EEE6216: MSc EEE
Energy Efficient Semiconductor devices

Part I: Solid State Lighting

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Policy on Hand-outs

- **I will print out enough hand-outs for everyone before the class**

- **I <u>will throw away</u> any copies not picked up at the end of the class**

- **I will not keep copies for you to pick up later**

- **I will put the lecture-notes in the web**

Objectives

- Understand principle of Solid State Lighting
- Understand fabrication of Solid State lighting
- Understand principle of Light Emitting Diode (LED)
- Understand Gallium Nitride LED device technologies
- Understand GaN LED operating characteristics, future prospects
- Understand organic LED (OLED) device technology
- Understand OLED operating characteristics, future prospects
- LED Lighting systems: colour rendering, power management

Course Books

- "Introduction to Solid-State lighting"
  By Arturas Zukauskas, Michael S Shur, Remis Gaska
  (A Wiley-Interscience Publication)

- "OLED Display Fundamentals and Applications"
  by Takatoshi Tsujimura
  (Wiley Series in Display Technology)

Course Organization

Professor Wang:
- **Introduction of Solid State Lighting (~1 Lecture)**
- **Inorganic LEDs for solid state lighting (3 lectures)**

Dr Smith:
- **Organic LEDs for solid state lighting (2 Lectures)**

What You Need to Know

- Take a look at

  EEE207 “Semiconductor Electronics and Devices”;

  EEE118 “Electronic Devices”

- Basic semiconductor physics: energy bands
- Band-gaps, electrons, holes, dopants, optical transitions….
- So on….

Introduction

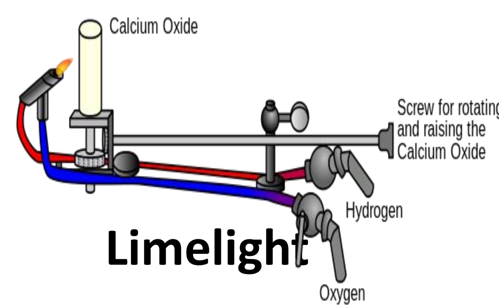
- Artificial lighting plays a vital role in the civilisation process.
- Artificial lighting shaped our health, safety, and happiness.

History of lighting: early stage

- 500,000 years ago- first torch
- 70,000 BC- first lamp; Dried plant material soaked in animal fat
- 3,000 BC- stone oil lamps
- 700 BC- Terracotta oil lamps used by Greeks

- 1792 - William Murdoch: gas lighting by heating coal
- 1807- Frederick Albert Winsor: light up the street of Pall Mall, London, with gas lighting
- 1826- Thomas Drummond: Limelight

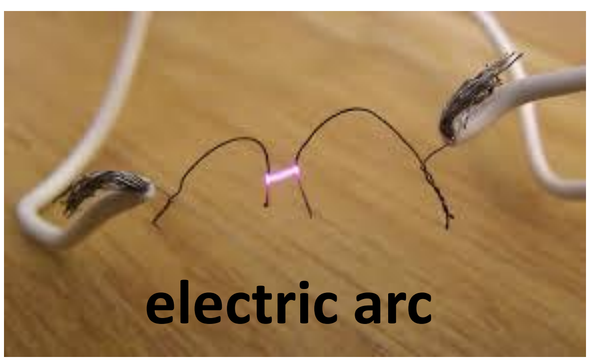
Gas lighting

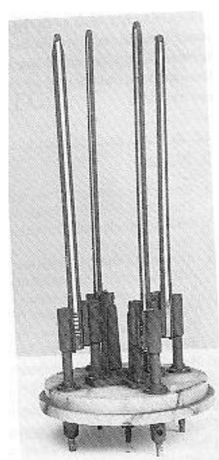


Limelight

History of lighting: electric lighting

- 1663- Otto von Gericke: demonstrate 1st electric arc
- 1809- Humphry Davy: electric carbon arc
- 1876- Pavel Yablochkov: 1st practical electric lighting
- 1878- Joseph Swan: demonstrated 1st practical incandescent lamp
- 1879- Thomas Edison Edison: demonstrated his lamp
- 1897- Nernst: a filament made of cerium oxide-based solid electrolyte
- 1900- Peter Cooper Hewitt: mercury vapor lamp.
- 1903- A. Just and F. Hanaman: tungsten filament
- 1938- GE and Westinghouse Electric Corporation put on the market the new colored and white fluorescent lamps.





Yablochkov (1876): 1st electric arc-based lighting

Global Warming and Energy Savings

End Use Applications*	
Motor Control	32%
Lighting	29%
Heating & Cooling	24%
Information Technology	15%

- U.S. DOE has chosen, energy efficient LED lighting to play the key role in reducing our electric light consumption by 50% by 2025

- Over the next 20 years, rapid adoption of LED lighting in the U.S. can:
  - Reduce electricity demands from lighting by 62%/year
  - Eliminate 300 million metric tons of carbon emissions/year
  - Avoid building 133 new power plants
  - Anticipate financial savings that could exceed $200 billion/year

Solid State Lighting- inorganic SSL

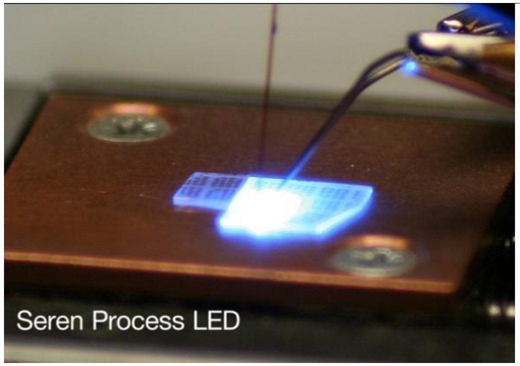
- Definition of solid-state lighting (SSL)
- Advantages of solid state lighting
- Category of solid-state lighting
- Key components of solid-state Lighting: LEDs
- Operational mechanism of LEDs
- Operational mechanism of white LEDs
- Fabrication of LEDs and white LEDs
- Characteristics of white LEDs
- Other applications of white LEDs
- Future development of solid-state lighting

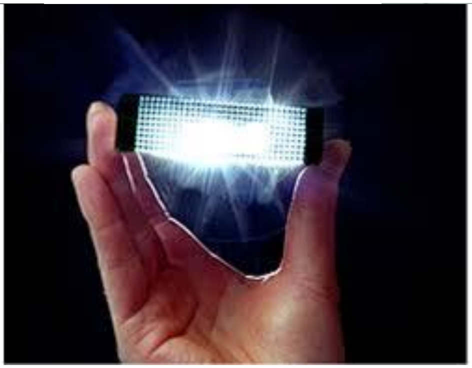
Definition of solid-state lighting

• SSL: refer to a type of lighting that utilizes light-emitting diodes (LEDs), which are solid state as sources of illumination rather than electrical filaments or gas.

• Term "solid-state“: refers to the fact that the light in an LED is emitted from a solid object—a block of semiconductor—rather than from a vacuum or gas tube, as in the case of incandescent and fluorescent lighting.

•Key components of SSL: semiconductor based LEDs





Category of solid-state lighting

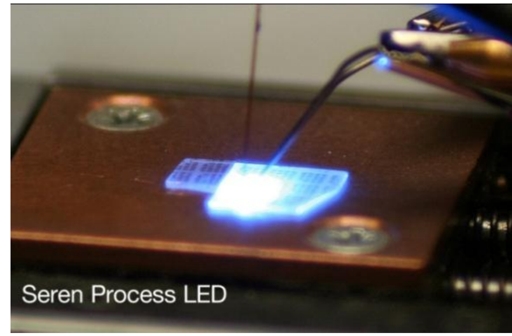
- **Inorganic LED (usually termed as LED):**

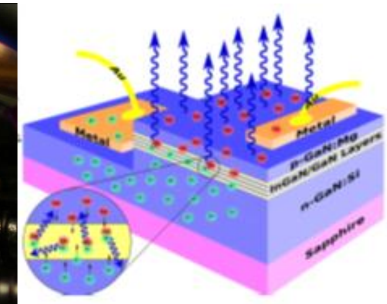
  Basically, III-V semiconductors

  470 nm InGaN (blue)

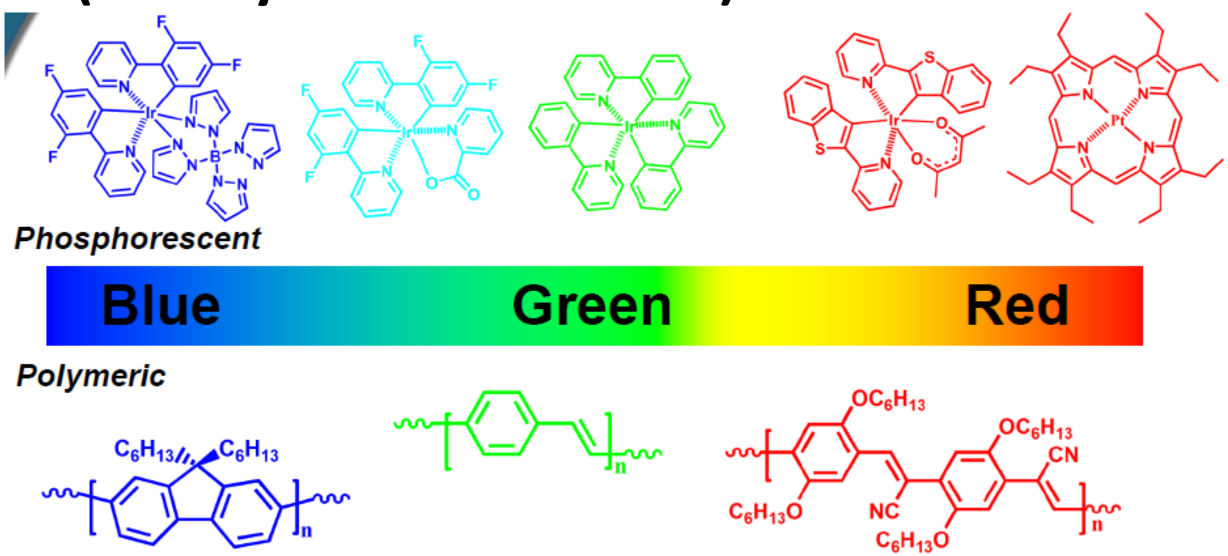
  540 nm InGaN (green)

  670 nm InGaP/AlGaInP (red)





- **Organic LED (usually termed as OLED):**



Color is determined by Molecular Structure

Major advantages of SSL (I)

• **Incandescent lamps (light bulbs)**: generate light by using electricity to heat a thin filament to a very high temperature and then producing visible light.

>90% of its energy is emitted as invisible infrared light (or heat) during the incandescing process (**highly inefficient!**)

Typical lifespan: **1,000 hours**.

• **Fluorescent lamps**: create light when electricity passes through mercury vapor to produce ultraviolet light, which is then absorbed by a phosphorous coating inside the lamp, generating glow or fluoresce.

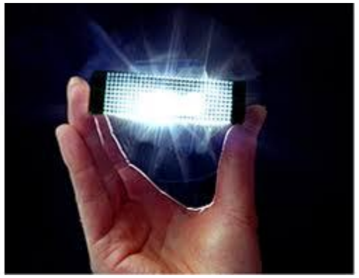
Energy loss in generating UV light & converting into visible light.

Mercury is **detrimental to health**

Typical lifespan: **10,000 hours**.

Major advantages of SSL (II)

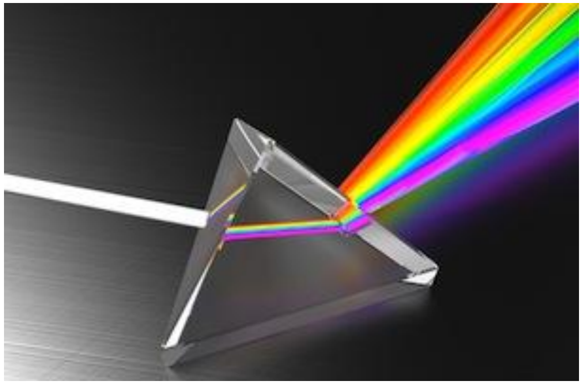
- SSL: grouping one or a number of LEDs creating a unified beam.
  - High durability - no filament or tube to break
  - Long life span - approximately 100,000 hours
  - Low power consumption
  - Flexible application – small size of LEDs devices
  - Low heat generation – very little energy loss

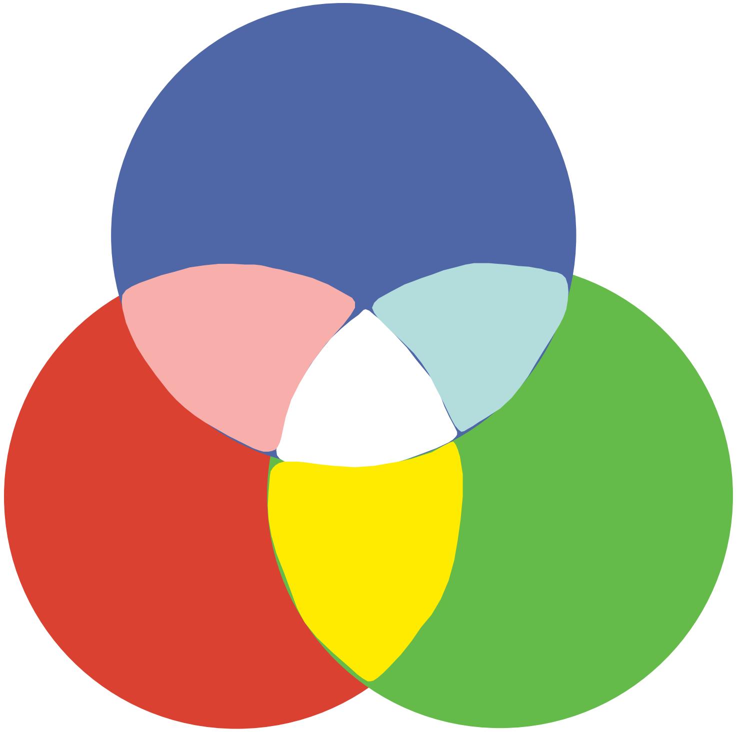


Light Source	Luminous Efficiency	Lifetime
Incandescent bulb	16 lumens/watt	1000 hours
Fluorescent lamp	85 lumens/watt	10,000 hours
Today's white LEDs	80-100 lumens/watt	20,000 hours
Future white LEDs	>200 lumens/watt	100,000 hours

White lighting

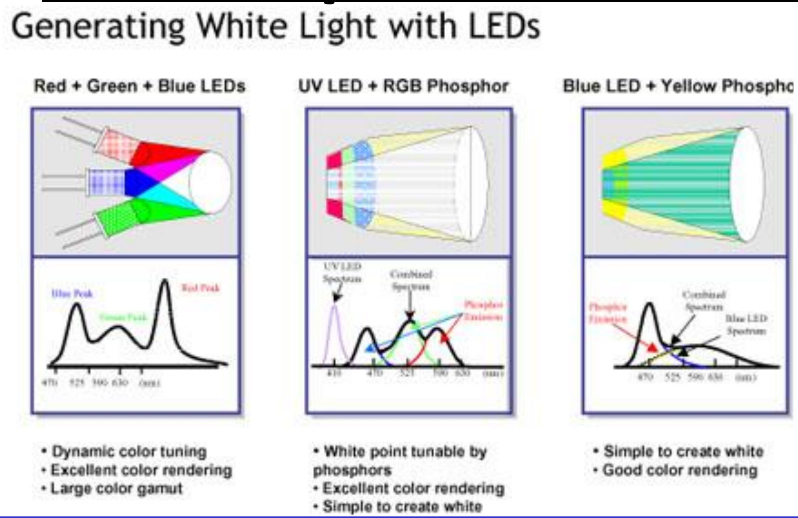
- Red + green: yellow
- Red + blue: magenta
- Green + blue: cyan
- Yellow (Red+ green)+ blue: white

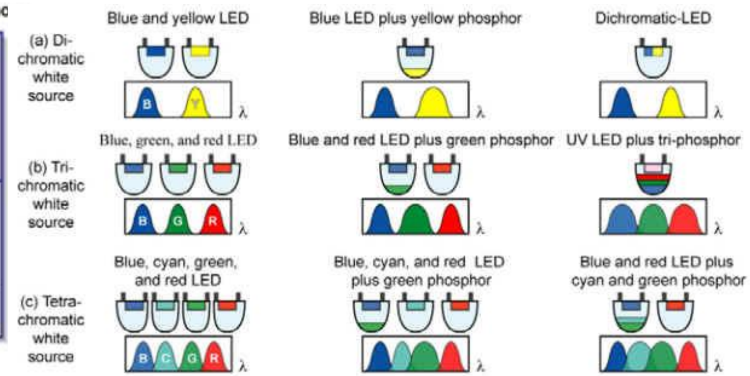




Newton originally (1672) divided the solar spectrum into 5 main colours (red, yellow, green, blue and violet). Later he included orange and indigo.

How to produce white light using inorganic LEDs?





Main components:
UV, BLUE, Green , Red
UV/Blue/Green: III-nitrides

- **Wavelength Conversion**.

· <u>Blue LED + yellow phosphor</u>: simple but energy loss due to down conversion

· <u>Blue LED + several phosphors</u>: similar to the above method, except that the blue light excites several phosphors, each emitting different color (blue, green, yellow, red)

Higher color-quality; energy loss due to down conversion

· <u>Ultraviolet (UV) LEDs + red, green and blue phosphors</u>: UV LED to excite several phosphors, each emitting different color (blue, green, yellow, red).

Highest color-quality light; but issue on UV LED; energy loss due to down conversion

- **Color Mixing:** multiple LEDs in a single lamp, mixing the light to produce white light.

Two LEDs (blue and yellow); three (red, blue, and green) or four (red, blue, green, yellow).

No down conversion energy losses;

Highest efficiency; highest color quality; but issue on fabrication

Light quality on healthy

Students under full spectrum light:

- **Learn faster**
- **Test higher**
- **Grow faster**
- **1/3 fewer absences due to illness**

- **LED: has a significant advantage over conventional lamps**
- **LED: color rendering index (CRI) can potentially be up to 100**

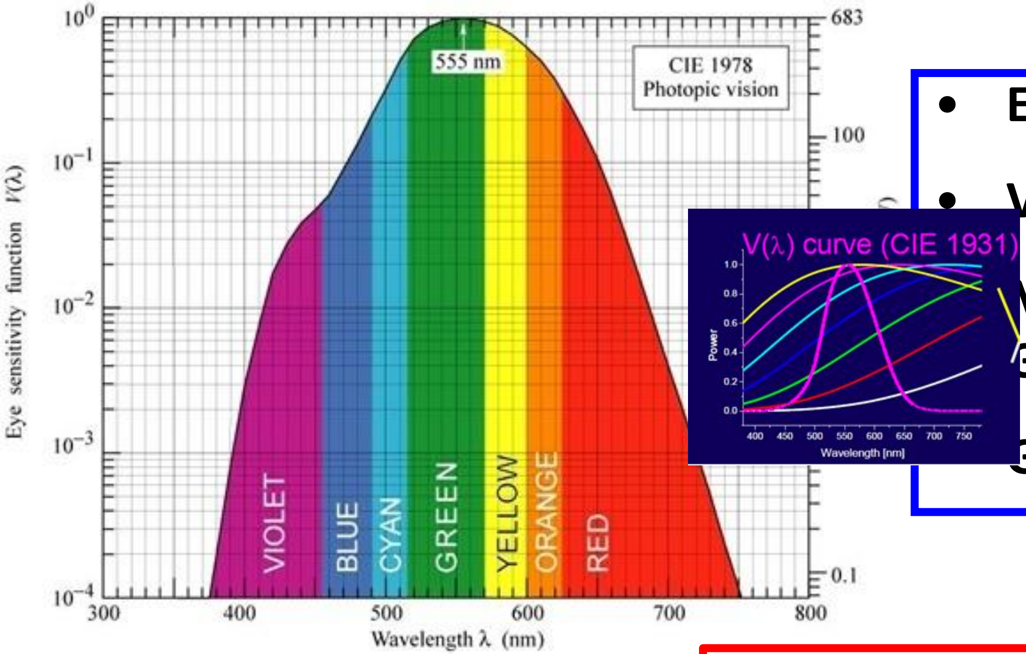
Experiments on mice, and on average mice can live

- Under **pink fluorescent** light: **7.5 months**
- Under **cool white** fluorescents (office) : **8.2 months**
- Under **natural sunlight**: **16.1 months**.

Characteristics of white lighting

- **Lumen:** SI unit of **luminous flux**, a measure of the total "amount" of visible light emitted by a source, depending on sensitivity of **human eye to different wavelengths**
- **Optical Power:** a measure of **radiant flux,** the total power of all electromagnetic waves emitted, **independent of human eye's sensitivity**. (Unit: Watt)
- **Luminous efficiency:** **(Different from "efficacy", misleading in current literature)**
  - A measure of the efficiency with which electricity converts into visible light, and is defined as the ratio of **luminous flux** to **power** (**lumen/Watt**)**,** namely, the ratio of luminous flux to radiant flux.
  - Not all wavelengths of light are detected by human eyes; radiation in the **infrared and ultraviolet** parts of the spectrum is useless for illumination.
  - The product of radiant efficiency (converts energy to electromagnetic radiation), and fraction (the emitted radiation detected by the human eye)
- **Correlated color temperature (CCT)**
- **Color rendering index (CRI)**

Luminous efficiency



- Eye sensitivity function, V(λ)
- Visible range: 380-780 nm
- Most sensitive wavelength: Green light at 555 nm
- Green Light with 1 Watt : 683 lumens

$$Lu\min ous \cdot efficiency = \boxed{\frac{Optical \cdot Power(W)}{Electric \cdot Power(W)}} \times \boxed{\frac{Lu\min ous \cdot flux(lm)}{Optical \cdot Power(W)}}$$

- 1st item: wall plug efficiency; radiation efficiency
- 2nd item: not all radiation contributes to visible light. Eye sensitivity drops upon moving away from the 555 nm wavelength
- luminous efficacy: fraction of the emitted radiation detected by human eyes

$$\boxed{lu\min ous \cdot efficacy = \frac{683 \times \int_{380}^{780} V(\lambda)S(\lambda)d\lambda}{\int_{0}^{\infty} S(\lambda)d\lambda}(lm/Watt)}$$

Correlated color temperature

•**Color temperature**: define as surface temperature of electromagnetic radiation emitted from an ideal black body (SI unit: kelvins),

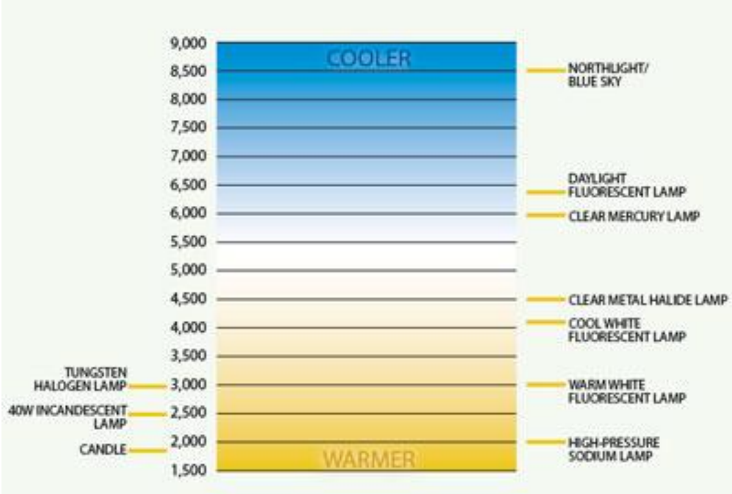
•**Wien's displacement law:** $\lambda = \dfrac{b}{T}$ **b:** 2.8977721×10^{-3} m K

As black boy is getting hotter, it turns red, orange, yellow, white and finally blue. The light incandescent lamp is thermal radiation, and it is a good black body. Its color temperature is the temperature of the filament.

