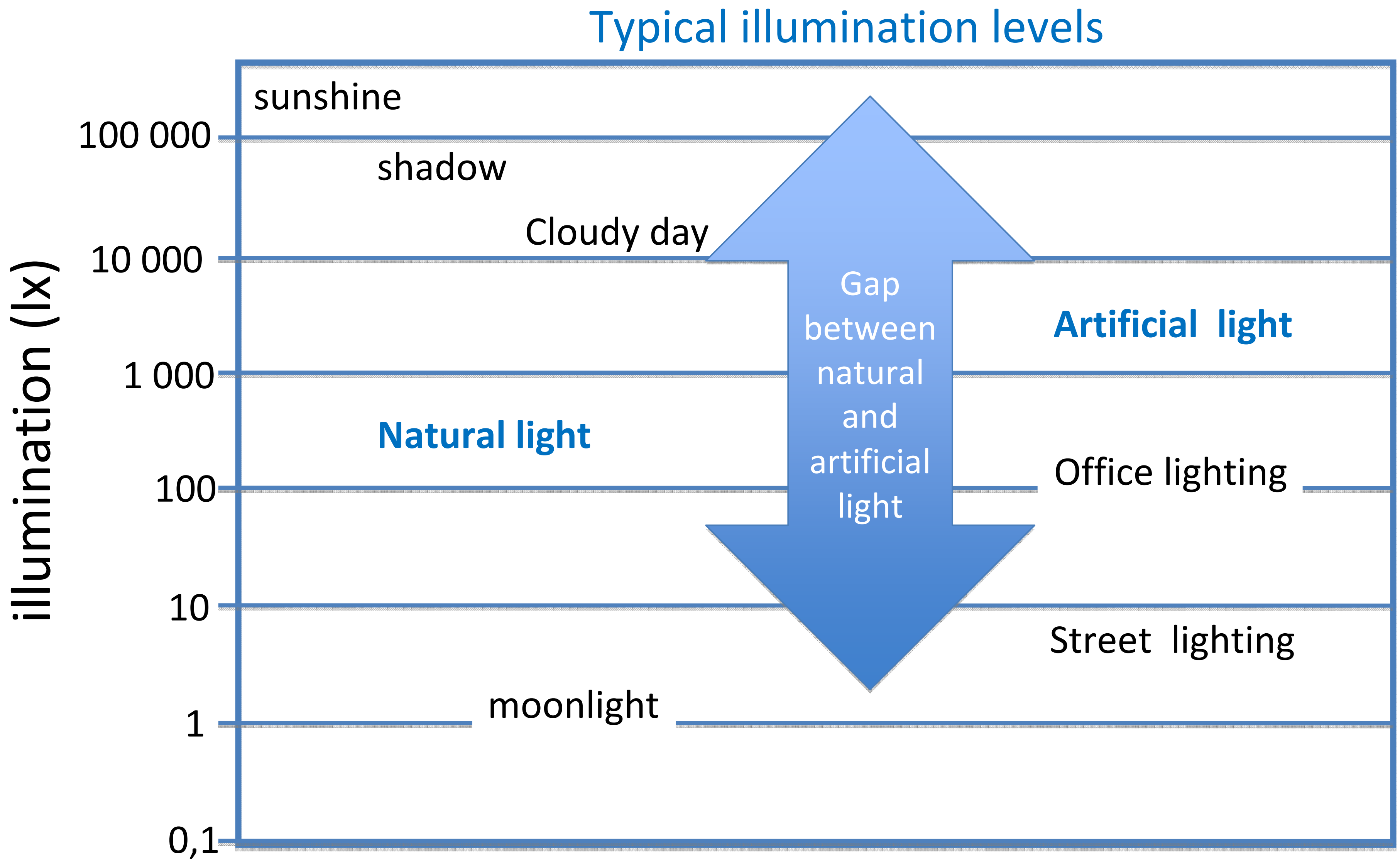
‘Light quality’ – comparison of light source to a blackbody radiator with same CCT

(based on light source reflectivity from 8 test samples …)

e.g, Incandescent bulb: CRI = 100 Na lamp: CRI = 10 - 20

*formally: luminous intensity at 555 nm of a source with a radiant intensity I(λ) of 1.46 x 10^{-3} W/sr

Huge difference between natural and artificial illumination
Factor 100 to 10 000

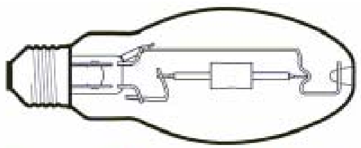


Lighting Technologies

Conventional Light Sources

No Perfect Artificial Light Source Exists (yet)

High Intensity Discharge

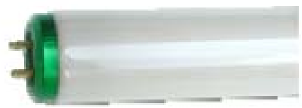


Pros: Cheap, efficient
Cons: Poor color,
long restart,
short lifetime

Incandescent

Pros: Very cheap, great color
Cons: Very short lifetime,
poor energy efficiency

Fluorescent



Pros: Cheap, energy efficient
Cons: Can not run in cold temp;
difficult/costly to dim,
control, Hg

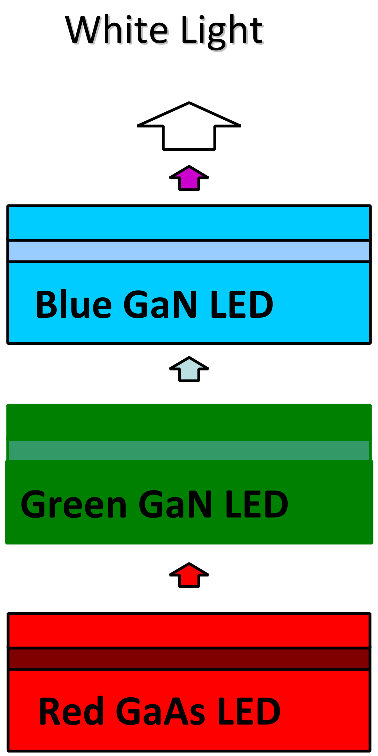
Compact Fluorescent

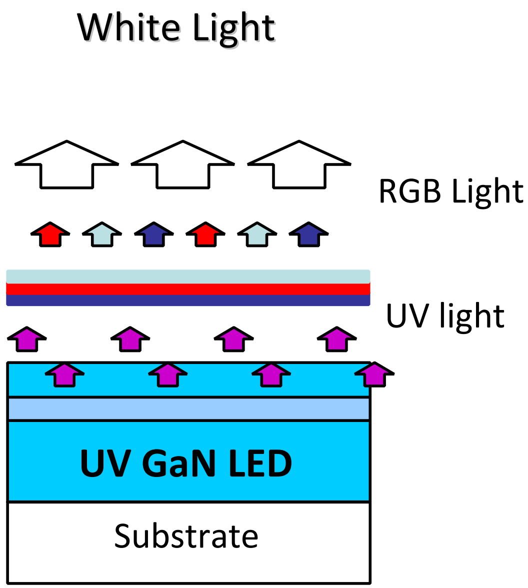
Pros: Energy efficient
Cons: Poor color quality,
Can not run in cold,
High cost vs. Incand, Hg

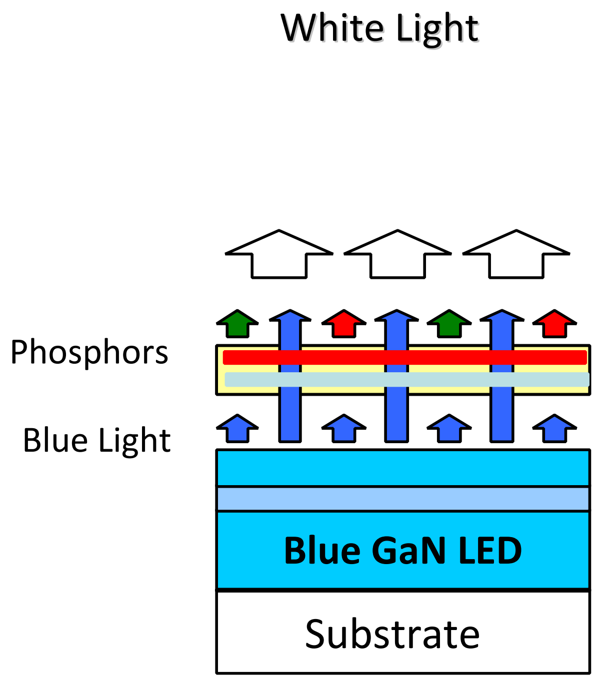
Halogen

Pros: Great color, focused light
Cons: Very short lifetime,
poor energy efficiency

Three Methods of Making White Light with LEDs







Multiple LEDs, RGB

- ~~good~~ efficiency
- highest cost
- tunable color

UV + Phosphors

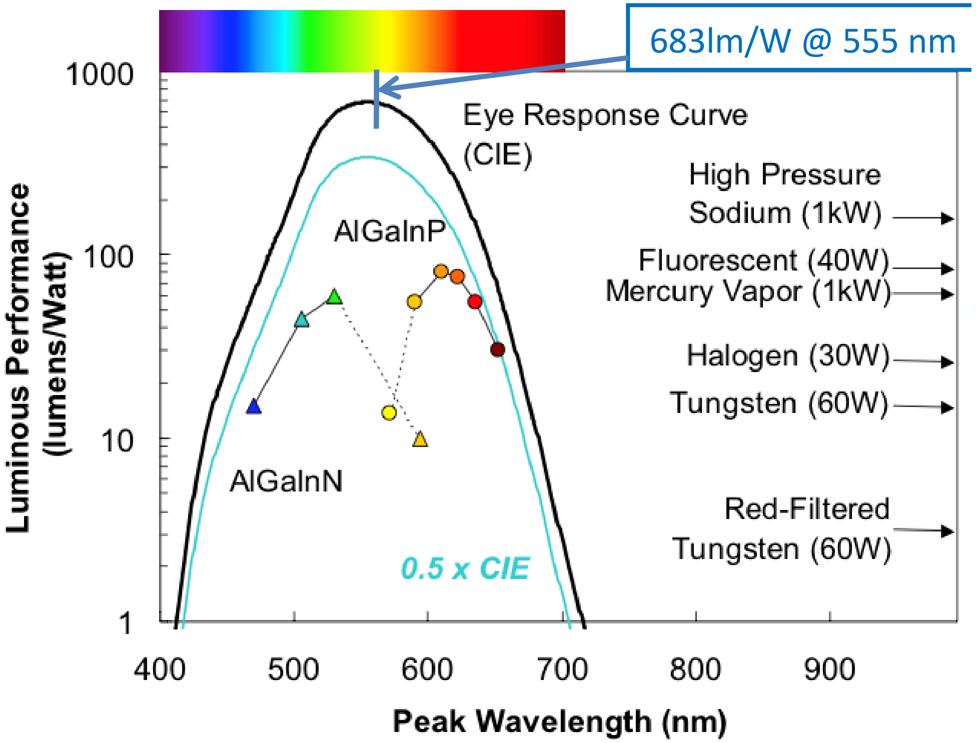
- best CRI,
- color uniformity
- low cost
- lower efficiency
  - -Phosphor conversion

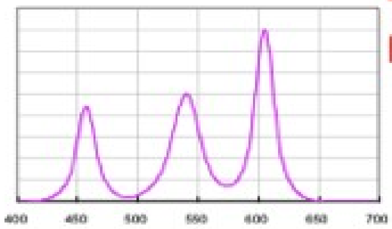
Blue + Phosphors

- lowest cost
- 100 lm/W
- >90% market share

Luminous Efficiency of a Source: lm/W – our metrics: lumen: effective lightoutput /W electrical power input

Goal 200 lm/W		Today's LEDs > 50%		Good color mix Up to 400 lm/W
Luminous Efficiency of a Source (lm/W)	=	**Wall Plug Efficiency**	x	**Luminous Efficacy** of Radiation (LER) (lm/W)
Luminous flux out (lm) / Electric power in (W)		Optical power out (W) / Electric power in (W)		Luminous flux (lm) / Optical power (W)





Theoretical maximum lm/W of a given source.

Determined only by the spectrum of the source.

85 % + LED internal quantum eff.
85 % + extraction efficiency
Best phosphors 90%+ IQE

Ideal LED SSL Efficiencies

Tradeoff between CCT, CRT and efficacy (lm/W)
Ideal: high CRI (100); low CCT (2700K); high lm/W!

RGB LEDs White Light

metric	2013 status	2020 target	goal
Luminous efficacy of radiation (lm/W)	400	400	400
Blue LED wall plug efficiency	55%	80%	80%
green LED wall plug efficiency	22%	35%	60%
red LED wall plug efficiency	44%	55%	60%
Weighted power conversion (LES/LER)	33%	39%	63%
Color mixed (CM) LED efficacy (lm/W)	**133**	**191**	**250**

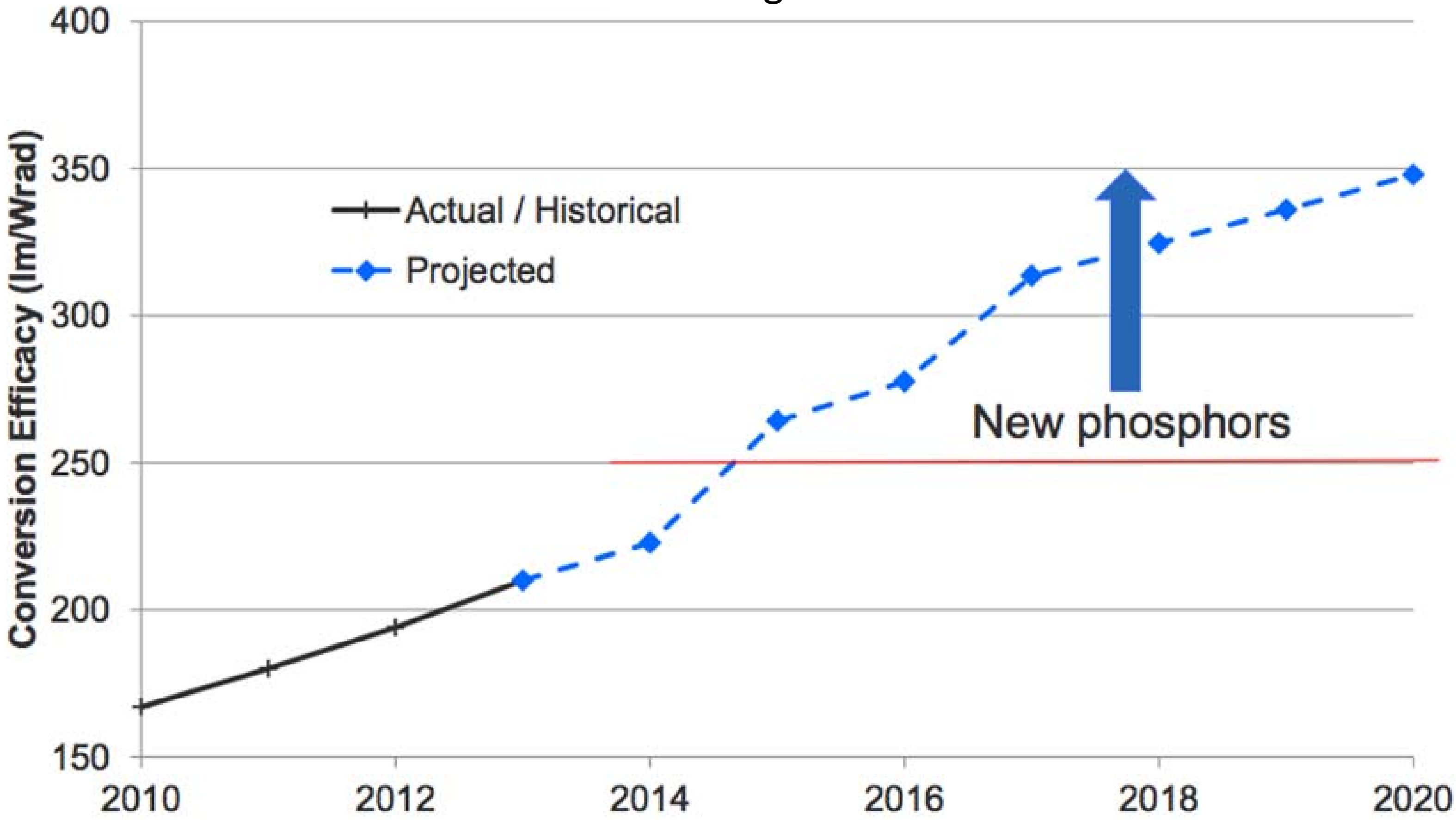
Blue + phosphor

metric	**2013 status**	**2020 target**	**goal**
Luminous efficacy of radiation (lm/W)	310	375	395
Blue LED WPE	55%	80%	80%
Green phosphor quantum efficiency	95%	95%	99%
Green phosphor **Stokes** efficiency	84%	84%	84%
Green phosphor conversion efficiency	80%	83%	83%
Red phosphor quantum efficiency	67%	71%	71%
Red phosphor **Stokes** efficiency	74%	74%	74%
Red Phosphor Conversion Efficiency	39%	62%	62%
Phosphor Converted (pc-) LED efficiency (lm/W)	**123**	**232**	**247**

DOE SSL MYPP 2014

Conversion Efficacy Roadmap
3500K and 4000K 80 CRI

Yi-Qun Li, Intermatix DOE manufacturing workshop
San Diego 2014



- Lighting system efficacy is conversion efficacy × LED WPE
- LED WPE expected to trend up to 76%-81% → 264-282lm/W system efficacy

SSL Efficiencies – the challenges

LED Efficiencies

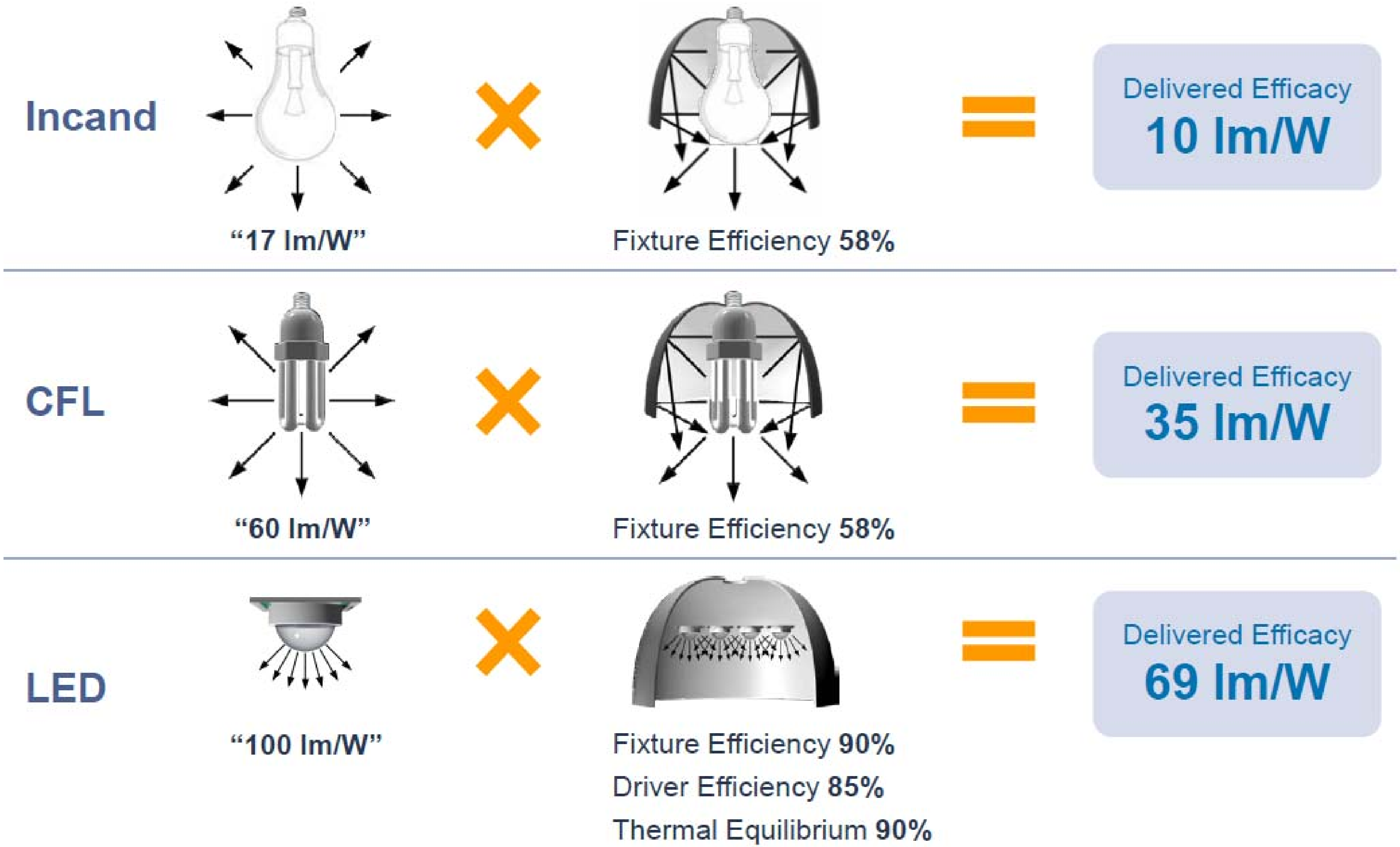
$\eta_{tot} = \eta_{elec} \times \eta_{IQE} \times \eta_{extrac}$

η_{elec} : Electrical efficiency … ohmic losses
Better contacts, doping, …

η_{IQE} : Internal quantum efficiency: electron-hole pairs to photons
Major issues:
Droop
Green gap

η_{extrac} : Extraction efficiency: escape efficiency for photons
Major issues:
Increase η_{extrac}
Directionality
Approaches here extend to system level issues

Overall System Efficiency



Cree (2010)

LEDs for lighting - the physical and materials basis

1. Light emitting diodes (LEDs) 101

2. Light sources – it is not just photons and watts

3. Visible LEDs, a long road from red to blue
   First red LEDs
   Difficulties to go to short wavelengths with the usual III V's
   ZnSe and nitrides
   The sad history of ZnSe
      The difficult road to nitiride success
   Then came nitrides
      Good surprises, … and bad…

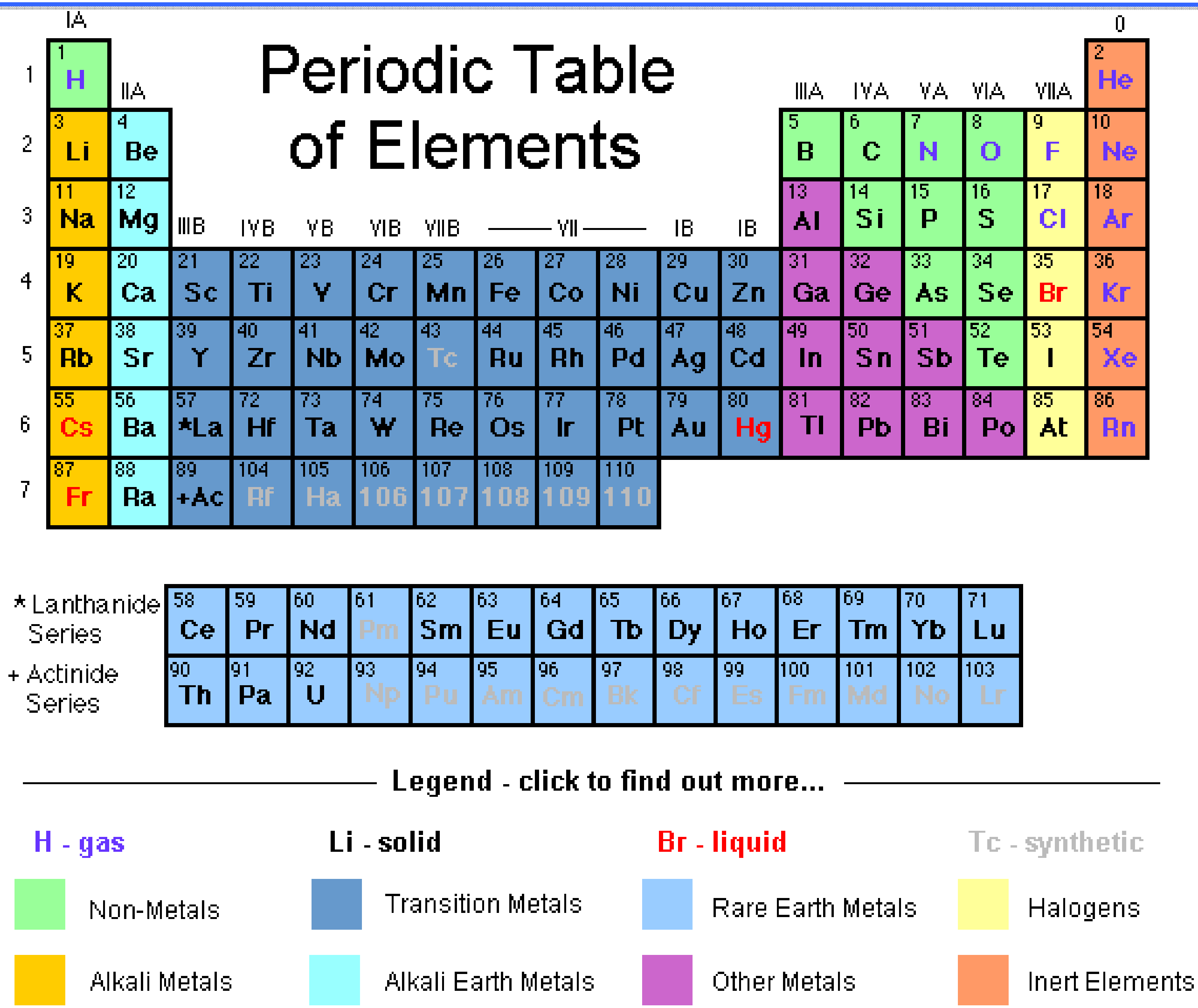
1. The state of the art - the remaining challenges

2. The impact 1 energy savings

3. The impact 2 bringing safe and cheap light where there is none

4. The impact 3 improving quality of light

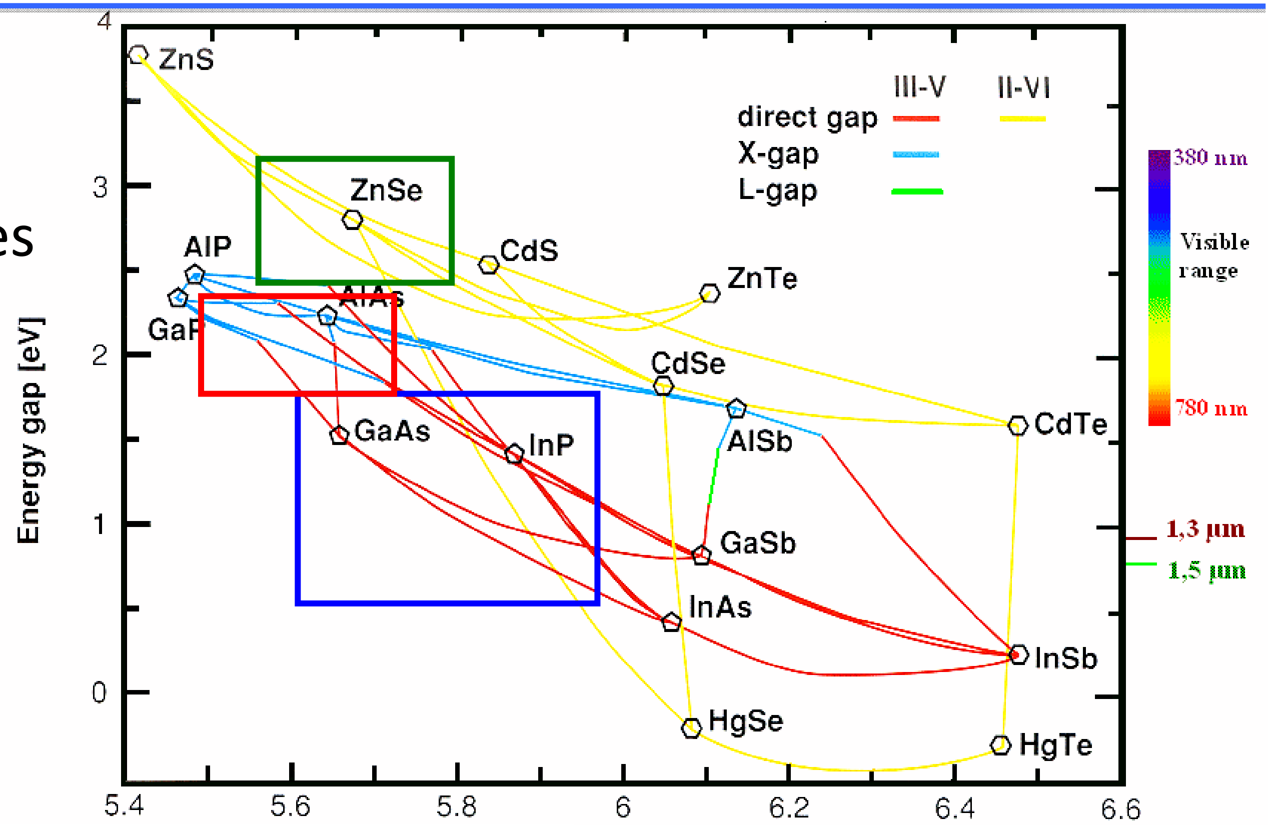
Chosing the right semiconductors



The Conventional View of the World

Mainly identified
in the '50ies-'60ies

Lattice matching
is a major issue



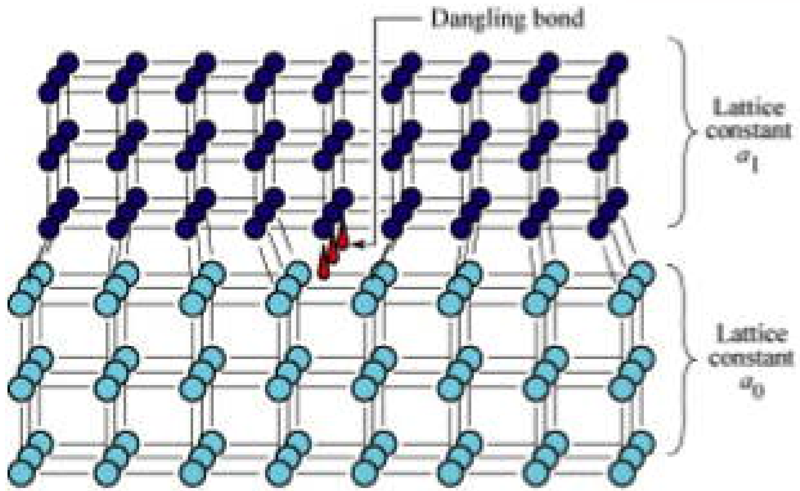


Fig. 7.12. Illustration of two crystals with mismatched lattice constant resulting in dislocations at or near the interface between the two semiconductors.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Infrared
GaAlAs/GaAs
GaInAsP/InP

visible
GaAlInP/GaAs
ZnSSe/GaAs

AlGaInP LEDs operate near the limits

George Craford, Overview of device issues in high brightness LEDs
Semiconductors and semimetales vol; 48, 1997, p. 47

