LEDs

(Light Emitting Diodes)

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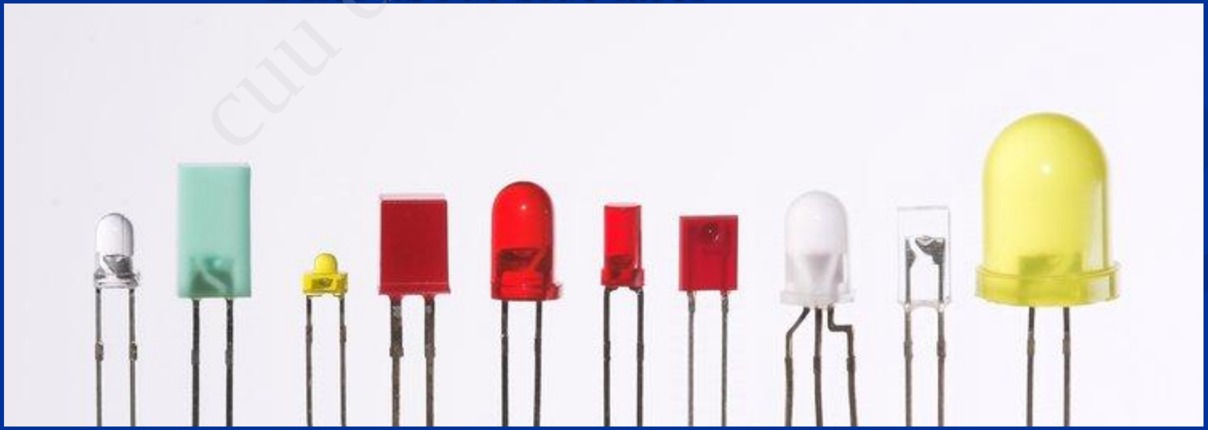
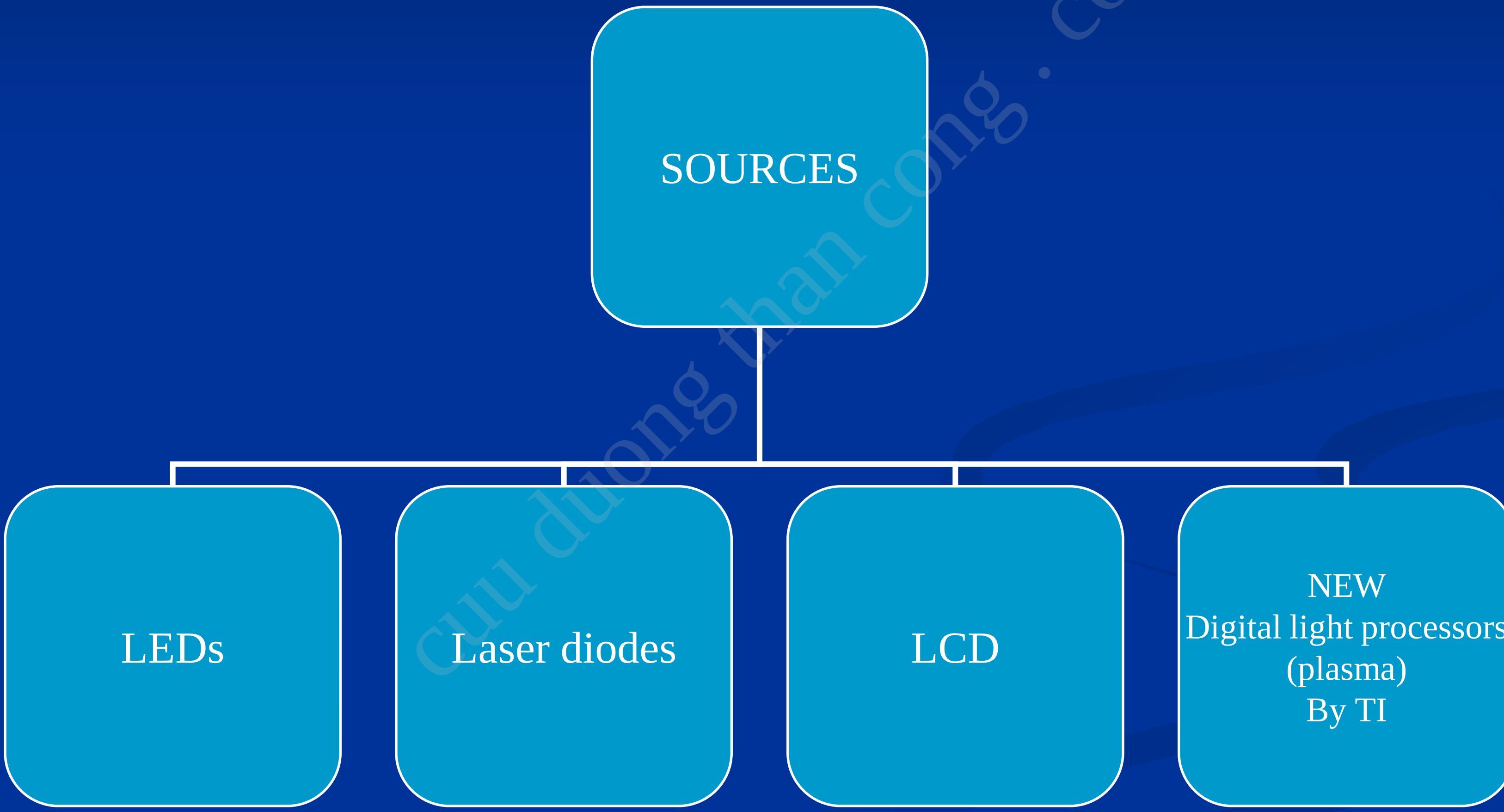
Winter 1384

Introduction

- Introduction to LEDs
  - How LEDs work + some points
  - Comparison with other sources of light
  - LED in communication
- Blue &White LED technologies
  - How they are made
  - Their application
  - Brief about blue laser



Light Sources in Electronics



LED

- Stands for light emitting diode.
- Semiconductor device:
  - p-n junction
  - forward-biased.current
    - emits incoherent narrow spectrum light

    (due to recombination in transition region near the junction.)
    - Color of the emitted light depends on the chemical of the semiconducting material used.

    (Near-ultraviolet, visible or infrared.)

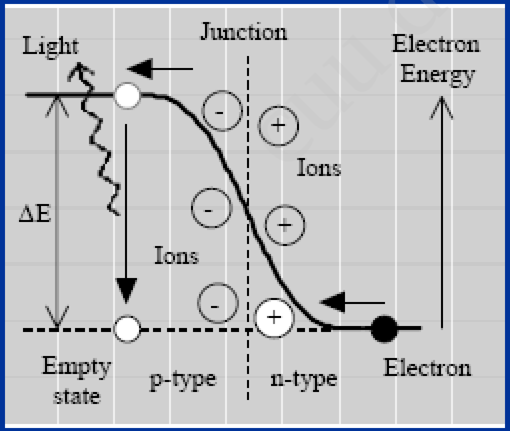
LED

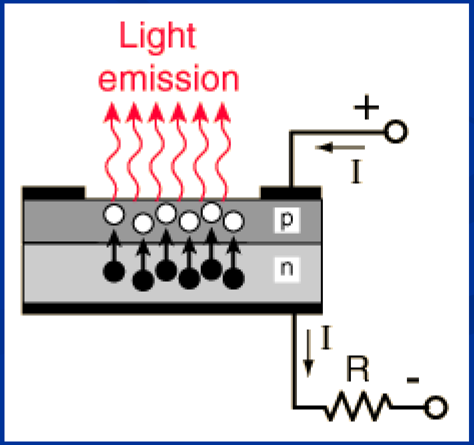
- Normally constructed of (Direct Gap):

GaAs, GaAsP , GaP :

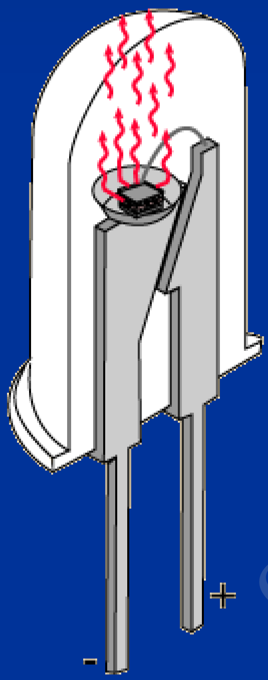
Recombination→light

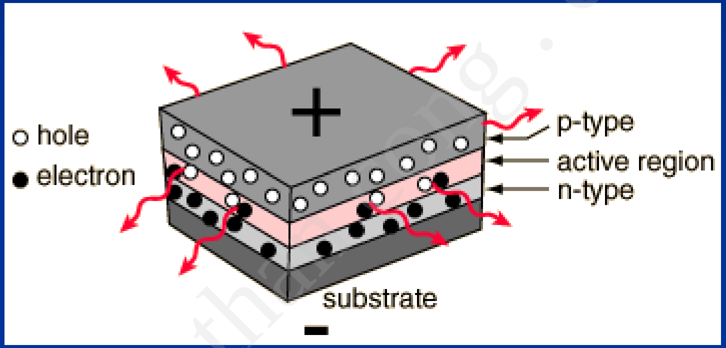
- Si and Ge are not suitable because of indirect band.→recombination result heat

