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 $\text{CO}_2$ abatement
Comparison of investment costs for technologies diminishing CO$_2$ emissions

McKinsey Impact of the financial crisis on carbon economy
Version 2.1 of the global greenhouse gas abatement 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
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$_2$ abatement
- changes lives for millions
- will bring new quality of life
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,\textsuperscript{1,2}
\textsuperscript{1} Materials Department, University of California at Santa Barbara, USA
\textsuperscript{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 Lighting = 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
~ 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 CO₂
"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.”
"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 (substrate, mismatched) materials
Compare II Vis

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

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

Optics
Light extraction
Rough surfaces and interfaces for ergodic light distribution
Photonic crystals 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 $W_{\text{opt}}/W_{\text{elect}}$ 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
A Light Emitting Diode (LED) produces light of a single color by combining holes and electrons in a semiconductor.
This would have a poor Photon extraction efficiency

p-type pad electrode

semitransparent electrode

p-type GaN

InGaN MQW

n-type GaN

Sapphire substrate

n-electrode

Typical Blue LED Structures on Sapphire

Roughened surface

Ceramic Submount

Active region, as described in figure xx

PATTERNED SAPPHIRE SUBSTRATE

Distance from chip to mirror (20 μm)

Patterned sapphire region

InGaN

n-GaN

3 μm

4.5 μm
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

\textbf{n-type semiconductor}

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

\textbf{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 $\approx$ 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

- n-type
- p-type

Metal contact

n doping donor atoms
p doping acceptor atoms

Built-in electric field

Electrons are repelled by energy barrier

Built-in potential
≈ $E_g$

holes are repelled by energy barrier
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 $h\nu \approx E_g$ bandgap
Current voltage characteristics of a p-n junction

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

$$eV_{\text{onset}} = E_G$$

A direct macroscopic measurement of a quantum mechanical phenomenon, the bandgap!
Principle of operation of LEDs at strong bias

Strong bias, "flat band potential"

\[ V \text{ applied} \approx V_{\text{bi}} \approx E_g \text{ bandgap} \]

Carriers are distributed along a carrier diffusion length thickness

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

Need to concentrate carriers

\[ qV \approx E_G \]

\[ h\nu \approx E_G \]

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

\[ E_{\text{conf},e} = \frac{\pi^2 \hbar^2}{2m_eL^2} \]

\[ E_{\text{conf},h} = \frac{\pi^2 \hbar^2}{2m_hL^2} \]

\[ -\frac{\hbar^2}{2mdx^2}\psi(x) = E\cdot\psi(x) \]

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

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

Infinite well approximation
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)

⇒ 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

<table>
<thead>
<tr>
<th>material</th>
<th>Bandgap energy (eV)</th>
<th>Recombination coeff. (cm³ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>Direct: 1.42</td>
<td>7.21 × 10⁻¹⁰</td>
</tr>
<tr>
<td>InAs</td>
<td>Direct: 0.35</td>
<td>8.5 × 10⁻¹¹</td>
</tr>
<tr>
<td>InSb</td>
<td>Direct: 0.18</td>
<td>4.58 × 10⁻¹¹</td>
</tr>
<tr>
<td>Si</td>
<td>Indirect: 1.12</td>
<td>1.79 × 10⁻¹⁵</td>
</tr>
<tr>
<td>Ge</td>
<td>Indirect: 0.67</td>
<td>5.25 × 10⁻¹⁴</td>
</tr>
<tr>
<td>GaP</td>
<td>Indirect: 2.26</td>
<td>5.37 × 10⁻¹⁴</td>
</tr>
</tbody>
</table>

*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 Lighting – it is not just photons and watts – lumens
   Lumens, Candelas, Lux, etc.
3. LED Lighting = 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 cm² 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 $4\pi \text{ lm} = 12.56 \text{ lm}$

- **Illuminance**: If a 1 m² 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/m².
## Light and Lighting – Definitions I

### Radiometry (physics)
- \( \Phi_e \): Radiant flux – energy flow (W)
- \( I_e(\lambda) = \frac{d\Phi_e}{d\omega} \): Radiant intensity - (W/sr)
- \( S(\lambda) = \frac{d\Phi_e}{d\lambda} \): Spectral power distribution (W/m)

### Photometry (includes human response!)
- \( \Phi_v \): Luminous flux – **Lumens (lm)**
- \( V(\lambda) \): 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)
  
- \( \eta_e = \frac{\Phi_e}{P} \): Radiant efficiency (P = input power)

- \( \eta_v = \eta_e \, K \): **Luminous efficiency**
  - Lumens/electrical watt (lm/W)