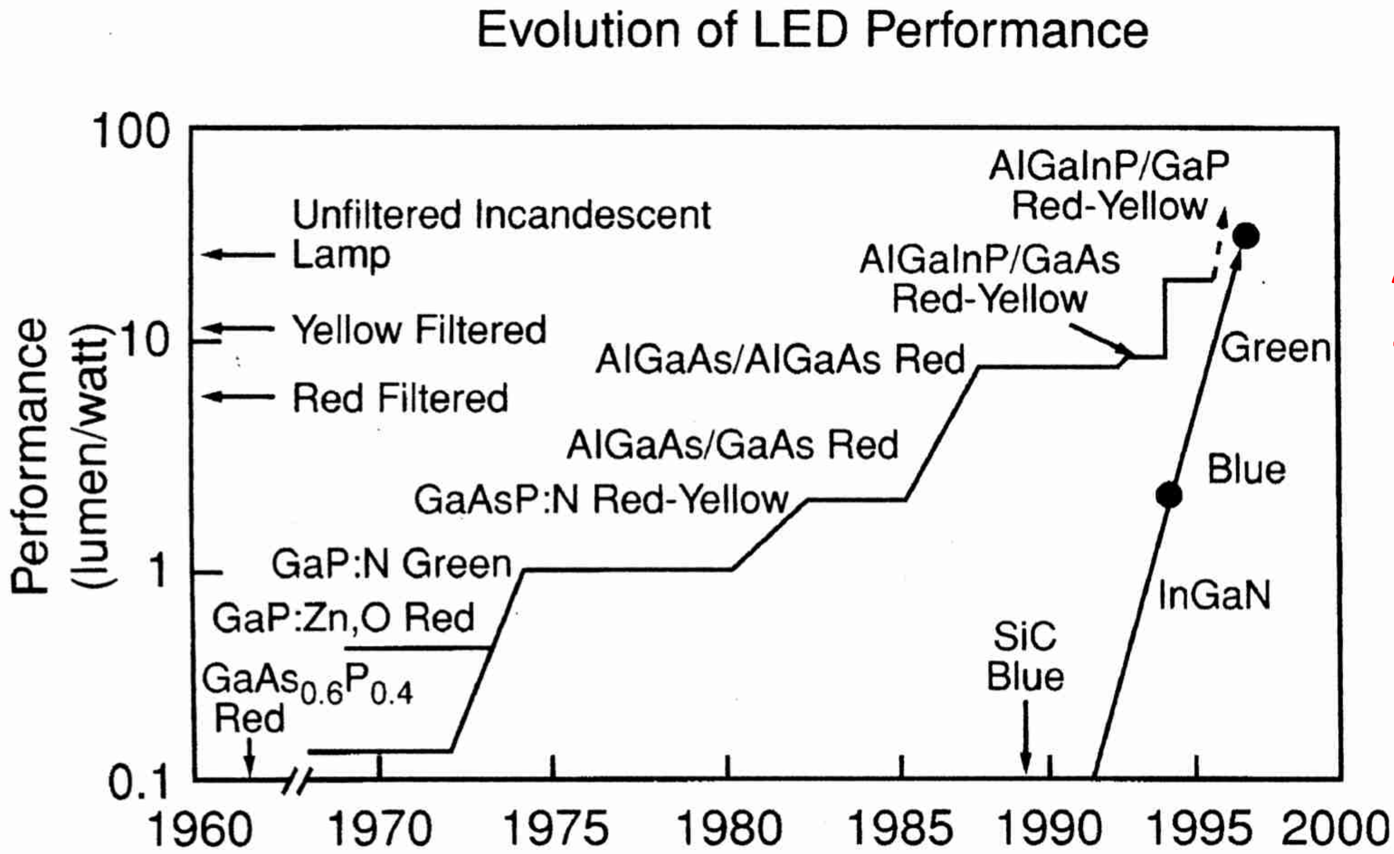
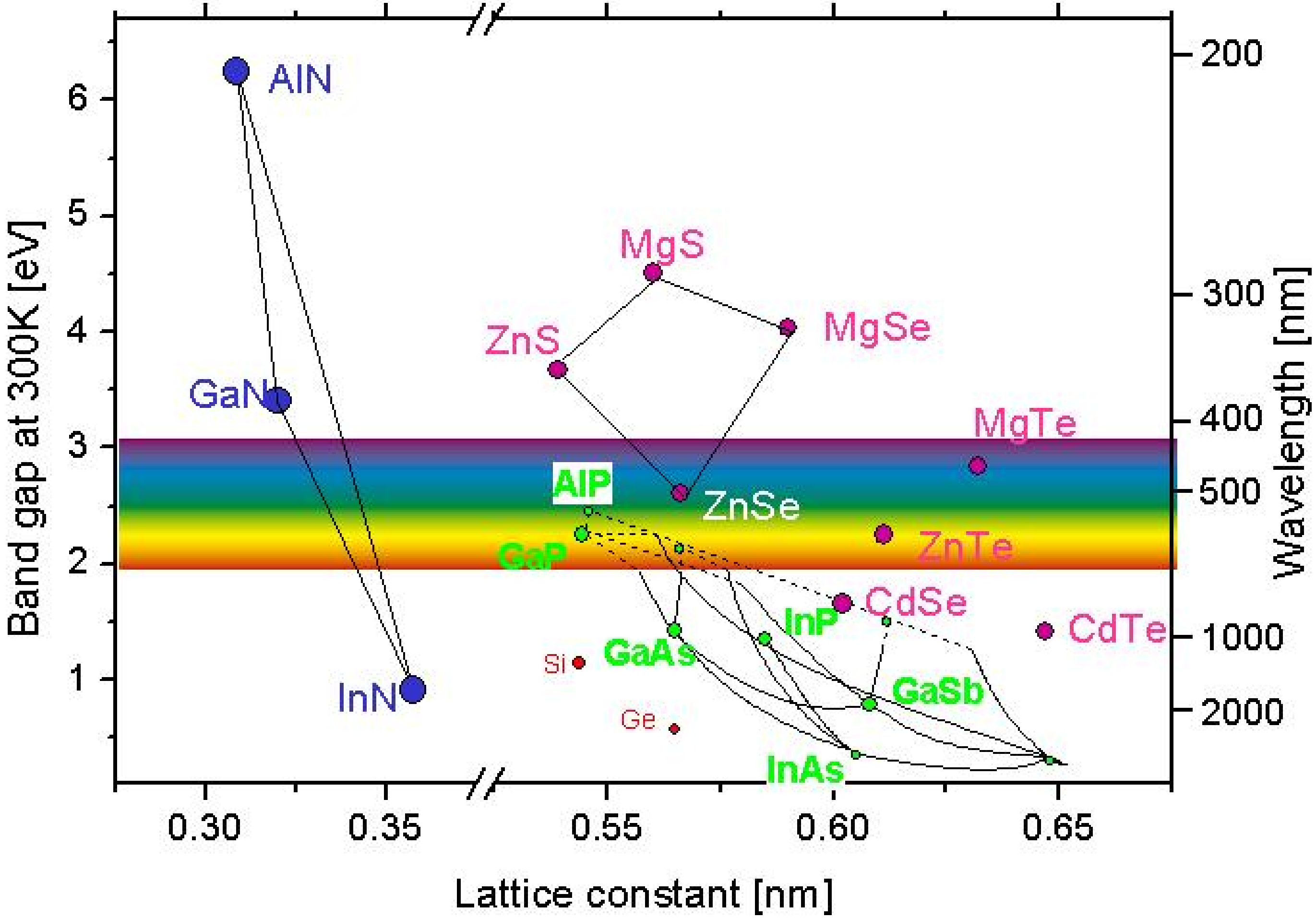


FIG. 1. Evolution of visible light-emitting diode (LED) performance with time. There has been about a tenfold improvement per decade in performance since high-volume commercial introduction.

About 20lm/W

Group III-Nitrides: Energy Gap Map
(New View of the World)



First II-VI based blue green laser diodes

Blue-green laser diodes

APL, Vol. 59, 1272, 1991

M. A. Haase, J. Qiu, J. M. DePuydt, and H. Cheng
3M Company, 201-1N-35 3M Center, St. Paul, Minnesota 55144

(Received 17 May 1991; accepted for publication 13 June 1991)

The first laser diodes fabricated from wide-band-gap II-VI semiconductors are demonstrated. These devices emit coherent light at a wavelength of 490 nm from a ZnSe-based single-quantum-well structure under pulsed current injection at 77 K. This is the shortest wavelength ever generated by a semiconductor laser diode.

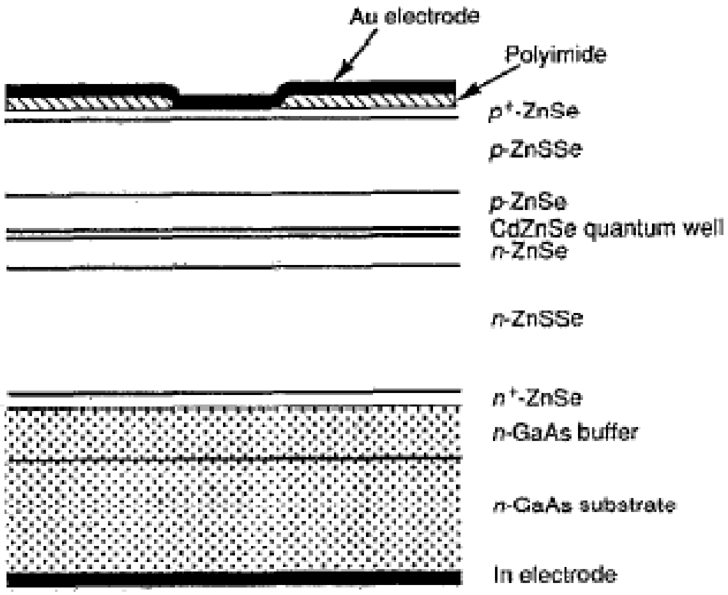


FIG. 1. A cross section of a blue-green laser diode.

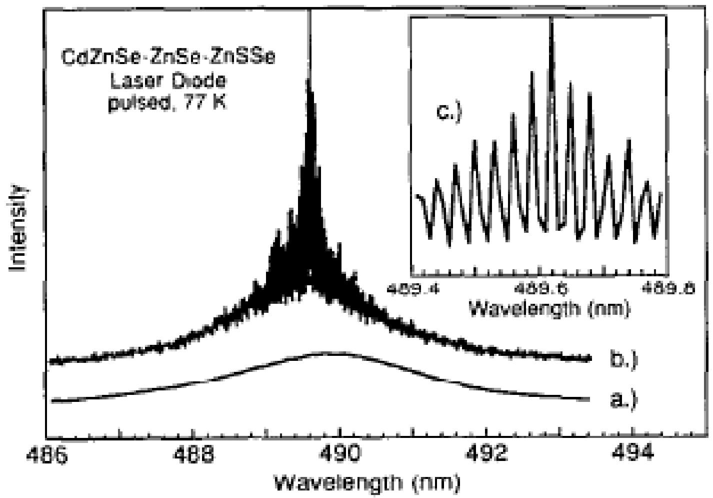
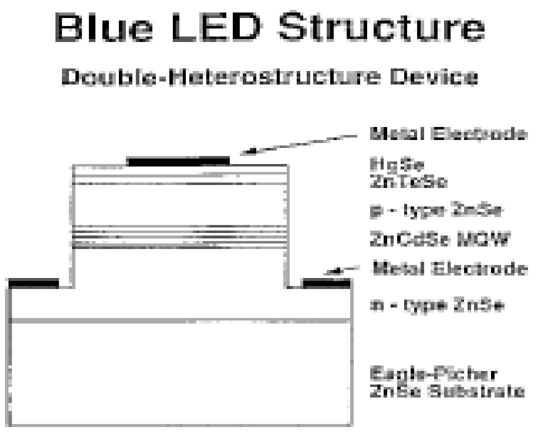


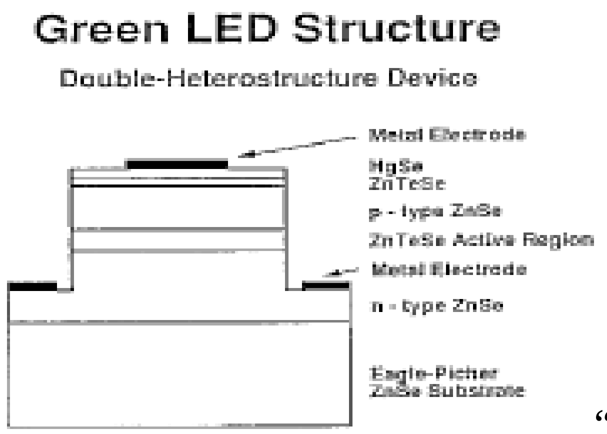
FIG. 3. The optical spectra for a blue-green laser diode: (a) below threshold; (b) above threshold; and (c) an expanded view of the lasing spectrum, taken with 0.01-nm steps. The device is 1020 μm long. Intensity scales for these three graphs are in arbitrary units, and are not the same.

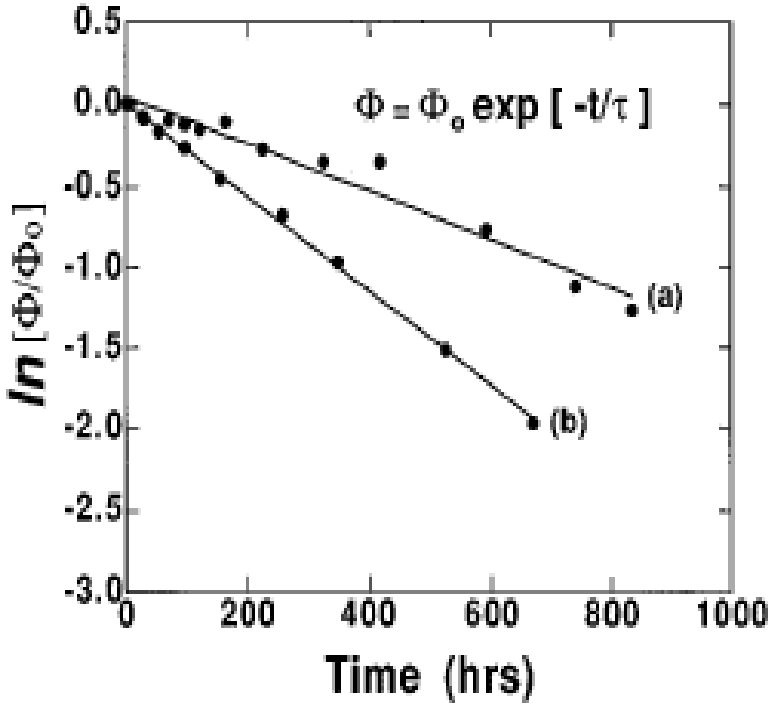
II-VI-based LEDs in 1995: fast degradation

(a)



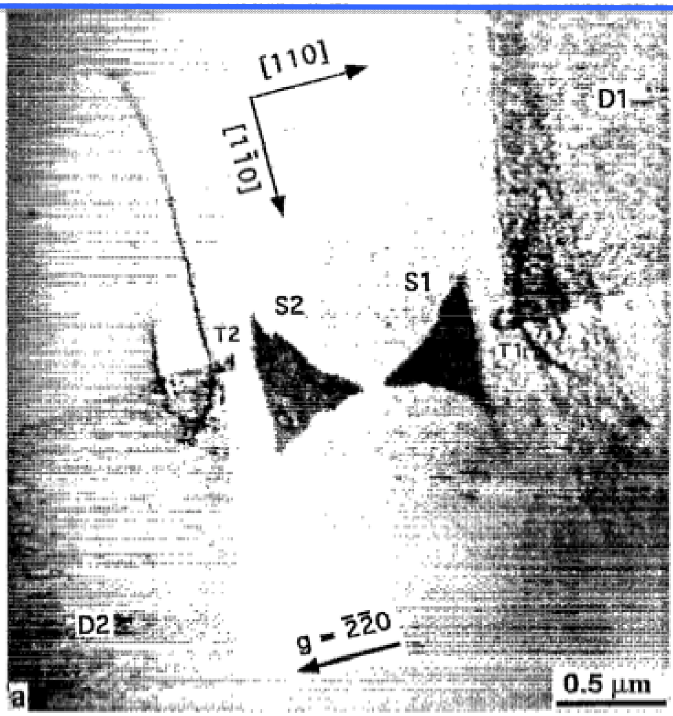
(b)



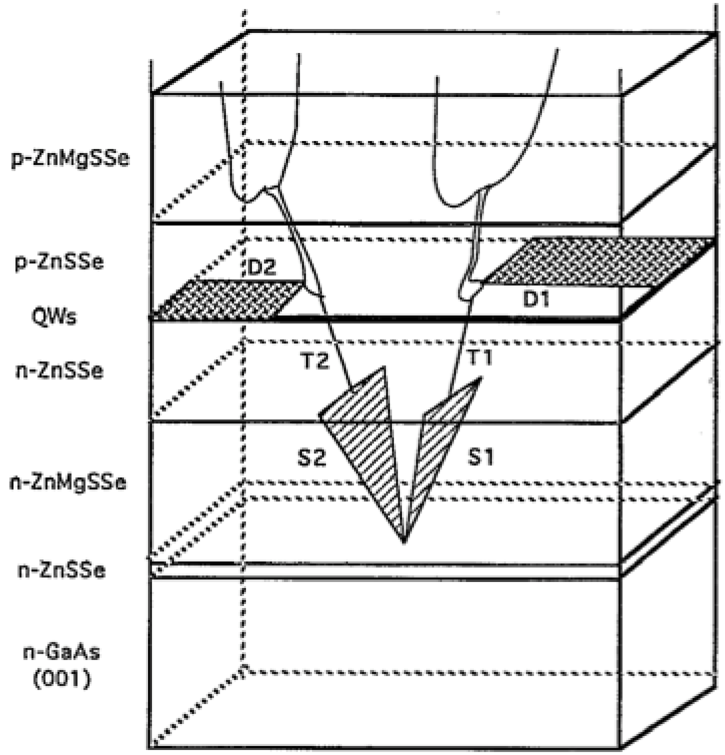


“High-brightness blue and green light-emitting diodes“
D.B. Eason et. all., Appl. Phys. Lett. Vol 66, 115 (1995)

II-VI-based LEDs in 1995: fast degradation dislocation climb



Hua et al. Appl. Phys. Lett., Vol. 65, 1331, 1994
Microstructure study of a degraded pseudomorphic separ
confinement heterostructure blue-green laser diode
ZnCdSe/ZnSSe/ZnMgSSe
separate confinement heterostructure (SCH) laser



S1, S2 Satcking faults: cubic becomes hexagonal
D1, D2: dislocation patches in QWs

Pre - History of LEDs

- Henry Joseph Round (1881 – 1966)
- 1907: First observation of electroluminescence
- 1907: First LED
- LED was made of SiC, carborundum, an abrasive material

A Note on Carborundum.

To the Editors of Electrical World:

SIRS:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

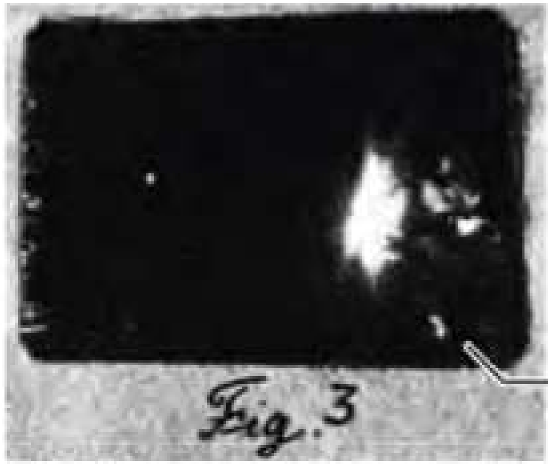
There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

NEW YORK, N. Y. H. J. ROUND.

Henry Joseph Round

Light-Emitting Diode – 1924 – SiC – Lossev

- Oleg V. Lossev noted light emission for forward and reverse voltage
- Measurement period 1924 – 1928

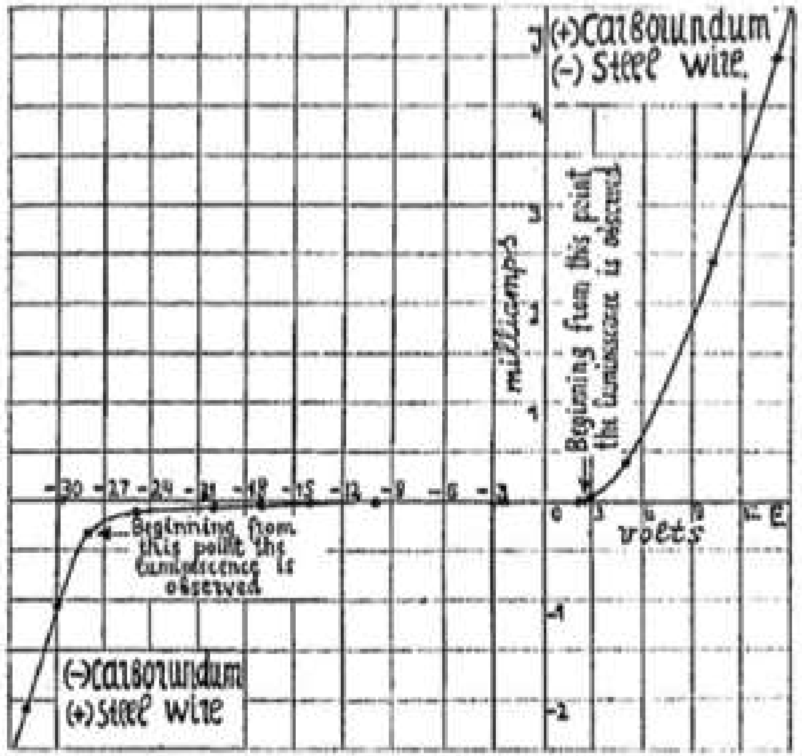


First photograph of light emitted by SiC LED

(after O. V. Lossev, 1924)

SiC crystal

First photograph of LED



Lossev's I-V characteristic

Prehistory Light emission in first LED

Schottky diode
Metal-semiconductor

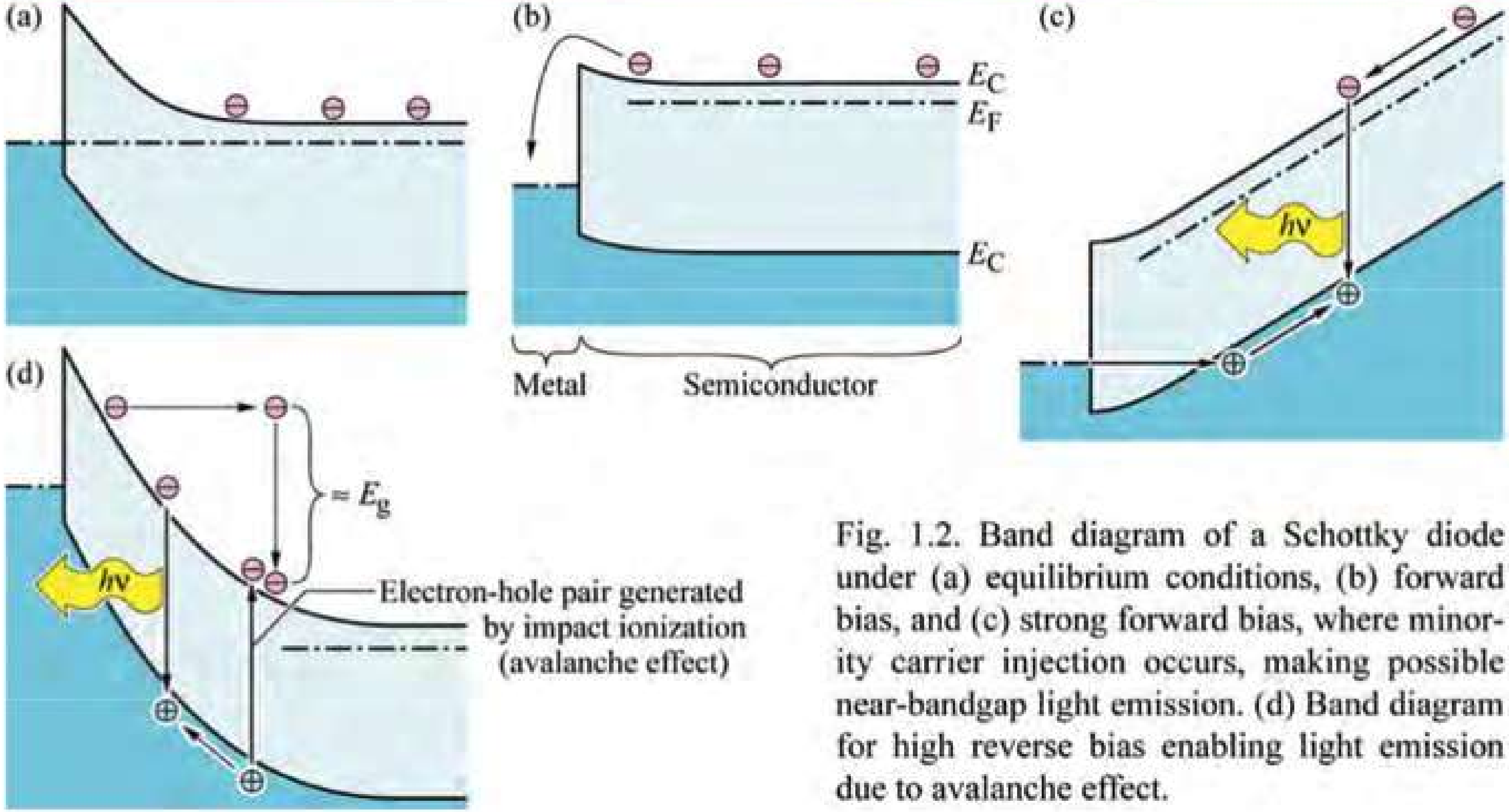
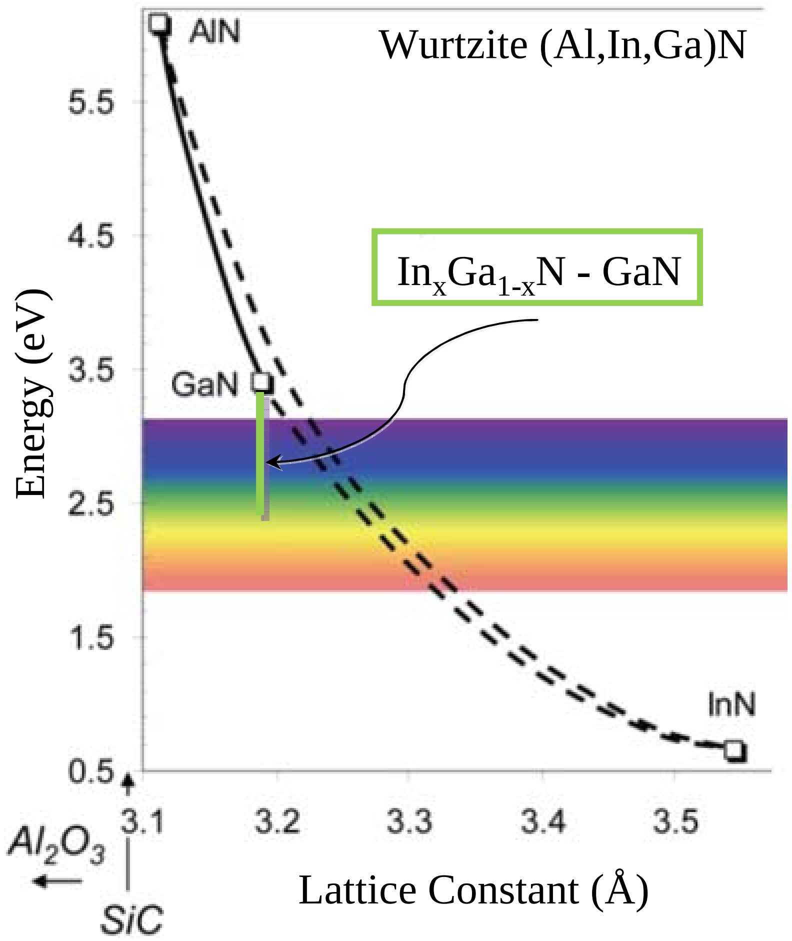


Fig. 1.2. Band diagram of a Schottky diode under (a) equilibrium conditions, (b) forward bias, and (c) strong forward bias, where minority carrier injection occurs, making possible near-bandgap light emission. (d) Band diagram for high reverse bias enabling light emission due to avalanche effect.