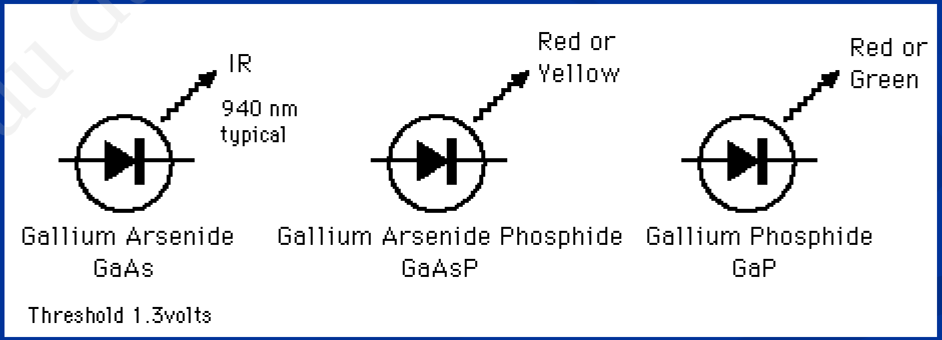




Structure and electroluminescence







Band Gap

- Various band gaps →different photon energies

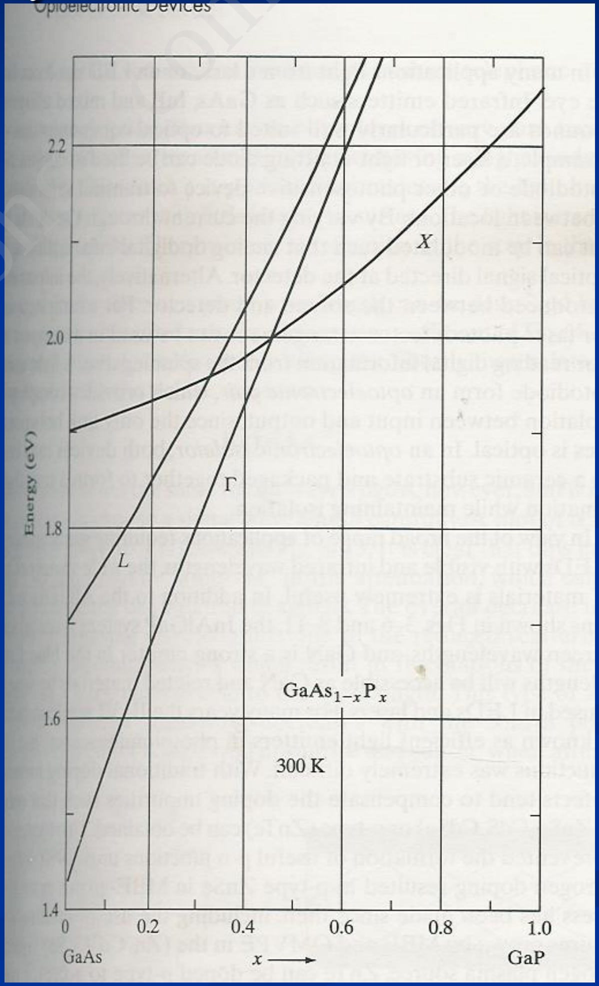
Ultra violet :GaN 3.4 ev –infra-red: InSb 0.18 ev

- Ternary&quarternary→increasing number of available energies

Example: $GaAs_{1-x}P_x$ 0<X<1

0<X<0.45→ Direct usually 0.4 used for LEDs

0.45<X<1→Indirect

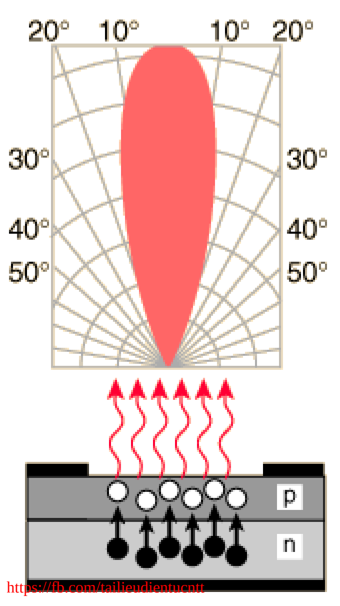


•Heisenberg uncertainty principle $\Delta_x \Delta_p \geq \frac{h}{2\pi}$

•Indirect $GaAs_{1-x}P_x$ can emit light if we add nitogen.

LED Radiation Patterns

- LED:Directional light source, maximum emitted power in the direction perpendicular to the emitting surface.
- typical radiation pattern shows that most of the energy is emitted within 20° of the direction of maximum light.
- Some packages for LEDs include plastic lenses to spread the light for a greater angle of visibility.



Colors

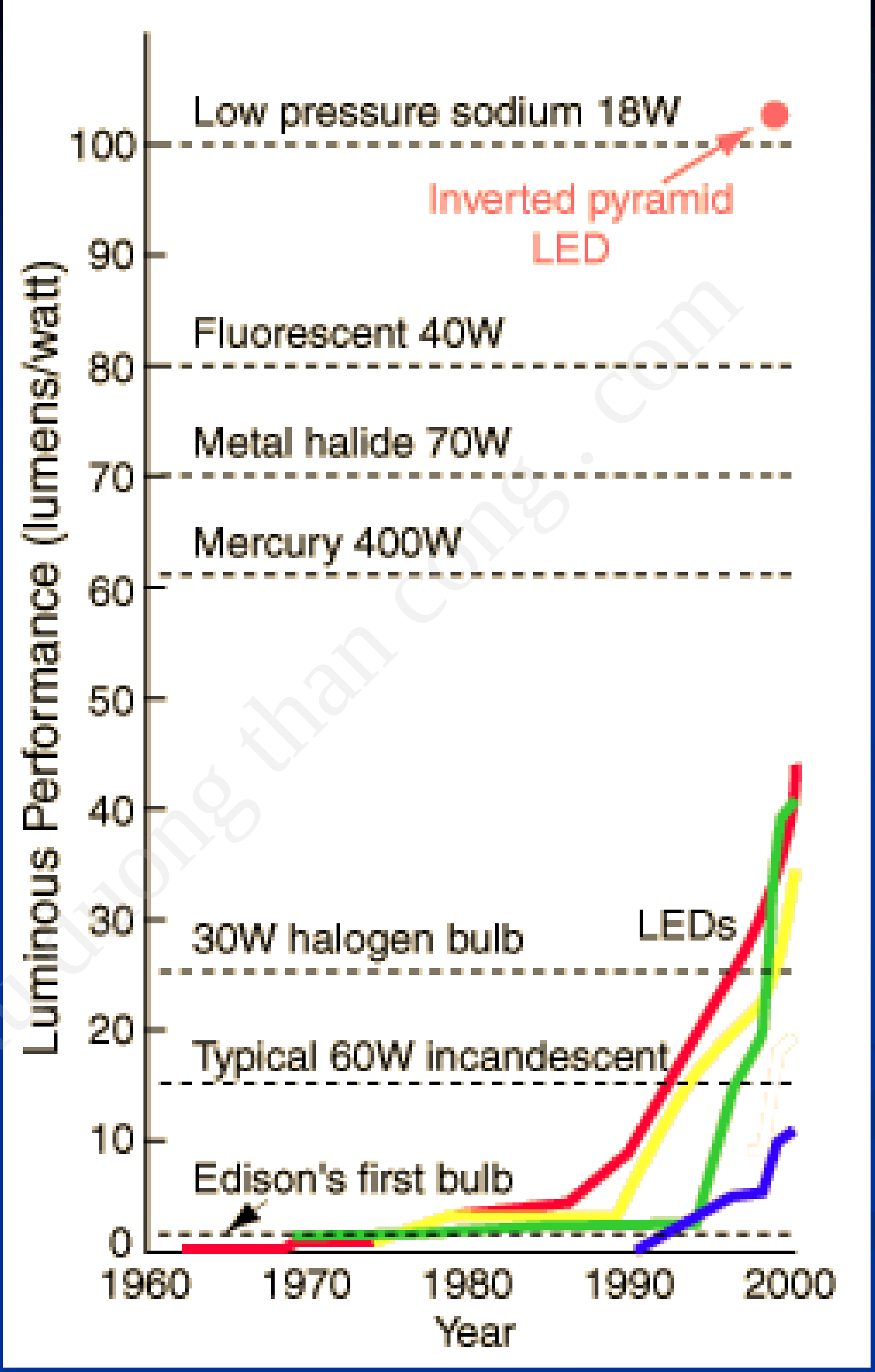
- III-V materials
- Before II-VI (hard to have p-n junction)
- Solution: Nitrogen ZnSe (MBE grown)
- Progress: using multilayer hetero structures by MBE(Mulecular Beam Epitaxy) & OMVPE

(organometalic vapor-phase epiaxy)

- (AlGaAs) - red and infrared
- (AlGaP) - green
- (AlGaInP) - high-brightness orange-red, orange, yellow, and green
- (GaAsP) - red, orange-red, orange, and yellow
- (GaP) - red, yellow and green
- (GaN) - green, pure green (or emerald green), and blue
- (InGaN) - near ultraviolet, bluish-green and blue
- (SiC) as substrate - blue
- (Si) as substrate - blue (under development)
- (Al2O3) as substrate - blue
- (ZnSe),(GaN) - blue
- (C) - ultraviolet
- (AlN), (AlGaN) - near to far ultraviolet
- New colors: pink and purple :2 layers of phosphors on Blue LED chip

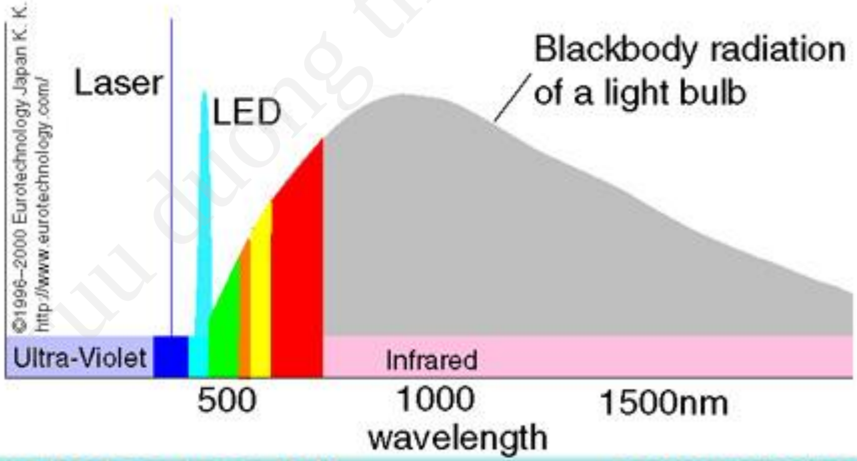
Definition

- Luminous performance:
  - The efficiency of a device in converting electrical power to visible light. (lumens/watt)
    - Low pressure sodium lights → very high efficiency (because of the dominance of the sodium d-lines in the response of sodium vapor.)
    - one type of red LED, the inverted pyramid type developed by Hewlett-Packard has exceeded the efficiency of "old yellow", the sodium light.