---

**Lumen - Eye-weighted radiant flux**

![CIE 1978 Photopic vision](image-url)
**Light and Lighting – Definitions**

**Lumen (lm):** \[
\text{Luminous flux} = \text{Luminous intensity} \times \text{solid angle}
\]
e.g., sphere \(4\pi \text{sr}\)

\[
\text{A candle: } 1 \text{ cd} \times 4\pi \text{ sr} = 12.6 \text{ lm}
\]

100 W incandescent lightbulb: \(\sim 1300 \text{ lm} \) (i.e., \(13 \text{ lm/W}\))

**Illumination 1lux = 1lm/m}^2\)**

**Correlated Color Temperature (CCT):**
Apparent blackbody temperature of a light source

e.g, Incandescent bulb, warm light LED lamp: \(\text{CCT} \sim 2800 \text{ K}\) ‘Cold white: \(\text{CCT} \sim 5000+ \text{ K}\)

**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: \(\text{CRI} = 100\) Na lamp: \(\text{CRI} = 10 - 20\)

*formally: luminous intensity at 555 nm of a source
with a radiant intensity \(I(\lambda)\) of \(1.46 \times 10^{-3} \text{ W/sr}\)
Huge difference between natural and artificial illumination
Factor 100 to 10 000

Typical illumination levels

<table>
<thead>
<tr>
<th>illumination (lx)</th>
<th>Natural light</th>
<th>Artificial light</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 000</td>
<td>sunshine</td>
<td></td>
</tr>
<tr>
<td>10 000</td>
<td>shadow</td>
<td></td>
</tr>
<tr>
<td>1 000</td>
<td>Cloudy day</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>Office lighting</td>
</tr>
<tr>
<td>10</td>
<td>moonlight</td>
<td>Street lighting</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0,1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Lighting Technologies
Conventional Light Sources

No Perfect Artificial Light Source Exists (yet)

**Incandescent**

*High Intensity Discharge*

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

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 light output / W electrical power input

- **Luminous Efficiency of a Source (lm/W)**
- **Luminous flux out (lm)**
  - Electric power in (W)
- **Optical power out (W)**
  - Electric power in (W)
- **Luminous flux (lm)**
  - Optical power (W)

- **Goal 200 lm/W**
- **Today’s LEDs > 50%**
- **Good color mix**
  - Up to 400 lm/W

- **683 lm/W @ 555 nm**

- **Luminous Efficacy of Radiation (LER) (lm/W)**

Theoretical maximum lm/W of a given source:
Determined only by the spectrum of the source.

- **85% + LED internal quantum efficiency**
- **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!

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

RGB LEDs White Light

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

DOE SSL MYPP 2014
Conversion Efficacy Roadmap
3500K and 4000K 80 CRI

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

Yi-Qun Li, Intermatix DOE manufacturing workshop
San Diego 2014
SSL Efficiencies – the challenges

LED Efficiencies

\[
\eta_{\text{tot}} = \eta_{\text{elec}} \times \eta_{\text{IQE}} \times \eta_{\text{extrac}}
\]

\(\eta_{\text{elec}}\): Electrical efficiency ... ohmic losses
    Better contacts, doping, ...

\(\eta_{\text{IQE}}\): Internal quantum efficiency: electron-hole pairs to photons
    Major issues:
    - Droop
    - Green gap

\(\eta_{\text{extrac}}\): Extraction efficiency: escape efficiency for photons
    Major issues:
    - Increase \(\eta_{\text{extrac}}\)
    - Directionality
    Approaches here extend to system level issues
Overall System Efficiency

- **Incand**
  - “17 lm/W”
  - Fixture Efficiency 58%
  - Delivered Efficacy 10 lm/W

- **CFL**
  - “60 lm/W”
  - Fixture Efficiency 58%
  - Delivered Efficacy 35 lm/W

- **LED**
  - “100 lm/W”
  - Fixture Efficiency 90%
  - Driver Efficiency 85%
  - Thermal Equilibrium 90%
  - Delivered Efficacy 69 lm/W

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 nitride 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