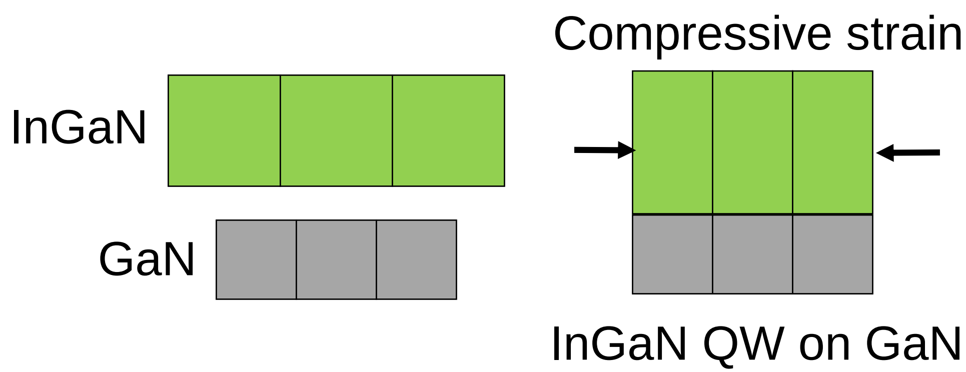
- First LED did not have pn junction!
- Light was generated by either minority carrier injection (forward) or avalanching (reverse bias)
- "Beginner's luck"

GaN-based visible light emitters



M. R. Krames *et al*., J. Disp. Technol. **3**, 160 (2007).

- InGaN quantum wells
- Wavelengths from UV to IR
- Compressively strained
  - Increases with indium composition
  - Piezoelectric field effects
  - Eventual relaxation



A (short) history of Nitride optoelectronics development

- 1968 HVPE growth Maruska and Tietjen
- 1971 LED Zn doping Pankove et al., optically pumped laser Dingle et al.
- 1973 Mg doping Maruska et al.

  problems with HVPE: gas purity, uncontrolled incorporation of impurities, oxygen (giving n type, not vacancies as previously thought) & hydrogen (H_2O, NH3) compensating p doping

1983 MBE GaN on high T crystalline AlN nucleation layer Yoshida

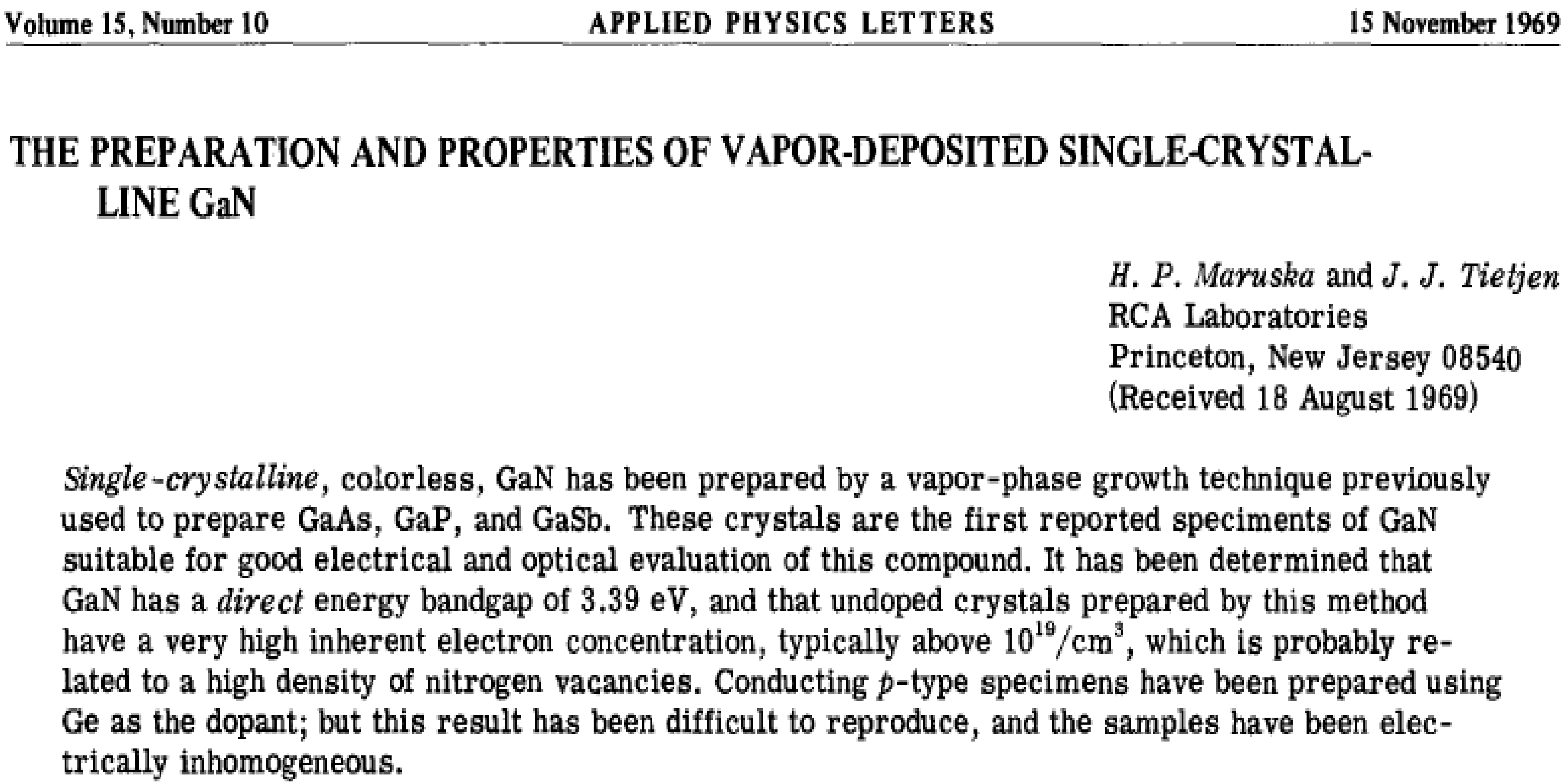
1984 switch to MOCVD (purer materials, cold walls , less O2)

1984 Blue LEDs Kawabata

Main Breakthroughs

- 1986 low T AlN nucleation layer before high T GaN growth Akasaki
- 1989 activation of Mg doped GaN by e beam irradiation (annealing) Akasaki
- 1989 first p-n junction LED Akasaki
- 1991 activation of Mg doped GaN by thermal annneling of Mg Nakamura
- 1992 Identification of H as the n compensation for Mg Nakamura
- 1991,1992 Two flow MOCVD reactor, delivers high quality n type Nakamura
- 1992 controlled In incorporation allows band to band blue and green Nakamura
- 1994 Candela class LED Nakamura
- 1995 High power SQW blue, green, yellow LEDs Nakamura
- 1996 blue laser Nakamura

First GaN Growth by HVPE



Volume 15, Number 10 APPLIED PHYSICS LETTERS 15 November 1969

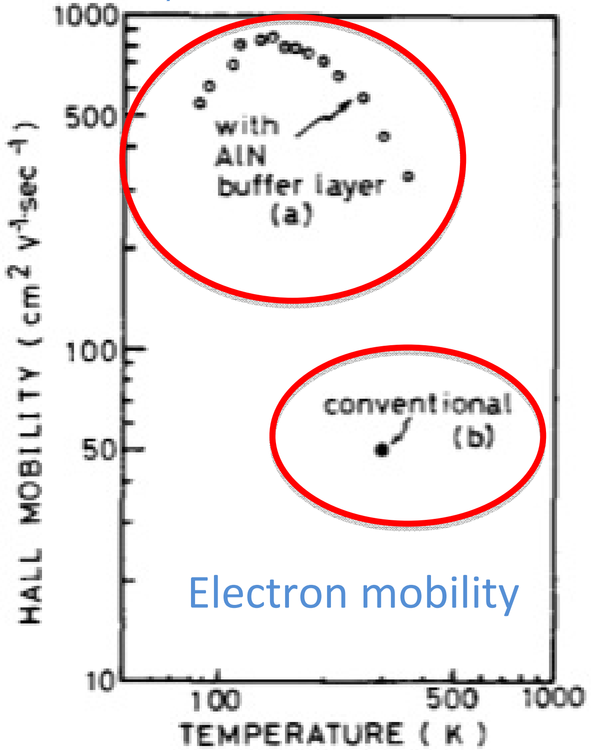
THE PREPARATION AND PROPERTIES OF VAPOR-DEPOSITED SINGLE-CRYSTAL-LINE GaN

H. P. Maruska and *J. J. Tietjen*
RCA Laboratories
Princeton, New Jersey 08540
(Received 18 August 1969)

Single-crystalline, colorless, GaN has been prepared by a vapor-phase growth technique previously used to prepare GaAs, GaP, and GaSb. These crystals are the first reported speciments of GaN suitable for good electrical and optical evaluation of this compound. It has been determined that GaN has a *direct* energy bandgap of 3.39 eV, and that undoped crystals prepared by this method have a very high inherent electron concentration, typically above $10^{19}/cm^3$, which is probably related to a high density of nitrogen vacancies. Conducting *p*-type specimens have been prepared using Ge as the dopant; but this result has been difficult to reproduce, and the samples have been electrically inhomogeneous.

Major breakthroughs: Akasaki &Amano

Akasaki **nucleation layer**
1986, 1989



Akasaki **nucleation layer**
1986, 1989

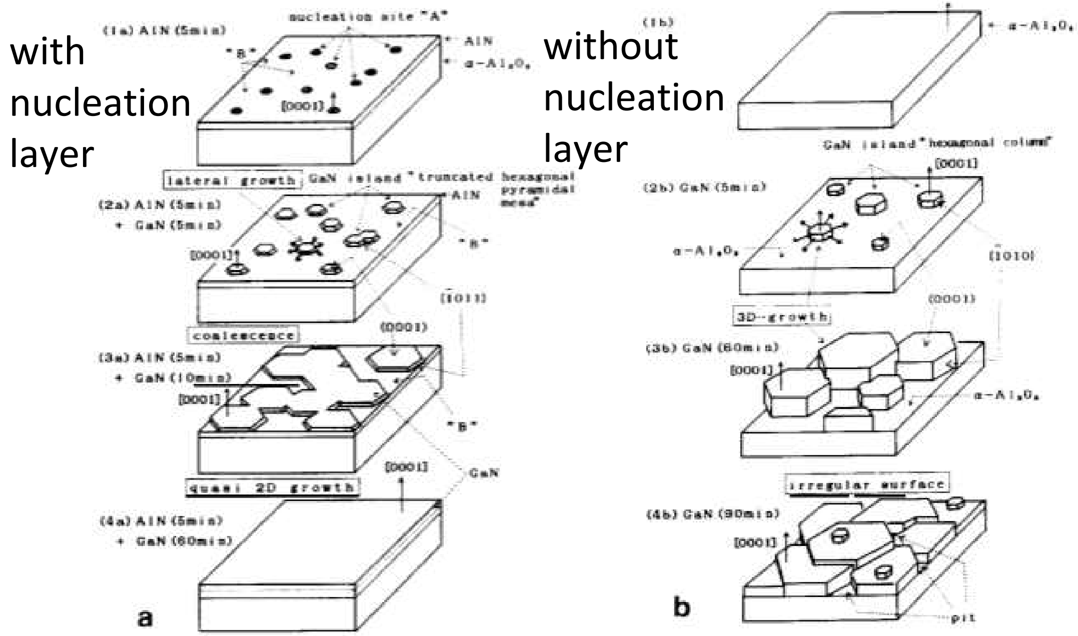
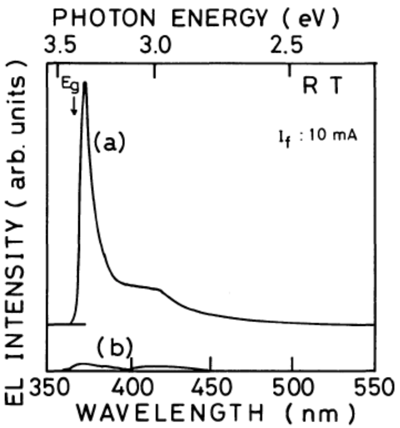


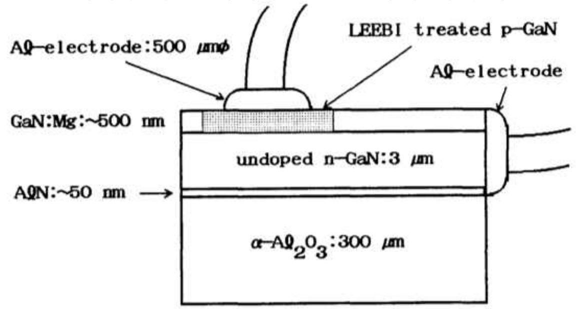
Fig. 14. Growth model for GaN film on (0001) sapphire substrate (a) with and (b) without AlN layer.

LEEBI treated	$\rho \sim 35\ \Omega\cdot$cm,	$p \sim 2\times10^{16}$ cm^{-3},	$\mu \sim 8$ cm^2/V·s
As grown	highly resistive, $\rho > 10^8\ \Omega\cdot$cm		



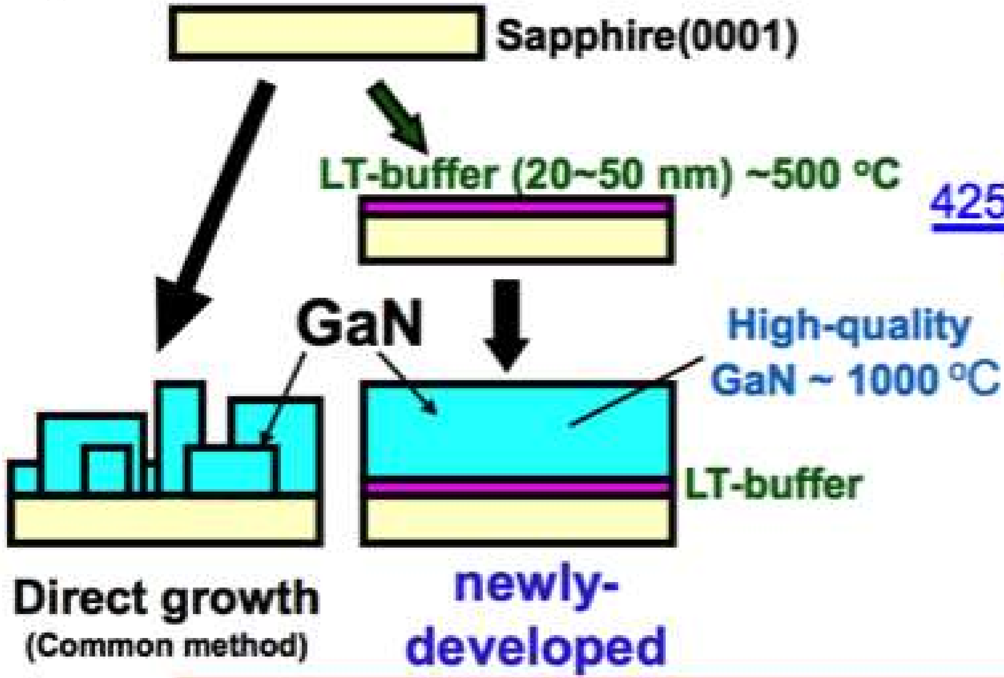
Akasaki **p-n junction LED**
1989

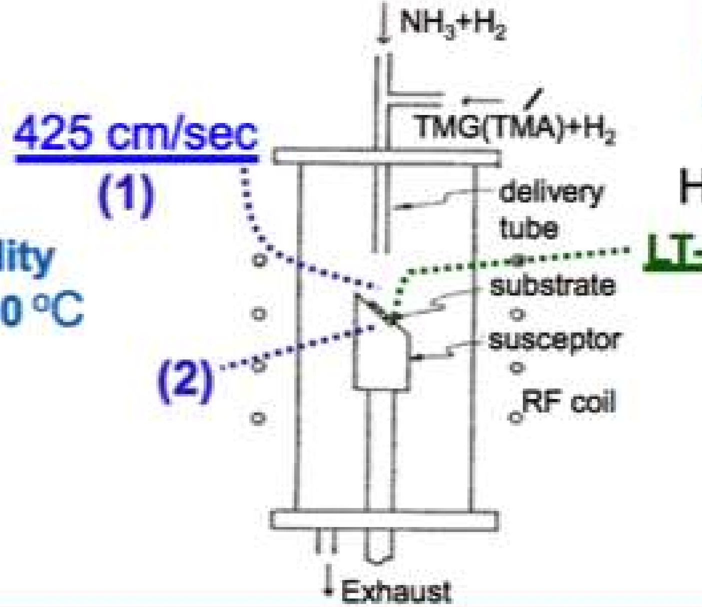
Akasaki **Mg p activation** by LEEBI
Electron beam irradiation 1989



(3) Innovation in MOVPE growth method (1985)

Low-temperature (LT-) buffer layer





H. Amano

Key technologies:

(1) Much higher-speed gas flow (425 cm/sec)

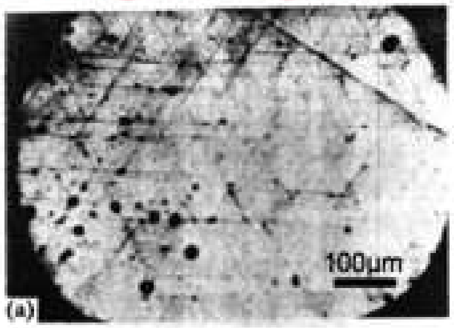
(2) Substrate inclined at a 45-degree angle

(3) Deposition of thin AlN buffer layer at about 500 °C,
before the growth of GaN single crystal at about 1000 °C

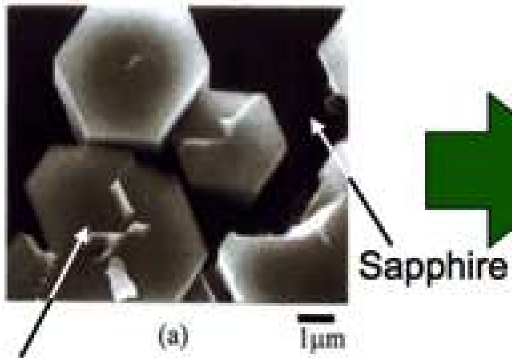
Creation of high-quality GaN (1985)

Until 1985

GaN grown by HVPE



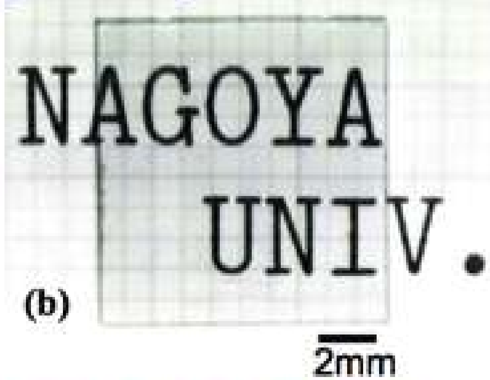
GaN grown by MOVPE



- Many cracks, pits
- Rough surface
- Dislocations: > 10^{11} cm^{-2}
- Free electron conc. >10^{19} cm^{-3}
- Electron mobility: ~20 $cm^2/V \cdot s$
- Weak luminescence

Since the late 1985

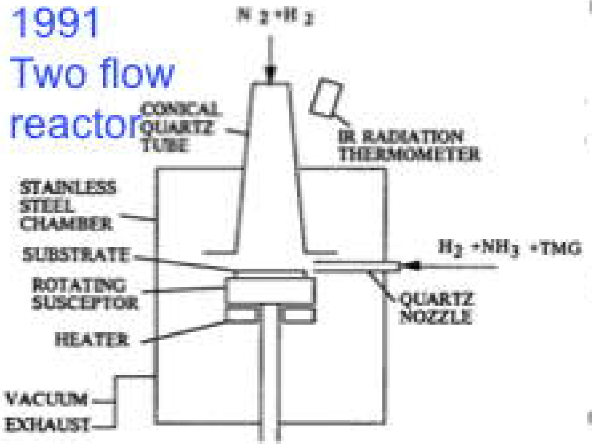
GaN grown by MOVPE using LT-buffer

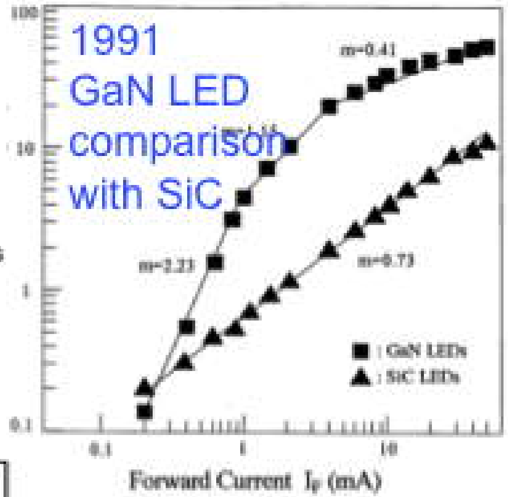


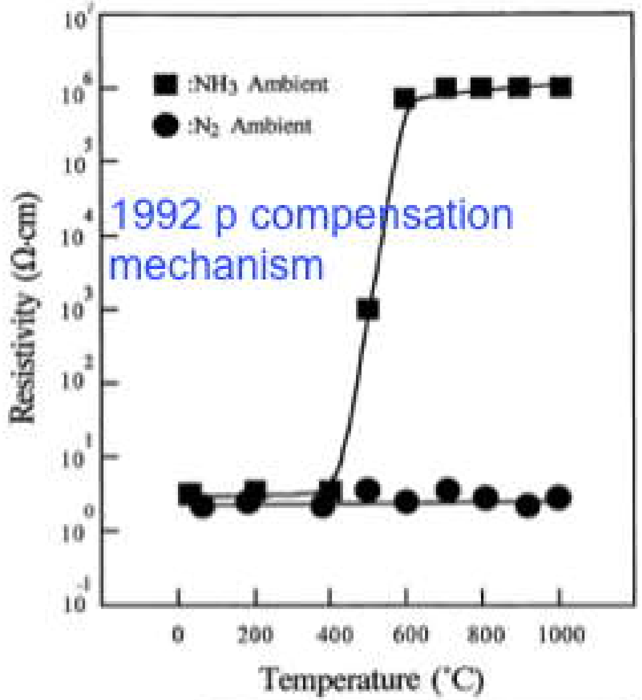
- Crack-free, pit-free
- Specular surface
- Dislocations: 10^8-10^9 cm^{-2}
- Free electron conc. < 10^{16} cm^{-3}
- Electron mobility: ~700 $cm^2/V \cdot s$
- Intense luminescence

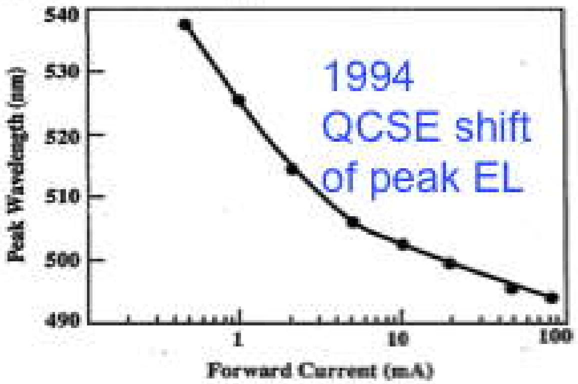
Crystal quality, electrical property, and luminescence property were dramatically improved at the same time

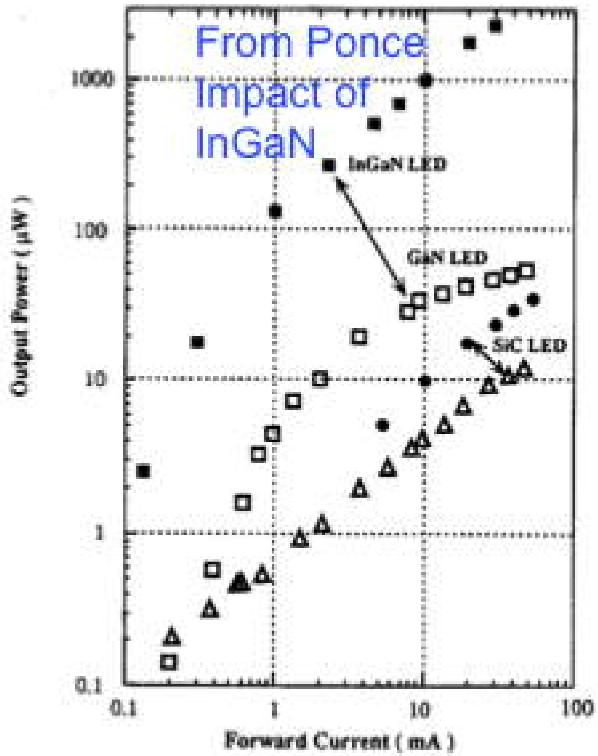
Major breakthroughs: Nakamura

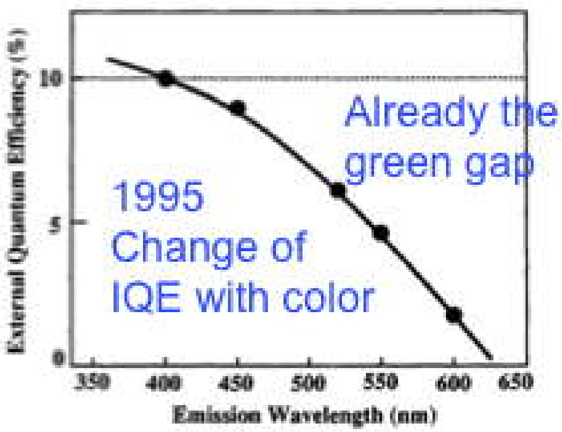


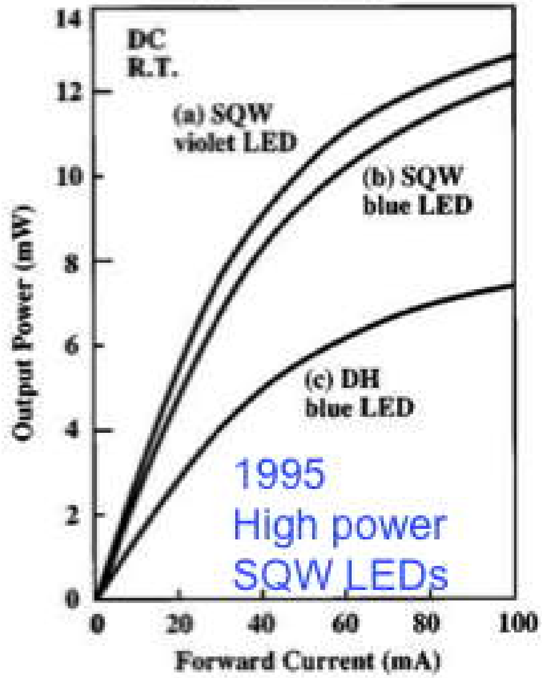












Invention of Two-Flow MOCVD

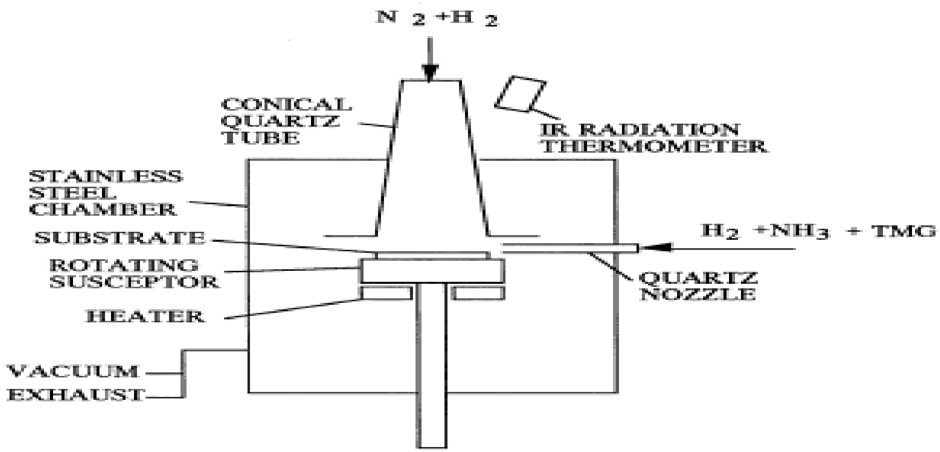


Fig. 1. Schematic diagram of novel MOCVD reactor for GaN growth.

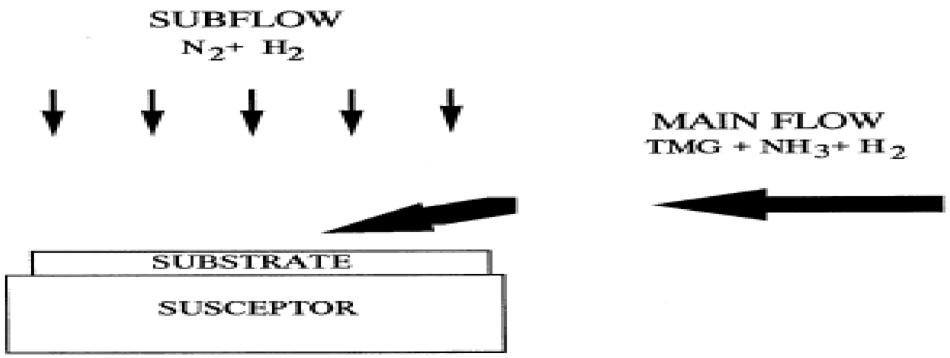


Fig. 2. Schematic principle figure of two-flow MOCVD.