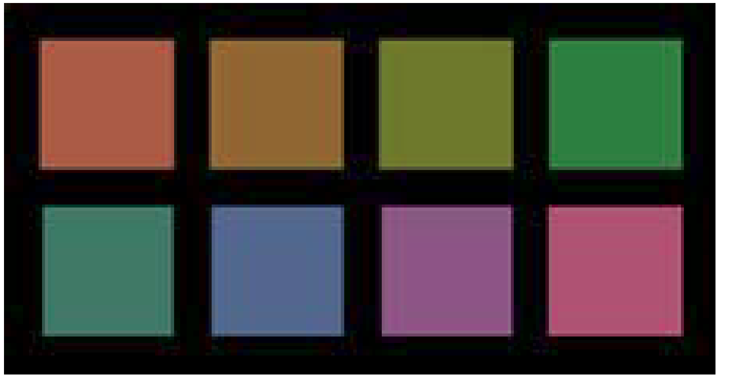
•LEDs emit light primarily not by thermal radiation, and the emitted radiation does not follow the form of a black-body spectrum. These sources are assigned what is known as a **correlated color temperature** (CCT).

•**CCT** is the color temperature of a black-body radiator which to <u>human color perception</u> most closely matches the light from the LED.
CCT refers to the appearance of a black body heated to high temperature.

•Higher CCT (blue): “cool”; lower CCT (red): “warm”



Color rendering index (CRI)



•CRI: is defined as being the measure of the degree of color shift of an object when illuminated by a light source as compared to when illuminated by a reference source of comparable Color Temperature. .

The test procedure involves comparing the appearance of eight color samples (see upper right for an approximation) under the light in question and a reference light source. The average differences measured are subtracted from 100 to get the CRI.

•Reference light: incandescent light or outdoor north sky day light day (CRI 100)

•Higher CRI : render those eight color samples well, i.e., very much like the incandescent or daylight references

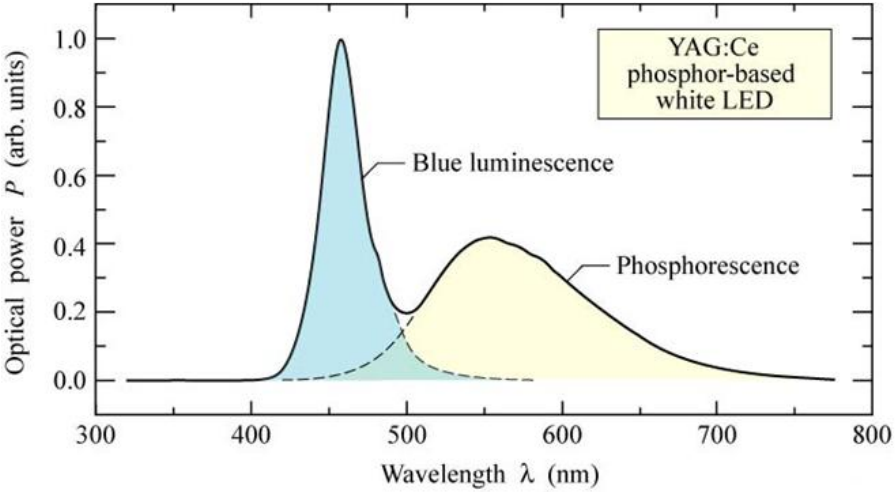
Illuminance

- Practical applications of lighting usually deal with illuminance
- lux (lx): the measurement unit for illuminance, which is density of the illuminous flux incident on a surface (lumen per square meter)
- Sun generates the illuminance on the earth's surface: 10^4 lx to 10^5 lx, depending on weather
- Moon generates the illuminance on the earth's surface ≤ 0.1 lx.
- Higher illuminance help the eyes distinguish details, small contrasts and color hues.
- Different activities require different levels of illuminance.

How much light do you need?

Type of Activity	Illuminance ($lx = lm/m^2$)
Orientation and simple visual tasks (public spaces)	30-100
Common visual tasks (commercial, industrial and residential applications)	300-1000
Special visual tasks, including those with very small or very low contrast critical elements	3,000-10,000

- **Key components: blue LEDs**
- **Improve efficiency of blue LEDs**
- **Improve quality of light**



Basic concepts (i)

- **What is LED?**

  Semiconductor (inorganic semiconductor)

  p-doing, n-doping

  Fermi-level

  Depletion region

  Forward Bias

  Reverse Bias

  minority carrier

  majority carrier

- **How does LED work?**
  - **Recombination of minority carriers with majority carriers**

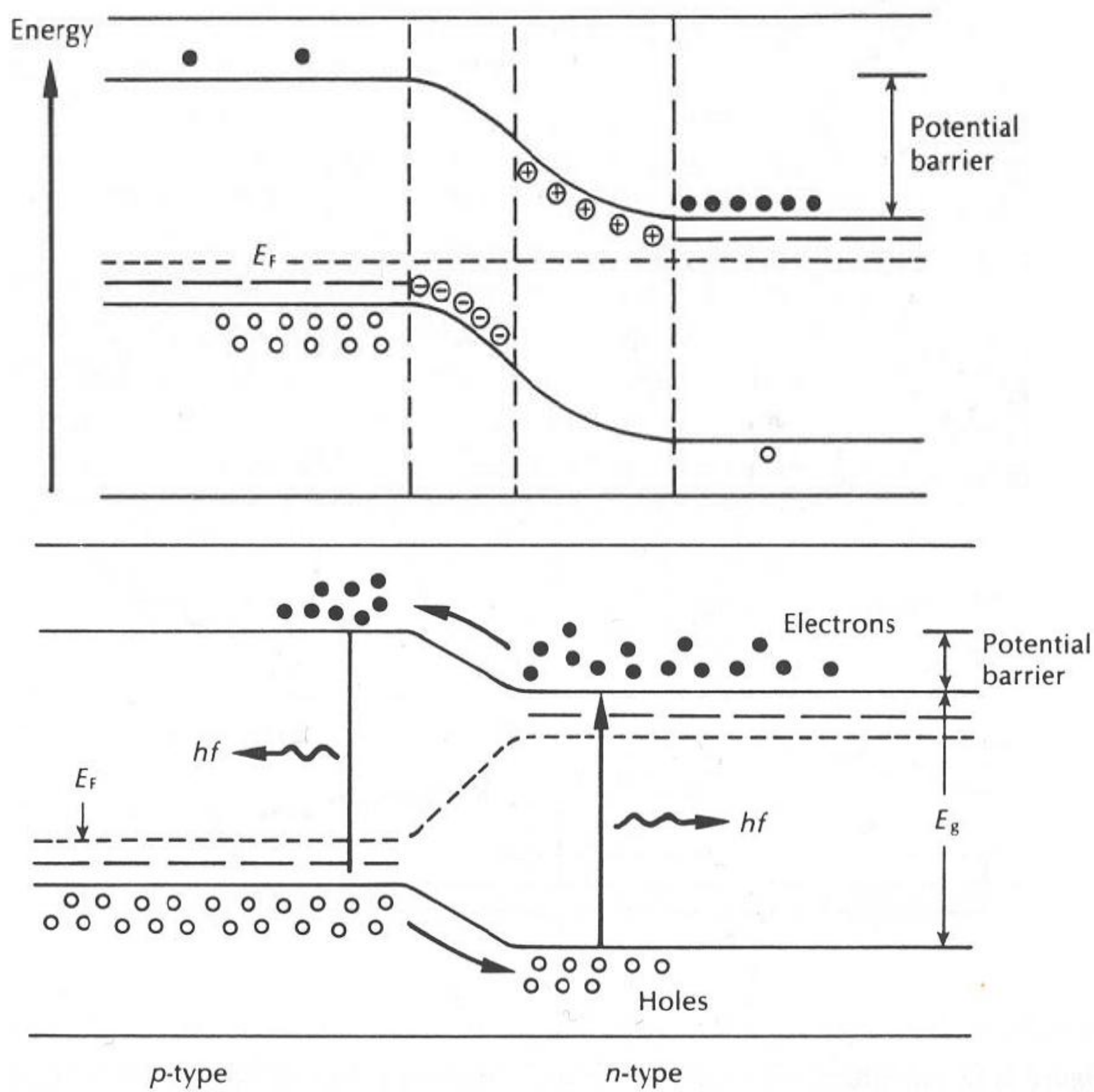
Homojunction LED

Zero biased
p-n junction

n_0, p_0= free carrier densities

Forward biased
p-n junction

Δn, Δp injected carrier densities



Review of p-n Junction

Review what we have learnt previously in p-n junction:
Excess minority charge (electrons and holes)
Contribution to currents: minority diffusion

$$\boxed{J_n(x) = q\mu_n n(x)\mathscr{E}(x) + qD_n \frac{dn(x)}{dx}}$$

Equilibrium: $V_0 = \frac{kT}{q}\ln\frac{p_p}{p_n} = \frac{\mathrm{kT}}{\mathrm{q}}\ln\frac{N_a}{n_i^2/N_d} = \frac{\mathrm{kT}}{\mathrm{q}}\ln\frac{N_aN_d}{n_i^2}$

$$\frac{p_p}{p_n} = \frac{n_n}{n_p} = e^{qV_0/kT} \quad (5\text{–}10) \qquad W = \left[\frac{2\epsilon(V_0 - V)}{q}\left(\frac{N_a + N_d}{N_aN_d}\right)\right]^{1/2} \quad (5\text{–}57)$$

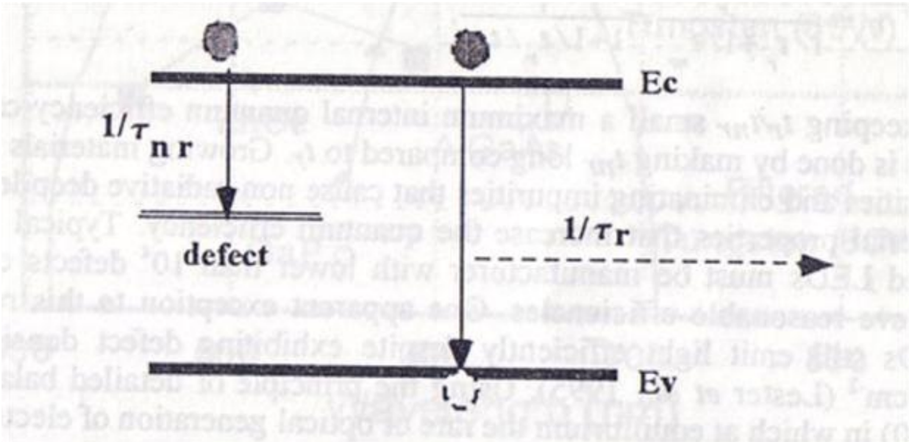
One-sided abrupt p^+-n: $x_{n0} = \frac{WN_a}{N_a + N_d} \simeq W$ (5–23) $\qquad V_0 = \frac{qN_dW^2}{2\epsilon}$

$$\Delta p_n = p(x_{n0}) - p_n = p_n(e^{qV/kT} - 1) \quad (5\text{–}29)$$

$$\delta p(x_n) = \Delta p_n e^{-x_n/L_p} = p_n(e^{qV/kT} - 1)e^{-x_n/L_p} \quad (5\text{–}31\text{b})$$

$$\boxed{\text{Ideal diode:} \quad I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)(e^{qV/kT} - 1) = I_0(e^{qV/kT} - 1)} \quad (5\text{–}36)$$

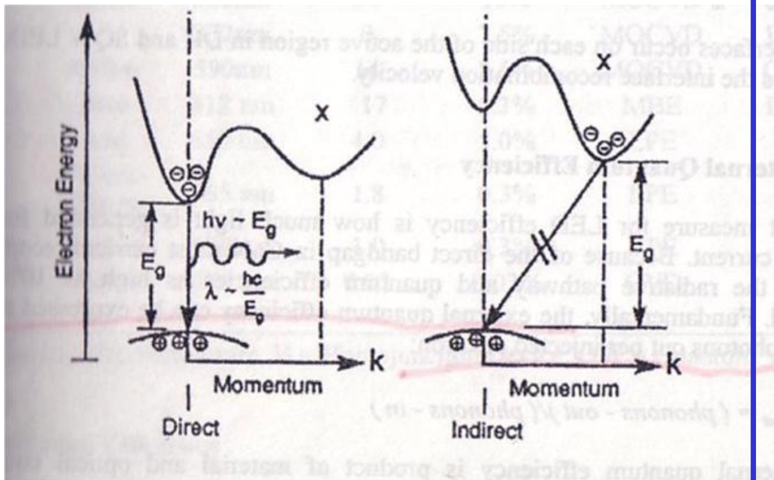
Electron-hole recombination



E-h recombination: radiative or non-radiative

- **Non-radiative recombination**: recombination at (i) defects; (ii) Auger recombination, etc
- **Radiative recombination** : intersubband transition, excitonic recombination, recombination through impurity center (InGaN:Zn, GaP:N)
- Very important issue: **Internal quantum efficiency (IQE)**

Choice of materials for LEDs

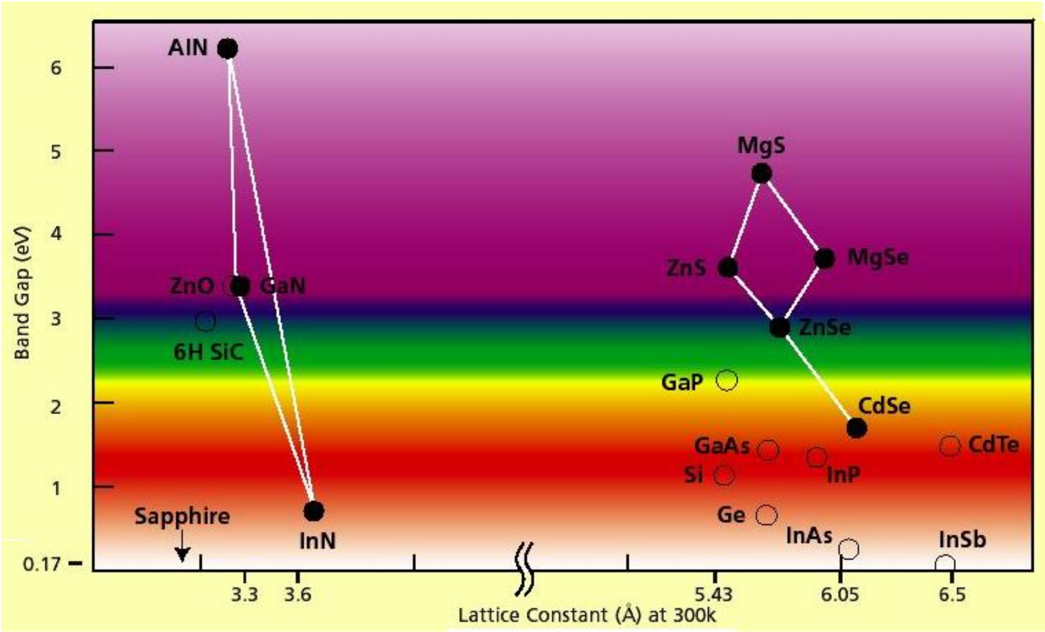


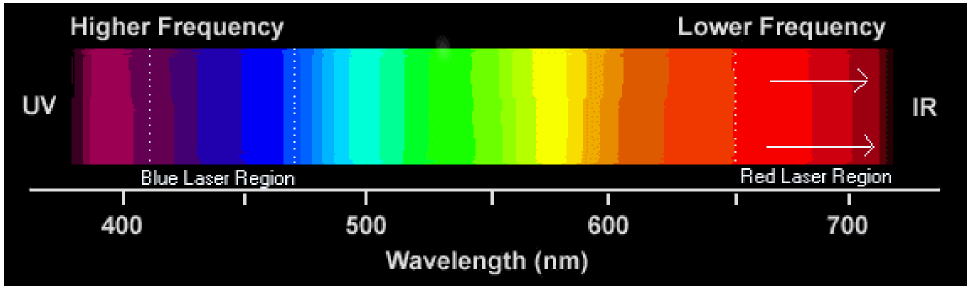
Direct bandgap:
Electrons in conduction band minima
Holes in valence band maxima
Both have the same momentum

Indirect bandgap:
Electron and hole have different momentum

Phonon is required to participate to allow the recombination **due to the requirement of the momentum conservation**
SiC LED : 0.02% quantum efficiency (first LED)
GaN LED: >20 % quantum efficiency

GaP, GaAs, GaP (N)





LED: Bandgap determines the emission wavelength (colour)
Band structure: direct bandgap
UV: III-nitrides, ZnO, II-VI groups
Visible: III-nitrides, GaNP, AlGaInP
Infrared: III-nitrides, InAs, InSb, InGaAs, etc

Basic parameters to describe LEDs

- **How to characterise LEDs?**

  Radiative recombination lifetime; Non-radiative recombination lifetime

  Internal quantum efficiency

  Extraction efficiency

  External quantum efficiency

Characteristics of LED performance (i)

(i) Internal quantum efficiency; (ii) Extraction efficiency; (iii) Injection efficiency; (iv) External quantum efficiency; (v) Luminous efficiency; (iii) wall plug efficiency;

IQE:

η_{int}= photons internally generated/electrons in

Extraction efficiency:

η_{ex}= photons out/photon generated

Injection efficiency:

fraction of the total diode current due to injection of electrons into p-side of junction

$$\eta_{inj} = \frac{\frac{D_e n_{po}}{L_e}}{\frac{D_e n_{po}}{L_e} + \frac{D_h p_{no}}{L_h}}$$

External quantum efficiency:

$\eta_{tot} = \eta_{inj} \bullet \eta_{int} \bullet \eta_{ex}$ (photons out/electrons)

Luminous efficiency:

η_{lum}= lumen out/electric power in

Characteristics of LED performance (ii)

IQE:

Ratio of radiative recombination rate to total recombination rate

Electrons in $\Rightarrow$ Radiative $\left(\frac{\Delta n}{\tau_{rad}}\right)$+ non-radiative$\left(\frac{\Delta n}{\tau_{non}}\right)$

photons $\Leftrightarrow$ Radiative $\left(\frac{\Delta n}{\tau_{rad}}\right)$

$$\boxed{\eta = \frac{\dfrac{\Delta n}{\tau_{rad}}}{\dfrac{\Delta n}{\tau_{rad}} + \dfrac{\Delta n}{\tau_{non}}} = \frac{\dfrac{1}{\tau_{rad}}}{\dfrac{1}{\tau_{rad}} + \dfrac{1}{\tau_{non}}}}$$

Characteristics of LED performance (iii)

$$\eta = \frac{\frac{1}{\tau_{rad}}}{\frac{1}{\tau_{rad}} + \frac{1}{\tau_{non}}} = \frac{1}{1 + \frac{\tau_{rad}}{\tau_{non}}}$$

Make τ_{non} long compared to τ_{rad}:

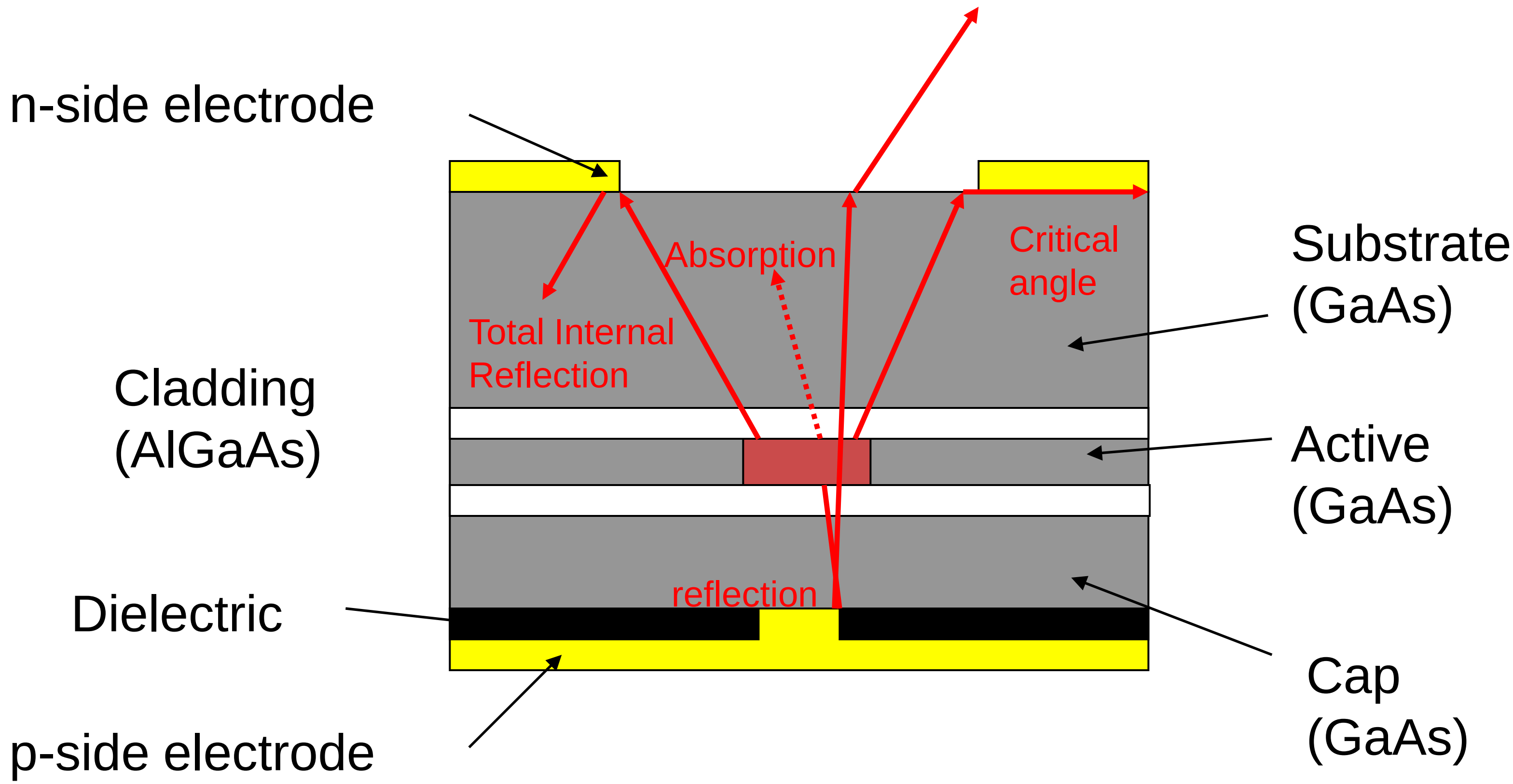
Growing materials with low defect densities

Eliminating non-radiative centres

To achieve reasonable IQE: GaP and GaAs-based LED
Defect density $< 10^4/cm^2$

However: GaN-based LED with high IQE
defect density $> 10^8/cm^2$

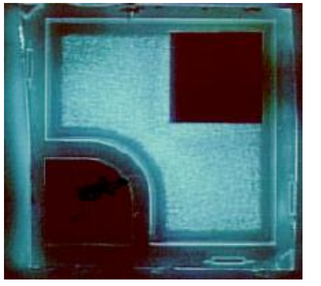
Optical Output Power



Typical external efficiencies of ~1-5%

Extraction efficiency (η_{ext})

Several factors determine η_{ext}:



1. Absorption: $I=I_0 exp(-\alpha d)$

•Homojunction LED:

d decreases, surface states destroy IQE

d increases, absorption is enhanced

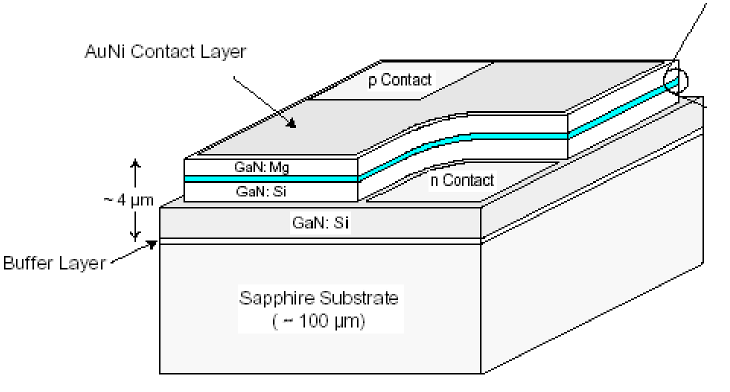
•DH-LED: absorption will be significantly reduced

