Prospects for LED lighting

Dr Kostantinos Petridis
Optoelectronics, Lasers and Plasma Technologies Group
Department of Electronics, TEI of Crete
Prospects for LED lighting

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Prospects for LED lighting
An Introduction

- Incandescent light bulb: The most traditional and oldest white light source bulb.
- Incandescent light bulb technology has changed at all since 1901 that the oldest working until now incandescent light bulb has installed (Livermore, California Fire station).

- Inside the bulb is a tungsten made filament that is heated by the flow of electricity until glows white and lights up the room.
- That technology is on the way out: These devices are too wasteful: 98% of the energy input ends up as heat instead of light.
Prospects for LED lighting
An Introduction

• Only in the USA (20% of the electricity generated is for lighting purposes) there are in residential, industrial and commercial settings more than 4 billion incandescent lamps and is clear why several countries are seeking to eliminate the bulbs entirely as a way to control carbon dioxide emissions.

• In 2007 the Australia decided to ban the incandescent bulbs entirely (the whole project will be completed in 2012).

• European Union has decided on a similar ban in 2008 and the USA has decided to eliminate most incandescent bulbs by 2014.

• The elimination of the incandescent bulbs makes environmental and economical sense but the race for long term replacement is wide open!!!

• At present the only technology that is mature enough to replace the incandescent bulbs is that of fluorescence bulbs (efficiency 10-15%)
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An Introduction

• Today the fluorescent bulb technology has dominated the industrial and commercial settings.

• Fluorescent lighting drawbacks:
  (a) Do not work well in cold temperatures.
  (b) Their lifetime is shorten if they are turned on and off very frequently.
  (c) Each lamp contains a small amount of mercury which is toxic. This presents consumers with a disposal problem at the end of the lamp’s life.
  (d) Low CRI.
  (e) Require special circuitry to operate with a dimming switch.

• All the above drawbacks can be solved but they seem serious enough to encourage innovators to search out successor technology.
Prospects for LED lighting
An Introduction

• “There are so many advantages to LEDs that we think there lies the future of lighting”, Hans van Sprang, senior scientist at Philips Research Laboratories.

• LEDs as white light sources firstly introduced in the early to mid 1990s

• This new technology is based on InGaAlP and InGaN and grew at a remarkable average annual rate of 42%

• LEDs compared to fluorescence lamps:
  (a) Have longer lifetimes (b) Are more robust (c) Twice more efficient
  (d) High energy efficiency (70 lm W\(^{-1}\)) (e) Design flexibility (f) absence of toxic substances

• LEDs are already used in:
  (a) Computers (b) Television sets (c) Outdoor lighting
  (d) In traffic lights & indicator lights on cars

• Philips and other investors invest huge amount of money in research, development of materials that has helped LED technology to evolve rapidly.
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An Introduction

• This market growth was driven by the adoption of LEDs in three application areas:
  (a) Signaling (traffic signals, automobile brake lights)
  (b) Displays (outdoor full color video screens, single color variable message signs)
  (c) Backlighting (automobile instrument panels, mobile phone LCD displays and keypads)
• In 2005 the growth of the LED had grown to 3.9 billion dollars.
• The performance of HB-LEDs continues to rise while the prices decline.
• LEDs next market opportunity: the general illumination market
• Since 2002 the lumen output of the best commercial white LEDs has increased by a factor of six, and the cost per lumen has decreased by a factor of seven.
• It is expected based on current trends to see a market of over 1 billion dollars for LEDs lighting by 2011.
### Prospects for LED lighting

### An Introduction

<table>
<thead>
<tr>
<th>Source</th>
<th>Light output (Im)</th>
<th>Electrical input (W)</th>
<th>Luminous efficacy (Im W⁻¹)</th>
<th>Lifetime (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-power white LEDs*</td>
<td>60–135</td>
<td>1.2–2.6</td>
<td>50–70</td>
<td>50,000</td>
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<tr>
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<td>19</td>
<td>2,000</td>
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<td>60</td>
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<td>Fluorescent T12, 48 inch, 2 pin</td>
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<td>32</td>
<td>87.5</td>
<td>20,000</td>
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<tr>
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<td>900</td>
<td>15</td>
<td>60</td>
<td>10,000</td>
</tr>
</tbody>
</table>