“Novel Metalorganic Chemical Vapor Deposition System for GaN Growth”
S. Nakmaura *et al.*, Appl. Phys. Lett. Vol 58, 2021 (1991)

Hydrogen Passivation of P-Type GaN

Annealing in N2 atmosphere

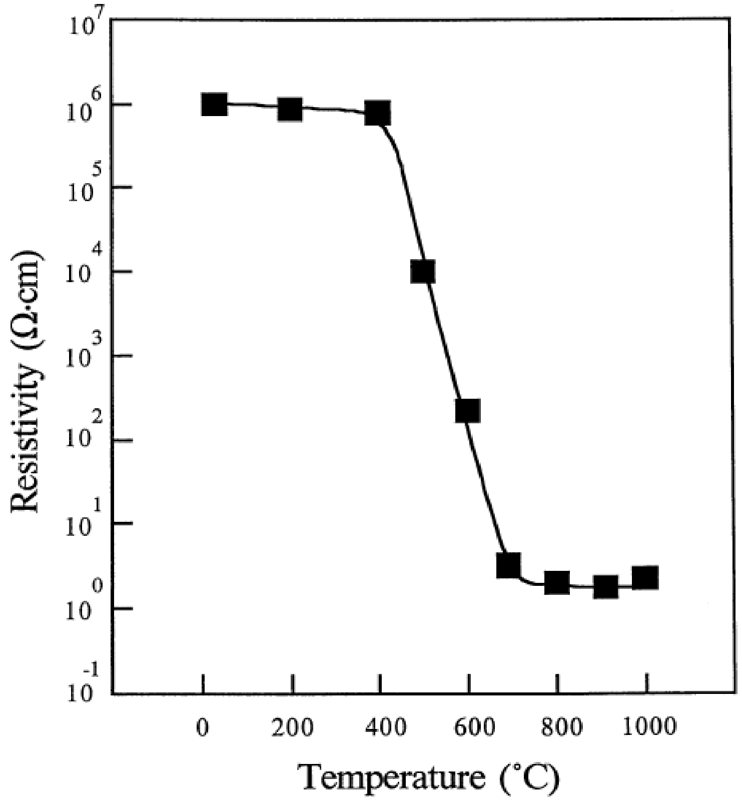


Fig. 1. Resistivity of Mg-doped GaN films as a function of annealing temperature.

S. Nakamura, T. Mukai, M. Senoh, and N. Iwasa, "Thermal annealing effects on p-type Mg-doped GaN films," Jpn. J. Appl. Phys., vol. 31, pp. L139–L142, 1992

Re annealing in NH_3 or N_2 atmosphere

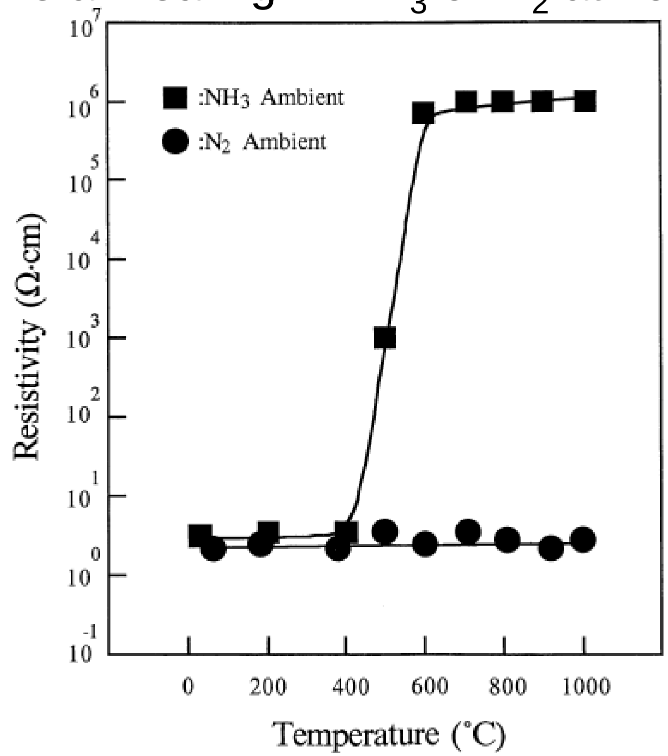


Fig. 1. The resistivity change in LEEBI-treated Mg-doped GaN films as a function of annealing temperature. The ambient gases, NH_3 and N_2, were used for thermal annealing.

S. Nakamura, N. Iwasa, M. Senoh, and T. Mukai, "Hole compensation mechanism of p-type GaN films," Jpn. J. Appl. Phys., vol. 31, pp. 1258–1266, 1992.

First InGaN QW Blue/Green/Yellow LEDs

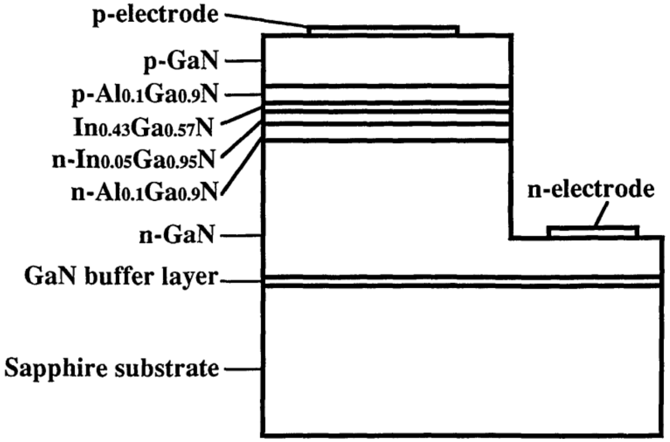


Fig. 1. The structure of green SQW LED.

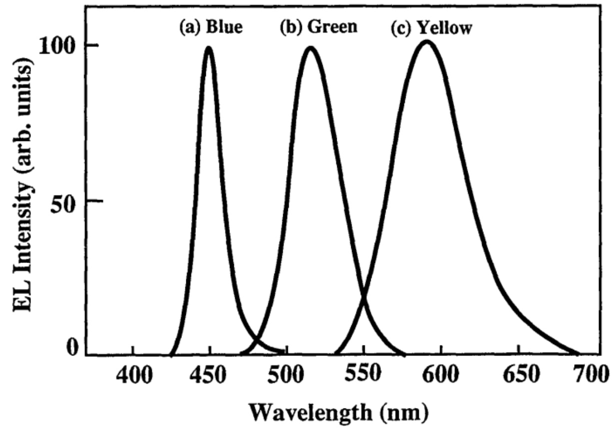


Fig. 2. Electroluminescence of (a) blue, (b) green and (c) yellow SQW LEDs at a forward current of 20 mA.

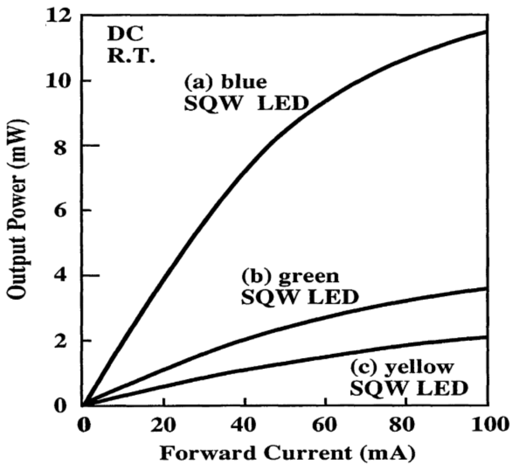
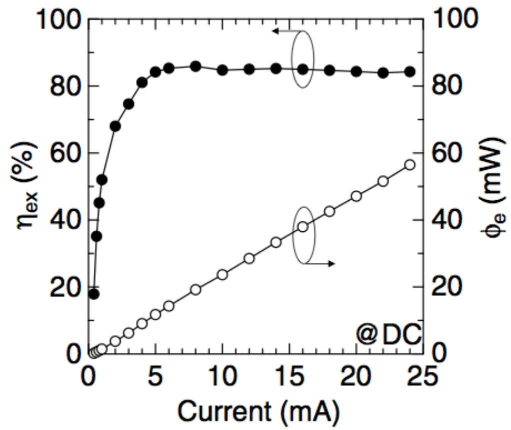


Fig. 4. The output power of (a) blue, (b) green and (c) yellow SQW LEDs as a function of the forward current.

Nakamura et al.,
"High-Brightness InGaN Blue, Green and Yellow Light-Emitting Diodes with Quantum Well Structures" Jpn. J. Appl. Phys. 34, pp. L797 (1995).

Narukawa
Blue LED
Nichia 2010



LEDs for lighting - the physical and materials basis

1. Light emitting diodes (LEDs) 101
2. Light sources – it is not just photons and watts
3. Visible LEDs, a long road from red to blue
4. The state of the art - the remaining challenges

   The (bad) and good surprise 1: high efficiency, despite large *intrinsic* internal electric fields
   The good surprise 2: high efficiency, despite high density of dislocations
   The good surprise 3: high reliability > 50 000h
   Remaining challenges

   Green gap
   Efficiency decrease at high intensity: the intensity "droop"

1. The impact 1 energy savings
2. The impact 2 bringing safe and cheap light where there is none
3. The impact 3 improving quality of light

SSL Efficiencies – the challenges

LED Efficiencies

$\eta_{tot} = \eta_{elec} \times \eta_{IQE} \times \eta_{extrac}$

η_{elec} : Electrical efficiency … ohmic losses

Better contacts, doping, …

η_{IQE} : Internal quantum efficiency: electron-hole pairs to photons

Major issues:

Droop

Green gap

η_{extrac} : Extraction efficiency: escape efficiency for photons

Major issues:

Increase η_{extrac}

Directionality

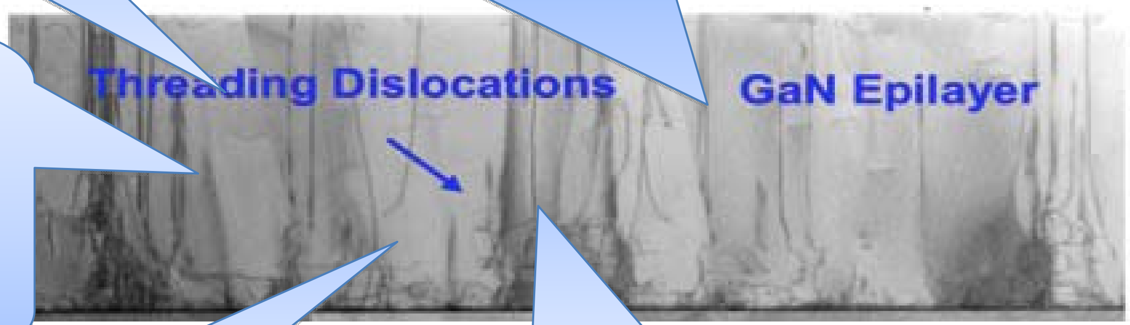
Approaches here extend to system level issues

Nitrides: not an obvious first choice for successful research!

• Lack of GaN substrate: No homo epitaxy (at least the first 15 years)
•16 % mismatch with sapphire

•large lattice mismatch/strain generating defects &huge dislocation density
•often a limitation to growth
•Requires efficient dislocation reduction schemes - Nucleation layer

•Large background n-doping
•No p-doping: at some point, it was thought that compensation by vacancies would forbid hole conduction

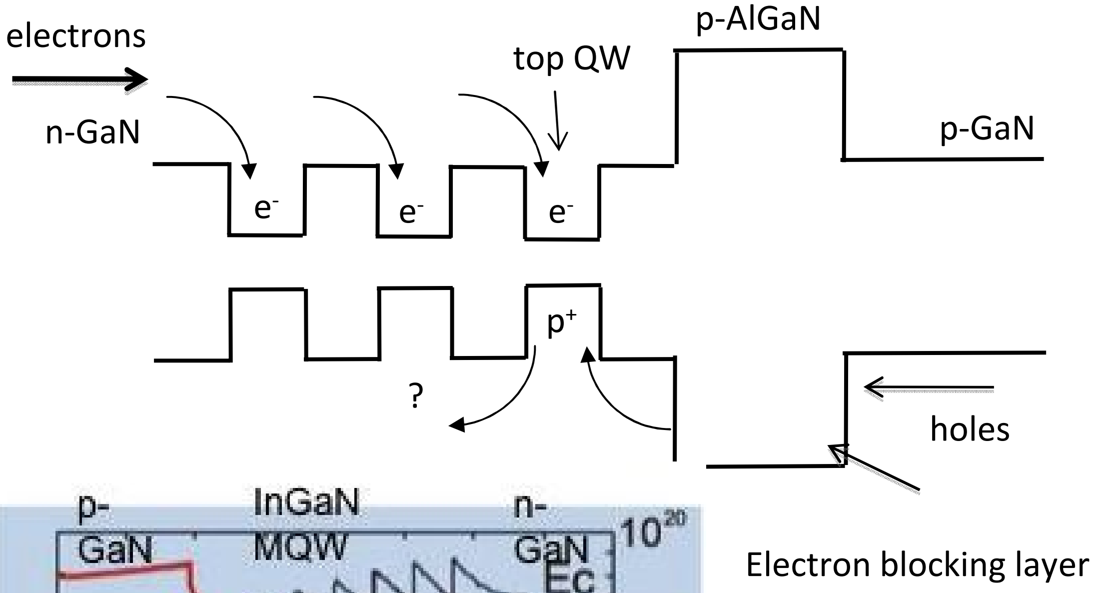


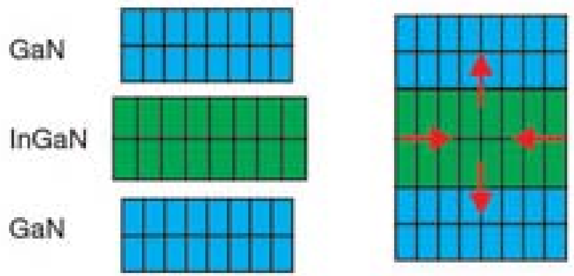
• strong piezoelectric effects acting on charge carriers- often a limitation to QW thickness

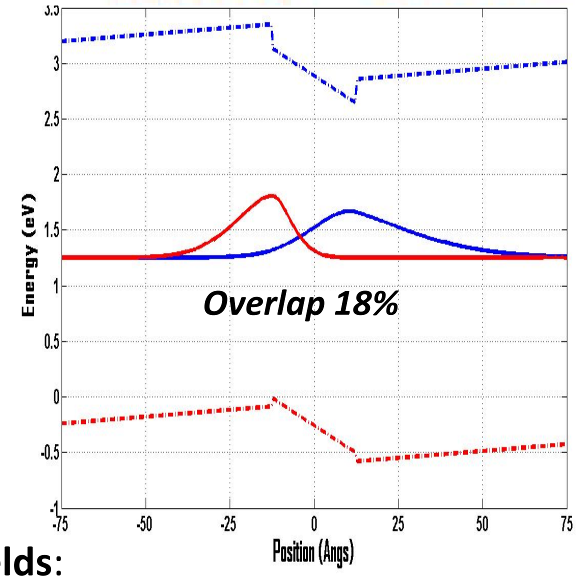
• Large photon energy
• NR recombination will break the bonds

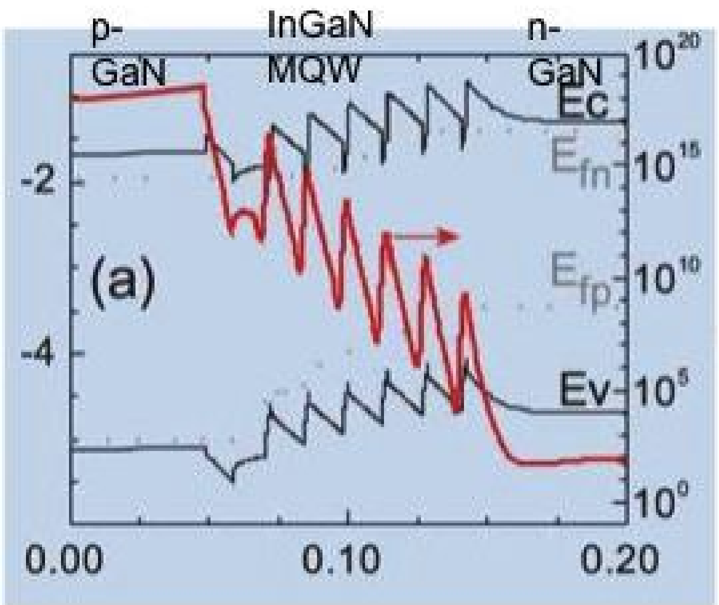
But a remarkable playground, unique in semiconductors by the wealth of phenomena, for researchers in defects and dislocations (so much to see in TEM), in strain and piezoeletric effects, ….

In spite of electrical and piezo electrical injection problems







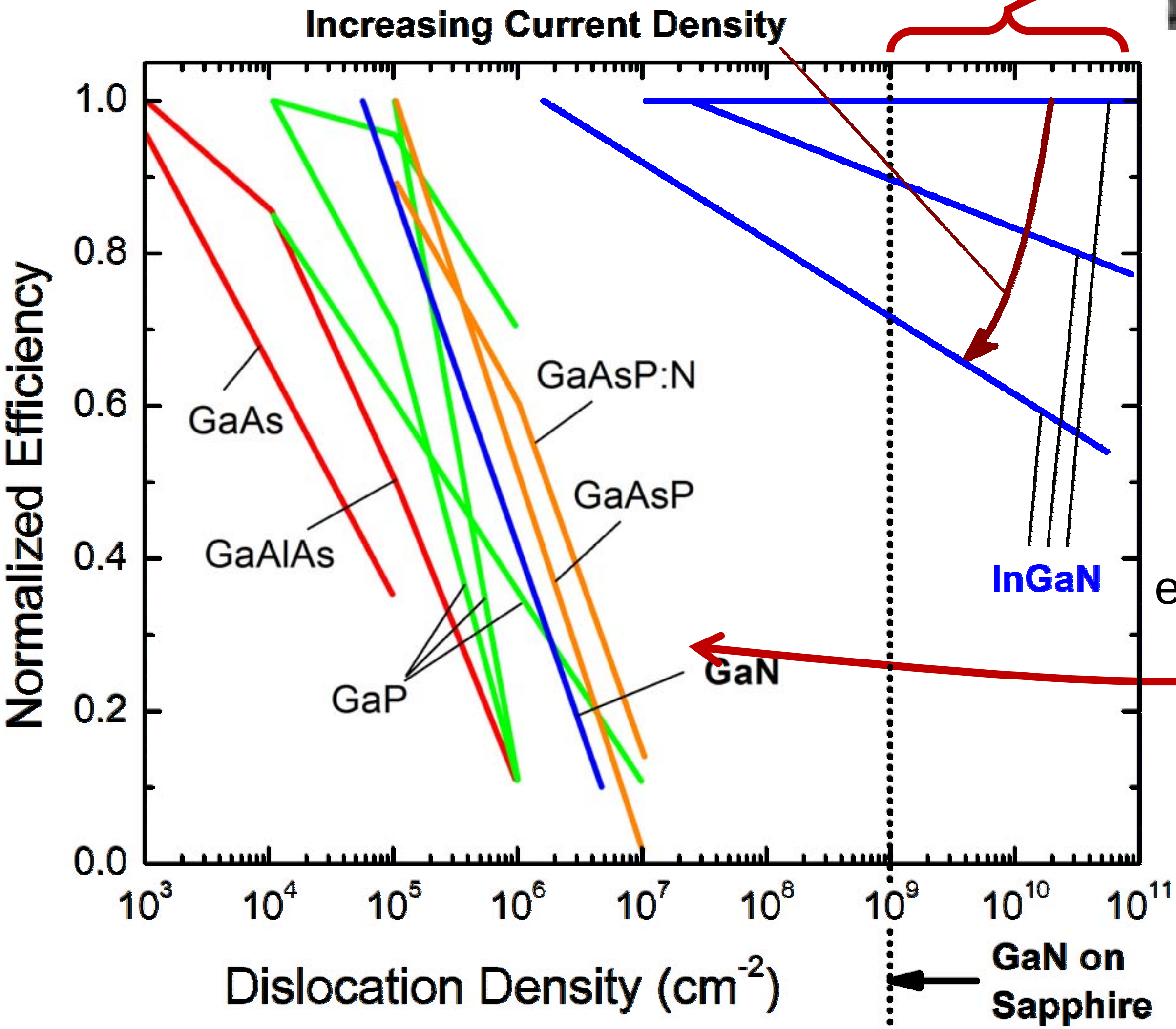


Band extrema and hole concentration in GaN/GaInN MQWs ***(from Ramer, Bridgelux, 2008)***

Huge internal electric fields:
- Spontaneous polarization fields at interfaces between materials with large differences in electronegativity.
-Strain induced piezoelectric fields, increase with In concentration (towards green, yellow, red).

-1V over 3nm = 3 10^6V/cm
Diminishes e-h overlap hence radiative recombination probability.

Comparison InGaN vs. other LEDs



After: Lester *et al*., *Appl. Phys. Lett.*, **66**, (1995) 1249

Inhomogeneous: (InGaN)

Bright (!) despite high defects

Higher currents mask inhomogeneity effects (valleys fill up)

Homogeneous: (GaN,AlGaN)

Dim as defects "swallow" electrons **without** producing light

InGaN Inhomogeneous Alloy=Bright

Homogeneous Materials like GaAs and GaN

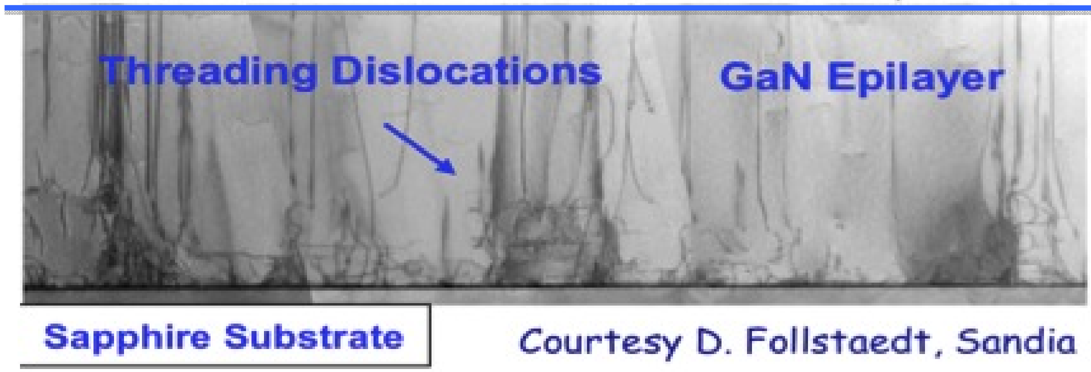
↓

★ **Dislocations**

act as nonradiative centers

η decreases with TD density

In spite of huge dislocations densities



Two mysteries

-**Why efficiency so high as grown?**
High efficiency seems due to presence of In:
-Localisation of carriers (In fluctuations, chains, interface disorder) prevents carriers to reach dislocations (most frequently, and in the beginning surely, any small amount of In increased the QE).
Many other explanations-still a matter of controversy
-Dislocations are not active as NR centers
-They are charged and repel carriers
-etc.
- **why doesn't it not deteriorate in operation?**
    - dislocations should glide under stress and generate new defects & dislocations
    - dislocations motion should be enhanced by non radiative-recombination local energy release.
    - also atoms should be "kicked" by high energy photon, like in IR laser diodes?

Possible Origin of High Efficiency

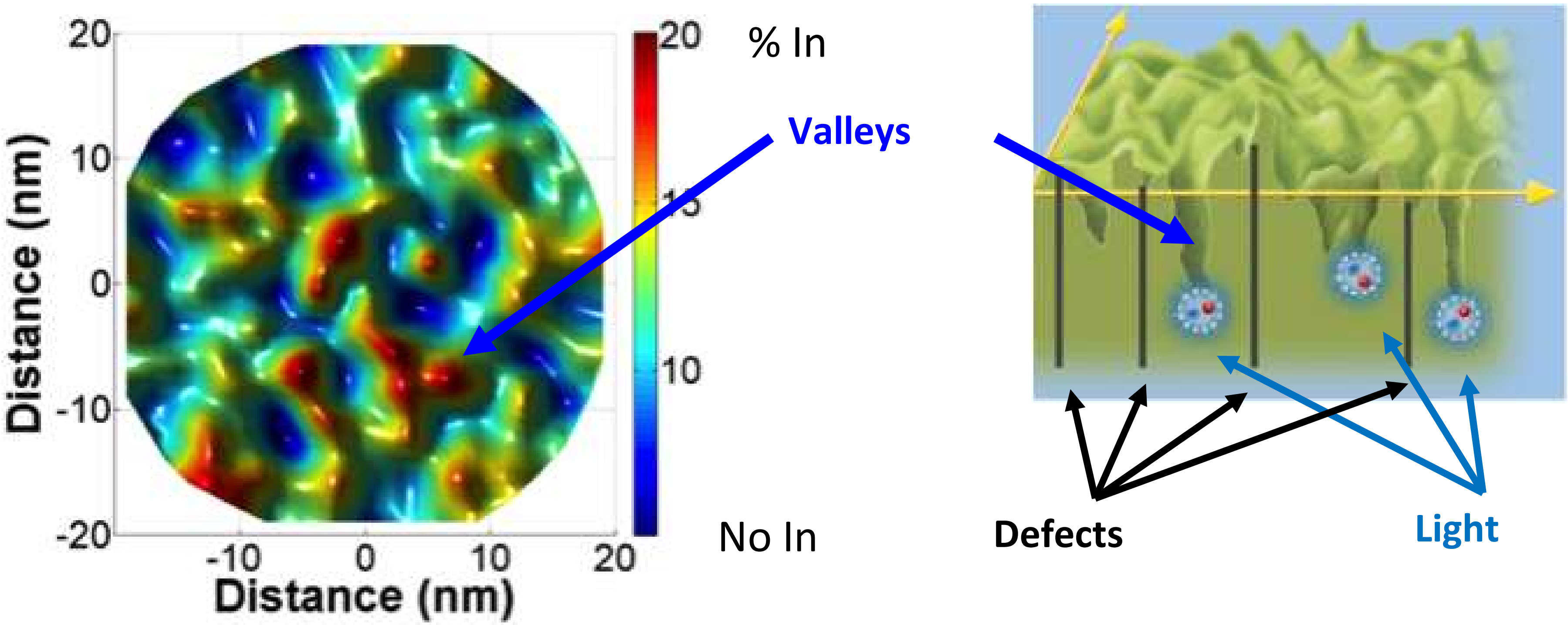
Indium Fluctuations form localized states:

Separate electrons from defects

Top view Indium in Active Layer

Random Binomial Distribution

Side View in Energy Landscape

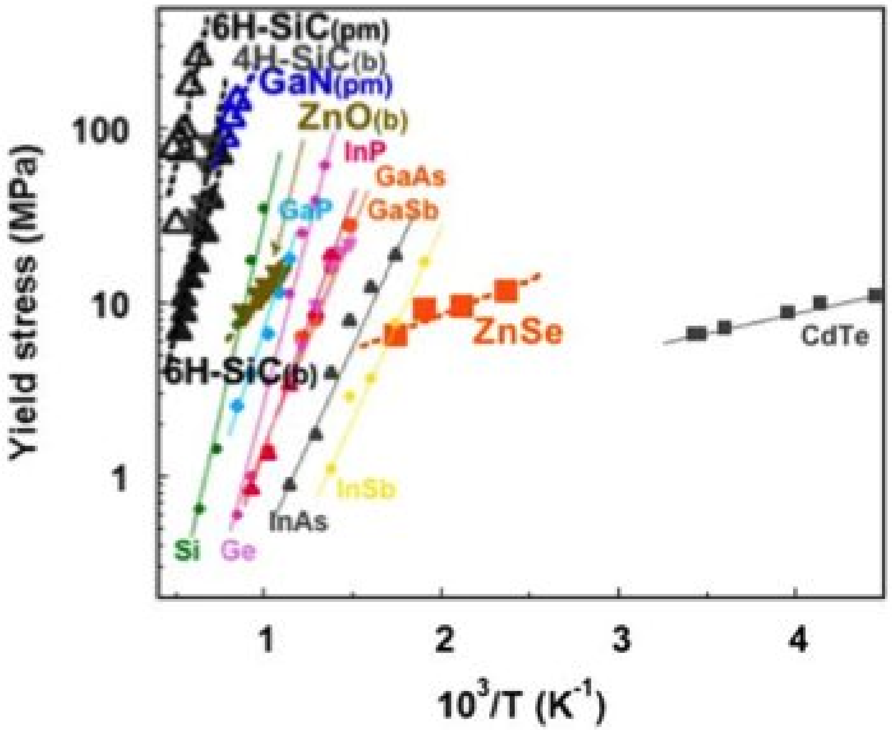


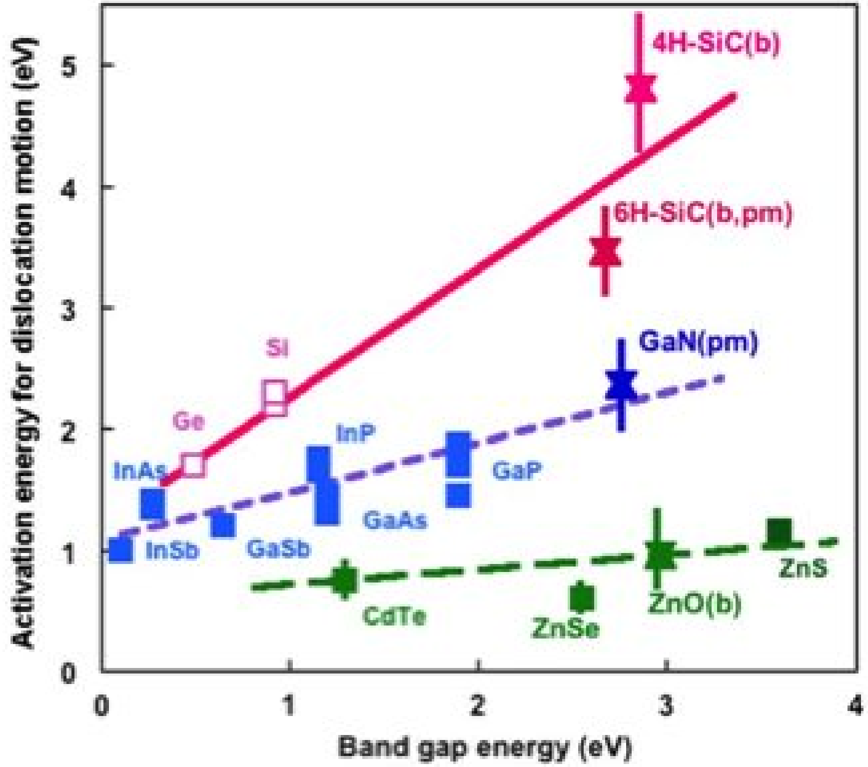
Atom Probe Tomography, D. Browne *et al.*, UCSB