2 Substrate absorption

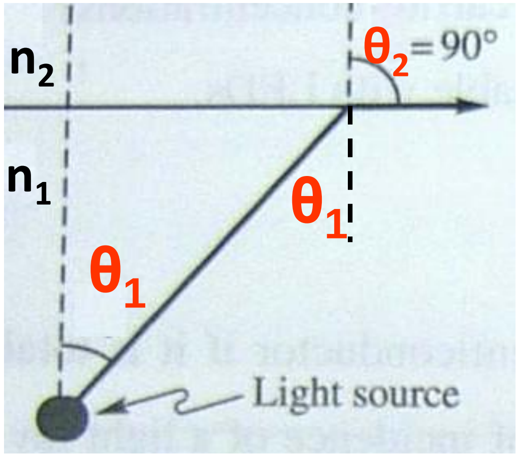
3 Transmission losses

4 Reflection at top contact

5 Absorption from top-contact



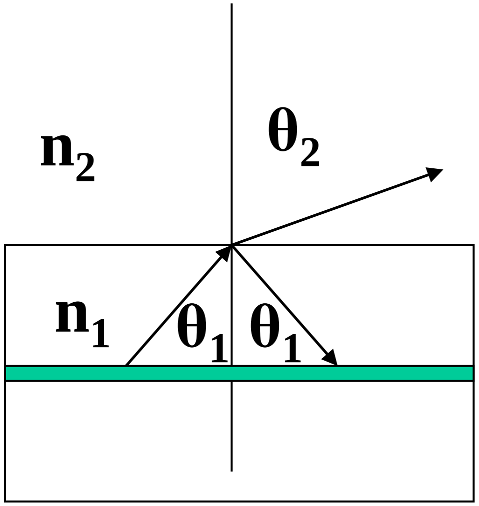
Transmission losses (i)



When light passes through from one material with n_1 to another one with n_2. The angle will be changed, and obeys: $n_1 \sin\theta_1 = n_2 \sin\theta_2$

When $n_1 > n_2$, $\theta_2 > \theta_1$. At a critical angle of θ_1(θ_c) , $\theta_2 = 90^0$

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$



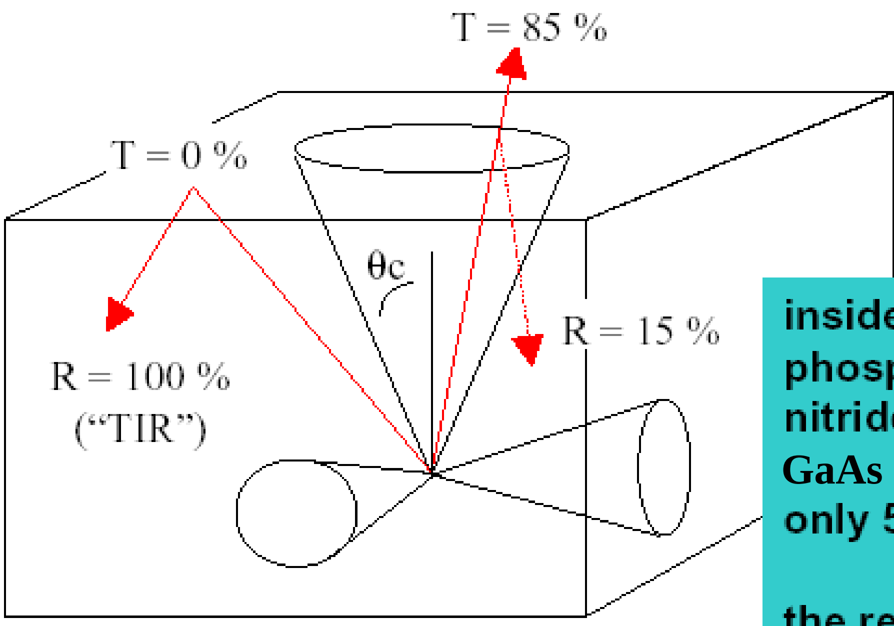
- $\theta_1 > \theta_c$: total internal reflection will take place
- $\theta_1 < \theta_c$: there is still loss of light due to reflection

For normal incident, i.e., $\theta_1 = 0^0$

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$$

$$T = 1 - \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$$

Transmission losses (ii)



inside
phosphides: n ≈ 3.3
nitrides: n ≈ 2.4
GaAs (0.8um): n=3.45
only 5 .. 10 % get through any plane surface,
the rest is internally reflected and bounces around until finally absorbed by free carriers, contacts, absorbing substrates, etc.

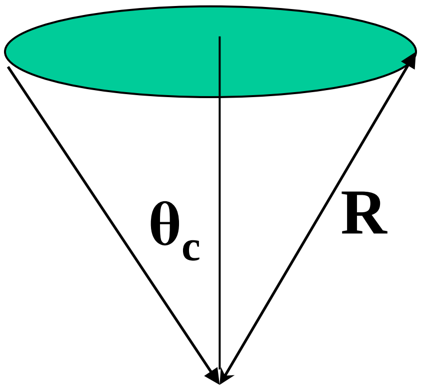
so, h_{ext} = 5% ???

Only emitted light with a cone of $2\theta_c$ can be extracted

Extraction efficiency

Assume the emitted light is constant in all directions, we can calculate how much the emitted light can be extracted, i.e., **Extraction efficiency.**

The distance from the original emitted point to the surface is R



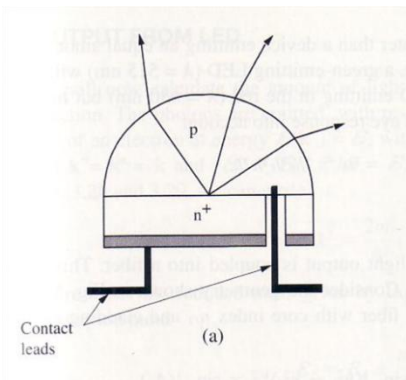
$$F = \frac{\pi(R\sin(\theta_c))^2}{4\pi R^2} = \frac{\sin^2(\theta_c)}{4} = \frac{(\frac{n_2}{n_1})^2}{4}$$

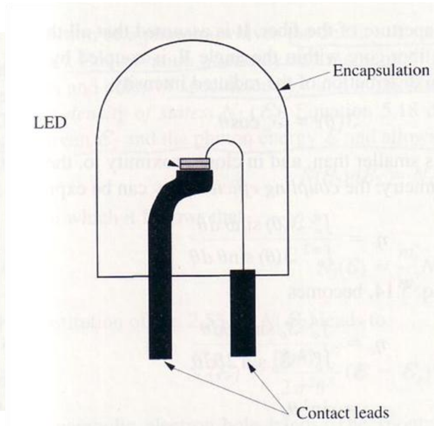
- Extraction efficiency

$$I = FT = \frac{1}{4}(\frac{n_2}{n_1})^2\left[(1-(\frac{n_1-n_2}{n_1+n_2})^2)\right]$$

For example: GaAs: n_1=3.45,
only 1.5% generated light can be extracted!!!

Solution to improve extraction efficiency (i)





$$I = FT = \frac{1}{4}\left(\frac{n_2}{n_1}\right)^2 \left[\left(1 - \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2\right) \right]$$

- **Polish the LED and make its surface as a hemisphere to avoid θ_c issue**
- **Depositing a material with an intermediate refractive index**

  n_2 increases, transmission increases
- **Depositing a layer which is an anti-reflection coating to make R $\rightarrow$ 0**

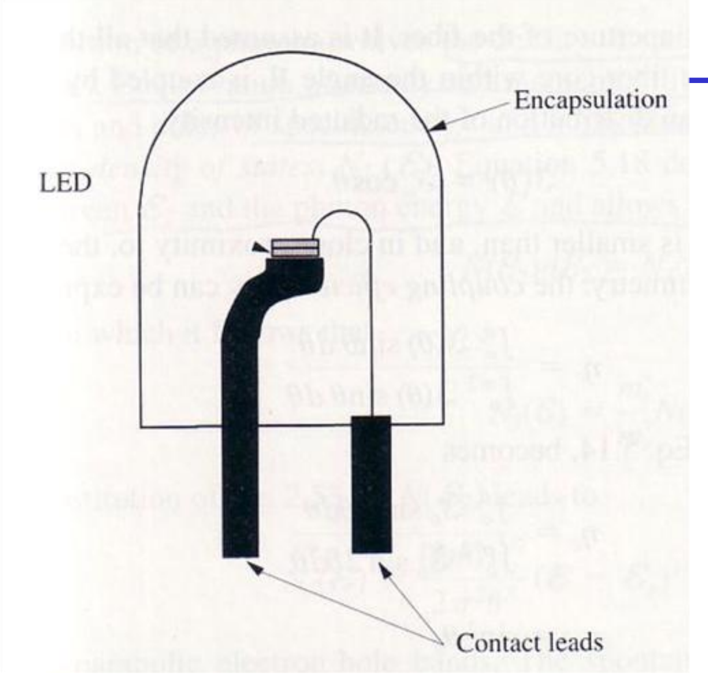
$$d = \frac{\lambda}{4n}(2L - 1)$$

Solution to improve extraction efficiency (ii)

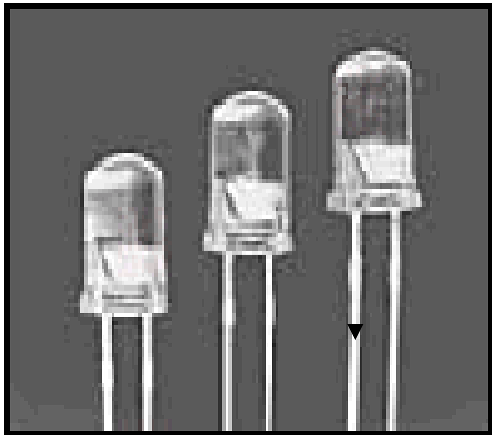
Combination of above the three methods

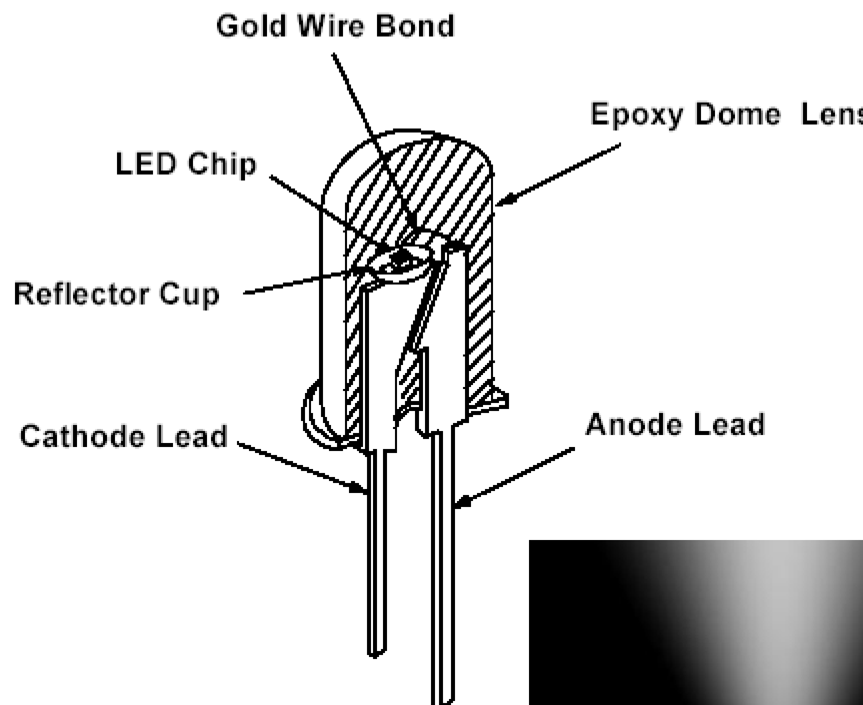
•Make the intermediate layer shaped as a hemisphere to avoid θc issue, and then coat an anti-reflection layer to maximise efficiency

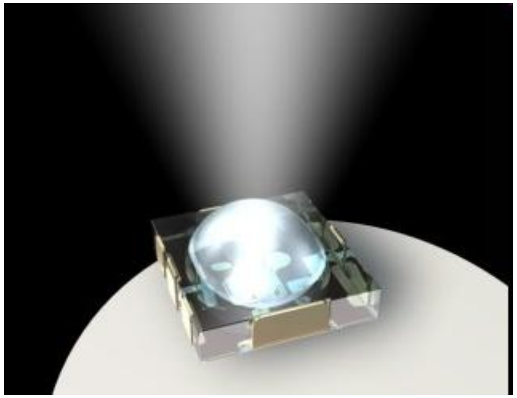
•The method of using a hemispheric intermediate layer using epoxy has been generally used in the LED industry.



Commercial LEDs



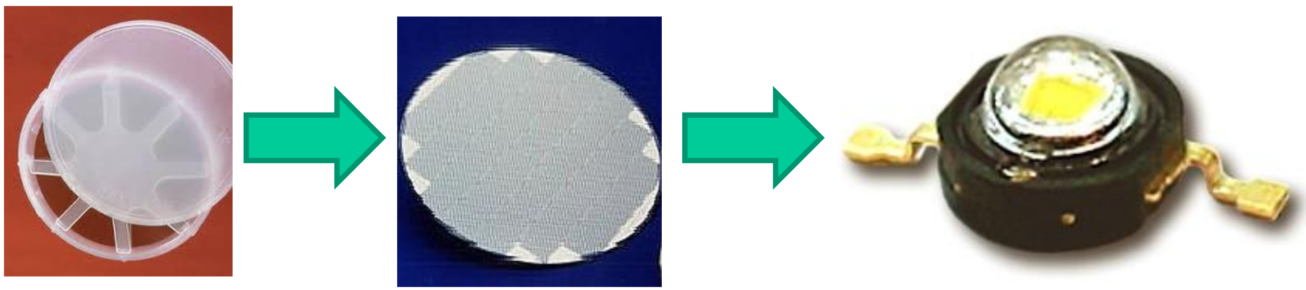


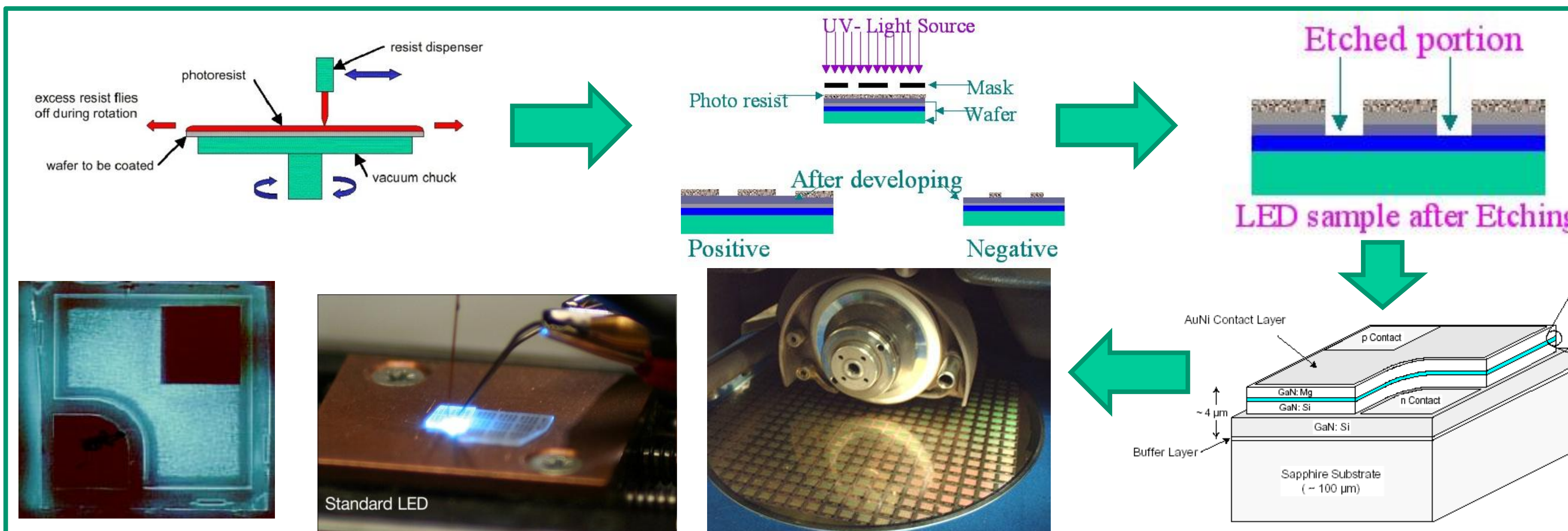


General use in the opto-electronics industry

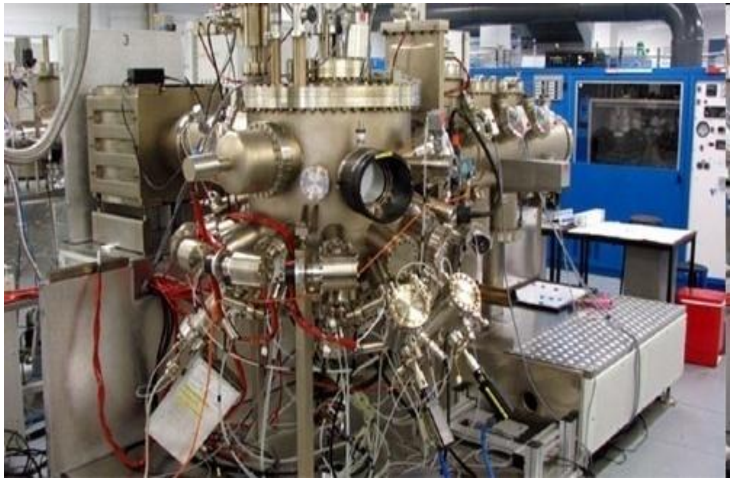
LED Design, Growth and Fabrication

- Epitaxial growth using MOVPE or MBE
- Wafer process using etching techniques and photolithgraph
- Final device packaging (Epoxy dome lens)





Epitaxial growth of III-nitrides



MBE MOCVD

No affordable substrate for homo-epitaxial growth

Epitaxial growth of III-nitrides

- In order to have visible LEDs, **n-type GaN, p-type GaN and InGaN** as emitting regions all with device performance are necessary

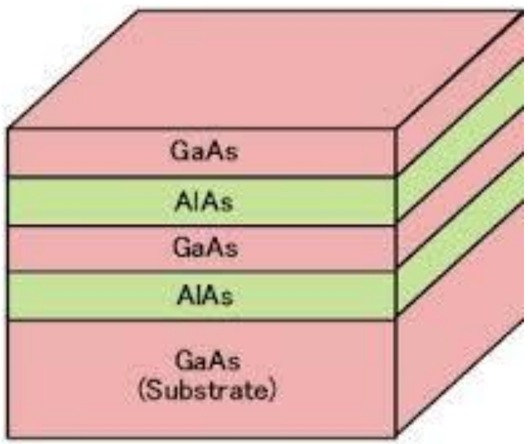
- III-nitride growth is basically on large lattice-mismatch heterepitaxy due to lack of native substrates

  A smooth surface with reasonably **good crystal quality** could not be obtained until 1986 when a major breakthrough was achieved

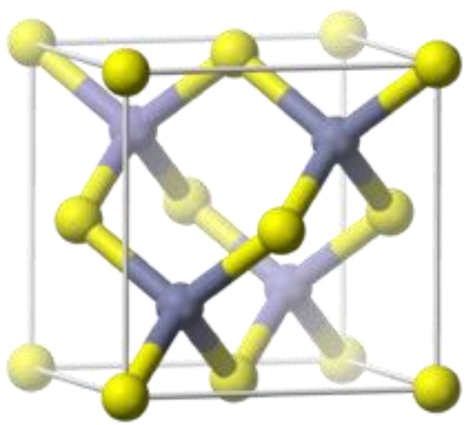
- **p-type GaN** was not obtained until 1989, when another major breakthrough was achieved

- High performance **InGaN** was not achieved until 1992

Lattice-mismatch of AlAs on GaAs as an example



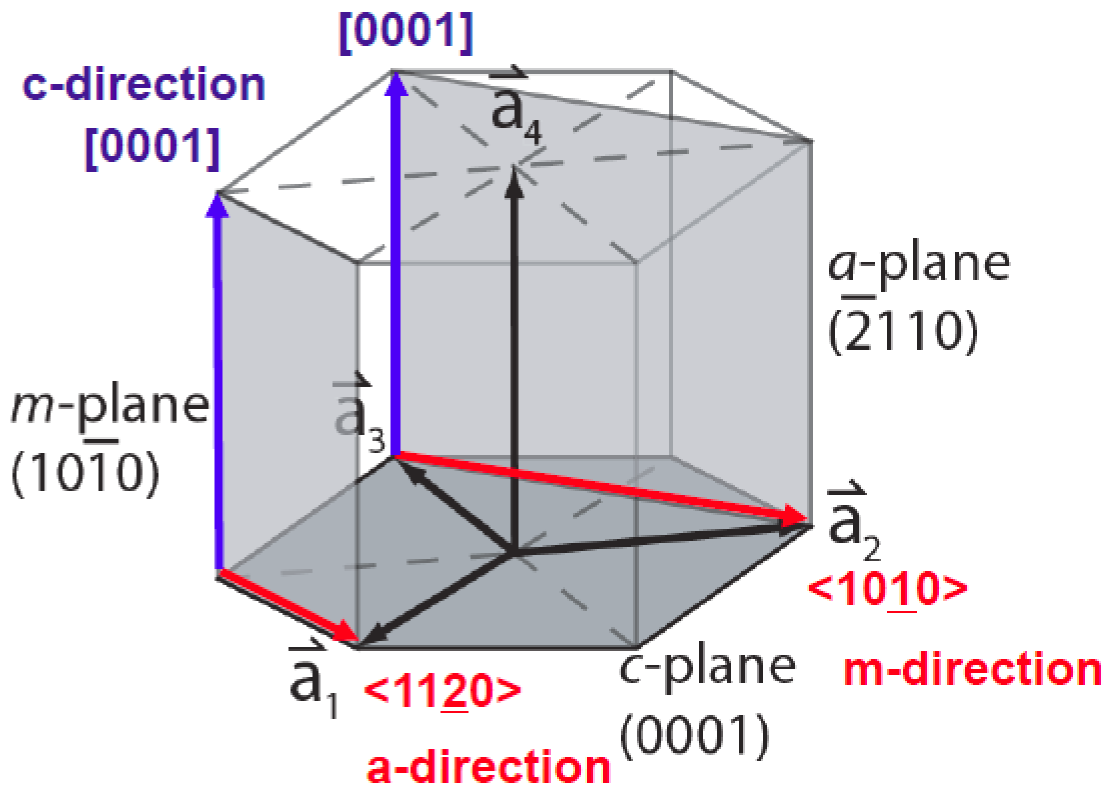
GaAs	AlAs
0.5653 nm	0.5660 nm



- **Lattice-mismatch between AlAs and GaAs**
$f=(a_{AlAs}-a_{GaAs})/a_{GaAs}=1.1\%$
- **Compressive stress (AlAs on GaAs substrate)**

zinc blende: two lattices (cubic) are positioned relative to one another

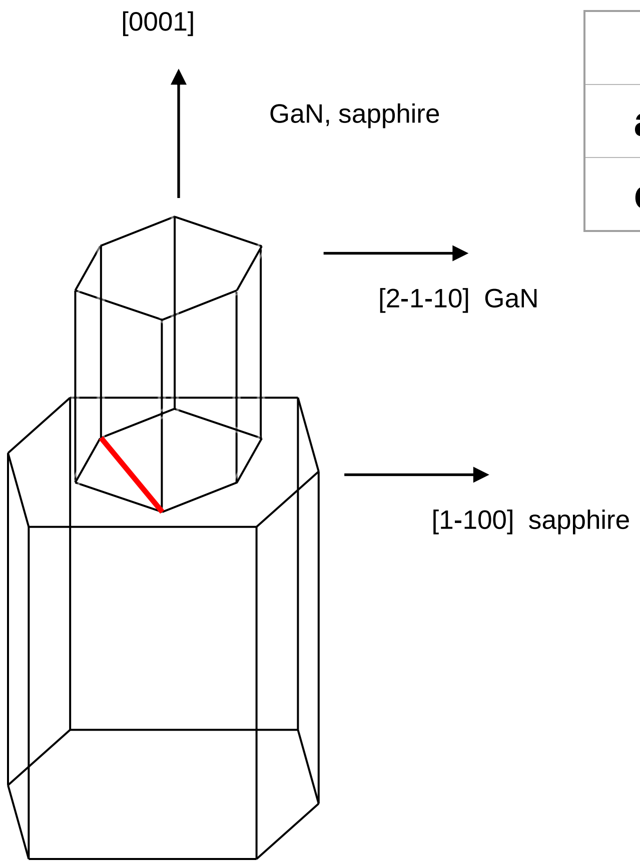
GaN crystal structure and choosing substrate



- **GaN, InN, AlN:** **wurtzite structure**
- **Sapphire:** **wurtzite structure**
- **6H SiC:** **wurtzite structure**

But (111) silicon: **cubic unit**

Lattice-mismatch in GaN/sapphire



GaN	AlN	InN	sapphire
a=3.189	a=3.112	a=3.548	a=4.785
c=5.185	c=4.982	c=5.760	c=12.991

Lattice-mismatch:
GaN/sapphire:
$f=(a_{GaN}-a_{sapphire})/a_{sapphire}=-33\%$ tensile?

