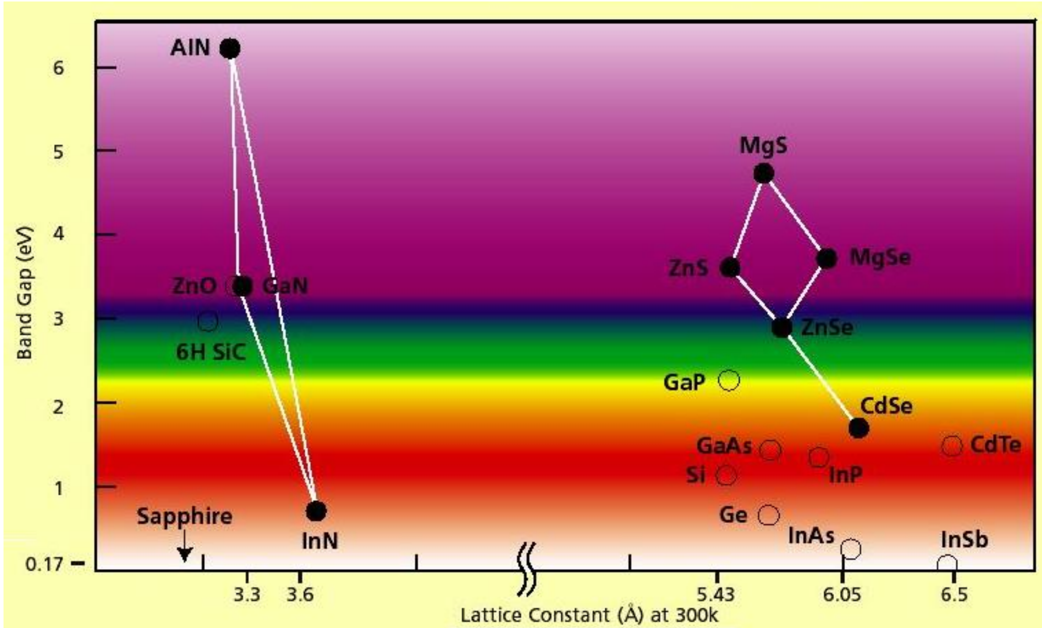
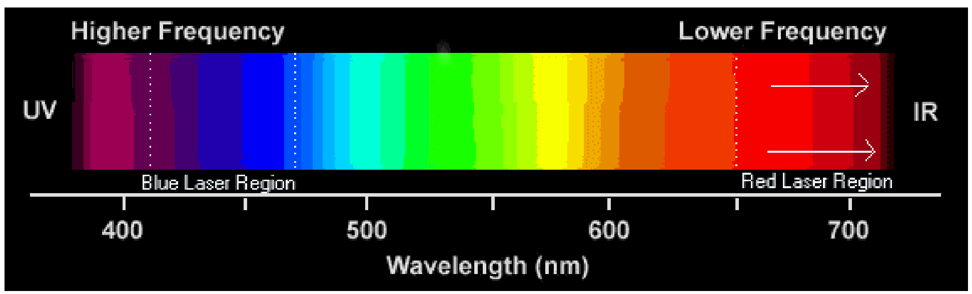
Topic 16

16 Introduction of III-nitride semiconductors

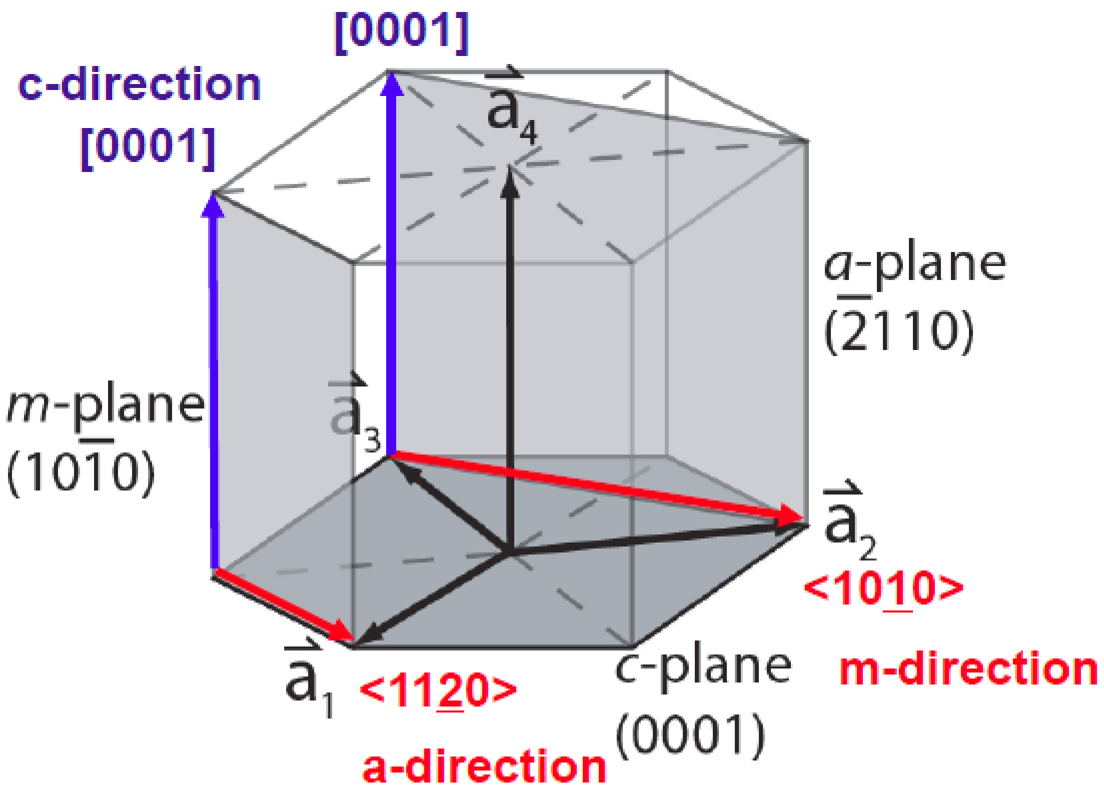
- 16.1 Background of III-nitrides
- 16.2 Basic parameters of III-nitrides
- 16.3 Epitaxial growth of III-nitrides
- 16.4 Thermal management of optical devices
- 16.5 Current challenges of III-N Optoelectronics
- 16.6 Possible solutions to current challenges





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

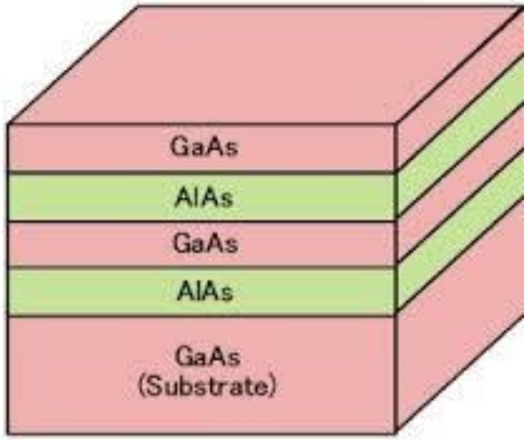
GaN crystal structure and substrate issue



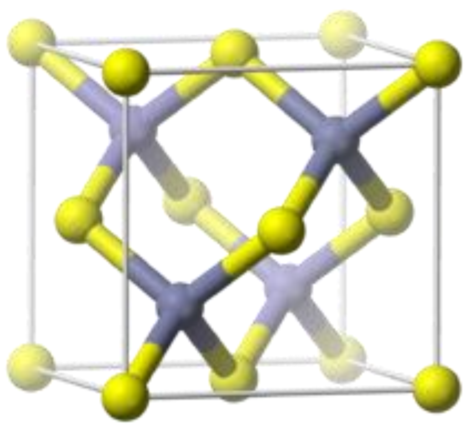
- **GaN, InN, AlN:** **wurtzite structure**
- **Sapphire:** **wurtzite structure**
- **6H SiC:** **wurtzite structure**

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

Lattice-mismatch of AlAs on GaAs as an example



GaAs	AlAs
0.5653 nm	0.5660 nm

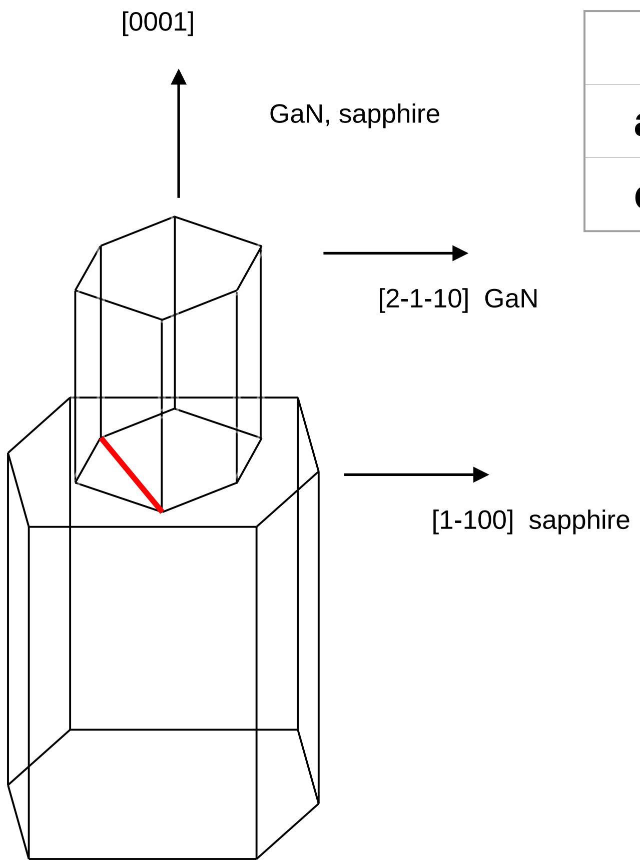


- **Lattice-mismatch between AlAs and GaAs**
$f=(a_{AlAs}-a_{GaAs})/a_{GaAs}=1.1\%$

- **Compressive stress (AlAs on GaAs substrate)**

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

Lattice-mismatch in GaN and 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^{0}C rotation of GaN basal plane

⇩

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

compressive !

Two-step growth approach(i)

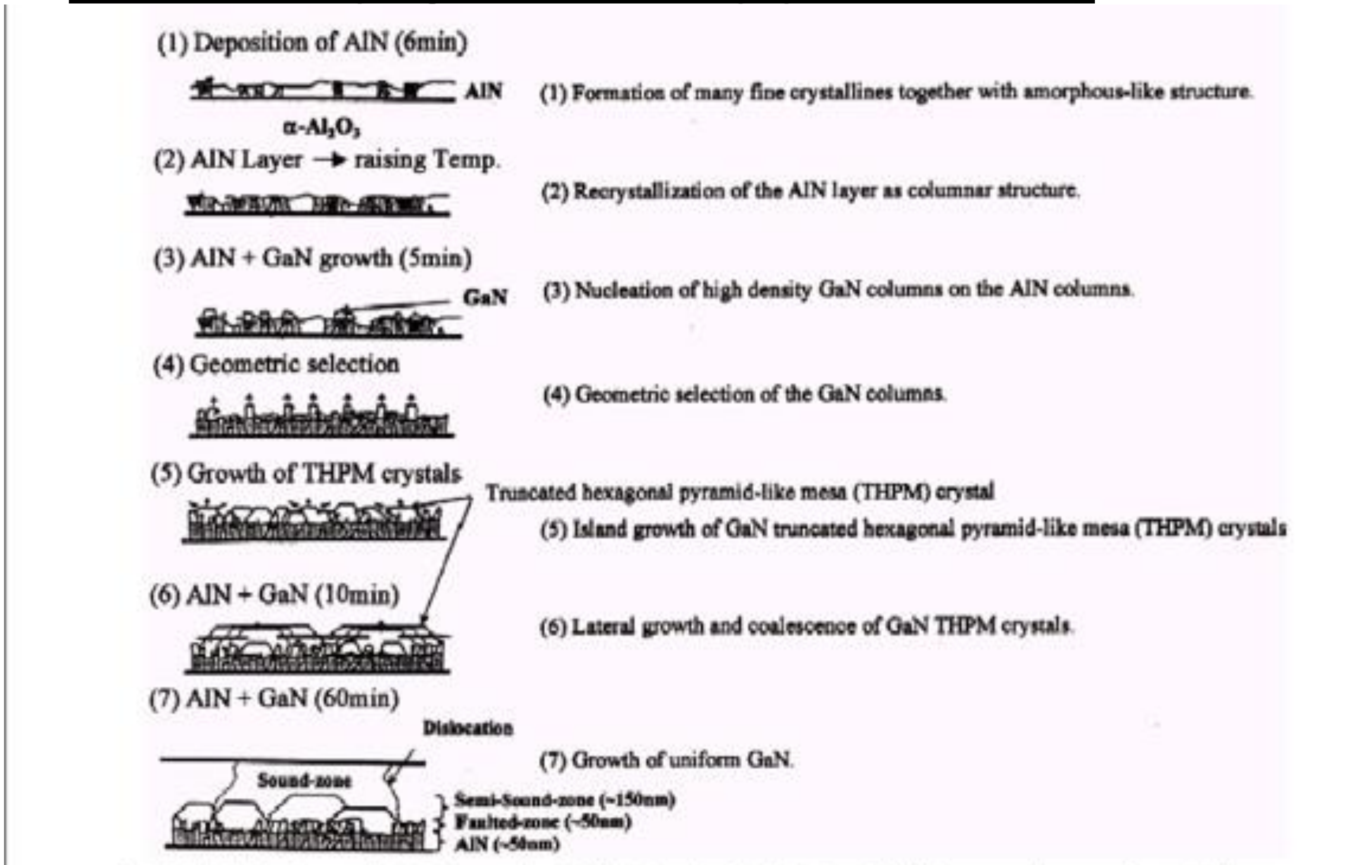
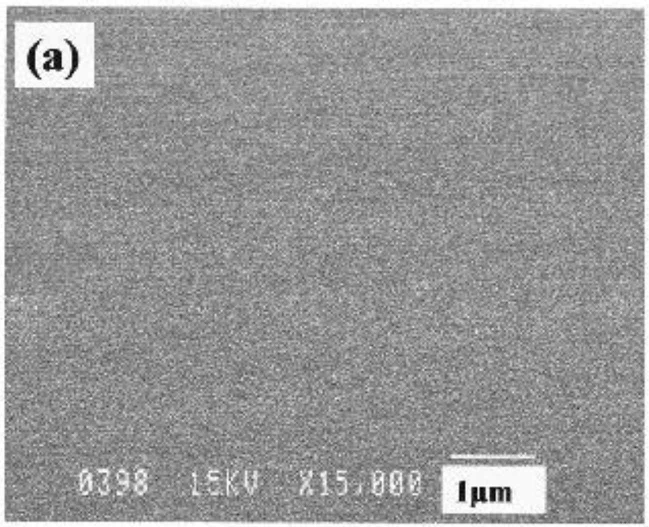


Fig. 3. Model for the growth of GaN grown by OMVPE using the LT-buffer layer. THPM; truncated hexagonal pyramid-like mesa.