Low pressure sodium 18W
Inverted pyramid
LED
Fluorescent 40W
Metal halide 70W
Mercury 400W
30W halogen bulb
LEDs
Typical 60W incandescent
Edison's first bulb
Luminous Performance (lumens/watt)
100
90
80
70
60
50
40
30
20
10
0
1960
1970
1980
1990
2000
Year

Light Spectrum of an LED, a Light Bulb and a Laser

- **Light bulb:** tungsten filament heated to about 3000 C emits "black body" radiation over a broad spectrum. Most emission is invisible infrared heat radition. The efficiency is low, because most input energy is converted into heat, not into light.
- **LED:** Light is emitted by the transition of electrons between energy levels, and therefore within a relatively narrow range of wavelenghts
- **Laser:** the emission of a laser is determined by the resonance of an "optical amplifier" and an optical cavity. The light emitted is coherent (this means that the light waves are continuous without break in phase over a considerable range in time and space). Lasers can emit light in a very narrow beam in a very narrow wave length spectrum



Advantages of LEDs

- Great stride in power and efficiency

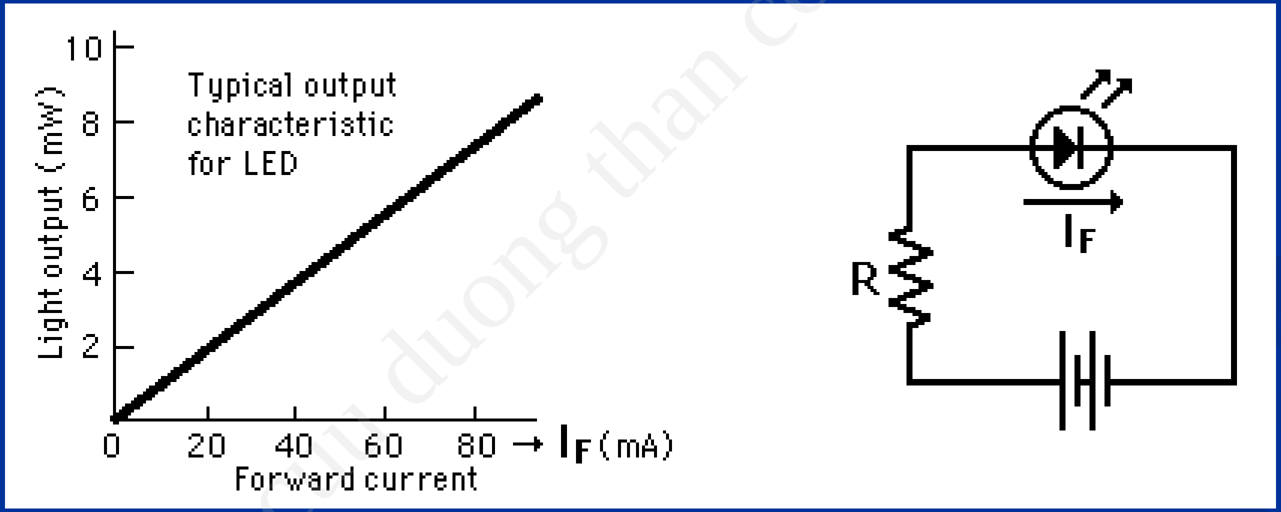
  100,000 hours of work compared to 1000 hours of life time for incandescent bulbs.
- LEDs :capable of emitting light of an intended color without the use of color filters that traditional lighting methods require.
- The shape of the LED package allows light to be focused. Incandescent and fluorescent sources often require an external reflector to collect light and direct it in a useable manner.
- LEDs are insensitive to vibration and shocks, unlike incandescent and discharge sources.
- LEDs are built inside solid cases that protect them, making them hard to break and extremely durable

Advantages continued

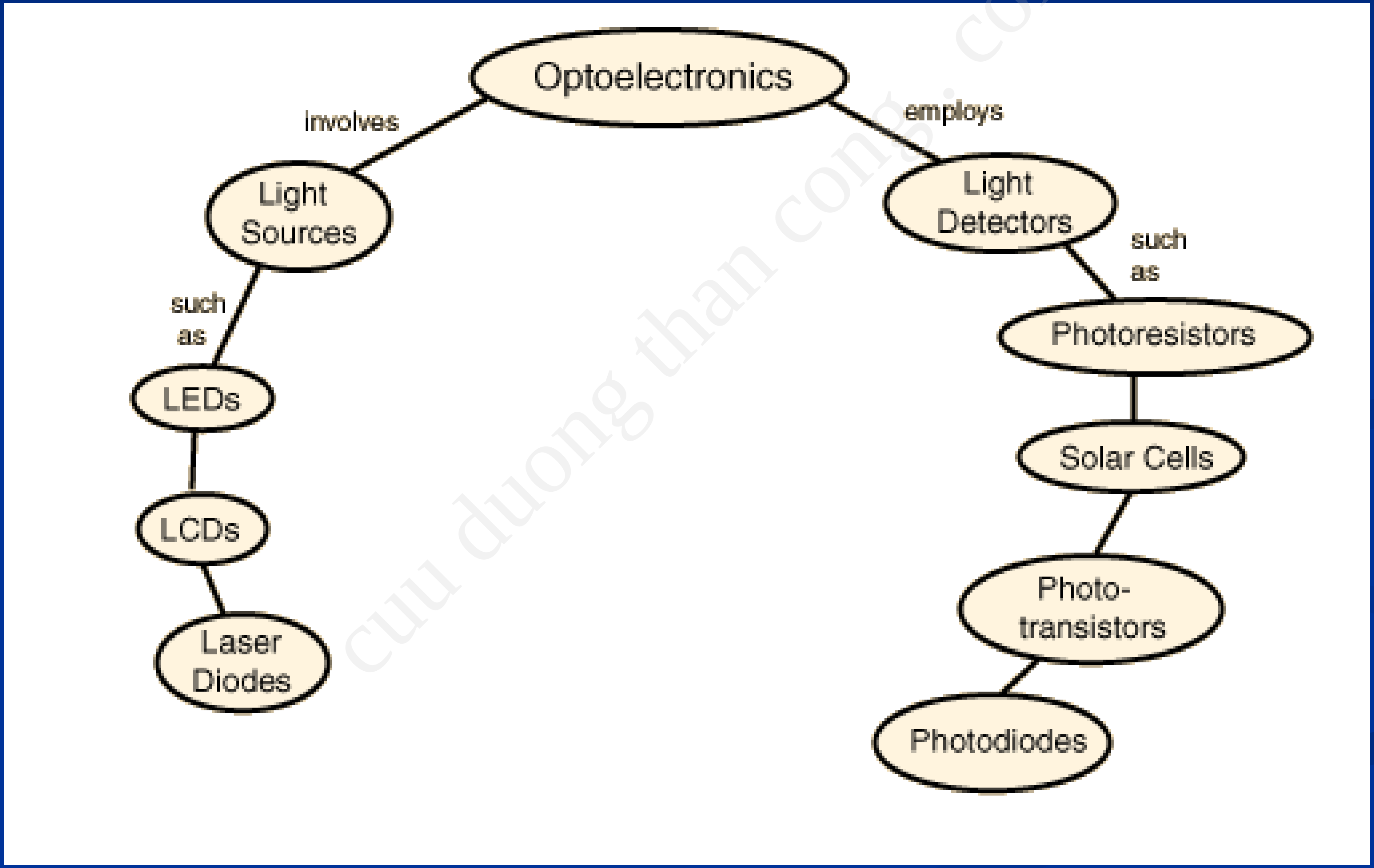
- LEDs have an extremely long life span: typically ten years, twice as long as the best fluorescent bulbs and twenty times longer than the best incandescent bulbs.
- Further, LEDs fail by dimming over time, rather than the abrupt burn-out of incandescent bulbs.
- LEDs give off less heat than incandescent light bulbs with similar light output.
- LEDs light up very quickly. A LED will achieve full brightness in approximately 0.01 seconds, 10 times faster than an incandescent light bulb(0.1 seconds), and many times faster than a compact fluorescent lamp, which starts to come on after 0.5 seconds or 1 second, but does not achieve full brightness for 30 seconds or more.
- Only disadvantage: needs positive voltage(forward bias)

LED Characteristics

- Forward biased ⟶ fast increase in current(control needed)