*Best white LEDs available at present on a commercial basis, typical performance.*
Prospects for LED lighting
An Introduction

Figure 1 Since the invention of the red LED in the late 1960s, every 10 years the light output per device has increased by a factor of 20 while the cost per lumen has fallen by a factor of 10. This trend is known as ‘Haltz’s Law’ after Roland Haltz, the scientist from Agilent Technologies who first analysed this behaviour. Open symbols denote cost per lumen (measured in US dollars) and closed symbols denote flux per package (measured in lumens).
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Semiconductor Concepts and Energy Bands

![Diagram of energy bands and band gaps in materials](image)
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Semiconductor Concepts and Energy Bands

• L.E.D.: Light Emitting Diode
• The energy of an electron in atoms and molecules is quantized and can have discrete values.
• In solids the energy levels of the atoms form energy bands…. For example (Li):

Electron Energy, $E$

In a metal the various energy bands overlap to give a single band of energies that is only partially full of electrons. There are states with energies up to the vacuum level where the electron is free.

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Semiconductor Concepts and Energy Bands

• The electron energies is little bit different than that one of the metals……

(a) A simplified two dimensional view of a region of the Si crystal showing covalent bonds. (b) The energy band diagram of electrons in the Si crystal at absolute zero of temperature.

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Semiconductor Concepts and Energy Bands

• An electron placed to the CB **is free to move** around the crystal and also **to respond to an electric field** because there are plenty of neighboring empty energy levels.

• Under the action of an external electric field can be transferred to higher energy levels and move through the crystal.

• **The effective mass** $m^*$ of an electron represents the electron freedom to move in the CB.

• How can we excite an electron from the VB to CB?
(a) A photon with an energy greater than $E_g$ can excite an electron from the VB to the CB.

(b) Each line between Si-Si atoms is a valence electron in a bond. When a photon breaks a Si-Si bond, a free electron and a hole in the Si-Si bond is created.

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• The free electron in the CB can wander around the crystal and contribute to the crystal conductivity……

• The hole – positive charge (an electron vacant position) can wander around the crystal and contribute to the crystal conductivity……

• Conduction in semiconductors occurs by both electrons and holes with charges -e and +e respectively and their own effective masses $m_e^*$ and $m_h^*$.

• Excitation mechanisms: Optical, Thermal and Electrical.
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Semiconductor Concepts and Energy Bands
Many important semiconductor properties are described by considering electrons in the CB and holes in the VB.

**Density of States** $g(E) \text{(DoE)}$: Represents the number of electronic states in band per energy per unit volume of the crystal.

For a 3D potential energy well the DoE increases with the energy as follows:

$$g(E) \propto (E - E_c)^{1/2}$$

The DoE gives information only on available states and not on their actual occupation.
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Semiconductor Statistics

- **The Fermi Dirac function** $f(E)$ is the probability to find an electron in a energy state with energy $E$ and is expressed in thermal equilibrium by the following relationship:

$$f(E) = \frac{1}{1 + \exp\left( \frac{E - E_F}{k_B T} \right)}$$

- **Fermi Energy** $E_F$: Is the last occupant energy level at $0^\circ C$. Any change in the $E_F$ represents work input or output per electron:

$$D E_F = eV$$
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Semiconductor Statistics

• The most important figure from Semiconductor Statistics is the number of electrons per unit energy per unit volume in the CB:

\[ n(E) = g_c(E) f(E) \]

• The total number of electrons in the CB can be calculated through the following integral:

\[ n = \sum_{E_c}^{E_c+c} g_{CB}(E) f(E) dE \]
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Semiconductor Statistics

- **Non-degenerate Semiconductors:**
  \[ E_c - E_F >> k_B T \implies n(E) = \exp[-(E_c - E_F)] \]

- Since the number of energy states are much more than the electrons in the VB for the of non-degenerate semiconductors we have:
  \[
  n = N_c \exp \frac{\frac{1}{k} \frac{E_c - E_F}{k_BT} - \frac{1}{\lambda}}{1}
  \]
  where \( N_c \) is a temperature dependent constant called the **effective density of states at the CB edge**.