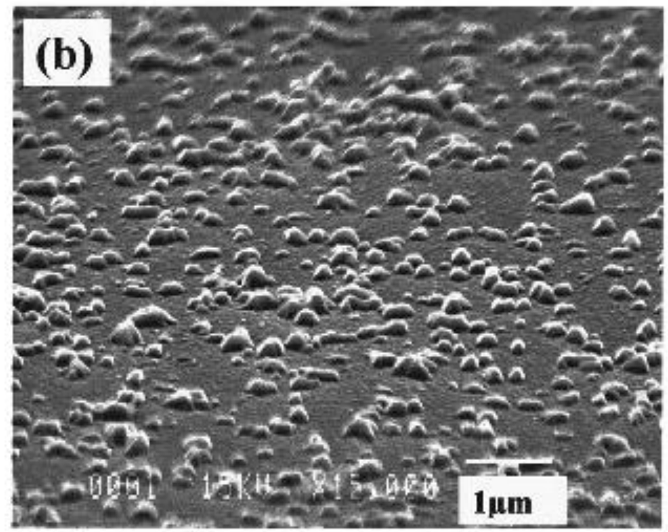
Amano and Akasaki (2014 Nobel Prize winners) invented the two-step growth method, first achieving GaN with an atomically flat surface (1986)

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

Two-step growth approach (ii)



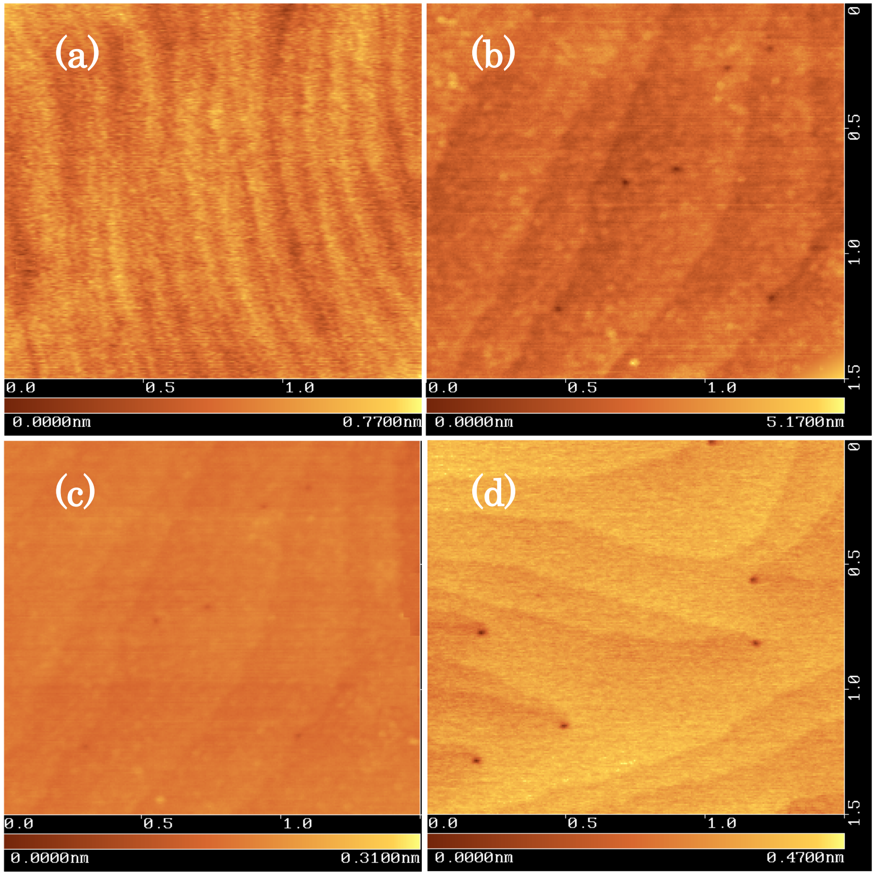
As-grown LT GaN buffer



LT GaN buffer after HT annealing

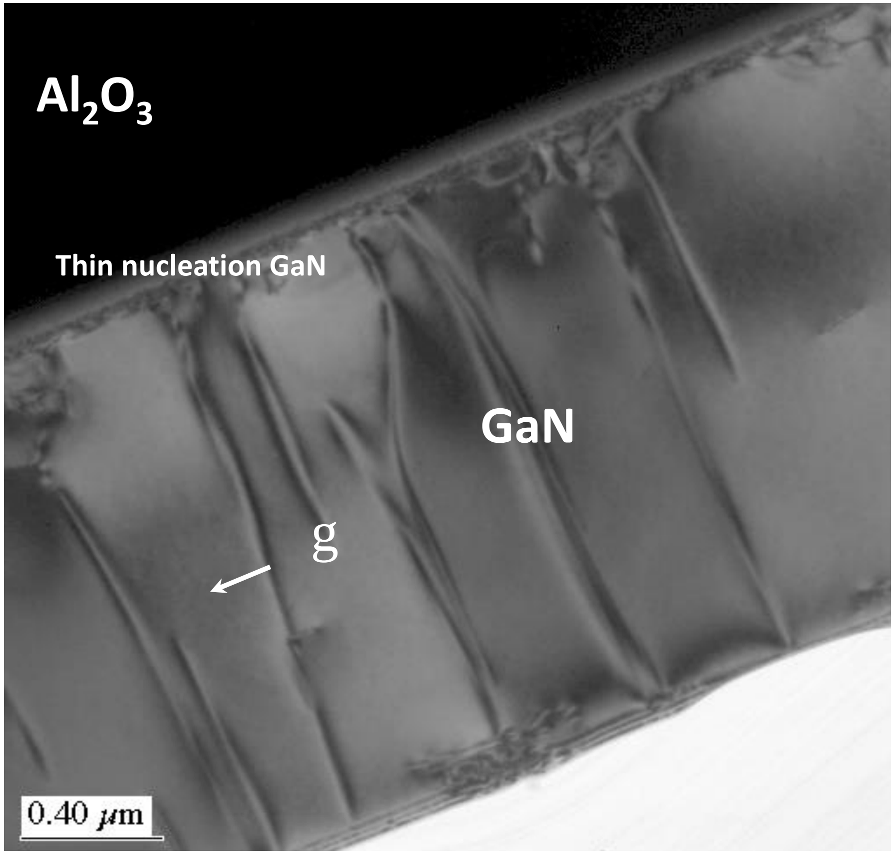
The thin nucleation layer

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.

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: $5x10^8/cm^2$

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 Akasaki first achieved a p-GaN (1989)**
- **S Nakamura achieved p-GaN in 1992 using HT annealing under nitrogen ambient (mass production)**

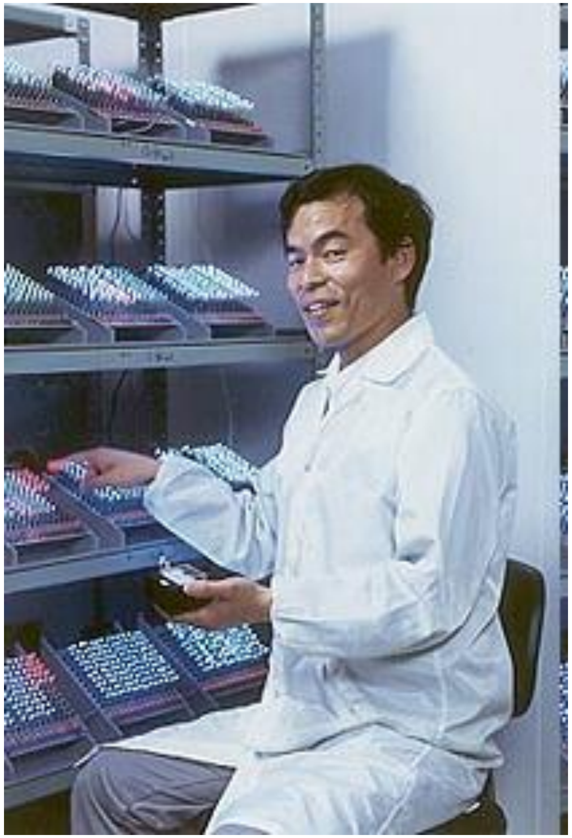
Opens new era: III-nitrides

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

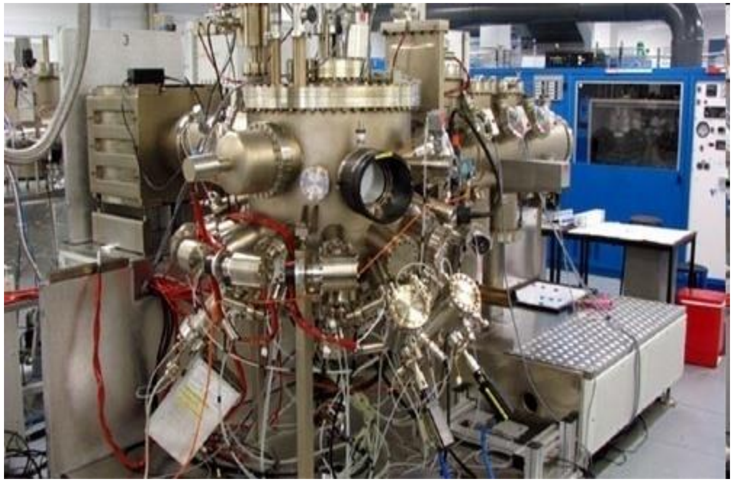


University of Tokushima, Japan
Nichia Chemical, Tokushima
Now, Prof at UCSB, USA

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 hetero-epitaxy 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

