GaN Based Light Emitting Diodes

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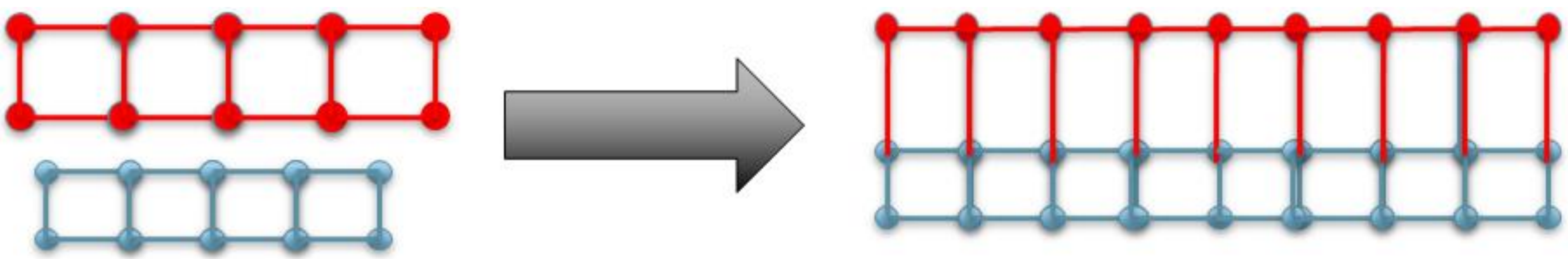
Importance of Heterostructure

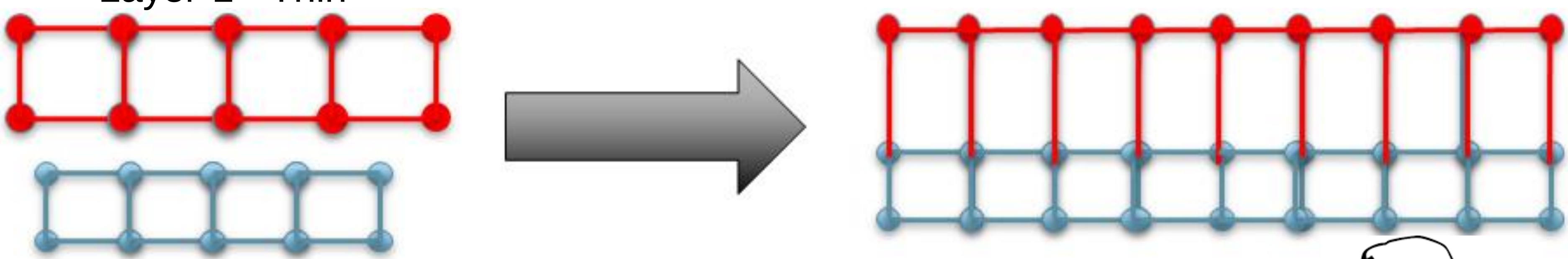
- Heterostructure increases richness of the available materials
  - Tuning of energy band-gap (Insulator and semiconductor)
  - Change in potential profile
  - Independent control of dopant, carriers and mobility



Heterostructure:

- Two Different materials *grown* on top of each other
- They *accommodate the differences* and appear largely as a single crystal without much defect

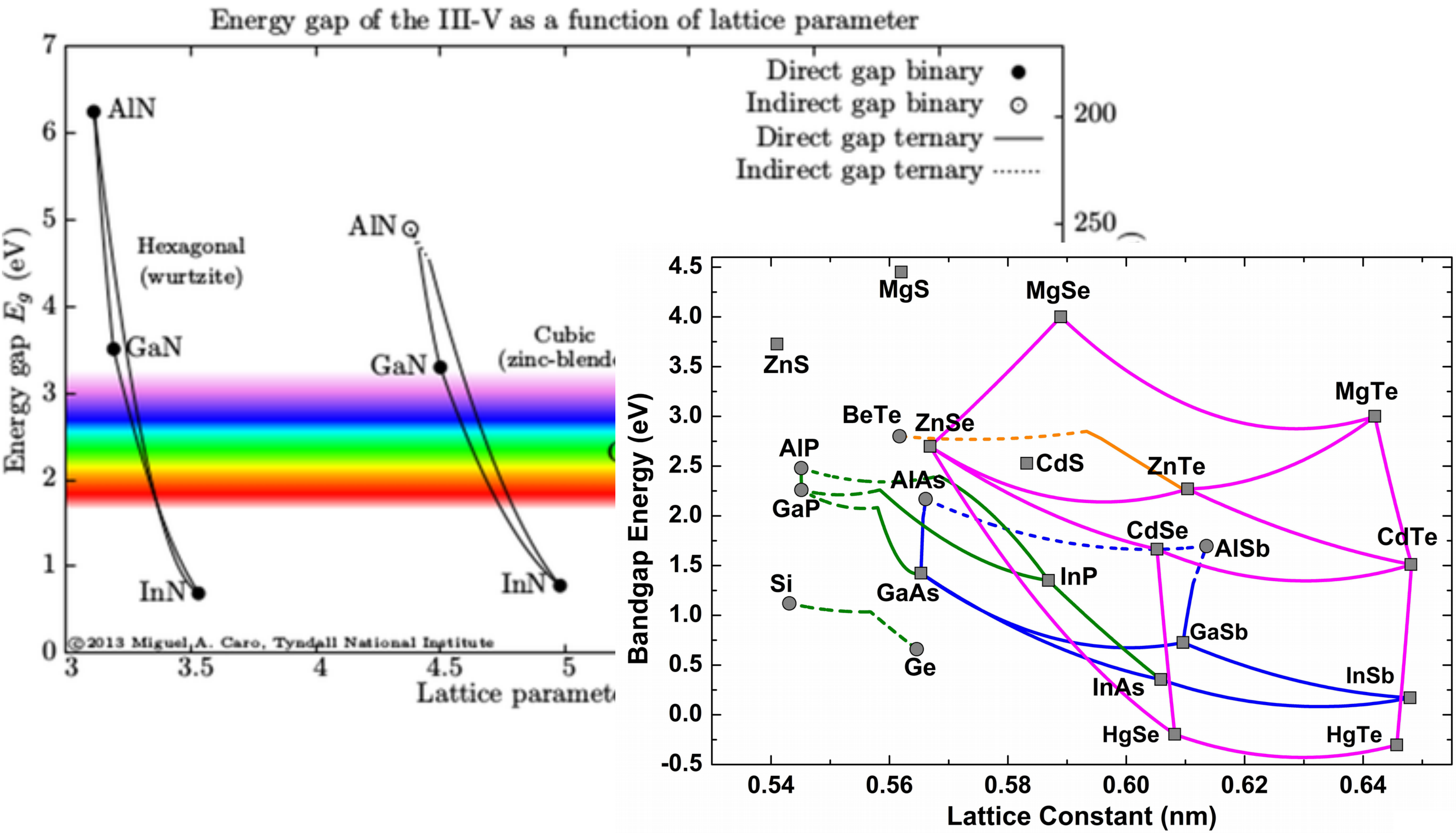
Friendliness – Lattice Matching



- *Larger strain with lesser friendliness(defects)*
- *More friendliness lesser diversity*