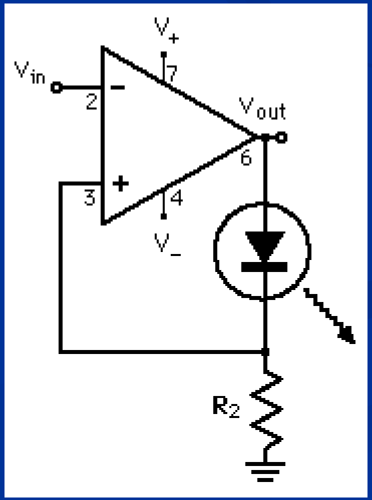
Overview on optoelectronics



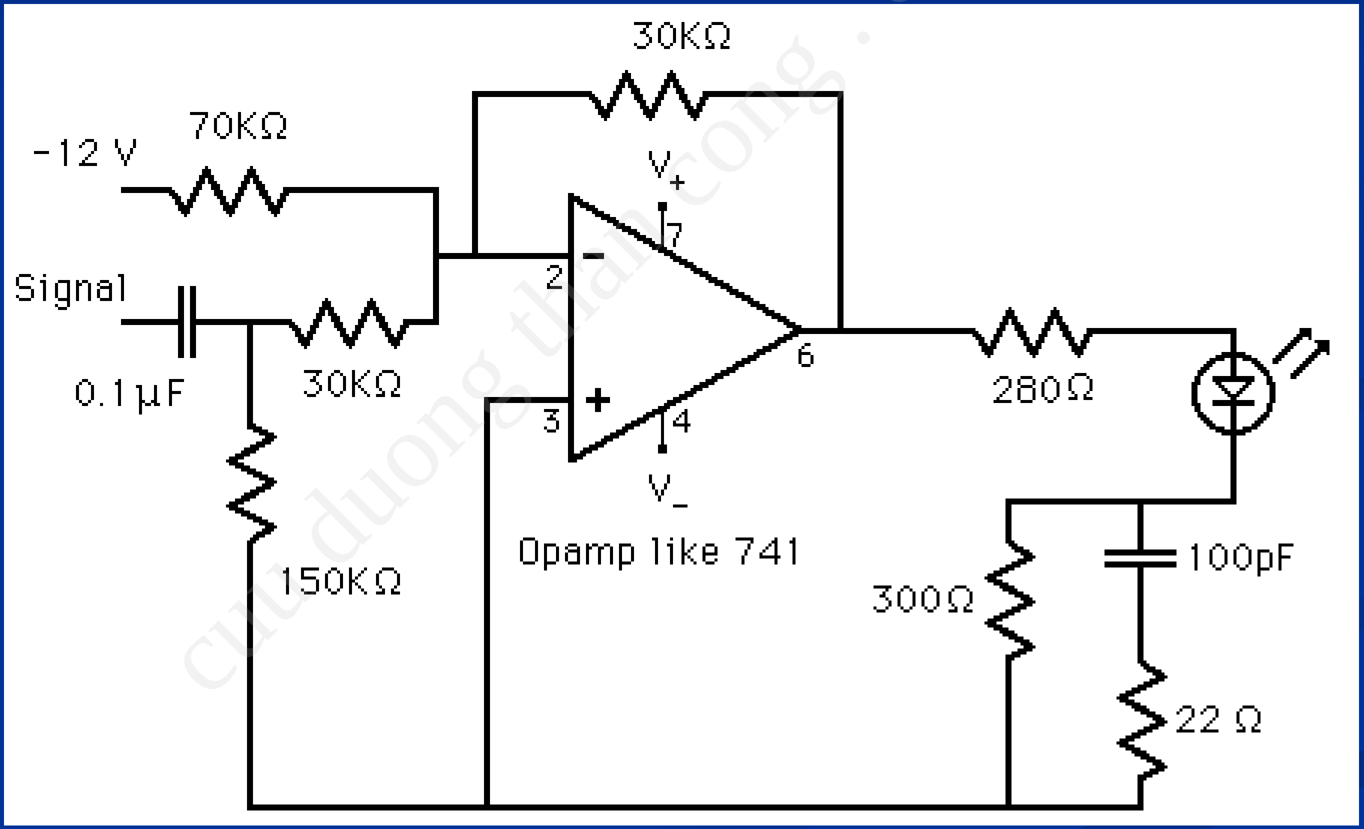
LED Modulation

- LED light output is linearly proportional to the current:

Usage in sending a signal, that signal can then be send through a fiber optic cable and detected on the other end.



LED Modulation Circuit



Fiber Optic Communication

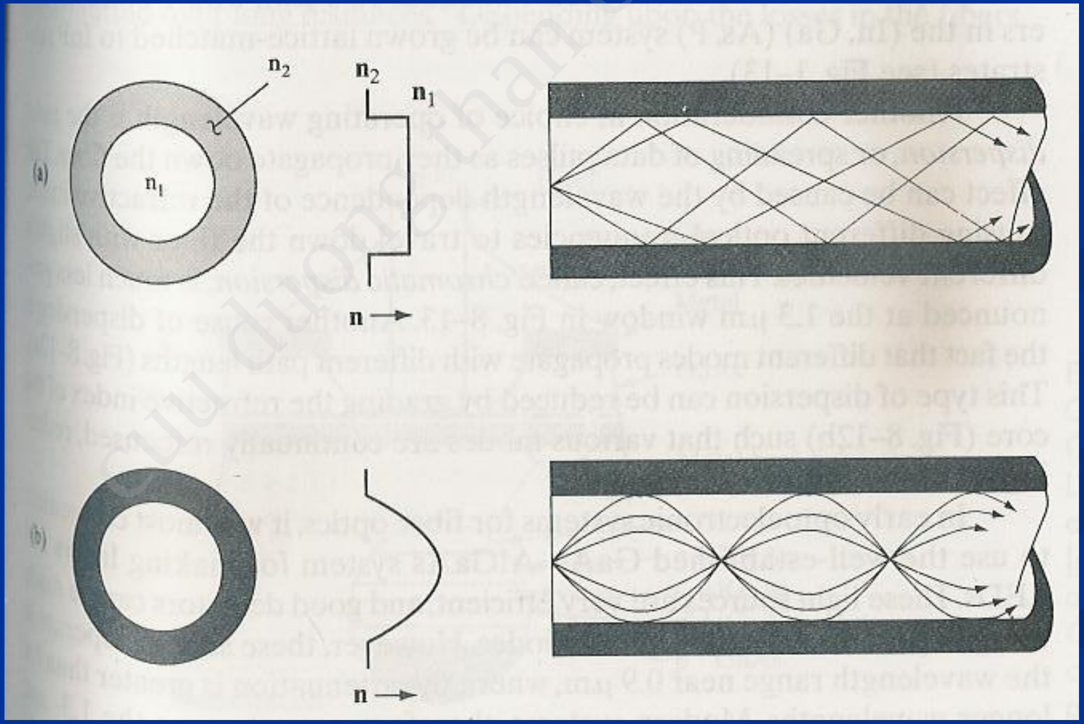
- Enhancement of optical communication by fiber between source and receiver
- Fiber : Light pipe or wave guide for optical frequencies
- Made of: Outer layer of pure fused silica, core of germanium