- Similarly for the holes we have:
  \[
  p = N_v \exp \frac{\frac{1}{k} \frac{E_F - E_v}{k_BT} - \frac{1}{\lambda}}{1}
  \]
  where \( N_v \) is the **effective density of states at the VB edge**.
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Semiconductor Statistics

- In an **intrinsic semiconductor** where \( n = p \) we get:

\[
E_{Fi} = E_v + \frac{1}{2}E_g - \frac{1}{2}kT \ln \frac{N_c}{N_v}.
\]

- **Mass Action Law**:

\[
np = N_c N_v \exp \left( \frac{E_g}{k_B T} \right) \frac{N_c}{N_v} = n_i^2.
\]

The above constant \((n_i^2)\) depends on the temperature and the material properties. The mass action law is valid whenever we have thermal equilibrium and the sample is in the dark.
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Semiconductor Statistics

(a) Energy band diagram. (b) Density of states (number of states per unit energy per unit volume). (c) Fermi-Dirac probability function (probability of occupancy of a state). (d) The product of \( g(E) \) and \( f(E) \) is the energy density of electrons in the CB (number of electrons per unit energy per unit volume). The area under \( n_E(E) \) vs. \( E \) is the electron concentration.

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Extrinsic Semiconductors

- **Extrinsic Semiconductor:**
  
  (a) The concentration of carriers of one polarity is much in excess.

(b) **n – type semiconductors:** By adding pentavalent impurities (donor impurity) such as arsenic in silicon we can obtain a semiconductor in which the electron concentration is larger than the hole concentration.

  **p – type semiconductors:** By adding trivalent impurity (acceptor) such as boron in silicon we can obtain a semiconductor in which the hole concentration is larger than the electron one.

(c) For example the electron that is left unbound in a n-type semiconductor can easily be freed (0,05 eV) by internal vibrations of the Si lattice. This electron will contribute positively to the semiconductor conductivity.

(d) The addition of the arsenic into silicon crystal will create additional energy levels 0.05 eV below the conduction band of the silicon.
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Extrinsic Semiconductors

(a) The four valence electrons of As allow it to bond just like Si but the fifth electron is left orbiting the As site. The energy required to release to free fifth-electron into the CB is very small.

(b) Energy band diagram for an n-type Si doped with 1 ppm As. There are donor energy levels just below $E_c$ around As$^+$ sites.

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Extrinsic Semiconductors

• If $N_d$ is the donor concentration and is valid that $N_d >> n_i$ then $p = n_i^2 / N_d$

• The conductivity $\sigma$ of the $n$-type semiconductor is then:

$$s = eN_d m_e$$

• Similar things are valid for $p$-type semiconductors:

(a) Boron doped Si crystal. B has only three valence electrons. When it substitutes for a Si atom one of its bonds has an electron missing and therefore a hole. (b) Energy band diagram for a $p$-type Si doped with 1 ppm B. There are acceptor energy levels just above $E_v$ around $B^-$ sites. These acceptor levels accept electrons from the VB and therefore create holes in the VB.

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Extrinsic Semiconductors

Energy band diagrams for (a) intrinsic (b) $n$-type and (c) $p$-type semiconductors. In all cases, $np = n_i^2$. Note that donor and acceptor energy levels are not shown.

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Degenerate and Non- Degenerate Semiconductors

• In a **non-degenerate semiconductor** the number of energy states in the Conduction Band is greater than the electrons. This means that: \( n \ll N_c \ & \ p \ll N_d \)
  Where \( N_{c,d} \) is a measure of the density of states in the CB and VB.