Epitaxial growth of III-nitrides

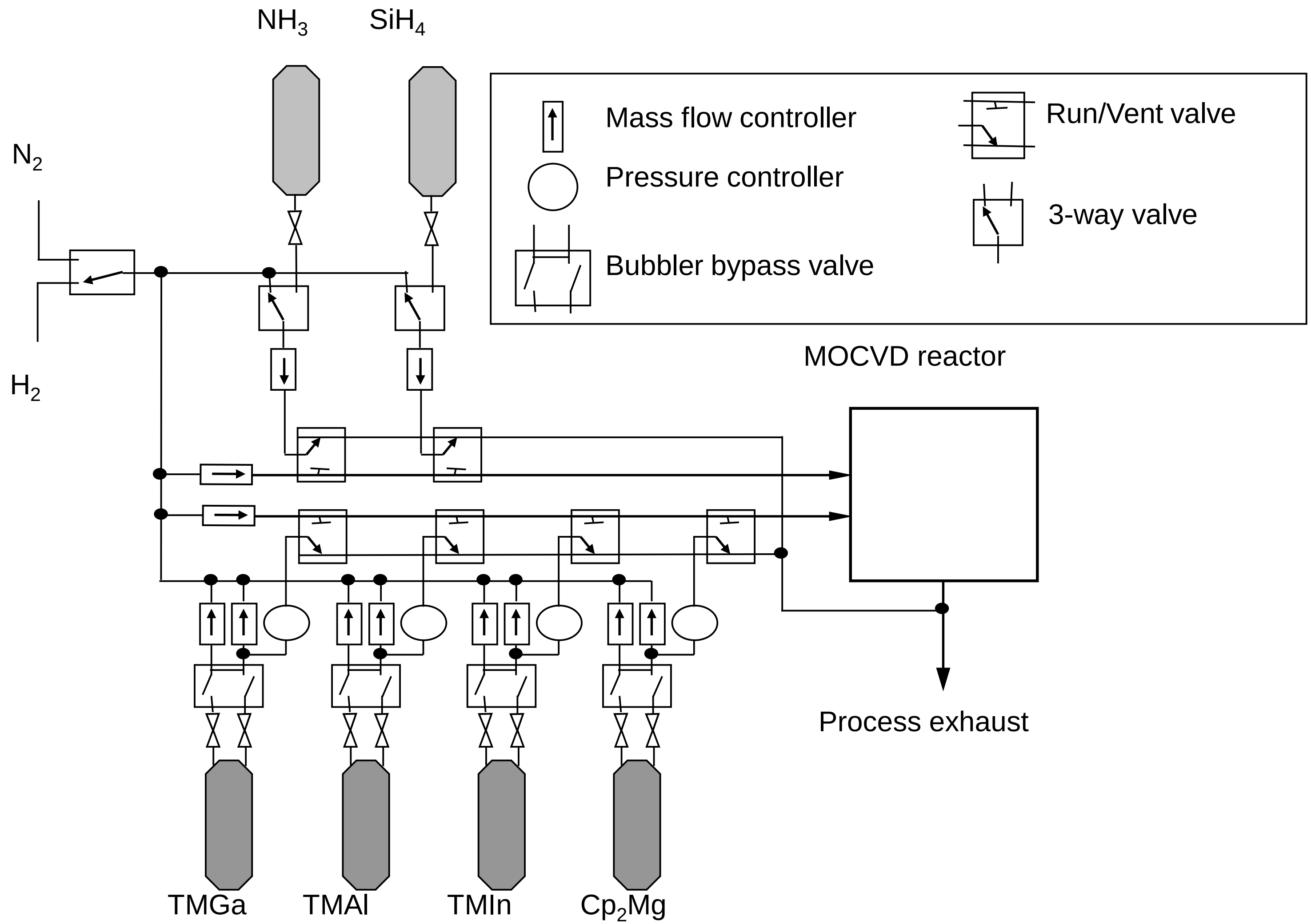


MBE

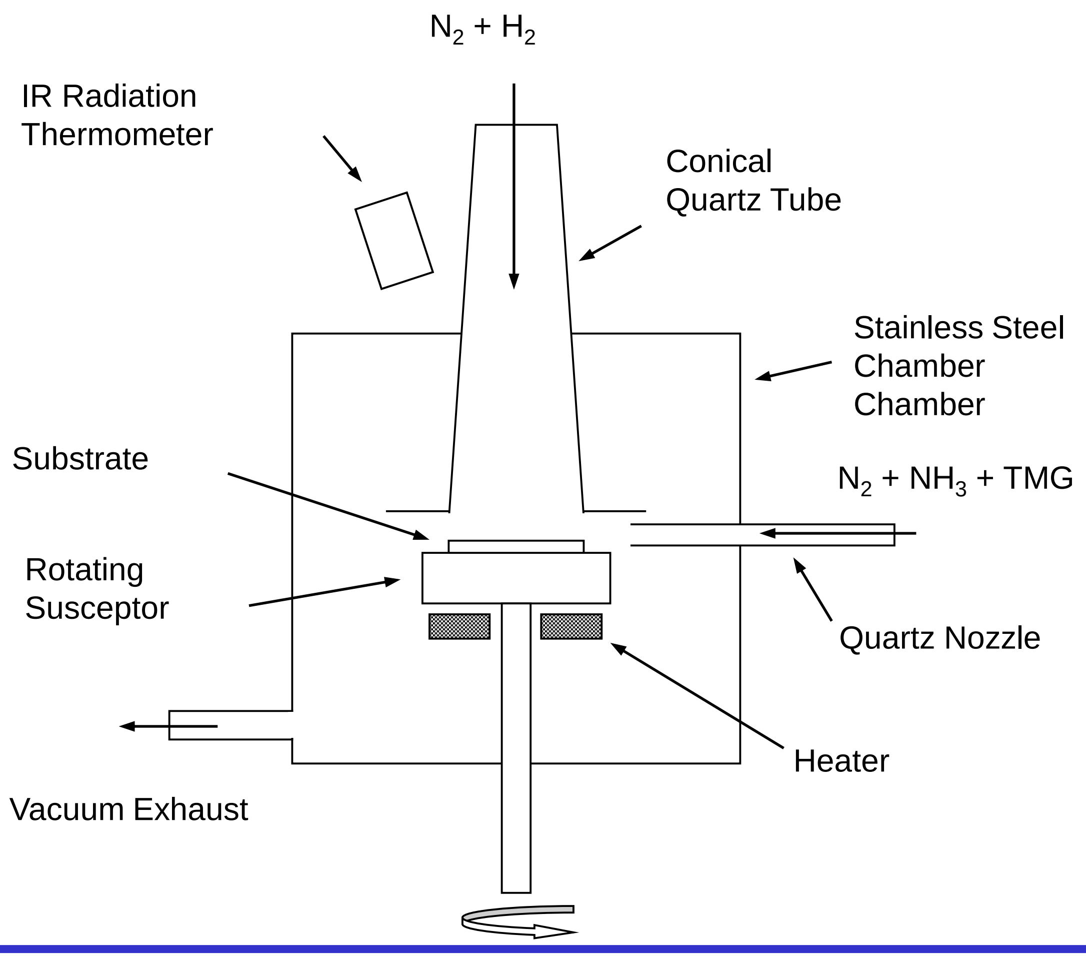
MOCVD

No affordable substrate for homo-epitaxial growth

Basic structure of MOCVD

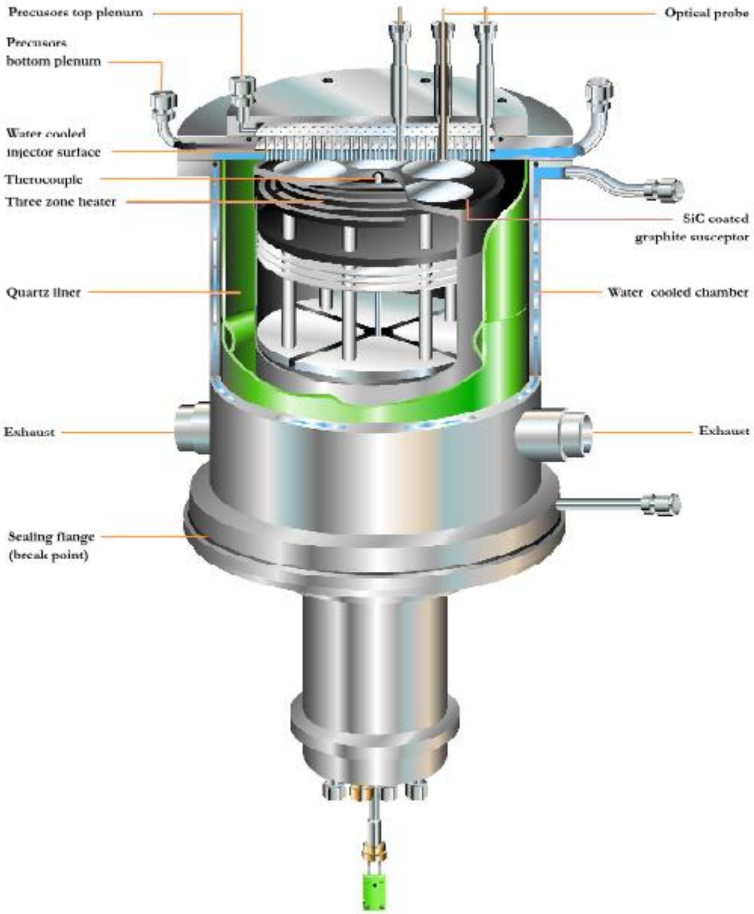


Two-flow MOCVD



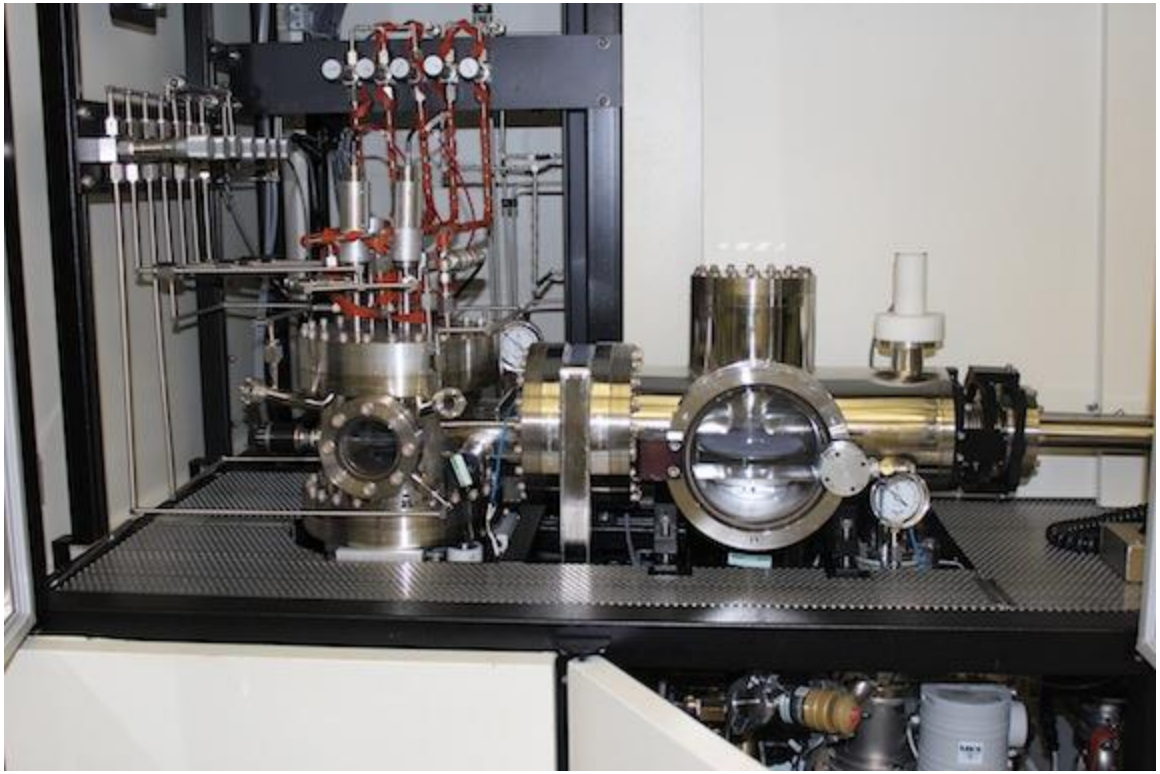
- **After S.Nakamura, *Jpn. J. Appl. Phys.* 30, L1705, (1991)**
- **First high brightness blue LED wafer was grown by this MOCVD**

CCS-MOCVD reactor



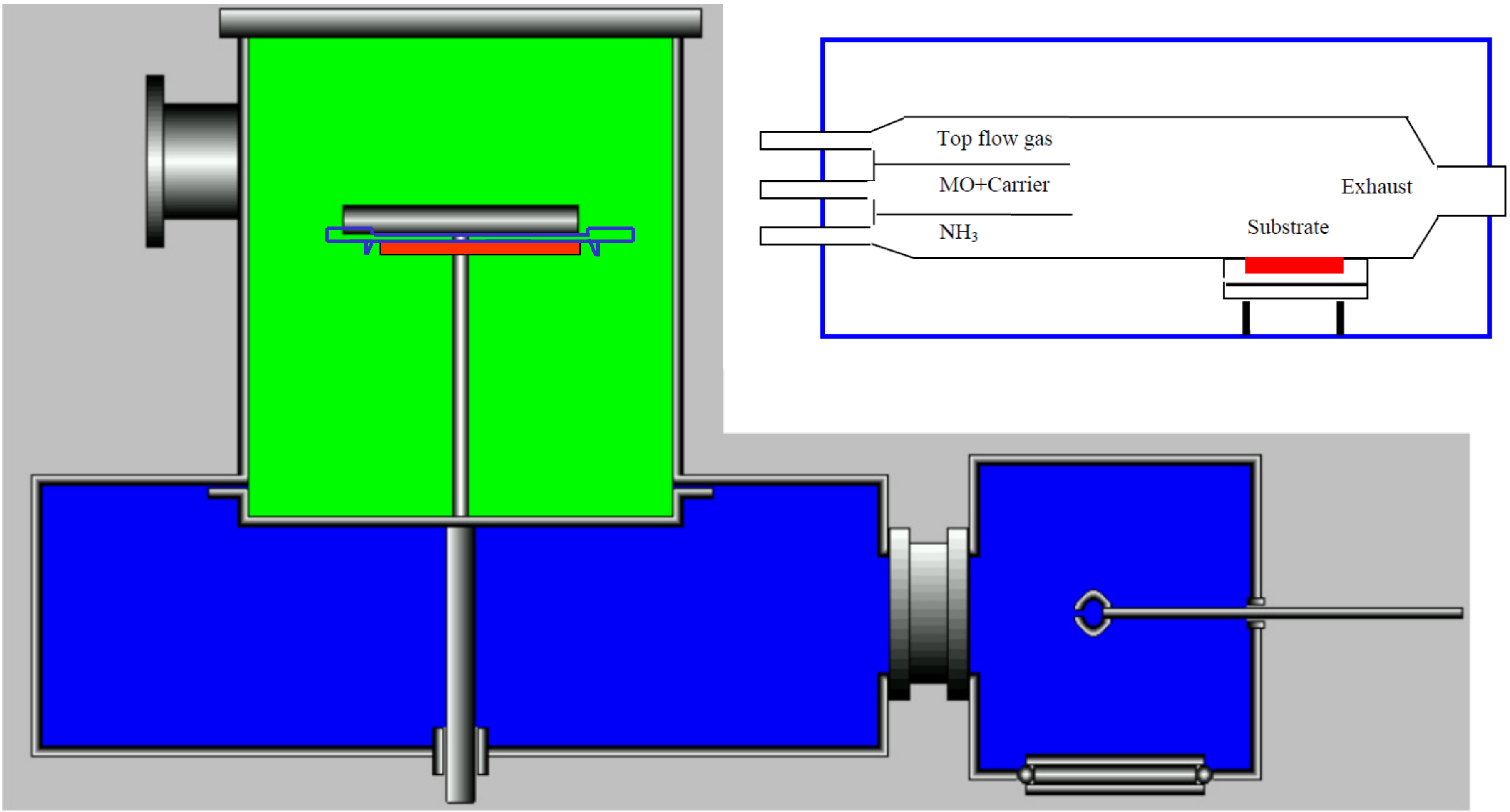
- **Close coupled showerhead (CCS)**
- **Sheffield has 1st CCS nitride MOCVD in the UK**

Emcore MOCVD reactor

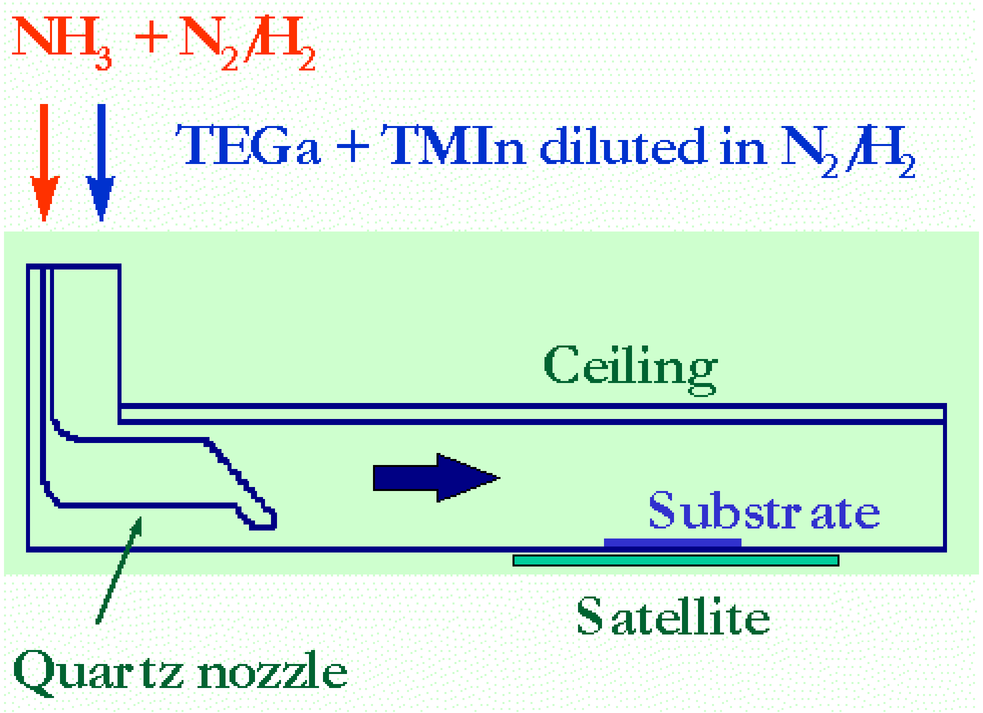


High speed rotation:
- **modify the gas flowing pattern**
- **decrease boundary layer thickness**