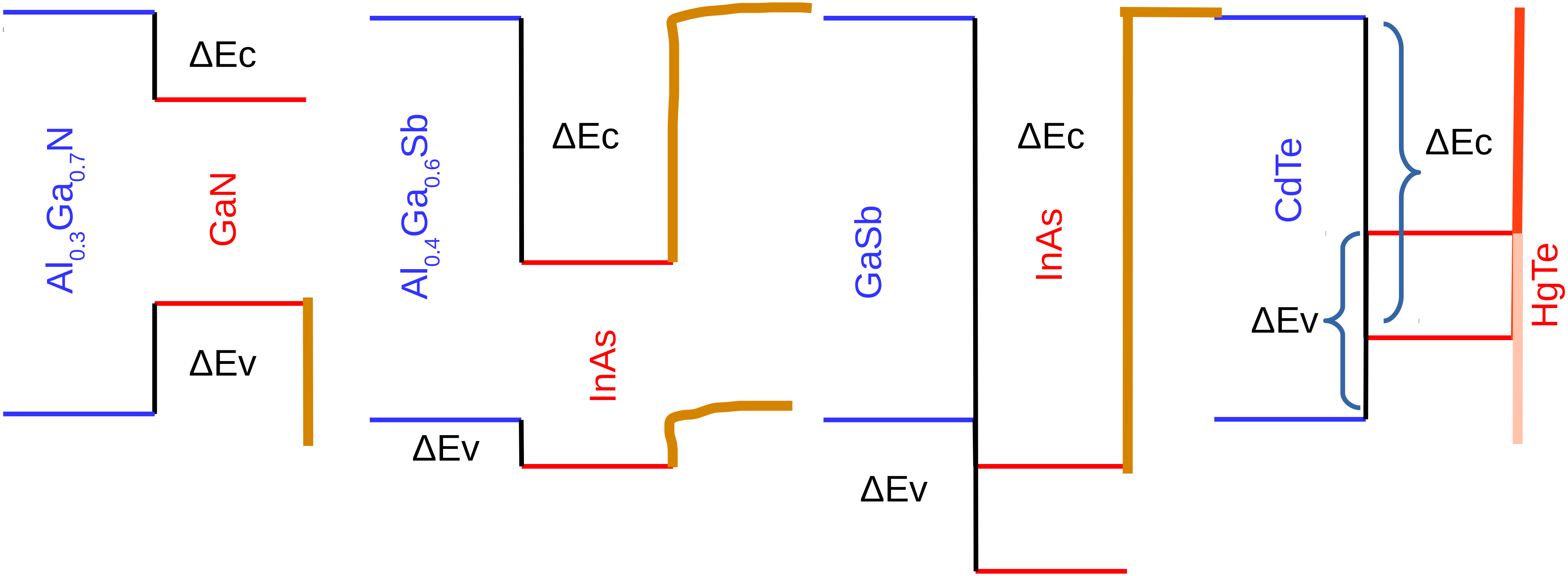
- <u>Lattice mismatch</u> not desired – same atomic separation and crystal structure
- <u>Substrate</u> decides the heterostructure lattice constant
- <u>Multiple layers</u> of dissimilar (alloyed) materials of same family – *3 layers* (for simple p-i-n LED to > *100 layers* for surface-emitting lasers)

Band-gap Tuning



- Key diagram for heterostructures
- Key diagram for designing new devices

Band-Edge Alignment



Type-I

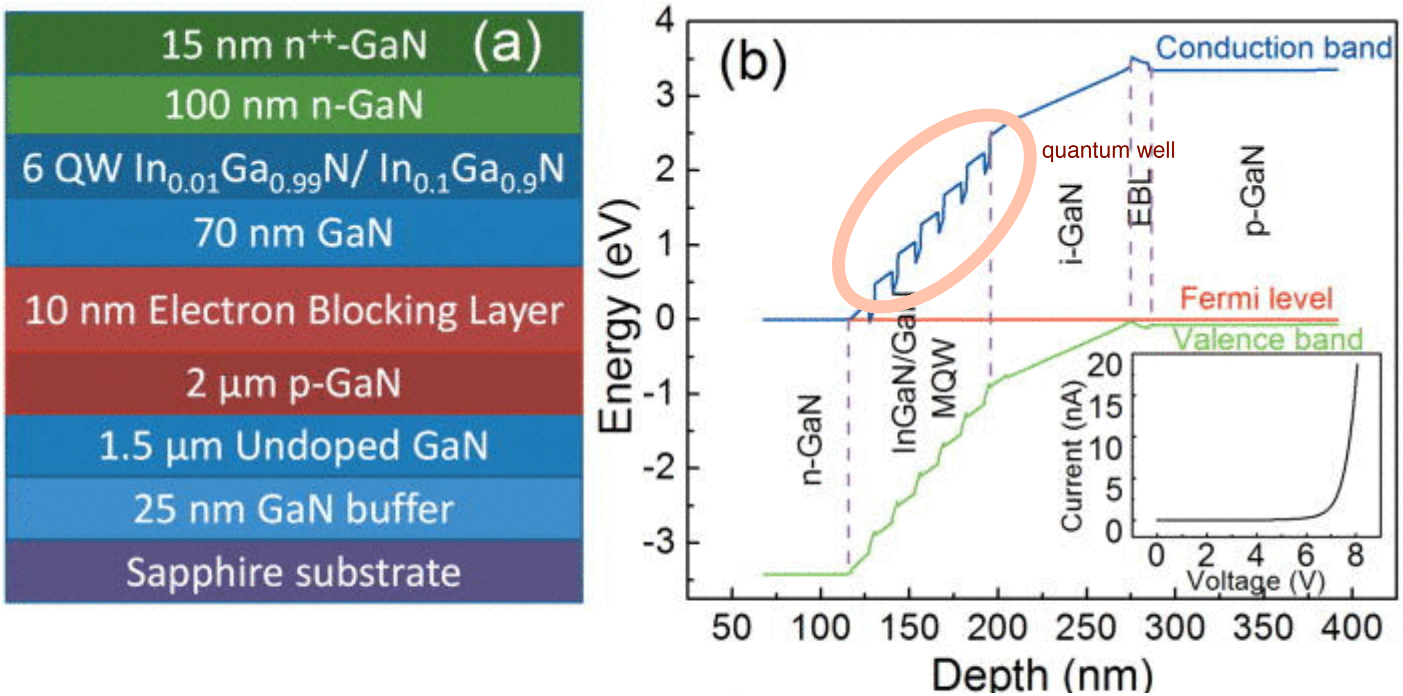
Type-II(Staggered)