• In the case of heavily doped semiconductors (impurities concentrations of the order of \( 10^{19} - 10^{20} \text{ cm}^{-3} \)) is valid that \( n > > N_c \ or \ p > > N_d \) and the semiconductor is called **degenerate**. **In this case the semiconductor exhibits properties that are more metal like** and all the statistics figures include a dependence on the absolute temperature.

• The result of the heavily doped semiconductors (n or p semiconductors) is the creation of energy bands within the conduction (n-type) or the valence band (p type) of the host atom.

• The mass action law \( np = n_i^2 \) is not valid in the degenerate semiconductors!!!
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Degenerate and Non-Degenerate Semiconductors

(a) Degenerate n-type semiconductor. Large number of donors form a band that overlaps the CB. (b) Degenerate p-type semiconductor.

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Energy Diagrams in an Applied Field

Energy band diagram of an $n$-type semiconductor connected to a voltage supply of $V$ volts. The whole energy diagram tilts because the electron now has an electrostatic potential energy as well.

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Direct and Indirect Band gap Semiconductors

• From the free electron model we get the following diagram energy band diagram for the direct gap semiconductors:

The $E$-$k$ diagram of a direct bandgap semiconductor such as GaAs. The $E$-$k$ curve consists of many discrete points with each point corresponding to a possible state, wavefunction $\psi_k(x)$, that is allowed to exist in the crystal. The points are so close that we normally draw the $E$-$k$ relationship as a continuous curve. In the energy range $E_v$ to $E_c$ there are no points ($\psi_k(x)$ solutions).

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Direct and Indirect Band gap Semiconductors

(a) In GaAs the minimum of the CB is directly above the maximum of the VB. GaAs is therefore a direct bandgap semiconductor. (b) In Si, the minimum of the CB is displaced from the maximum of the VB and Si is an indirect bandgap semiconductor. (c) Recombination of an electron and a hole in Si involves a recombination center.

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pn Junction Principles

Properties of the pn junction.

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Forward Bias a pn Junction

Forward biased pn junction and the injection of minority carriers (a) Carrier concentration profiles across the device under forward bias. (b). The hole potential energy with and without an applied bias. $W$ is the width of the SCL with forward bias.

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Forward Bias a pn Junction

The total current anywhere in the device is constant. Just outside the depletion region it is due to the diffusion of minority carriers.

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Forward Bias a pn Junction

Forward biased $pn$ junction and the injection of carriers and their recombination in the SCL.

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Reversed Bias pn Junction

Minority Carrier Concentration

Electrons ➔ Drift ➔ Holes

Thermally generated EHP

Reverse biased pn junction. (a) Minority carrier profiles and the origin of the reverse current. (b) Hole $PE(x)$ across the junction under reverse bias

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Energy band diagrams for a **pn** junction under (a) open circuit, (b) forward bias and (c) reverse bias conditions. (d) Thermal generation of electron hole pairs in the depletion region results in a small reverse current.

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Light Emitting Diodes

(a) The energy band diagram of a p-n+ (heavily n-type doped) junction without any bias. Built-in potential $V_o$ prevents electrons from diffusing from n+ to p side. (b) The applied bias reduces $V_o$ and thereby allows electrons to diffuse, be injected, into the p-side. Recombination around the junction and within the diffusion length of the electrons in the p-side leads to photon emission.

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Device Structure

• The p side is on the surface from which light is emitted and is therefore narrow in order the generated photons do not be absorbed by the material.
• To ensure that the most of recombination takes place closer to the p region that n region is heavily doped with suitable impurities.
• Epitaxial layers and Substrate crystals should match in order to avoid the creation of crystal defects that lead to radiationless EHP recombinations.

A schematic illustration of typical planar surface emitting LED devices. (a) p-layer grown epitaxially on an n$^+$ substrate. (b) First n$^+$ is epitaxially grown and then p region is formed by dopant diffusion into the epitaxial layer.

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(a) Some light suffers total internal reflection and cannot escape. (b) Internal reflections can be reduced and hence more light can be collected by shaping the semiconductor into a dome so that the angles of incidence at the semiconductor-air surface are smaller than the critical angle. (b) An economic method of allowing more light to escape from the LED is to encapsulate it in a transparent plastic dome.