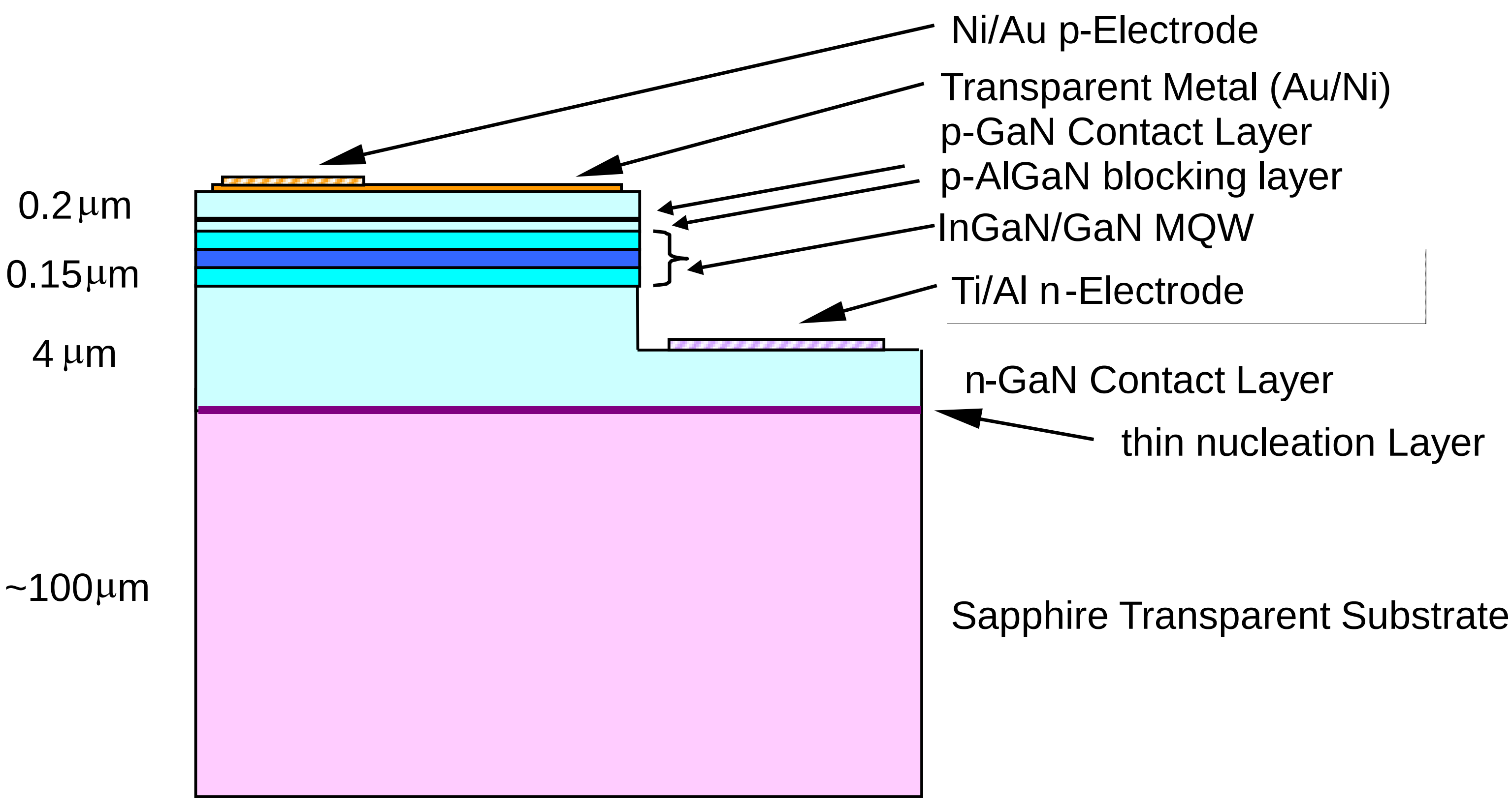
Nippon-Sanso MOCVD reactor



Axitron MOCVD reactor

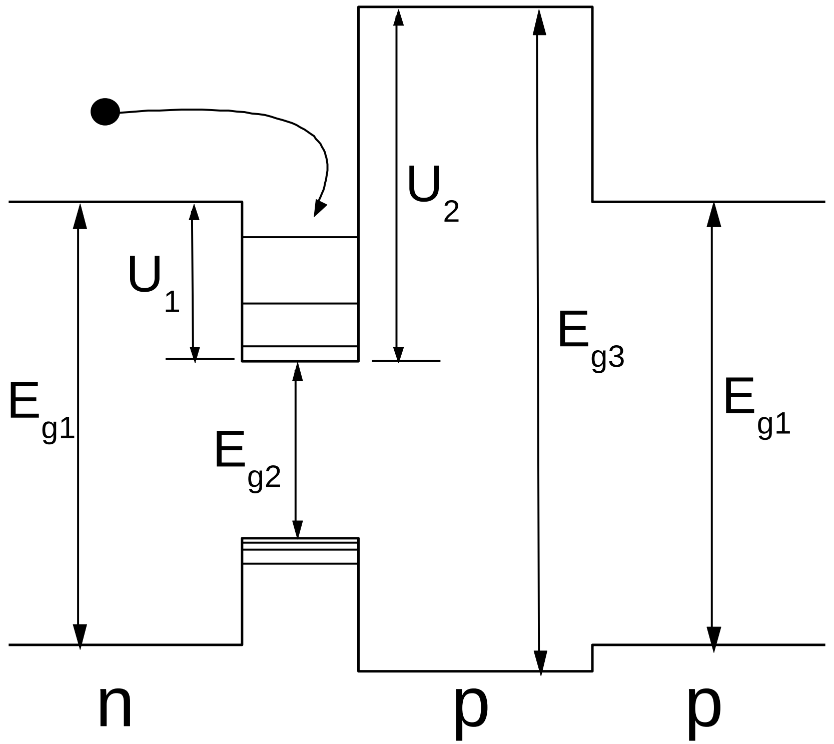


Chip structure of blue LEDs



(**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

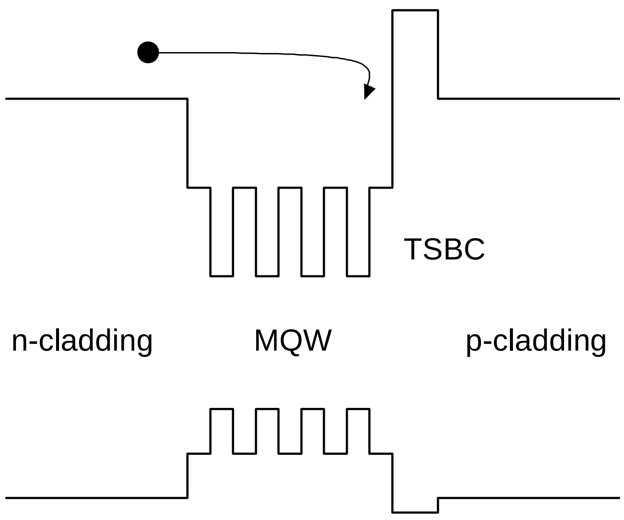
•Large difference in carrier concentrations between electron and hole

•Large difference in carrier mobilities between electron and hole

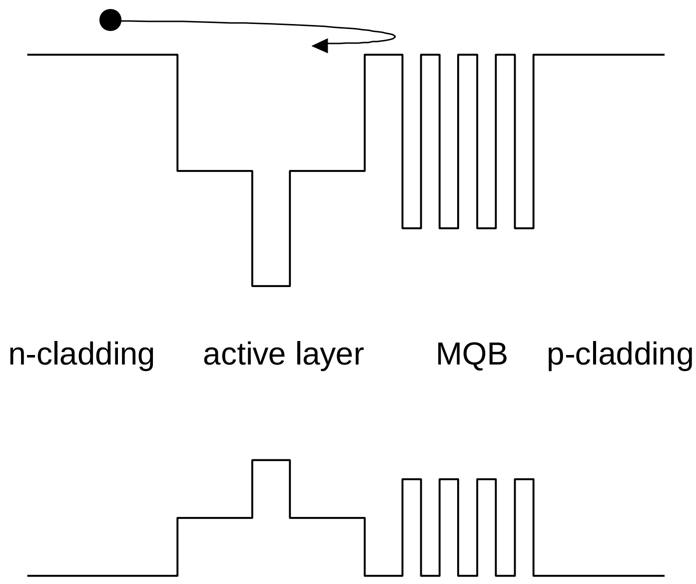
Electron mobility: 300 cm^2/VS (room temperature)

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

(a)



(b)

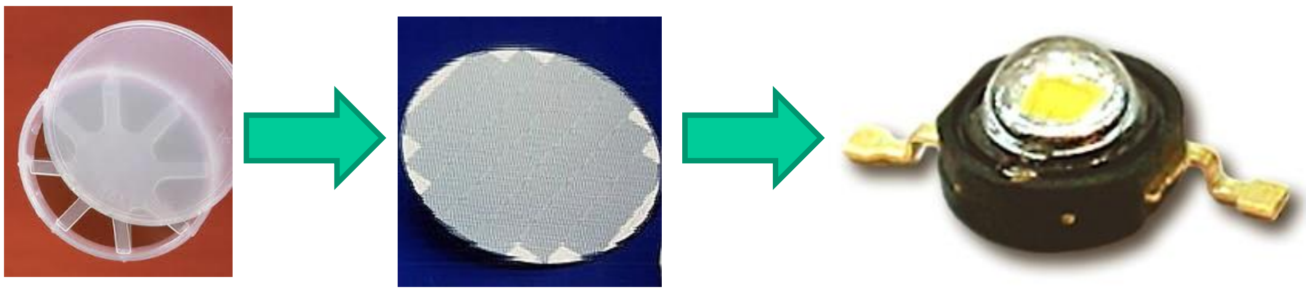


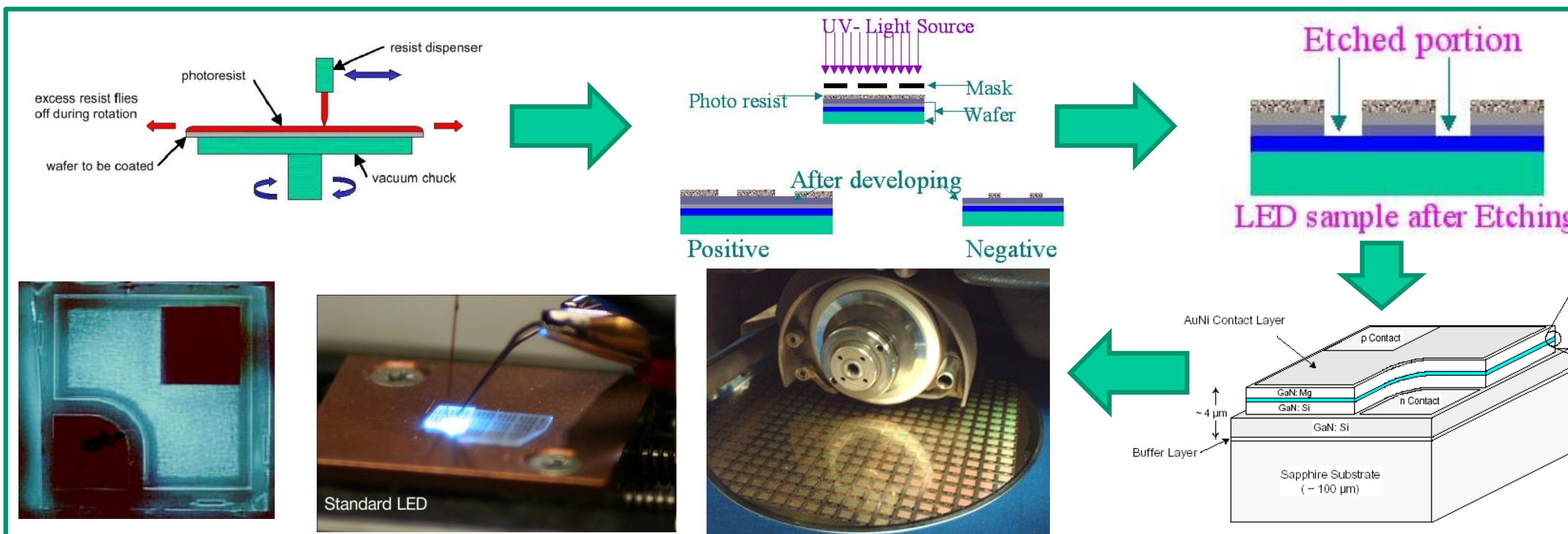
Reducing electron overflowing:

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

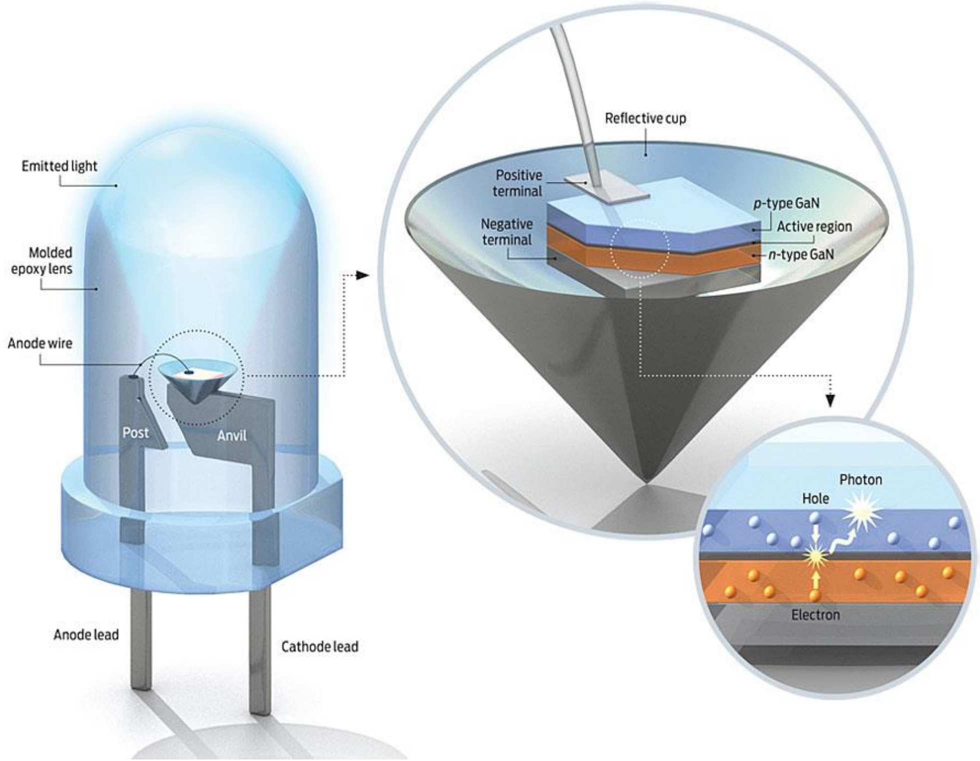
LED Design, Growth and Fabrication

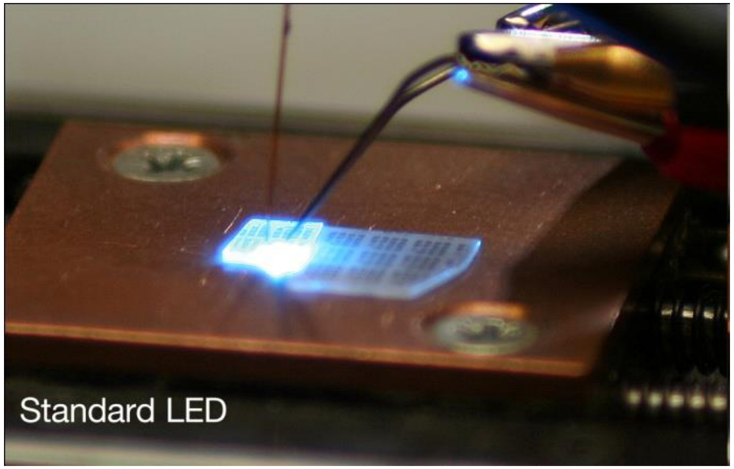
- Epitaxial growth using MOVPE or MBE
- Wafer process using etching techniques and photolithgraph
- Final device packaging (Epoxy dome lens)





Blue LEDs


Emitted light
Molded epoxy lens
Anode wire
Post
Anvil
Anode lead
Cathode lead
Reflective cup
Positive terminal
Negative terminal
p-type GaN
Active region
n-type GaN
Photon
Hole
Electron


Standard LED

Thermal management

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

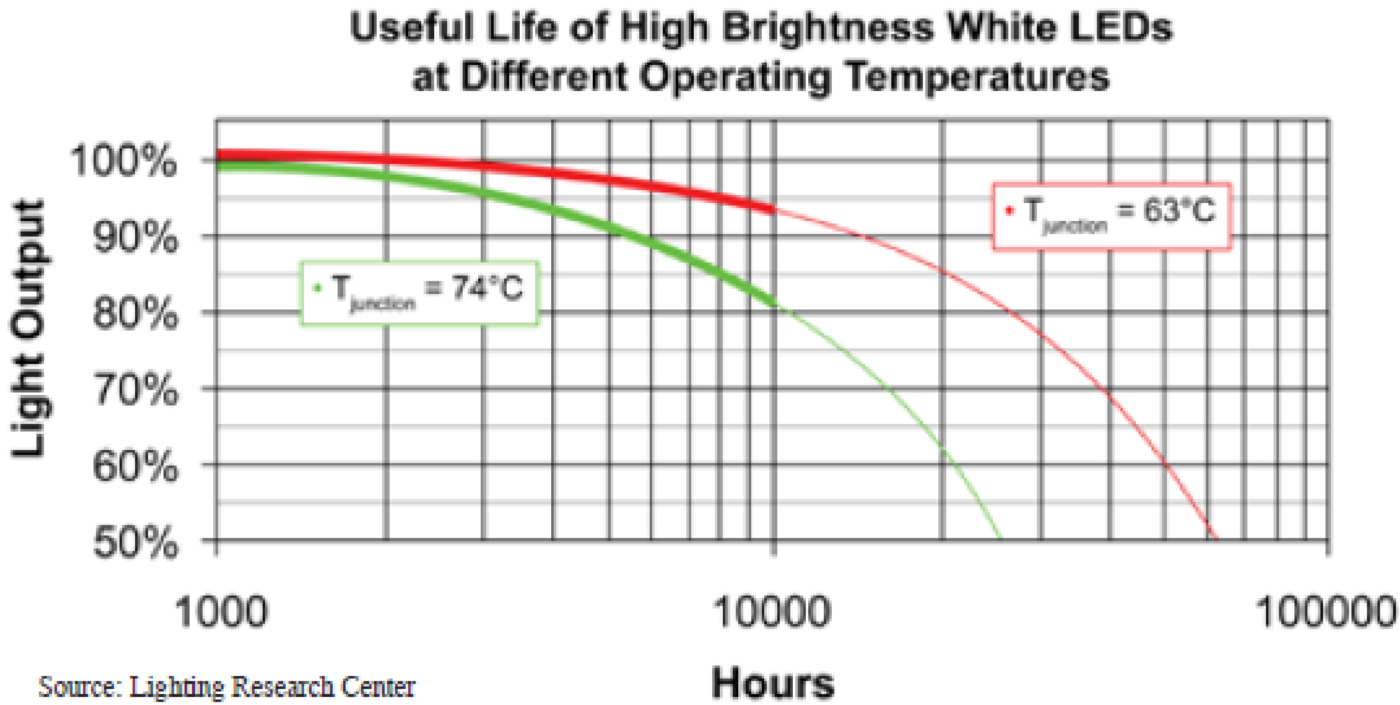
Activation energy of Mg-doped p-GaN is very large, **130-150 meV**, compared with silicon-doped n-GaN (<20 meV)

For example, Mg-doping level of $10^{20}/cm^2$ means room temperature hole concentration of ~$10^{20}\times exp(-150meV/KT)$, which is about $3\times10^{17}/cm^2$

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

- Heat dissipation due to sapphire substrate

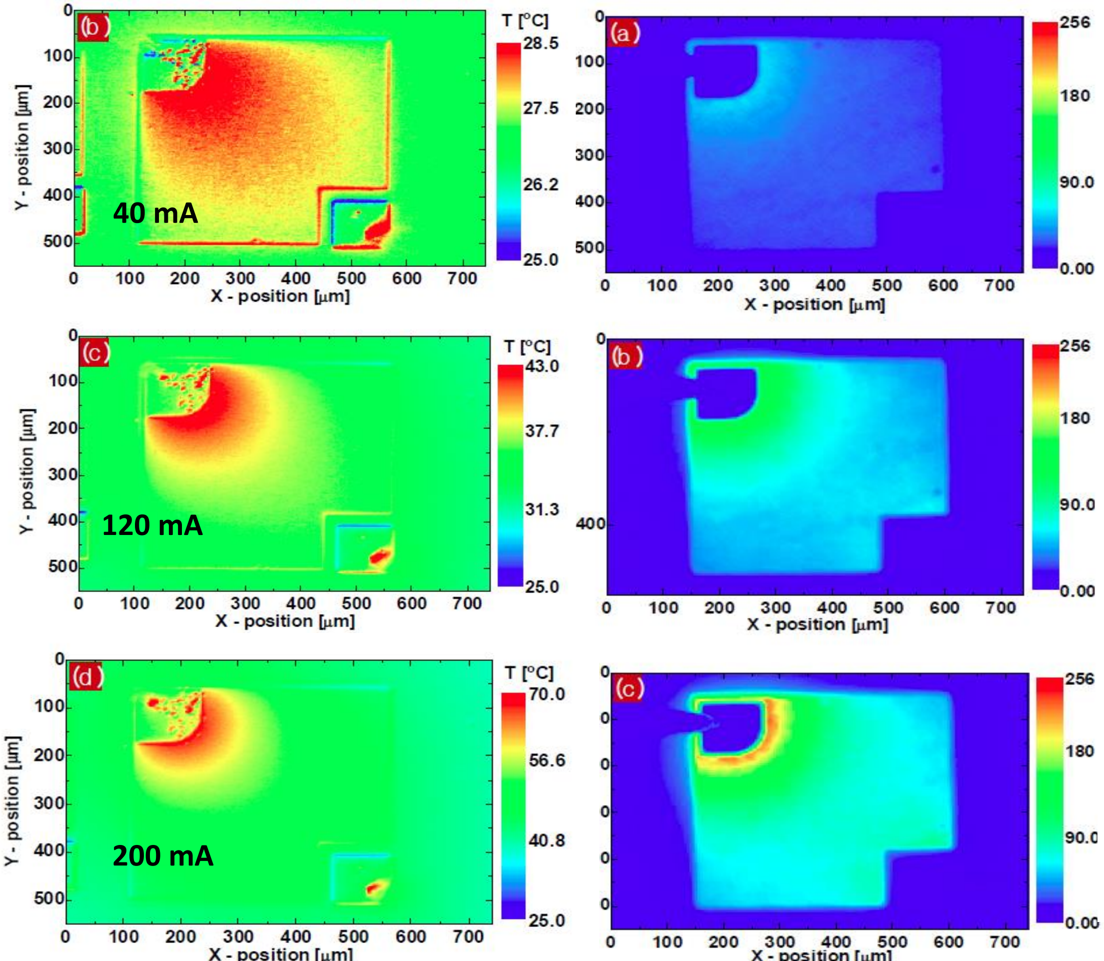
Thermal management

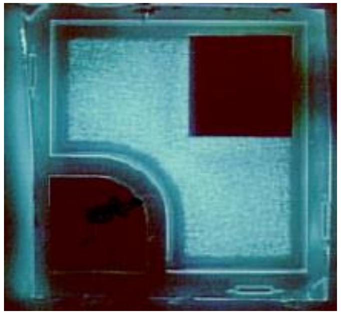


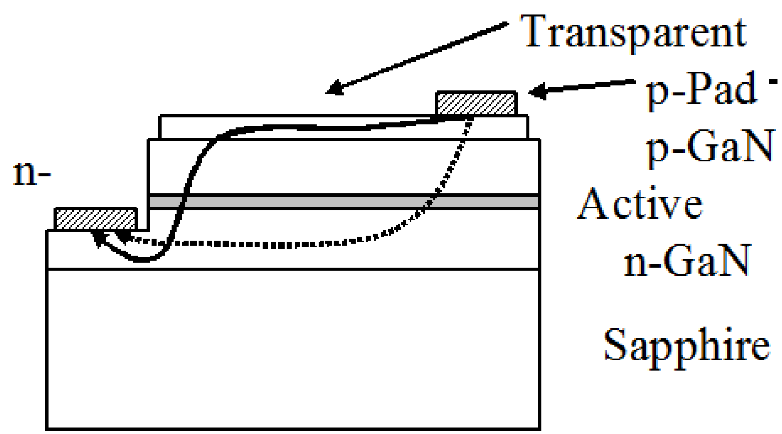
Source: Lighting Research Center

- **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



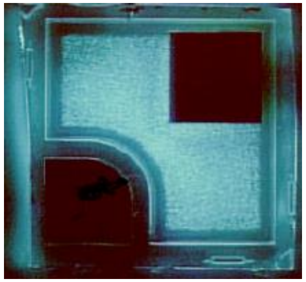


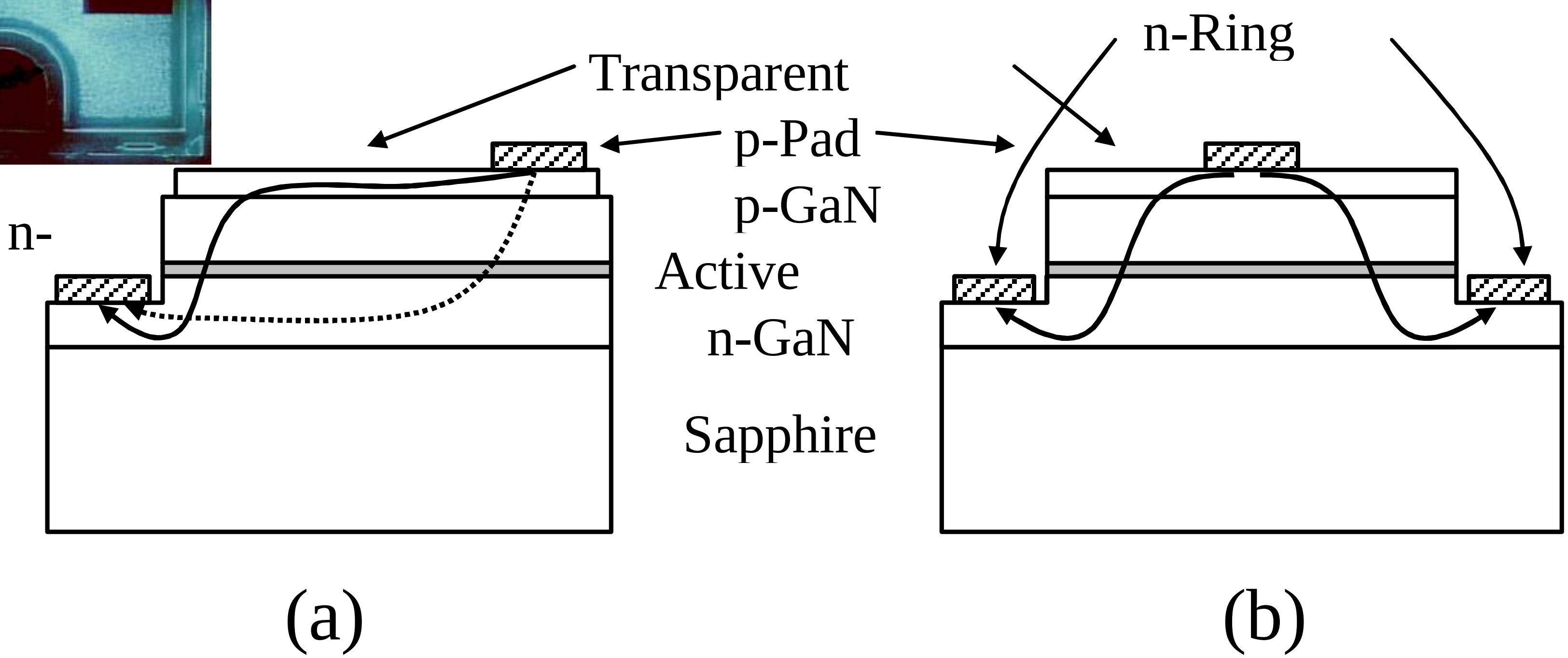


- **p-GaN generates so-called current crowding issues**
- **Long path for current to go through p-GaN laterally, generating:**

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.