Type-II (Broken/ Mis-aligned)

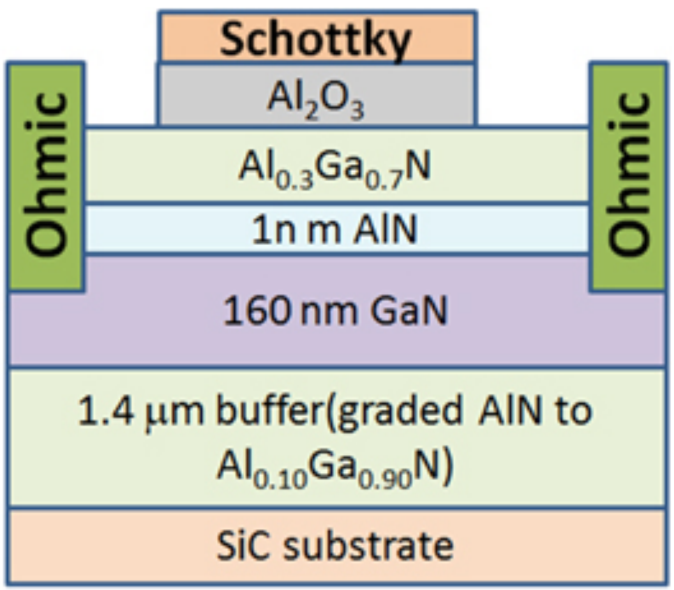
Type-III

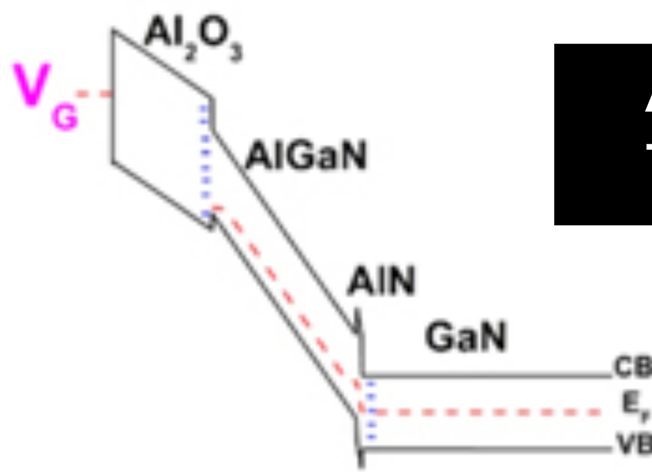
Type-I	Type-II (Staggered)	Type-II (Broken)	Type-III
e- and h+ confinement in the same material	e- and h+ confinement in different materials	e-and h+ confinement in different materials e- and h+ band overlap	Semi-metal with inverted band and semiconductor

Density and Electric Field Modulation



A typical GaN-LED structure





A typical GaN Transistor structure

Heterostructure – LED Advantages

- Carrier confinement
- Photon confinement
- Quantum efficiency – Less re-absorption

when photon is releases it has lower energy than corresponding bandgab ofthe material
bandgap of gan is less than ga al n

- Wavelength tuning – material and quantum-confinement

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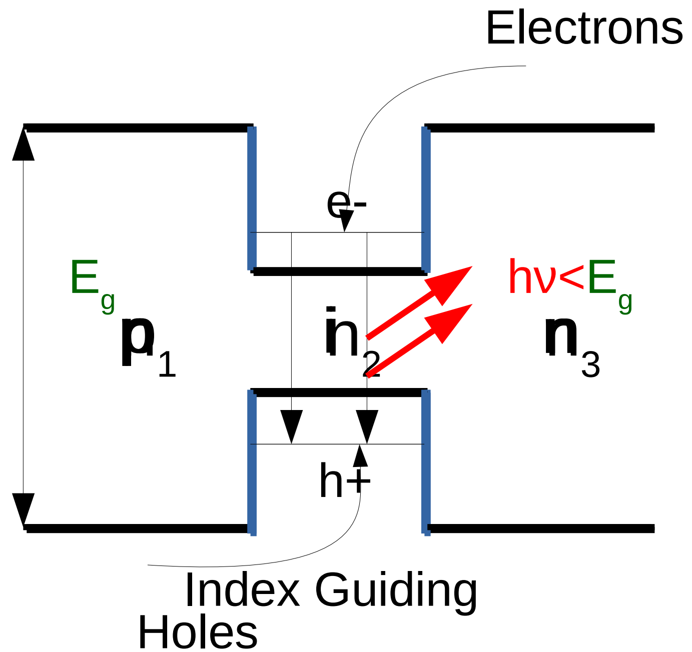
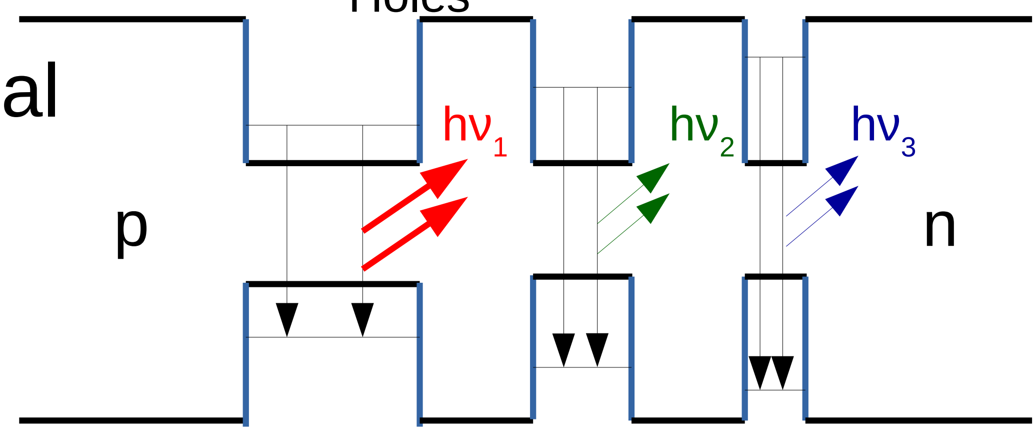
- Multi-colour LED