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Free space wavelength coverage by different LED materials from the visible spectrum to the infrared including wavelengths used in optical communications. Hatched region and dashed lines are indirect $E_g$ materials.

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Heterojunction High Intensity LEDs

• **Homojunction**: A pn junction between two differently doped semiconductors that are of the same material (the same bandgap).

• **Heterojunction**: A pn junction between two different bandgap semiconductors.

• The refractive index of a semiconductor depends on its bandgap. The wider bandgap semiconductor the lower refractive index has. So we can create a waveguide to guide the generated photons out from the recombination region.
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Heterojunction High Intensity LEDs

(a) A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs).

(b) A simplified energy band diagram with exaggerated features. $E_F$ must be uniform.

(c) Forward biased simplified energy band diagram.

(d) Forward biased LED. Schematic illustration of photons escaping reabsorption in the AlGaAs layer and being emitted from the device.

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LED Characteristics

(a) Energy band diagram with possible recombination paths. (b) Energy distribution of electrons in the CB and holes in the VB. The highest electron concentration is \((1/2)k_B T\) above \(E_c\). (c) The relative light intensity as a function of photon energy based on (b). (d) Relative intensity as a function of wavelength in the output spectrum based on (b) and (c).

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LED Characteristics

(a) A typical output spectrum (relative intensity vs wavelength) from a red GaAsP LED.
(b) Typical output light power vs. forward current. (c) Typical I-V characteristics of a red LED. The turn-on voltage is around 1.5V.

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Figure 1 | White light from a cone-shaped LED illuminates researchers from the University of California, Santa Barbara. From left to right, Hisashi Masui, Steve DenBaars, Shuji Nakamura, Natalie Demille.
Prospects for LED lighting

- More than one – fifth of US electricity is used to power artificial lighting!!

- LEDs based on group III / nitride semiconductors are bringing a revolution in energy efficient lighting.

- Advantages of white light sources based on LEDs:
  (a) Low energy consumption
  (b) Environmentally friendly
  (c) User friendly source
Prospects for LED lighting

- If all the conventional white – light sources in the world were converted to the energy efficient LED light sources:
  (a) energy consumption could be reduced by around 1000 TW h yr\(^{-1}\) (equivalent to the energy that 230 500 MW coal plants produce).
  (b) **Reducing greenhouse gas emission by about 200 million tones.**
- The production of efficient, reliable white LEDs is a hot research topic in the field of RES.
- Until recently for white light two or more wavelengths are required to generate a broad spectrum of light.
- One way to produce additional wavelengths is to use phosphors.
Prospects for LED lighting

• In order to generate white light through using of phosphors ultraviolet, violet or blue LED is required.
• The GaN revolution has provided efficient ultraviolet, violet and blue light emitters.
• GaN is a direct band gap material with a 3.45 eV bandgap which corresponds to near – ultraviolet light (346 nm).
Prospects for LED lighting

- In 1960s GaN was studied as a potential material for LEDs by Paul Maruska and Jacques Pankove (Radio Corporation of America – RCA).
- Later GaN was studied extensively by Isamu Akasaki (Nagoya University) and Shuji Nakamura (Nichia Corporation).
- The first high efficient (1.5%) blue LED was introduced in 1992.
- 1995 the efficiency of the green and blue LEDs have reached the 10%.
- Due to the above achievements is possible now to generate white light source using LEDs.
Prospects for LED lighting
The metrics for judging a white-light source

• **Luminous efficacy:**
This parameter describes the ability of the white light source to produce a visual sensation. Luminous efficacy derives from convoluting the spectral power distribution of the light source with the spectral sensitivity of the human eye (peaks at 555 nm – green). This parameter is calculated by taking the ratio of the produced visual sensation (in lumens) to the electrical power required to produce the light.