However, the actual epitaxial relationship between GaN and sapphire:

30^0C rotation of GaN basal plane

⇩

$f=(\sqrt{3}\,a_{GaN}-a_{sapphire})/a_{sapphire}=\mathbf{16\%}$

compressive !

Two-step growth approach(i)

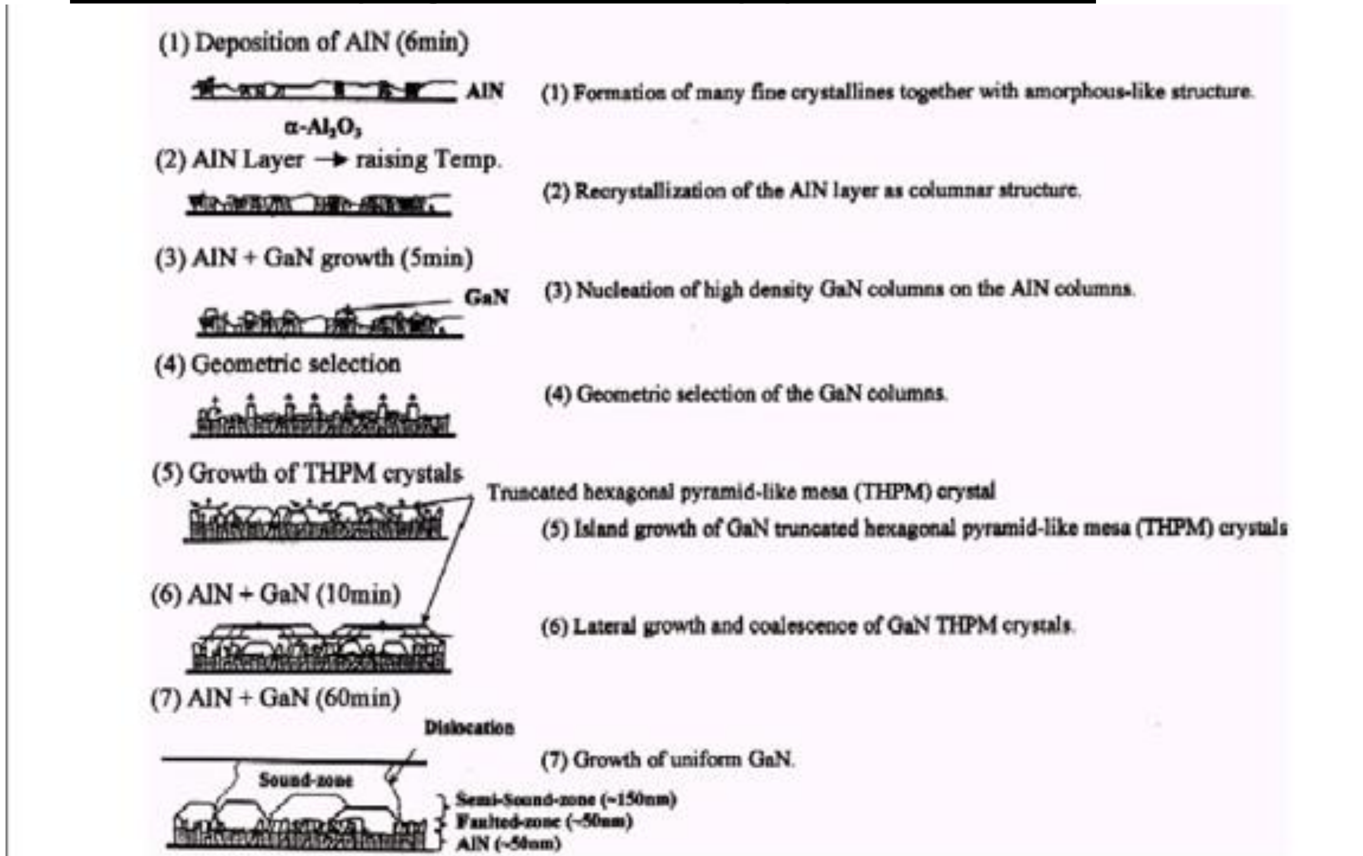
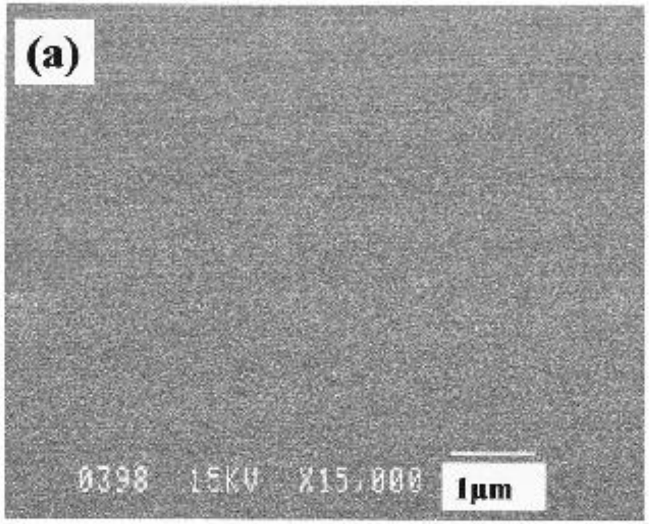


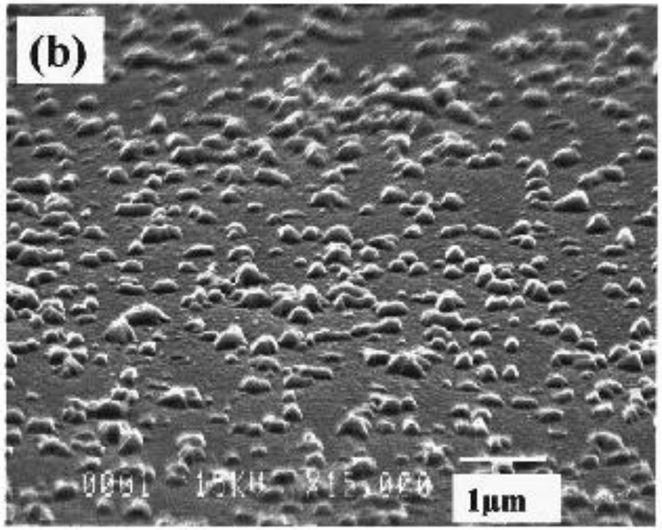
Fig. 3. Model for the growth of GaN grown by OMVPE using the LT-buffer layer. THPM; truncated hexagonal pyramid-like mesa.

Amano and Akasaki (2014 Nobel Prize winners) invented the two-step growth method, first achieving GaN with an atomically flat surface (1986)

- **A thin LT nucleation layer (500-600^{0}C)**
- **Subsequent HT (>1000^{0}C) GaN buffer + any further structure**

Two-step growth approach (ii)



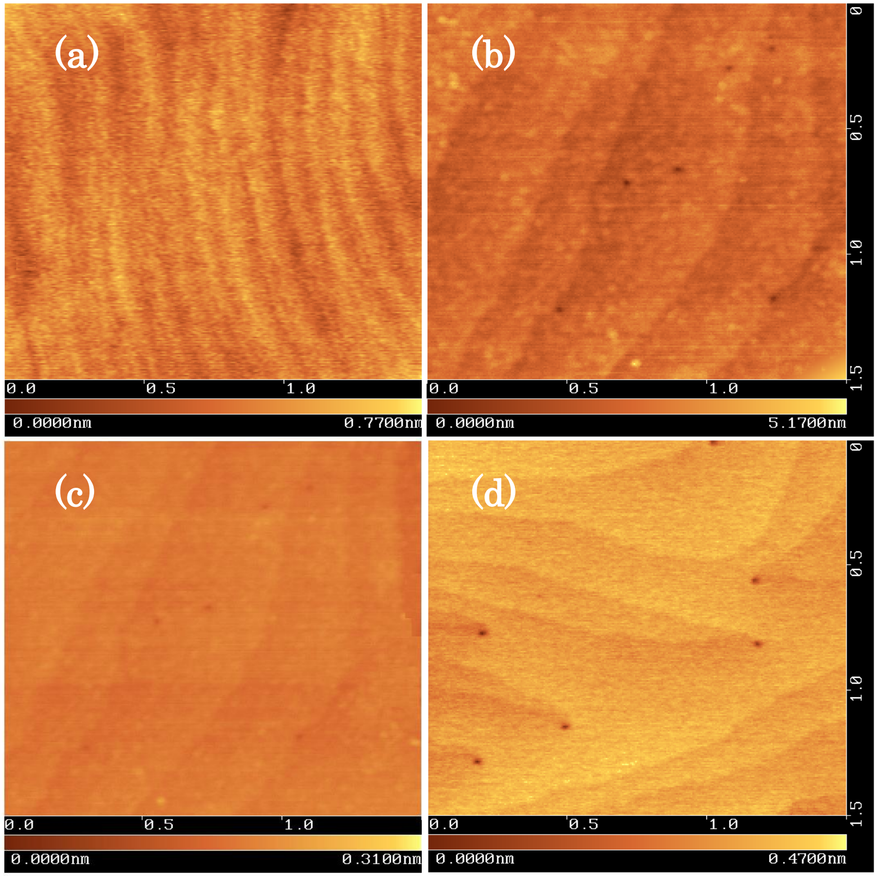


As-grown LT GaN buffer

LT GaN buffer after HT annealing

The thin nucleation layer

Two-step growth approach (iii)



An atomically flat smooth surface can be achieved by the two-step growth method through tuning the thickness of the thin nucleation layer.



2014 Nobel Prize winners for Physics

P-Type Conduction in Mg-Doped GaN achieved through Being Treated with Low-Energy Electron Beam Irradiation or High temperature annealing under N_2 ambient

H Amano and I Akaski first achieved a p-GaN (1989)

S Nakamura achieved p-GaN in 1992 using HT annealing under nitrogen ambient (mass production)

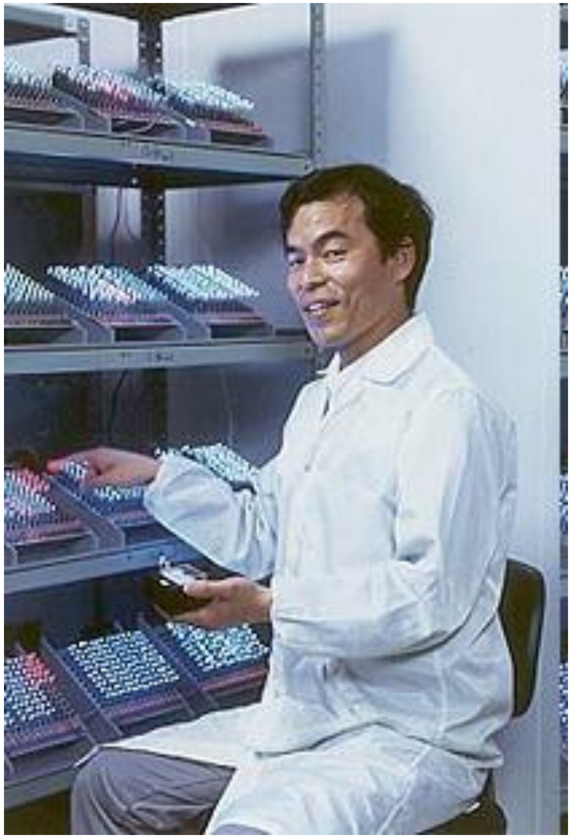
Opens new era: III-nitrides

1 S. Nakamura, *et al.*, "**InGaN-based multi-quantum-well-structure laser diodes,**" *Japan J. Appl. Phys. 2*, 35(1B):L74-1, 1996.

2 S. Nakamura, T. Mukai, M. Sengh, "**Candela-class high-brightness InGan-AlGan double heterostructure blue light-emitting diodes,**" *Appl. Phys. Lett.*, 64(13):1687-9, 1994.

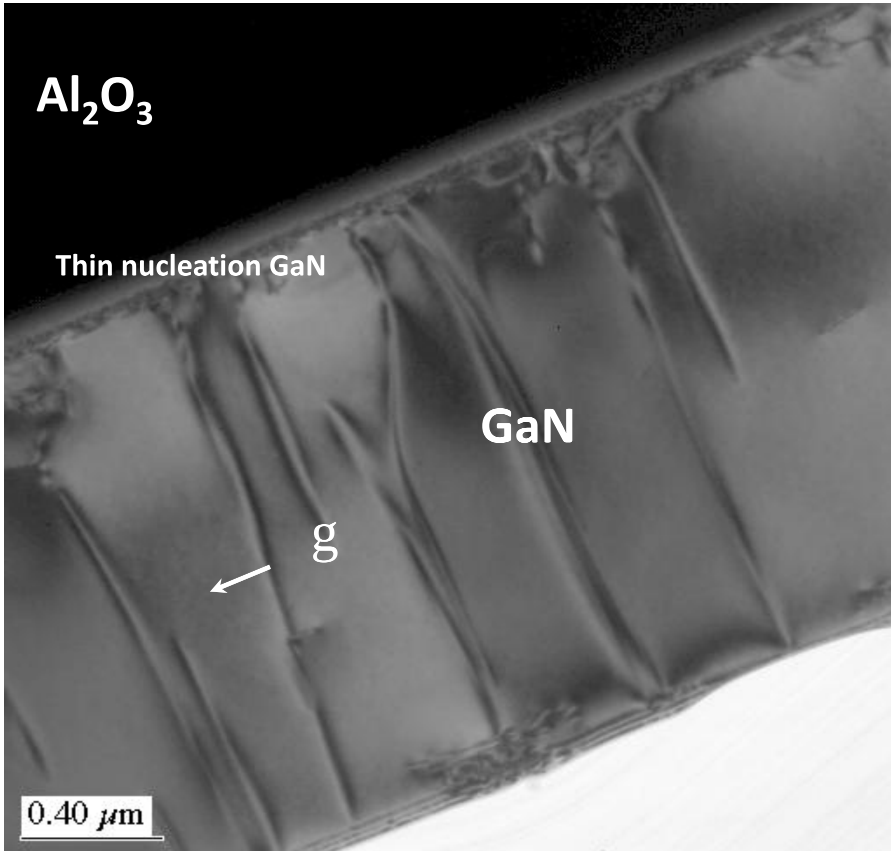
3 Nakamura, *et al.*, "**Superbright green InGaN single-quantum-well structure light-emitting diodes,**" *Japan J. Appl. Phys. 2*, 34(10B):1332-5, 1995.

Dislocation density of GaN: > 10^8/cm^2



University of Tokushima, Japan
Nichia Chemical, Tokushima
Now, Prof at UCSB, USA

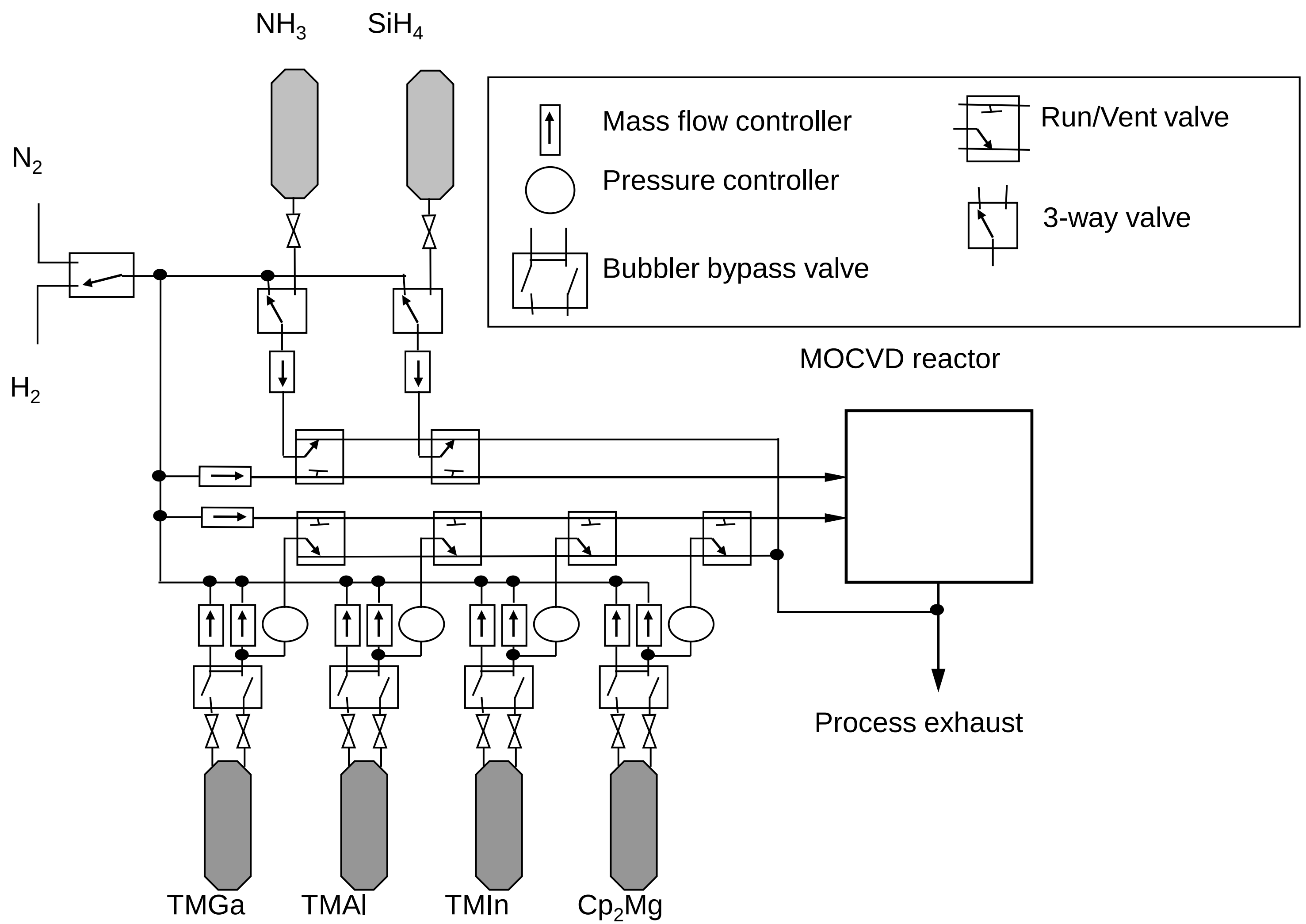
Crsytal quality of GaN on sapphire



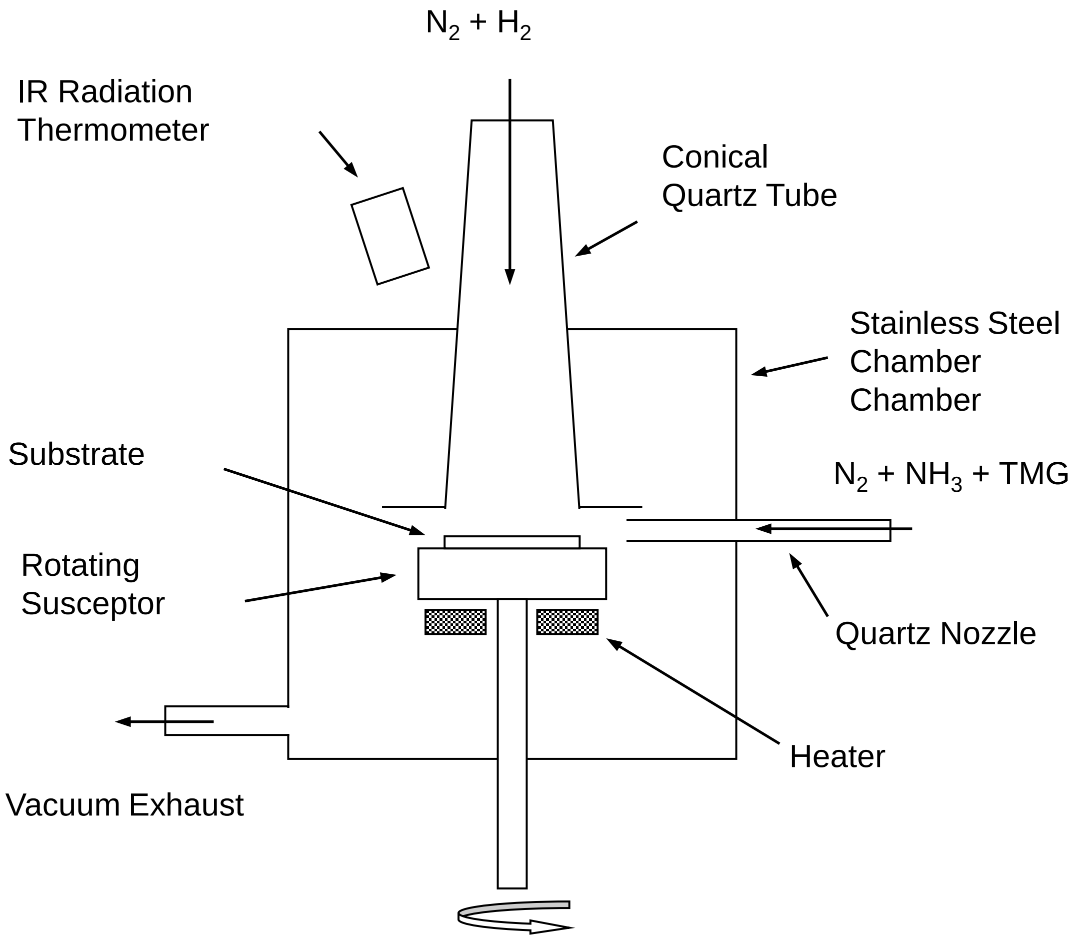
g=[-2110]

- TEM cross-sectional image of 2 μm un-doped GaN grown on sapphire using the two-step growth method
- Dislocation density: **5x10^8/cm^2**