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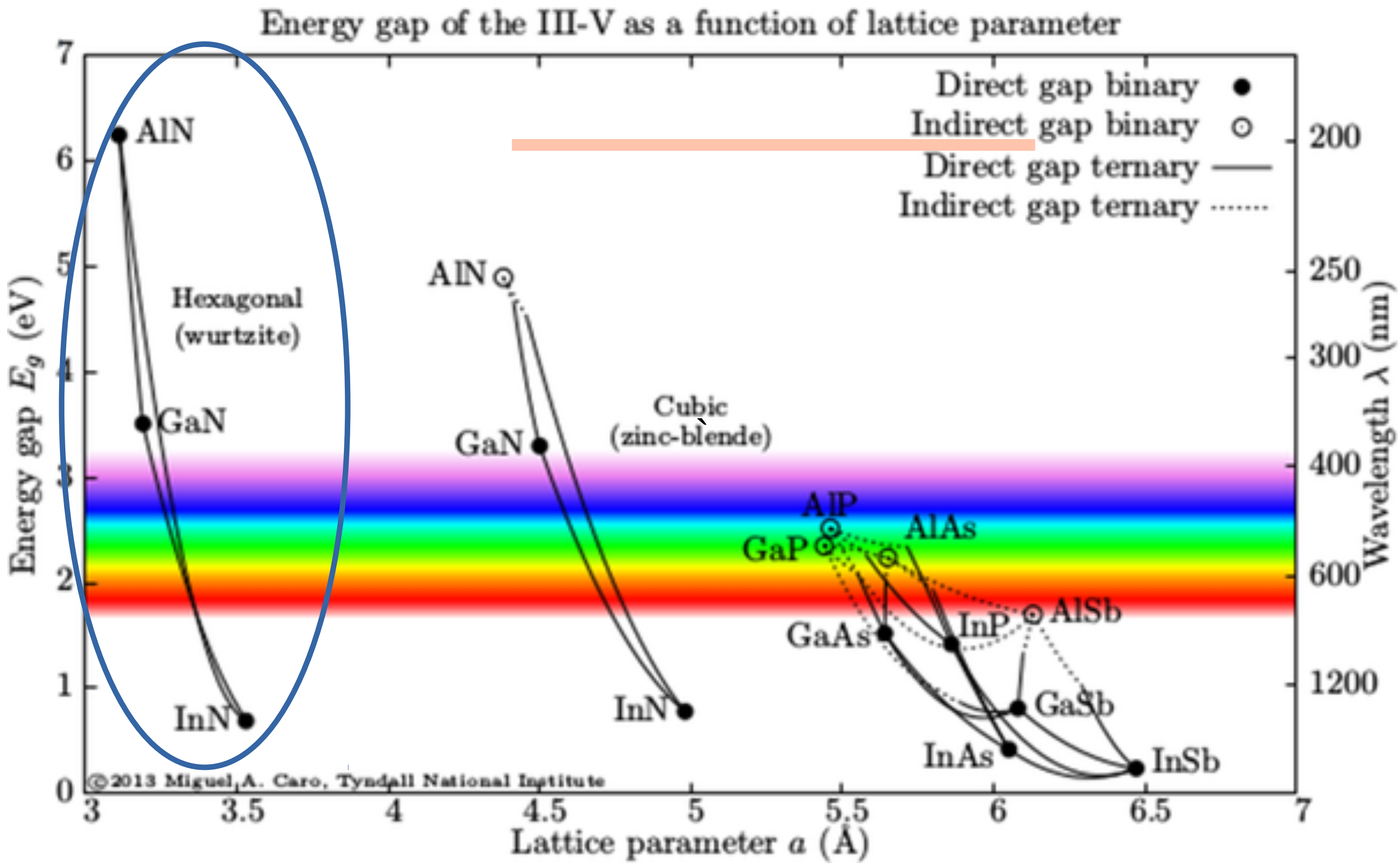
Heterostructure - Applications

- Light emitting/detecting Devices –
  - Wavelength – IR, Visible and UV
  - Devices – LEDs, Lasers and Single photon sources; photo-diodes, solar-cells
  - Applications – Everywhere
  - Strategic Applications require special mention
- Computational Devices
  - Transistors – HEMTs, MESFETs, HFETs, BJTs
  - Speed – few Hz to 300 GHz
  - Applications – Switching and analog applications
  - Strategic applications for MMIC

Why Gallium Nitride (GaN)?