Chichibu, Nakamura *et al.*, *Appl. Phys. Lett.*, **69** (1996) 4188; *Nature Mater*. **5**, (2006) 810

Dislocation glide: dislocation velocity v seems very low due to hardness

$$v = v_0(\tau/\tau_0)^m \exp(-Q/k_B T).$$





≈ 1 eV increase in Q for GaN means v ≈10^{10} slower than in II-VIs

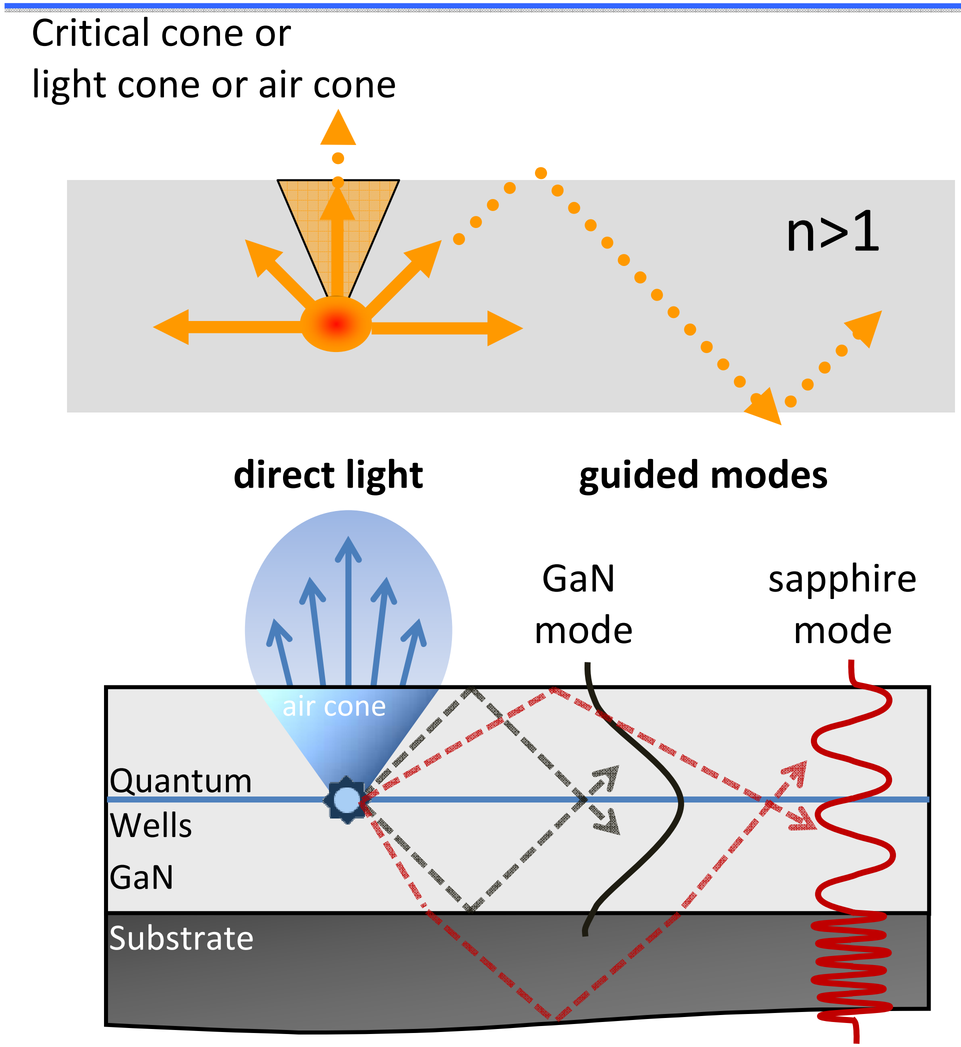
Based on identation, not clear SiC has moving dislocs

Peierls stress is low in II VIs

More subtle effects: no shear stress in basal plane in c axis GaN -no dislocation motion in that plane

I. Yonenaga et al. Physica B 404 4999 (2009)

Light extraction in LEDs



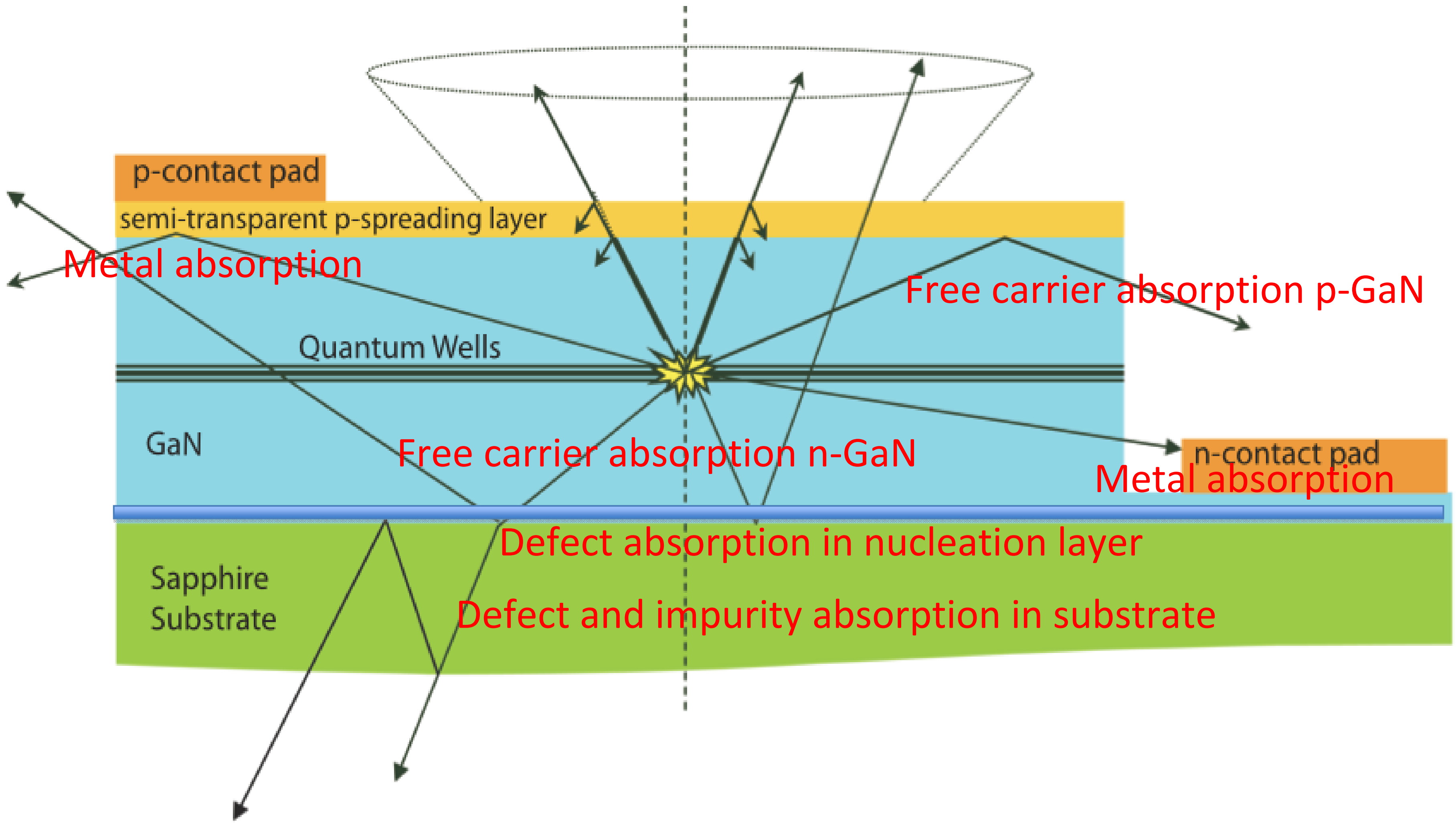
~ 12% of emitted light is extracted
~ 88 % is trapped in the semiconductor as guided modes due to total internal reflection at the semiconductor air or encapsulant interface

More precisely, in planar structures, light is emitted in modes guided either in the nitride layers (66%) or in the substrate (22%)

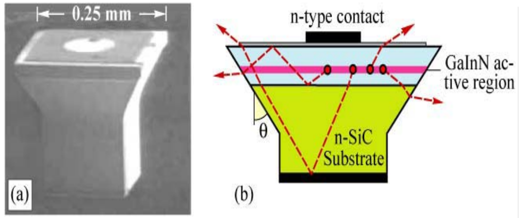
Dominant light extraction schemes are based on destruction of the propagating guided modes by using non-planar structures. The physics of extraction is well described by geometrical optics concepts and ray tracing simulations

Light should be absorbed after many passes ?

In real LEDs many dissipation opportunities are competing with multipass extraction



Light extraction in LEDs: present techniques

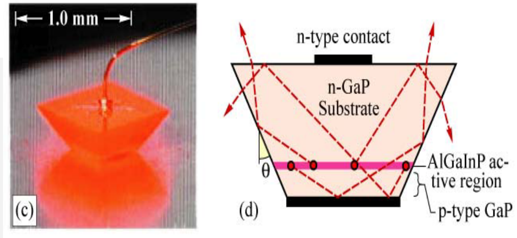


Shaped SiC substrate
Cree

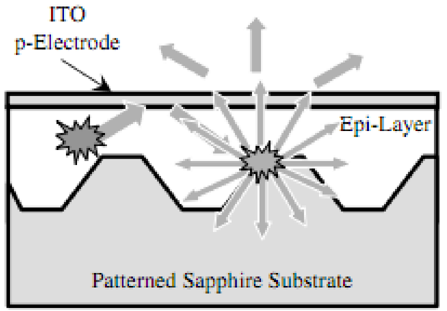
Up to 80%+
Complex process

Shaped transparent substrate

- non planar process
- light propagates long distance; requires ultra low internal loss



Krames, Craford
philips lumileds 1994

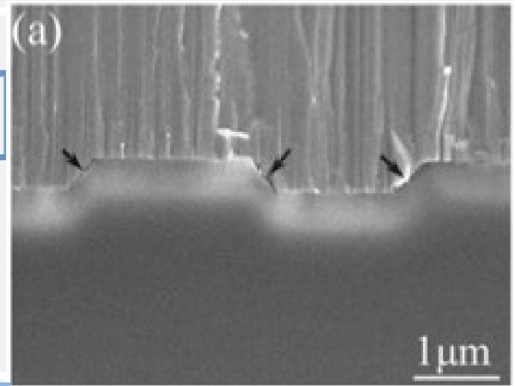


Micromirrors
ThinGaN OSRAM

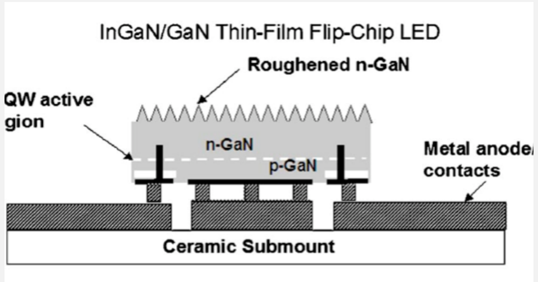
PSS: Patterned Sapphire Substrate

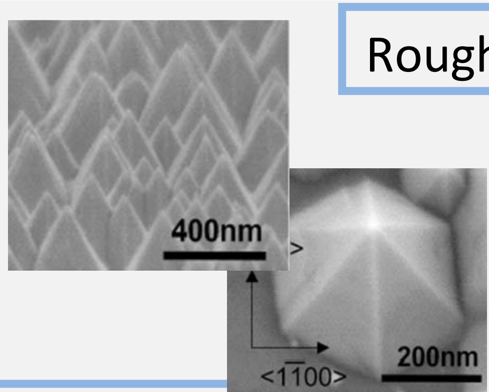
- poor thermal properties
- Improved IQE

Mitsubishi 2001, Nichia 2002



Fujii, Nakamura 2004



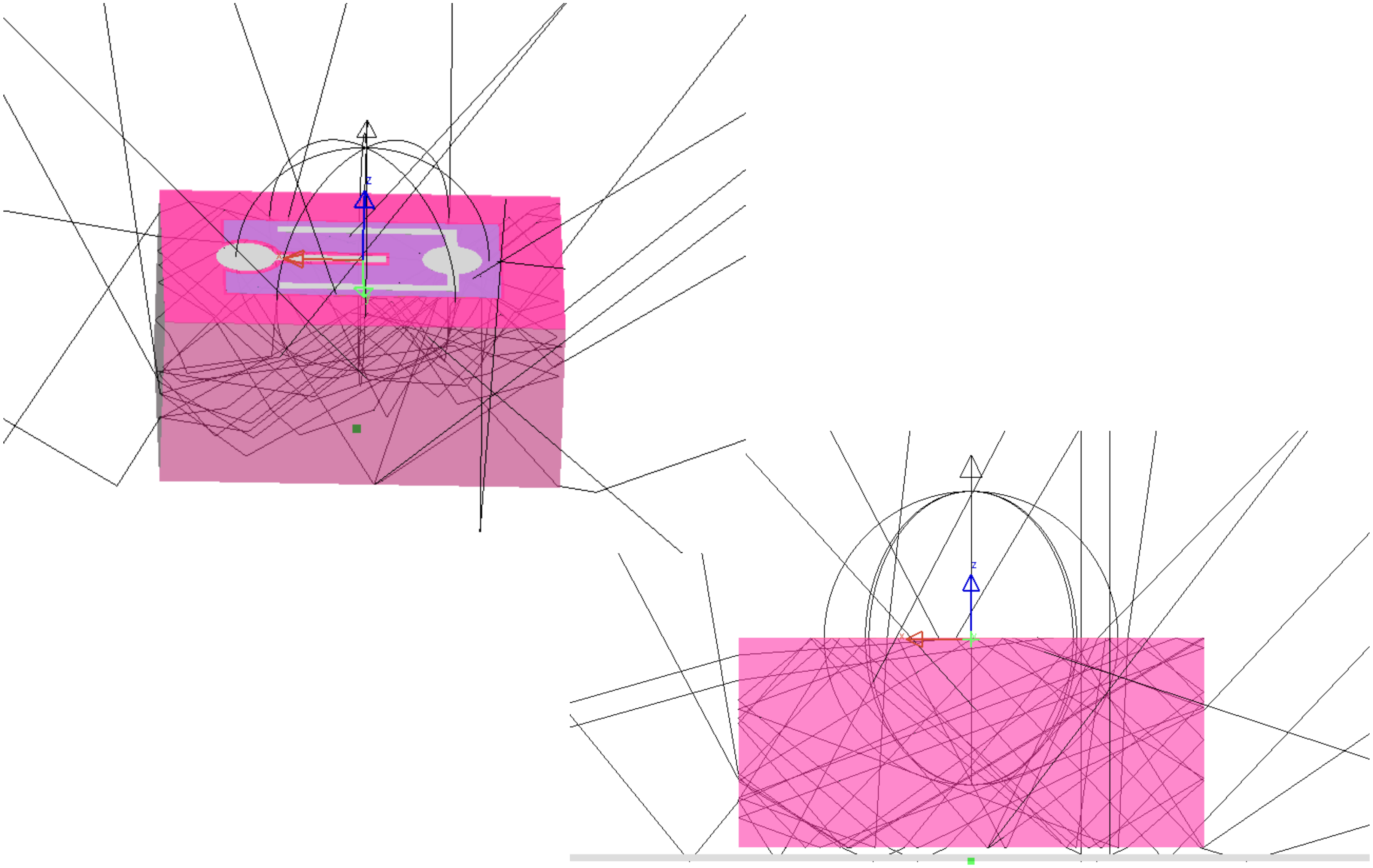


Roughened surface

- not efficient if substrate not removed
- needs thinning down to minimize materials absorption
- complex and expensive fabrication

Flip Chip + Roughened surface Philips Krames

Ray Tracing for Light Extraction Modeling



LEE Comparison for the Three Chip Designs

	Roughened GaN Substrate Chip	Patterned sapphire substrate	Flip Chip
Total Efficiency	**72.1**	**78.1**	**77.8**
Loss in PSS		0.3	-
Loss in GaN substrate or buffer layer	12.1	0.2	1.1
Loss on n-contact	0.8	0.6	-
Loss on Mirror	5.6	4.5	18.0
Loss in ITO	3.6	6.8	-
Loss on p-contact	3.5	5.1	-
Loss in n-GaN	1.5	2.0	1.4
Loss in p-GaN	0.8	2.4	1.8

@92%

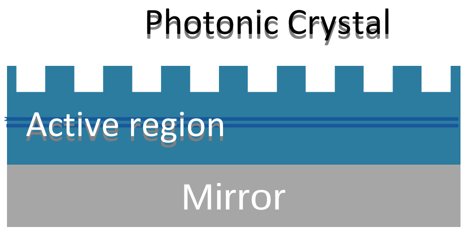
Values given for chips encapsulated in epoxy

Light is extracted after 2.5-3 roundtrips

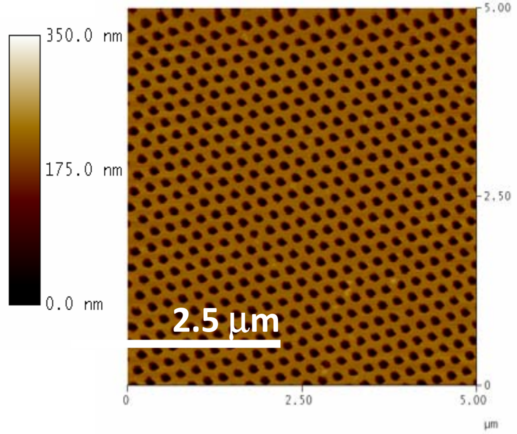
Various types of PhC LEDs: hope-beat losses better than by roughness

Optimizing horizontal structure

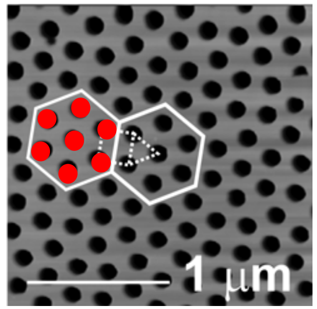
Surface photonic crystals



Triangular lattice



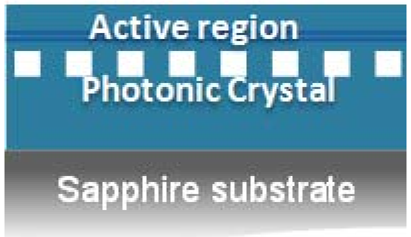
Archimedean lattice

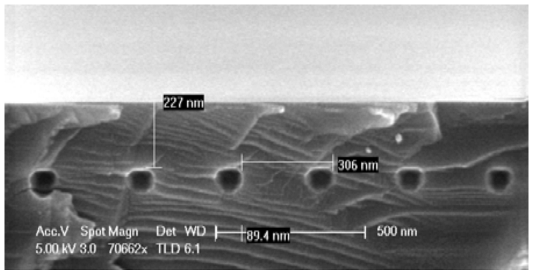


7 atoms (holes) / unit cell
→ constructive interference on some diffraction orders

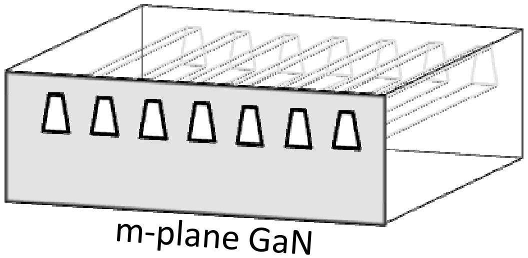
Optimizing vertical structure

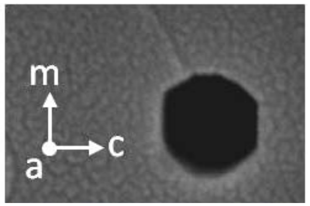
Embedded photonic crystals



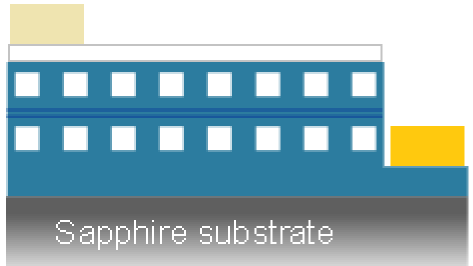


Embedded stripe PhC for Polarized LED

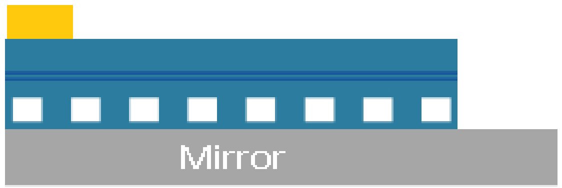




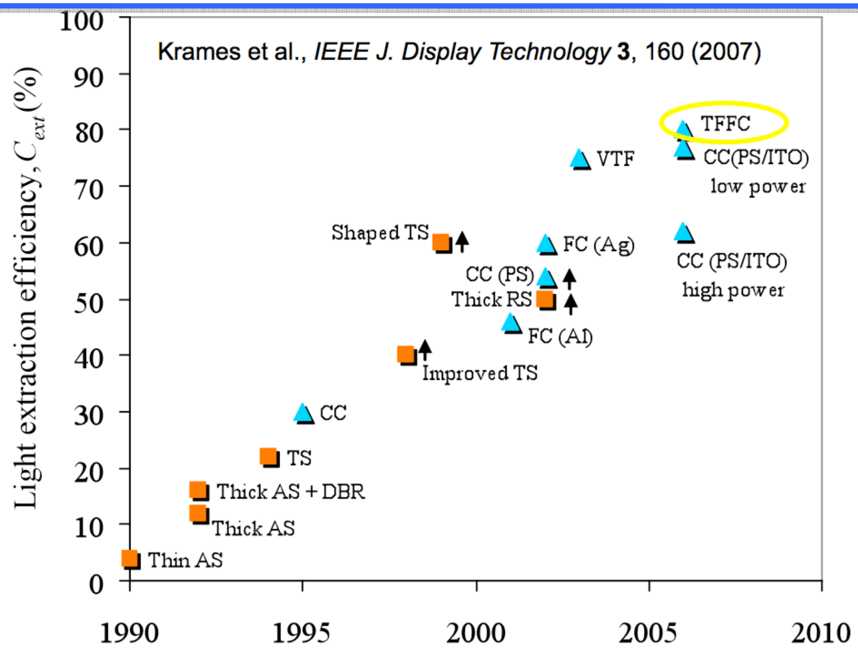
Double embedded PhCs



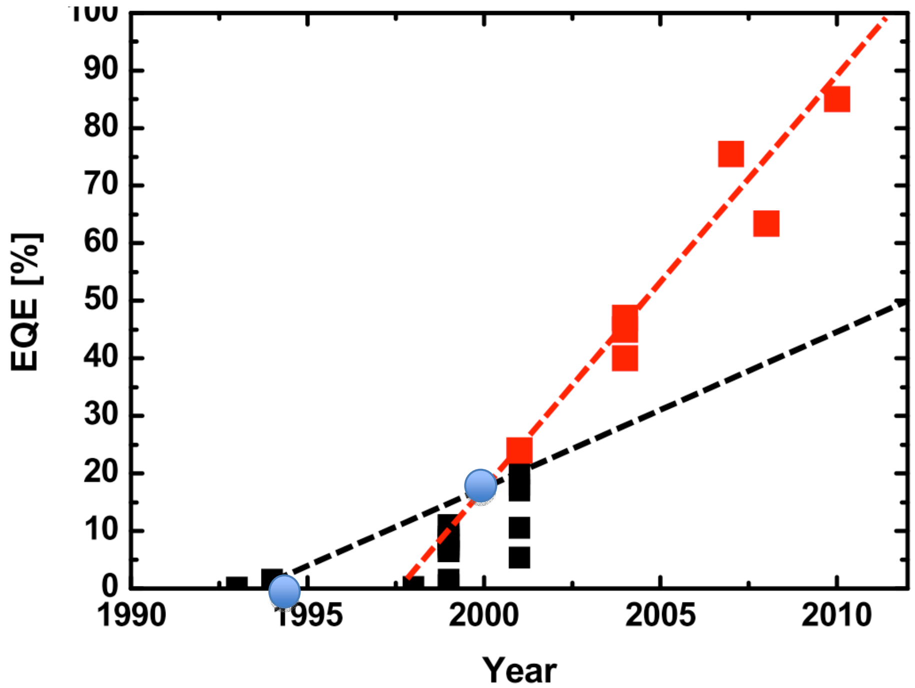
Flip-chip (FC) embedded PhCs



History of the improvement of EQE of GaN-LEDs



M. Krames et al., Status and Future of High-Power Light-Emitting Diodes for Solid-State Lighting. IEEE J. Dsplay Technol. 3, 160 (2007).

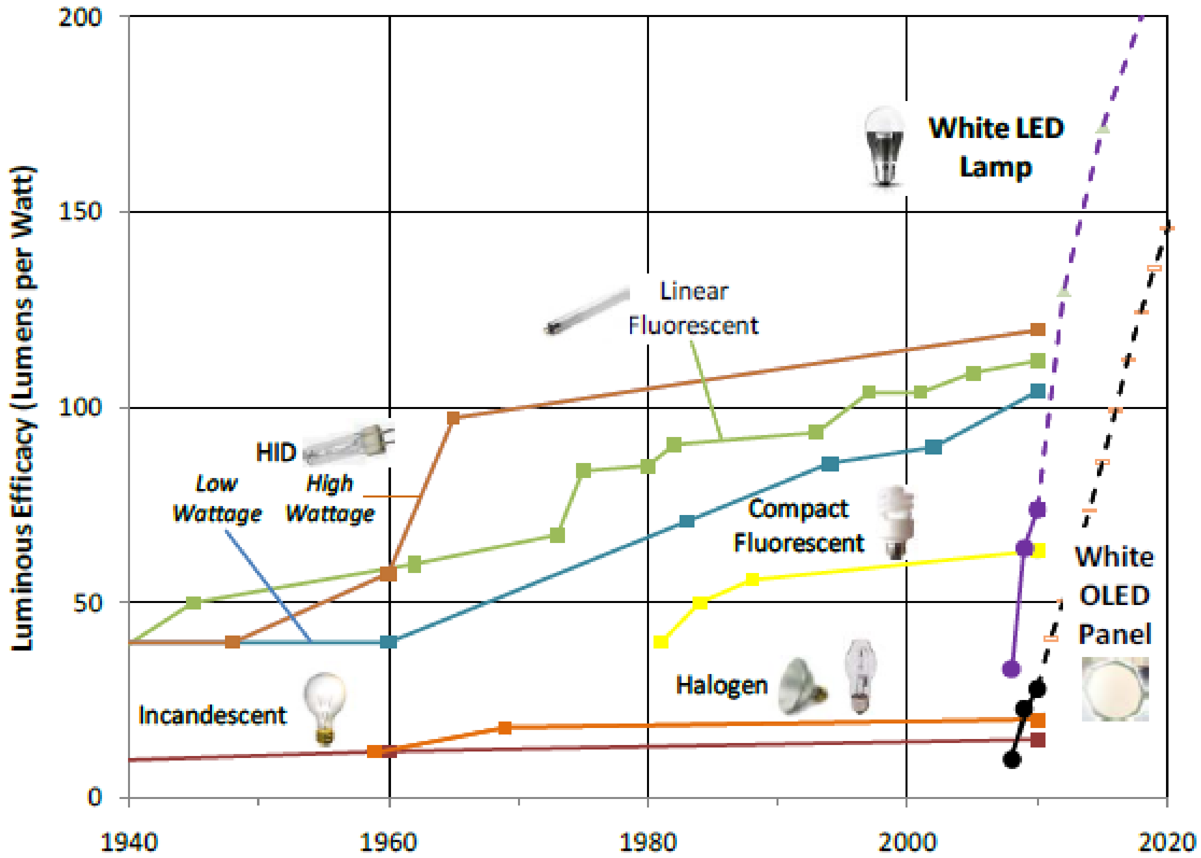


Kazuyuki Tadatomo
Epitaxial Growth of GaN on Patterned Sapphire Substrates
T.-Y. Seong et al. (eds.), *III-Nitride Based Light Emitting Diodes and Applications*, pp. 59-81
Topics in Applied Physics 126, Springer
Dordrecht 2013

A big part of the progress in the past 10 years has been on extraction efficiency more than on IQE