Basic structure of MOCVD

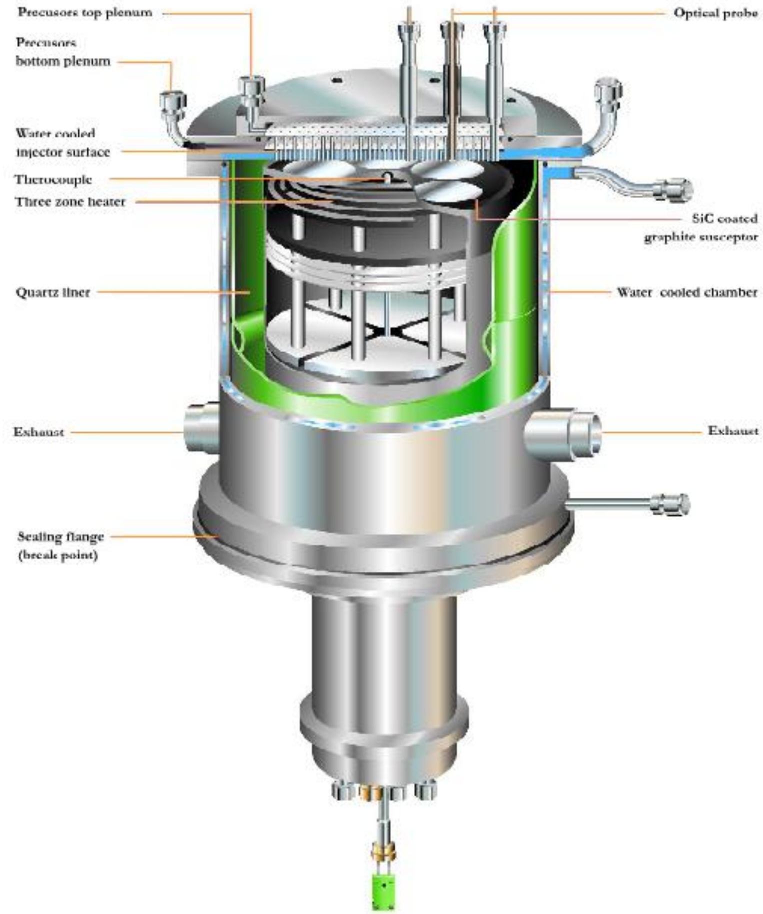


Two-flow MOCVD



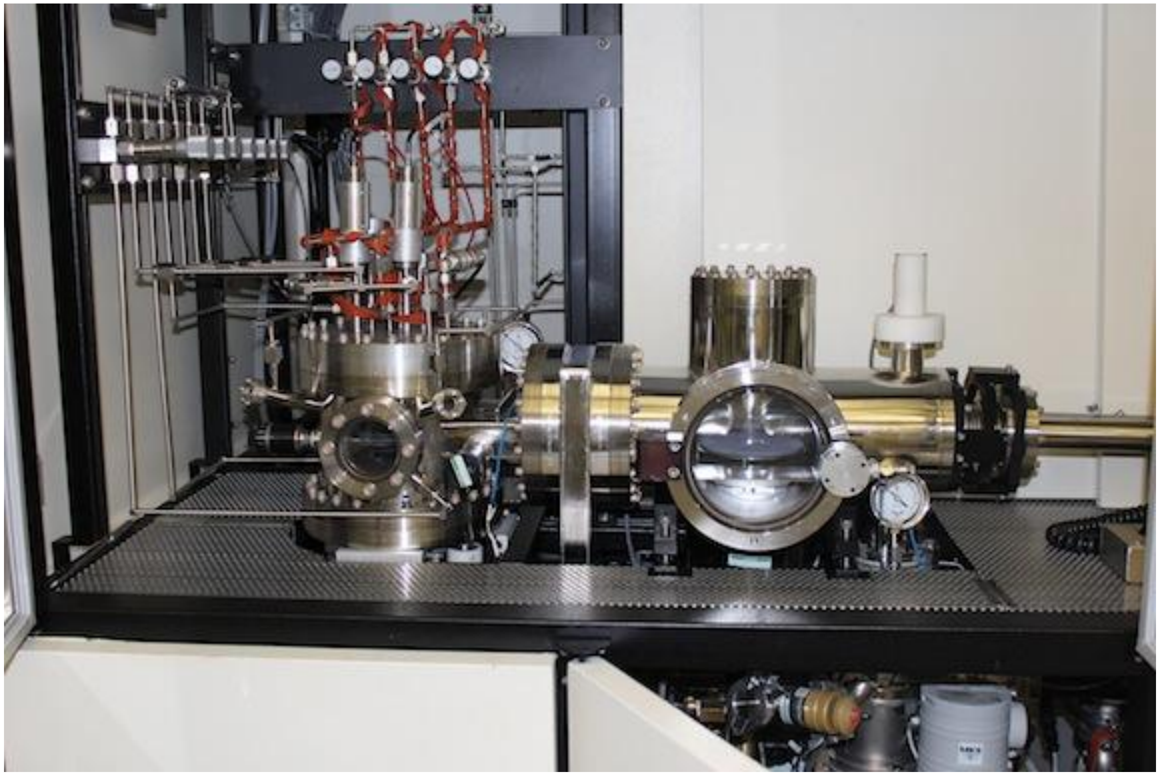
- **After S.Nakamura, *Jpn. J. Appl. Phys.* 30, L1705, (1991)**
- **First high brightness blue LED wafer was grown by this MOCVD**

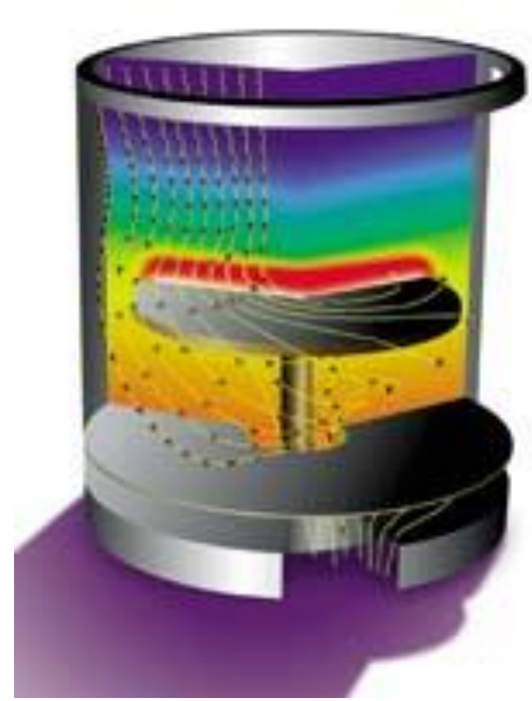
CCS-MOCVD reactor



- Close coupled showerhead (CCS)
- Sheffield has 1st CCS nitride MOCVD in the UK

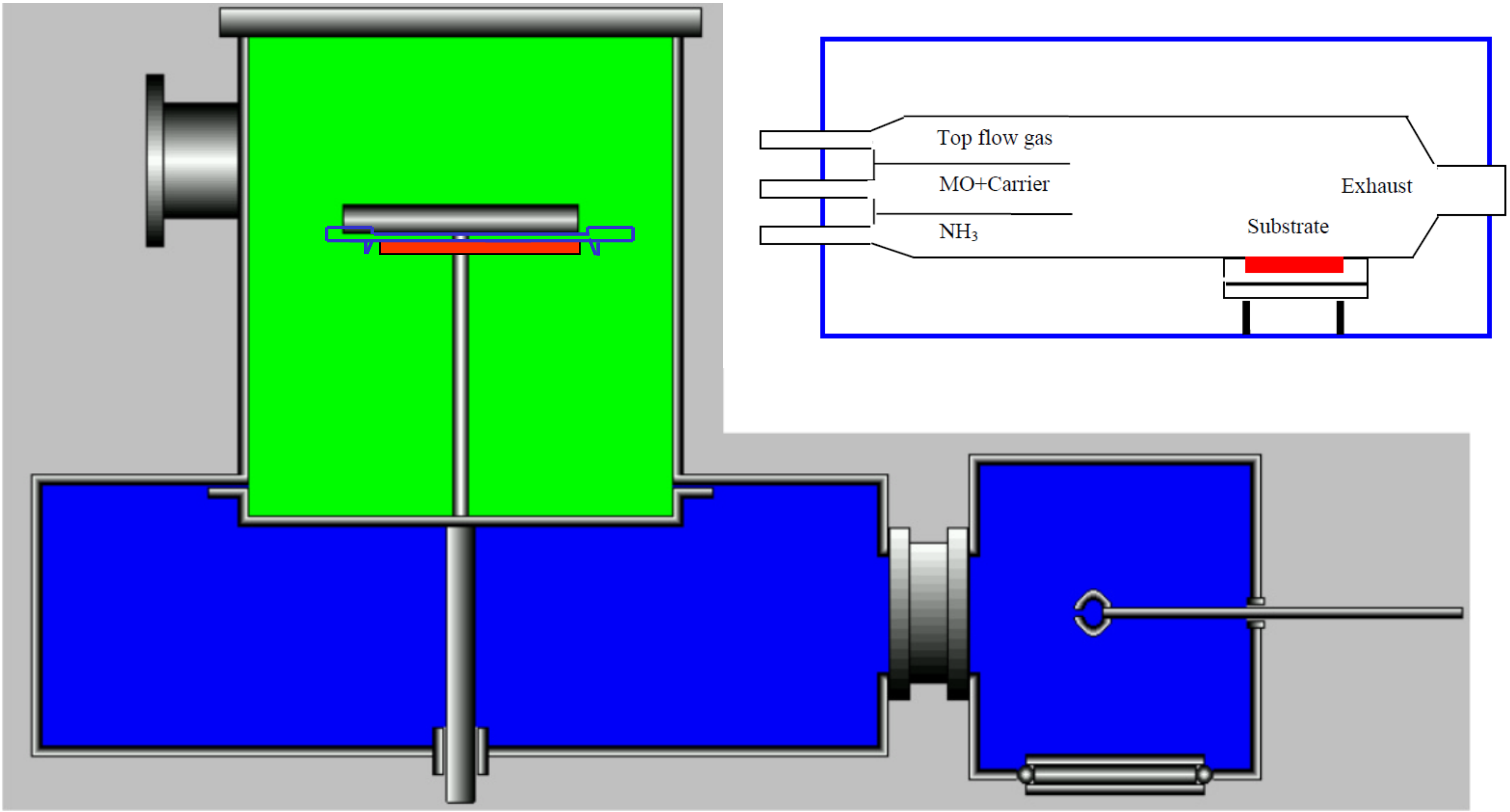
Emcore MOCVD reactor



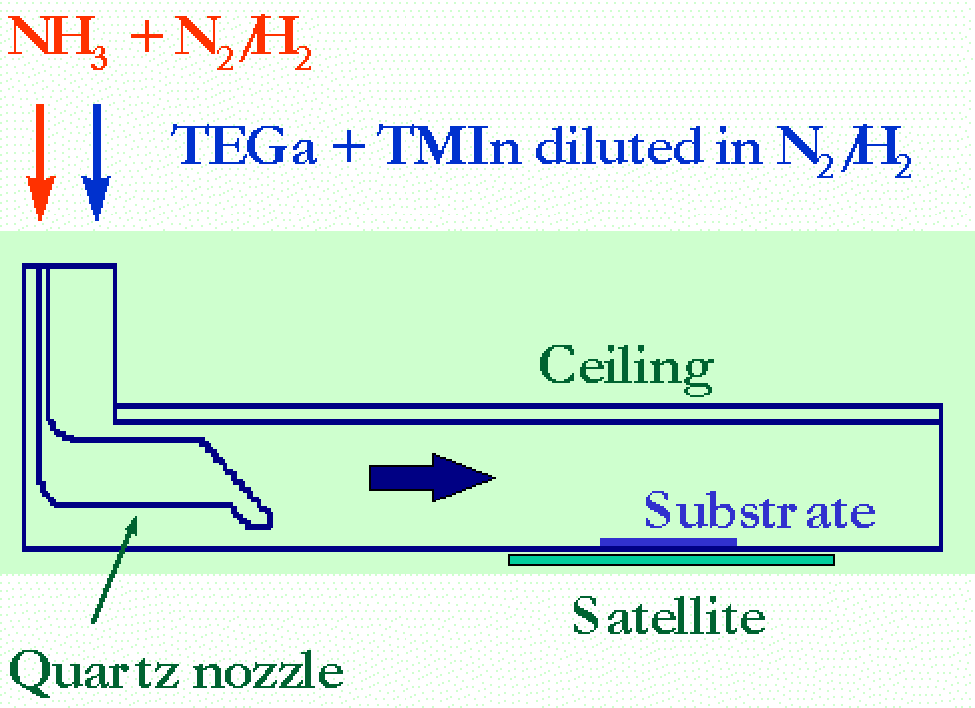


High speed rotation:
- **modify the gas flowing pattern**
- **decrease boundary layer thickness**

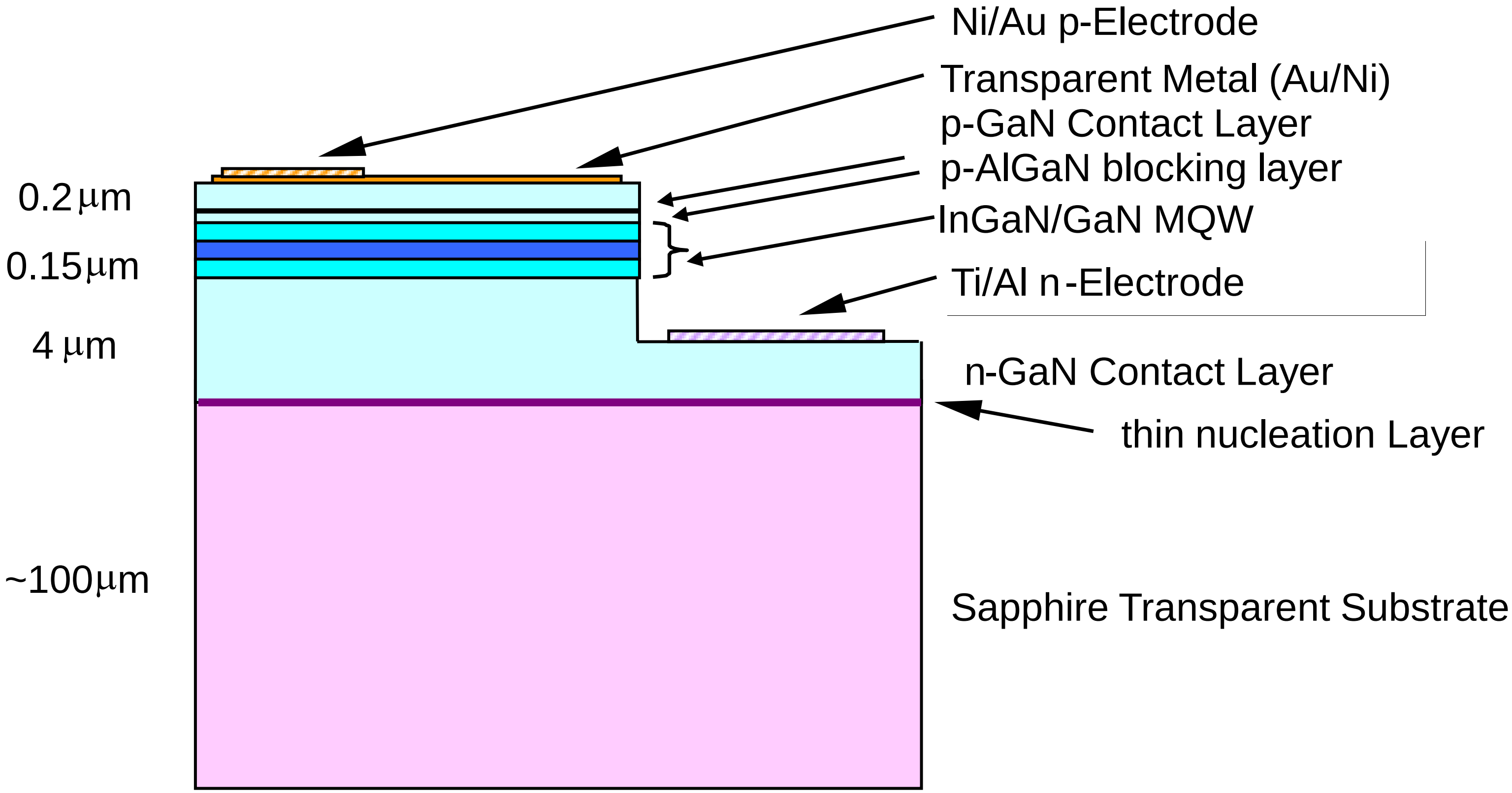
Nippon-Sanso MOCVD reactor



Axitron MOCVD reactor

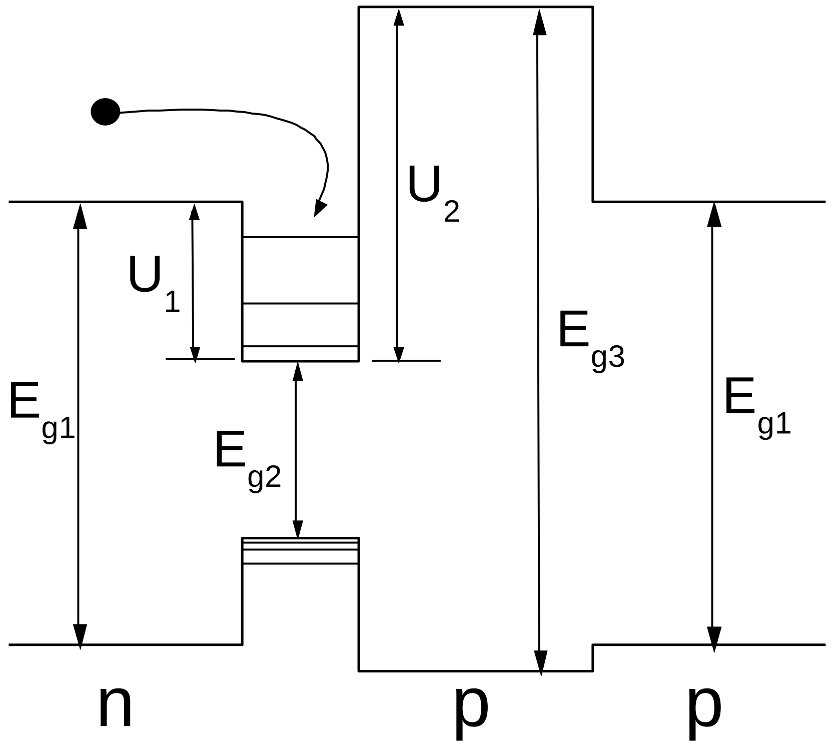


Chip structure of blue LEDs



(**Modified after S.Nakamura and G.Fasol, *The Blue Laser Diode: GaN Based Light Emitters and Lasers,* Springer, Berlin, 1997**).

Electron Blocking Layer



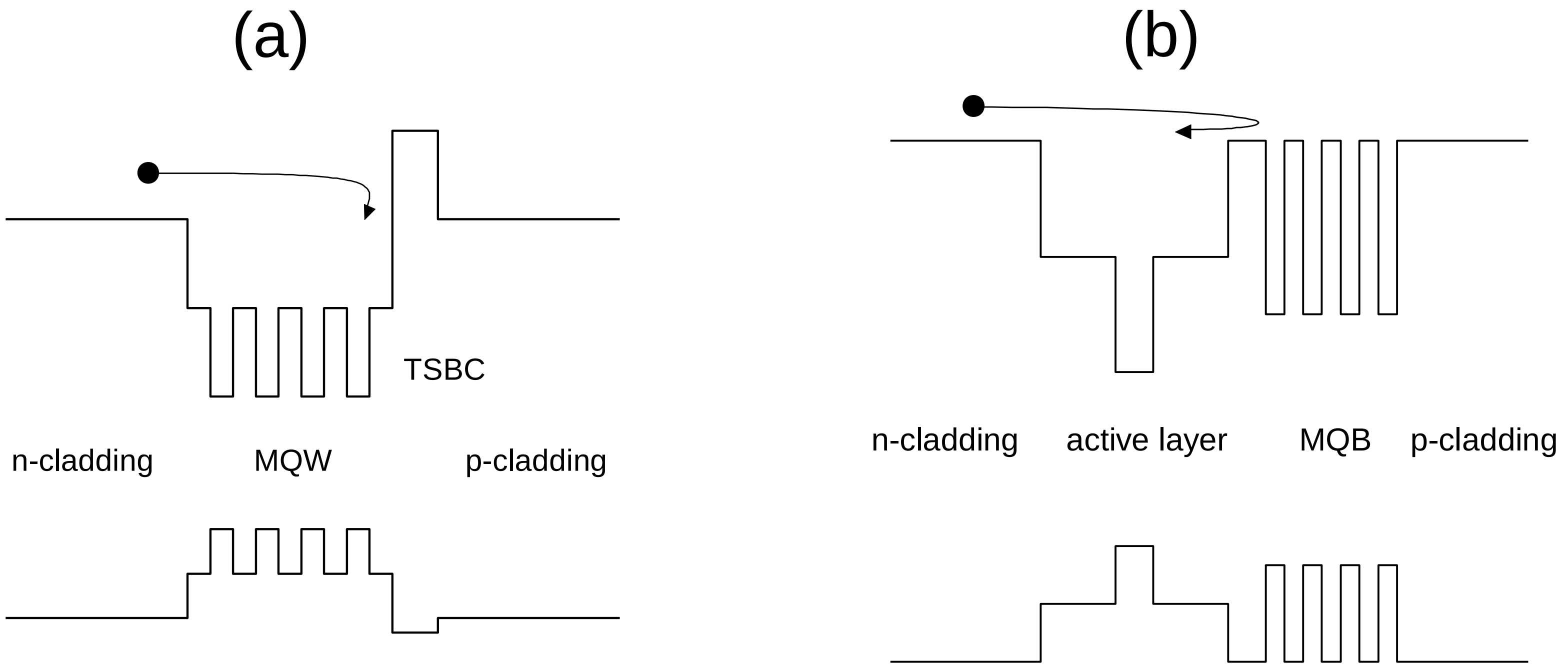
Electron overflowing: recombination in p-type region

•Large difference of carrier concentrations between electron and hole

•Large difference of carrier mobilities between electron and hole

Electron mobility: 300 cm^2/VS (room temperature)

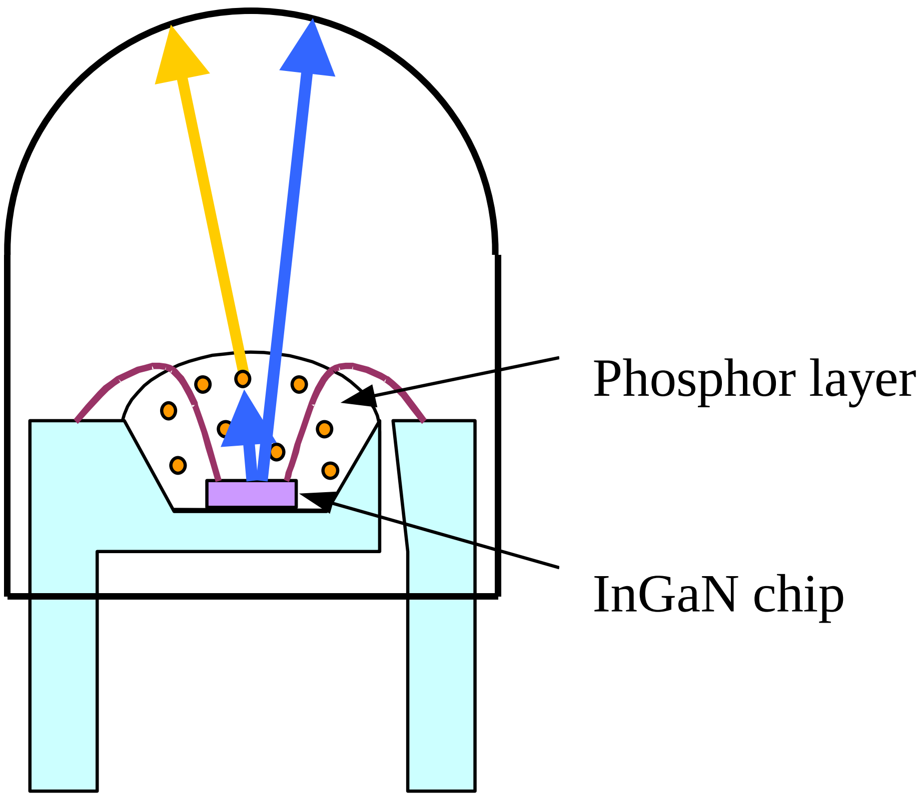
Hole mobility: <20 cm^2/VS (room temperature)



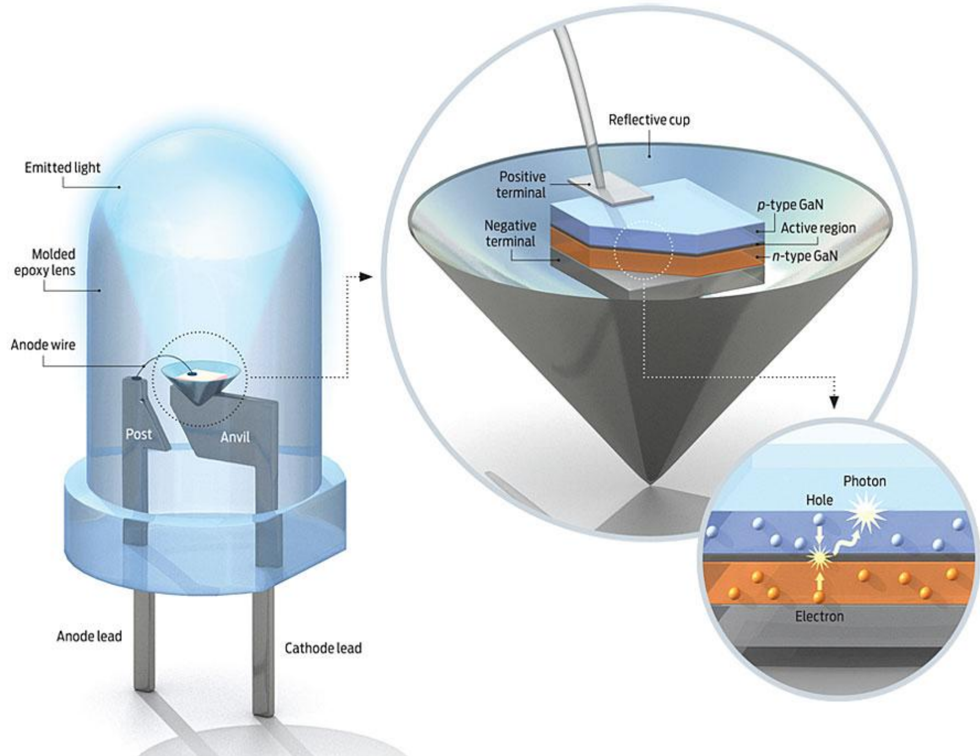
Reducing electron overflowing:

(a) Structure with electron blocking layer
(after S.J.Chang *et al., IEEE Photonic Tech. L.* 9, 1199, 1997)
(b) Structure with a multiquantum barrier (MQB)
(after C.S.Chang *et al., IEEE J. Quantum Elect.* 34, 77, 1998).