Periodic Table of Elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Period</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1</td>
<td>IIA</td>
</tr>
<tr>
<td>Li</td>
<td>2</td>
<td>IA</td>
</tr>
<tr>
<td>Na</td>
<td>3</td>
<td>IA</td>
</tr>
<tr>
<td>Mg</td>
<td>4</td>
<td>IIA</td>
</tr>
<tr>
<td>Al</td>
<td>5</td>
<td>IIA</td>
</tr>
<tr>
<td>Si</td>
<td>6</td>
<td>IVA</td>
</tr>
<tr>
<td>P</td>
<td>7</td>
<td>VA</td>
</tr>
<tr>
<td>S</td>
<td>8</td>
<td>VIA</td>
</tr>
<tr>
<td>Cl</td>
<td>9</td>
<td>VIIA</td>
</tr>
<tr>
<td>Ar</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>19</td>
<td>IIA</td>
</tr>
<tr>
<td>Ca</td>
<td>20</td>
<td>IA</td>
</tr>
<tr>
<td>Sc</td>
<td>21</td>
<td>IB</td>
</tr>
<tr>
<td>Ti</td>
<td>22</td>
<td>IB</td>
</tr>
<tr>
<td>V</td>
<td>23</td>
<td>IB</td>
</tr>
<tr>
<td>Cr</td>
<td>24</td>
<td>IB</td>
</tr>
<tr>
<td>Mn</td>
<td>25</td>
<td>IB</td>
</tr>
<tr>
<td>Fe</td>
<td>26</td>
<td>IB</td>
</tr>
<tr>
<td>Co</td>
<td>27</td>
<td>IB</td>
</tr>
<tr>
<td>Ni</td>
<td>28</td>
<td>IB</td>
</tr>
<tr>
<td>Cu</td>
<td>29</td>
<td>IB</td>
</tr>
<tr>
<td>Zn</td>
<td>30</td>
<td>IB</td>
</tr>
<tr>
<td>Ga</td>
<td>31</td>
<td>IIIA</td>
</tr>
<tr>
<td>Ge</td>
<td>32</td>
<td>IIIA</td>
</tr>
<tr>
<td>As</td>
<td>33</td>
<td>IIIA</td>
</tr>
<tr>
<td>Se</td>
<td>34</td>
<td>IIIA</td>
</tr>
<tr>
<td>Br</td>
<td>35</td>
<td>IIIA</td>
</tr>
<tr>
<td>Kr</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Rb</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Sr</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>Zr</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>Mo</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>Tc</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>Ru</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>Rh</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Pd</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>Cd</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>In</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>Sn</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Sb</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>Te</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>Xe</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>Cs</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Ba</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>La</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>Ce</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>Pr</td>
<td>59</td>
<td></td>
</tr>
<tr>
<td>Nd</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Pm</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>Sm</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>Eu</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Gd</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Tb</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>Dy</td>
<td>66</td>
<td></td>
</tr>
<tr>
<td>Ho</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>Er</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>Tm</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td>Yb</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Lu</td>
<td>71</td>
<td></td>
</tr>
</tbody>
</table>

* Lanthanide Series
+ Actinide Series

Legend - click to find out more...

- **H** - gas
- **Li** - solid
- **Br** - liquid
- **Tc** - synthetic

- **Non-Metals**
- **Transition Metals**
- **Rare Earth Metals**
- **Halogens**
- **Alkali Metals**
- **Alkali Earth Metals**
- **Other Metals**
- **Inert Elements**
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.

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 semimetals vol; 48, 1997, p. 47

Evolution of LED Performance

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.
Group III-Nitrides: Energy Gap Map
(New View of the World)
Blue-green laser diodes

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

“High-brightness blue and green light-emitting diodes“
Microstructure study of a degraded pseudomorphic separate confinement heterostructure blue-green laser diode ZnCdSe/ZnSSe/ZnMgSSe separate confinement heterostructure (SCH) laser

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

S1, S2 Stacking faults: cubic becomes hexagonal
D1, D2: dislocation patches in QWs
History of LEDs

- 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.
Prehistory

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)

First photograph of LED

Lossev’s I-V characteristic
- 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

- 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 (H₂O, 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 annealing 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
THE PREPARATION AND PROPERTIES OF VAPOUR-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 specimens 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 $10^{19}/\text{cm}^3$, 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
- With nucleation layer
- Without nucleation layer

**Akasaki p-n junction LED**
- 1989

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

Electron mobility

![Graph showing electron mobility](image1)

![Diagram showing growth model](image2)
2. Creation of GaN single crystal with excellent quality

(3) Innovation in MOVPE growth method (1985)

**Low-temperature (LT-) buffer layer**

- Sapphire (0001)
- LT-buffer (20~50 nm) ~500 °C
- GaN
- Direct growth (Common method)
- Newly-developed

**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
2. Creation of GaN single crystal with excellent quality

**Creation of high-quality GaN (1985)**

**Until 1985**
- GaN grown by HVPE
- Many cracks, pits
- Rough surface
- Dislocations: $> 10^{11}$ cm$^{-2}$
- Free electron conc. $> 10^{19}$ cm$^{-3}$
- Electron mobility: $\sim 20$ cm$^2$/V·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: $\sim 700$ cm$^2$/V·s
- Intense luminescence