• **Color Temperature:**
White light may be classified as being warm, neutral or cold when is compared with the light that is emitted by an ideal white light source at certain temperature. Without filters, incandescent bulbs typically glow a warm yellowish white. Fluorescent lights are generally bluish, but recent phosphor engineering has pushed their emission into warmer, yellowish white.
Prospects for LED lighting
The metrics for judging a white-light source

- **Colour – rendering index:**
  
  This is the ability of the white light source of interest to reproduce the colors of an illuminated object as these colors appear when the object is illuminated with an ideal white light source. From these deviations the CRI can be quantified. In this scheme the sun and the incandescent bulbs have a value of 100. For indoor lighting values above 80 are acceptable whereas for outdoor lighting lower values are required. **LED based white light sources are characterized by CRI values between 60 – 95.**
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Performance parameters

• **External Quantum Efficiency (EQE):**
  Is defined as the product of the internal quantum efficiency, injection efficiency and the extraction efficiency. Peak EQE approximately equal to 75%.

  **The injection efficiency** describes the number of electrons that are injected into the quantum wells to those provided by the power source.

  **The internal quantum efficiency** defines the ratio of the generated photons to the number of electron – hole pairs that are recombined.

  **The extraction efficiency** describes the ratio of photons leaving the LED to those generated.

  In the case of white light generation using phosphors a conversion efficiency that describes the ratio of photons of longer wavelengths to the number of absorbed photons of shorter wavelengths must be also calculated in the EQE.
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Improvement of LED performance parameters

• To reach IQE values close to 100% non-radiative recombination centers should be eliminated.
• Change the growing techniques and shift from polar to nonpolar devices.
• Concerning the extraction efficiency due to the refractive index variation between these ones of the GaN and the air 95% of the produced photons are trapped within the LED due to TIR. In order to avoid TIR perpendicular incident angles are desired.
• Progress is also being made in phosphor technology in order to improve the conversion efficiency and improve the quality of the white light through longer wavelength phosphor emission.
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- The three most popular approaches are shown:
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- The efficiencies of the previously mentioned architectures for white light source are shown:
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- There advantages and disadvantages among the three proposed schemes for white light source based on LEDs:

  (a) The combination of blue LED and yellow phosphors provides high efficiency that makes this combination an attractive, cheap, bright white source. This combination disadvantage is a lower value in the colour rendering index (CRI). Due to this disadvantage these LEDs are undesirable for indoor use.

  (b) The combination of the ultraviolet LED with phosphor mixtures provide higher CRI (suitable for indoor use) but at the expense of poorer efficiency.

  (c) The combination of LEDs is attractive and provides higher efficiency of the (b) combination but is an expensive solution. Also because is consisted from three different LEDs their lifetimes are not the same, so the light will change in colour as the lamp ages.
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Selenide nanocrystals

- One potential solution has been proposed by **Sandra Rosenthal** from Vanderbilt University:

  To use an ultraviolet emitting LED to energize the electrons in cadmium selenide nanocrystals, which respond by re-emitting a white light with very high CRI.
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Organic LEDs

- Another solution is offered from the technology of organic electronics: Instead of silicon wafers to use organic solutions!!

- Organic Light Emitting Diodes (OLEDs): The mechanism of producing light is the same except that the positive and negative charges originate in organic compounds rather than in crystal line semiconductors. By tailoring the composition of the organic material, it is possible to create devices that emit red, green, blue or collectively white light when electrically driven.

- **Advantages:**
  
  (a) **Low cost production** that is the same with the one that is used to handle other types of plastic films.

  (b) High efficiency (70-100 lm W⁻¹) – compared to that one of incandescent (12 lm W⁻¹) and fluorescent lamps (90 lm W⁻¹)

- **Disadvantages:**

  (a) Organic materials are degrade by the water and the oxygen.

  (b) Faster degradation is occurring in the blue OLEDs that are required to be used in company with the red and green OLED in order to produce white light.
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Organic LEDs

- Applications:
  (a) General lighting
  (b) Backlights for portable electronics
  (c) Flat panel displays
- According to Universal Display Corporation phosphorescent OLEDs will be able to break the 100 lm W\(^{-1}\) by 2010.
- Phosphorescent OLEDs are able to convert 100% of the electrons injected into the device into photons; whereas this figure is limited to 25% for OLEDs relying on fluorescence.
- PHOLEDs fabricated by vacuum thermal evaporation because this gives the best performance characteristics.
- Other production techniques: organic vapour phase deposition, spin coating, laser-induced thermal imaging, ink-jet printing, organic vapour printing.
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Organic LEDs

The typical structure of a PHOLED: By fabricating the device on a plastic substrate, thin, flexible light sources can be created.