Different Types

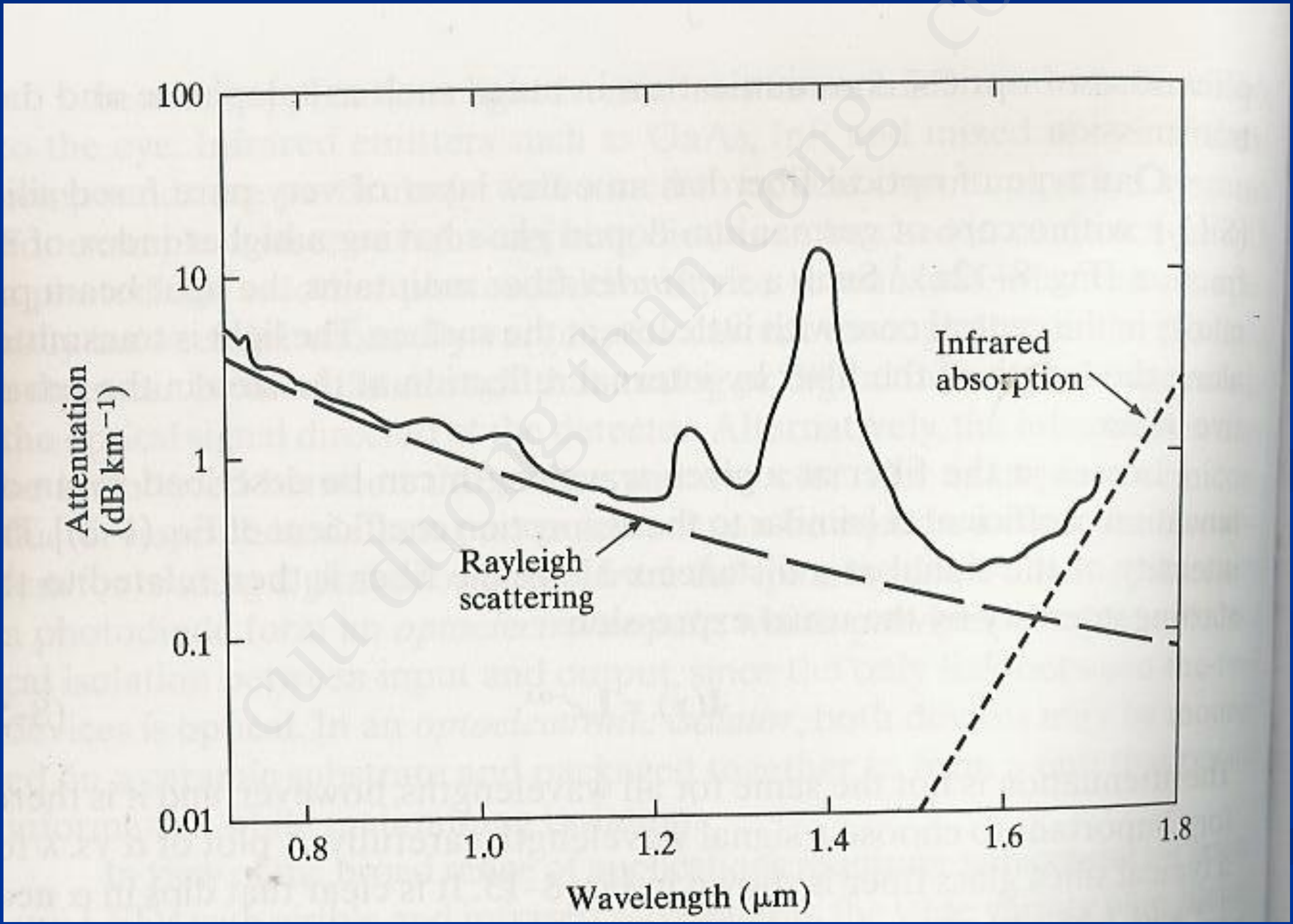
$$I(x) = I_0 e^{-\alpha x}$$

Step Index

Graded index



$$\alpha = f(\lambda)$$



Reyleigh Scattering

- Reyleigh Scattering

reduced scattering from small random inhomogeneties.

Fluctuations of n1

Decrease with fourth power of wavelenghth

You can see the effect while sun rise and sunset

Infrared Absorption

- Dominates for wavelength longer than about 1.7μm
- Due to vibrational excitation of atoms making up the glass

Pulse Dispersion

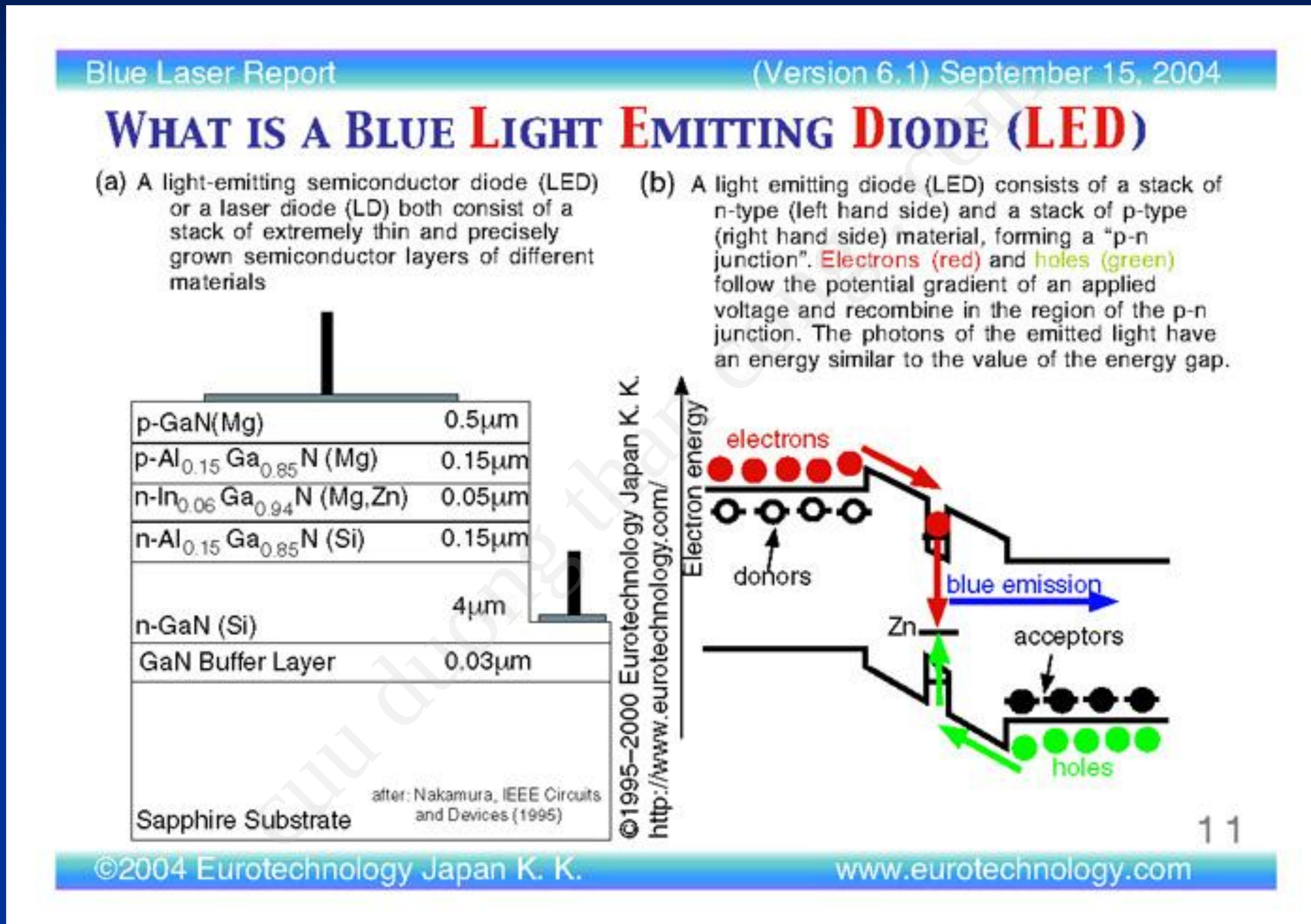
- Spreading the data propagating the fiber
- Reason: n=f(λ)→different frequencies travel with different velocity→less for 1.3 μm window
- Another reason: different modes propaget in different path lengths

Application

- Toys, Illumination, remote control, traffic signal, 7-segments and so on…

BLUE LED


NASDAQ
NASDAQ
NASDAQ
NASDAQ
WELCOME LEVEL 3 COMMUNICATIONS
NASDAQ
Condé Nast


Blue Laser Report
(Version 6.1) September 15, 2004
WHAT IS A BLUE LIGHT EMITTING DIODE (LED)
(a) A light-emitting semiconductor diode (LED) or a laser diode (LD) both consist of a stack of extremely thin and precisely grown semiconductor layers of different materials
p-GaN(Mg) 0.5μm
p-Al0.15 Ga0.85N (Mg) 0.15μm
n-In0.06 Ga0.94N (Mg,Zn) 0.05μm
n-Al0.15 Ga0.85N (Si) 0.15μm
n-GaN (Si) 4μm
GaN Buffer Layer 0.03μm
Sapphire Substrate
after: Nakamura, IEEE Circuits and Devices (1995)
©1995–2000 Eurotechnology Japan K. K.
http://www.eurotechnology.com/
(b) A light emitting diode (LED) consists of a stack of n-type (left hand side) and a stack of p-type (right hand side) material, forming a "p-n junction". Electrons (red) and holes (green) follow the potential gradient of an applied voltage and recombine in the region of the p-n junction. The photons of the emitted light have an energy similar to the value of the energy gap.
Electron energy
electrons
donors
blue emission
Zn
acceptors
holes
11
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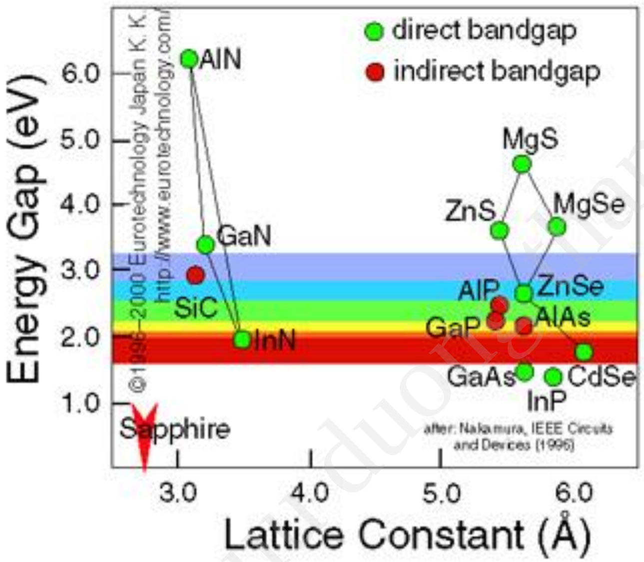
Why Gallium Nitride (AlGaN/InGaN)?



- AlN, GaN, InN materials all have a direct band gap, i.e. the optical transitions across the bandgap are "allowed" and therefore much stronger than in the case of indirect bandgaps (which have "forbidden" transitions), as in the case of Silicon Carbide (SiC).
- Before Nichia brought GaN blue LEDs on the market, commercial blue LEDs used SiC, which are much less efficient due to the indirect bandgap
- Before Shuji Nakamura commercialized GaN blue LEDs it was generally thought that II-VI compounds were the path to blue LEDs and Lasers however defects in these materials could not be controlled sufficiently and the life-time of the devices was too short

Application

- Blue LEDs are important for the development of high-information-density storage on optical disks, as well as a host of other applications such as high-resolution television and computer displays, image scanners and color printers, biomedical diagnostic instruments, and remote sensing.