Why do we worry ? Major challenges remain

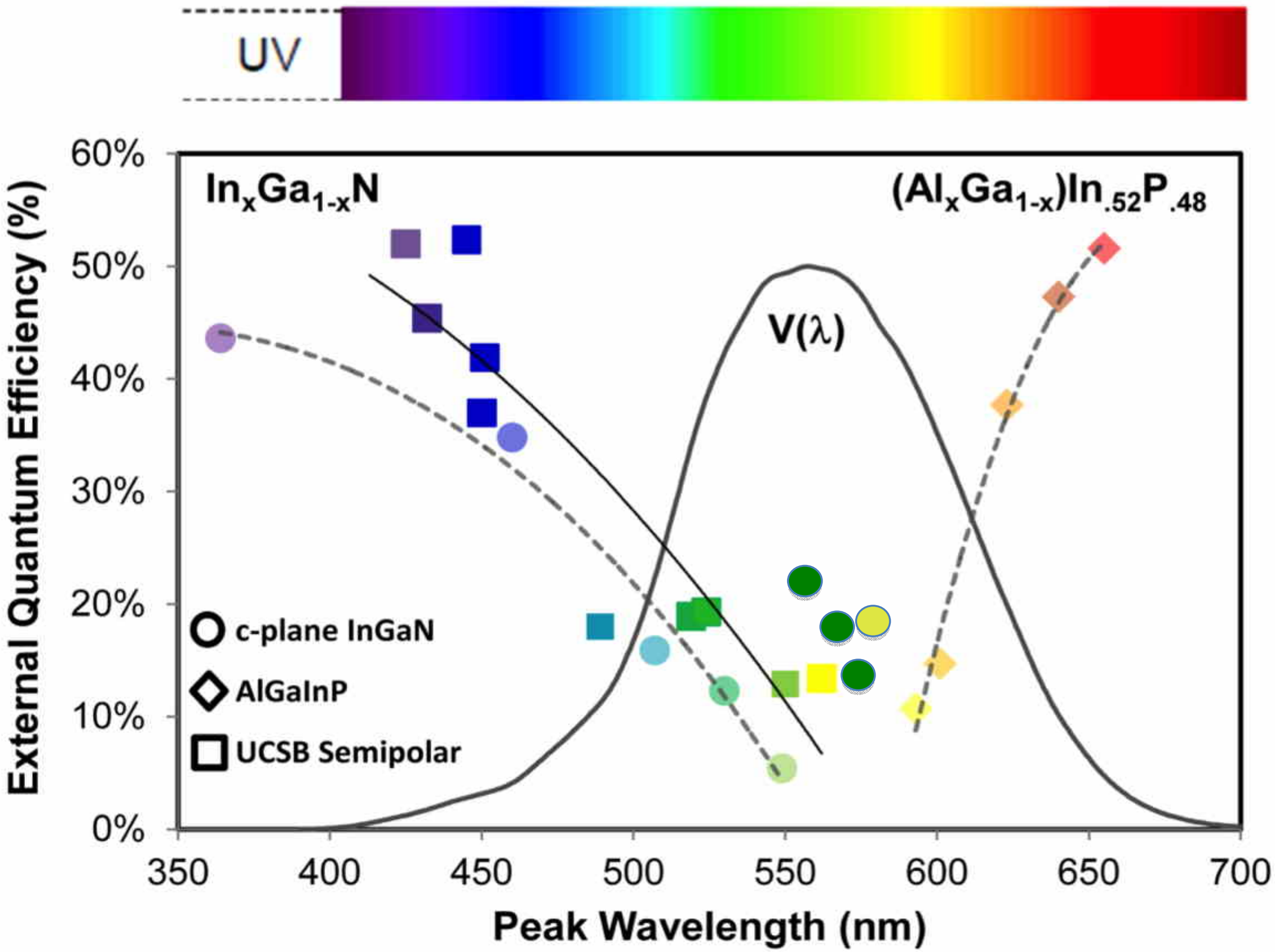
300 lm/W
R&D hero



>120 lm/W
Mfgr basis

- -Green gap
- -Droop: all nice figures given at low current density (pulse operation, controlld temperature)
- -Cost – price shock compared to conventional lamps

The ‘Green Gap’



- Hashimoto et al., Phys. Status Solidi C **11**, 628 (2014)
- Saito et al., Applied Physics Express 6, 111004 (2013)

Difficulty to incorporate high Indium concentrations, without defects

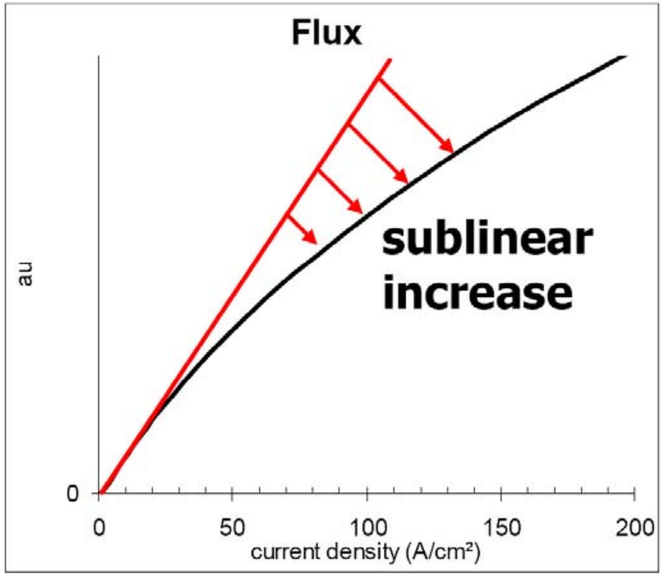
Electric field becomes very large as strain is very large (Indium atom very large)

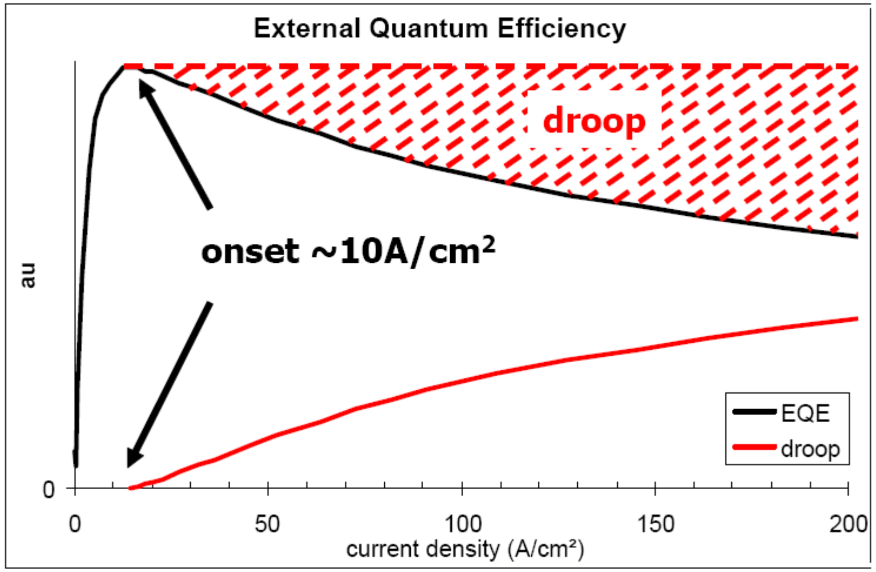
Semipolar LEDs may have the potential to solve the green gap

*C-plane data are from non-thin-film flip-chip devices

**All data collected at 22 A/cm^2 or 35 A/cm^2

Efficiency Droop





InGaN-based LEDs

→ Peak EQE at 1 - 10 A/cm^2
→ At higher current, LED rapidly lose efficiency
→ Independent of color

Potential Cause: **Auger** recombination (internal efficiency) ~n^3

- Based on scaling of non-radiative loss - experimental measurement
  [Shen et al. Appl. Phys. Lett. **91** 141101 (2007)]
- First-principles rate indicate Auger recombination may be a significant
  [K.T.Delaney, P. Rinke, and C.G.Van de Walle, Appl. Phys. Lett. **94** 191109 (2009)]

The cost of droop

Seoul Semiconductor announces 140 lm/W AC-driven LED light engine

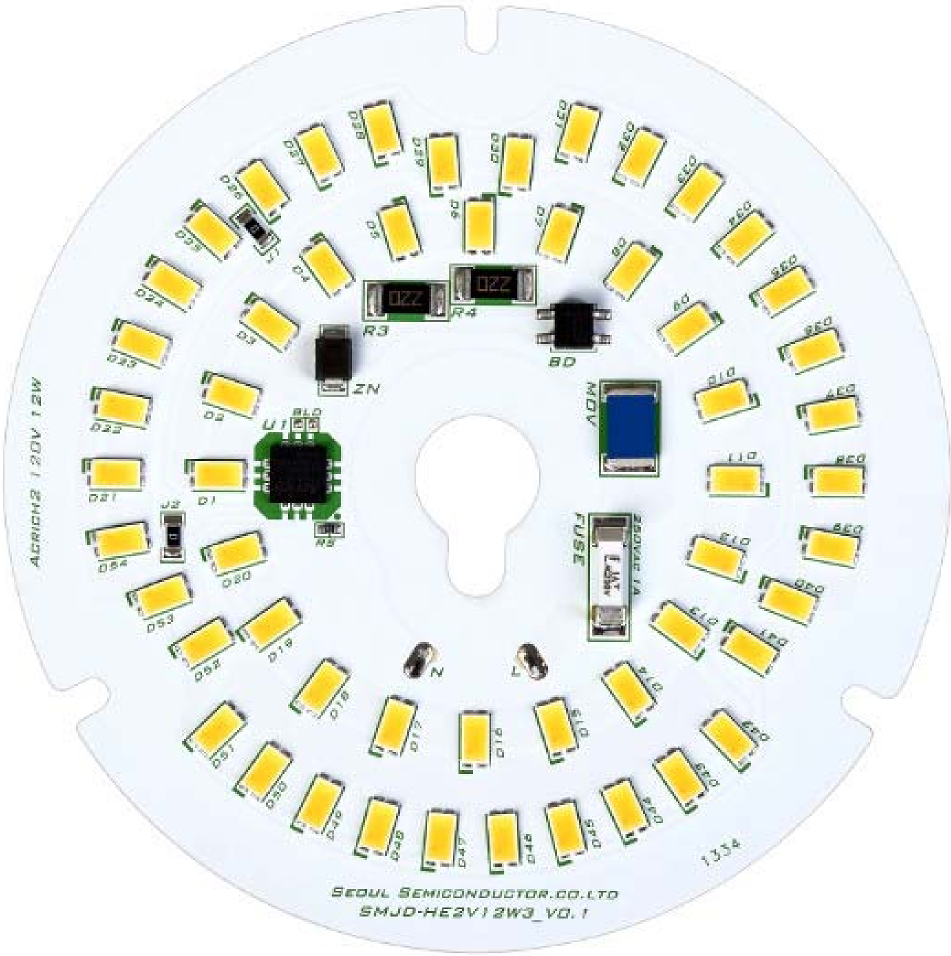
LEDs MAGAZINE

16 Sep 2013

Because of efficiency droop
at high current density,
many chips are required

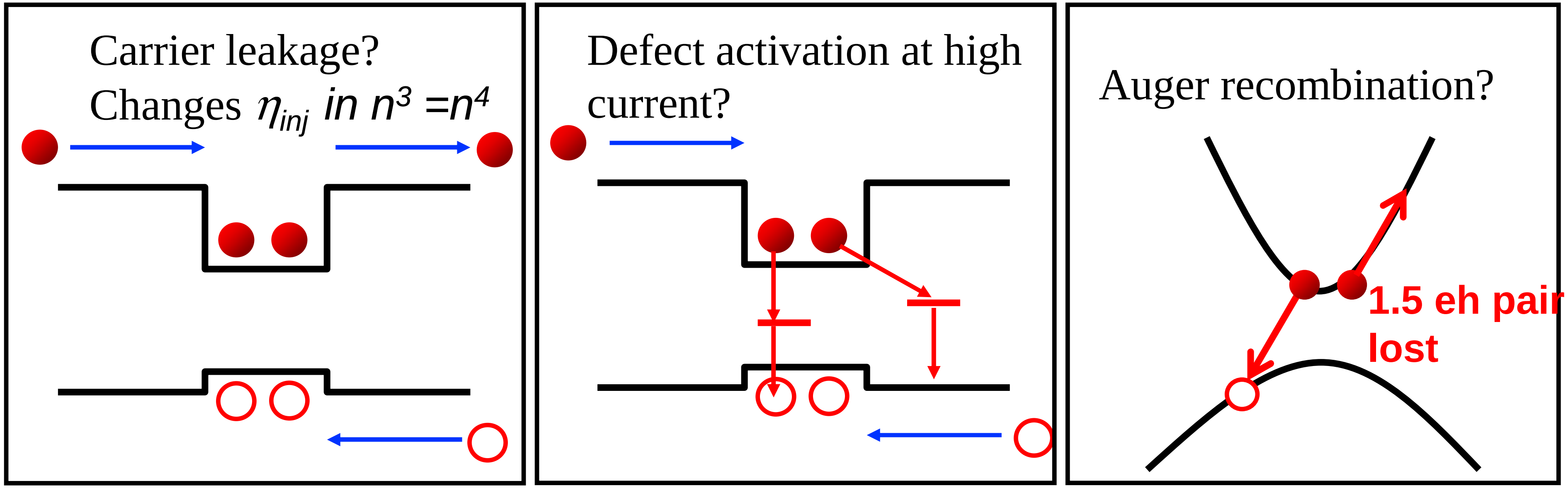
Droop is solved at a cost!

10W => 3A
60 LEDs @ 1mm^2 = 0.6 cm^2
=> 5A/cm^2



10W modules deliver 1400 lm in cool white or 1250 lm in warm white

Origins of efficiency droop

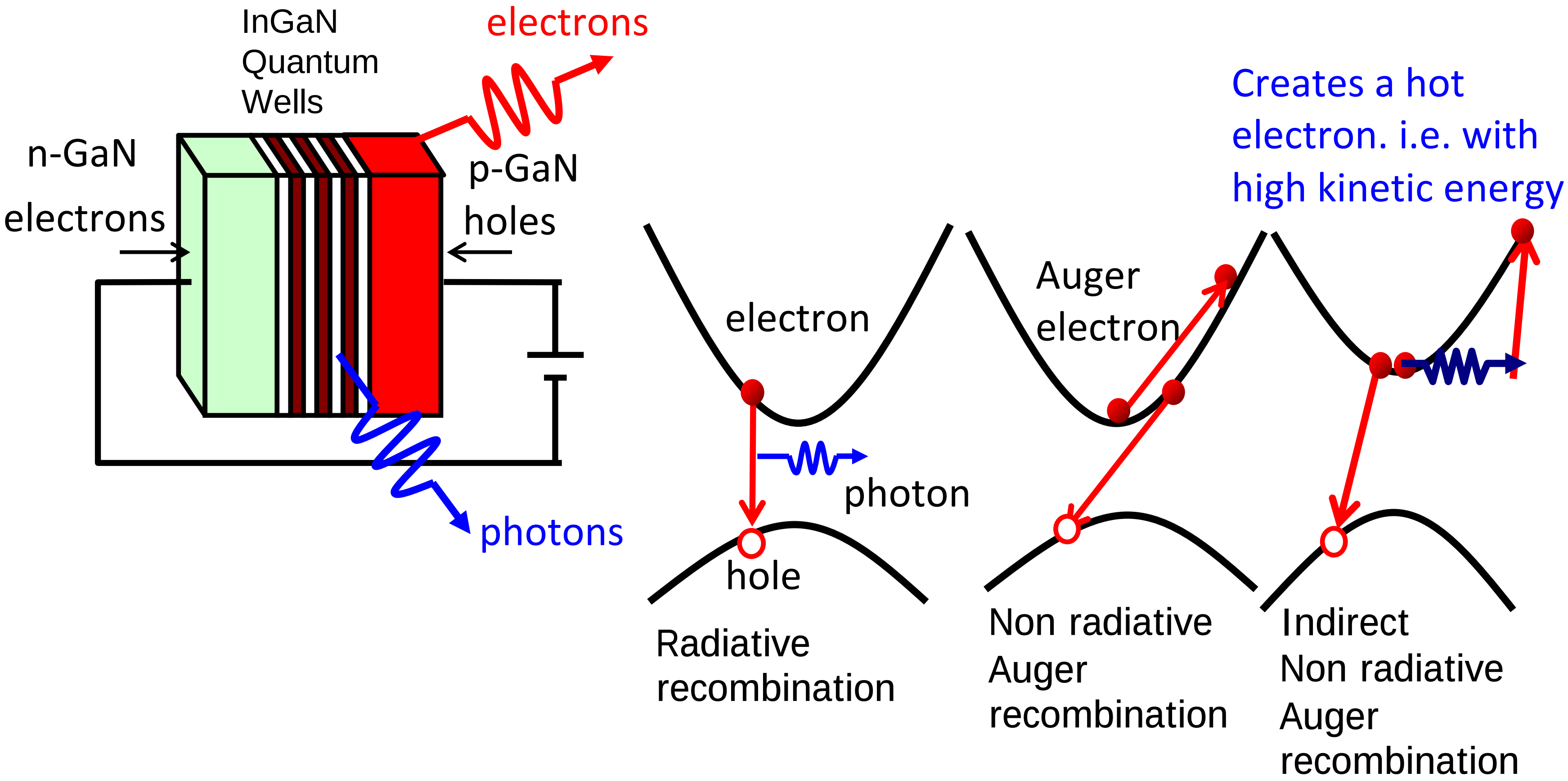


Engineer barrier heights, EBL, dopings, etc.	Carriers are localized at low current, avoiding NR defects	Rate ~n^3 Diminish carrier density

- Based on scaling of nonradiative loss ~n^3 Auger effect been invoked (Shen2007)
- But other mechanisms can be fitted too.
- Curative effects also not a unique signature of Auger effect: increasing active layer volume to diminish carrier density also diminishes leakage mechanisms

So far, hard experimental "signature" for any mechanism missing

Focus on favoured droop mechanism: Auger recombination process



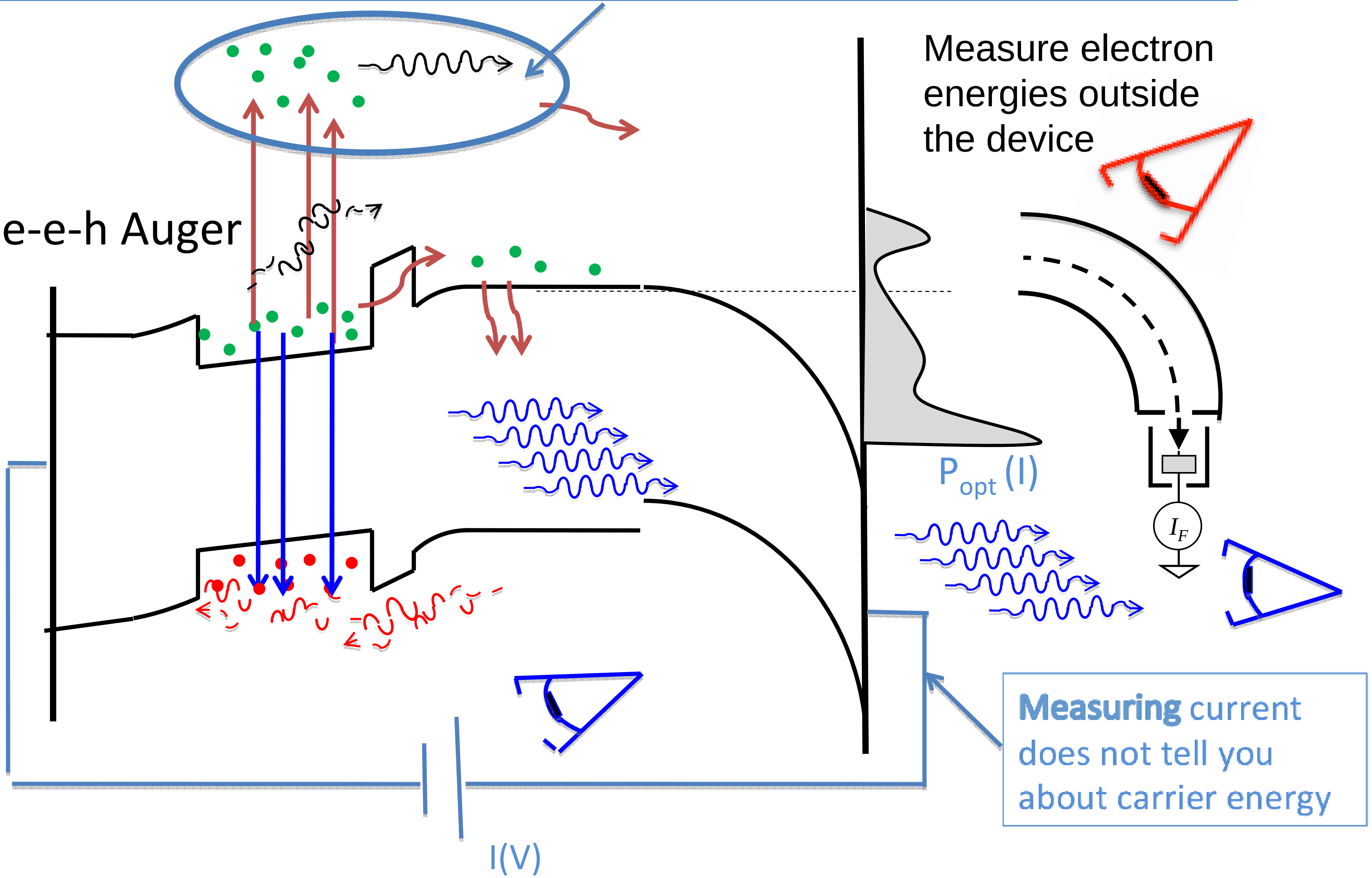
The signature of an Auger process is the generation of electrons with high kinetic energy

Theory: direct Auger process probability is small, but phonon-assisted Auger of the order of few $10^{-31} cm^6 s^{-1}$

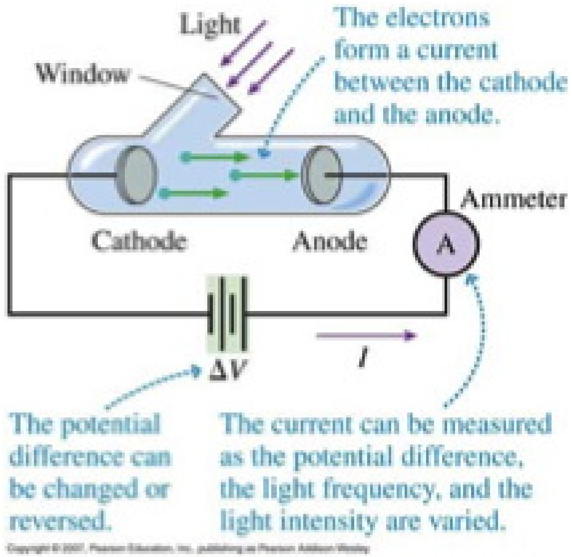
Kioupakis, Rinke, Delaney, Van de Walle, APL 2011

A new technique to directly observe Auger recombination as the droop mechanism

If there is Auger recombination , you should see hot electrons

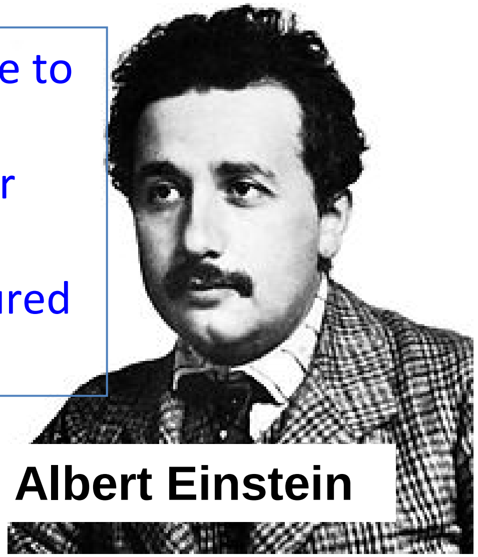


Measuring electron energy outside materials: an old story
The photoelectric Effect (Hertz, 1887)

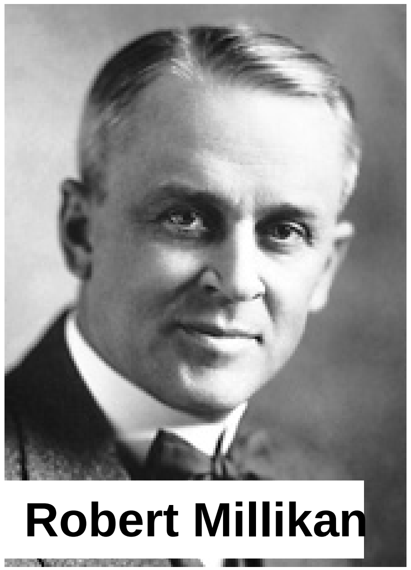


Light quantization 1905

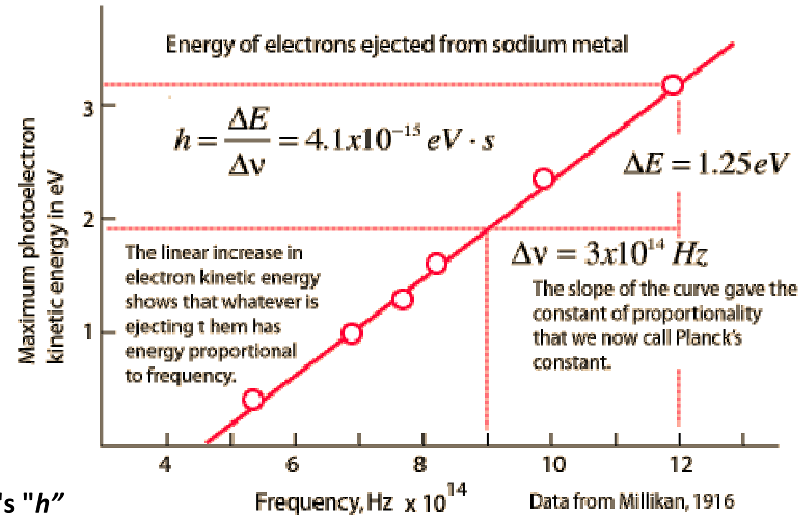
- Electrons are ejected from metal due to photoexcitation.
- Through ejection they conserve their kinetic energy
- Ejected electron energies are measured by a retarding/accelerating potential



Measurement of Planck's constant 1916

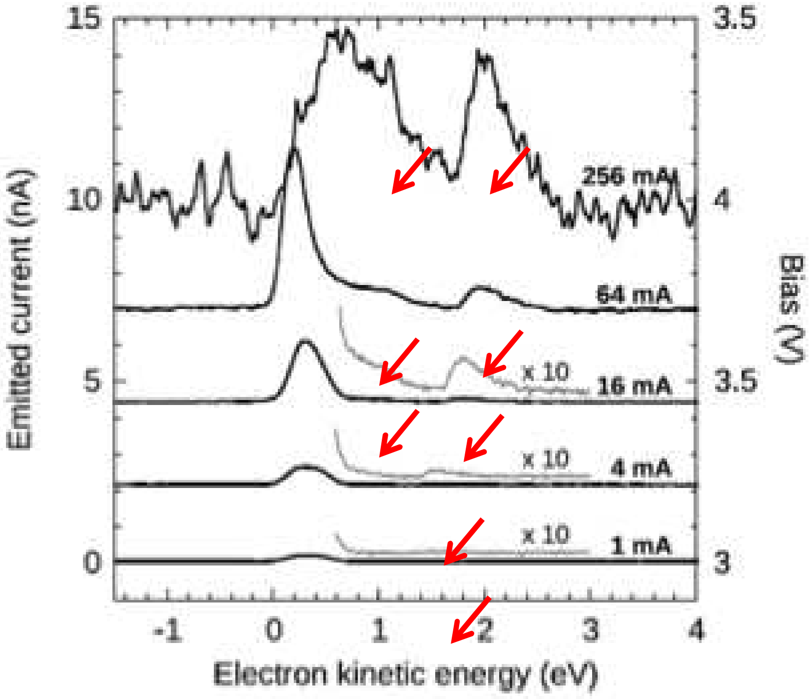


R.A. Millikan Phys. Rev. 7, 355–388 (1916)
"A Direct Photoelectric Determination of Planck's "*h*"

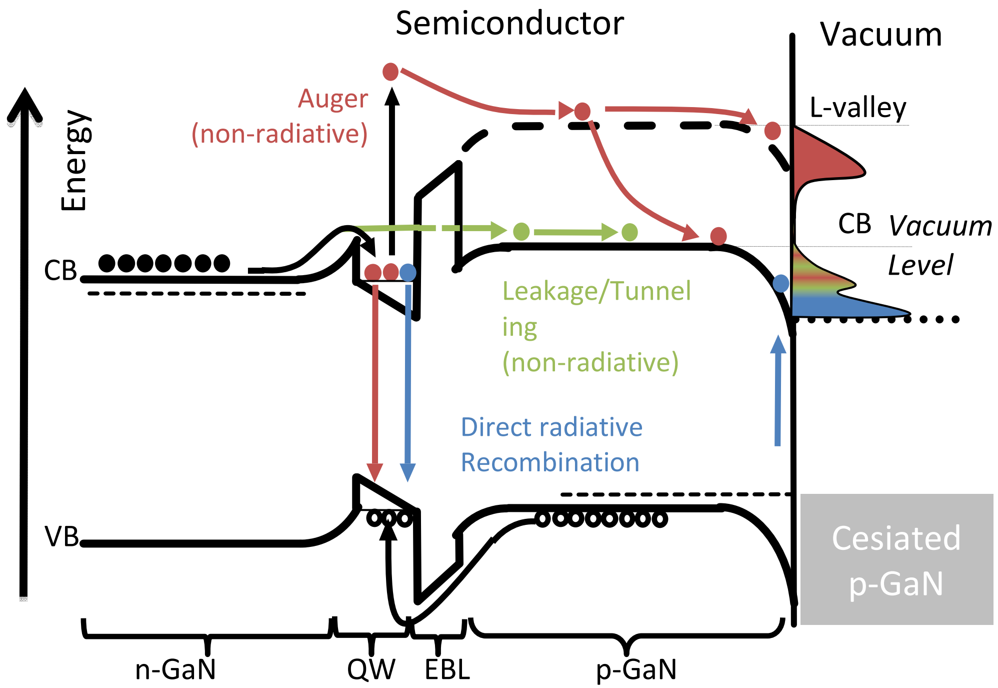


Energy analysis of ejected electrons, mechanism

Under high current injection, high kinetic electrons appear, which can only be generated by Auger effect in the LED as there is no high electric field or large energy barrier discontinuity in the structure



•Pulsed measurements (reduce heating)
•Field distortion at high current reduces signal



J. Iveland, L. Martinelli, J. Peretti, J. S. Speck and C. Weisbuch, "Direct Measurement of Auger Electrons Emitted from a Semiconductor LED, Phys. Rev. Lett. 110,177406 (2013)

Same peak positions as observed in photoemission

Piccardo, Martinelli, Iveland, Young, DenBaars, Nakamura, Speck, Weisbuch, and Peretti. Phys. Rev. B 89, 235124 (2014)

Why go for the few last efficiency %?