Turning blue LEDs to white LEDs

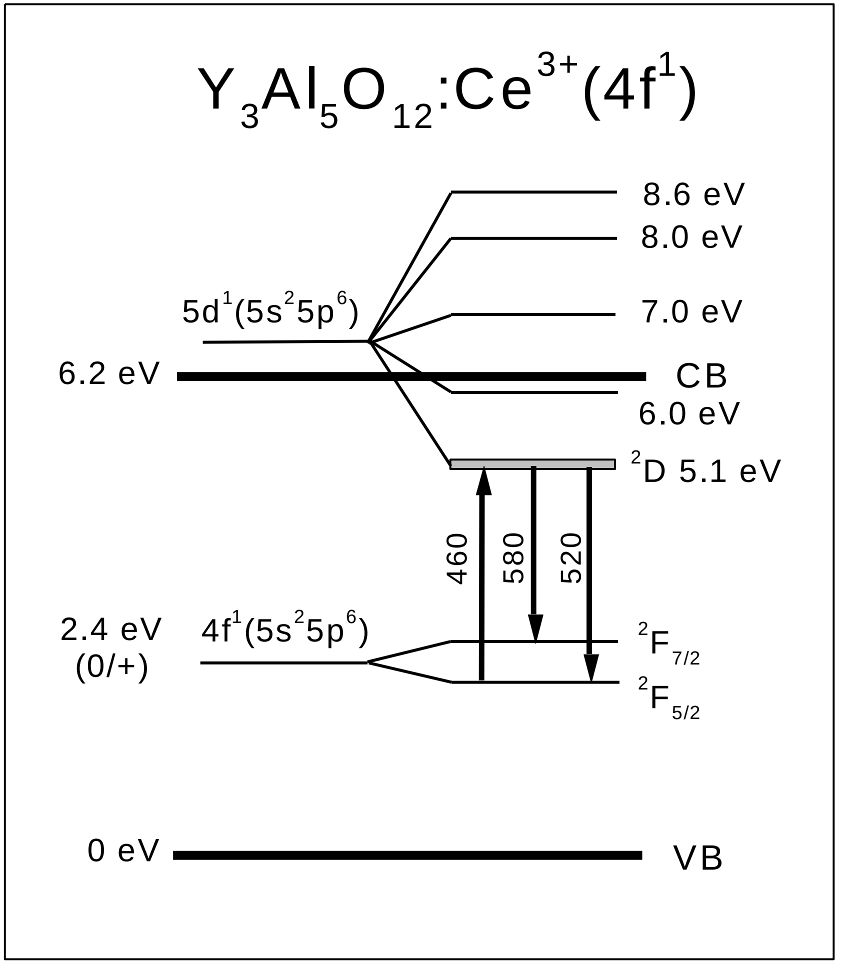


White LED

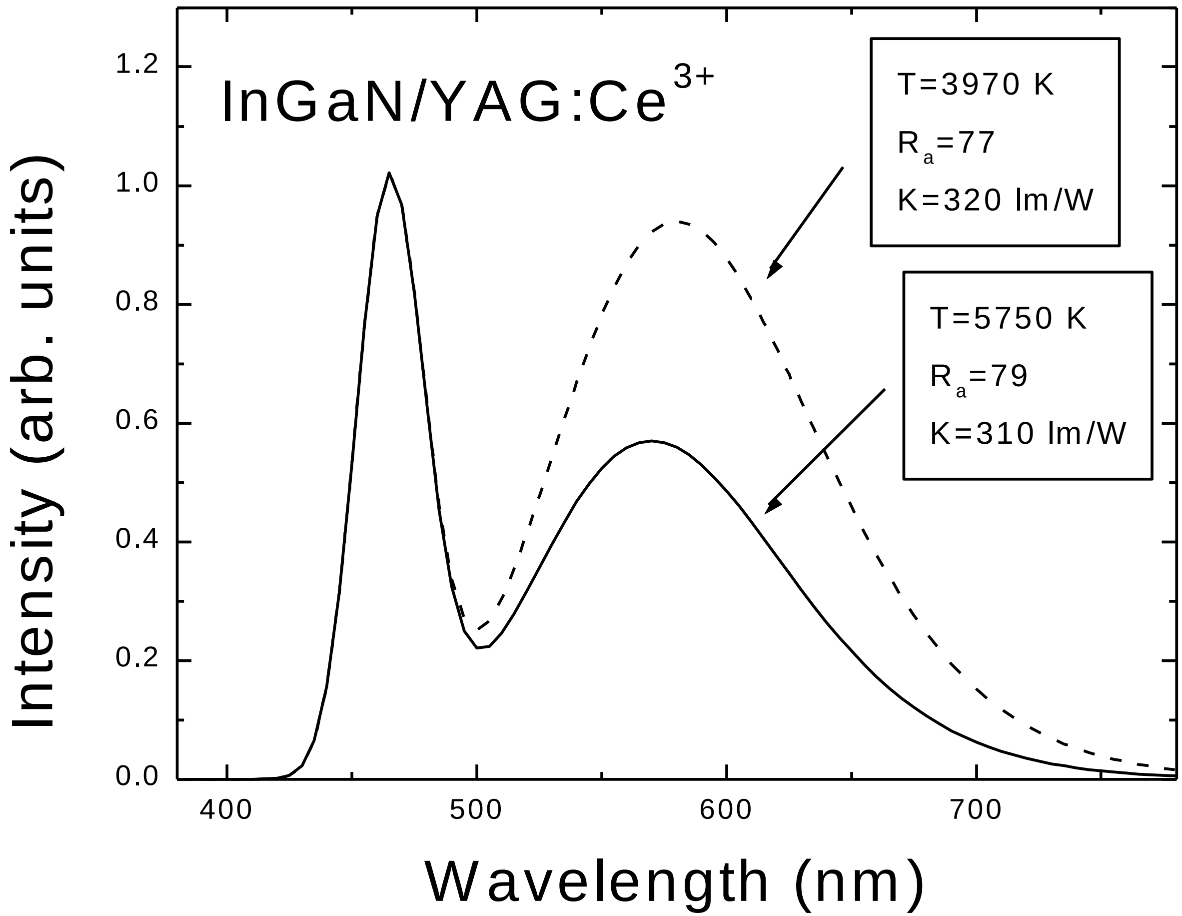


Blue LED

InGaN based luminescence conversion white LED



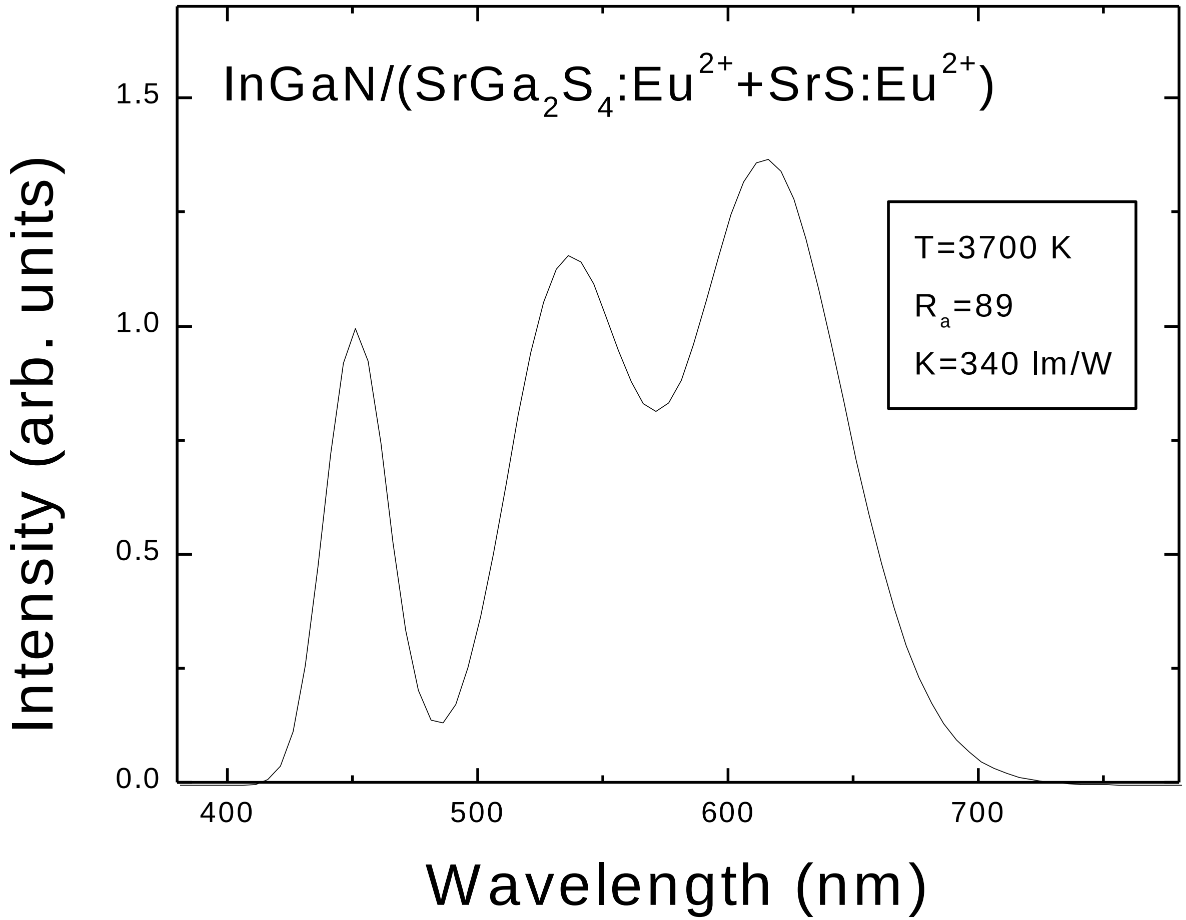
<u>Energy levels of Ce3+ (4f1) in yttrium aluminum garnet Y3Al5O12 (after M.Batenschuk *et al., MRS Symp. Proc. 560, 215,* 1999).</u>



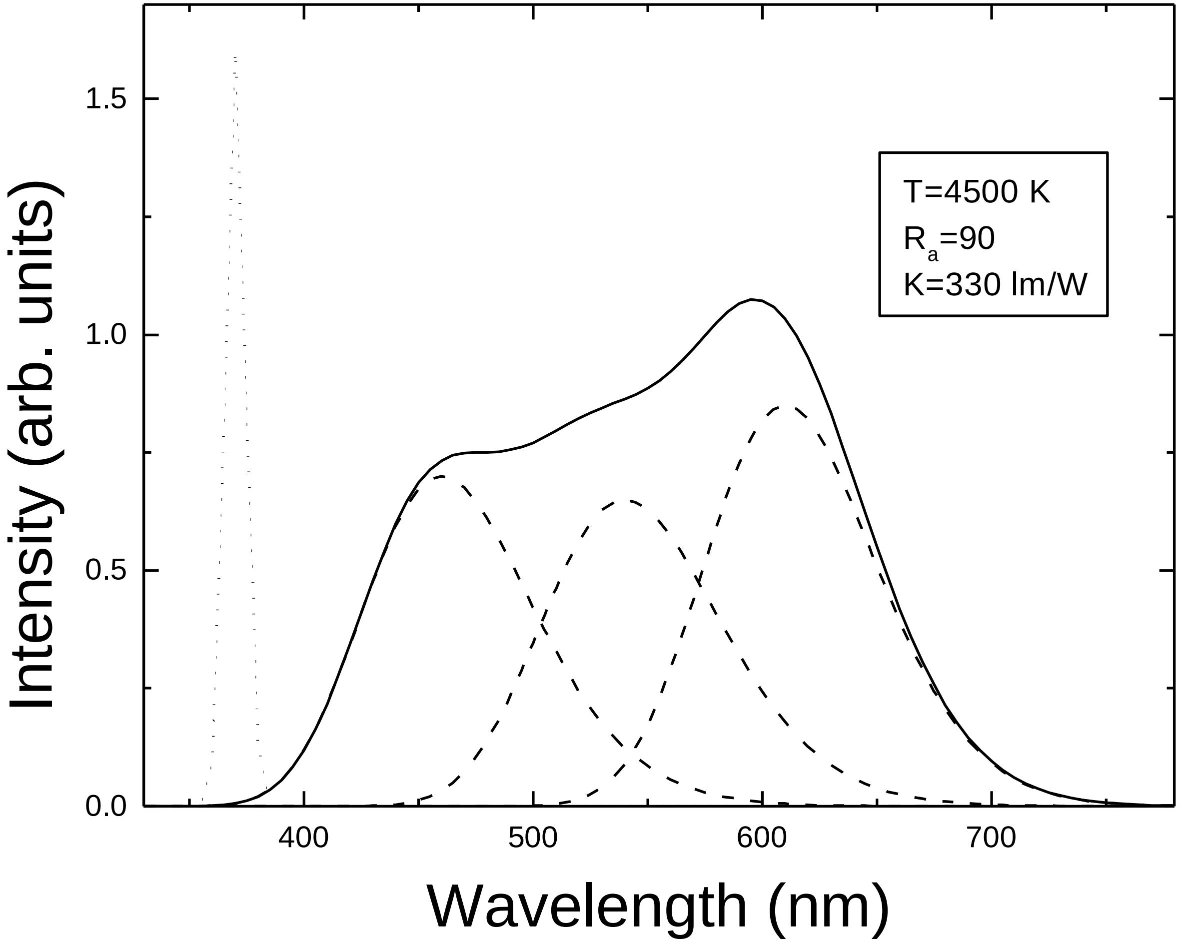
Simulation:

Model emission spectra of AlInGaN+(Y1-aGda)3(Al1-bGab)5O12:Ce3+ white LEDs for two compositions of garnet.

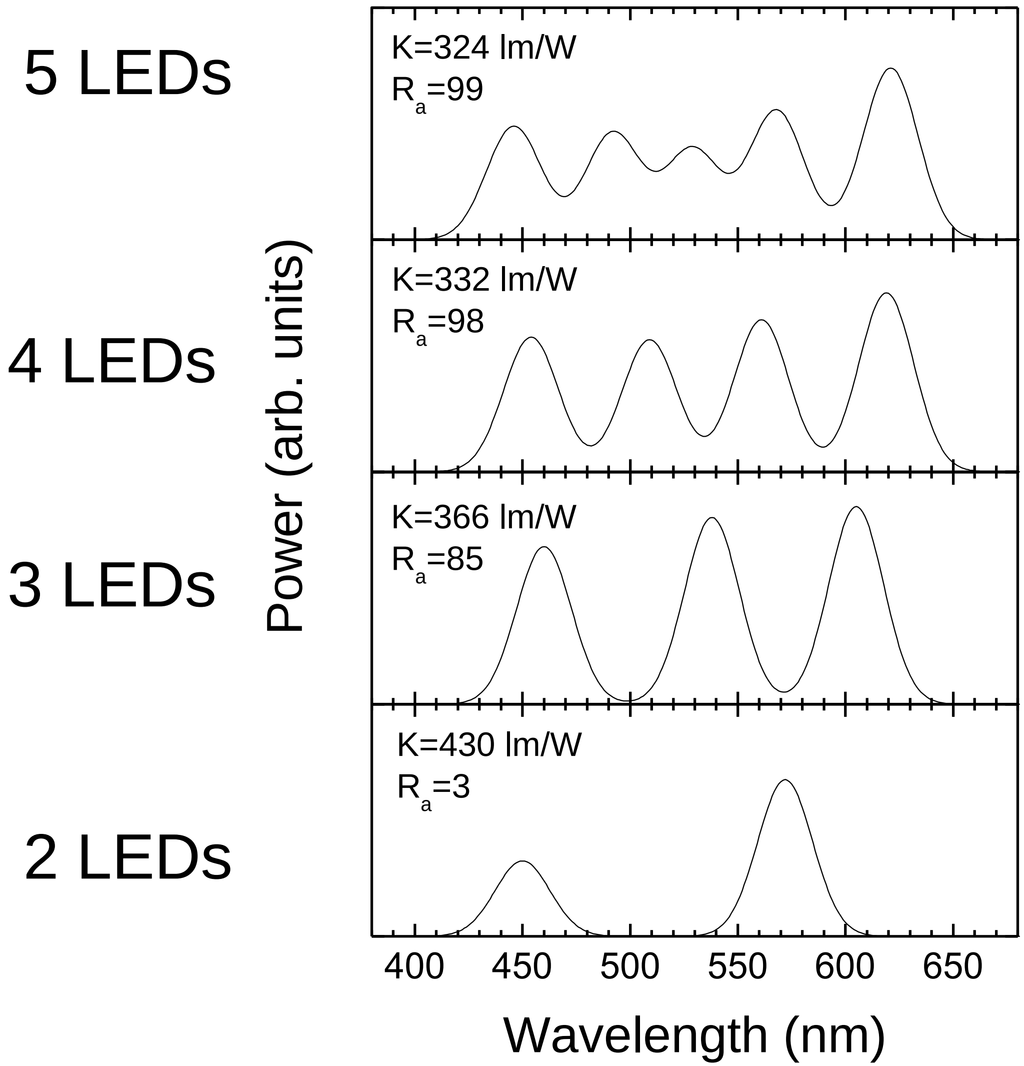
Solid line: 570 nm phosphor; and dashed line: 580 nm phosphor



Simulation: white emission spectrum from AlInGaN+(SrGa2S4:Eu2++SrS:Eu2+) system (after R.Mueller-Mach and G.O.Meuller, *Proc. SPIE* 3938, 30, 2000).



Simulation: white emission spectrum from UV pump + 3 phosphors (after D.Eisert *et al., Inst. Pure Appl. Phys. Conf. Ser.* 1, 841, 2000).



- **Simulation: optimized spectral power distributions**
- **4 or 5 LEDs with different colors from blue to red would be ideal**

Thermal management

• Current crowding due to the conductivity issue of p-GaN

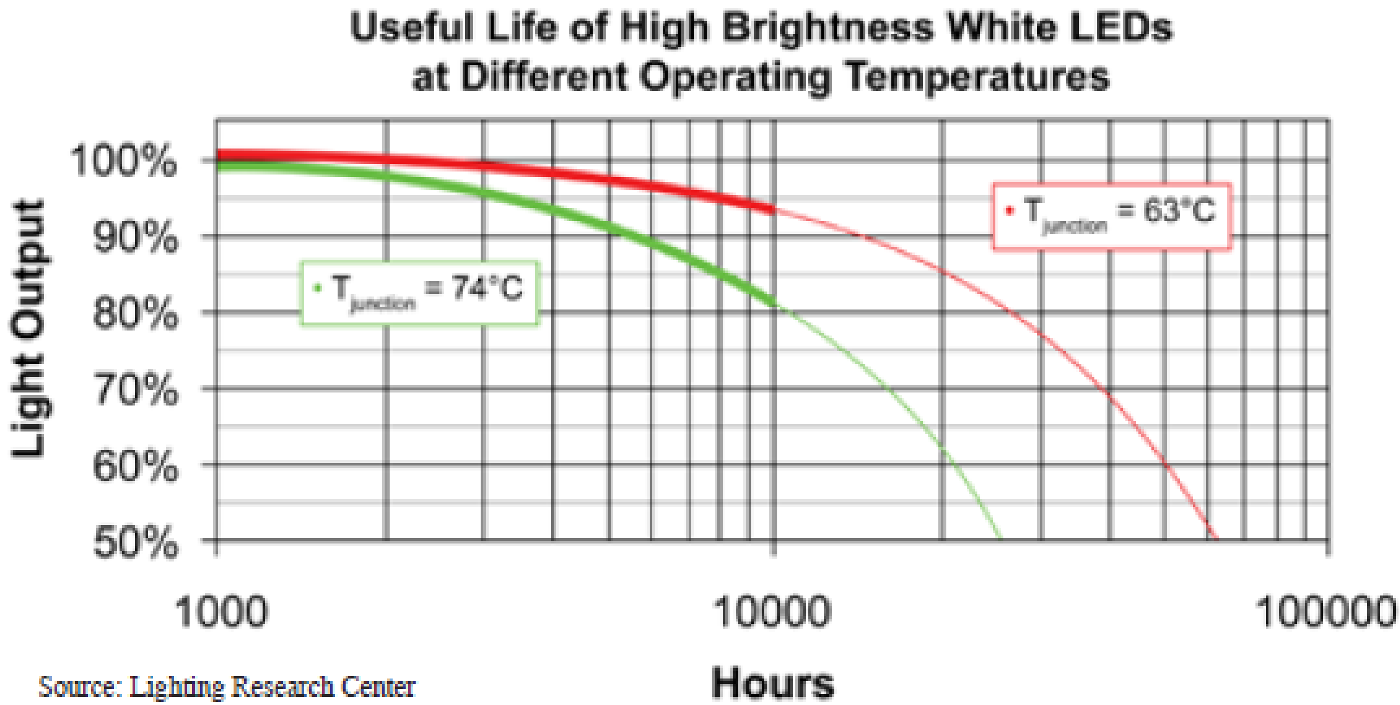
Activation energy of Mg-doped p-GaN is very large, 130-150 meV, compared with silicon-doped n-GaN (<20 meV)

For example, Mg-doping level of $10^{20}/cm^2$ means room temperature hole concentration of $\sim 10^{20} \times \exp(-150meV/KT)$, which is about $3 \times 10^{17}/cm^2$

silicon-doped n-GaN with a doping level of $10^{20}/cm^2 \sim$ electron concentration of $10^{20}/cm^2$

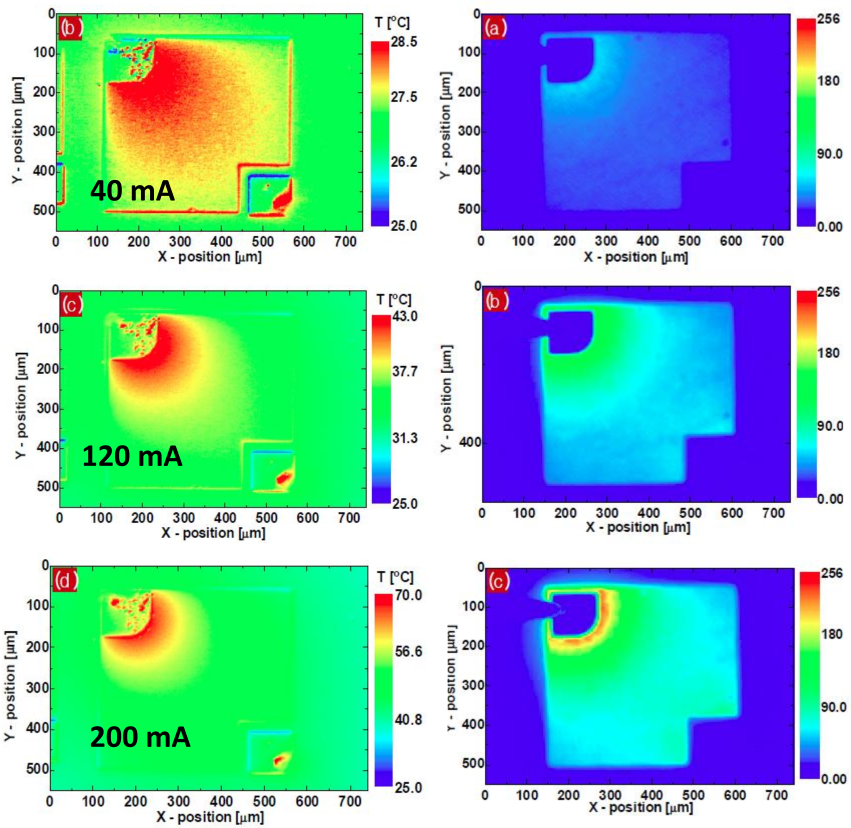
• Heat dissipation due to sapphire substrate