Ways to obtain Blue Light

- doubling the frequency of red or infrared laser diodes (Used by Matsushita and Hitachi)
- The material used for the diode was gallium nitride GaN. Nichia has also produced an InGaN laser diode which lases in the blue-violet region of the spectrum. (Japan in 1994)

Shuji Nakamura

Innovative MOCVD Technique

- Nakamura's road to that invention began with his development of a new technique for Metal-Organic Chemical Vapor Deposition (MOCVD). With the conventional MOCVD technique, semiconductors are made by flowing reactant gases over a substrate. Nakamura pioneered a method whereby the gases flow in two directions instead of one, thereby improving the material quality.
- That novel MOCVD technique enabled Nakamura to make a blue LED. And the blue LED lead to the white LED and the blue laser.

What Nakamura exactly did?

- What Nakamura did was to figure out how to grow the crystal so that it would have the n and p semiconductor structure that would create "quantum wells" for the electrons at the junction. One key thing he did to create the wells was to add indium to the gallium nitride crystal. Without the indium, the gallium nitride crystal produces a higher frequency ultraviolet light, which is not visible. The addition of indium results in lowering the frequency of the emitted photons to visible blue, but the indium also creates the quantum well effect, so that electrons falling into the passing holes first fall into the well and therefore collect en mass before being injected into the holes. That massing in the well creates a more vigorous injection.

Three Key steps to GaN devices

THREE KEY DIFFICULTIES HAD TO BE SOLVED:

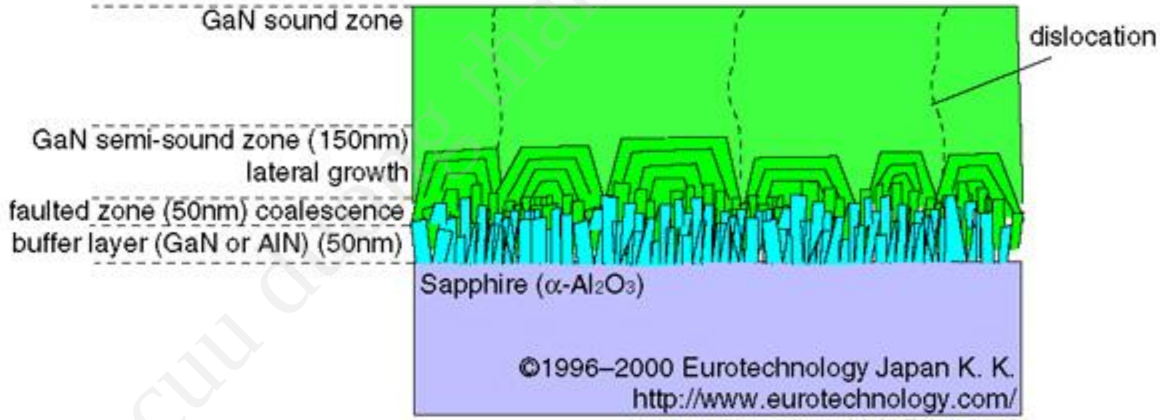
1. Lattice mismatch
   - ◆ GaN is grown on Sapphire, which has a 15% smaller lattice constant than GaN, and different thermal expansion, leading to a very high defect density and cracking of the layers when the structures are cooled down after growth
   - Akasaki solved this problem by developing AlN buffer layers
   - Nakamura grew GaAlN buffer layers
2. High growth temperature
   - ◆ thermal convection inhibits growth
   - **Nakamura solved this problem with his two-flow growth reactor** (this invention by Shuji Nakamura is at the core of the US$ 600 million law suits before the Courts of Japan between Shuji Nakamura and Nichia Chemical Industries)
3. p-doping was impossible
   - ◆ A semiconductor laser, semiconductor light emitting diode, transistor structures and other device structures require pn-junctions, I.e. junctions between p-type and n-type materials. Previous to Akasaki's work p-type doping of GaN was impossibly
   - Akasaki demonstrated p-type material which was e-beam annealed
   - Nakamura found that annealing in Ammonia gas passivated the acceptors and solved this problem

1. Lattice Mismatch (A)

- Choice of substrate
  - Silicon Carbide (SiC): good lattice matching, very expensive, patent issues
  - Sapphire: used at present for most devices
  - Ideally: GaN. However, GaN substrate wafers have not been available. Once they become available, it is expected that GaN devices grown on GaN will have much better properties than devices grown on Sapphire with high lattice mismatch
- Sapphire as substrate
  - 15% difference in lattice constants between Sapphire and GaN and very large difference in thermal expansion initially made growth of devices impossible.
  - Akasaki solved this issue by designing and growing a AlN buffer layer (Akasaki US-Patent 4855249, Applied Physics Letters)
  - Nakamura grew GaAlN buffer layers (Nakamura US-Patent 5290393, Japanese Journal of Applied Physics)

1. Lattice Mismatch (B)

- Problem: large lattice mismatch and large difference in thermal expansion between Sapphire substrate and GaN/AIN
- Solution: AIN Buffer layer (Akasaki, US-Patent 4855249, Applied Physics Letters
- Solution: GaAIN Buffer layer (Nakamura, US-Patent 5290393, Japanese Journal of Applied Physics)
- Ideal solution for the future: GaN substrates (still need to be developed, recent progress looks promising)



after: Akasaki (APL, 1986)

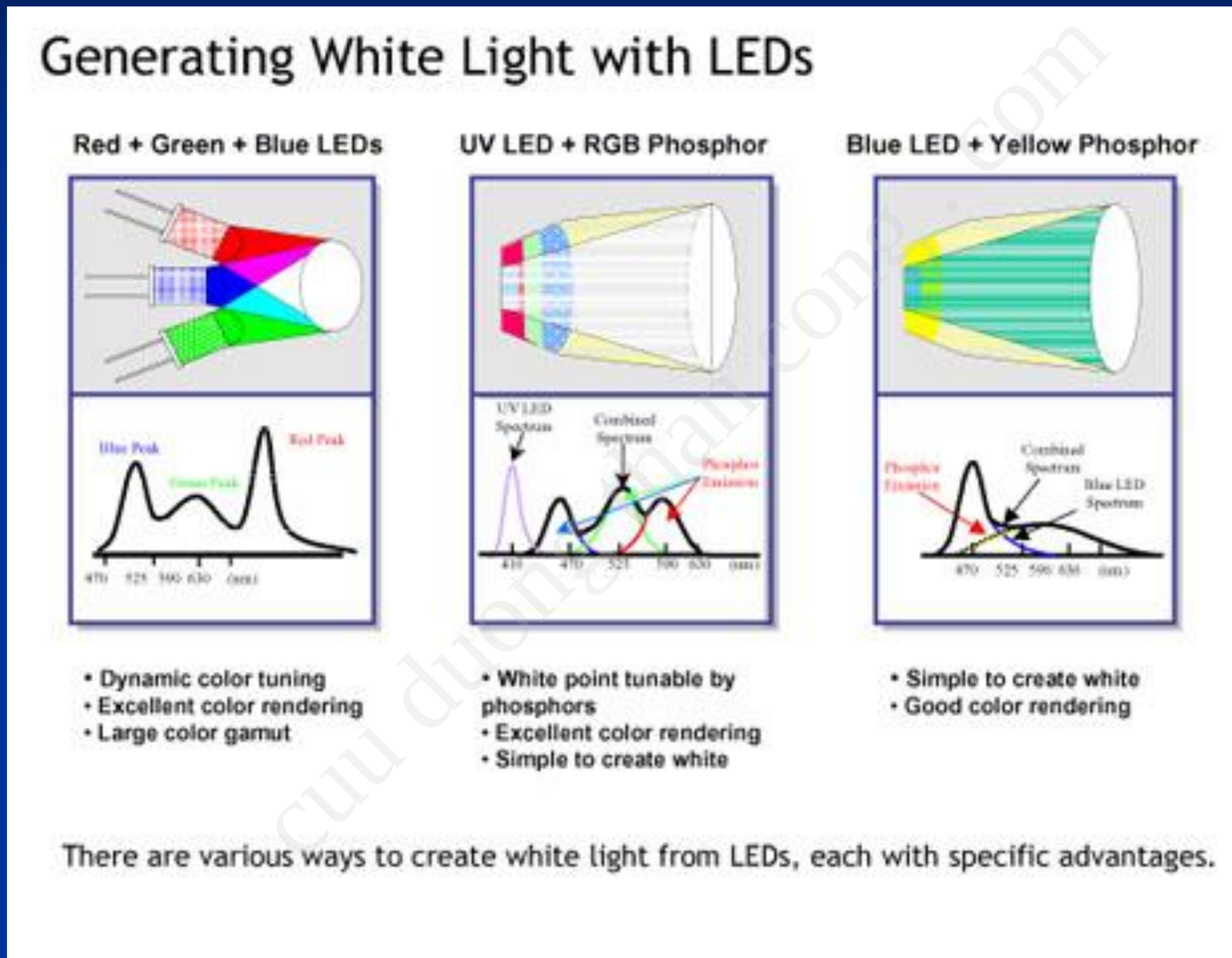
White LED


Ways to make white LED

- Rarely used: Blue LED added to existing red and green LEDs.
- Most "white" LEDs in production today use a 450 nm – 470 nm blue GaN (gallium nitride) LED covered by a yellowish phosphor coating usually made of cerium-doped yttrium aluminum garnet .("Lunar White" Nichia 1996)
- White LEDs can also be made by coating near ultraviolet (NUV) emitting LEDs with a mixture of high efficiency europium based red and blue emitting phosphors plus green emitting copper and aluminum doped zinc sulfide (ZnS:Cu,Al) similar to fluorescent lamps.