- Why absolute efficiency matters: needed to displace high efficency fluorescents
- Why are the last % are essential: improvement is non linear if thermal load is the limiting factor (diminishes need for complex cooling architectures, thermal droop).
- Think about system

	WPE 40%	WPE = 60%	WPE = 80%
Heat extracted from lamp sets chip power limit	20W	20W	20W
Heat % of input power: 100% - WPE	60%	40 %	20 %
Total input power	33.3W	50 W	100 W
Light output: (input) – (heat)	13.3W	30 W	80 W
Relative power compared to 40% LED	0%	225 %	600 %

LEDs for lighting - the physical and materials basis

1. Light emitting diodes (LEDs) 101
2. Light sources – it is not just photons and watts
3. Visible LEDs, a long road from red to blue
4. The state of the art - the remaining challenges
5. The impact 1 energy savings
   The huge energy reservoir to tap from
   The competition – needed/ more than 100lm/W
   The cost of change –cost of ownership
6. The impact 2 bringing safe and cheap light where there is none
7. The impact 3 improving quality of light

Tapping the energy reservoir

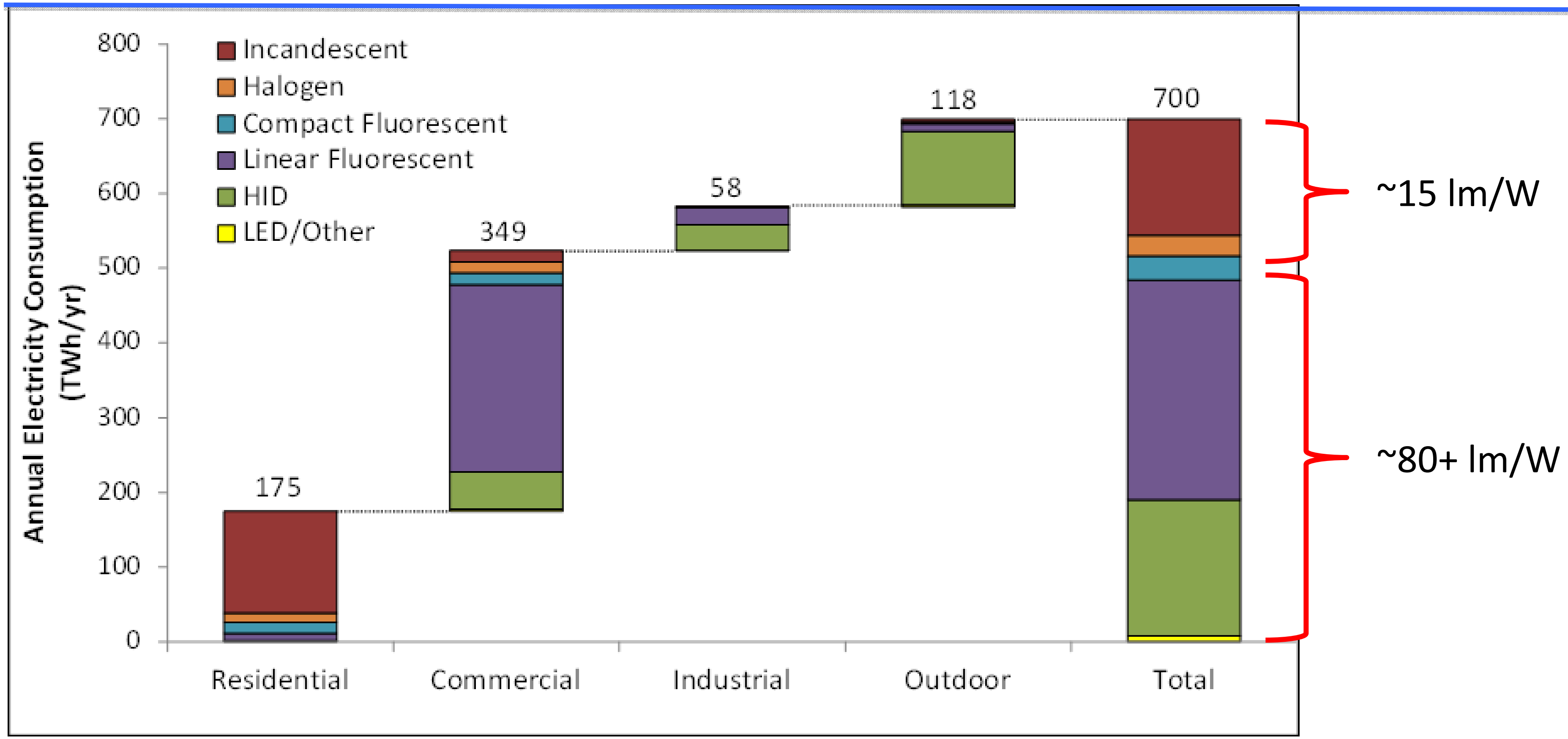
In the US, lighting is 22% of total electricity use

In Europe, lighting is 15% of total electricity use

Worldwide average: 20%

Objective: saving at least half of this electricity consumption

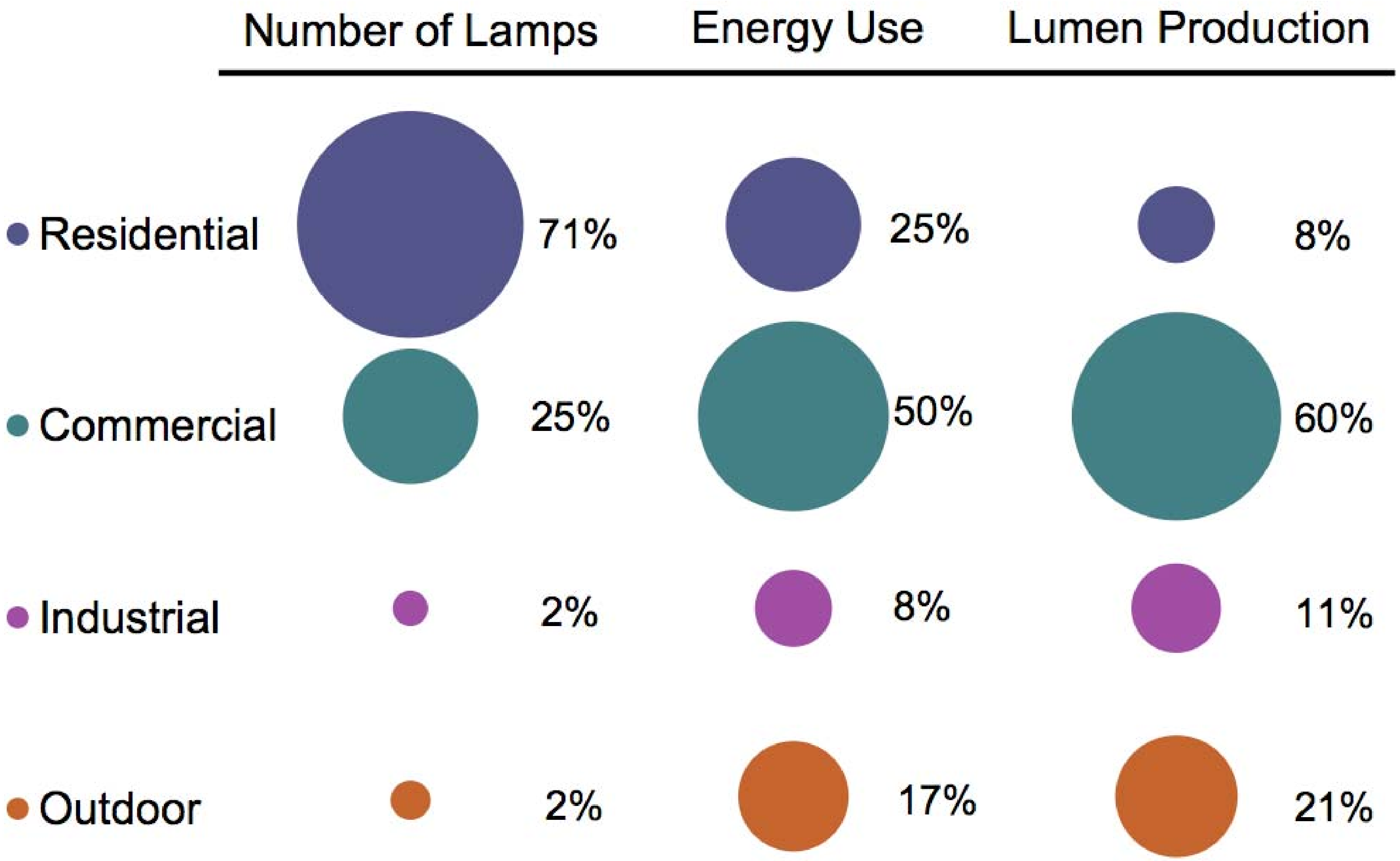
Lighting – U.S. Lumens Production



Linear fluorescent and HID, ~80-120+ lm/W: ~4.5 x 10^{12} lm
Incandescent + halogen, ~15 lm/W: ~0.35 x 10^{12} lm

*SSL ultimately needs >>100 lm/W to displace linear fluorescent and HID**

Source: DOE SSL MYPP 2014 – available at:
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2014_web.pdf



U.S. LIGHTING INVENTORY, ELECTRICITY CONSUMPTION, AND LUMEN PRODUCTION, 2010 [1]

Source: 2010 U.S. Lighting Market Characterization. Prepared by Navigant Consulting, Inc., January 2012.

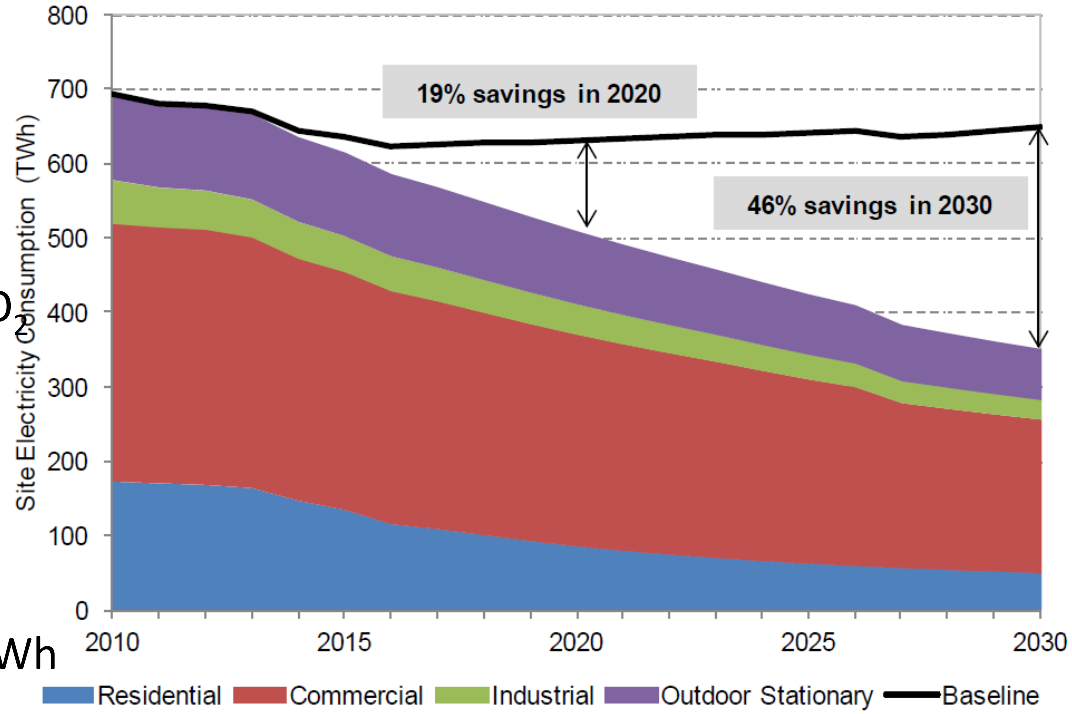
Does 5% change in lighting efficiency make a difference?

Electricity production worldwide: 41% coal, 21 % gas
In terms of *equivalent coal*, as gas produces half as much CO_2 as coal, 50% coal.
1Kilogram Coal = 24 megajoules
(6.7 kWhs) - produces 3.6kg of CO_2

1kWh produces 0.5 x 3.6/6.7= 0.27 kG of CO2/ plant efficiency 0.38 = 0.71 kG CO_2

World electricity production: 22 000 TWh = $2.2\ 10^{13}$ kWh in 2011

Lighting uses 20% of electricity $4.4\ 10^{12}$ kWh



5% change in light generation efficiency is $22\ 10^{10}$ kWh, means $22\ 10^{10} \times 0.71\ 10^{-3}$ tons of CO_2

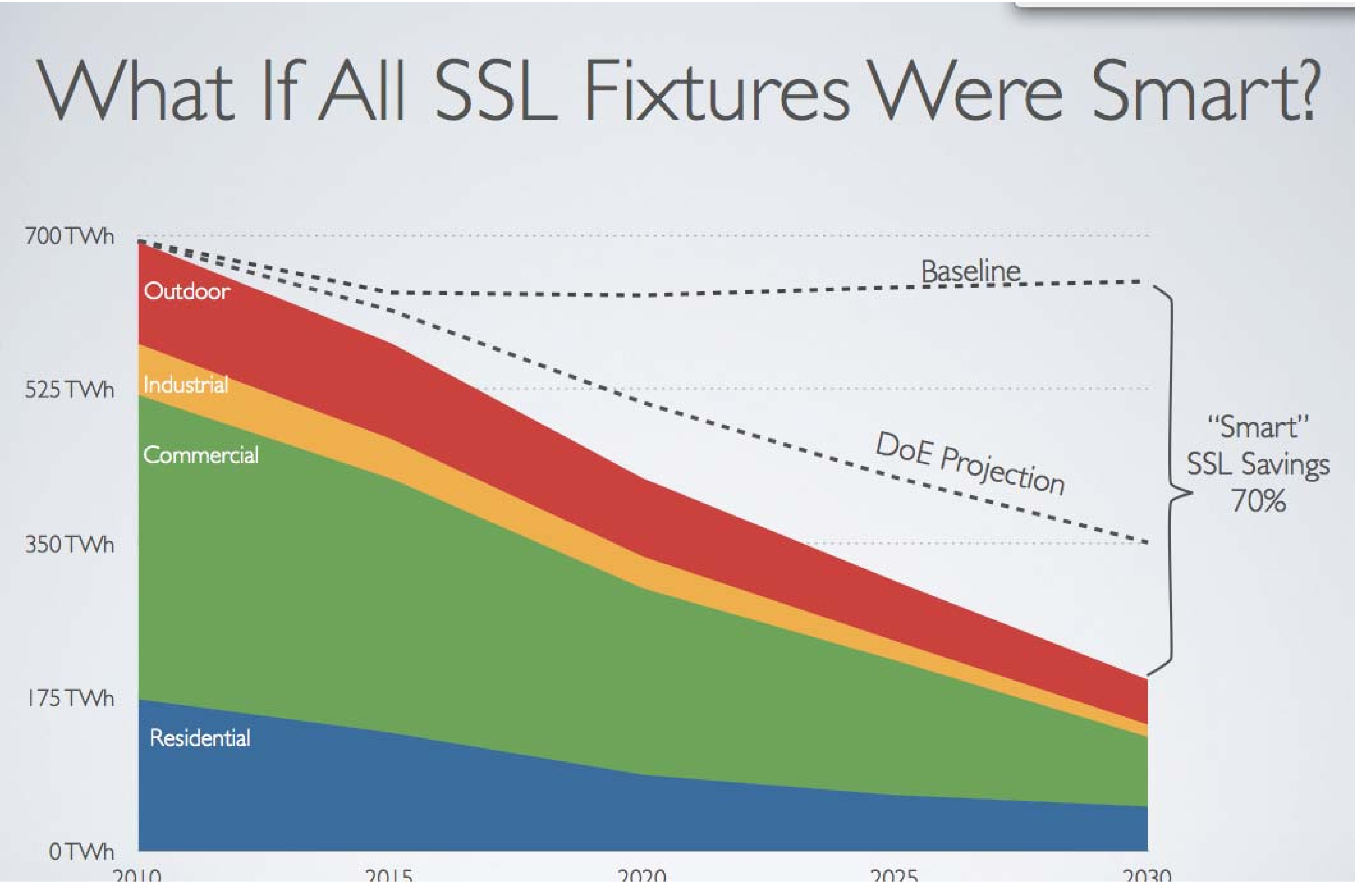
5 % change in light generation efficiency is 150 million tons of CO_2 per year

This is for today's electricity consumption for light generation, @ 75 lm/W average

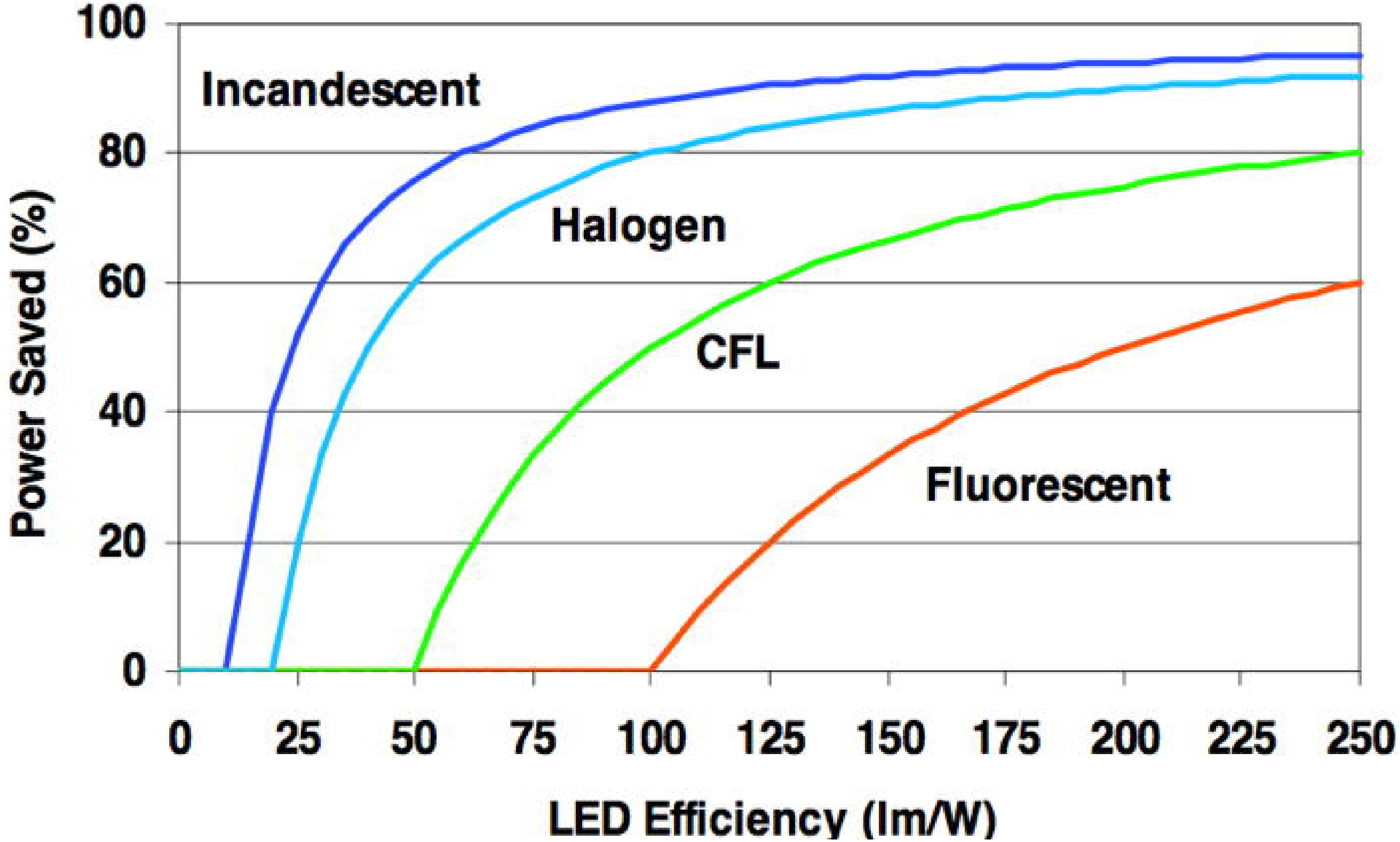
If tomorrow average is 150lm/W, then 5% change represents 75 million tons of CO_2 per year

Additional savings by smart lighting

Brian Chemel, DoE SSL R&D Workshop 29 Jan 2013



Potential Power Savings vs. Traditional Lighting



To save electricity compared to incandescent, 15 lm/W is enough; to save compared to fluorescent, at least 100 lm/W is needed.

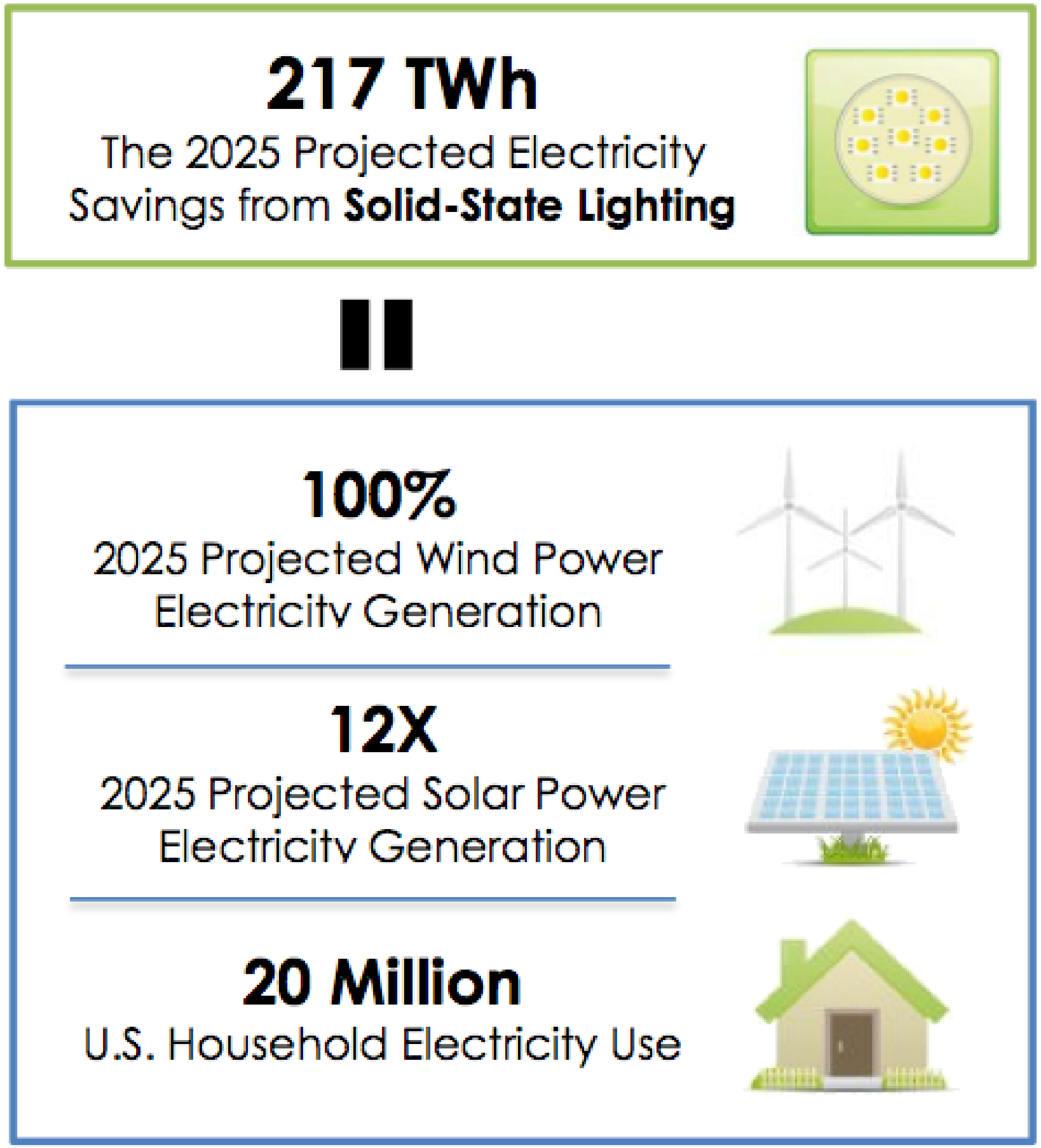
Paul S. Martin Lumileds

2025 Projected Annual Electricity Savings from SSL *provided we reach 200lm/W*

Numbers from "Annual Energy Outlook 2014 Table: Renewable Energy Generating Capactiy and Generation, Reference Case,"

Energy savings for the US only

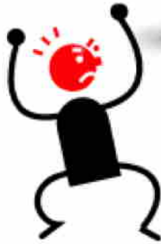
Source: DOE MYPP 2014



Upfront Cost:

Sticker Shock:

All sources: ~ 800 lumens
Warm White
Tier 1 brand



<$1

$3-5

$40 X

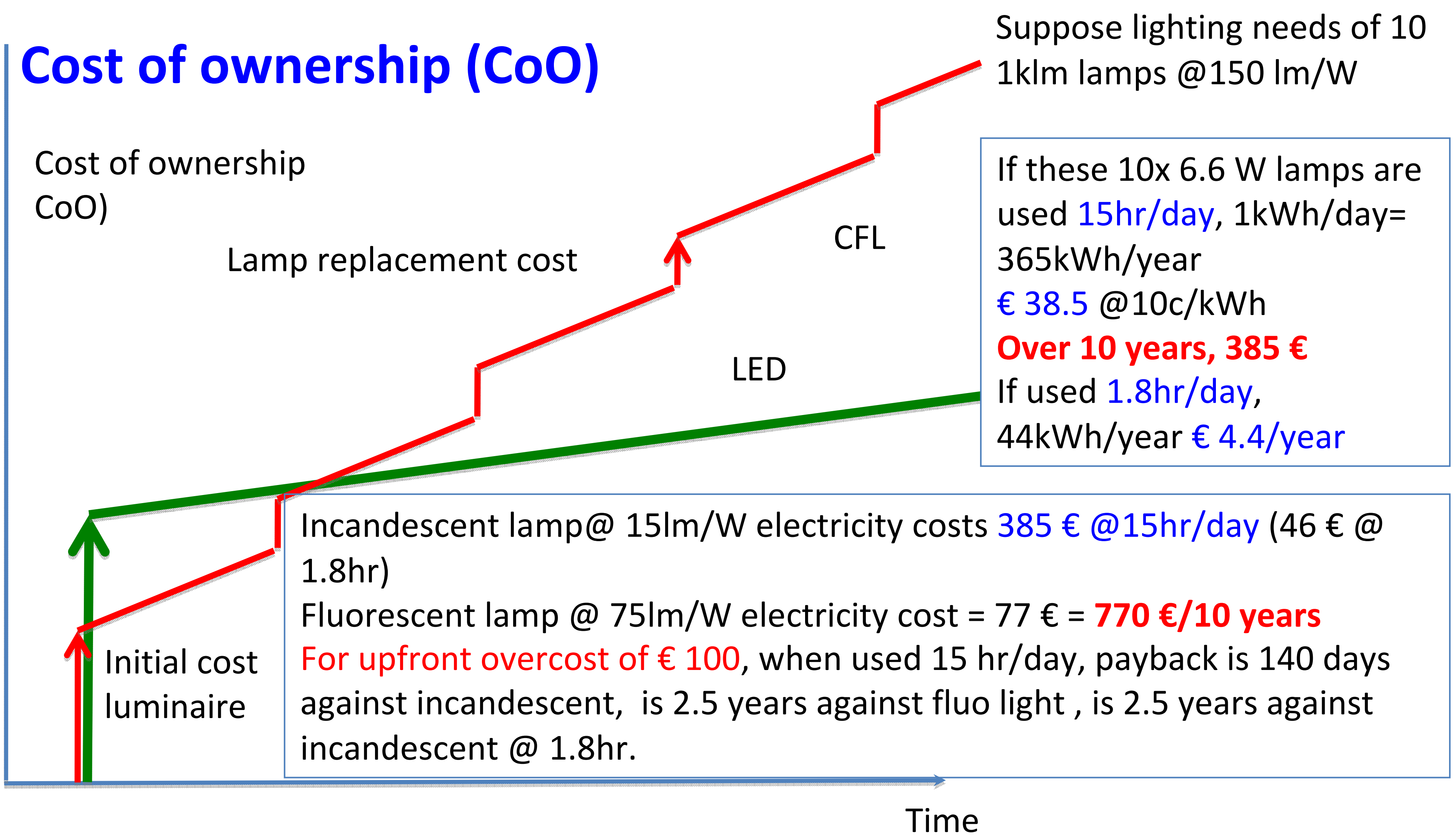
In 2011

Need to reduce $/lumen !

Now: $ 10!

Why pay so much a new (replacement) lamp?

Cost of ownership (CoO)



The larger the number of hours use per day, the faster the cost advantage (payback)

LEDs for lighting - the physical and materials basis

1. Light emitting diodes (LEDs) 101
2. Light sources – it is not just photons and watts
3. Visible LEDs, a long road from red to blue
4. The state of the art - the remaining challenges
5. The impact 1 energy savings
6. The impact 2 bringing safe and cheap light where there is none
   The existing ligthing system: kerosene lamps
   Associating solar cells and LED lamps
7. The impact 3 improving quality of light


Off-Grid Lighting: GaN Blue PC LED + Solar Cell + Battery

• Kerosene lighting and firewood are used by 1/3 of the world; they cause countless fires and are very inefficient (0.03 lm/watt).