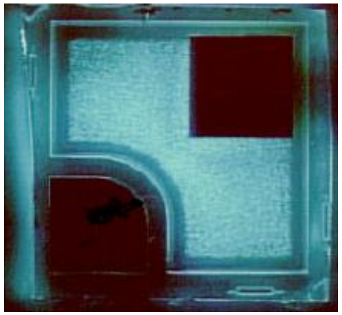
Thermal management

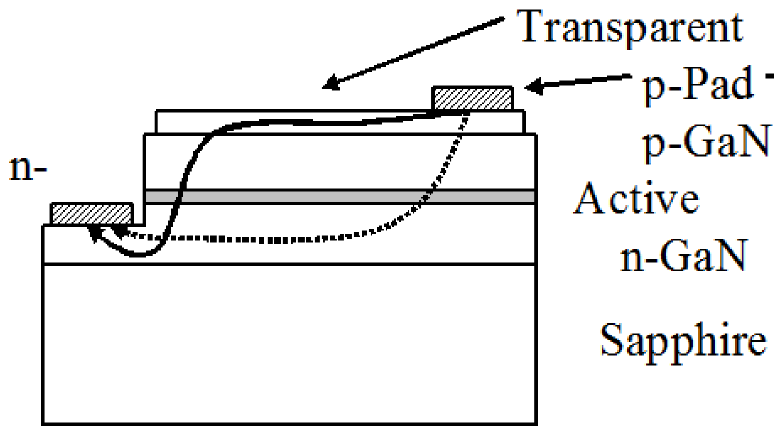


- **Factors which can affect the junction temperature of LED**
  (1) Driving current
  (2) Current flowing path
  (3) Current crowding due to the conductivity of p-GaN

Current Crowding due to p-GaN



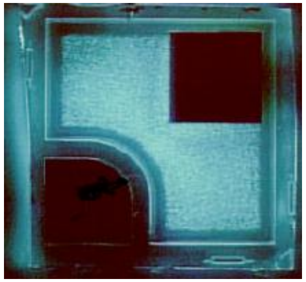


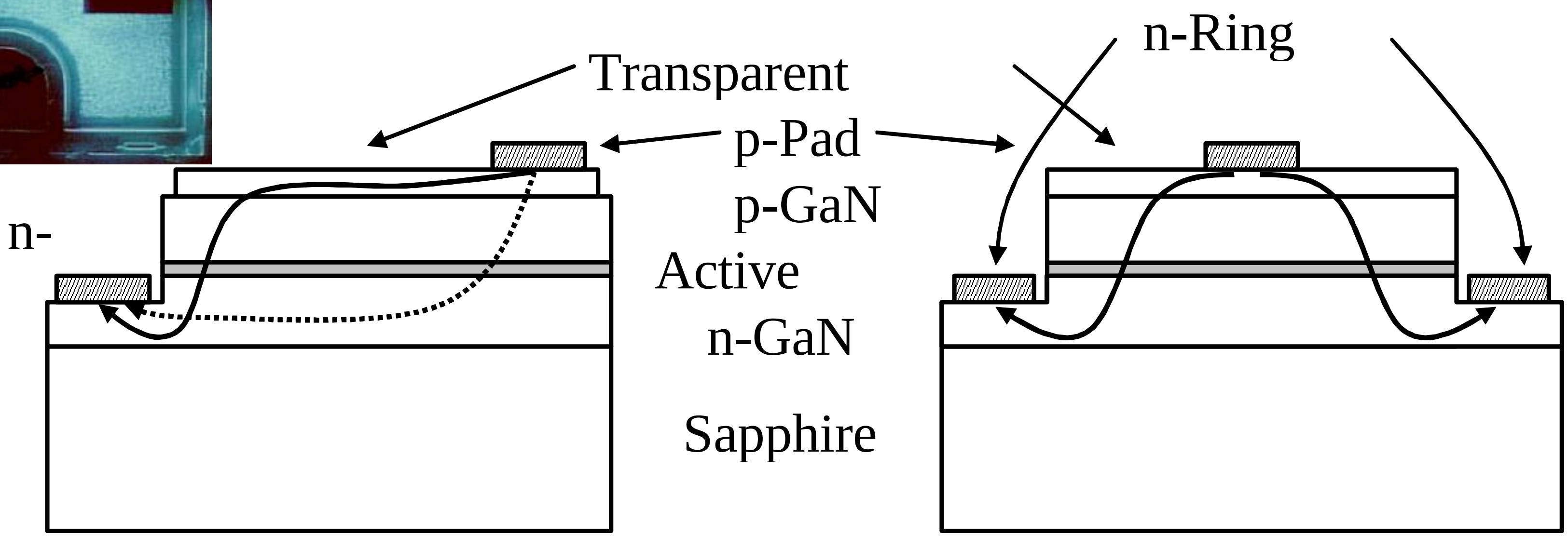


- **p-GaN generates so-called current crowding issues**
- **Long path for current to go through p-GaN laterally, generating:**

EL intensity: decreases exponentially with increasing distance from the p-contact edge

Junction temperature: strong non-uniform distribution with increasing the bias current; the temperature near the p-contact edge is much higher than that elsewhere.



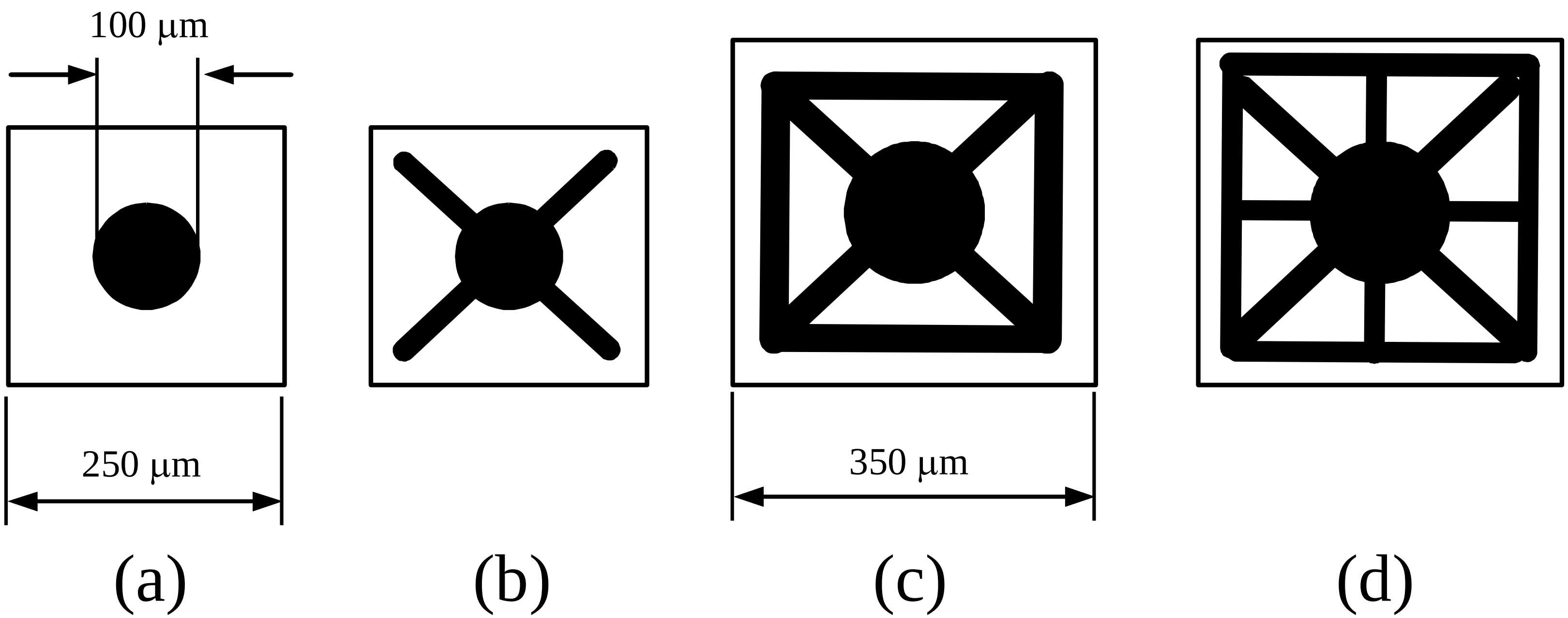


(a) (b)

Current paths in AlInGaN chips grown on sapphire.

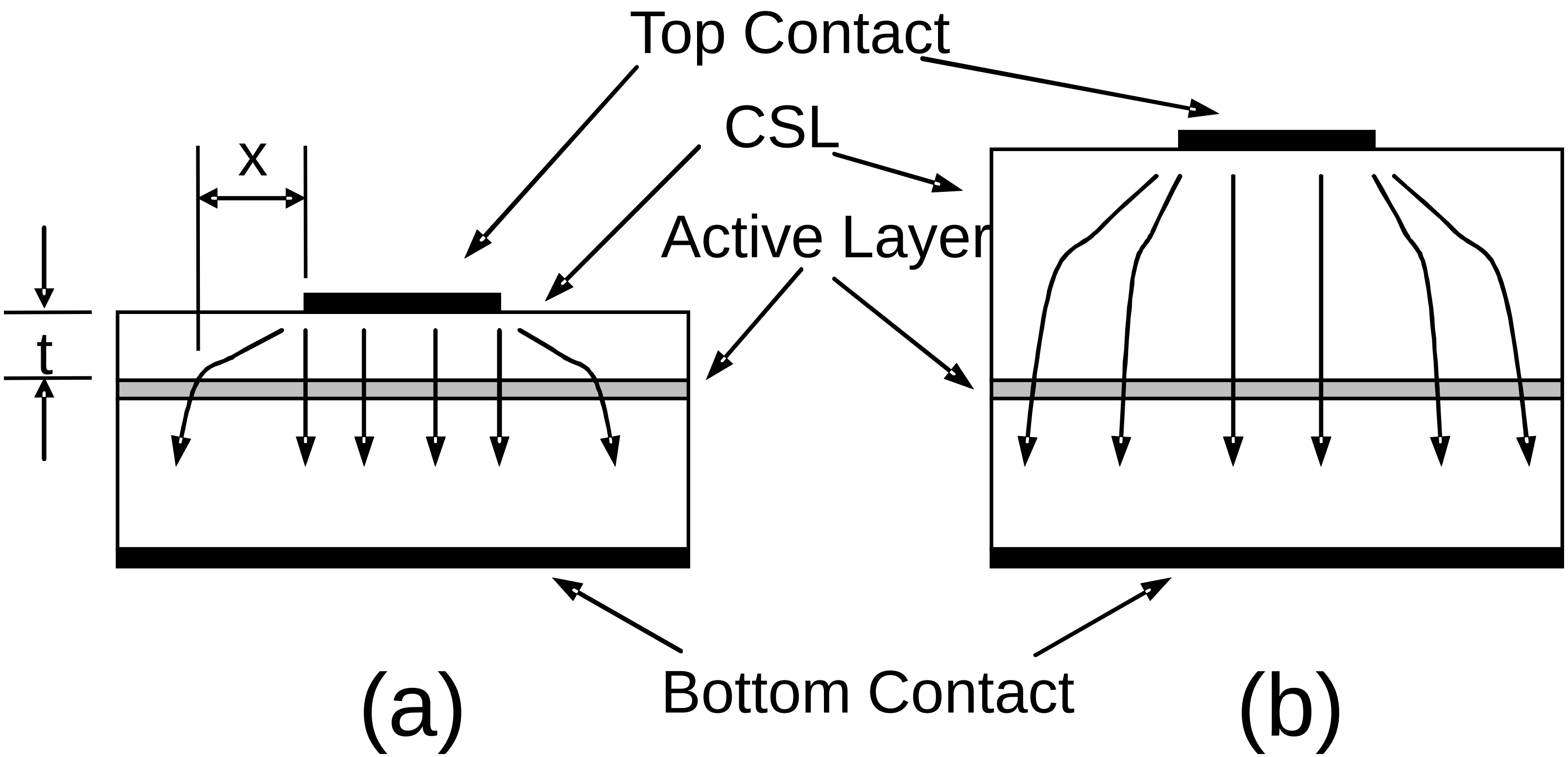
(a) Asymmetric design with current crowding towards the *n*-pad;
(b) Symmetric design with a ring *n*-pad
(after M. R. Krames *et al., Proc. SPIE* 3938, 2, 2000).

Contact Geometries



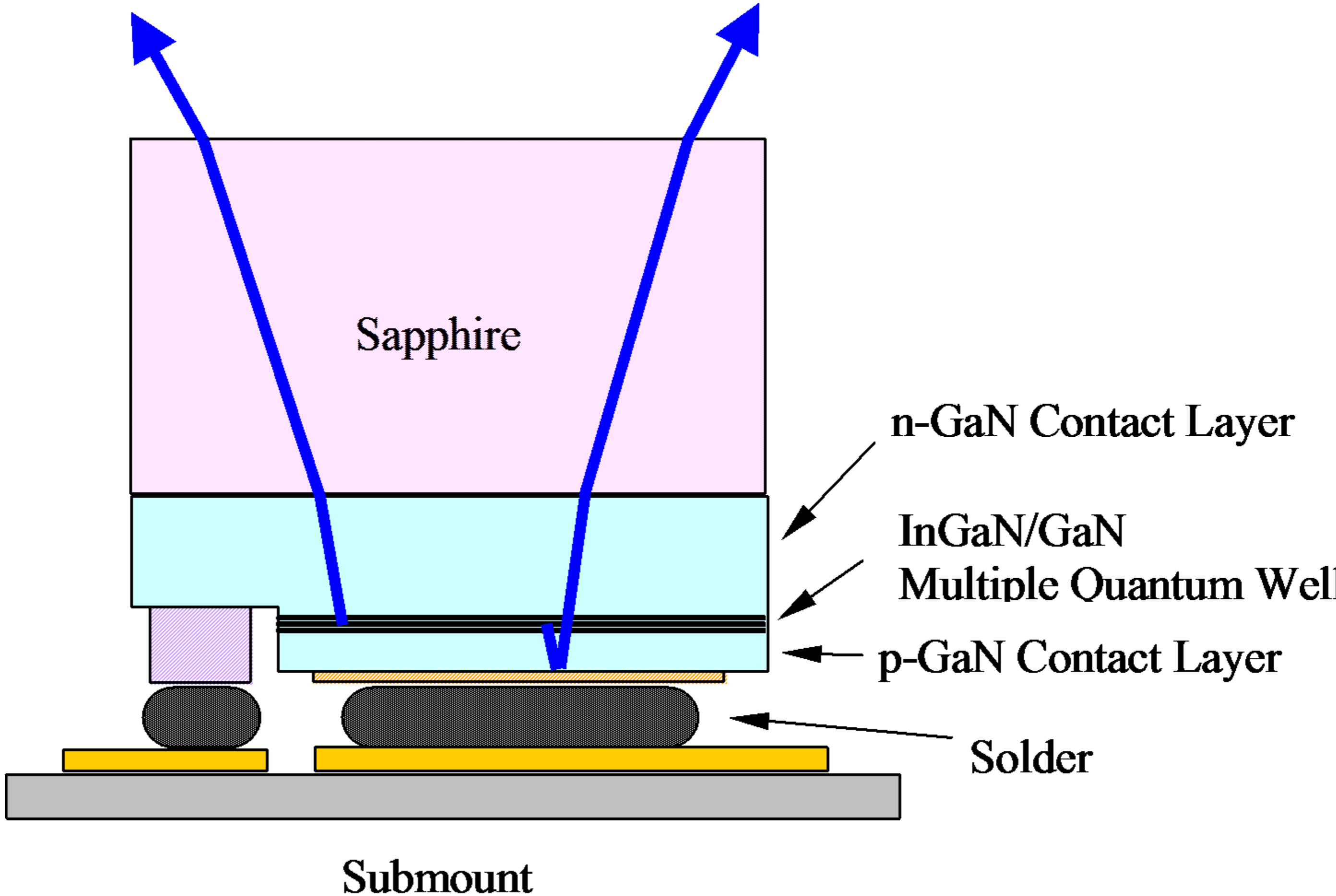
- Contact for better current spreading
- Pay attention to an issue on contact non-transparency

Contacts and Current Spreading



a) Thin/low-conductivity current spreading layer. The current crowds under the top contact (p-GaN).
b) Thick/high-conductivity CSL.
The current uniformly spreads over the entire cross-section.

Flip-Chip LED



- Contact for better current spreading (large p-contact)
- Avoid non-transparency of contact
- After J. J. Wieret *et al.*, *Appl. Phys. Lett.* 78, 3379, 2001.

Heat dissipation

2

3

4

5

Heat sink: a passive heat exchanger that cools a device by dissipating heat into the surrounding medium, which has been widely used in computers (CPU), high power LEDs and LDs, transistor, etc.

A heat sink: need to maximize its surface area in contact with the cooling medium surrounding it, such as the air.

Materials fabricated for heat sink:

• Al alloy: the most common materials; thermal conductivity of 201-229 W/m•K

• Cu: excellent heat sink properties in terms of its thermal conductivity, corrosion resistance, biofouling resistance, and antimicrobial resistance; ~twice the thermal conductivity of Al and faster; more efficient heat absorption; (but denser and more expensive)

•Diamond: thermal conductivity of 2000 W/m•K, exceeding copper five-fold

Challenges of current III-nitrides

- **Technological challenges:**

  III-nitride Growth------ lattice mismatched heteroepitaxy

  Lack of suitable and affordable substrates: III-nitrides are generally grown on large mismatched substrates (Sapphire, SiC, Si, etc), generating an extremely high dislocation density up to $10^{11}/cm^2$.

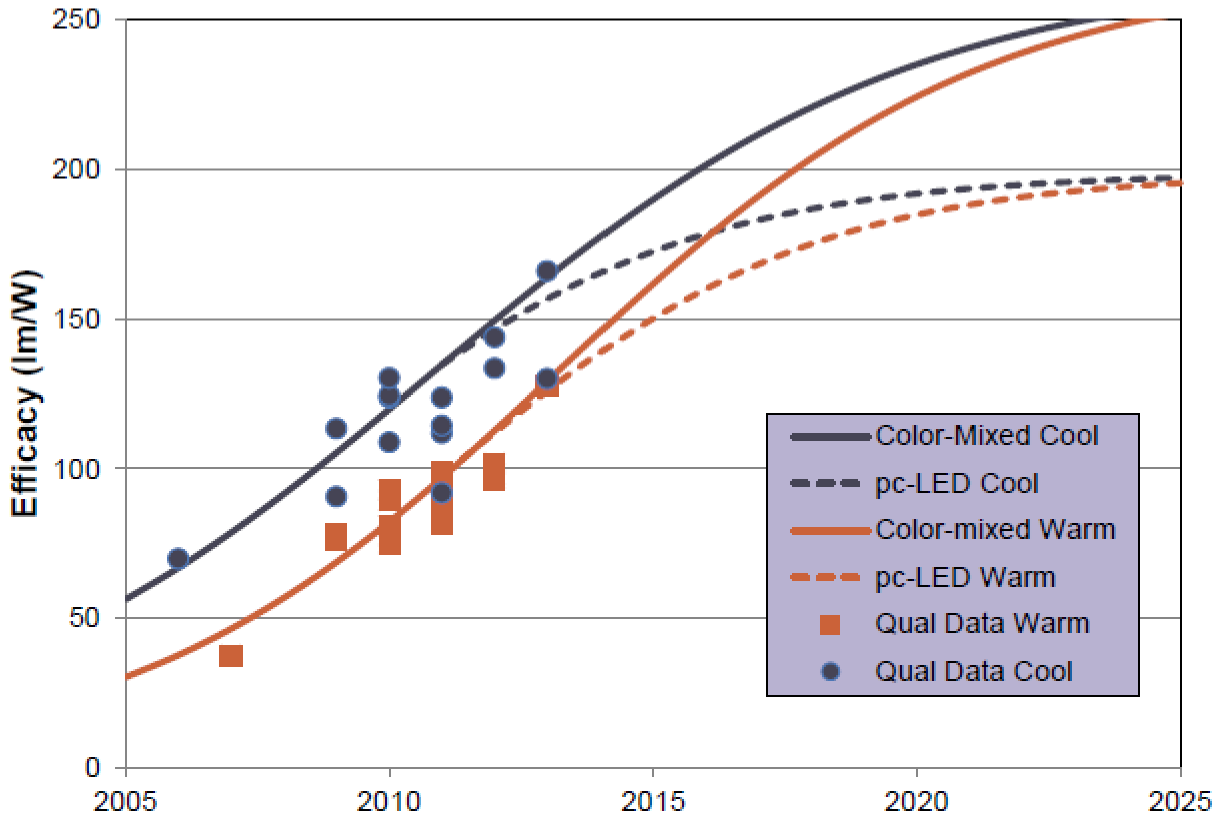
- **Scientific challenges**

  Polarization induced self-built electric fields

  Efficiency droop

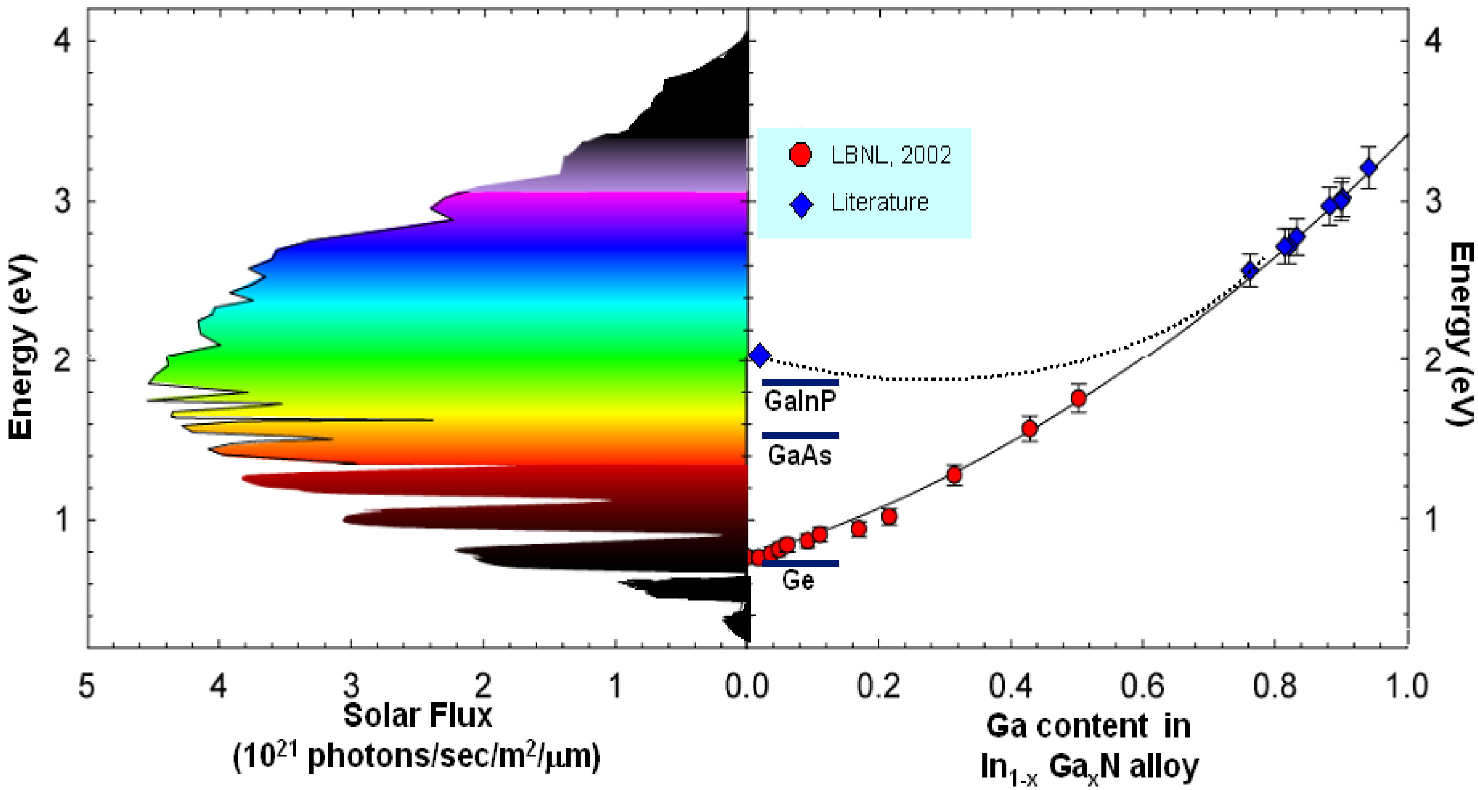
  Difficulty in incorporation indium into GaN