Continued…

- The newest method used to produce white light LEDs uses no phosphors at all and is based on homoepitaxially grown zinc selenide (ZnSe) on a ZnSe substrate which simultaneously emits blue light from its active region and yellow light from the substrate.
- A new technique just developed by Michael Bowers, a graduate student at Vanderbilt University in Nashville, involves coating a blue LED with quantum dots that glow white in response to the blue light from the LED. This technique produces a warm, yellowish-white light similar to that produced by incandescent bulbs

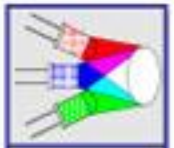


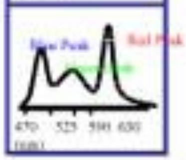
Generating White Light with LEDs
Red + Green + Blue LEDs
UV LED + RGB Phosphor
Blue LED + Yellow Phosphor
• Dynamic color tuning
• Excellent color rendering
• Large color gamut
• White point tunable by phosphors
• Excellent color rendering
• Simple to create white
• Simple to create white
• Good color rendering
There are various ways to create white light from LEDs, each with specific advantages.

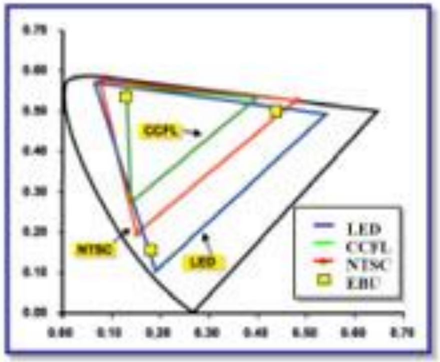
Creating white light- the RGB Solution

Combining Red, Green and Blue LEDs

- Advantages
  - Long term likely the most efficient!
  - Dynamic tuning of color temperature possible!
  - Excellent color rendering!
  - Very large color Gamut available!
- Challenges
  - Color mixing can be tricky!
  - Yellow-Green Gap!

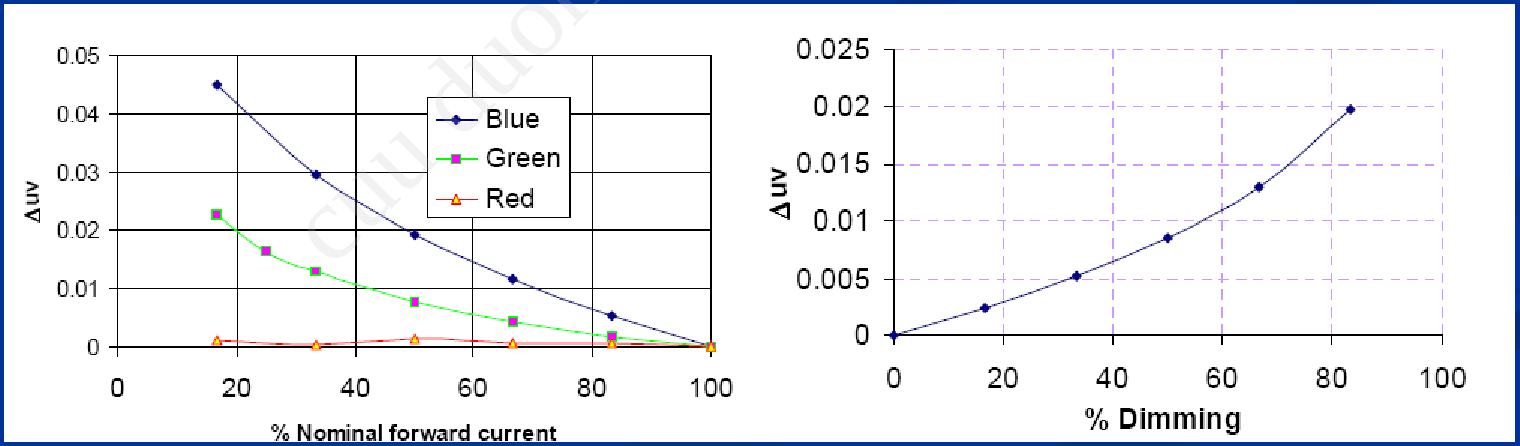




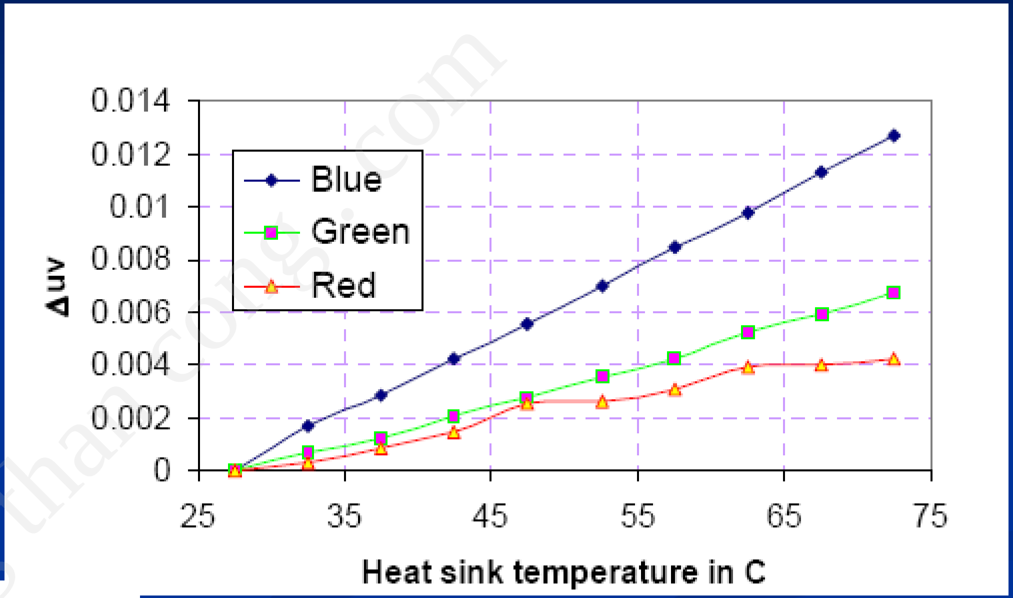


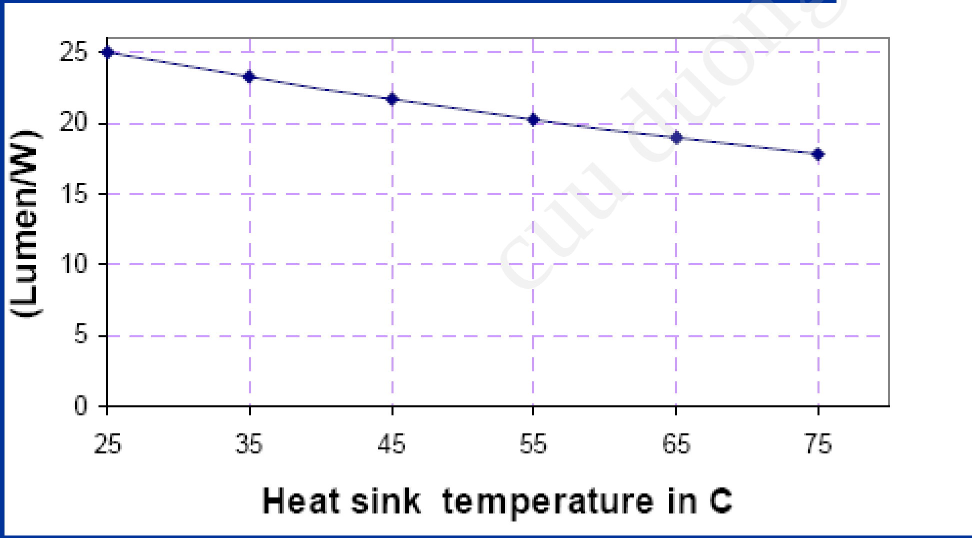
RGB problems

- wavelength and lumen output change by:
  - Temperature
  - Time
  - Forward Current