Several thin – film layers (10 – 50 µm thickness) are deposited on each other and each layer performs a defined function such as generation of specific colour or the transportation of electronic charge away from the electrodes towards the organic dopants.

The collective aim is to maximize the recombination of electrons and holes and cause organic molecules to emit light.
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Organic LEDs

The efficacy of PHOLEDs is expected to break 100 lm W\(^{-1}\) by 2010. The best devices so far offer around 60 lm W\(^{-1}\).
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Organic LEDs

A PHOLED panel from UDC that emits high-quality white light with sufficient colour rendering to clearly distinguish red, green yellow and blue objects.

An optical fixture that is used to double PHOLED power efficacy.
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*Organic LEDs*

## Table 1 Performance for a 25 cm² white PHOLED

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum size</td>
<td>25 cm²</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.7 mm (without optical fixtures)</td>
</tr>
<tr>
<td></td>
<td>1.2 cm (with optical fixtures)</td>
</tr>
<tr>
<td>Drive voltage</td>
<td>5.6 V</td>
</tr>
<tr>
<td>Colour-rendering Index</td>
<td>71</td>
</tr>
<tr>
<td>Efficacy</td>
<td>30 lm W⁻¹ at 1,000 cd m⁻²</td>
</tr>
</tbody>
</table>
Prospects for LED lighting

Organic LEDs

• The lifetime of an OLED is defined as the time that takes light output to decrease by 50% when the device is driven at constant current.
• The PHOLED satisfies the lifetime requirement for night lighting that is equal to 10,000 hrs. From the other hand significant development is still required to be occurred to satisfy the display lifetime requirement (equal to 50,000 hrs).
• Significant amount of work to be done before high efficacy white PHOLEDs become a commercial reality:
  (a) Scaling the size of the technology. PHOLEDs are required to have active areas in excess of 25 cm² to generate 600 lumens.
  (b) The conductivity of the transparent electrode in a large device is high enough to avoid increased operating voltages, resistive heating, non-uniform emission, and differential ageing across the active area.
Prospects for LED lighting

Induction and Catholuminescence Lambs

- **The induction lamp** was firstly introduced in Nikola Tesla in 1890s.
- The newest devices feature an electrodeless bulb that is filled with argon gas plus a small amount of metal halide salts.

A microwave generator produces a microwave that is channeled through a waveguide and concentrated on to the container, where it ionizes the gas to form a plasma and vaporizes the salts. The plasma and the vapour together generate a broad spectrum white light source with an efficiency similar to that of LED.
**Prospects for LED lighting**

*Induction and Catholuminescence Lambs*

- **The cathodoluminescence lamps** uses a source of electrons to bombard a phosphorescent material coated on the inside of a glass bulb causing the material to emit light.

- The cathodoluminescence lamps are white light sources that are characterized by:
  
  (a) High CRI
  
  (b) High efficiency

- Initial applications: Home usage.
Prospects for LED lighting
Induction and Cathodoluminescence Lambs

• Both Induction and Cathodoluminescence lamps face the following drawback:
  It is not a solid state technology so they have moving parts that are disadvantages when it comes to ruggedness and long life.