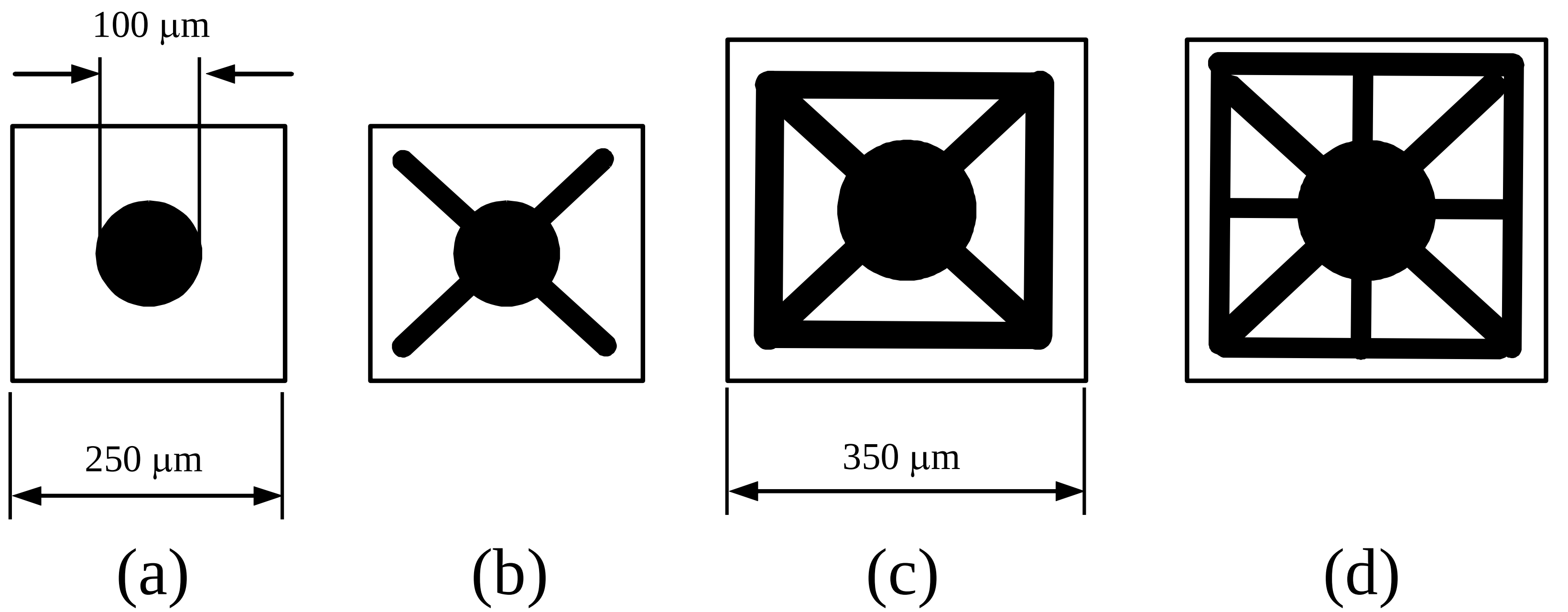




Current paths in AlInGaN chips grown on sapphire.

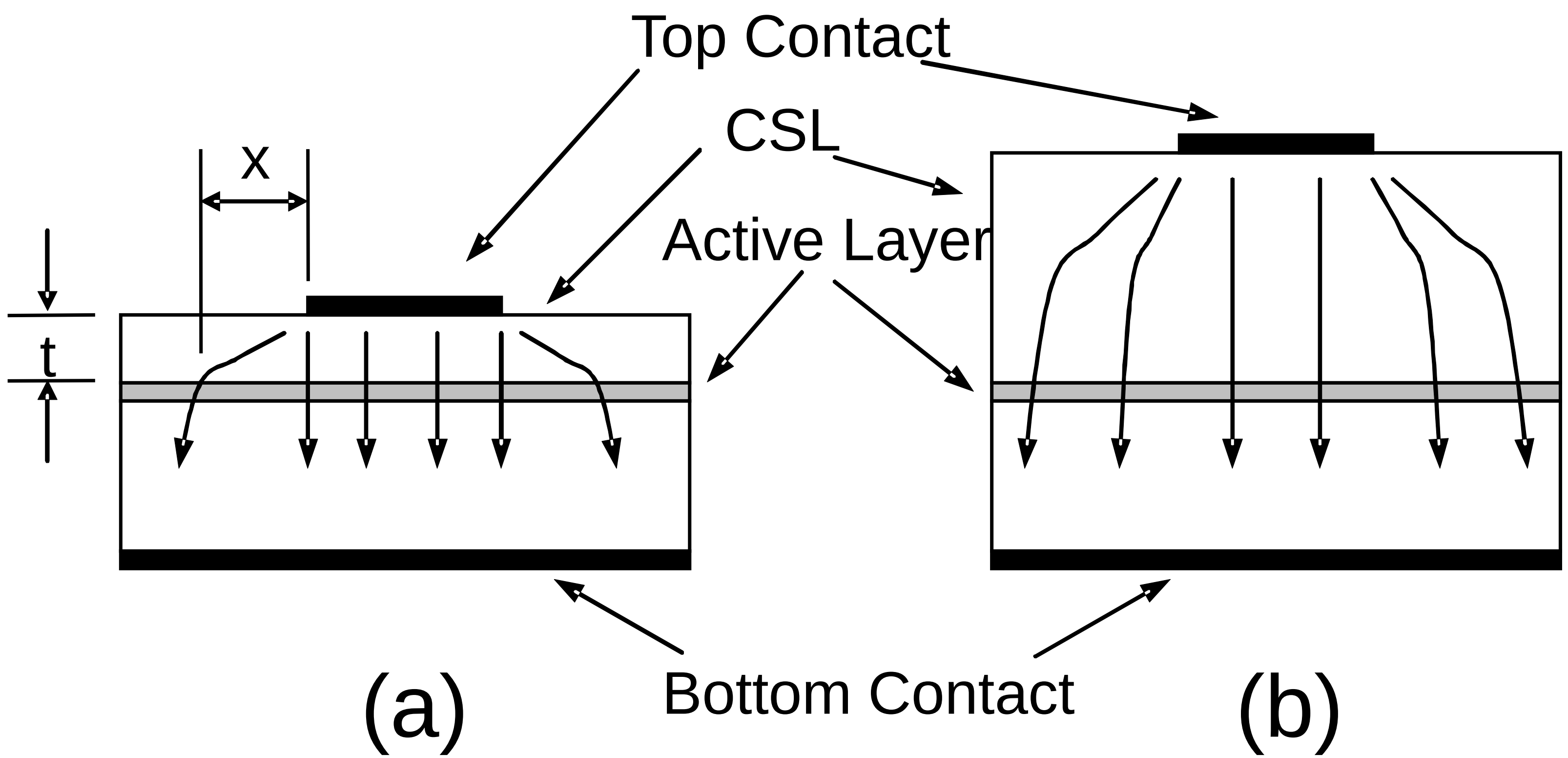
(a) Asymmetric design with current crowding towards the *n*-pad;
(b) Symmetric design with a ring *n*-pad
(after M. R. Krames *et al., Proc. SPIE* 3938, 2, 2000).

Contact Geometries



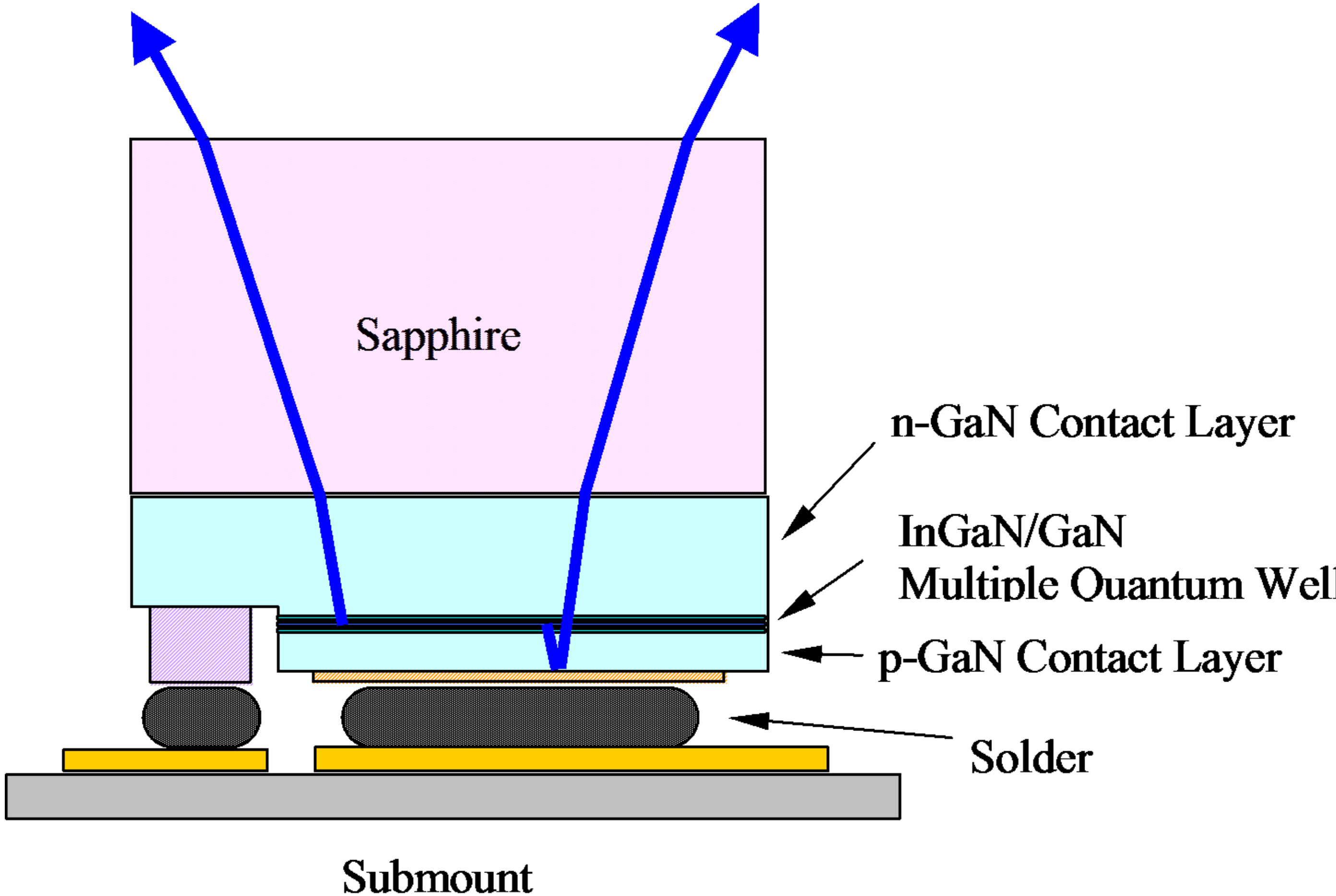
- **Contact for better current spreading**
- **Pay attention to an issue on contact non-transparency**

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 hetero-epitaxy

  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 $10^{11}/cm^2$.