Crystal quality, electrical property, and luminescence property were dramatically improved at the same time.
Major breakthroughs: Nakamura

1991 Two flow reactor

1991 GaN LED comparison with SiC

1992 p compensation mechanism

1994 QCSE shift of peak EL

From Ponce impact of InGaN

1995 Change of IQE with color

Already the green gap

1995 High power SQW LEDs
"Novel Metalorganic Chemical Vapor Deposition System for GaN Growth"
**Hydrogen Passivation of P-Type GaN**

**Annealing in N2 atmosphere**

![Graph showing resistivity vs. temperature for annealing in N2 atmosphere](image)

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


**Re annealing in NH3 or N2 atmosphere**

![Graph showing resistivity vs. temperature for reannealing in NH3 or N2 atmosphere](image)

Fig. 1. The resistivity change in LEEBI-treated Mg-doped GaN films as a function of annealing temperature. The ambient gases, NH3 and N2, were used for thermal annealing.

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.

Narukawa Blue LED
Nichia 2010
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**

\[ \eta_{\text{tot}} = \eta_{\text{elec}} \times \eta_{\text{IQE}} \times \eta_{\text{extrac}} \]

\( \eta_{\text{elec}} \): Electrical efficiency ... ohmic losses
    Better contacts, doping, ...

\( \eta_{\text{IQE}} \): Internal quantum efficiency: electron-hole pairs to photons
    Major issues:
    - **Droop**
    - **Green gap**

\( \eta_{\text{extrac}} \): Extraction efficiency: escape efficiency for photons
    Major issues:
    - Increase \( \eta_{\text{extrac}} \)
    - 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 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

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

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 piezoelectric effects, ....
In spite of electrical and piezo electrical injection problems

Electron blocking layer

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 \times 10^6 V/cm

Diminishes e-h overlap hence radiative recombination probability.

Band extrema and hole concentration in GaN/GaInN MQWs (from Ramer, Bridgelux, 2008)
Comparison InGaN vs. other LEDs

**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

$\eta$ decreases with TD density

In spite of huge dislocations densities

-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

% In

Valleys

No In

Side View in Energy Landscape

Defects

Light

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

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

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

Based on indentation, not clear SiC has moving dislocs
Peierls stress is low in II VIIs
More subtle effects: no shear stress in basal plane in c axis GaN -no dislocation motion in that plane

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

**Up to 80%+**

**Complex process**

**Shaped transparent substrate**
- non planar process
- light propagates long distance; requires ultra low internal loss

**PSS: Patterned Sapphire Substrate**
- poor thermal properties
- Improved IQE
  - Mitsubishi 2001, Nichia 2002

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

- Shaped SiC substrate
  - Cree

- Micromirrors
  - ThinGaN OSRAM

- Flip Chip + Roughened surface
  - Philips Krames

- Krames, Craford
  - Philips Lumileds 1994

- Fujii, Nakamura 2004
Ray Tracing for Light Extraction Modeling
## LEE Comparison for the Three Chip Designs

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

Values given for chips encapsulated in epoxy

Light is extracted after 2.5-3 roundtrips @92%
Various types of PhC LEDs: hope-beat losses better than by roughness

Surface photonic crystals

Photonic Crystal

Active region

Mirror

Optimizing horizontal structure

Triangular lattice

Archimedean lattice

2.5 µm

Æ

constructive interference on some diffraction orders

Optimizing vertical structure

Embedded photonic crystals

Embedded stripe PhC for Polarized LED

Double embedded PhCs

Sapphire substrate

m-plane GaN

7 atoms (holes) / unit cell

Flip-chip (FC) embedded PhCs

Mirror
The history of the improvement of EQE of GaN-LEDs has been a significant area of research in recent years. A big part of the progress in the past 10 years has been on extraction efficiency more than on IQE.


Kazuyuki Tadatomo
Epitaxial Growth of GaN on Patterned Sapphire Substrates
Why do we worry? Major challenges remain

300 lm/W
R&D hero

>120 lm/W
Mfg basis

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

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/cm² or 35 A/cm²
InGaN-based LEDs

- Peak EQE at 1 - 10 A/cm²
- At higher current, LED rapidly lose efficiency
- Independent of color

Potential Cause: Auger recombination (internal efficiency) \( \sim n^3 \)

- Based on scaling of non-radiative loss - experimental measurement
- First-principles rate indicate Auger recombination may be a significant
10W modules deliver 1400 lm in cool white or 1250 lm in warm white

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

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

Carrier leakage?
Changes $\eta_{inj}$ in $n^3 = n^4$

Defect activation at high current?
Auger recombination?