• More specifically the induction lamp based on sulphur failed to gain a foothold in the market because of its problematic behaviour in high temperatures.
Prospects for LED lighting

LEDs in automotive industry

- Millions of new cars today use LEDs for rear vehicle lighting and the technology is fast spreading into other parts of the car.
- The use of LEDs for exterior automotive functions began in the late of 1980s in Japan (30 630 nm LEDs in stop lamps).
- The technical reasons why the vehicle makers adopted this technology are:
  a. Energy efficiency: According to the International Energy Agency 55 million liters of gasoline and diesel were used for car lighting worldwide in 2005. LED technology: fit and forget & environmental friendly
  b. Small size (few square of millimeters)
  c. Fast time response (few milliseconds)
  d. Customized color emission
- The constraints of cost and performance have been sufficient to slow their introduction into the market.
Prospects for LED lighting

LEDs in automotive industry

• Today Toyota, Honda, Nissan, Cadillac, Lincoln, Volvo, Jaguar, BMW, Audi are using LEDs for various exterior lighting applications (high mount stop lambs, turn lights, front sidemarker lamps).

• White – light applications on vehicles are now a reality. Impressive output and efficiency improvements in white LED over the past two years have brought the number of devices required to make a low beam headlamp to less than 10 (Audi and Toyota).

• To conclude it is expected that the following 5-10 years the LEDs will power every lighting applications on the vehicles.
Prospects for LED lighting

LEDs in automotive industry

The headlamp unit used in an Audi luxury car. A cluster of five white LEDs forms the daytime running lamp, but the main beam is still generated by traditional means.

A rear lamp unit from an infinity G35. The individual LED emitters can clearly be seen beneath the plastic shield.

The LED daylight running lamps of an Audi in action.

A Luxeon K2 LED chip from Lumileds, a subsidiary of Philips Lighting that specializes in high-power LED technology.
Prospects for LED lighting

Historic Development of the most used white light sources
Prospects for LED lighting

Bright Future

• It is expected that the white light sources based on LEDs are developed so fast that have already exceed the Haitz’s law:
  “Every 10 years the amount of light generated by an LED increases by at least a factor of 20 while the cost per lumen drops at least a factor of 10”
• Ultimate goal: To replace all the incandescent and portable fluorescent lamps.
• Cost of white light source based on LED: 50 times as expensive as incandescent lamps and 7 times more expensive than compact fluorescent lamps.
• LEDs longer lifetime makes them: A seventh of the cost of incandescent lamps and two – thirds of the price of compact fluorescent lamps.
• Limitations to white LED performance:
  (a) Theoretical maximum efficacy ~ 260 lm W\(^{-1}\)
  (b) Thermal management at high currents (silicon substrates is the solution)
  (c) Degradation of the polymer material that encapsulates the LED.
Prospects for LED lighting

Blazing Competition

- The alternatives technology is not far ahead of incandescent bulbs. US Department of Energy data published in 2008 found that commercially available LEDs were about half as efficient as compact fluorescent lights.
- Conclusion: The general use incandescent bulbs may be replaced by more than one alternatives: E.g. Semiconductor LEDs (more light intensive tasks) and OLEDs (area lighting through flat panels).

Light-emitting diodes, such as these in Craigieburn, Australia, can be combined to create huge displays.
Prospects for LED lighting
Bright Future

- Industrial news:
  
  (a) **Osram-Opto-Semiconductors** has begun intensifying its research and development of organic LEDs with an emphasis on developing white OLEDs for general lighting.

  (b) **General Electric solid state lighting department** has paid 100 million dollars to buy out the 49% stake owned by its partner in the venture Emcore. At the same time has also announced a strategic alliance with Nichia Corporation, a leading Japanese maker of LEDs and phosphors.

  (c) **Philips Royal Electronics** plans to double its high power LED production capacity thanks to new plant in Singapore. The company expects the high power LED market to grow at an annual rate of 25% in coming years.

  (d) **Epistar Corporation** the biggest manufacturer of LED chips in Taiwan has further expanded by merging with both Epitech Technology and Highlink Technology Corporation. Targeted market of this corporation will include LCD backlighting, laptops, LCD televisions, automobiles and outdoor displays.
Prospects for LED lighting
Bright Future

• Industrial news (continue):

(e) US Department of Energy invests 5 million dollars in new funding for seven research projects to push the development of solid state lighting.
Prospects for LED lighting

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• *Time to change the bulb*, Stefano Tonzani, Nature Vol. 459, 21 May 2009