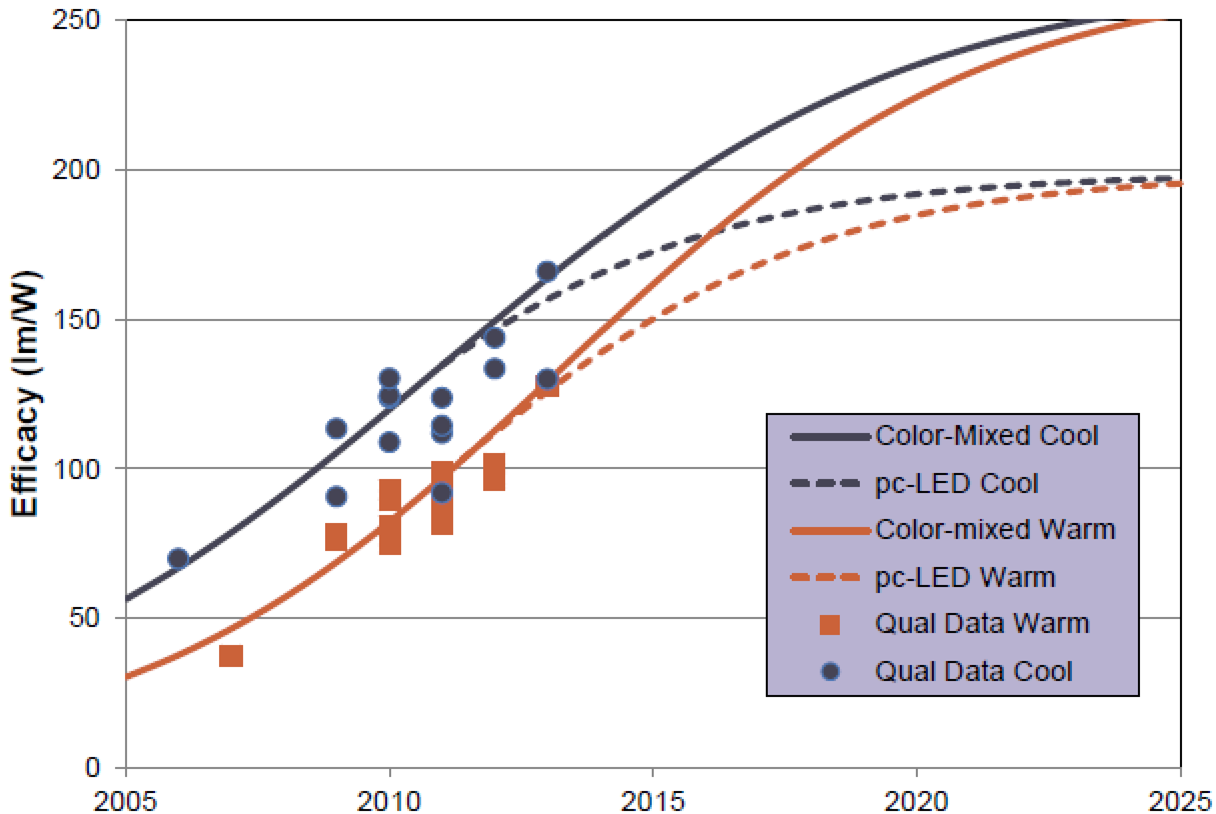
- **Scientific challenges**

  Polarization induced self-built electric fields

  Efficiency droop

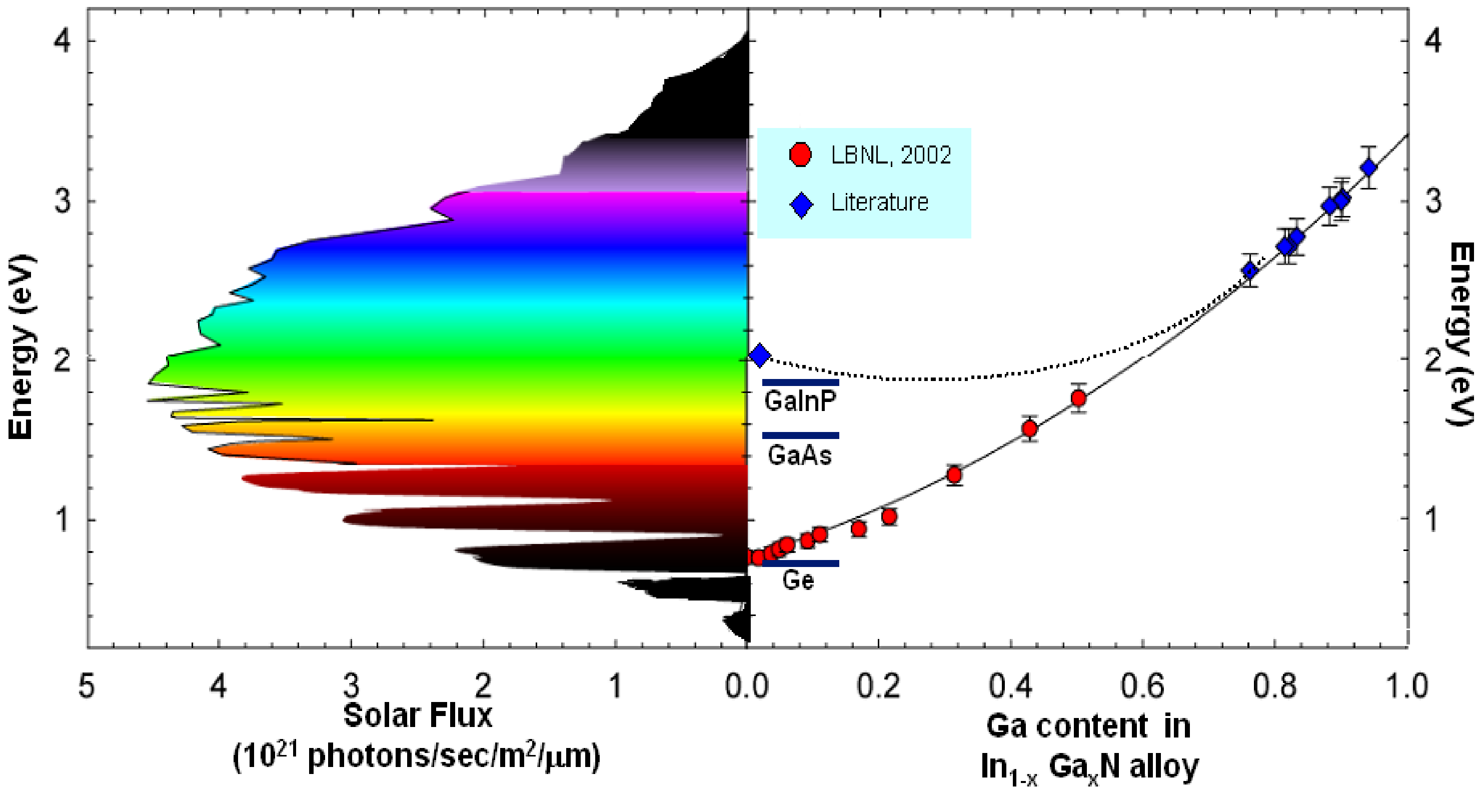
  Difficulty in incorporation of indium into GaN

US DOE road-map for SSL



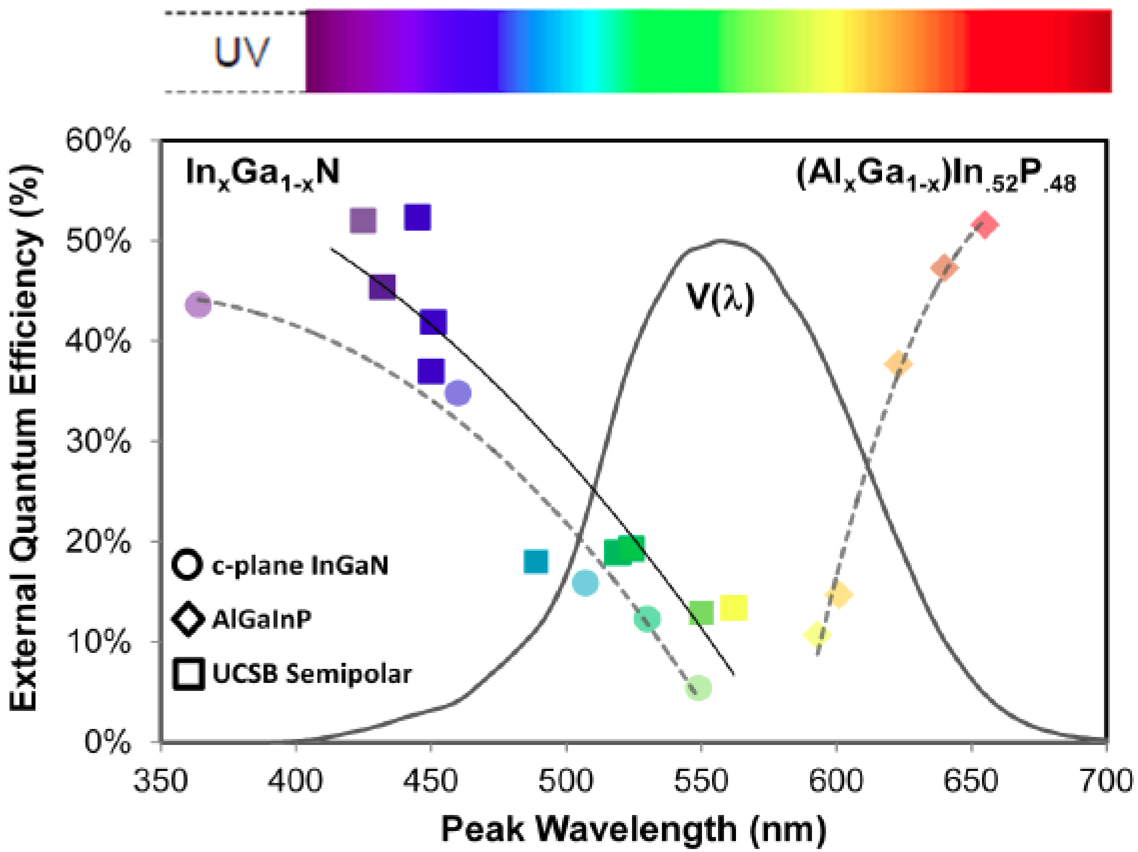
- **Blue LED +Yellow phosphor: <200 lm/Watt**
- **Color Mixed LEDs: Blue, Green, Yellow LEDs (red LED is no problem at all) requested**
- **Challenges: green/yellow LEDs (high indium content)**

III-nitrides for future SSL and sustainable energy



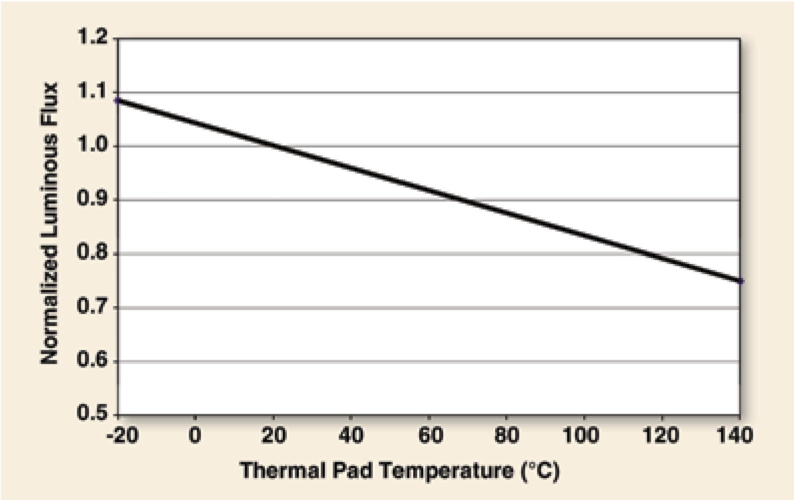
Challenges: High indium content InGaN

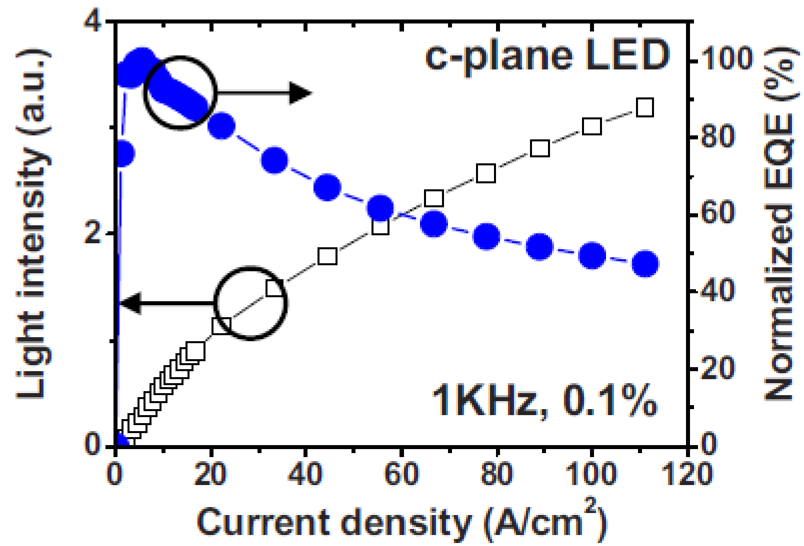
Green/Yellow Gap



Great challenge: how to enhance indium incorporation into GaN

Current issues on blue LEDs





Thermal droop

Efficiency droop

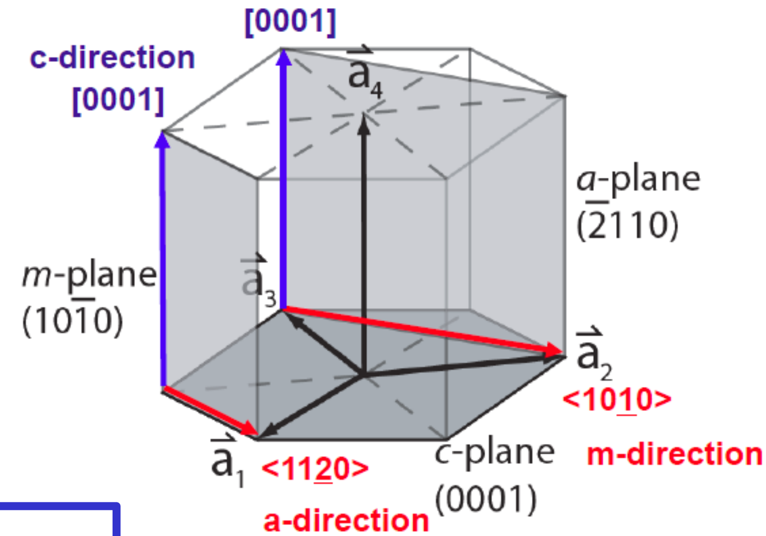
Thermal droop: The temperature of InGaN LEDs in operation is well above room temperature in practical applications. The increased temperature leads to a reduction in optical efficiency of blue LEDs

Efficiency droop: Optical efficiency of blue LEDs initially increases with increasing injection current density, and then decreases significantly with further increasing injection current. At injection currents required for practical applications the efficiency drops significantly.

How to calculate actual optical efficiency?