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

- Based on scaling of nonradiative loss $\sim n^3$ 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 $10^{-31}\text{cm}^6\text{s}^{-1}$

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

Measure electron energies outside the device

Measuring current does not tell you about carrier energy
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


"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

Same peak positions as observed in photoemission


**Why go for the few last efficiency %?**

- Why absolute efficiency matters: needed to displace high efficiency 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

<table>
<thead>
<tr>
<th></th>
<th>WPE 40%</th>
<th>WPE 60%</th>
<th>WPE 80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat extracted from lamp sets chip power limit</td>
<td>20W</td>
<td>20W</td>
<td>20W</td>
</tr>
<tr>
<td>Heat % of input power: 100% - WPE</td>
<td>60%</td>
<td>40 %</td>
<td>20 %</td>
</tr>
<tr>
<td>Total input power</td>
<td>33.3W</td>
<td>50 W</td>
<td>100 W</td>
</tr>
<tr>
<td>Light output: (input) – (heat)</td>
<td>13.3W</td>
<td>30 W</td>
<td>80 W</td>
</tr>
<tr>
<td>Relative power compared to 40% LED</td>
<td>0%</td>
<td>225 %</td>
<td>600 %</td>
</tr>
</tbody>
</table>
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
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:
U.S. LIGHTING INVENTORY, ELECTRICITY CONSUMPTION, AND LUMEN PRODUCTION, 2010 [1]
Electricity production worldwide: 41% coal, 21% gas. In terms of equivalent coal, as gas produces half as much CO₂ as coal, 50% coal. 1Kilogram Coal = 24 megajoules (6.7 kWh) - produces 3.6kg of CO₂.

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

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 × 0.71 × 10^-3 tons of CO₂.

5% change in light generation efficiency is 150 million tons of CO₂ 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 CO₂ per year.
Additional savings by smart lighting

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

What If All SSL Fixtures Were Smart?

- Baseline
- DoE Projection
- “Smart” SSL Savings 70%

- Residential
- Commercial
- Industrial
- Outdoor
To save electricity compared to incandescent, 15 lm/W is enough; to save compared to fluorescent, at least 100 lm/W is needed.
2025 Projected Annual Electricity Savings from SSL provided we reach 200lm/W


Energy savings for the US only

Source: DOE MYPP 2014
Upfront Cost:

Sticker Shock:
All sources: ~ 800 lumens
Warm White
Tier 1 brand

Need to reduce $/lumen!

In 2011

Now: $10!
Why pay so much a new (replacement) lamp?

Cost of ownership (CoO)

Suppose lighting needs of 10 1klm lamps @150 lm/W

If these 10x 6.6 W lamps are used 15hr/day, 1kWh/day=
365kWh/year
€ 38.5 @10c/kWh
Over 10 years, 385 €
If used 1.8hr/day,
44kWh/year € 4.4/year

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 lighting 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

UCSB
Light up the World Foundation: www.lutw.org
SSLEC
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
Off-Grid Status Quo:
Fuel Based Lighting Expensive, Unhealthy, and Inefficient

Kerosene for lighting is a $10-40 billion per year industry

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


Peter Alstone, Berkeley
LED Lighting Off the Grid
DOE SSL R&D Workshop 2015
Solid State Lighting for the Developing World - The Only Solution

Light Up The World Foundation, University of Calgary, Canada

6 times more lumens at 5% of the cost

staying healthy

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

Assumes 1$/$kWh
By solar PV+storage
Customer Impact: Education

How did the studying conditions for your children improve?

- Better Lighting
- Ability to Use Whole Room
- Better Performance at School
- More Efficient Working
- Other

- 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 Technologies Ltd
Light (3W) → Information (5W) → Communications (10W) → Entertainment (25W) → Work (80W) → Energised

- 2 lights, phone
- + lights, radio, torch
- + DVD / Internet tablet
- + TV
- + Fridge / Sewing Machine
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
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
- Street Lighting
- Moonlight

Illumination [lx]

Gap between natural and artificial light
Health and well-being

- We expect offices will increase and optimize lighting for productivity
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
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 tiring 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 patient.
LEDs in agriculture

Fruits

Leafy Greens

Photosynthetic curve (Plant)

Photopic curve (Human)

Flowers

Medicine

(Images of fruits, leafy greens, flowers, and 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 m² GaN under 1kW/m² 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/cm²) instead of 10mA/cm²
(@ concentration x1000 (1000x1kW/m²=100W/cm²@30%=30W/cm² = 10A/cm² @ 3V)