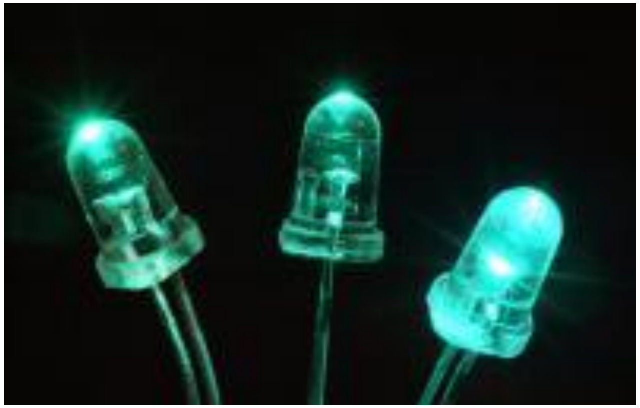


- Energy band-gap – 0.7 eV (InN) to 6.1 eV (AlN)
- Covers IR to UV range – Visible range for lighting
- AlGaN surface states act as donors – high electron density

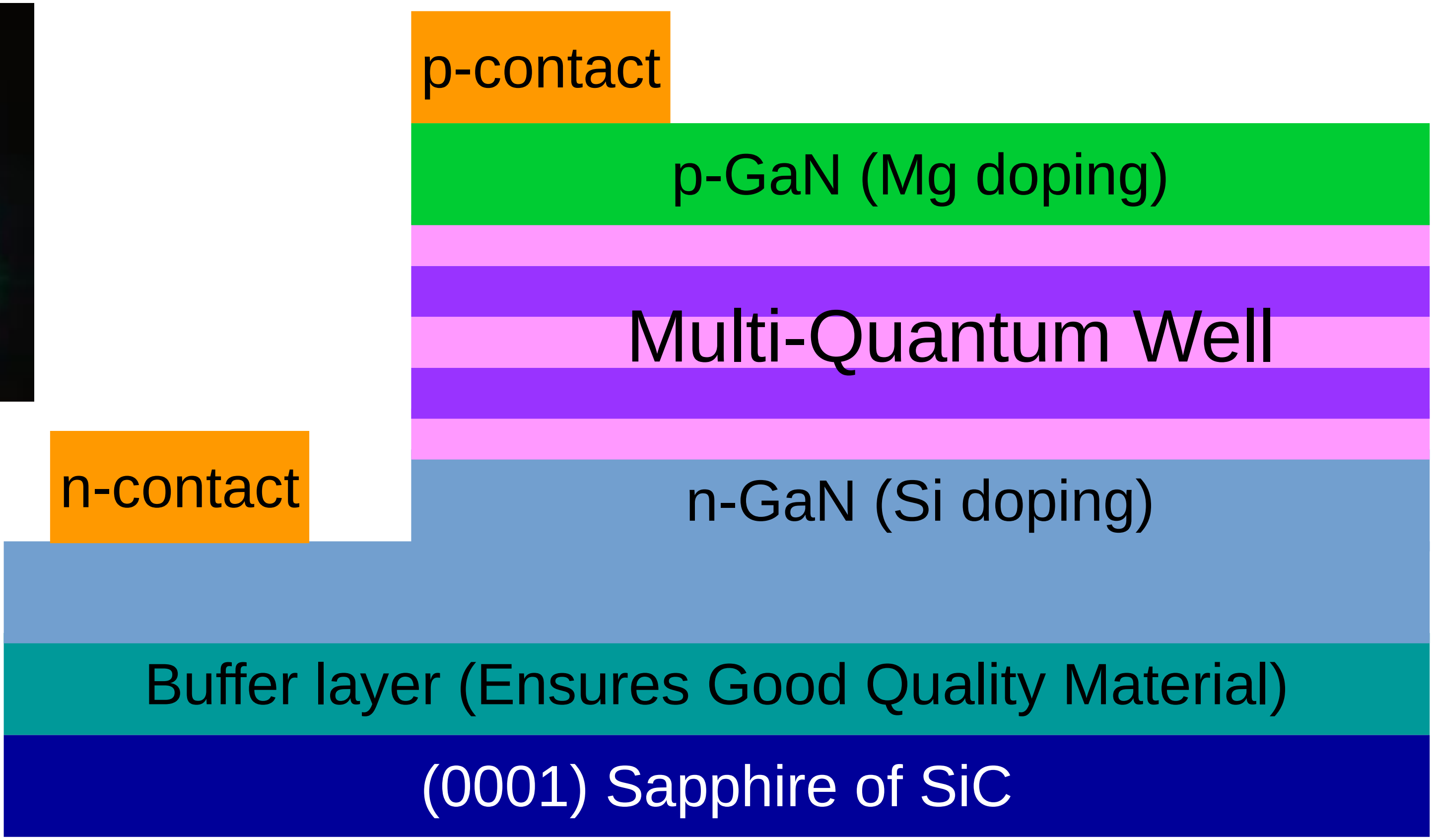
GaN – Superior Material Properties

Attrtibute	Si	GaAs	SiC	GaN
Energy Gap (eV)	1.11	1.43	3.2	3.4
Breakdown Field (V/cm)	6×10^5	6.5×10^5	3.5×10^6	3.5×10^6
Saturation Velocity (cm/s)	1.0×10^7	6×10^6	1.9×10^7	2.5×10^7
Electron Mobility (cm^2/V.s)	1350	6000	800	1600
Thermal Conductivity (W/cmK)	1.5	0.46	3.5	1.7
Maximum Operating Temperature (^oC)	300	300	600	700