• The average villager spends 10-25% of their annual income on kerosene.

• LED Lighting costs much less on an annual basis and payback period is just 6 months.

• LED Lighting allows education at night and increases safety for the Third World.

Lighting kit - $38
Solar cell
Battery (5 h charge)
2 x 1000 lm lights

Kerosene Lighting Hazards

- **Air pollution –** particulates, carbon monoxide carcinogenic gases

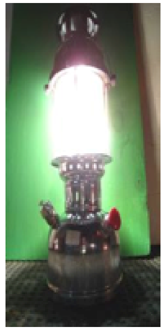
- **Health problems –** respiratory infections, lung and throat cancers, serious eye infections, cataracts, as well as low birth weights

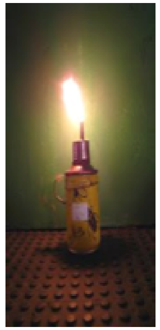
World Bank estimates 780 million women & children inhale equivalent of smoke from 2 packs of cigarettes a day

- **Fire danger – Burns and house fires.** In India 2.5 million people (*350,000 of them children*) suffer severe burns each year from house fires, due to overturned kerosene lamps

Photo Credit: India Impex

Off-Grid Status Quo :
Fuel Based Lighting Expensive, Unhealthy, and Inefficient





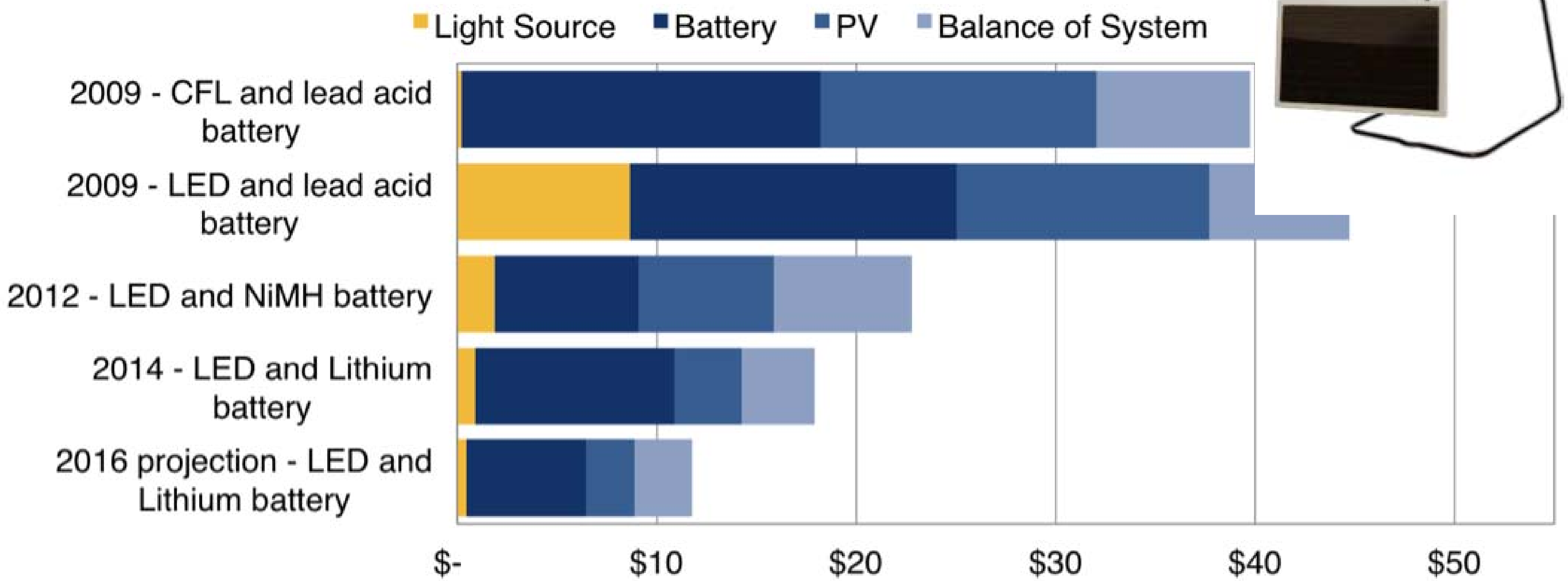
Kerosene for lighting is a **$10-40 billion per year** industry
(sources: CCAC, 2014, UNEP, 2013; Lighting Global, 2012)

Peter Alstone, Berkeley
LED Lighting Off the Grid
DOE SSL R&D Workshop 2015

Pico-power (~0.1 – 10 Watt solar PV) and solar home systems (10-100 W)

Peter Alstone, Berkeley
LED Lighting Off the Grid
DOE SSL R&D Workshop 2015

Super efficiency in action: pico-solar cost decline



Phadke, A., Jacobson, A., Park, W.Y., Lee, G.R., **Alstone, P.**, and Khare, A. *Super-Efficient Appliances Can Enable Expanded Energy Access Using Off-grid Solar Power Systems* (in preparation for early 2015)

Peter Alstone, Berkeley
LED Lighting Off the Grid
DOE SSL R&D Workshop 2015

Solid State Lighting for the Developing World - The Only Solution

R. Peon, G. Doluweera, I. Platonova,D. Irvine-Halliday, G. Irvine-Halliday
Light Up The World Foundation, University of Calgary, Canada

6 times more lumens
at 5% of the cost

staying healthy

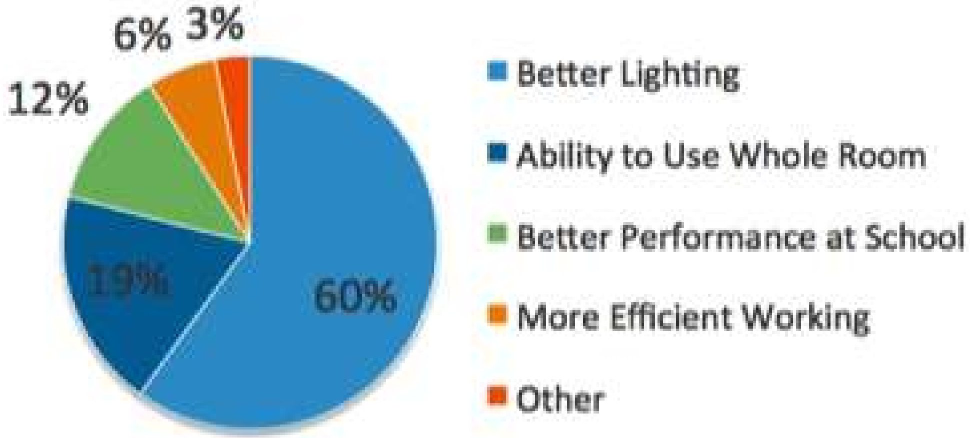
parameter	CFL	kerosen	DEL lamp
lamp power use	7 W	0.05 l/hr	1W
lamp initial cost	3	1	10
lamp cost 50 000 hrs	25	10	10
Luminous output (lm)	**250**	**10**	**60**
lamp lifetime (heures)	6000	5 000	50 000
Light production 50 000 hrs (lmxhrs)	$12.5\ 10^6$	$0.05\ 10^6$	$3\ 10^6$
Lamp energy use 50 000 hrs	350 kWh	2500l	50kWh
Energy cost 50 000 hrs	**350**	**1250**	**50**
Cout total sur 50 000 hrs	**375**	**1260**	**60**
lm cost 50 000 hrs	1.5	126	1
Cost for 10^4 lm x hr (10lm x 3 hrs/day x 365)	3.33	251	0.2
lm cost over 50 000 hrs	**1.5**	**126**	**1**

Proc. of SPIE Vol. 5941 59410N-1 (2005)

Assumes 1$/kWh
By solar PV+storage

Customer Impact: Education

How did the studying conditions for your children improve?

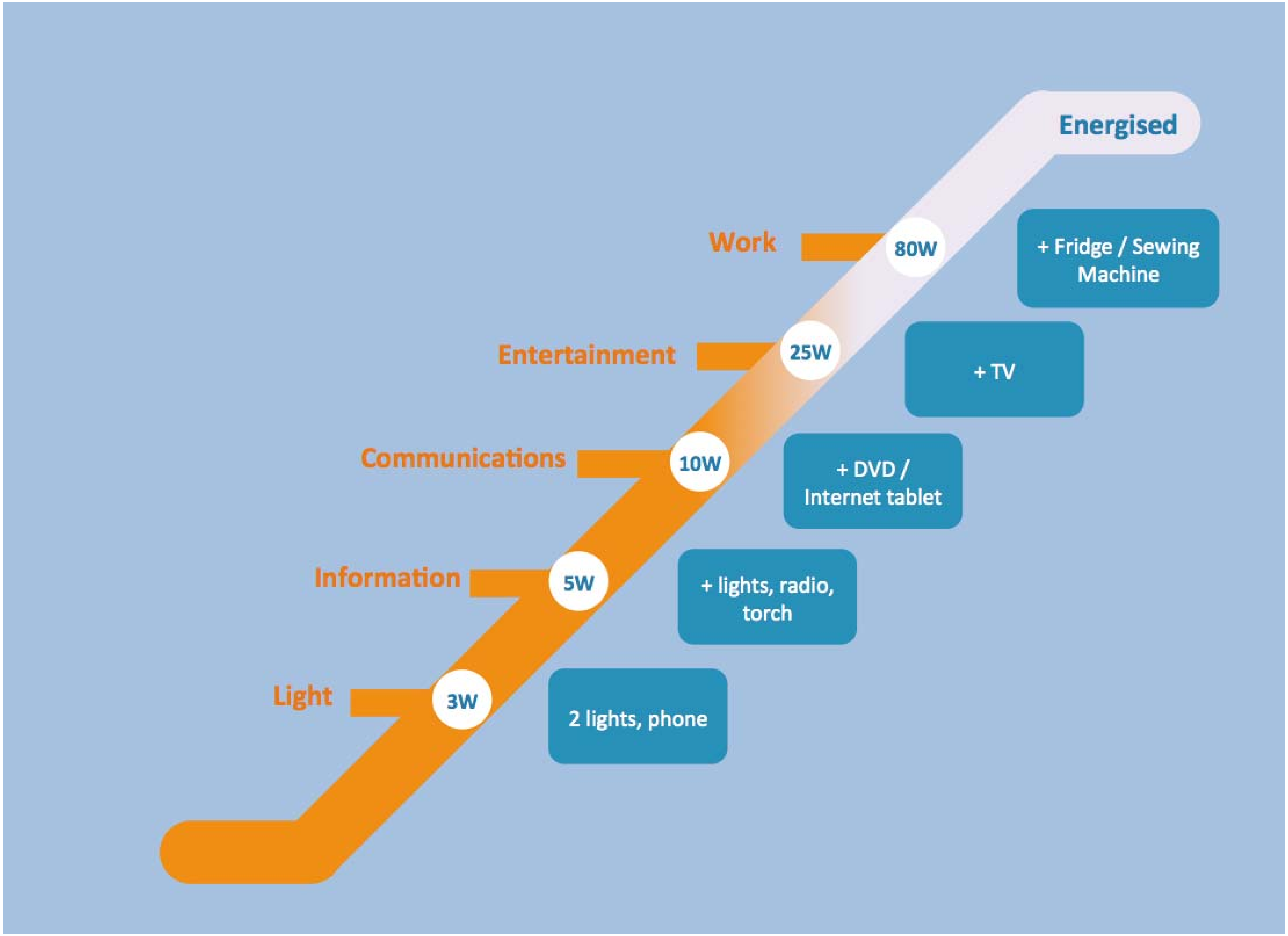


- On average, four children study at home after school
- 97% of the customers claimed that their children study more and are more motivated since they have Indigo
- Parents reported feeling safer allowing their children to study independently

"For me, the most important is that my children can finally study at night. Even when I am not at home."

- Teacher, Ugunja

azuri

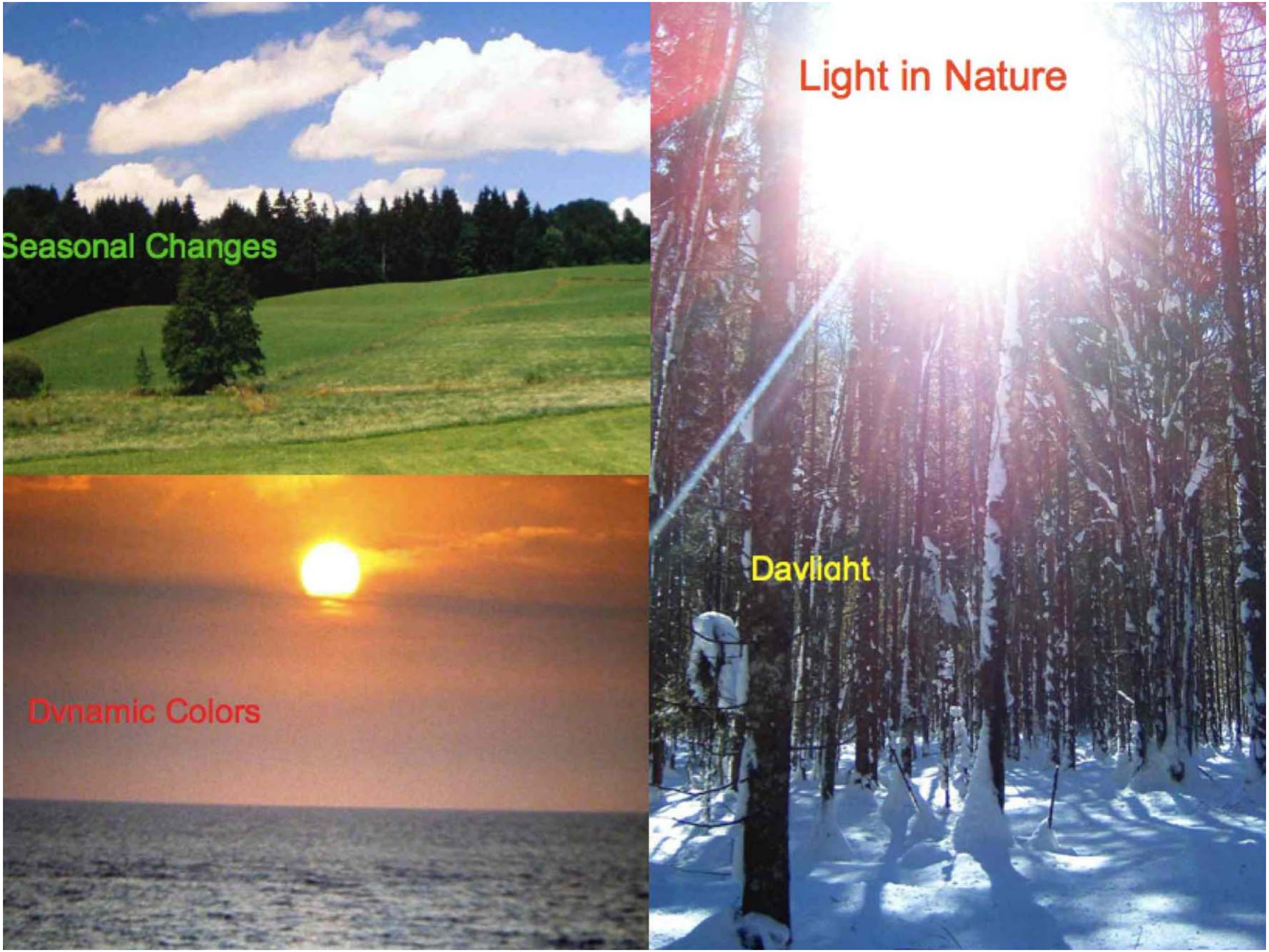

Energised
Work
80W
+ Fridge / Sewing Machine
Entertainment
25W
+ TV
Communications
10W
+ DVD / Internet tablet
Information
5W
+ lights, radio, torch
Light
3W
2 lights, phone

LEDs for lighting - the physical and materials basis

1. Light emitting diodes (LEDs) 101
2. Light sources – it is not just photons and watts
3. Visible LEDs, a long road from red to blue
4. The state of the art - the remaining challenges
5. The impact 1 energy savings
6. The impact 2 bringing safe and cheap light where there is none
7. The impact 3 improving quality of light
   What is natural light ?
   Various environments where quality of light matters a lot

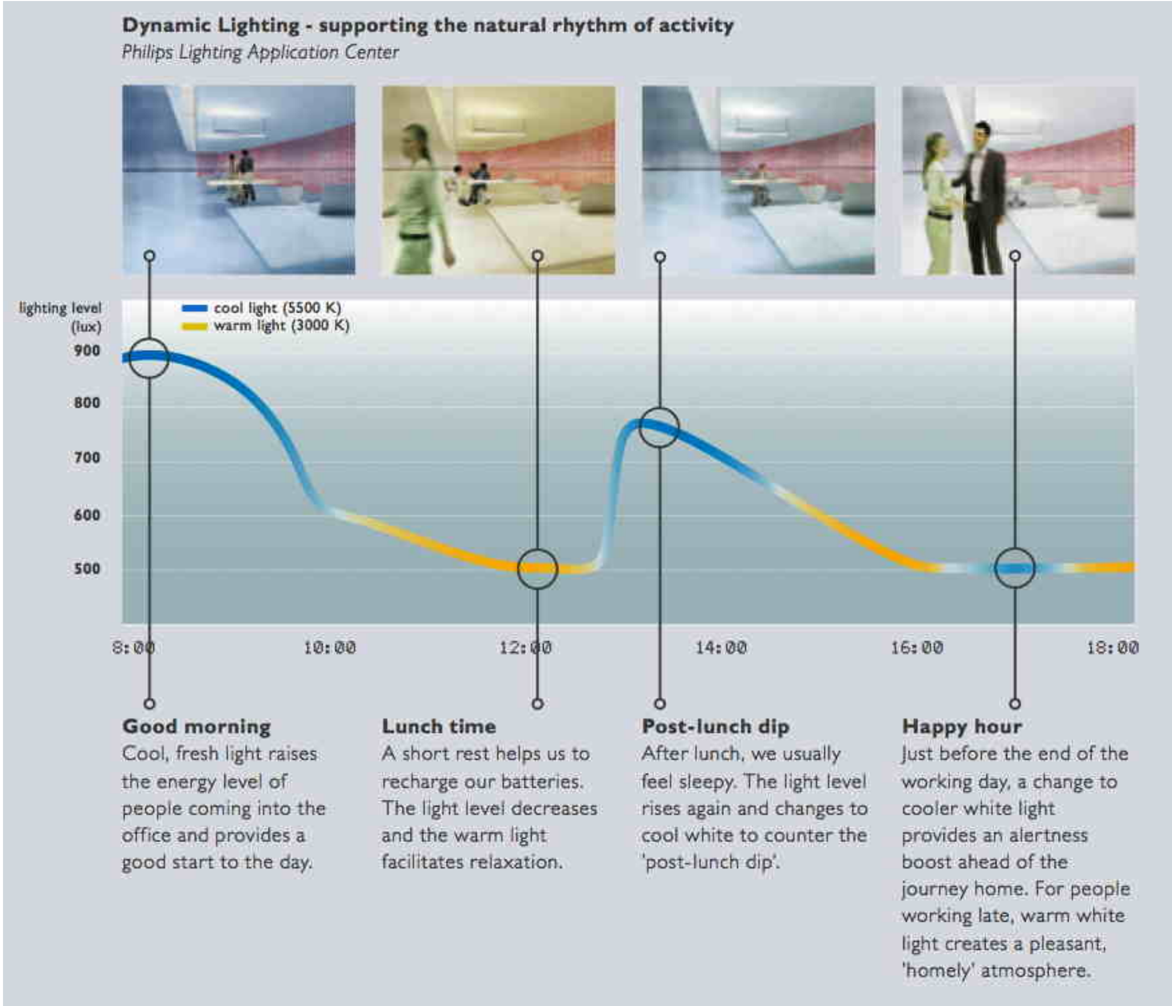
Once we have saved the planet….

Improve quality of life

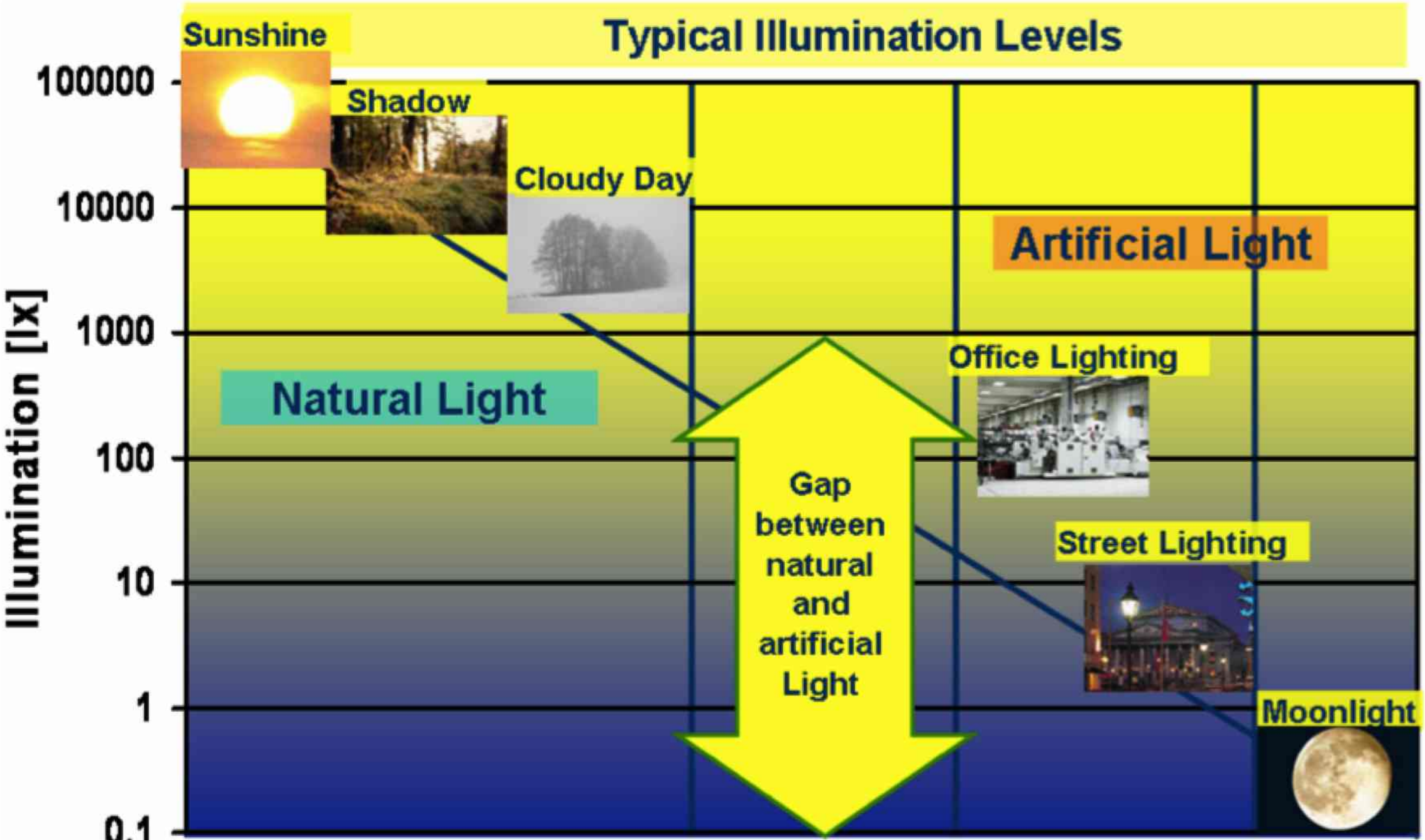

Light in Nature
Seasonal Changes
Daylight
Dynamic Colors

The future needs: dynamic/adaptive lighting

Requires
RGB LEDs with independent
current control



Solving the green gap: compare WPE of green LED to WPE of blueLED + green phosphor



Typical Illumination Levels
Sunshine
Shadow
Cloudy Day
Artificial Light
Natural Light
Office Lighting
Gap between natural and artificial Light
Street Lighting
Moonlight
Illumination [lx]
100000
10000
1000
100
10
1
0,1

Health and well-being

- We expect offices will increase and optimize lighting for productivity

Source: Google Images

Health and well-being

- Education

NORMAL

Normal Class Lessons Standard Color Tone

ENERGY

Support Fresh Start (Morning) or (Early Afternoon)
Very Cool Color Tone

FOCUS

Concentration for Testing Cool Color Tone

CALM

When Class Is Hyperactive Warm Color Tone

 Source: Philips, RPI

LEDs in operating rooms

Light temperature can be adjusted between 3,500 and 5,000 Kelvin.
Regardless of whether surgeons are operating on tissues in which the blood flow is heavy or light, they can make contrasts more visible by changing colour temperatures.
For long interventions, light is tuned more greenish, which is less tirng for the surgeon, allowing longer operations.
For endoscopy, the light can be dimmed across an unusual range of 10-100%

Many single converging lenses, in different amounts, combined into homogenous and shadow-free light, like a '3-D light'

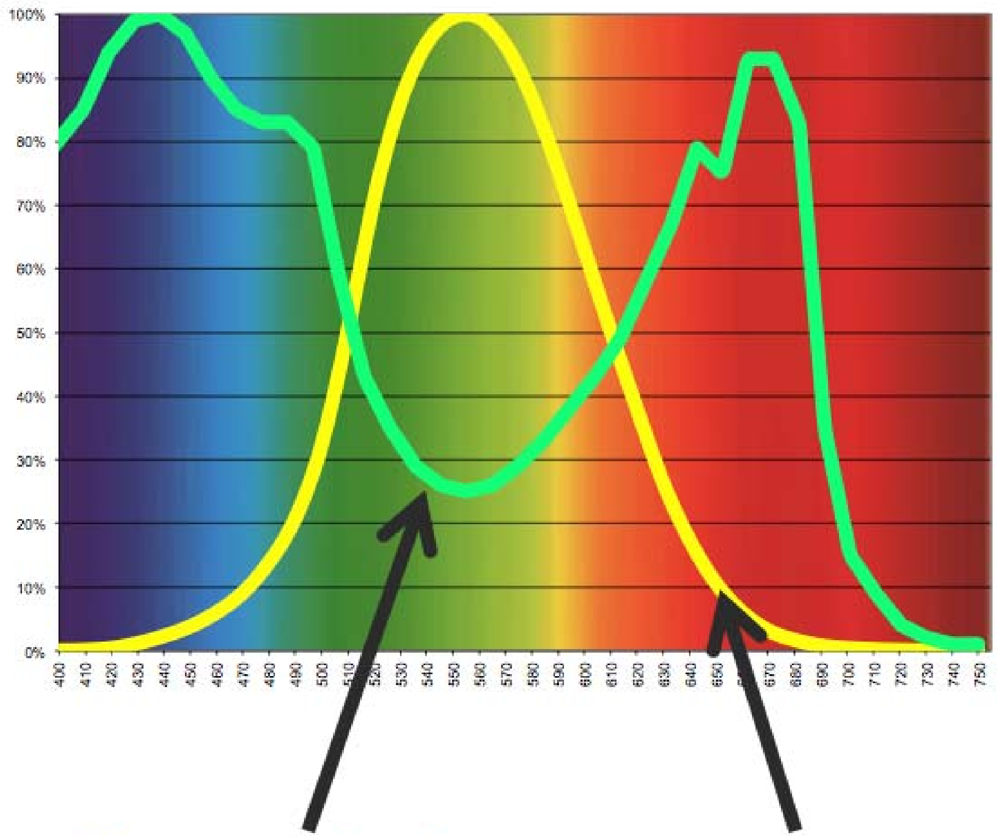
The total luminosity of iLED amounts to 160,000 Lux

The 'cold' IR-free light of the LEDs means that even directly under the lamp, practically no heat emission can be felt: 6 °C less on the operation table, meaning less blood drying, and more comfort for surgeon and pateint.

LEDs in agriculture

Fruits

Leafy Greens



Photosynthetic curve (Plant)

Photopic curve (Human)

Flowers

Medicine

LEDs in agriculture

- Eastern Japan 2013, **25000** Sq. Ft.
- 18 racks each 15 levels, **17000** LED fixtures
- **10000** heads of Lettuce per day (100 fold density increase from outside)
- Grows **2.5X** faster than outside
- Waste from **50% to 10%** compared to outside
- **1%** of water usage compared to outside
- LED **40%** less power than florescent light

A dilemma: PV ou LED?
What if materials become scarce ?

I have good GaN : should I do LEDs or solar cells? (to save the world)
To save the planet, is it better to produce electricity with PV solar cells made with this GaN or should I save electricity substituting lighting sources by LEDs from the same GaN?

Let's consider 1 m^2 GaN under $1kW/m^2$ sun power

PV suppose 30% efficiency (optimistic) => generates 300 W during **6h/day** at peak power (2190h/year, not France/Germany average where it is 800/1000h) => **generates 657 kWh/year**

LED: injected power= 3V x 25A/cm2 x 10 000cm2 = 750 kW, during **3 h/day (of course in commercial/industrial it is 12-15h/day) uses 2250 kWh**
Saved power is at least 3 times as much, at they replace sources which are 4 (CFLs) to 10 (incandescence) times less efficient (includes luminaire efficiencies) => 2.25 MW times 1000h, saves **2.25 10^6 kWh/year - 3000 times more**

Even with x1000 concentration (quite a limit), still a factor 3 difference (12 if lamps are operated 12h/day)!

This is due to the much larger courant density in the LEDs (25 A/cm^2) instead of $10mA/cm^2$
(@ concentration x1000 ($1000x1kW/m^2$=$100W/cm^2$@30%=$30W/cm^2$ = $10A/cm^2$ @ 3V)