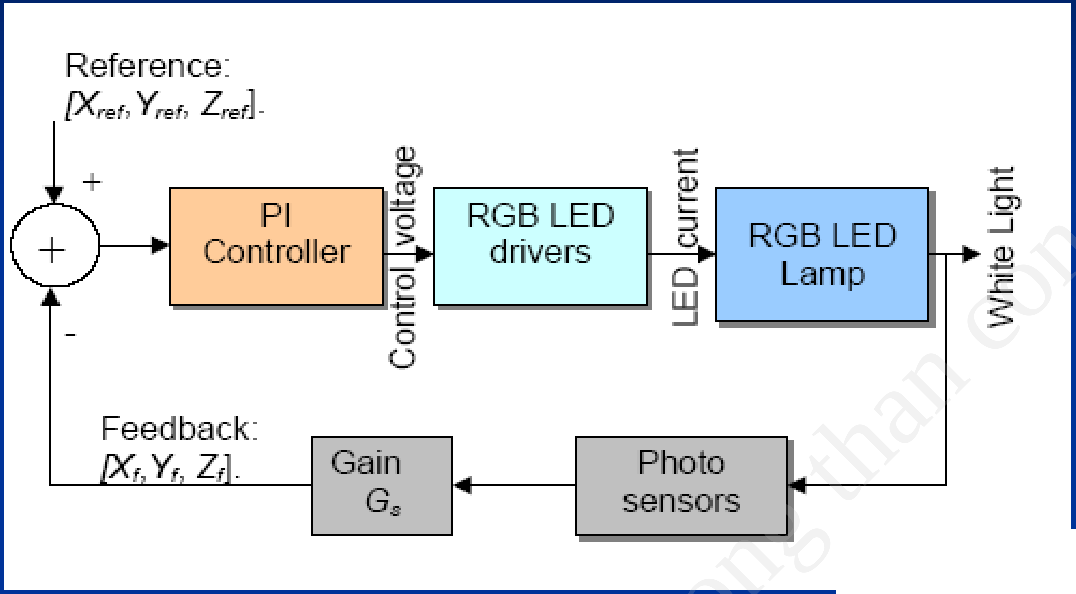


Temperature Effect

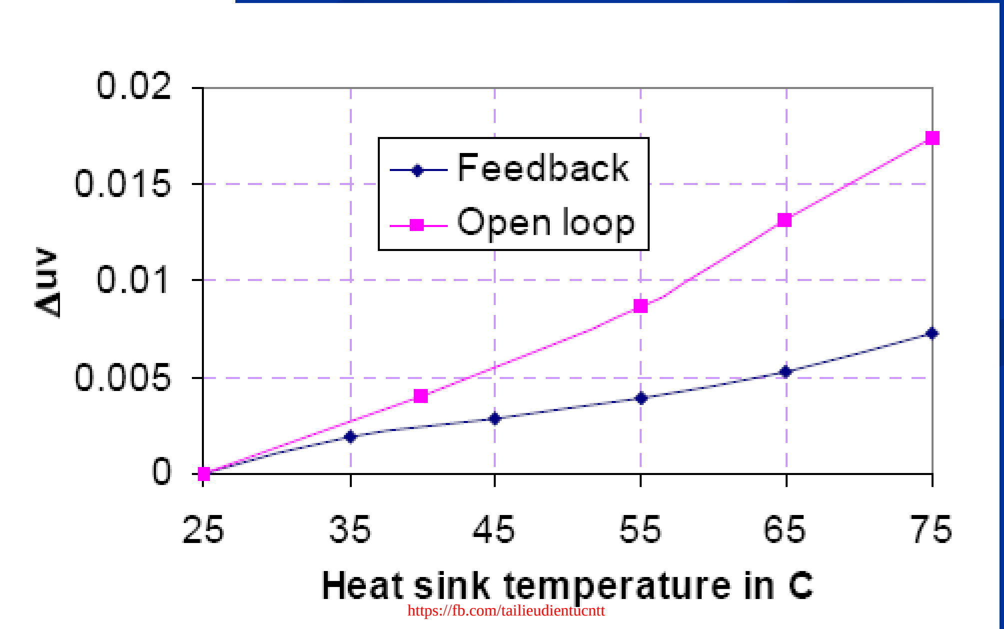




Solution

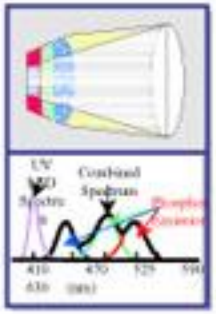


Reference:
$[X_{ref}, Y_{ref}, Z_{ref}]$
+
-
PI Controller
Control voltage
RGB LED drivers
LED current
RGB LED Lamp
White Light
Feedback:
$[X_f, Y_f, Z_f]$
Gain G_s
Photo sensors



0.02
0.015
0.01
0.005
0
Δuv
Feedback
Open loop
25
35
45
55
65
75
Heat sink temperature in C

Creating white light- UV LED pumped with RGB Phospohors



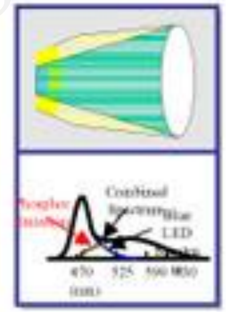
UV LED pumped RGB Phosphors

- Advantages
  - White point determined by phosphors at given temperature and angle! (i.e. tolerant to LED variation)
  - Excellent color rendering possible!
  - Theoretically "Simple to manufacture!" (Looks like TV or Fluorescent lamp except for pump is now UV LED rather than electrons.)
  - Temperature stability of phosphors. (Can be great!)
- Disadvantages
  - Potential for damaging UV light leakage.
  - Fundamental limits on efficiency due to phosphor conversion efficiency, Stokes shift, self absorption,...
  - Variation of white color point with angle can be big!
  - Phosphors are temperature dependent too!!

Creating White Light- Blue LED with Phosphor(s)

White Light from Blue LED + Phosphor(s)

- Advantages:
  - Simple and single Yellow phosphor versions available today!
  - Decent color rendering (Ra = 75 for Blue LED + Yellow Phosphor)
  - Temperature stability of phosphors. (Can be great!)
  - Only Lumileds offers products with uniform white color vs. angle!
- Disadvantages
  - Limits on efficiency due to phosphor conversion efficiency, Stokes shift, self absorption,...
  - Better color rendering (i.e. multi phosphor comes at cost of efficiency)
  - Temperature stability of phosphors not all the same!



Application In Communication

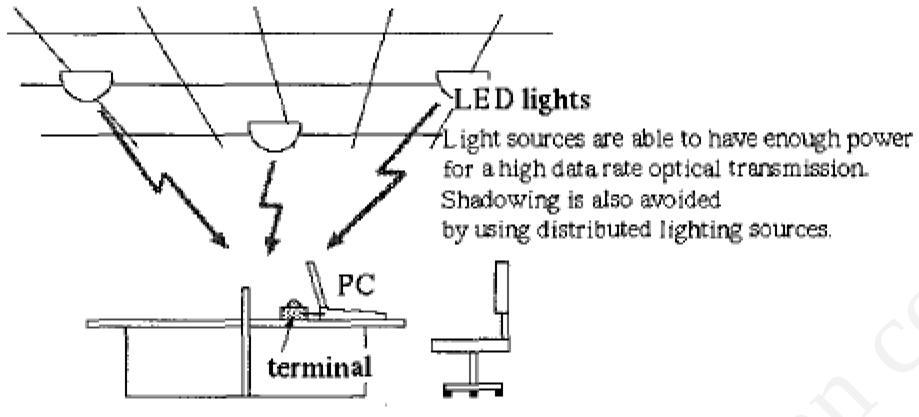
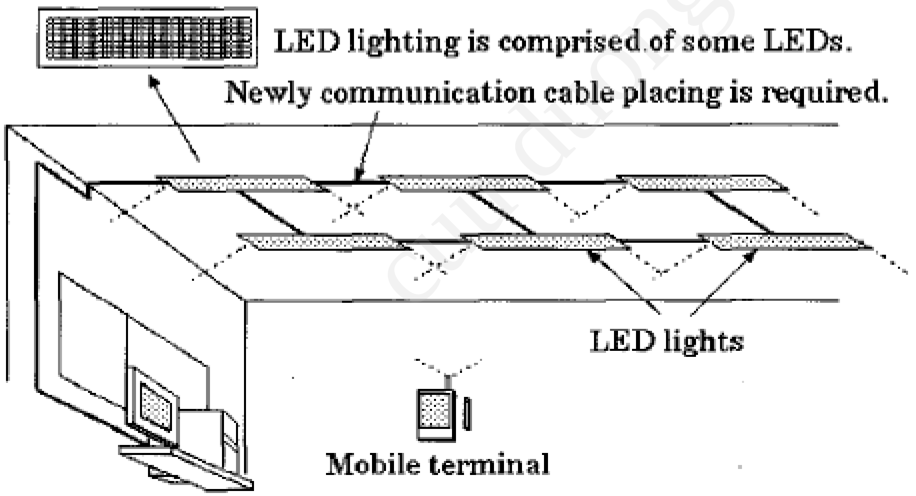


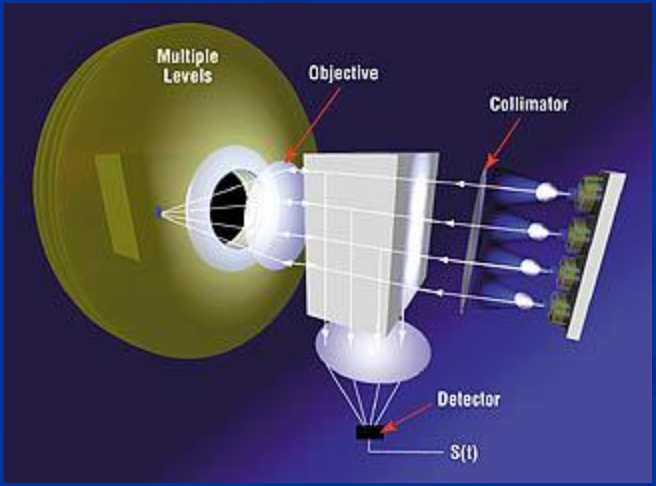
Fig. 1. White LED visible-light communication system.



Ministry of
International Trade and Industry
of Japan estimates, if LED
replaces half of all incandescent
and fluorescent lamps
currently in use, Japan could save
equivalent output of six
mid-size power plants, and reduce
the production of
greenhouse gases

Blue Laser

- With LEDS the photons emitted are in a range of similar frequencies--i.e., the blue. With lasers, the frequency of the photons is all the same. To amplify a single frequency of light in a crystal, Nakamura figured out how to etch a highly polished mirror on each side of the crystal so that the light bouncing back and forth between the mirrors moves to resonating at the same frequency. His breakthrough work consisted not only of making the mirrors on the crystal but also enabling the crystal to take the high current necessary to create the high-frequency blue laser light.



Application

- Substitute blue lasers for the infrared lasers used in compact-disc players and get five times as much data on the CD. Blue lasers may eventually mean as much as a 35-fold increase in the amount of information that can be contained on a CD. And blue lasers presage not only more data on CDs, but also DVDs.

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- **With special thanks to google!**

Thank you!