US DOE road-map for SSL



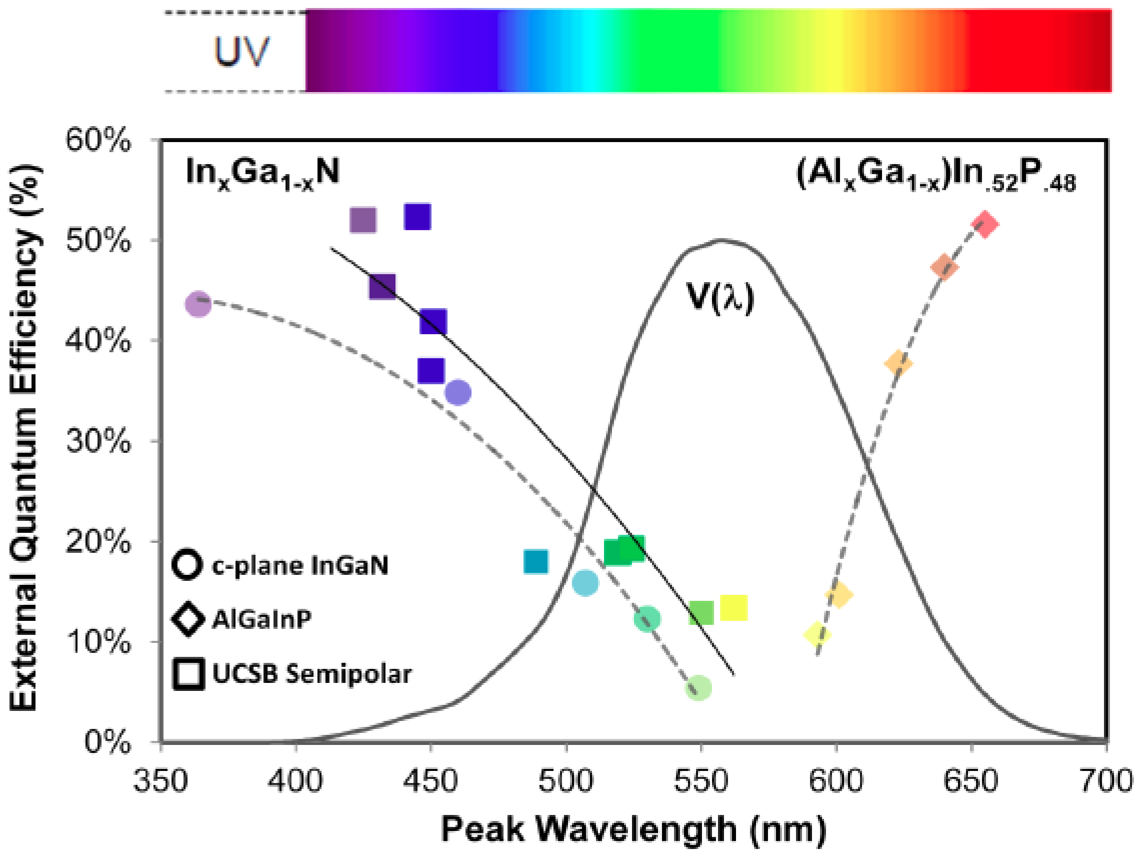
- **Blue LED +Yellow phosphor: <200 lm/Watt**
- **Color Mixed LEDs: Blue, Green, Yellow LEDs (red LED is no problem at all) requested**
- **Challenges: green/yellow LEDs (high indium content)**

III-nitrides for future SSL and sustainable energy



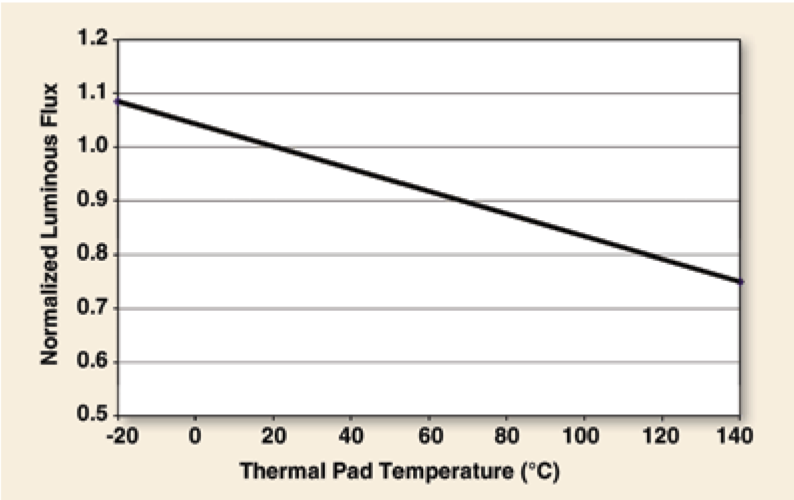
Challenges: High indium content InGaN

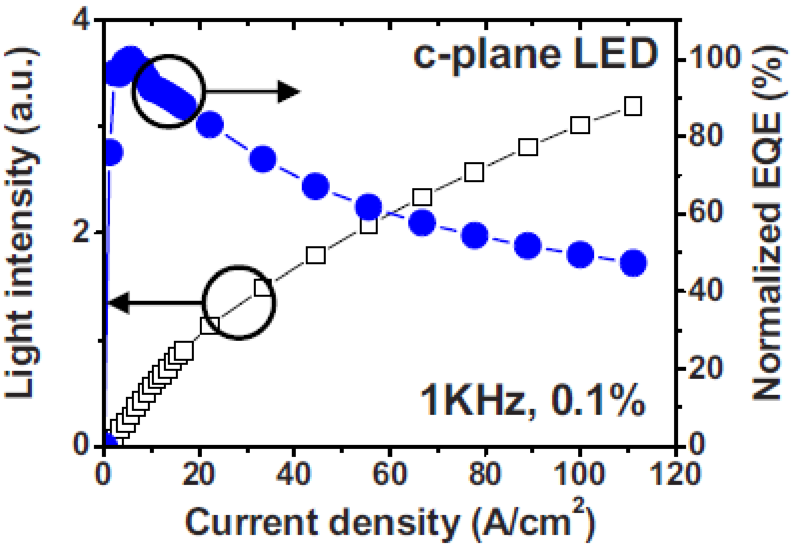
Green/Yellow Gap



Great challenge: how to enhance indium incorporation into GaN

Current issues on blue LEDs



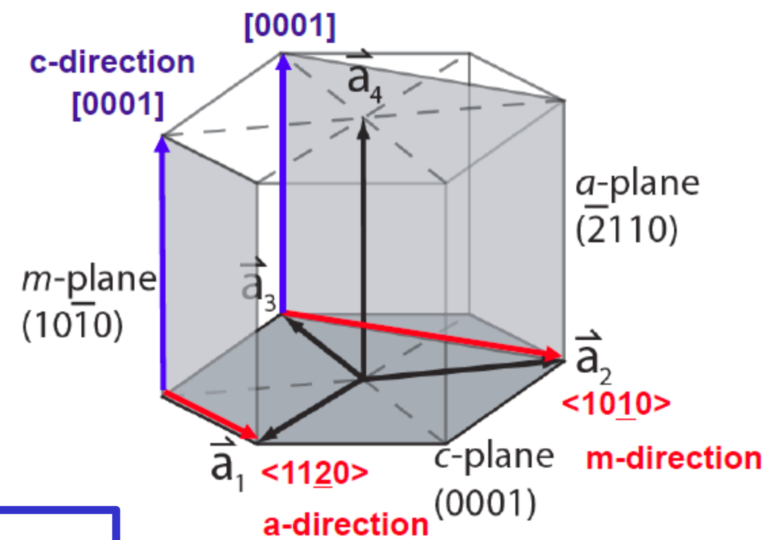


Thermal droop

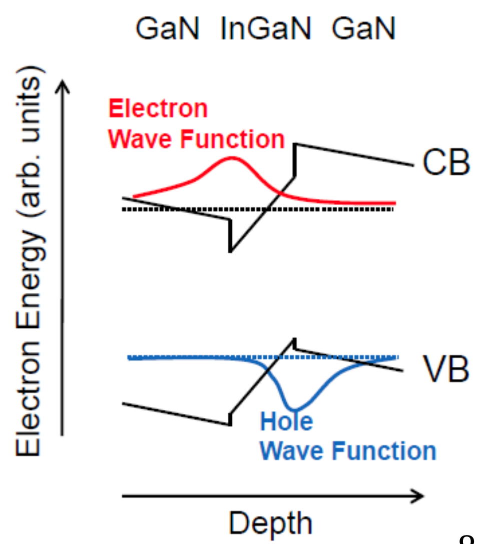
Efficiency droop

Fundamental limits for current III-nitride LEDs

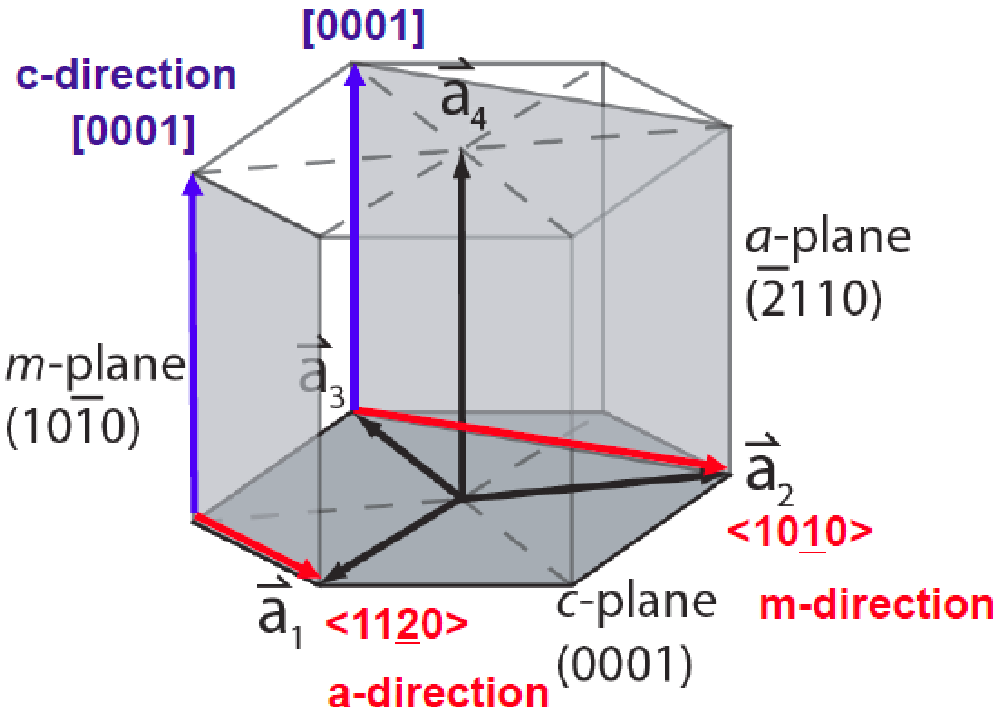
Strained InGaN QWs: induce piezoelectric polarization across QW

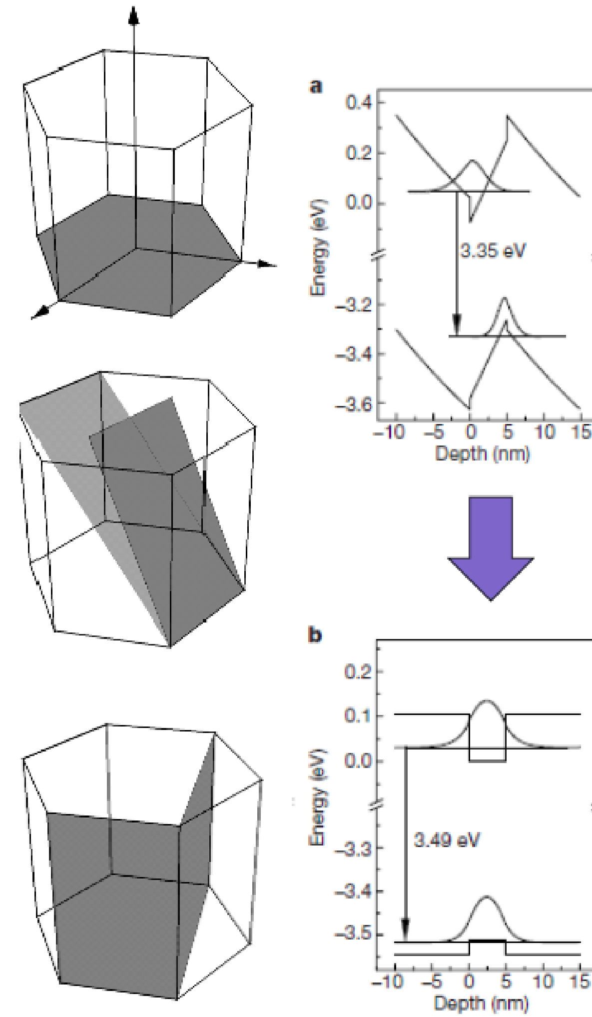


- **Reduced wavefunction overlap**
- **Reduced radiative recombination rate**
- **Reduced transition energy**
- **Carrier transport issues**
- **Emission blue-shifts with current density**
- **QWs are limited in width**



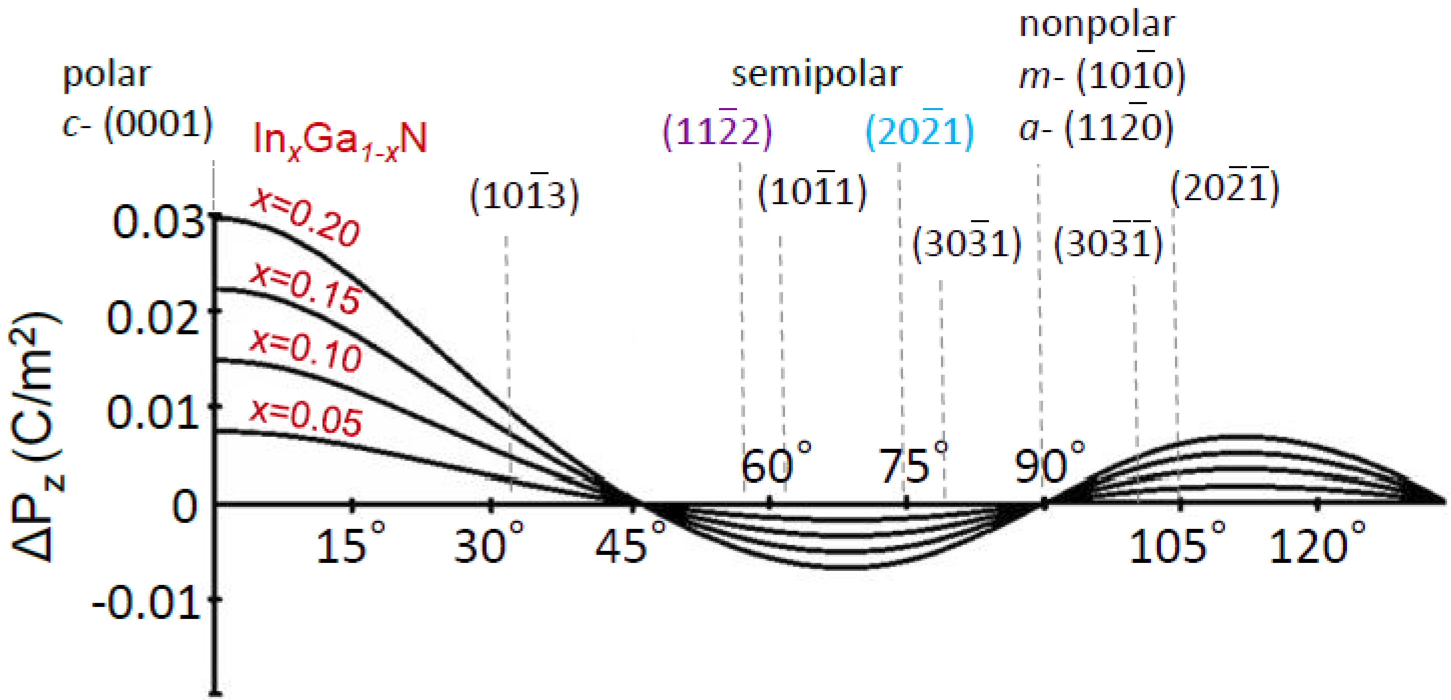
Possible solution: semi/non-polar GaN (i)

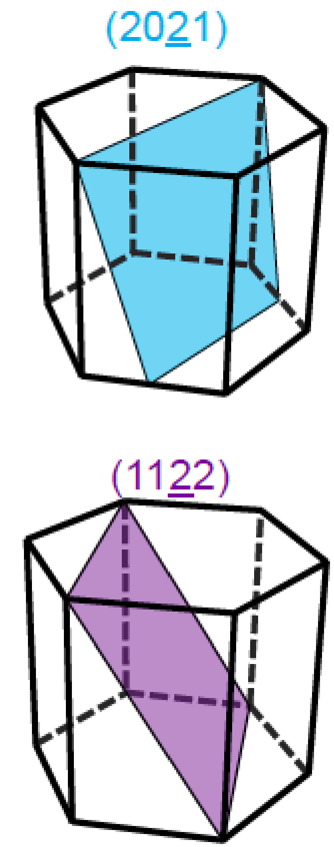




- **Minimise wavefunction separation**
- **Enhance radiative recombination rate**
- **Minimise emission shift with current density**
- **Enhance indium incorporation into GaN**

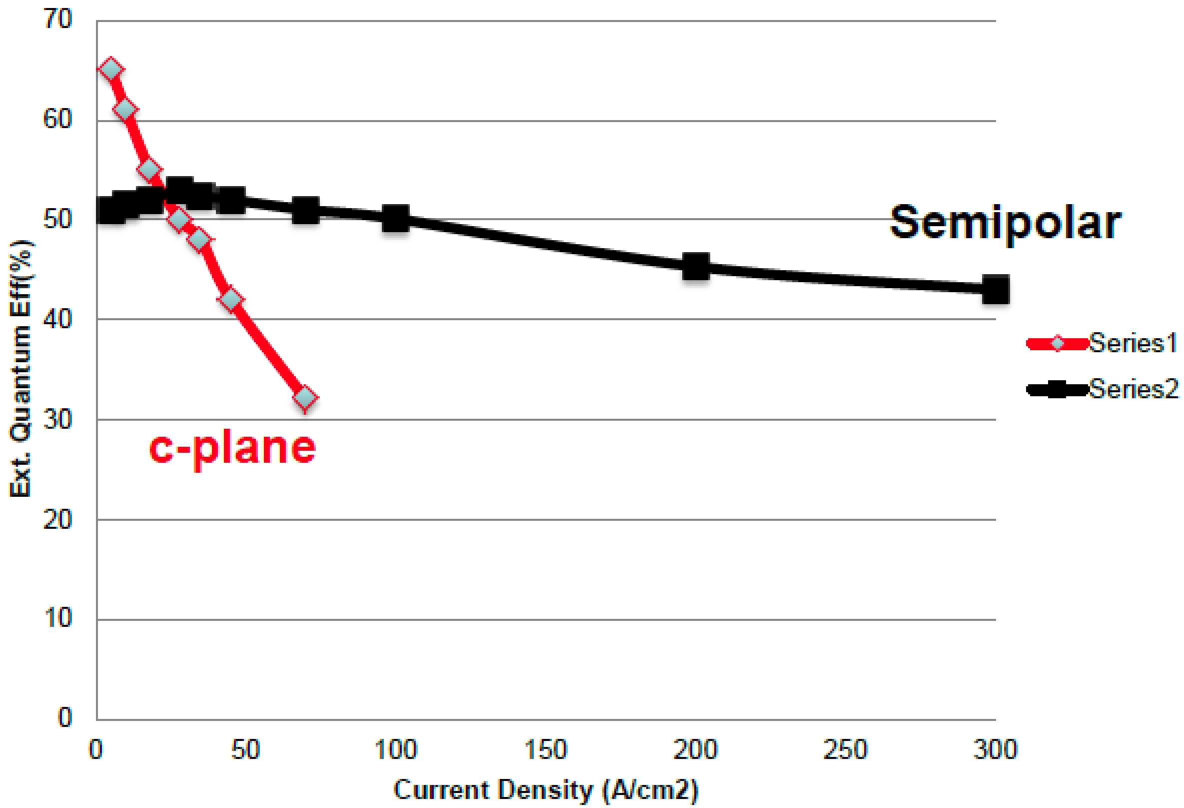
Possible solution: semi/non-polar GaN (ii)





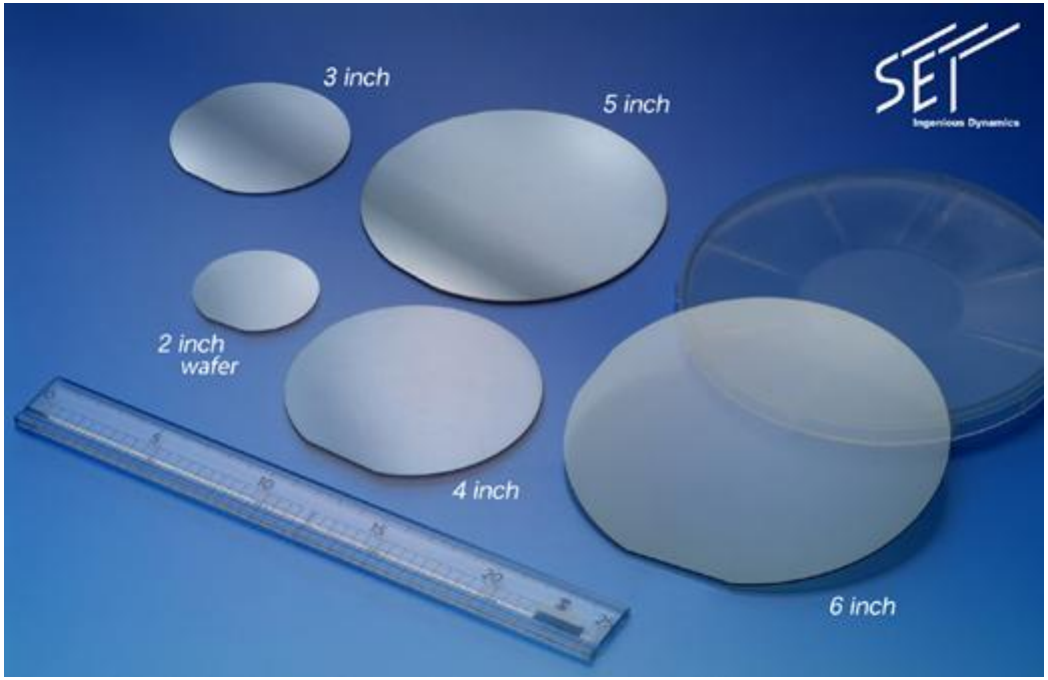
- Most popular semi-polar orientations (11-22) and (20-21)
- A number of advantages

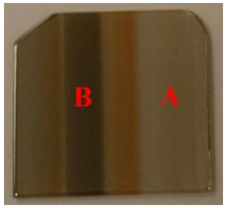
Possible solution: semi/non-polar GaN (iii)



- Significant reduction in efficiency droop
- Challenges: growth on extremely expensive semipolar GaN free-standing substrates

Challenges of current semi/non-polar GaN





1x1 cm^2
Non/semi-polar GaN

- Current: 1x1 cm^2 non/semi-polar GaN (1000 US dollar)
- Challenges: ≥2 inch non/semi-polar GaN with high quality

- Lots of work on III-nitrides for SSL is waiting for you!