GaN LED – Typical Structure



Credit: University of Cambridge



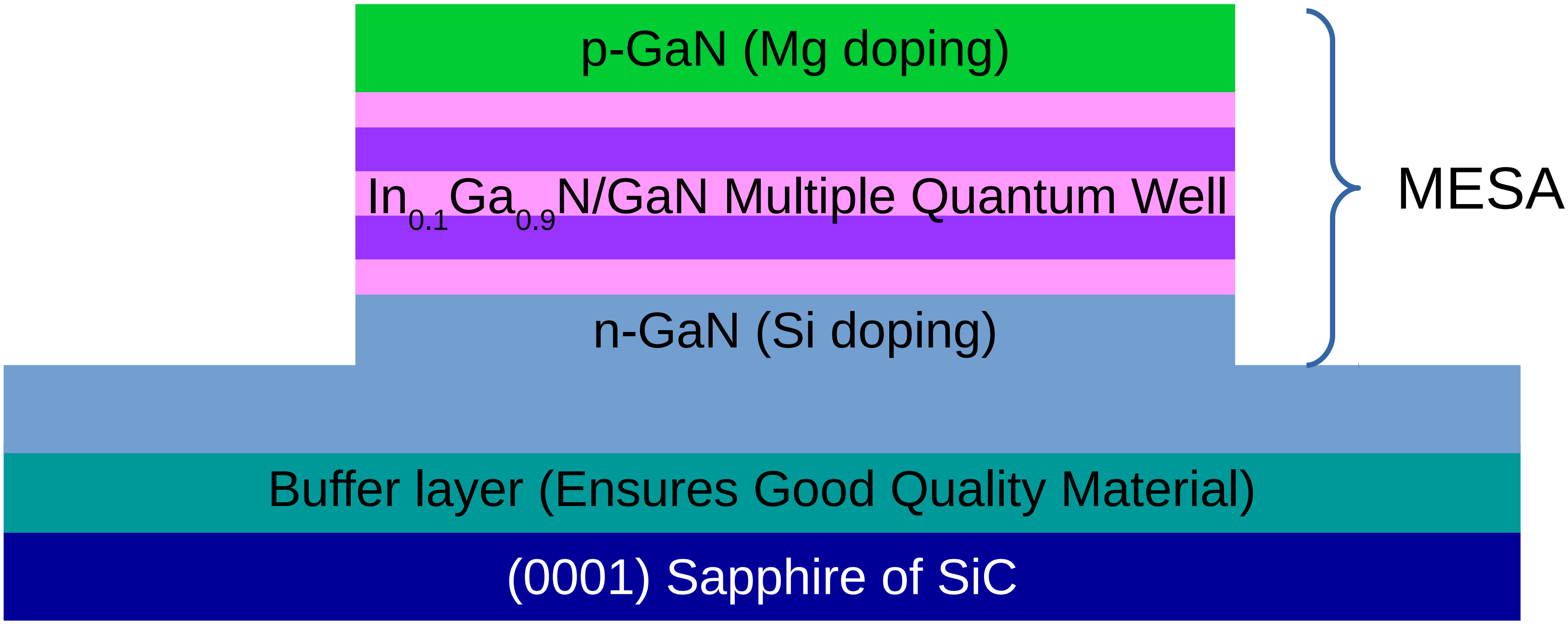
Heart of the device

- p-i-n heterostructure – Grown by MOCVD or MBE
- Three primary steps for fabrication
  - Mesa – Etching by ICP-RIE
  - n-ohmic – Ti/Al/Ni/Au annealed in RTP
  - p-ohmic – Ni/Au annealed in RTP

GaN LED - Design

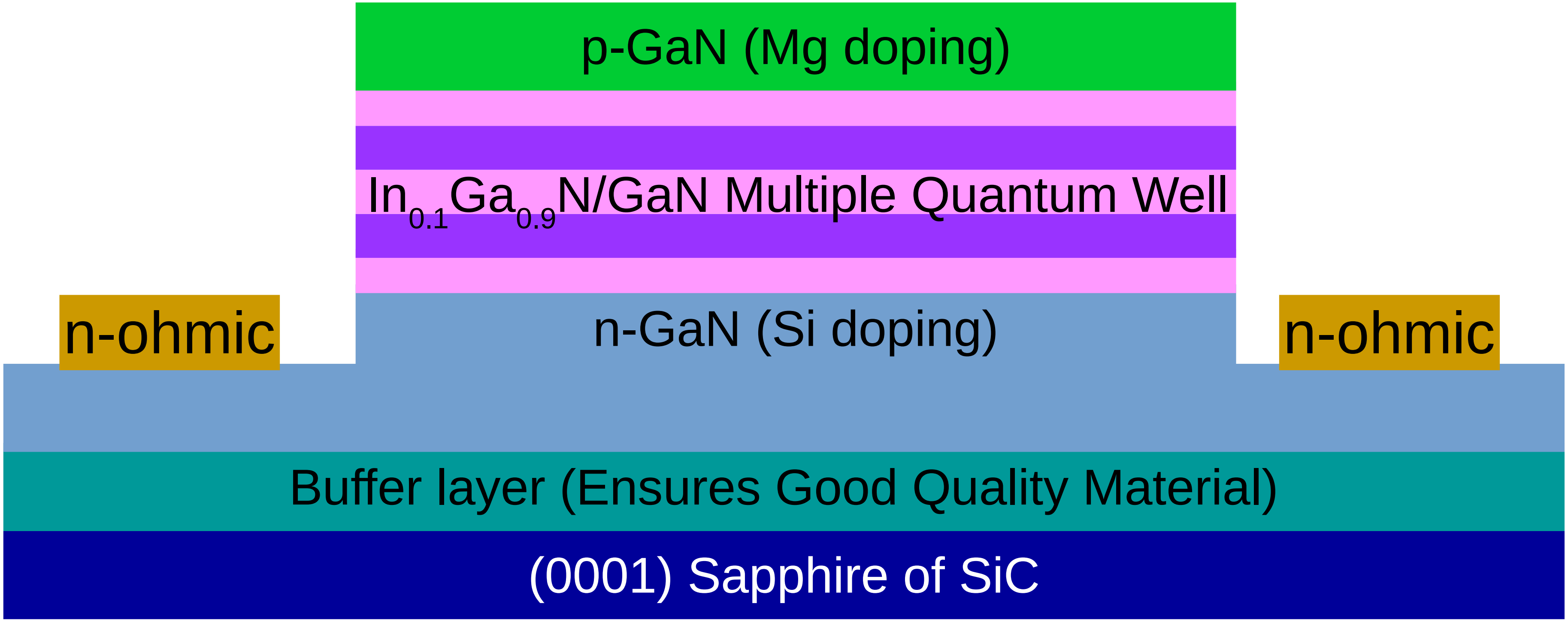
- Wavelength – Choice of material for active region (GaN, AlGaN, InGaN) – Simulation
- Heterostructure – lattice mismatch, Barrier regions, blocking layers, quantum confinement, n- and p-regions
- Nano-structure – Quantum well, wire or dot; dot in a well
- Device topology – Edge emitting, surface emitting (top or bottom)
- Device layout – Mesa size, n- and p-ohmic contact layout
- **Packaging**