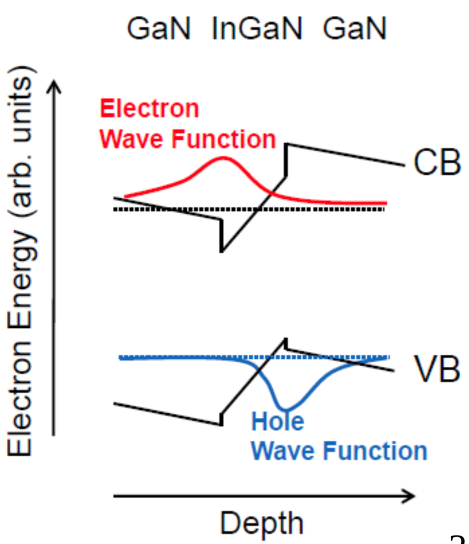
$$\boxed{\eta_{act} = \eta_{peak} \times (1 - \eta_{th}) \times (1 - \eta_{eff})}$$

Fundamental limits for current III-nitride LEDs

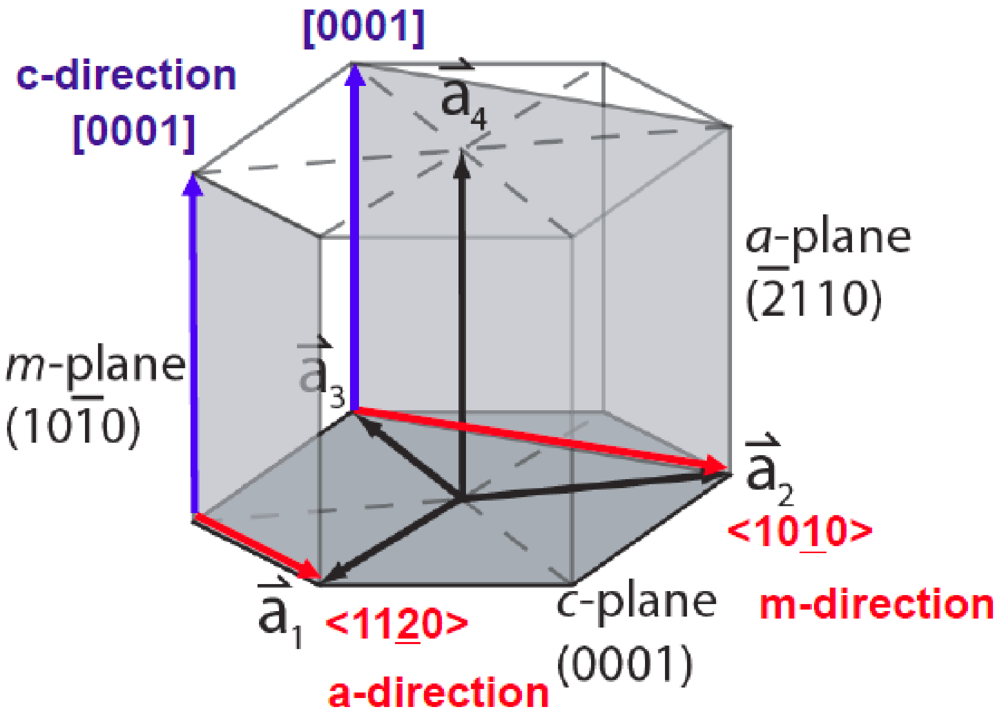


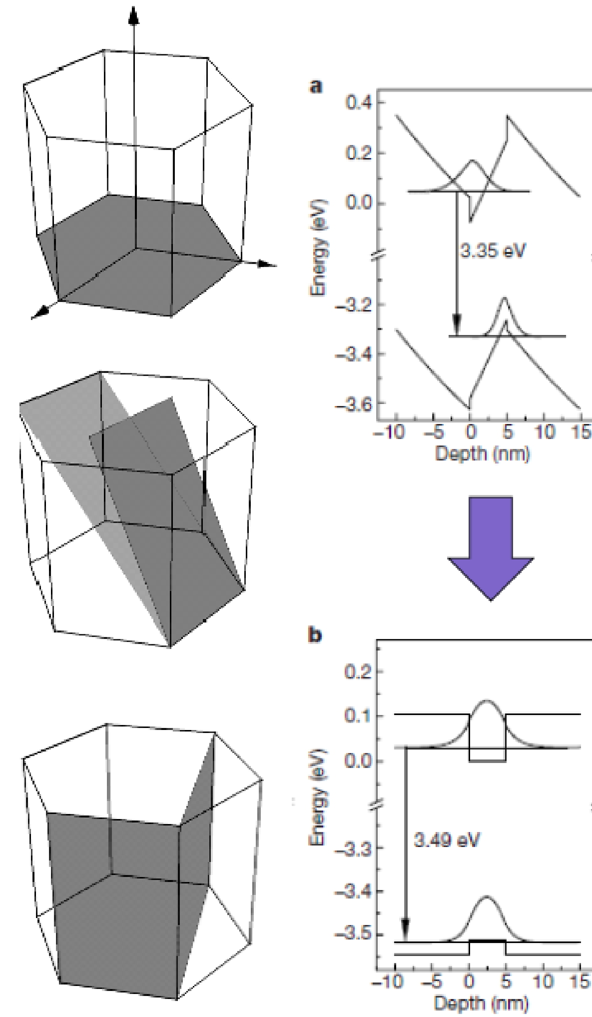
Strained InGaN QWs: induce piezoelectric polarization across QW

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



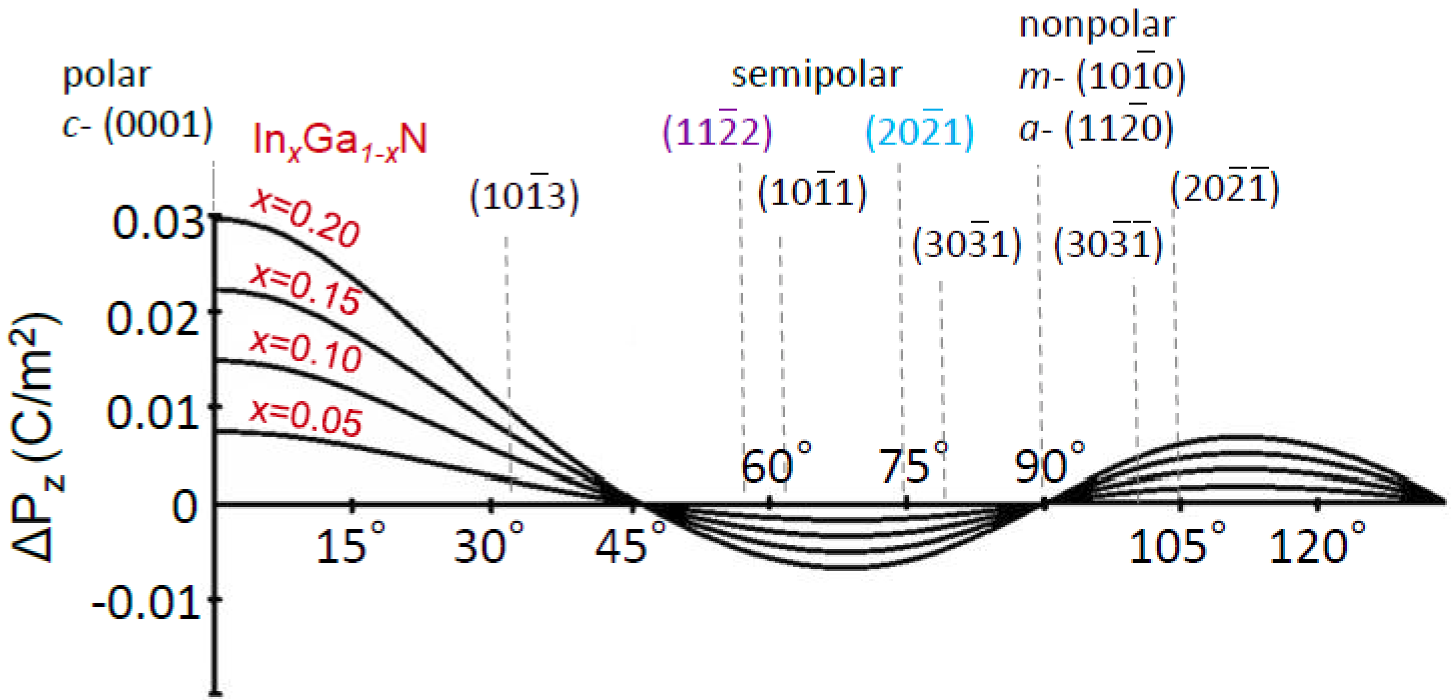
Possible solution: semi/non-polar GaN (i)

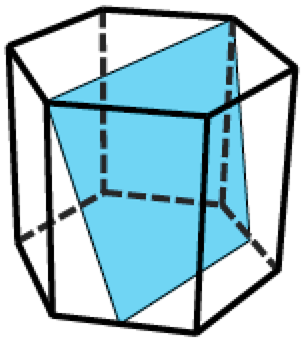


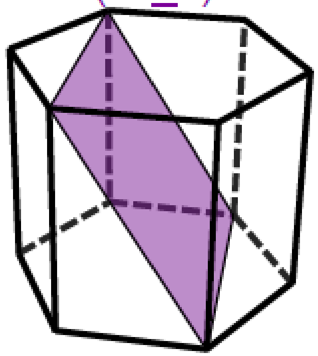


- **Minimise wavefunction separation**
- **Enhance radiative recombination rate**
- **Minimise emission shift with current density**
- **Enhance indium incorporation into GaN**

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

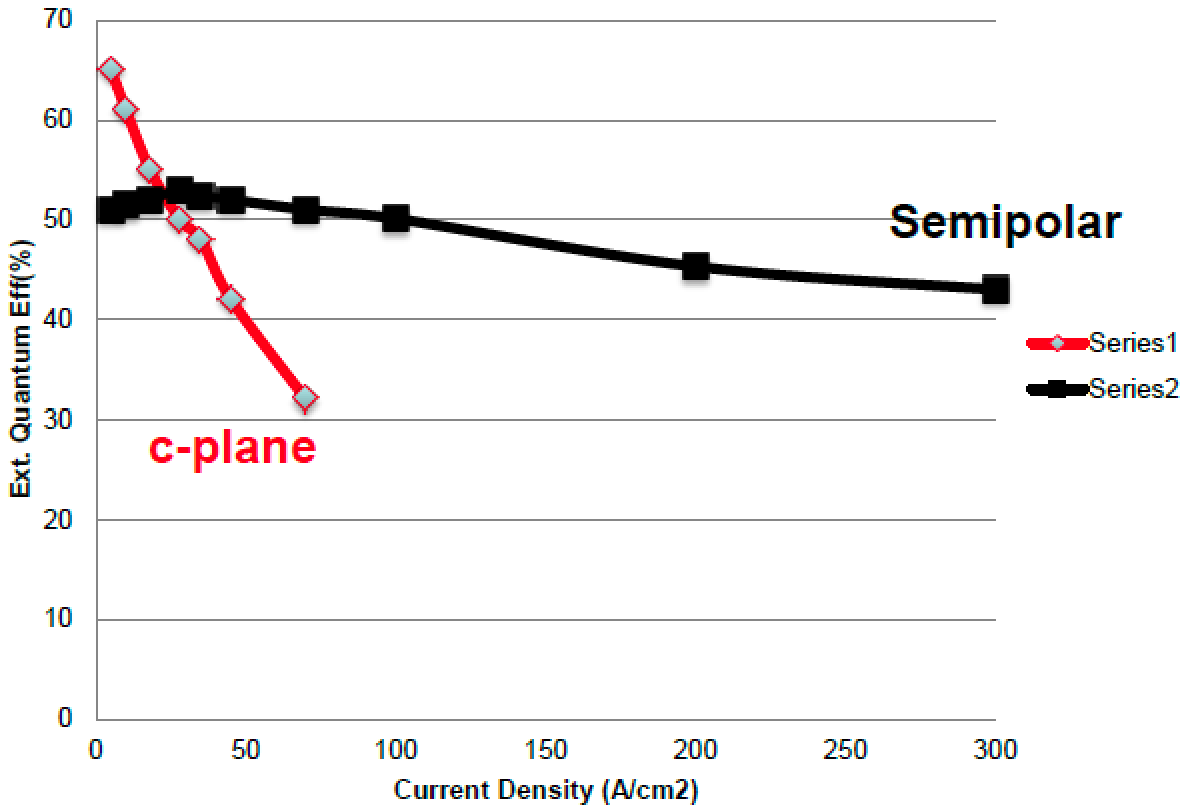






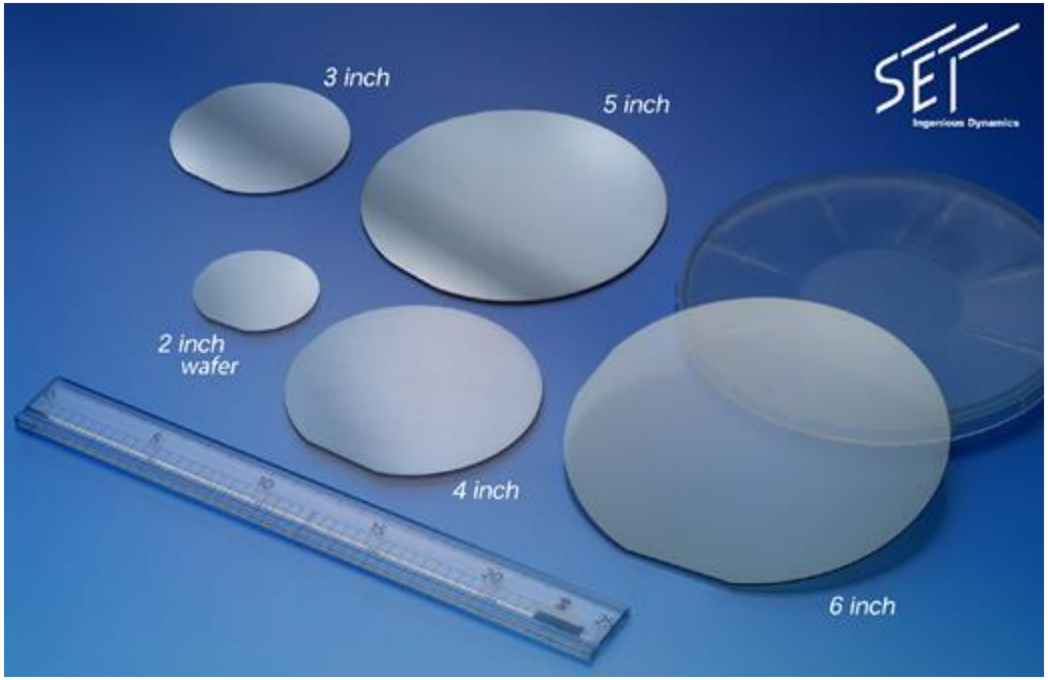
- **Most popular semi-polar orientations (11-22) and (20-21)**
- **A number of advantages**

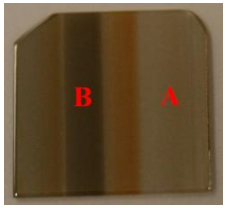
Possible solution: semi/non-polar GaN (iii)



- 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!**

T16 Tutorial Questions

- Explain crystal structure of GaN
- Calculate lattice-mismatch of GaN grown sapphire
- Explain thermal droop and efficiency droop of GaN-based LEDs
- Calculate actual optical efficiency
- Design structure of GaN based LEDs
- Explain thermal dissipation
- Design in Fabrication of GaN based LEDs in order to minimise thermal management
- Fundamental issues on current GaN based optoelectronivs
- Possible solution to current GaN optoelectronics