GaN LED – Mesa Formation



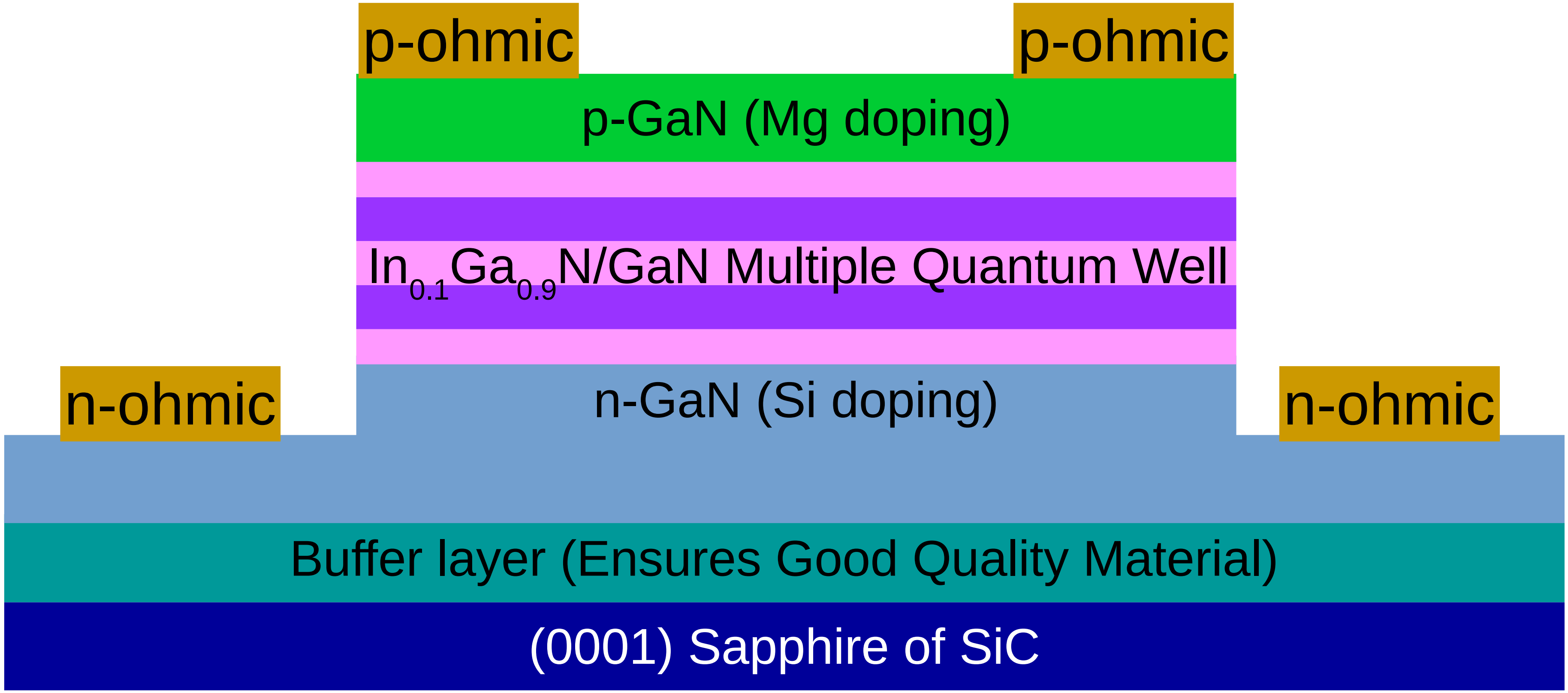
- Expose n-region for contact
- Device isolation
- Low current spreading resistance desired
- $Ar/Cl_2/BCl_3$ etching in ICP-RIE tool

GaN LED – n-Ohmic



- Ti/Al/Ni/Au – 30/100/30/300 nm by e-beam evaporation
- Annealing by rapid thermal process in N_2 environment at ~800 ^{o}C
- TiN formation, N-vacancy in GaN, tunneling current

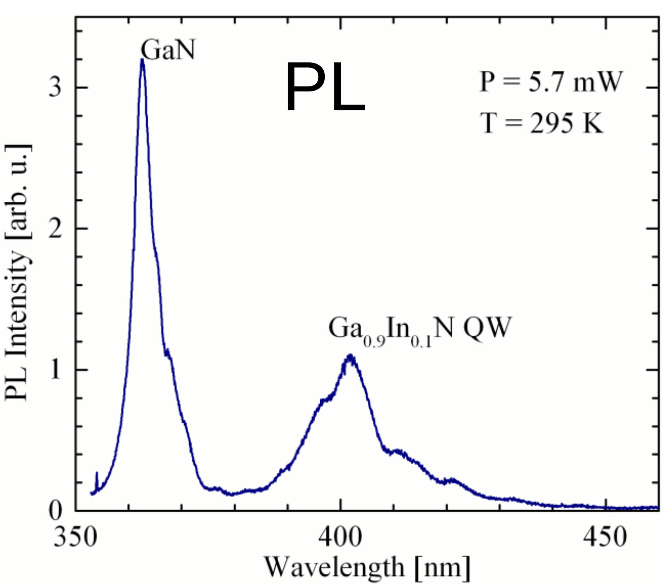
GaN LED - p-Ohmic

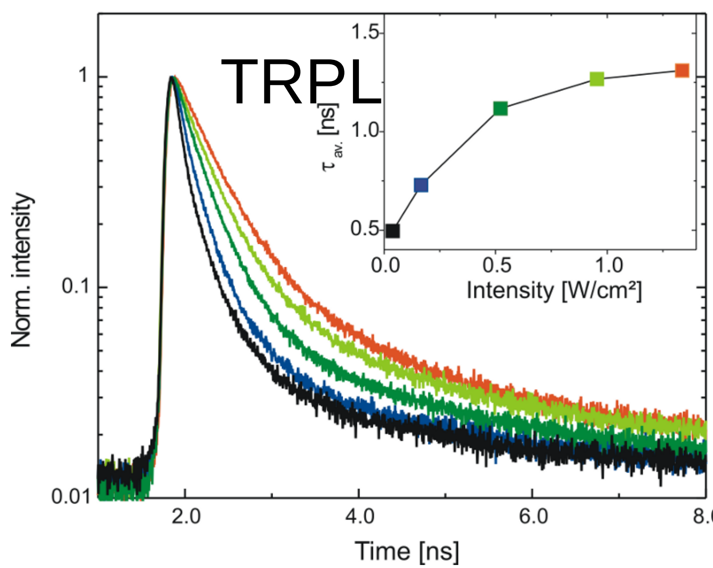


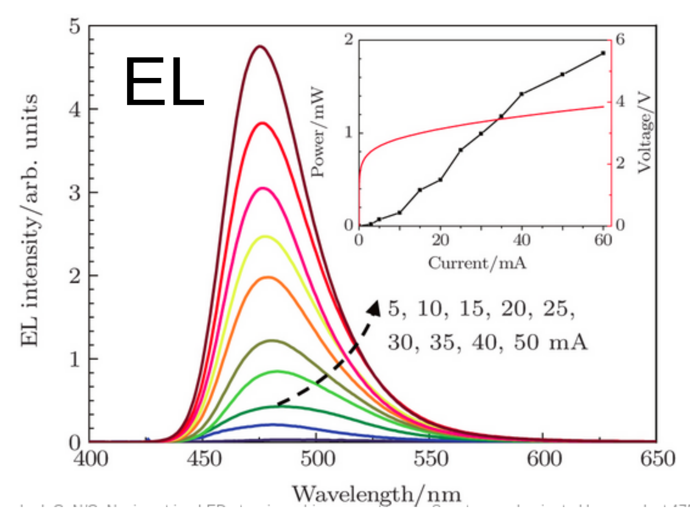
- Ni/Au – 30/30 nm by e-beam evaporation
- Annealing in O_2 environment at 500 °C by RTP
- NiOx formation and tunneling current
- Still a challenge for GaN and high x in $Al(In)_xGa_{1-x}N$

GaN LED Characterizations

- Heterostructure characterizations – Photo-luminescence (wavelength), Time resolved PL
- Device electrical characterizations – I-V, C-V
- Device optical characterizations – Electro-luminescence, LI
- Device performance – Wall-plug efficiency (P_{out}/P_{in}), injection efficiency, internal quantum efficiency, external quantum efficiency







Heterostructure - Characterizations

- Hall Measurements – Doping characterizations
- XRD – Stoichiometry and crystal quality
- SIMS – Si and Mg concentration for n- and p-regions
- TEM – Defects at the interface and crystal quality
- XPS – Band-edge alignment
- EDX – Approximate stoichiometry
- SEM – Physical inspection
- CV and DLTS – Electrical defects

Current Technological Challenges

- Substrate – Sapphire, SiC, GaN, Si
- Packaging – Increase external quantum efficiency
- Efficiency droop – Due to Auger recombination
- Larger In and Al composition in the heterostructure – Green (gap) emission is difficult, UV and IR still a challenge
- Large area uniformity – 30 cm or higher
- p-doping
- Current spreading layer – particularly for p-contact
- Device heating – change in colour

Interesting Research Problems

- Equal carrier distribution in the multi-quantum well structure
- Reduce
-
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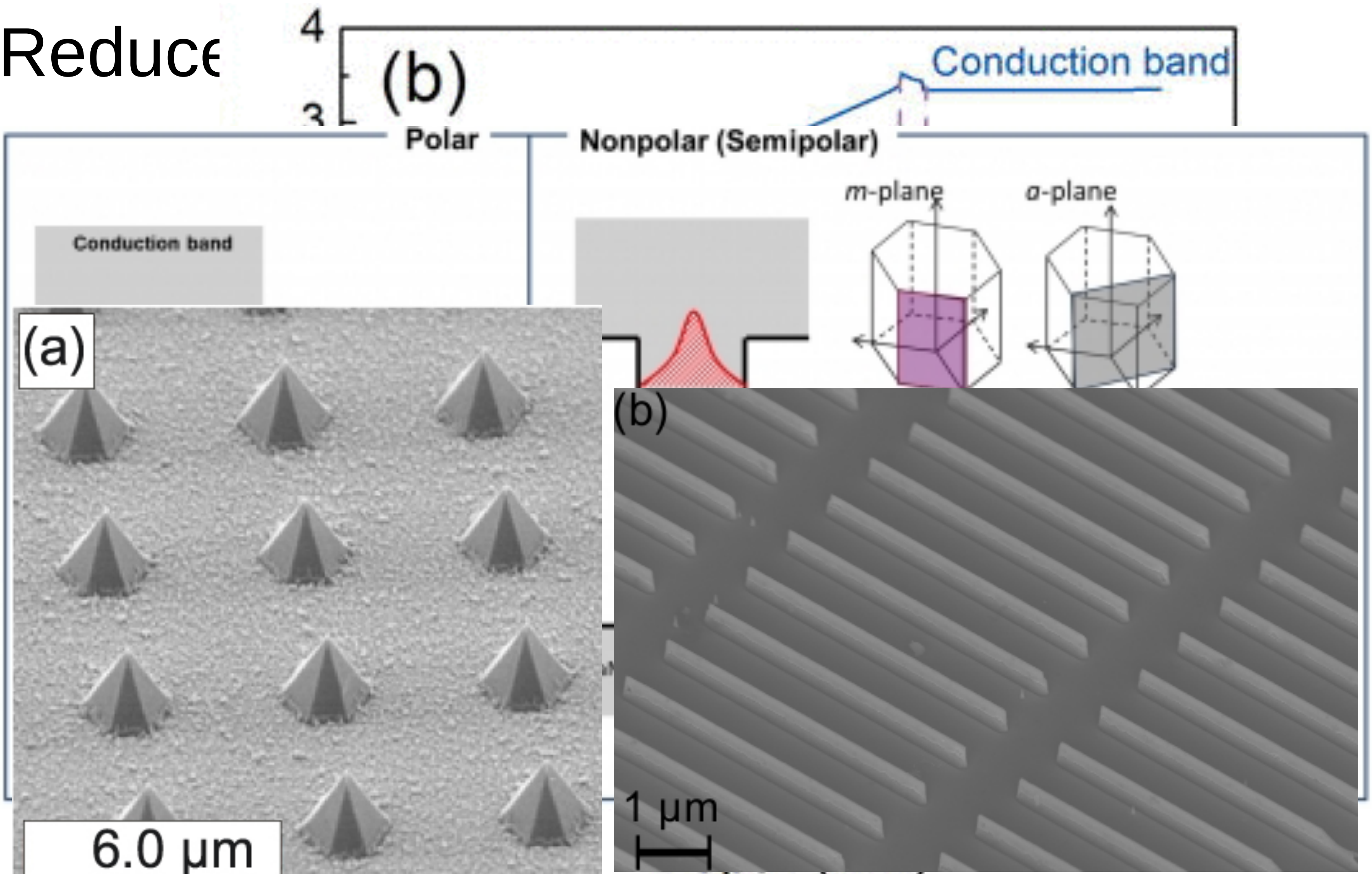

Thank You